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GEOLOGICAL AND GEOTHERMAL MAPPING IN DJÚPAVATN-VIGDÍSARVELLIR AREA, SW-ICELAND

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ABSTRACT

Geological and hydrothermal mapping was carried out in the Djúpavatn–Vigdísarvellir area which is a part of the Krýsuvík-Trölladyngja geothermal area on the Reykjanes Peninsula, SW-Iceland. The bedrock consists mainly of Late Pleistocene hyaloclastites and interglacial lava flows and Holocene lavas. They are divided into 11 hyaloclastite units and 3 interglacial lava flows. The geological age of the volcanic field extends from Holocene, through the last glaciation, the last interglacial period, the 2nd last glaciation, the 2nd last interglacial period, the 3rd last glaciation, and the 3rd last interglacial period. The oldest bedrock units outcrop in the northeast part of the study area and are from the third last interglacial period and third last glaciation, while Holocene lava flows occur in the northwest and east sides of the study area. The Krýsuvík-Trölladyngja area has two main hyaloclastite ridges, with the valley between covered by Holocene lava flows. Two tephra layers were found in the soil section on top of the youngest lava, the earlier from Reykjanes AD 1226 and the latter from the Katla volcano dated from 1485. The tectonics of the study area is controlled by the regional tectonics of the Reykjanes Peninsula. The main structural features are NE-SW trending hyaloclastite ridges. Numerous NE-SW trending normal faults were mapped in the study area. The main geothermal manifestations occur in the southern part of the study area. The alteration ranges from slight alteration to intense and indicates relatively young geothermal activity, but all of it is extinct on surface within the study area.

1. INTRODUCTION

1.1 The study area

Djúpavatn-Vigdísarvellir area is located on the Reykjanes Peninsula, about 30 km south of Reykjavík, the capital of Iceland (Figure 1). The Reykjanes peninsula stretches out into the Atlantic Ocean. The ocean temperature is affected by the so-called Irminger current of the warm Gulf Stream which greatly moderates the climate of Iceland. The area has a relatively high annual rainfall, between 1200 and 2000 mm per year. Winters are temperate with a mean daily temperature in the range between -2°C

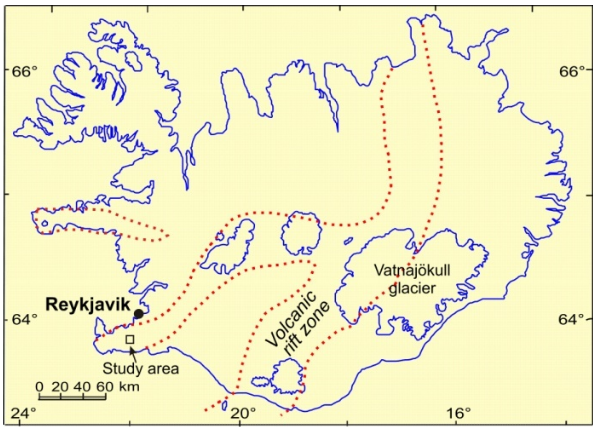

FIGURE 1: Location map of the study area

and -4°C, during the coldest month, while the summers are moderate, with a mean monthly temperature of about 8-10°C (The Icelandic Meteorological Office, 2007).

The present report is a part of the author's 6 month training at the United Nations University Geothermal Training Programme (UNU-GTP) in Iceland. An important part of the training in geological and geothermal exploration was to create a geological map and a geothermal map of the study area, the chief aim of the present study. In 2006, the energy company HS Orka hf, was awarded a ten year long geothermal research licence for the entire Krýsuvík area (Krísuvík area), and is accordingly conducting extensive geophysical and geological geothermal surveys and exploration drilling. The energy potential has been estimated as high as 200-300 MW of electricity.

1.2 Methodology

The main goals of this study were to make geological and geothermal maps of a volcanic field and to find out if a relationship could be established between the tectonic setting and the geothermal manifestations of the study area. The geological mapping exercise was carried out from the 24th of July to the 1st of September, 2009. Instruments and tools used to carry out the field work included the following:

1) A Garmin - GPS 72 to locate and track the structural, stratigraphical and alteration features such as faults, fractures, dykes and stratigraphic boundaries and alteration zonation.
2) Aerial photos and compass used to trace the aerial extent of the major structures and their strike and dip directions and distribution within the study area.
3) A geological hammer, a metric tape and a hand lens used for field inspection of rock samples and unit thicknesses.
4) A shovel, and small plastic sample bags to collect samples from the different alteration zones and different rock units for XRD and petrographic studies, in order to figure out the degree of alteration and the mineral assemblages that exist in the hydrothermally altered areas, and also to differentiate and correlate the different rock units from outcrop to outcrop in the study area.

1.3 Previous work

The study area has been explored intermittently by many geo-scientists over the last few decades. Most of this exploration work was done for geothermal exploration purposes. Reference is made to only a few reports and papers, most of which are written in Icelandic. A regional geological map was published by Orkustofnun after many years of mapping by Jónsson (1978), who mostly was sorting out the sequence of Holocene lavas of the Reykjanes peninsula at large. Later, a geological map on the scale 1:250,000 was published (Saemundsson and Einarsson, 1980). Several geothermal studies have been undertaken since the 1950s. Some 20 shallow exploration wells were drilled before 1950 as a part of the first exploration effort. These wells were mostly drilled within the Krýsuvík, Seltún and Austurengjar subfields, and identified with H as a prefix of the drillhole series (later identified as KV-series). In the early 1970s, four additional exploration wells were drilled there, identified as KR-1, KR-2, KR-3 and KR-4. This important exploration programme was described by Arnórsson et al. (1975) also including description of 4 new wells, KR-5, KR-6, KR-7 and KR-8. Wells KR-7 and KR-8 are within the range of the present study area. Additional work was done in the early 1980s, including a resistivity survey. A review report on the geothermal knowledge of the Krýsuvík-Trölladyngja area was published by Orkustofnun in 1986 (Flóvenz et al., 1986), focussing to some extent on well KR-6, and manifestations in the Sog geothermal field, partly described last year by Al-Dukhain (2008) and Mbogoni (2008). Other work includes reports by several UNU Fellows who have done practical training within the Krýsuvík-Trölladyngja area in surface and subsurface geology (Muhagaze, 1984; Kifua, 1986). A report on ideas of potential steam production and transmission to an energy park was published by Orkustofnun (Ármannsson et al., 1994).

The earlier reports (ISOR database) reported a maximum logged temperature in the Krýsuvík area as high as 260°C in well KR-06. Using geothermometry, the maximum quartz temperature was calculated as 261°C, Na/K temperature as 261°C and gas temperature as high as 285°C (Arnórsson, 1987). A recent exploration effort involved a detailed TEM resistivity survey of the Trölladyngja field (Eysteinsson, 2001), followed by drilling of two deep wells: TR-01 in 2001 (Fridleifsson et al., 2002) and well TR-02 in 2006 (Kristjánsson et al., 2006, Mortensen et al., 2006). Temperature logging showed in well TR-01 values up to 360°C at 2300 m depth and 320°C in well TR-02 at the depth 2200 m (ISOR database). More recently, additional resistivity data has been collected (Hersir et al., 2009). Data from some of these reports were used in the present study to assist in creating a geological-geothermal model of the study area, which is a direct southward extension of the field area mapped and studied by Al-Dukain in 2008.

2. GEOLOGICAL SETTINGS

Iceland lies astride the Mid-Atlantic Ridge and is an integral part of the global mid-oceanic ridge system. It is the largest landmass of the mid-oceanic ridge system above sea level. Iceland developed on the Mid-Atlantic Ridge as a result of interaction between the dilating plate boundary and a rising mantle plume which has been active during the last 20-25 million years (e.g. Saemundsson, 1979). Being a hot spot above a mantle plume, Iceland has been piled up through voluminous emissions of volcanic material with a much higher production rate per time unit than in any other region in the world. Accordingly, the western part of Iceland, west of the volcanic zones, belongs to the North American plate and the eastern part to the Eurasian plate. The oldest rock outcrops are in Northwest and East Iceland. There are also rocks of similar age in West Iceland and in the centre of North Iceland due to rift jumps associated with the continuous movement of the mantle plume. The rate of spreading has been observed as close to 1 cm/year in each direction (e.g. Gudmundsson and Högnadóttir, 2007 and references therein).

