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GEOLOGICAL AND GEOTHERMAL MAPPING OF THE SLAGA- ARNARVATN AREA, REYKJANES PENINSULA, SW-ICELAND

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ABSTRACT

Slaga-Arnarvatn area is part of the Krýsuvík geothermal field, one of 27 known high-temperature geothermal fields in Iceland. Geothermal resources in the Krýsuvík field are not exploited today but several research programmes have been carried out intermittently since the 1950s. The research project described here is a part of the author's UNU-GTP mapping exercise in 2009. This contribution also serves as part of a current geological mapping survey of the Krýsuvík geothermal field, undertaken by ISOR for the HS Orka hf energy company. The geology, geothermal manifestations and surface hydrothermal alteration have been mapped, resulting in two separate maps: a geological map and a geothermal map. The bedrock is composed of four hyaloclastite units, erupted subglacially in Upper Pleistocene time, and three interglacial basaltic lava series and Holocene lavas. The hyaloclastite units form NE-SW trending ridges dissected by normal faults, fissures and fractures which predominantly trend NE-SW. The study area also exhibits eruptive craters of Upper Pleistocene and Holocene ages. The linear distribution of both active and extinct geothermal manifestations correlates to the fault system. The surface alteration grades in intensity from slight to intense. A simple hydrothermal conceptual model is presented at the end of this report, based on the present study and a literary review of earlier and current research in the Krýsuvík field.

1. INTRODUCTION

1.1 Scope of study

The United Nations University-Geothermal Training Program (UNU-GTP) at Orkustofnun, Iceland, has been operating a six month training course for scientists and engineers from developing countries for 31 years. This year, 2009, 22 fellows from 16 developing countries participated in 6 different study lines. This report is a part of the six month training in exploration geology, including geothermal resource assessment and development. This geological and geothermal mapping project followed introductory lectures, many field excursions, specialized courses and geoscientific surveys extending from mid-April to mid-July 2009. The fieldwork was undertaken during July and August.

1.2 Location and accessibility

The Slaga-Arnarvatn area is located within the Sveifluháls hyaloclastite ridge, west of Lake Kleifarvatn, some 30 km south of Reykjavík (Figure 1). The study area is reachable by the main road from Reykjavík-Hafnarfjörður to Krýsuvík. The field being studied can be accessed from both the Seltún-Hveradalir geothermal manifestations on the east side of the Sveifluháls ridge, and from the west along a gravel road which extends from a big quarry (Vatnsskardsnáma) southwards between the Sveifluháls and Núpshlíðarháls hyaloclastite ridges. The landscape is sparsely vegetated providing excellent exposures of the volcanic rock formations.

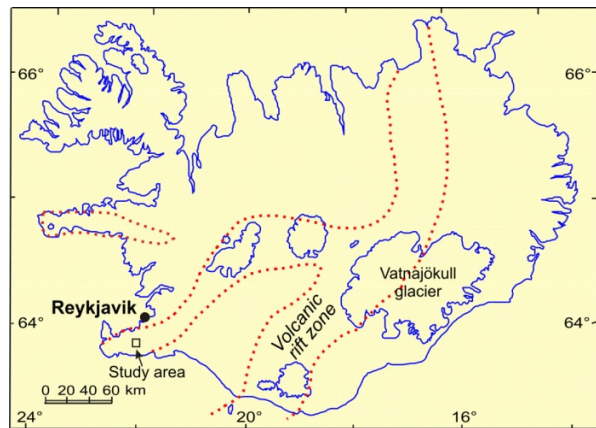


FIGURE 1: Location of the study area

1.3 Topography, climate and hydrological aspects

The topography of the study area is dominated by a Holocene lava flow with an average elevation of 150-200 m on the west side, and a mountainous rise of hyaloclastite ridges reaching up to 330 m above sea level (a.s.l.). The study area is in the vicinity of the Atlantic Ocean, and is affected by the warm Irminger current, which greatly moderates the climate along Iceland's southern and western coasts. Winters are mild with a mean daily temperature in the range between -2°C and -4°C . Summers are temperate, with a mean monthly temperature of about $8\text{-}10^{\circ}\text{C}$ (The Icelandic Meteorological Office, 2009).

The study area receives a relatively high mean annual rainfall (1200-2000 mm/year). More than 60% of the population of Iceland is supplied with freshwater from the Reykjanes Peninsula but there is no perennial runoff on it (Sigurdsson, 1986). The analysis of the freshwater movements within and around the hyaloclastite ridges indicates drainages towards the Atlantic Ocean as shown in Figure 2.

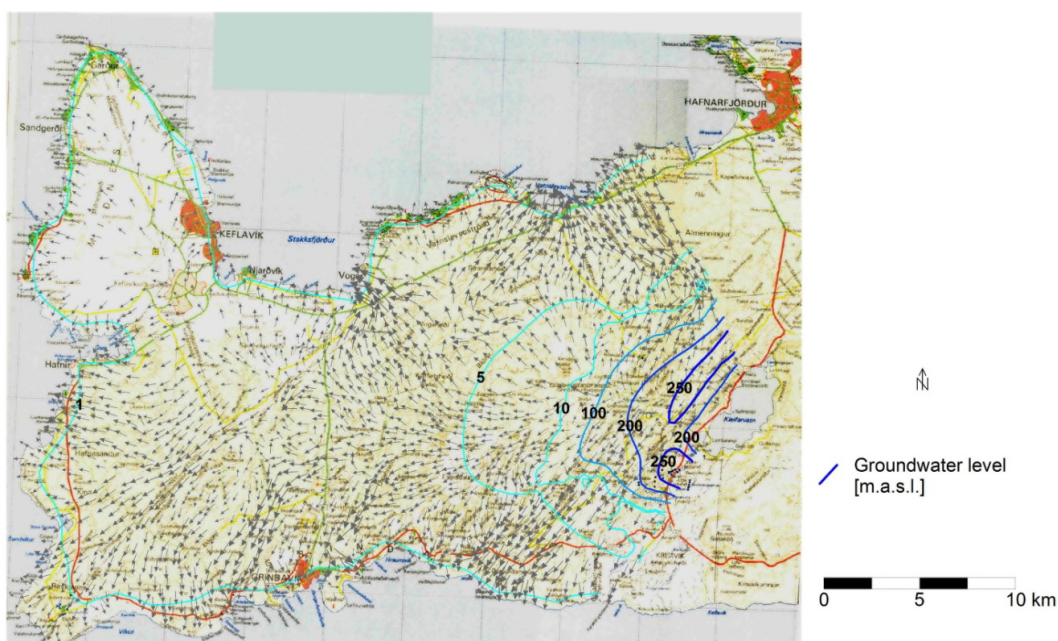


FIGURE 2: Calculated water contours (blue lines) of the Reykjanes Peninsula in metres above sea level (m a.s.l.); the black arrows show the groundwater flow directions (Vatnaskil, 2009)

The permeability of the bedrock is quite high, which affects the water balance and infiltration. The infiltration rate has been estimated at up to 1600 mm/year (Flóvenz et al., 1986). As illustrated by Figure 3, the groundwater table within the Reykjanes Peninsula is much higher in the less permeable hyaloclastite mountains than in the highly permeable lava series in its western part where freshwater floats on a sea water reservoir within the rocks, like oil on water (Sigurdsson, 1986).

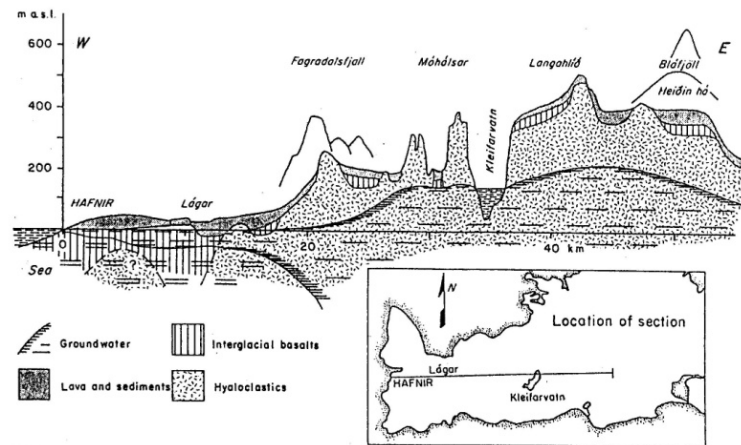


FIGURE 3: A profile showing the groundwater level along the Reykjanes Peninsula (from Sigurdsson, 1986)

1.4 Methodology, materials and tools

The geological and geothermal survey carried out in the Slaga-Arnarvatn area consisted of detailed mapping. The research has been done stepwise with an understanding and a description of rock units, the structural features of the study area, the geothermal alterations and the relationship between them. During the survey use was made of materials and tools specifically provided by UNU-GTP for that purpose: a Garmin-GPS 72 to locate and track the structural lineaments in addition to mapping the main rock units and the areas that show geothermal alterations of different types such as clay and zeolite; aerial photographs; a geologic hammer; a hand lens magnifier; and a compass.

The field data was downloaded into computers at ISOR, Iceland GeoSurvey, and processed for geological and geothermal maps using the Arc-Map program.

1.5 Previous surveys

Geothermal research programmes of varying intensity have been carried out in the Krýsuvík-Trölladyngja area since the 1950s. Geologically, the first detailed map of the Sveifluháls ridge, surrounding the study area, was done in 1973, where eight hyaloclastite units were mapped (Imsland, 1973). Jónsson (1978) published detailed geological maps of the whole Reykjanes Peninsula (scale 1:25,000) but focused on the Holocene lava series, not on the details of the older hyaloclastite formations. A regional geological map on the scale 1:250,000 was published in 1980 (Saemundsson and Einarsson, 1980). Flóvenz et al. (1986) reviewed earlier studies and made the following observations on the Krýsuvík -Trölladyngja geothermal potential:

- The geothermal field can be separated into two parts, one at an upper level at 300-500 m depth, and another one below 1000 m depth;
- Drilling down to the lower system with approximately 1500 m deep wells was the main proposal;
- Proposed drilling sites: close to Eldborg and between Sog and Oddafell (later a site for well TR-01).

During 1941-1953, 22 shallow wells (H-series but later referred to as KV-series) were drilled in Krýsuvík as a first phase of an exploration to investigate the potential for electricity generation within the Krýsuvík field. In 1960, three exploratory wells, 329-1270 m deep (wells KR-1, KR-2 and KR-3) were drilled, with somewhat disappointing results. A fourth well KR-4 was drilled to 300 m depth in 1962 (Ármannsson et al., 1994). The third systematic survey to assess the characteristics of the geothermal reservoir accompanied by drilling was carried out from 1970-1973 (Arnórsson et al.,

1975). This research included a detailed assessment and the exploration drilling of 4 additional slim holes (wells KR-5, KR-6, KR-7 and KR-8) in 1971-1973. As in the first wells, a temperature reversal was reported in the new wells (Arnórsson et al., 1975). The drilling sites were selected based on geophysical interpretation, geochemistry and data from old wells to delineate temperatures using the hydrogen content, hydrothermal alteration and to calibrate resistivity surveys (Arnórsson, 1987). Well KR-8 is within the present study area, and well KR-7 is a little further west within Al-Sabri's (2009) field area.

Hydrothermal alteration within the wells was found to consist of zeolites, which disappeared where smectites began to coexist with chlorite (mixed layer clays). Smectites were encountered from the surface down to the mixed layer clays depth. The alteration was reported to be of a similar pattern as in other high-temperature fields in Iceland.

The last effort in the exploration of the geothermal area was the drilling of two deep wells in Trölladyngja, well TR-01 in 2001, and TR-02 in 2006, both of which are more than 2 km deep (Fridleifsson et al., 2002; Kristjánsson et al., 2006; Mortensen et al., 2006). The drilling was done by Jardlind Ltd. and Hitaveita Sudurnesja Ltd. Currently, HS Orka Ltd. (formerly Hitaveita Sudurnesja) has a 10 year research permit since 2006 for the entire Krýsuvík area, with its four subfields. HS Orka Ltd. enrolled ISOR – Iceland Geosurvey, to undertake extensive geological and geophysical surveys. These include a gravity survey, TEM and MT resistivity surveys and detailed geological and geothermal mapping. All these surveys are currently active, and the present field work and mappings fit into the program for a part of the large area. HS Orka has permitted UNU-GTP the use of some of the unpublished geophysical and geological data.

2. OUTLINE OF THE GEOLOGY AND GEOTHERMAL RESOURCES OF ICELAND

2.1 Geology

Iceland is located astride the Mid-Atlantic Ridge (MAR), the boundary between the North American and the Eurasian plates. Iceland is the product of an interaction between a spreading plate boundary and a hot mantle plume, the source of additional volcanism under the country, which moves slowly northwest across it (Vink, 1984; White et al., 1995). The Greenland - Iceland - Faeroes Ridge is thought to be the trail of the Icelandic hot spot, which has been active from the time of opening of the North Atlantic Ocean, 60 million years ago to the present. Nowadays, the plume is located approximately under Vatnajökull glacier (Thordarson and Larsen, 2007).

The spreading direction is N10°E and the drift velocity has been estimated from magnetic studies to be about 1 cm/year in each direction (Björnsson, 1985). The creation of Iceland in its current form is thought to have begun some 24 million years ago (Saemundsson, 1979). The oldest rocks are 16-14 million years old and are exposed in the extreme northwest and east, while the youngest rocks are located within the neovolcanic zones (Jóhannesson and Saemundsson, 1999). Iceland's topography has been radically changed by intense erosion, especially in Pleistocene time.

The geological formations of Iceland are grouped into the following four major groups (Figure 4) which from the oldest to the youngest involve: Tertiary (16-3.3 Ma: Miocene-Pliocene), Plio-Pleistocene: 3.3-0.8 Ma, Upper Pleistocene: 0.8-0.011 Ma (Brunhes magnetic epoch) and Postglacial: 11,000 - present.

Iceland is mainly composed of basalts (80-85%) and intermediate to acid rocks (10%) while sedimentary rocks of volcanic origin represent only 5-10 %. The Pleistocene rocks are confined mainly to a broad SW-NE trending zone between the Tertiary plateau basalt areas, and are also exposed within the Tjörnes, Snaefellsnes and Skagi peninsulas.

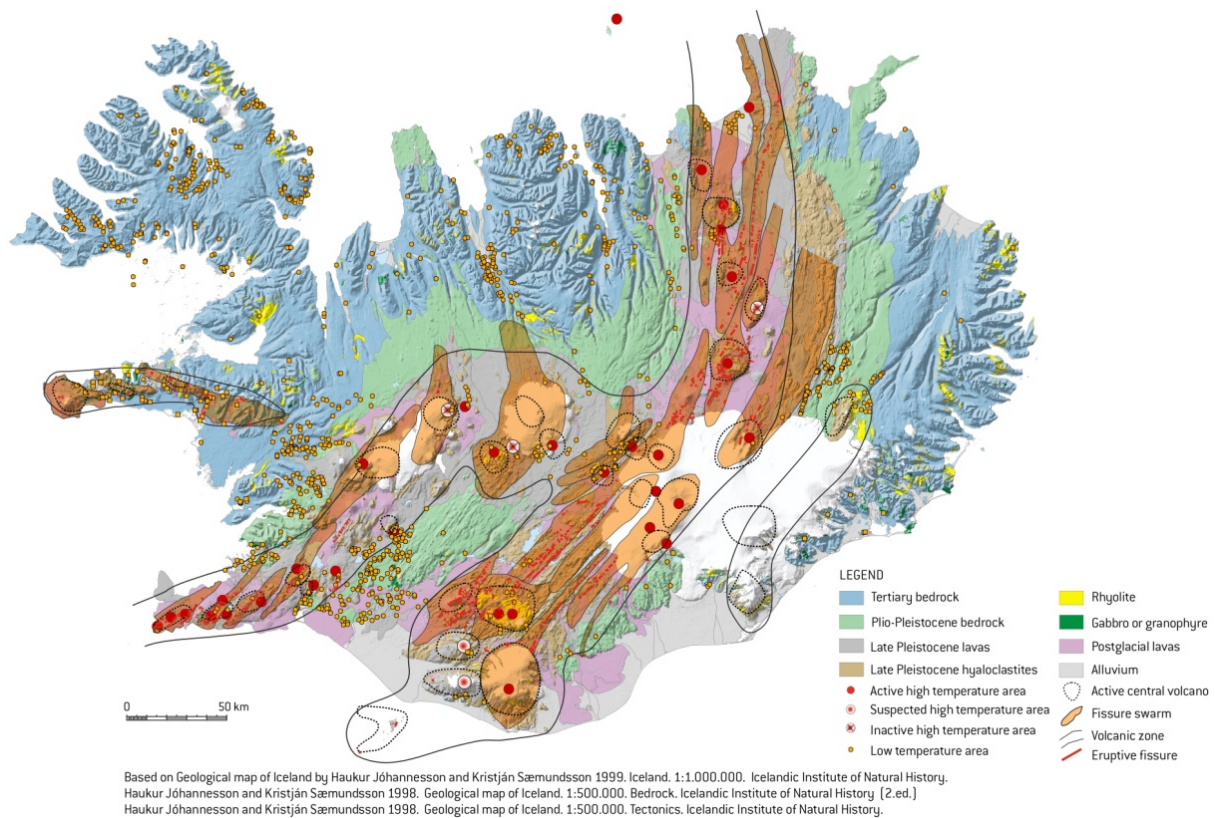


FIGURE 4: Geological map of Iceland (Jóhannesson and Saemundsson, 1999)

In the Pleistocene formation there are three main lithofacies: interglacial basaltic *lava flows* generally grey in colour and of coarser texture than the Tertiary ones and subglacial volcanic formations made by *pillow lavas*, breccias and brownish *tuffs*, known as palagonite and rich in hydrated and otherwise altered basaltic volcanic glass. The volcanoes built up subglacially are of two types: ridges and 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. The table mountains are isolated mountains, circular to sub-rectangular in shape.

The current active rift zone of Iceland extends from the Reykjanes Peninsula, in the southwest, through the country as shown in Figure 4. The volcanic zones are about 40-50 km wide, and comprise en-echelon arrays of volcanic fissure swarms within the main zone, often associated with a central volcano, each of which is approximately 5 to 15 km wide and up to 200 km in length. Iceland is tectonically and volcanically very active and the MAR along Iceland is a location of predominantly divergent tectonic plate movement, but also has two zones of transform movements (Tjörnes Fracture Zone and the South Iceland Seismic Zone).

2.2 Introduction to the Reykjanes Peninsula

The Reykjanes Peninsula in SW-Iceland is the onshore continuation of the Mid-Atlantic Ridge. Four NE-SW trending volcanic systems, which cross the peninsula along the plate boundary, are arranged in an en-echelon pattern along the ridge axis. These are the Reykjanes-Svartsengi, Krýsuvík-Trölladyngja, Brennisteinsfjöll-Bláfjöll and the Hengill systems, which define the peninsula (Figure 5). The Reykjanes Peninsula became active 6-7 million years ago (Saemundsson, 1979; Jóhannesson, 1980; Jenness and Clifton, 2009). The dominant tectonic features on the peninsula are a series of NE-striking, sub-parallel eruptive fissures and normal faults, which, because of the rift zone's obliquity, are not oriented perpendicular to the sea-floor spreading direction (Jenness and Clifton, 2009).