2.1 General aspects of the geology of Iceland

Iceland is built almost exclusively of volcanic rocks, predominantly basalts. Silica and intermediate rocks, rhyolites, dacites and andesites constitute about 10% and volcanogenic sediments another 10% (Saemundsson, 1979). Icelandic rocks can be divided into four main formations (Figure 2):

- The Upper Tertiary plateau basalt formation;
- The Upper Pliocene and Lower Pleistocene grey basalt formation;
- The Upper Pleistocene palagonite (hyaloclastite) móberg formation; and
- The Postglacial Formation, which besides postglacial lavas includes sediments such as till and glacial sediments from the retreat of the last ice cover, marine, fluvial and lacustrine sediments and soils of Late Glacial and Holocene age.

The Tertiary basalt formation comprises East and Southeast Iceland, the main part of West Iceland and the western part of North Iceland, altogether about half the country's area (Figure 2). In East Iceland, basaltic lava flows, mainly tholeiitic, comprise about 80% of the volcanic pile above sea-level, which has a stratigraphic thickness of about 10,000 m. Silicic (rhyolitic) and intermediate rocks and detrital beds form the rest. Dykes are common and intrusions of gabbro and granophyres occur, exposed within the eroded central volcanoes (Fridleifsson, 1983). Beds of tephra and ignimbrite are found in and around many of the central volcanoes. So far, the oldest rocks above sea level that have been K/Ar dated are about 16 million years old. Thus, the oldest basalts are no older than Middle Miocene and much younger than the basalts in Britain, Greenland and the Faroe Islands. In the Tertiary Icelandic basalts, lava vesicles are commonly infilled by alteration minerals such as rock crystal (quartz), jasper and chalcedony, calcite, or with zeolites.

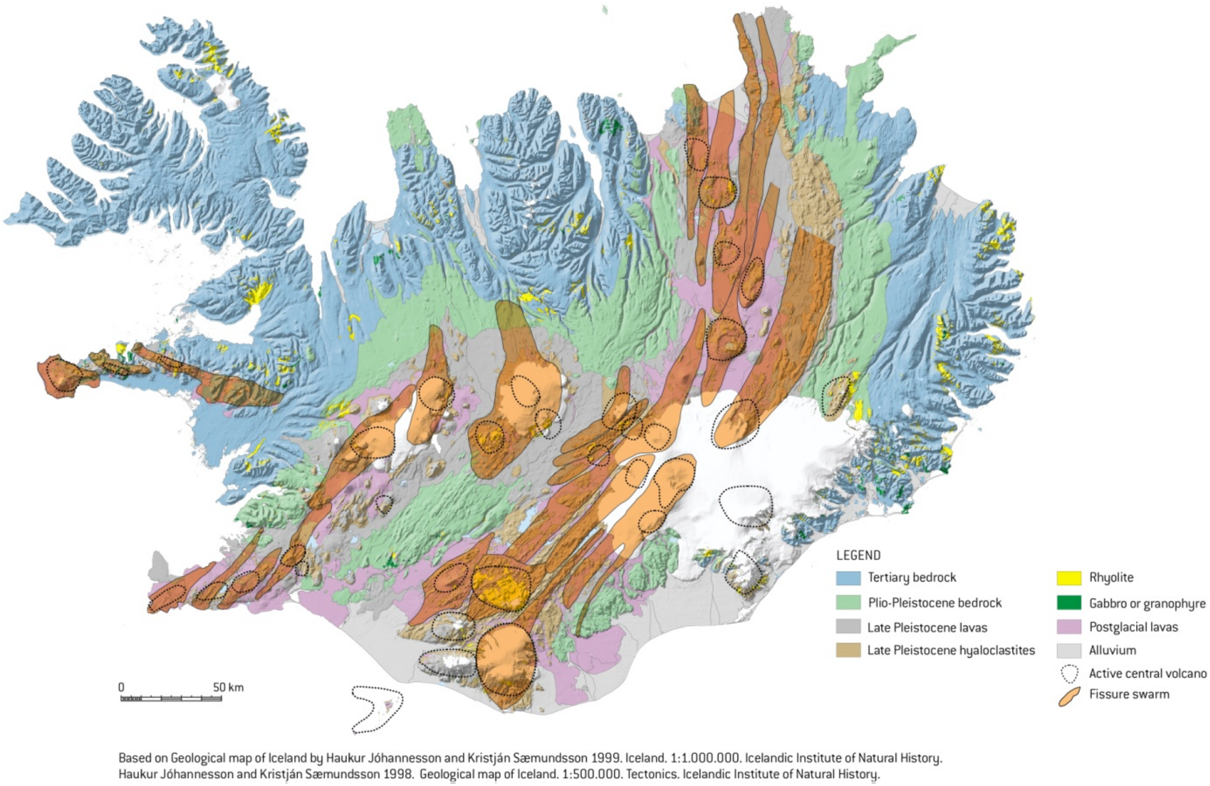

FIGURE 2: Geological map of Iceland (Jóhannesson and Saemundsson, 1999)

Intercalated between the plateau basalts, especially in Northwest Iceland, are plant-bearing sediments and thin layers of lignites. Species found include beech, maple, vine, liriodendron and conifers. The mixed forests of conifers and warmth-loving broad-leaf trees indicate a warm-temperate climate. The warmth-loving trees gradually disappeared during the Miocene when the climate slowly grew cooler and the first glacial sediments, tillites, turned up. The thin layers of lignites are inferior in quality as fuel seams, although they have been used on a small scale in some places (Saemundsson and Gunnlaugsson, 2002).

Pleistocene rocks are confined mainly to a broad SW-NE trending zone between the Tertiary plateau basalt areas, and are also exposed on Tjörnes, Snaefellsnes and Skagi (Figure 2). Pleistocene rocks are divided into two formations and the limit between them is set at the last magnetic reversal, occurring about 800,000 years ago (Saemundsson, 1979). The Pleistocene formations show three main facies:

(i) Interglacial basalt lava flows which are generally grey in colour and of coarser texture than Tertiary ones;
(ii) Subglacially formed pillow lavas, breccias and brownish tuffs, known as palagonite (móberg), and rich in hydrated and otherwise altered basaltic volcanic glass (hyaloclastite), and;
(iii) Glacial, fluvial, lacustrine and marine sediments that are interbedded within the volcanic strata. The thickest series of marine strata are found on the Tjörnes peninsula in North Iceland.

Stratigraphic studies indicate about 30 Upper Pliocene and Pleistocene glacial periods. During the main periods, the country was almost completely covered by ice. Broad-leaf and conifer forests disappeared during the Lower Pleistocene, but birch, willow and rowan survived all the glacial periods, and alder survived all but the last two.

During the Pleistocene glacial periods, thick ice blanketed the volcanic activity, which consequently took place mainly under water (melt water) and thus under conditions similar to the submarine parts of the World Rift System. The volcanoes which built up subglacially in the volcanic zones mainly depict two types: hyaloclastite ridges and hyaloclastite table mountains. The ridges are steep-sided and serrated and run in parallel lines, NE-SW in South Iceland, and N-S in North Iceland. Table mountains are isolated mountains, circular to sub-rectangular. The tops of these mountains consist of shield lavas resting on an accumulation of pillow lavas and palagonite tuffs and breccias from the earlier volcanic phases of the same eruptions. The lava shields were formed by subaerial outflow of lava when the accumulations had grown high enough to protrude through the ice cover (Gudmundsson and Högnadóttir, 2007).

2.2. Regional geology of the Reykjanes peninsula

At latitude 63°48'N, the Reykjanes ridge comes onshore at the Reykjanes Peninsula. The ridge bends gradually eastwards between longitudes 24°30'W and 23°30' W until it is oriented approximately 30° oblique to the direction of plate motion (DeMets et al., 1994). A major ridge jump approximately 6-7 million years ago initiated active spreading on the Reykjanes Peninsula (Jóhannesson, 1980). The peninsula is characterised by arrays of eruptive fissures, spaced on average approximately 5 km apart, and having an average strike of 40°E. Volcanism takes place mainly within four fissure systems along the peninsula (Jakobsson, 1972) (Figure 3). The tectonic map in Figure 3 shows fissure swarms (black lines), eruptive fissures (red lines), strike slip faults (green lines), and the approximate location of the plate boundary (dashed line), and geothermal centres (blue stars). The four volcanic systems are shown in grey shading and black ellipses.

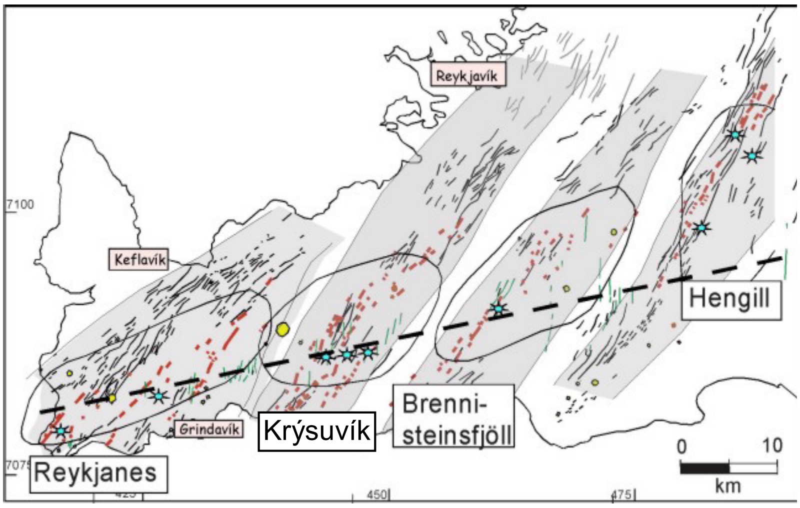

FIGURE 3: Fissure systems on the Reykjanes Peninsula (Clifton, 2006)

Several rock units of different ages and lithology cover the Reykjanes peninsula, including postglacial basaltic lavas, interglacial lavas, hyaloclastites and tuffaceous sediments beside other glacial and recent sediment. Most of the mountains on the Reykjanes Peninsula are composed of basaltic hyaloclastites, formed by subglacial eruptions. Highly permeable rock formations, tectonics, low elevation and high precipitation combined with high heat flow from the ridge axis result in active high-temperature hydrothermal systems. These systems are localized at the surface within the volcanic fissure swarms, and produce surface or near surface alteration which varies from "spotting" of the basalt by silica, calcite and low temperature zeolites to complete replacement by clay minerals within extinct or active fumarolic fields.

2.3 Earthquakes on the Reykjanes Peninsula

The Reykjanes Peninsula and the South Iceland Seismic Zone are left lateral shear or transform fracture zones that connect the Reykjanes ridge and the Eastern Volcanic Zone which runs through central Iceland. The Reykjanes peninsula is an oblique shear zone. On June 17, 2000 at 15:40:41 GMT, the South Iceland Seismic Zone was shaken by a 6.5 Mw event (Clifton et al., 2003). Within seconds, swarms of smaller earthquakes were triggered westward from the main shock epicentre over 100 km of the plate boundary. Three of the largest rocked the central part of the Reykjanes Peninsula. These three events were spaced approximately 10 km apart and occurred within 5 minutes of one another. During the following year, fieldwork was conducted in a 420 km^2 area encompassing the epicentres of those earthquakes to examine the surface effects of each in order to better constrain fault characteristics (Clifton et al., 2003).

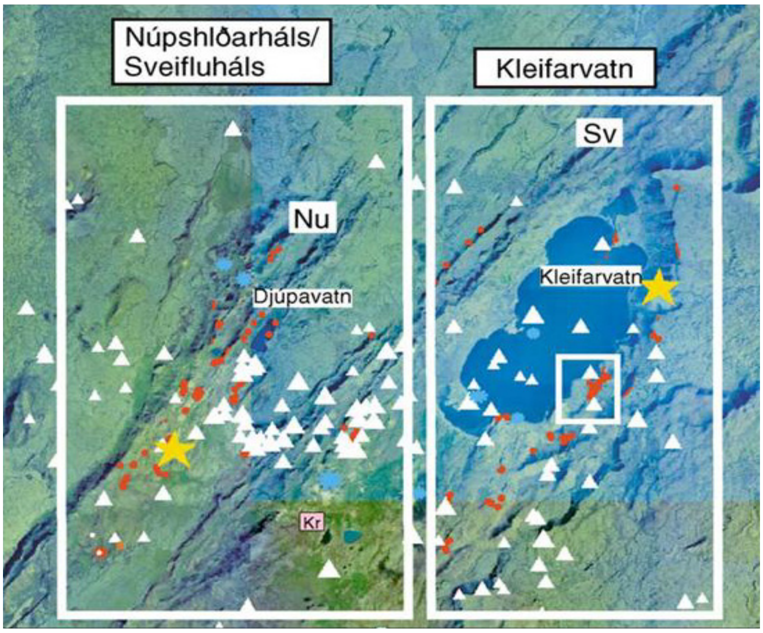

FIGURE 4: Earthquake events in the Krýsuvík area (Clifton et al., 2003)

Widespread rock falls and minor surface ruptures occurred along the Núpshlídarháls ridge (Figure 4) just west of Djúpavatn, and in the vicinity of the present field area. Minor, sub-vertical fault surfaces were found close to the base of the west-facing slope, and open fissures were found at all elevations. The fissures, with openings on the order of centimetres, generally followed the topography, indicating that they were related to rotational or translational block sliding of slope material. Rock falls and block sliding were observed on several steep slopes between Djúpavatn and the earthquake epicentre 3 km to the south. The intensity of deformation decreased towards the south and concentrated along north-trending structures which crosscut the central segment of the northeast trending volcanic ridge. This same segment of the ridge crosses the high-temperature geothermal area, and is at the centre of maximum volcanic production.

On the Sveifluháls ridge, separated from Núpshlídarháls by a 1 km wide valley, large blocks fell from the most unstable and highest cliffs. Evidence of possible fault reactivation was found on a low platform overlying the geothermal area on the eastern side of the ridge. A 200 m long series of linear pressure ridges trending N23°E defined a previously unmapped fault segment. Fresh openings were observed at the base of the pressure ridges within grass-filled fissures and in soils between them. The importance of this discussion relates to the author's study area, where the mapping of young and/or active faults and fissures was undertaken.

2.4. Groundwater and hydrological aspects of Reykjanes Peninsula

Precipitation on the Reykjanes Peninsula (Trölladyngja area) is high (1500-2000 mm/year; The Iceland Meteorological Office, 2007) and all the water percolates deep into the bedrock through faults, open fissures and fractures as well as through the porous lava flows. Some of the precipitation percolates deeper into the geothermal system, but the bulk of it flows laterally along faults and permeable horizons before it discharges at Straumsvík and Vatnsleysuvík, north of the area

(Sigurdsson, 1986). Anisotropy is apparent with higher permeability along faults rather than across them. Relatively low permeability, with an associated low infiltration rate in the hydrothermally altered hyaloclastite ridges, builds up a high groundwater table. In places where the water table is intersected by gullies, and/or faults at low ground, cold springs or seepages may appear, witnessing groundwater tables, which may be true or false. These springs and seepages sustain small stream run-offs which eventually disappear into the lava flows at the foot of the hyaloclastite ridges. The springs, seepages and lakes are used as markers of the groundwater table at various elevations. The groundwater outflow from the Reykjanes peninsula is estimated to be 30-70 m^3/s, depending on the definition of the area, distribution of precipitation and the rate of evaporation (Sigurdsson, 1986). On the extensive lava fields in the western part of the peninsula and at its northern coast, the groundwater level is low, only 1-3 m above sea level. That means the fresh water is floating as a thin layer, 30-100 m thick, on top of a groundwater-sea mixture in the rocks (Sigurdsson, 1986).