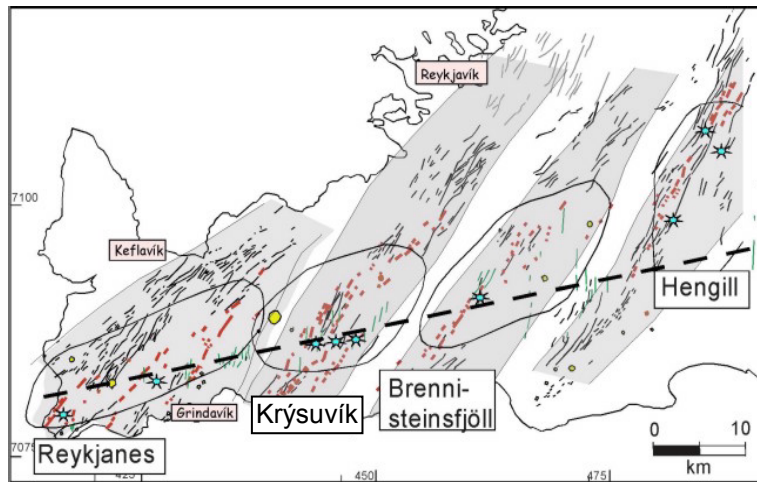


FIGURE 5: Volcanic systems and high-temperature fields on the Reykjanes Peninsula (Clifton, 2006)

The general topography has been modelled by sub-glacial and post-glacial fissure eruptions which generated the northeast trending hyaloclastite ridges and crater rows. Lava shields and eruptive fissures have been active on the peninsula during the Holocene time, and from tephrochronology and C^{14} dating of fossil charcoals, the last known eruptive phase occurred in the 10th century on the eastern side of the peninsula and ended in the 13th century at the western side (Jóhannesson and Einarsson, 1988; Jenness and Clifton, 2009).

Six high-temperature areas are found along the Reykjanes Peninsula and these are, from the west to the east, the Reykjanes geothermal area, the Eldvörp area, the Svartsengi area, the Krýsuvík-Trölladyngja area, the Brennisteinsfjöll area and the Hengill area. The Reykjanes, Svartsengi and Hengill areas are already exploited for electricity production and space heating.

2.3 Geothermal resources of Iceland

The MAR is characterized by high heat flow in the crestal region which decreases symmetrically across the MAR structure. In the active volcanic rift zones the heat flow is estimated to be 300 mW/m^2 while outside the volcanic areas the heat flow is estimated around 80 mW/m^2 . Outside the geothermal areas, the thermal gradient varies between 50 in the oldest crust and 170°C/km for the youngest crust (Flóvenz and Saemundsson, 1993). Geothermal areas in Iceland are divided into high-temperature and low-temperature fields. The high-temperature areas are localized within the rift zones, mostly confined to central volcanic complexes. The base temperature within them is typically above 200°C at 1 km depth. The geothermal activity of the high-temperature areas is ascribed to intrusive activity at high levels within the upper crust. The low-temperature areas are mainly found outside the volcanic rift zones and include geothermal systems of temperatures below 150°C . They are located within the Pleistocene and Tertiary environments (Flóvenz and Saemundsson, 1993).

3. GEOTHERMAL HISTORY OF SLAGA-ARNARVATN AREA

The study area is located within Krýsuvík-Trölladyngja high-temperature field. Surface exploration in Krýsuvík has been carried out since the 1950s.

3.1 Resistivity data

In all, 43 Schlumberger and 52 central-loop TEM soundings in Krýsuvík geothermal field have been interpreted using one-dimensional inversion programs SLINV and TINV, respectively (Kebede, 2001). In 2007-2008, additional twelve NW-SE profiles of MT and TEM soundings were carried out in the Krýsuvík area and interpreted based on a joint inversion of TEM and MT data (Hersir et al., 2009). From the resistivity cross-section along the profile SA7 (Figure 6) running through wells KR-07 and KR-08, the following descriptions can be made.

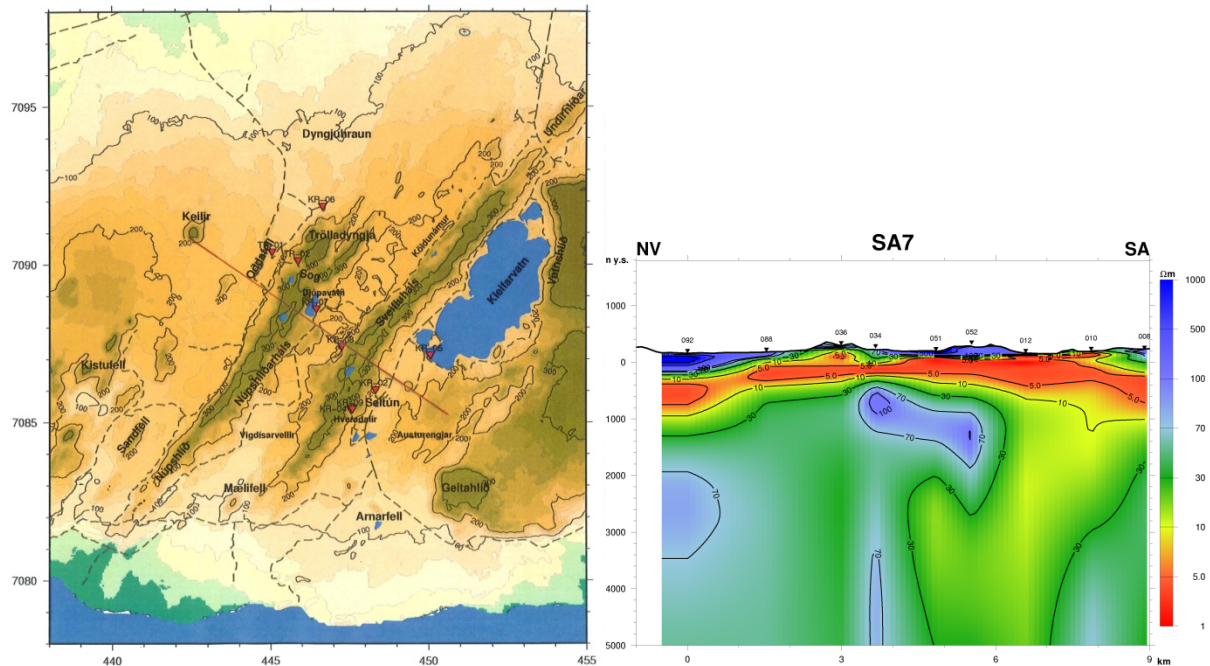


FIGURE 6: a) Map of the Krýsuvík area showing the location of wells and resistivity cross-section SA7; b) Resistivity cross-section SA7 (Hersir et al., 2009)

- The near-surface highly resistive layer ($>100 \Omega\text{m}$) probably corresponds to the fresh basaltic rocks of postglacial volcanism. The next layer (200-1000 m b.s.l.) is characterized by low resistivity (1-30 Ωm). The low resistivity here is explained as a result of geothermal alteration.
- At 1000 m b.s.l., three anomalous zones of high resistivity ($>70 \Omega\text{m}$) underneath the low resistivity are found along the cross-section: one in the northwestern part at 2000 m b.s.l., and the other two in the central part between 1000 and 2000 m b.s.l. This anomalous zone should be interpreted as a high-alteration zone dominated by the chlorite-epidote mineral zone (240-250°C), confirmed by the analysis (XRD) of clay minerals done in well KR-08 (Arnórsson et al., 1975).

3.2 Temperature profiles

Figures 7 (H.8 = KR-08: H.wells = KR-series) and 8 exhibit the temperature logs in deep wells in the Krýsuvík-Trölladyngja high-temperature area (Flóvenz et al., 1986). Arnórsson et al. (1975) noted a thermal reversal and proposed two hypotheses:

- 1) Separate upflow zones not yet localized by wells and a mushroom shaped body of hot-water and rock at the top of these zones;

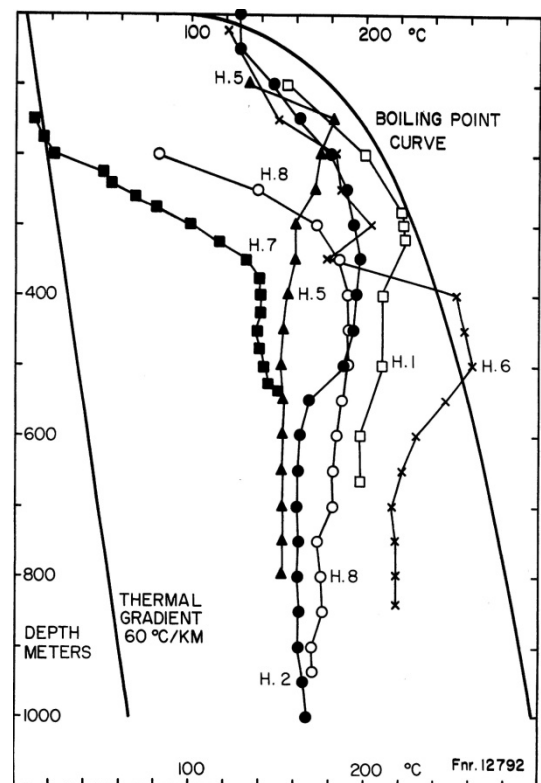


FIGURE 7: Temperature profiles of deep boreholes in the Krýsuvík area (Arnórsson et al., 1975)

- 2) Gradual cooling from above and below of a hydrothermal reservoir by relatively fresh water which is replacing originally more saline water. This second hypothesis fits well with the distribution of the hydrothermal minerals with regard to the underground temperature conditions (Arnórsson et al., 1975).

3.3 Seismicity in the study area

Divergent movements, a hot spot and intense volcanic activity are responsible for the high frequency of earthquakes within the SISZ, TFZ and in the vicinity of the hot spot. Medium and big earthquakes are not very frequent in Iceland, some 6–7 earthquakes of magnitude above 6.0 every 100–150 years in the Southern Lowlands of Iceland (SIL) and similar in TFZ. Those seismic events are mostly shallow (10-20 km deep), probably with 7 (in 1912) as the maximum magnitude on the Richter scale. From 1994-2000, 145,000 seismic events with a magnitude higher than 1 on the Richter scale have been recorded by the SIL network. The majority of events originated in the Hengill - Ölfus area, the triple joint between the SISZ, the Reykjanes Peninsula (RP) and the West Volcanic Zone WVZ (Clifton et al., 2003).