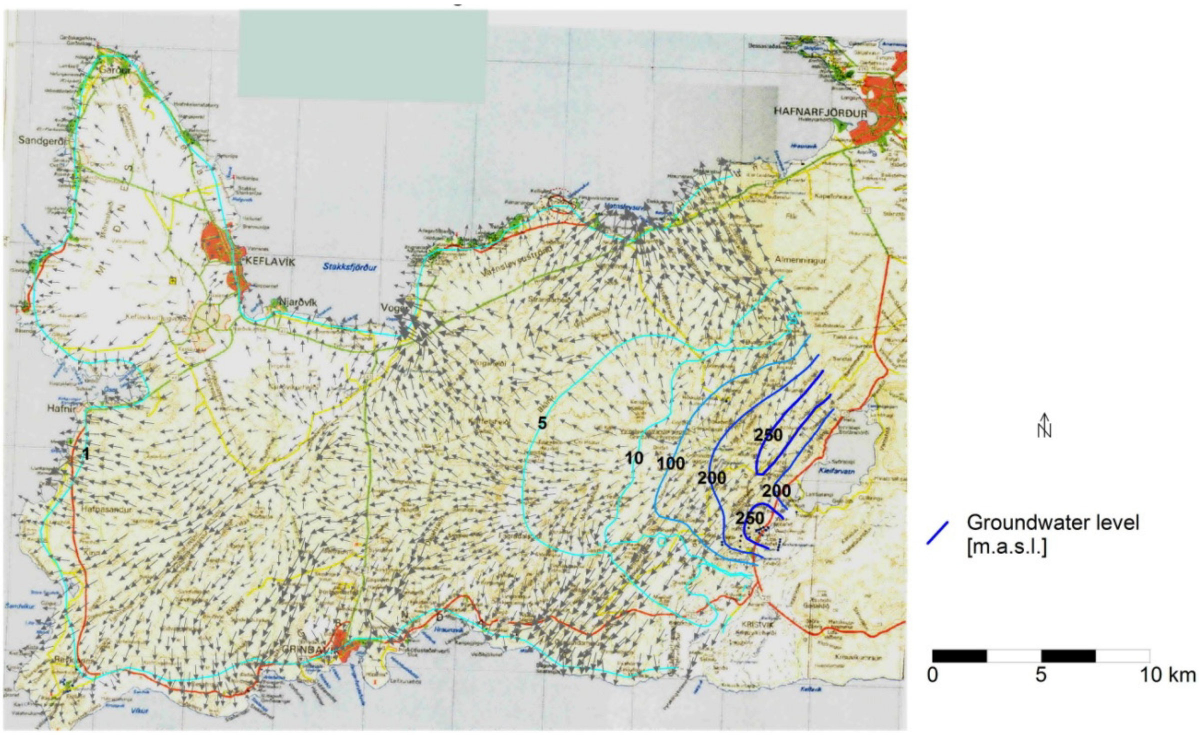

FIGURE 5: Calculated water contours (dark/blue lines) of the Reykjanes Peninsula in metres above sea level (m a.s.l.); the arrows show the groundwater flow directions (Vatnaskil, 2009)

The contours shown on the map in Figure 5 indicate that the water table varies between 5 and 200 m a.s.l., and in the present field area the groundwater table is close to Lake Djúpavatn's elevation, ~200 m a.s.l. The maximum depth of Lake Djúpavatn is 16.7 m. Nine cold springs were found and mapped by the author in the Djúpavatn-Vigdísarvellir area; eight springs are located in the middle of area and one is just west of Djúpavatn. The temperature of these springs ranges between 5.6 and 11.0°C and the water flow ranges from 0.5 to 8 l/s.

2.5 Resistivity in the Krýsuvík area

The typical resistivity in basaltic rocks in Iceland above the water level is 5,000-50,000 Ωm, in recent lava flows, 1000-1500 Ωm in water saturated basalts and 100-300 Ωm in palagonite. In high-temperature geothermal fields the typical resistivity is 1-5 Ωm. Several resistivity surveys have been done in the Krýsuvík area, most recently in 2007 and 2008. The results have been summarised by Hersir et al. (2009). These results were used to assist with the current geothermal modelling. Several cross-sections from this TEM and MT survey cross the study area. Cross-section SA7, trending NW-

SE, is shown as an example (see map and section in Figure 6). In simplified terms, it shows high resistivity in the uppermost 300 m but low resistivity from there down to 900 m, where the resistivity starts to increase again. The resistivity pattern, together with the surface alteration pattern, the tectonic pattern and temperature information from the drill holes within the field area, were used to create a hydrothermal model of the field.

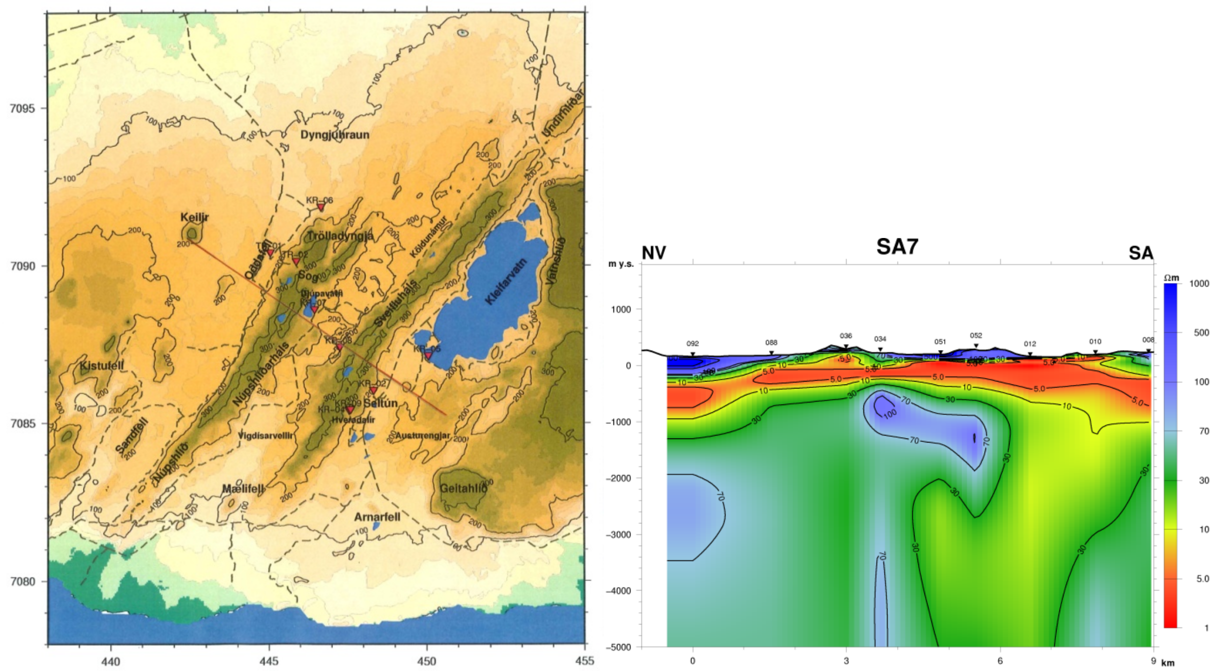

FIGURE 6: Resistivity measurements in the area, a) Map showing locations of wells and cross-section SA7; b) Cross-section SA7, trending NW-SE through the area (Hersir et al., 2009)

3. GEOLOGICAL MAPPING OF THE DJÚPAVATN–VIGDÍSARVELLIR AREA

The Djúpavatn-Vigdísarvellir area is a part of the Krýsuvík-Trölladyngja high-temperature geothermal area on the Reykjanes Peninsula. The low and flat lands are predominantly covered by Holocene lava flows covering the older hyaloclastite formation at low grounds, and in places alluvium erosional deposits below the mountain slopes. The topography is dominated by NE–SW trending ridges formed by different units of hyaloclastites, which are all products of subglacial eruptions. The elevation is between 200 and 300 m a.s.l. These mountains are considered to have formed during the last 2-3 glaciations (Jakobsson and Gudmundsson, 2008). The thickness of ice covering the area during the last glaciation was estimated to be around 300 m (Arnórsson et al., 1975; Abdelghafoor, 2007). The generally accepted geological time scale of concern in discussing the volcanic activity in the area is now as follows (e.g. EPICA Community Members, 2004):

Holocene	~ 0-11,700 years
Last glaciation (Weichsel)	~ 11,700-110,000 years
Last interglacial period (Eemian)	~ 110,000-130,000 years
Second last glaciation (Saale)	~ 130,000-200,000 years
Second last intergl. period (Holstein)	~ 200,000-240,000 years
Third last glaciation (Mindel)	~ 240,000-300,000 years
Third last interglacial period	~ 300,000-340,000 years

3.1 The bedrock units

The bedrock of the area consists of NE-SW trending hyaloclastite ridges. The rock units in the Djúpavatn-Vigdísarvellir area are hyaloclastites, interglacial lava flows and Holocene lavas, all of which were mapped, and are presented on the geological map in Figure 7. Three geological cross-sections are also presented in Figure 8. The units are made of fragmented glassy basalts (hyaloclastites) erupted within the confines of glacial ice where the material piled up but did not flow out like the subaerial basaltic lavas do during ice-free periods like today. Eleven eruptive hyaloclastite units and 3 interglacial lava flows were mapped. The oldest rock units are found within the northeast part of the study area and are from the third last interglacial period and the third last glaciation.

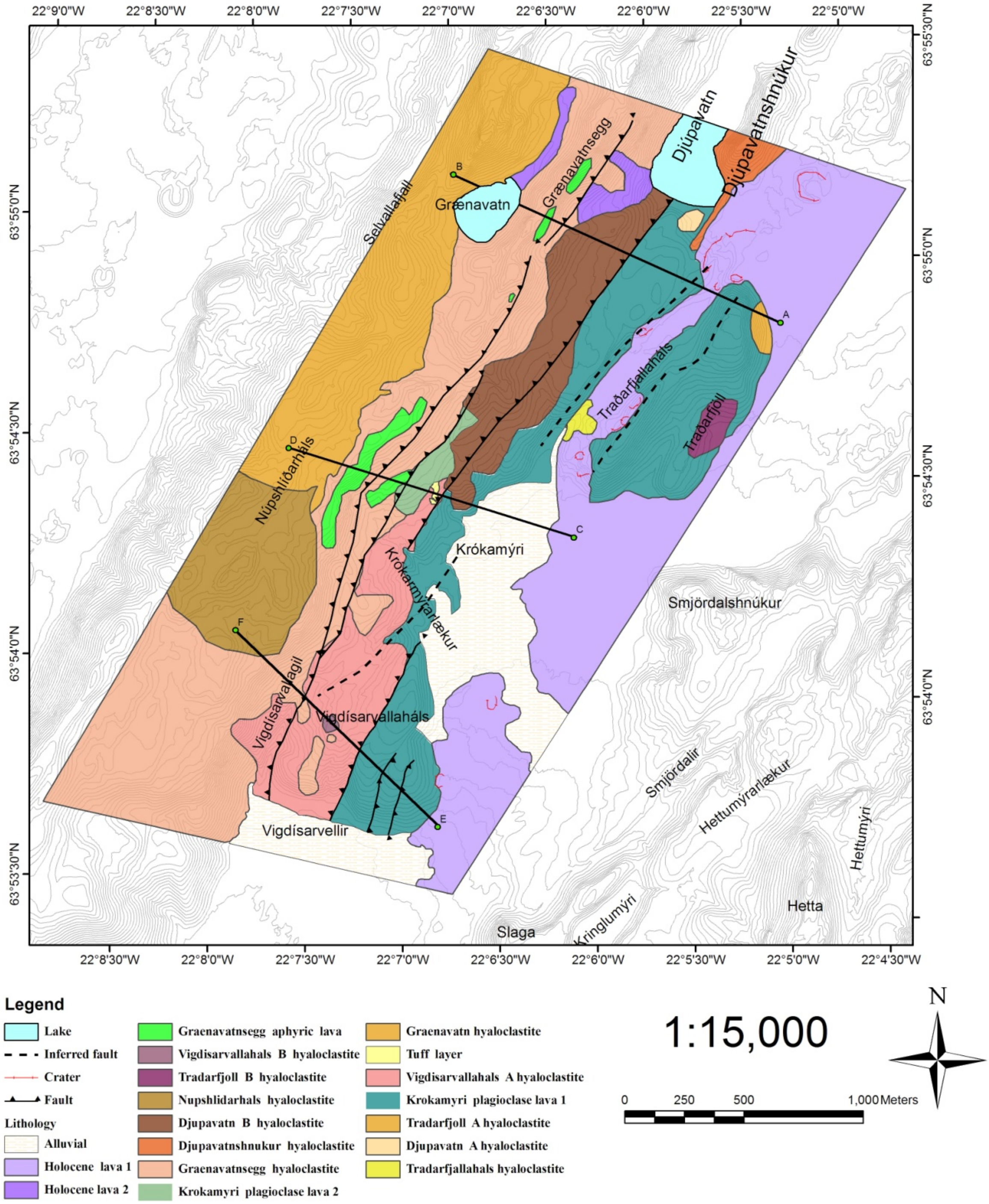

FIGURE 7: Geological map of the study area

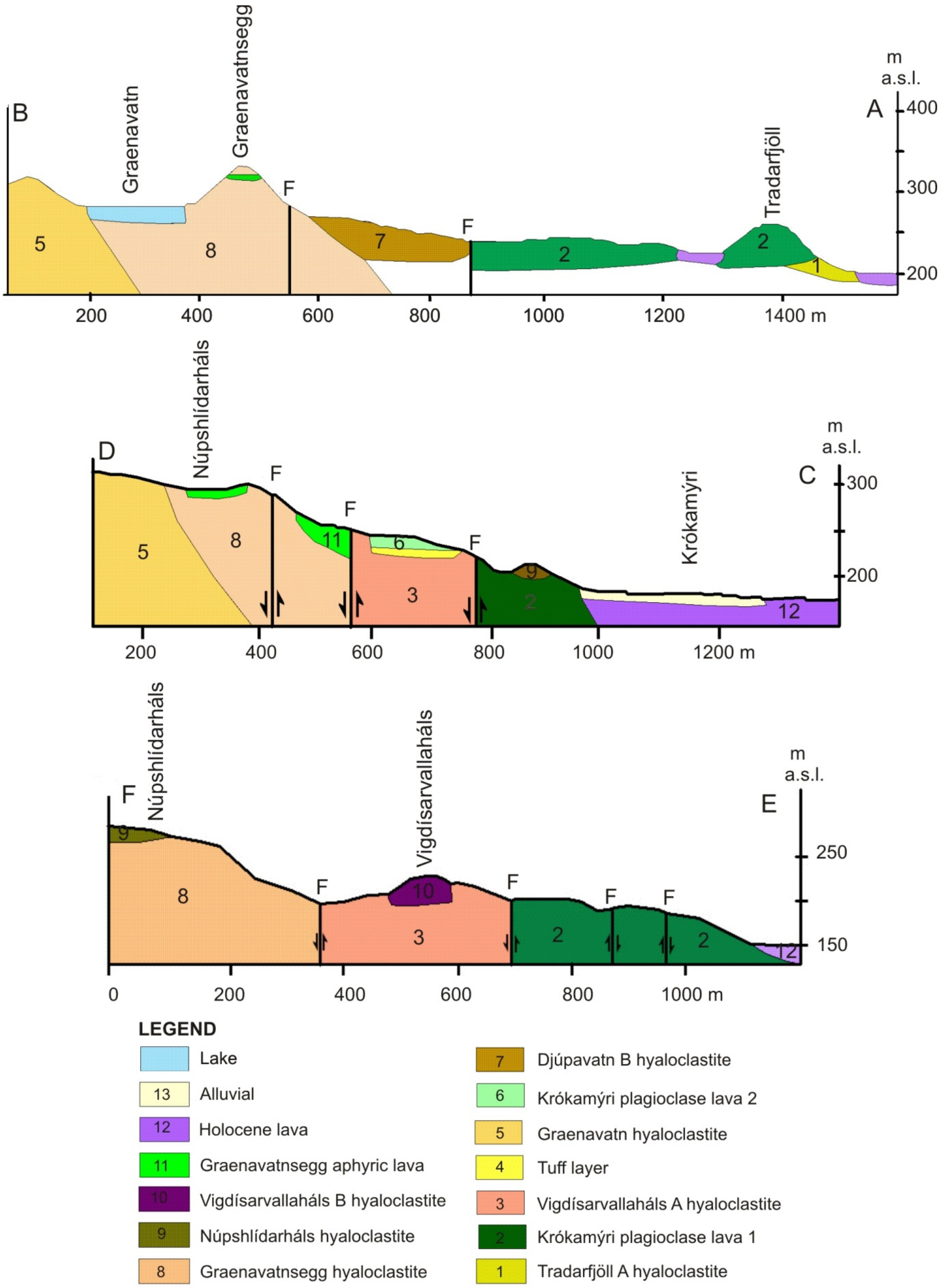

FIGURE 8: Geological cross-sections through the study area; locations are shown in Figure 7

The Tradarfjallaháls hyaloclastite unit is composed of very fine-grained aphyric hyaloclastite, and is believed to have formed during the third last glacial period, based on the present geological mapping.

The Djúpavatn hyaloclastite unit A crops out at the south side of Lake Djúpavatn in a small outcrop and consists of coarse grained aphyric hyaloclastite.

The Tradarfjöll hyaloclastite unit A crops out in the northeast part of the mapped area in a small outcrop. It consists of very vesicular aphyric hyaloclastite. Sparse inclusions of gabbroic xenoliths are found within this unit, indicating intrusive rocks at some depth.

The Krókamýrí plagioclase lava 1: The oldest basaltic lava in the area can be found east of the main hyaloclastite ridge in Krókamýri. This unit consists of highly plagioclased porphyritic lava, which is hydrothermally altered.

Vigdísarvallaháls hyaloclastite unit A: This unit crops out in the middle of the area and continues southwards. It consists of layered tuff and underlying aphyric hyaloclastite. The Graenavatn hyaloclastite unit and Vigdísarvallaháls hyaloclastite unit A formed during the second last glacial period.

The Graenavatn hyaloclastite unit crops out northwest and west of Lake Graenavatn and continues southwest (see Figure 8). This unit is characterised by coarse-grained basaltic aphyric hyaloclastite.

The Krókamýrí plagioclase lava 2 crops out in the middle part of the mapped area at the top of Vigdísarvallaháls hyaloclastite A. This unit consists of highly plagioclased porphyritic fresh lava.

The Graenavatnsegg hyaloclastite unit: This unit crops out west of Lake Djúpavatn and continues to the south (see map in Figure 8). It consists of fine-grained aphyric hyaloclastite and contains dense or massive lithic basalt fragments.