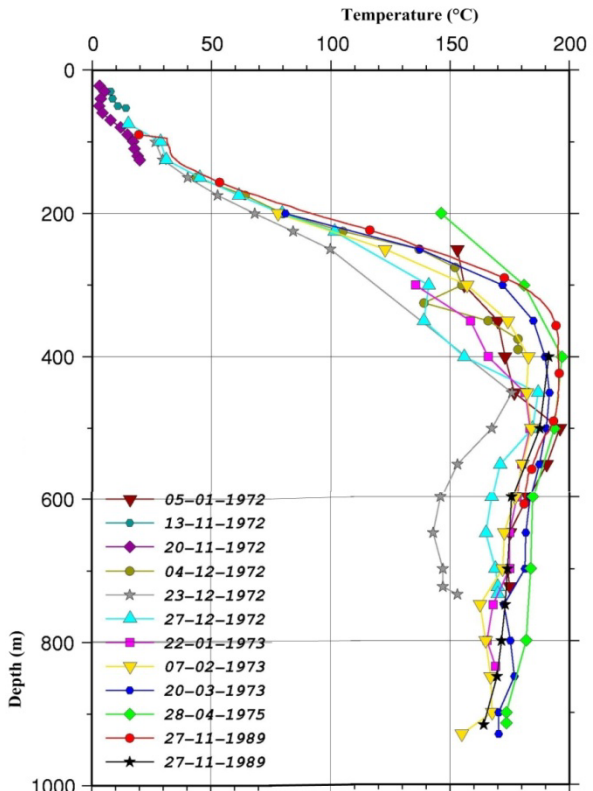


FIGURE 8: Temperature profile of borehole KR-08 (ISOR database)

Within and near the area of survey, many seismic events have been recorded since 1991 when the SIL network was activated. The upper crust of the study area is highly heterogeneous and significantly aseismic (Foulger et al., 2003). Analysis done by Geoffroy and Dorbath in 2008 (Figures 9 and 10)

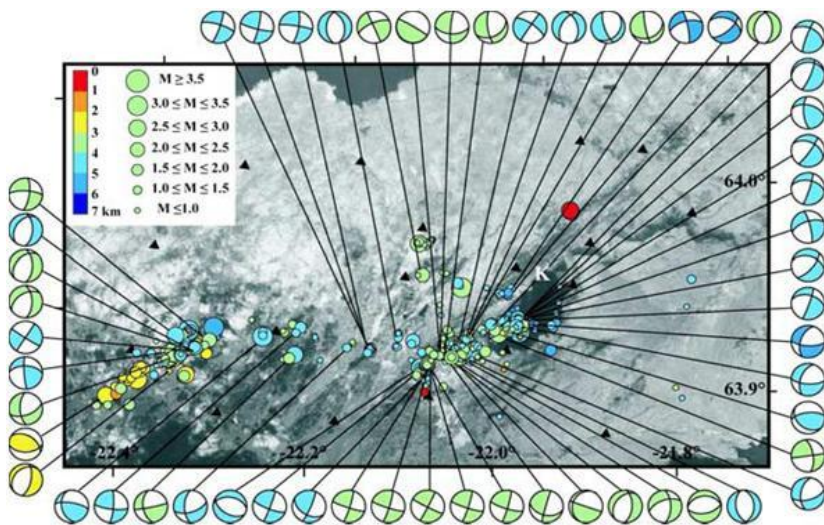


FIGURE 9: Map of relocated epicentres from 10/04 to 30/08/2005, with fault mechanisms for 55 events shown on the inset photo; symbol size represents magnitude and colours indicate focal depth (Geoffroy and Dorbath, 2008)

identified two main areas of anomalously low v_p/v_s in the surroundings of Arnarvatn Lake: the Krýsuvík-Kleifarvatn sector where epicentres are arranged in clusters roughly aligned along the N60°E trend and overlaps the hot spring areas; and the Grindavík area located along a single N60°E fracture zone.

A major seismic event occurred in the study area during June 2000 and the event fractured the upper crust and increased the permeability around Lake Kleifarvatn. About 12% of

the water inside the lake drained down through the upper crust at an average rate of $2 \text{ m}^3/\text{s}$ during the eighteen months following 17th June 2000 (Clifton et al., 2003). The study area is active and the seismicity is tectonically controlled.

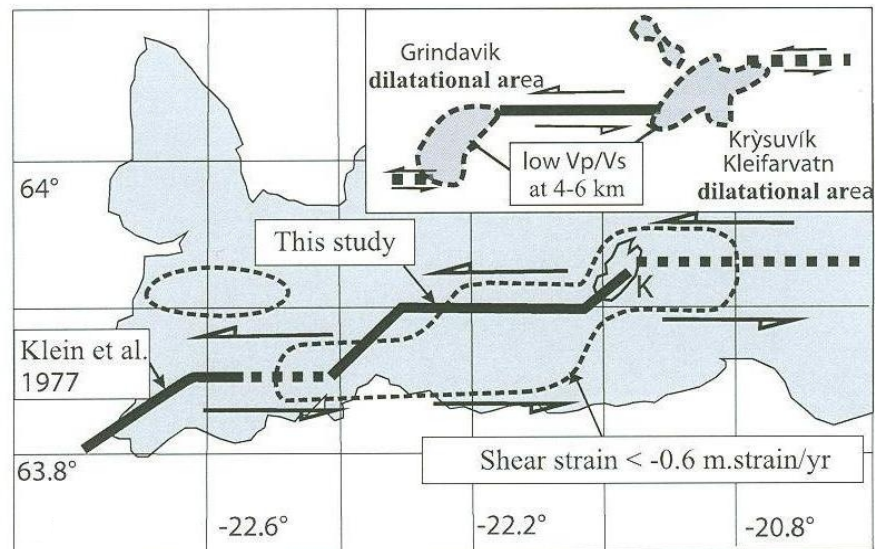


FIGURE 10: Tectonic interpretation. Plate separation in the RP is dominated by left-lateral transform like shearing along N090E – trending segments arranged en echelon; short dashed lines delineate areas of maximum left-lateral shear inferred from GPS data during the period 2000–2006 (Geoffroy and Dorbath, 2008)

3.4 Geochemistry of the geothermal fluids in the study area

Geochemical surveys were done in the 1970s in the four exploratory wells drilled to a depth of 800-1000 m and other two wells drilled to a depth of 1000-1200 m. The main reason for this was that the pillow breccias out of which steam emerged did not allow the collection of pure steam samples for geochemical studies (Arnórrsson, 1987). The concentration of carbon dioxide in fumarole steam was reported to be in the range of 200-300 mmole/kg and constituted 80-90% of the total gases. The remaining fraction was found to be mainly hydrogen sulphide and hydrogen. The nitrogen, which was found in the samples, was believed to be due to air contamination. Methane was reported to be very low in the samples. The condensation in the upflow zones was evaluated and was reported to be due to: 1) conductive heat loss and 2) mixing of steam with cold water, estimated to be in the range 0-30%.

Geothermometers indicated temperatures up to 280°C for the Sveifluháls area (Arnórrsson, 1987). Arnórrsson et al. (1975) reported that the bedrock was intensely altered by acid surface leaching. Also, that thermal waters from wells in the Krýsuvík high-temperature area display a large variation in dissolved solids, unlike other areas where the hot water chemistry is very homogeneous. Geothermometry on gas from fumaroles in Sveifluháls (298°C) and from well KR-09 (288°C) suggests that the reservoir temperature may be close to 300°C (Ármansson and Thórhallsson, 1996; Bjarnason, 2000).

4. GEOLOGICAL AND GEOTHERMAL MAPPING OF THE SLAGA-ARNARVATN AREA

Field work was carried out in the Slaga-Arnarvatn area intermittently during late July to early September, 2009. The first goal was to sort out the lithology. Four eruptive hyaloclastite units, three interglacial lavas, Holocene lavas, and old and recent sediments were recognized in the area and mapped. The second objective was to map the tectonic structures of the study area with the main focus on faults, dykes, fissure swarms, and craters within the hyaloclastites and recent basaltic lavas. The third topic was to map the different forms of geothermal manifestations, extinct geothermal

features, of all levels of extent from low to intense, and active geothermal manifestations. Rocks and clay samples from altered zones were also collected for laboratory analysis.

The field survey was facilitated, as mentioned above, by a set of materials and tools including a GPS, hand lens magnifier, geologic hammer, compass, measuring tape, aerial photographs of the study area and surroundings, digital camera, sample plastic bags etc.

4.1 Geological mapping

4.1.1 Volcanic activity of postglacial time

For convenience, the volcanic activity in Iceland during Holocene is often divided into historic time, during the last 1100 years (since the year of settlement of Iceland, AD 874) and prehistoric, i.e. prior to AD 874. During the historic epoch, sixteen volcanic systems in Iceland have been active. Within the Reykjanes Peninsula four volcanic systems erupted during the last 1100 years (Thordarson and Larsen, 2007).