The Graenavatnsegg aphyric lava crops out on top of the Graenavatnsegg hyaloclastite ridge and a part of that unit, implying the subglacial volcanic eruption surfaced out of the melt lake. This unit consists of a very fine-grained aphyric lava sheet.

The Djúpavatnshnúkur hyaloclastite unit: An altered brown hyaloclastite unit; crops out to the east of Lake Djúpavatn and is bordered on the east by Holocene lava. The tuff-rich unit contains fine-grained aphyric basalt fragments.

The Núpshlídarháls hyaloclastite unit: This unit is found within the Núpshlídarháls hyaloclastite ridge (Figure 7). It consists of fine-grained aphyric hyaloclastite.

The Djúpavatn hyaloclastite unit B: crops out south of Lake Djúpavatn and continues to the middle of the mapped area. This unit is characterised by relatively fined-grained aphyric hyaloclastite.

The Tradarfjöll hyaloclastite unit B crops out east of the mapped area in a small area. It consists of fine-grained hyaloclastite with plagioclase crystals.

The Vigdísarvallaháls hyaloclastite unit B crops out in the southern sector of the mapped area where it forms a small hill. It consists of fine-grained aphyric hyaloclastite.

The Holocene lavas: The valley floor between the main hyaloclastite ridges is covered by Holocene lava flows and several eruptive crater rows (Figures 9). The lava flow in the mapped area is about 2000

FIGURE 9: A Holocene crater

years old. The Holocene lavas are in places covered with outwash and soil deposits, due specifically to the deposition of Aeolian and fluvial materials, eroded from the surrounding tuff-rich hyaloclastite hills. Within the soil deposits, tephra layers occur from different volcanic eruptions. The two dark tephra layers seen in the soil section in Figure 10 are from a lava eruption at Reykjanes in 1226 (historic time), and from an eruption in the Katla central volcano in 1485, respectively. The thickness of these layers is 2-5 cm.

FIGURE 10: A soil section with two tephra layers

3.2 Tectonics and structures

The tectonics of the study area is controlled by the regional tectonics of the Reykjanes peninsula. The main structural feature is NE-SW trending hyaloclastite ridges. Numerous NE-SW trending normal faults were also mapped in the study area (Figure 7). They define graben structures along the axis of Djúpavatn hyaloclastite B, Graenavatns-eggjar hyaloclastite and Vigdísarvallaháls hyaloclastite A. Three large faults run along Djúpavatn hyaloclastite B, Graenavatnsegg hyaloclastite and Vigdísarvallaháls hyaloclastite A (Figures 7 and 11). Two small faults run along the southern part of the Krókamýri plagioclase lava 1.

FIGURE 11: NE-SW trending fault in Djúpavatn B hyaloclastite unit

4. GEOTHERMAL MAPPING OF THE DJÚPAVATN-VIGDÍSARVELLIR AREA

4.1 Geothermal activity in Iceland

Geothermal activity in Iceland is divided into high-temperature and low-temperature fields. The high-temperature fields are defined by temperatures above 200°C in the uppermost kilometre of the crust and are related to the active volcanic systems along the plate boundary. Geothermal manifestations in high-temperature fields are represented by fumarolic fields, characterised by the occurrence of fumaroles, mud pools, hot springs and geysers. The low-temperature areas are fracture-dominated and derive their heat from convection within the cooling lithospheric plate. The low-temperature activity is manifested by hot and warm springs, with the highest thermal output along the flanks of the volcanic zones (Saemundsson, 1979).

4.2 Geothermal exploration in the study area

The underground temperatures in the Krýsuvík geothermal area have been estimated by geochemical methods using a hydrogen geothermometer on steam vents, yielding results in the range 260-285°C (Arnórsson et al., 1975, Arnórsson 1987). The conventional silica and alkali geothermometers could not be applied as the deep geothermal reservoir waters do not reach the surface.

Earlier exploration studies in the Krýsuvík area involved several exploration drillholes. One of these wells, KR–07, was drilled in the study area and shows the highest temperature of about 150°C at 550 m depth (Figure 12). Well KR-07 is just east of the southern tip of Djúpavatn, drilled into the Holocene lava at the surface. The following description of the lithology is translated from Arnórsson et al. (1975).

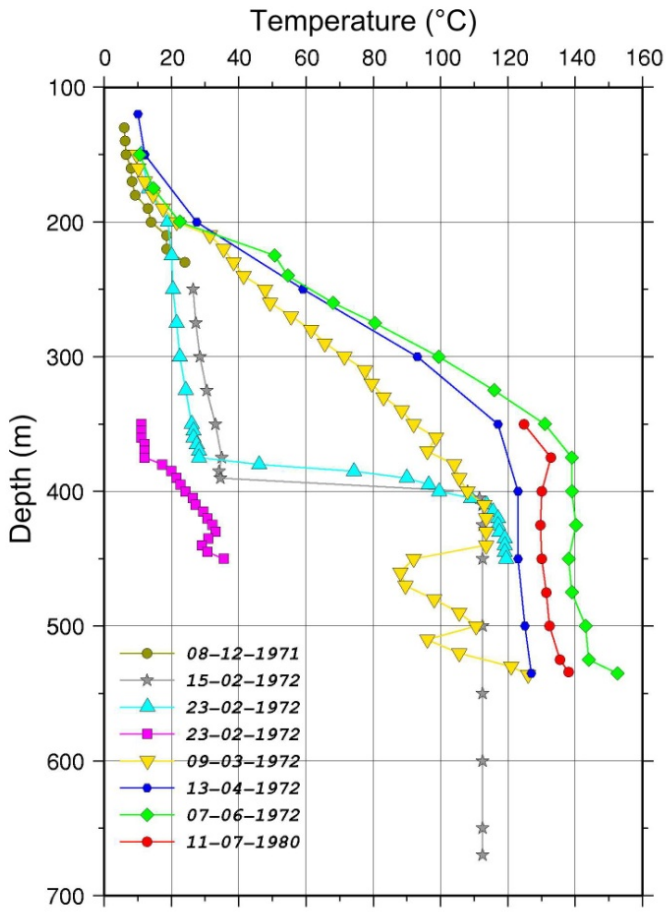

FIGURE 12: Temperature profiles of well KR-07 in the area (ISOR-database)

"No data is available from drill cuttings from the surface down to 40 m depth. Cutting analysis began at 40 m depth, showing tuffs down to about 44 m depth. The hyaloclastite glass is slightly altered, but the brown colour of the palagonites is dominant. Tuff continues into sedimentary agglomerate, down to 76 m depth. The alteration of the sedimentary agglomerate is of low intensity. The basaltic grains are often porous and partly filled with brown clay. Then an eighteen metre gap in the cutting samples may relate to circulation loss, but below that depth, from 94 m down to 212 m depth, a lava unit composed of plagioclase porphyritic basalt lavas is found. The basalts are fairly fresh, but alteration seems to increase with depth. The porous rock is often filled with brown clay. Other alteration minerals are rare, while calcite first appears at about 100 m depth. Hyaloclastite unit then extends from 212 down to 386 m, below which no cuttings were available. It is all classified as sedimentary agglomerate, although there are varying amounts of basaltic grains and black glass. The alteration is not great, but it is variable. It is most intense at about 250 m depth where some zeolites appear along with clay."

4.3 Geothermal mapping in the study area

Figure 13 shows a map of geothermal manifestations in the study area. No active fumaroles or hot springs were found in the study area, but the bedrocks show hydrothermal alteration from low intensity (slight alteration) to clayish alteration (intense alteration). The clayish alteration indicates formerly active fumaroles where the hyaloclastite rocks have been completely replaced by secondary minerals (mostly clays).