The soils above and below the lavas of different age contain ash or tephra layers, which emanated from different volcanoes within the country. Some of the tephra layers may be from local volcanoes, while others emanated from famous central volcanoes like Hekla or Katla in South Iceland. By studying the soil section and tephra layers it is often possible to put constraints on the relative age of the individual lava flows. The method used is called tephrochronology, and was applied here for the Holocene lavas within the field. Two soil logs 84 and 85 (Figure 11) were developed, both on the top of the recent Holocene lava in the survey area (2000 years old):

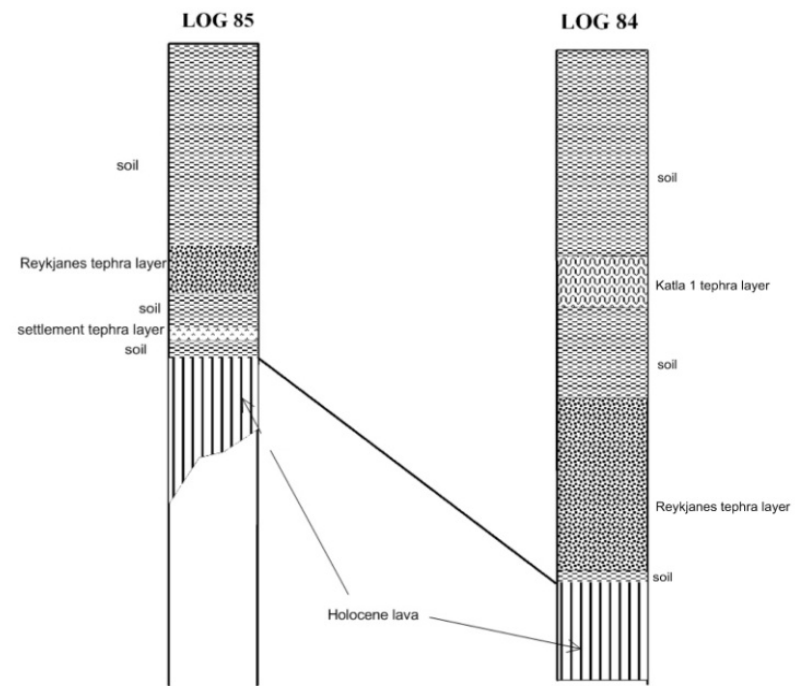


FIGURE 11: Log 84 and 85 in the study area
(for location see Figure 13)

Log 84 (46.5 cm): 1 cm of soil (S41) on the top of Holocene lava (H4); 15 cm of the year 1226 tephra layer, 8 cm of brown soil (S42); 4.5 cm of a black fine grained ash layer of 1485 Katla eruption (K14); 18 cm of brown soil (S43).

Log 85 (27.5 cm) : 1 cm of brown soil (S51) developed on Holocene lava (H5), 1.5 cm settlement tephra layer of year 871 (St5), 3 cm of brown soil (S52), 4 cm of year 1226 tephra layer (R5) and on the top of the sequence, 18 cm of soil (S53).

4.1.2 Rock classification

The topography of the Slaga-Arnarvarn field is dominated by NE-SW trending ridges composed mainly of different units of hyaloclastites, products of subglacial volcanic eruptions, most of which have not surfaced the ice sheet during eruptions. Figure 12 is a classical diagram, showing how

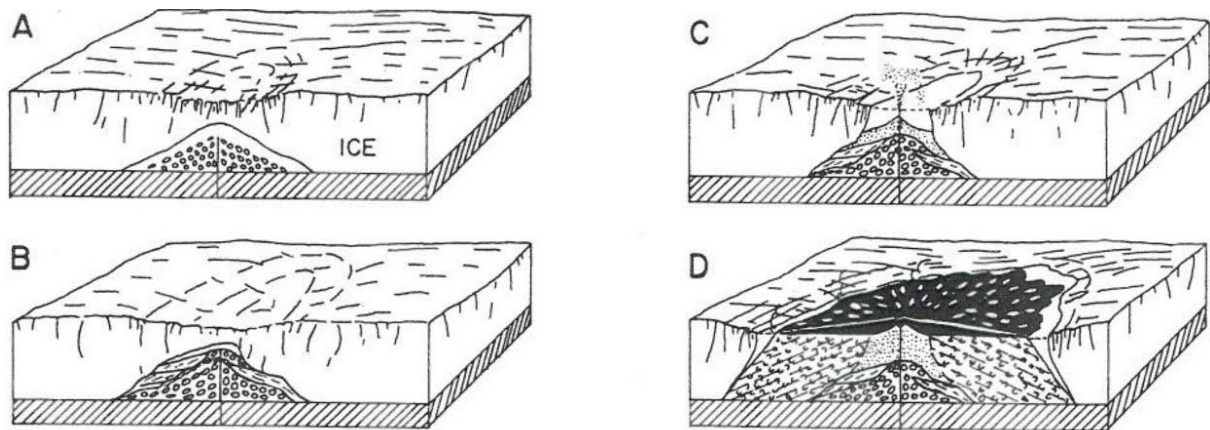


FIGURE 12: Growth of subglacial monogenetic volcano (Jones, 1969; Saemundsson, 1979);
 A) A pile of pillow lava forms deep in a melt water lake; B) Slumping on the flanks of the pillow
 lava pile produces pillow lava breccia; C) Hyaloclastite tuffs erupted under the shallow water;
 and D) A lava cap propagates across its delta of foreset breccia

subglacial eruption proceeds (from Jones 1969, and Saemundsson 1979). The hyaloclastite units in the area did not reach stage C, as shown in Figure 12. The average elevation is estimated to be between 150 to 300 m a.s.l. The thickness of ice covering the area during the last glaciation has been estimated to be around 300 m (Arnórrsson et al., 1975; Abdelghafoor, 2007).

4.1.3 Chronostratigraphy of the Slaga-Arnarvatn area

The details of the stratigraphic units mapped are described below, from the oldest to the youngest formation, Figure 13 shows a geological map of the study area, and Figure 14 shows three representative geological cross section along profiles AB, EF and GH.

1. *Smjördalshnúkur old sediments and Ketill basaltic lava unit*

The oldest sediments are located in two restricted outcrops in the western part of the study area and correspond to an assemblage of subaerial layered sediments. An outcrop in the northeast corner of the study area reveals an aphyric subaerial lava flow underneath the Smjördalshnúkur hyaloclastite unit. The lava was probably formed during the third last interglacial epoch (300,000-340,000 years).

2. *Hyaloclastites*

The hyaloclastites, divided into four units, are the most common component of the lithology of the Arnarvatn area. In places (see Figure 13) they are intercalated by interglacial lavas:

Smjördalshnúkur hyaloclastite unit

The oldest hyaloclastite unit in the area is localized at the westernmost rim of the study area. This unit shows locally low-grade clay alteration and its main component is tuffaceous materials with aphyric fine-grained basaltic clasts, occasionally coarse-grained. Layered structures are common within this unit. The layering can be explained as a result of subglacial eruptive phases (thickest layers) with the thinner layers made up by mud representing the fall-off tail during some seconds to minutes of non eruptive phases. This oldest hyaloclastite unit is found to contain some gabbroic xenoliths.

Slaga hyaloclastite unit

The Slaga hyaloclastite is localized in the crestal parts of the longest ridge of the study area; it is composed of dense tuff with very few lithic fragments in it, and is relatively fresh. Locally, the aphyric tuff is brecciated, and only occasionally are plagioclase phenocrysts found within it. This hyaloclastite unit should be equivalent to *moberg C* in Abdelghafoor's report (2007).

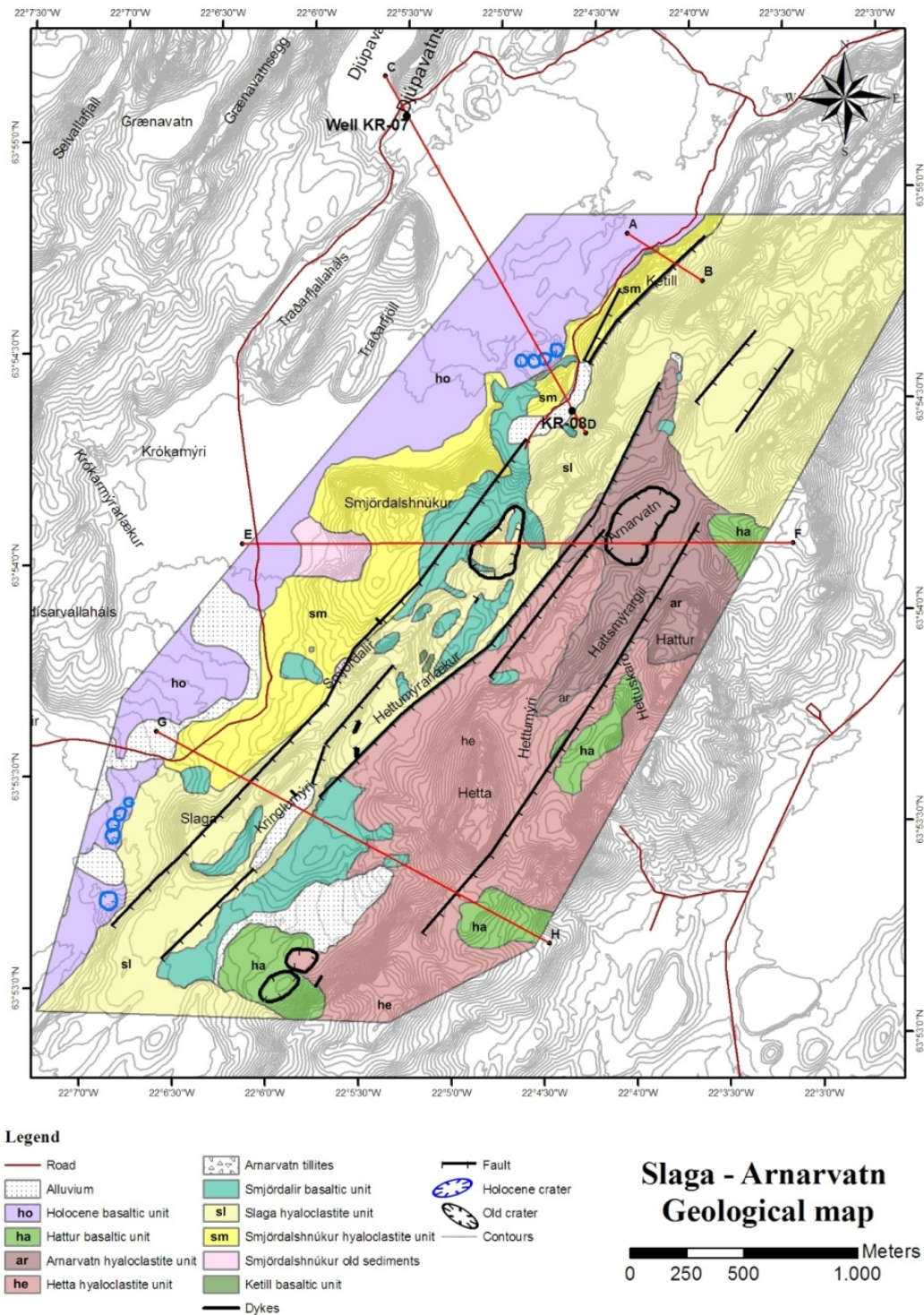


FIGURE 13: Slaga-Arnarvatn geological map

Hetta hyaloclastite unit

The main components of the Hetta unit are basaltic pillows with brownish glasses in between at deeper levels, aphyric but occasionally coarse-grained. The upper part of the unit consists mainly of layered tuffaceous hyaloclastites. This hyaloclastite unit occupies the southeast part of the mapped Slaga-Arnarvatn area. Its contact with the Smjördalir interglacial basaltic lava unit in the south is also characterized by a relatively active geothermal zone with steam-dominated vents and whitish to reddish clays (high- to low-grade geothermal alteration zones).