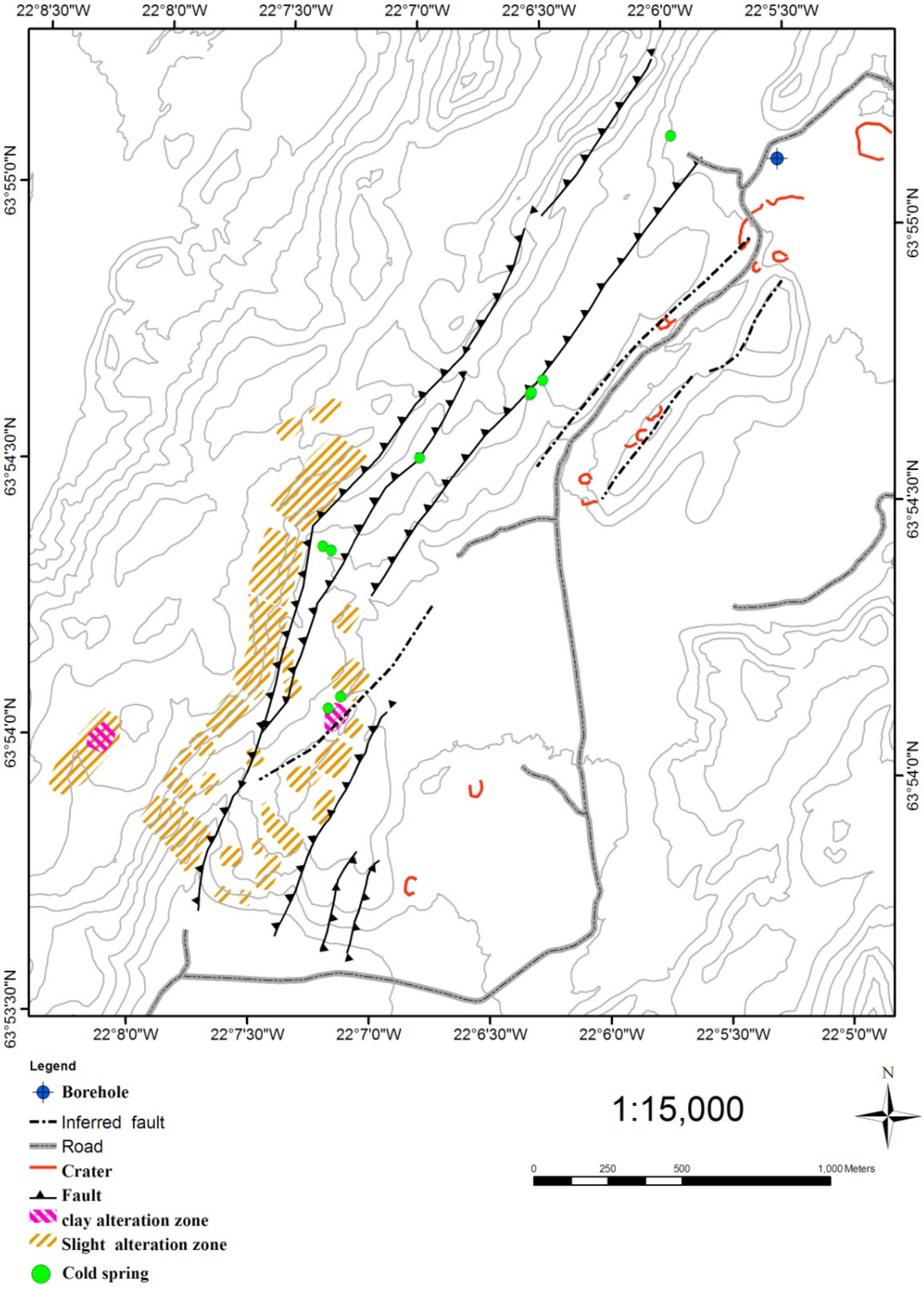

FIGURE 13: Geothermal map of the study area

4.4 Geothermal manifestations

Geothermal manifestations are more common in the southern part of the mapped area. Two types of geothermal alteration were distinguished (see Figure 13). Slight alteration, mostly characterised by slight colour changes of the tuffs to lighter colours and also involving some calcite veins, and higher grade alteration where the host rock has been completely replaced by clay. Hydrothermal surface alteration, hot or cold, indicates the presence of a subsurface hydrothermal system at some time.

Therefore, mapping the surface alterations is useful in delineating a hydrothermal system. The alteration intensity increases with increasing activity.

Thin calcite veins were found in the southwest part of the study area. The hyaloclastite rock of Vigdísarvallaháls hyaloclastite A shows some narrow calcite veining (Figure 14). An XRD analysis of a sample confirmed the presence of calcite (Figure 1 in Appendix I).

Several samples were collected for clay analysis by XRD (Appendix I).

FIGURE 14: Example of calcite veins

Slight alteration
The slightly altered rocks are confined to the Vigdísarvallaháls and Graenavatnsegg hyaloclastite units in the southwestern part of the field area (see Figure 13). Both these units are from the second last glacial period. Their alteration is most likely younger and could relate to burial and thermal activity during the last glacial period. There also seems to be some structural control as the alteration pattern is parallel to the fault direction. The slightly altered hyaloclastites are somewhat darker in appearance than the normally palagonitized hyaloclastites, which show reddish brown weathering colour. The darker colours relate mostly to the development of low temperature smectites. A clay sample from this alteration zone was analysed by XRD to determine the type of clay, which revealed smectites and also mixed-layer clays (Figures 2 and 3 in Appendix I).

Clay alteration
The extinct clay alteration is not common in the studies field, only found in two places within the slightly altered rocks (Figure 13). A clay sample from one of these sites was analysed by XRD and also showed smectite (Figures 4 and 5 in Appendix I).

4.5 Geothermal model

In creating the geothermal model shown in Figure 15, a use was made of the subsurface data from wells KR-07 and KR-08. The fossil temperature distribution is based on the alteration zone temperatures, ranging from the smectite-zeolite zone closest to the surface (formed at temperatures below 200°C), down through the mixed-layer clay zone (formed at temperatures between 200 and 240°C), into the chlorite and chlorite-epidote zones (formed at temperatures >240°C (Kristmannsdóttir 1979)). In addition, the lithology of the two wells was correlated and linked to the surface rocks as possible. Well KR-07 showed little or no alteration down to a depth of 212 m and intense zeolites at a depth of 250 m, formed at low temperatures, depending on the zeolite type, most likely below 100°C. Well KR-08 showed four mineral zones of hydrothermal alteration with increasing depth, from the smectite-zeolite zone at the depth 250 m, mixed-layer clays zone at the depth 350 m, the chlorite zone at the depth 450 m and the epidote zone at a depth of 825 m, where the temperatures may have approached some 250°C in the past. Today, the temperature logs from the two boreholes show maximum temperatures of 150°C at 550 m depth in KR-07 and almost more than 200°C between 350-550 m depth in KR-08 (ISOR data and Ngaruye, 2009). Today, the bottomhole temperature in KR-08 is close to 170°C, showing a clear reversal, and evidently some 50°C cooling from the peak alteration temperature of the past. The conceptual model is only tentative and will change when more drillholes add data to the overall picture.