Hetta, Slaga and Smjördalshnúkur hyaloclastite units are dated from the third last glaciation, also called Mindel (240,000-300,000 years) (Johannesson, pers. comm.).

Smjördalir interglacial basaltic lava unit 2

Aphyric, fine-grained basaltic lava patches are found dispersed within the older hyaloclastite units. It is not clear if these lavas were formed in a single eruption or more, during the 2nd last interglacial period.

Arnarvatn tillites

Lithified heterogeneous and unsorted glacial sediment form a grey layer on the top of the Slaga hyaloclastite unit and the interglacial lava unit 2. This tillite marks a glacial period when the suspended sediments were deposited as the glacier advanced.

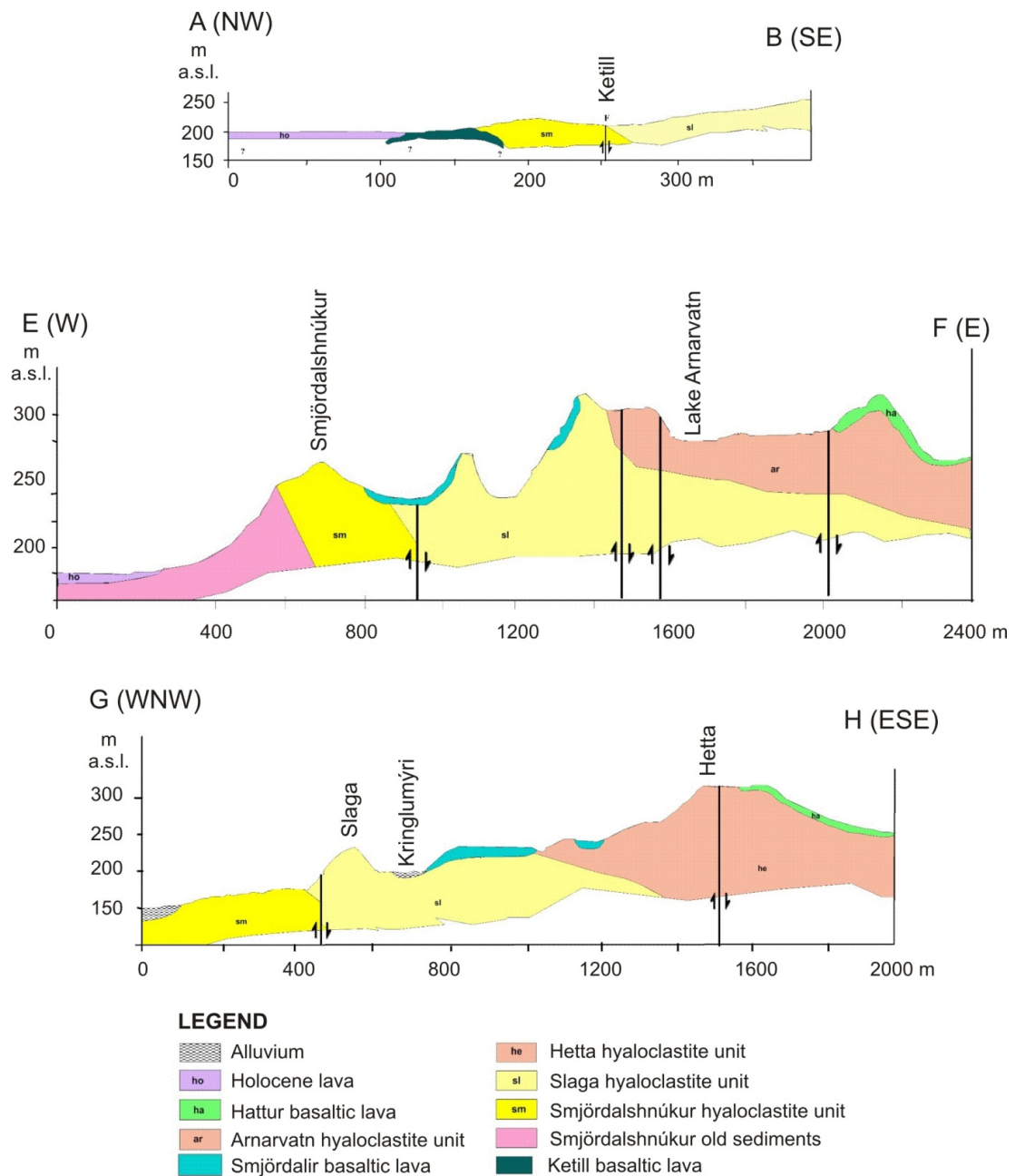


FIGURE 14: Geological cross-sections AB, EF and GH; for location see Figure 13

The Smjördalir interglacial basaltic lava unit 2 was formed during the second last interglacial period, also named the Holstein interglacial period (200,000-240,000 years). Arnarvatn tillite was formed during the second last glaciation.

Arnarvatn hyaloclastite unit

The hyaloclastite unit is composed of relatively fresh looking and young hyaloclastite, which is rich in small lithic fragments of very scoraceous material, containing small plagioclase phenocrysts. This hyaloclastite formation is quite fractured and within it is the Arnarvatn crater lake, which was formed much later in relation to the Hattur basaltic unit.

The Arnarvatn hyaloclastite unit belongs to the second last glacial period (Saale: 130,000-200,000 years).

Hattur interglacial basaltic lava unit

This porphyritic lava corresponds to the last interglacial period (Eemian) aged between 110,000 and 130,000 years. It is mainly represented in the eastern part of the study area, and is composed of porphyritic lava with plagioclases and sometimes big xenoliths. During the survey, it was realized that in the study area there appears to be a hiatus of the last glacial period (Weichsel: 12,000-110,000 years).

3. Holocene lavas (0-12,000 years)

Regional and detailed geological mapping of the Reykjanes Peninsula has enabled geologists to group the Holocene eruptions into four volcanic episodes (Jónsson, 1978; Saemundsson, 1979; Jóhannesson and Einarsson, 1988; and Jóhannesson, pers. comm.).

- Early Holocene lava shield volcanoes, like the Thráinsskjöldur and Almenningar
- Three younger volcanic episodes, all involving fissure eruptions, some 5000-7000 years ago, 2000-3000 years ago and 700-1100 years ago (see also Table 1).

Within the study area, lavas from all periods but the oldest are present. However, a distinction is not made between the individual Holocene lavas as presented on the geological map (Figure 13). The last eruptive period in the study area has been characterized by N45°E ranges of craters along the fissure swarms. The Krýsuvík lava flows cover about 36.5 km² and Einarsson et al. (1991) have estimated the volume of lavas to be close to 0.22 km³.

4. Outwash, tephra layers and recent sediments

The surroundings of main faults, micro-grabens and craters of the mapped area, are theatres of eroded material deposition. Those depressions are covered to various extents with outwash and soils due specifically to the deposition of aeolian and fluvial materials. The origin of all these materials is from the tuffaceous hyaloclastites, palagonites and some scoraceous debris.

4.1.4 Structural geology

The most important tectonic features in the study area are NE-SW fissure swarms which have dissected the elongated ridges of hyaloclastites as shown in Figure 13. Normal faults are prominent (Figures 15 and 16). The average direction is N20°E (faults I and II) and N30°E (fault III). The throw of the faults is often difficult to measure, but range within metres. The faults that dissect the study area are more common within the hyaloclastite ridges than in the younger lavas which simply relates to age.

It should also be mentioned that additional to the normal fault, four explosive craters have been mapped within the Upper Pleistocene hyaloclastite units. They are generally surrounded by scoraceous materials, which are the first products to come out during an eruption, and aphyric and fine-grained basaltic lava. Also, there are two crater rows (oriented NE-SW) mapped within the

Holocene basaltic lava. Slaga and Hetta hyaloclastite units show many fractures and a few dykes have been pointed out and mapped (Figure 13).

4.2 Geothermal mapping

In Krýsuvík, thermal manifestations on the surface have been estimated to cover some 40 km² (Arnórsson et al., 1975; Ármannsson et al., 1994). Investigations carried out by drilling have shown that the rocks down to 2 km are predominantly composed of basaltic hyaloclastite and lavas. The rocks and hyaloclastites are of either olivine tholeiites type or tholeiites type.

4.2.1 Mapping of surface manifestations

Figure 17 shows the results of the geothermal mapping in the Slaga-Arnarvatn area. Active geothermal manifestations, such as fumaroles, mud pools and hot grounds, and slight- to high-grade extinct alteration, are found within the study area.