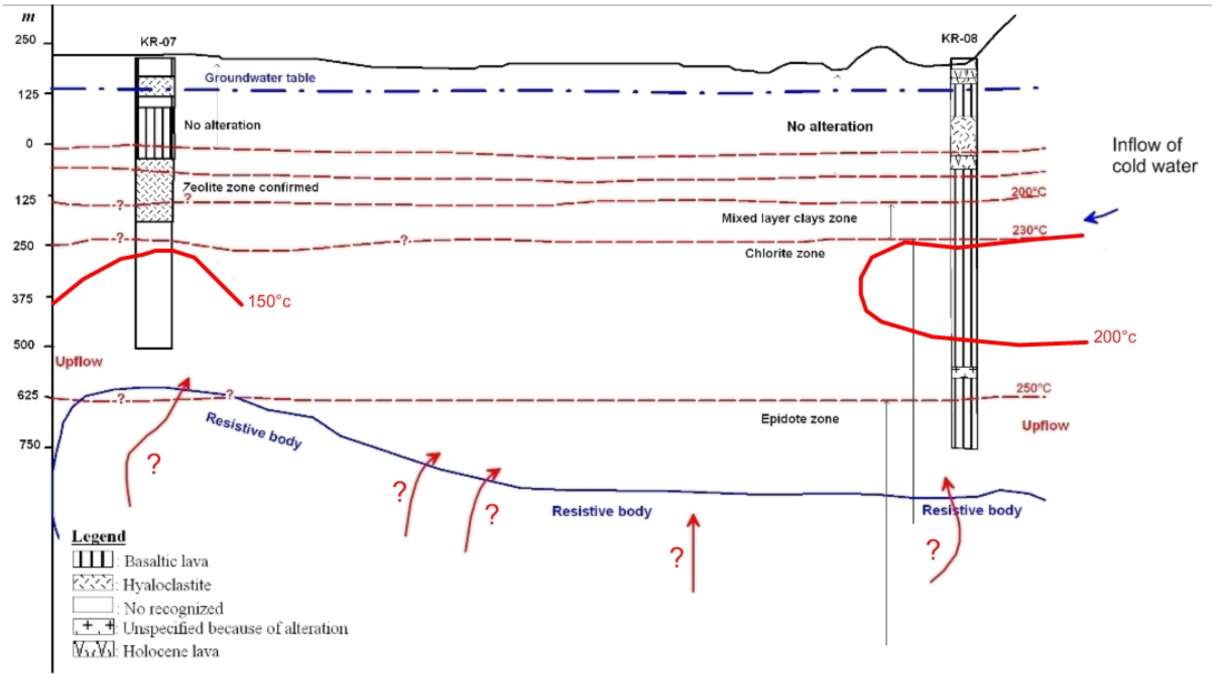

FIGURE 15: A geothermal model of the study area

5. CONCLUSIONS

The study area is located within the Krýsuvík-Trölladyngja volcanic system, which is one of four main volcanic systems within the Reykjanes Peninsula. The age of the volcanic activity in the area spans from Holocene down to the third last interglacial period, or some 300,000 years. The bedrock consists mainly of hyaloclastites with sparser interglacial lava flows and young Holocene lava at the lowest elevation. The stratigraphy is divided into 11 hyaloclastite units. The oldest bedrock units are Tradarfjallaháls hyaloclastite, Djúpavatn hyaloclastite A, and Tradarfjöll hyaloclastite A; these units are partly covered by plagioclase porphyritic basaltic lava. Holocene lava flows are mainly confined to low elevation on the east side of the mapped area. Several normal faults and fissures, trending N40°E, occur within the field area, in addition to minor fractures. The main geothermal activity, which is now extinct, occurred in the southwestern part of the study area. The major structural trends that seem to control the geothermal manifestations orient NE–SW. Two types of alteration zones are distinguished on the map, slight alteration, and extinct clay alteration.

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APPENDIX I: XRD analyses of samples from the Djúpavatn-Vigdísarvellir area

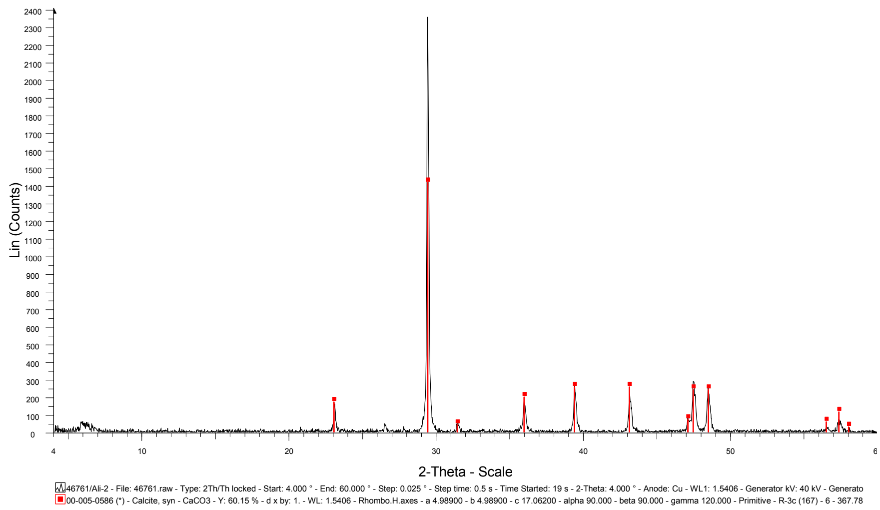

FIGURE 1: XRD analysis of sample Ali A-2 (calcite)

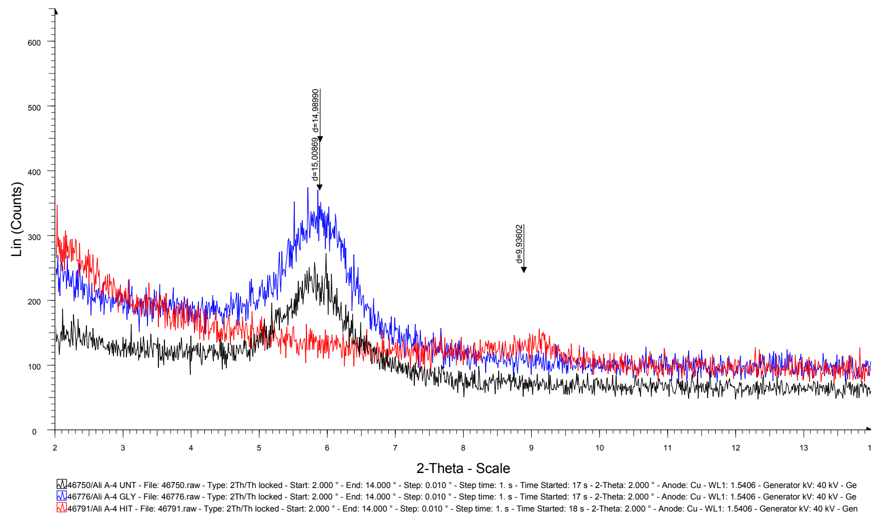

FIGURE 2: XRD analysis of sample Ali A-4 (smectite)

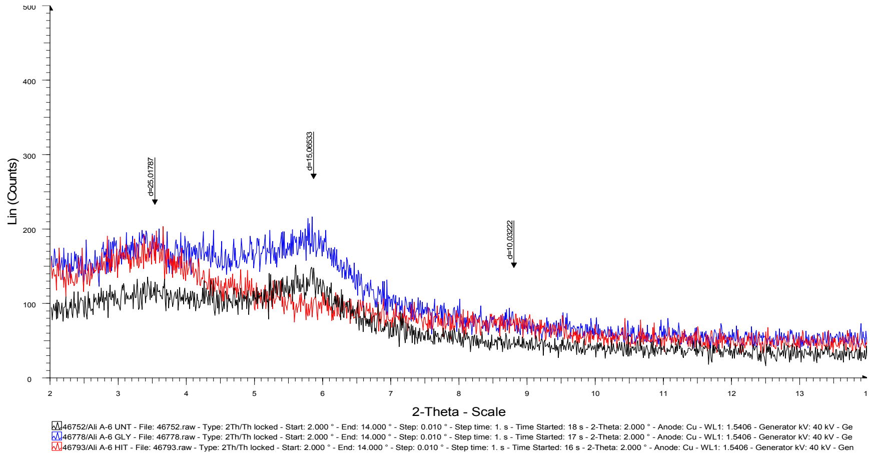

FIGURE 3: XRD analysis of sample Ali A-6 (smectite and mixed-layer clay)

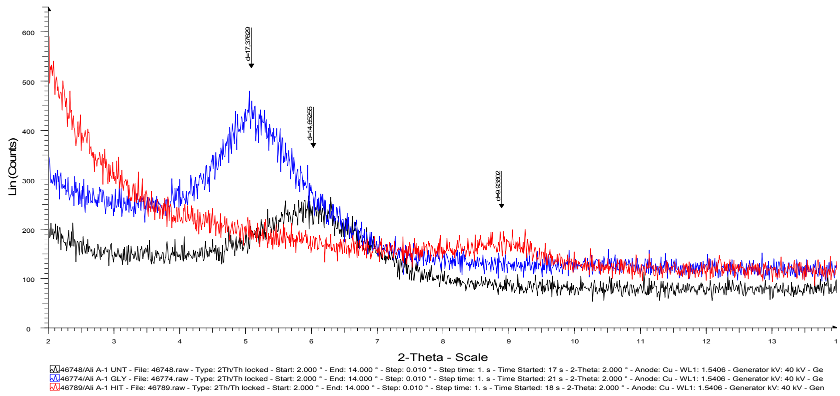

FIGURE 4: XRD analysis of sample Ali A-1 (smectite)

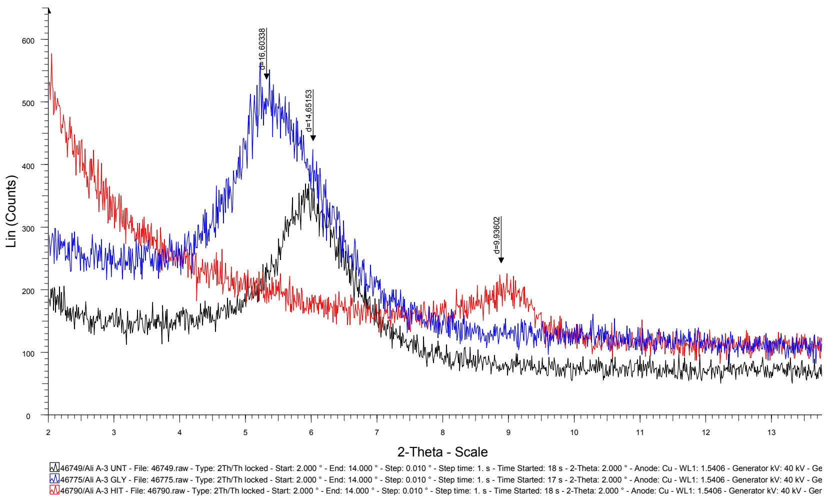

FIGURE 5: XRD analysis of sample Ali A-3 (smectite)