A description of the active sites is given below:

Fumaroles, mud pools and hot grounds

Within the study area, four active geothermal sites were mapped (Figure 17). Temperature measurements were done using a digital thermometer connected by a cable through a 1 m long metallic rod, fixed at the tip with a sensor. The surface temperatures were carefully measured for mapped sites and were in the range of 60-100°C. Common in the mapped active sites was the smell of hydrogen sulphide. Figures 18 and 19 show active fumaroles and mud pools in the area.

The most active geothermal sites within the study area are farthest to the south in the mapped field, located between two highly altered but extinct geothermal manifestations. The active manifestations seem to be in a state of cooling. The remaining ones consist of 2-3 fumaroles in the main part, one steam vent in the other and warm to hot grounds around the fumaroles. Regarding the extinct ones, the one further to the west is covered by relatively thick soils, whereas the one located to the southeast consists of a clayish ground of yellowish, white and reddish colours.



FIGURE 15: Tectonic features within the area

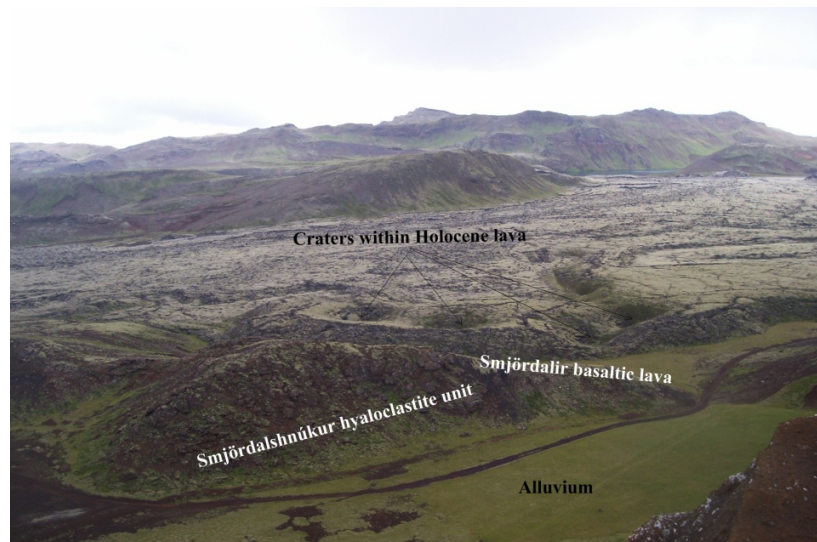


FIGURE 16: Craters within Holocene lava

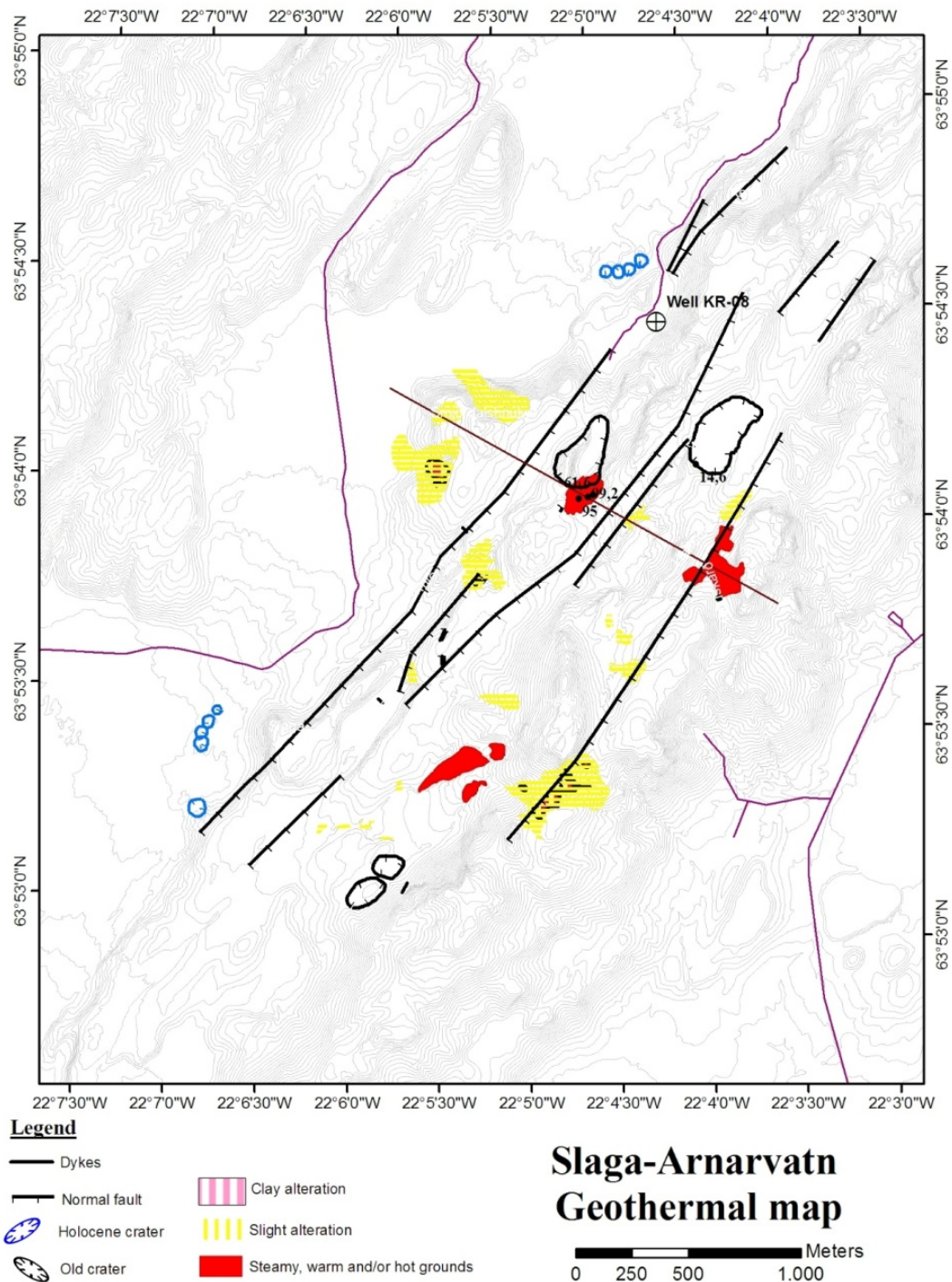


FIGURE 17: Geothermal map of Slaga-Arnarvatn area

The second active geothermal site in the Slaga-Arnarvatn area is located about 500 m southwest of the lake. It is a combination of steamy grounds and fumaroles covering an area of around 15x20 m within the Slaga hyaloclastite unit. The steamy ground is mostly hot and dry, while occasional mud pools appear after rainy days. The bedrock is completely altered to yellowish, whitish and grey-blue clays.

The two remaining active geothermal sites are located astride the boundary between Hetta and Arnarvatn hyaloclastite units, 500 m southeast of Arnarvatn Lake. The northern site mainly consists

of 5-10 m of steamy ground with mud pools while the southern one is dominated by hot ground (surface temperature measured: 98.9°C) with fumaroles evenly distributed.

Hot grounds where the bedrocks have been heated and highly altered by acid surface leaching are common in the four mapped zones. Grey, yellow, and red to white clay minerals are dominant in active geothermal sites within the study area.

The active geothermal sites occur near normal faults, a fact that seems to suggest that the fumaroles could be tectonically controlled. In most cases, they are surrounded by less intense alteration zones, characterized by reddish to grey soils. The soil within these active fields is yellowish coloured due to the high soil temperatures (above 60°C).

Extinct geothermal manifestations

Extinct geothermal sites within the study area grade in alteration degree from slight to intense. An example of slight alteration is shown in Figure 20, and an example of very intense alteration in Figures 21 and 22. Samples of clay were taken in the field for XRD analysis, which indicated that the most common clay type is smectite (discussed in 4.2.2).



FIGURE 18: Active fumaroles near Hattsmýrargil trough fault



FIGURE 19: Mud pool within cooked hyaloclastite



FIGURE 20: Slight alteration in the study area

4.2.2 Rock alteration and geothermal mineral assemblage

As mentioned above, the intensity of rock alteration ranges from very weak to very intense. The host rock concerned, affected by hydrothermal alteration, is predominantly glassy hyaloclastite. The interglacial lavas have, in places, also been slightly affected, but elsewhere they may postdate the geothermal alteration.

Two types of slight alteration are distinguished: a) a change in colour of the typical light brown palagonite tuffs to a much darker brown to reddish coloured tuffs, and b) white coloured minerals of calcite, aragonite or zeolites occur within pores or fractures within the host rocks.

Both within active and extinct manifestations, there are sites where rock alteration has reached completion, where all the hyaloclastite has been replaced by clays (Figure 21). XRD analysis of clay samples (JC-01, 10, 12, 20 and 25) has shown that the most common clay type is smectite (Appendix I). The colour of the clays ranges from white to dirty white to brown and over to red. Yellow specs related to sulphur deposition are also common within the high alteration zones, as are mineral salts called pickerengite.



FIGURE 21: Intense alteration south of Hetta



FIGURE 22: White coloured materials (white clays and silica sinters) south of Arnarvatn Lake on Hattsmýrargil fault

In one clay sample, JC-20 OMH (Appendix I, Figure 5), mixed-layer clay mineral may be suggestive of some erosion as the temperatures for mixed layering approached 200-230°C. However, the low-temperature mineral alteration of the study area is characterized by smectite-zeolites, formed at temperatures from around 40°C up to boiling, close to 100°C.

5. CONCEPTUAL GEOTHERMAL MODEL AND DISCUSSION

The general scheme of alteration minerals in Iceland indicates that smectites, zeolites, calcium silicates, calcite, pyrite and quartz are formed at rock temperatures below 200°C. Smectite transforms into mixed-layer clay mineral and swelling chlorites in the temperature interval of 200-230°C. At

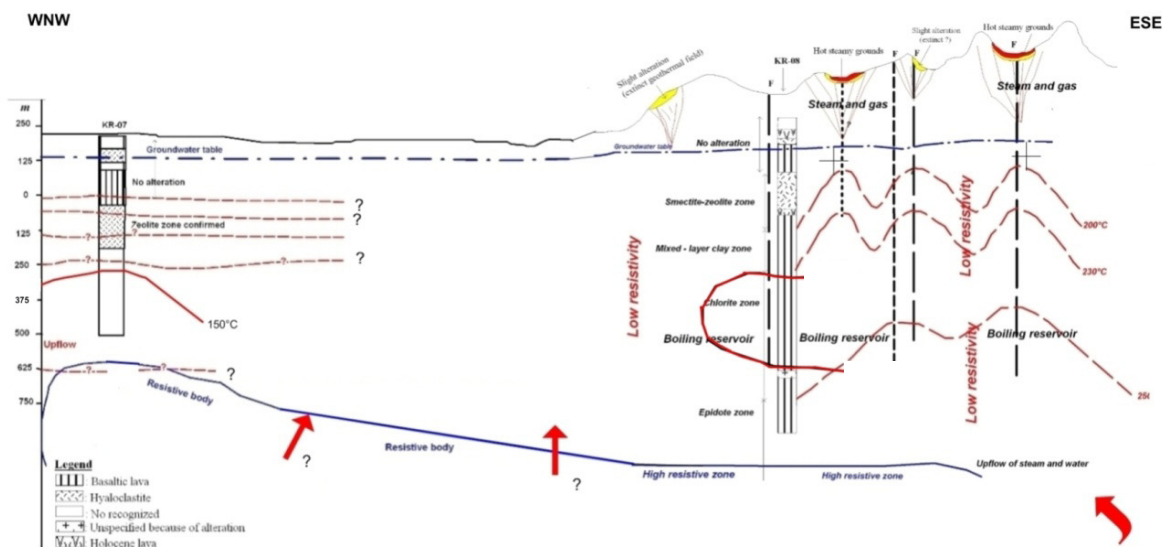


FIGURE 23: Conceptual model of the geothermal activity in the Slaga-Arnarvatn area (cross-section WNW-ESE combining profile CD in Figure 14 through KR-07 and KR-08 and profile AB of Figure 17)

240°C, chlorites become dominant while epidote and prehnite are formed at similar temperatures and above; actinolite appears at temperatures approaching 300°C (Kristmannsdóttir, 1979). In the Krýsuvík field, similar alteration minerals were observed in well H-2 (Kamah, 1996).

A simple conceptual model is shown in Figure 23. There, an attempt is made to link the main lithological, tectonic and hydrothermal features of the surface to the subsurface manifestations in boreholes KR-8 and KR-7, to the SA7 resistivity cross-section discussed in Section 3. The main feature for all wells in the Krýsuvík area is a deep convective gradient (Vargas, 1992). The second fact worth pointing out is that all wells (with the exception of KR-7) present a thermal reversal below 300-600 m depth (Ármannsson et al., 1994). The 200°C measured interval in KR-8 is shown by a solid red line in the model. Well KR-8 presents a temperature reversal in the depth range of 400-500 m. During well logging of KR-8, 11 aquifers (or feed points) were detected within 400-900 m. There, it seems quite likely that the cooling is controlled by the inflow of cold water (represented by blue arrows) from meteoric waters percolating in the ground, taking advantage of the primary porosity and/or the secondary porosity established by the faults, fractures and fissure swarms.

Alteration mineral zones in the same borehole show: low-temperature smectite-zeolites at upper levels: the presence of quartz as it draws deeper at temperatures >180°C, at a depth below 150 m; a mixed-layer clay zone formed at temperatures ranging between 200 and 230°C at depths between 350 and 450 m; and a chlorite zone at temperatures above 240°C at a depth below 450 m in well KR-8. Epidote, which in Icelandic geothermal fields implies temperatures above 230-260°C, is found at depths below 800 m. These mineral zone isotherms are shown in the conceptual model in Figure 23.

The geothermal manifestations are distributed on linear NE-SW normal faults (Figure 17) which is an indication that the upflow zones are structurally controlled as shown by the developed conceptual model. Warm or cold springs are not present in the study area, and all the geothermal manifestations are steaming fumaroles, or warm and hot grounds; occasionally mud pots form during a rainy season. This suggests that all the surface manifestations contain steam heated surface waters that are not representative of the reservoir waters.

The alteration processes are facilitated by ascending geothermal steam, rich in CO₂, H₂S and H₂, which reacts with surface waters, which becomes pretty acid and causes leaching of the host rocks. The sparse occurrences of sinters are suggestive of extinct geyser activity, which may have occurred when the Pleistocene groundwater situation was different from the present day status.

6. CONCLUSIONS AND RECOMMENDATIONS

The lithology of the Slaga–Arnarvatn is dominated by NE-SW trending hyaloclastite units built up subglacially by four separate eruptions. The oldest hyaloclastite unit is 240,000-300,000 years old whereas the youngest is 130,000-200,000 years old. The hyaloclastite units are mostly tuff dominated and contain aphyric, fine- to coarse-grained lithic fragments of different sizes but occasionally small plagioclase phenocrysts are found (Slaga and Arnarvatn hyaloclastite units).

Three interglacial periods are represented by three interglacial basaltic lava units (300,000-340,000 to 130,000-110,000 years old). Holocene lavas are also present in the study area. Except for the Hattur porphyritic interglacial lava unit (110,000-130,000 years old), the interglacial lavas are aphyric and mostly fine grained. In the study area a hiatus of the last glacial period is tentatively suggested. Correlation with neighbouring geological maps from Abdelghafoor (2007) and Maweje (2007) does not support this idea – they suggested that the Arnarvatn formation was from the last glaciation. The present author believes that the porphyritic lava flow (Hattur flow) is from the last interglacial period and, thus, the underlying hyaloclastite of Arnarvatn must be from the second last glacial period. The Hattur flow has been clearly denuded by glaciers.

Tectonically, the study area is dominated by normal faults and fissures trending N20-40°E. In addition, craters within both the hyaloclastite units and Holocene lava flows and dykes striking in N-S to NE-SW direction are found in the study area.

Mapped geothermal manifestations in the area are grouped into active and extinct zones, both ranging from slight alteration to intense clay alterations, where there is currently hydrothermal surface activity, or where it was most active in the past. The hydrothermal alteration patterns are structurally controlled.

For better understanding of the local geodynamics, and the history of the geothermal resource of the study area, the following studies are recommended:

- More detailed geological surveys with emphasis on mapping the lithology and local structures, with tephrochronology applied to the fossil geothermal manifestations located underneath relative thick soils;
- Passive seismicity combined with detailed analysis of resistivity data for the deep structural features;
- Mapping of CO₂ and other gases originating from magmatic chambers; and
- Drilling of two additional wells: a directional well (NW-SE) near KR-8 and a vertical deep well (2000 m) in the Kringlumýri depression (southwest of the study area).

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APPENDIX I: XRD analysis of samples from Slaga-Arnarvatn area

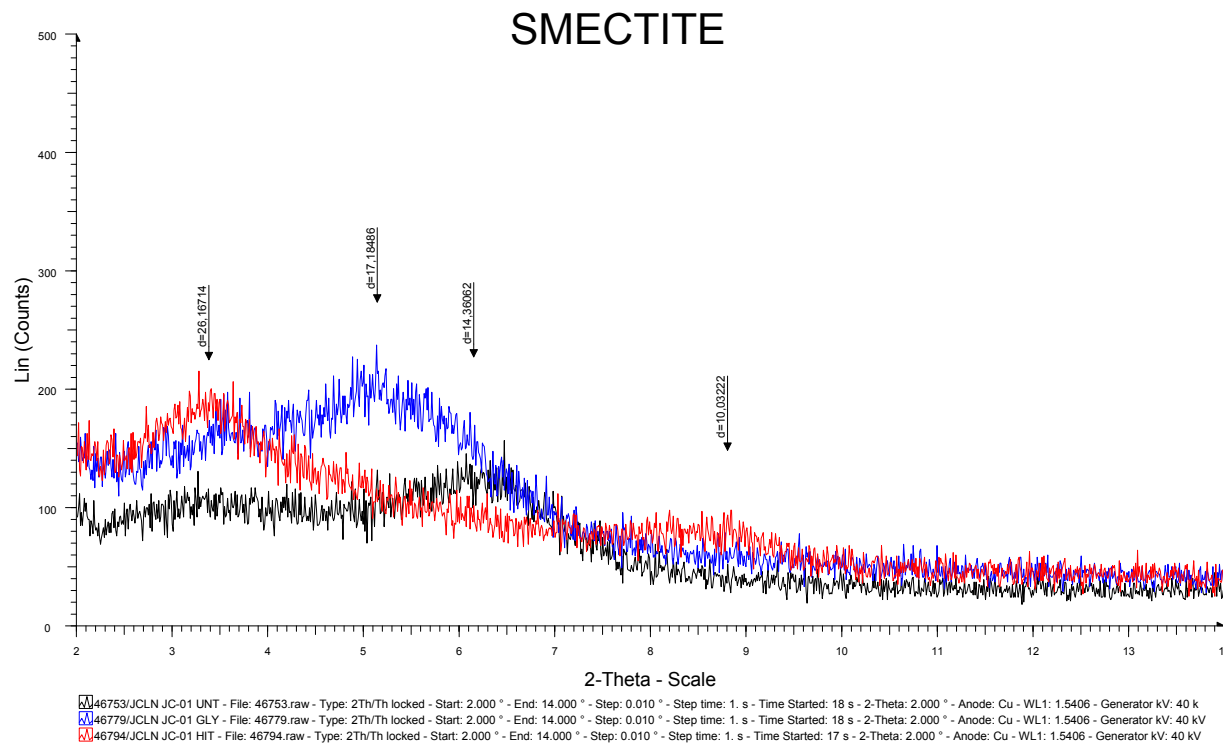


FIGURE 1: XRD analysis of sample JC-01 UNT

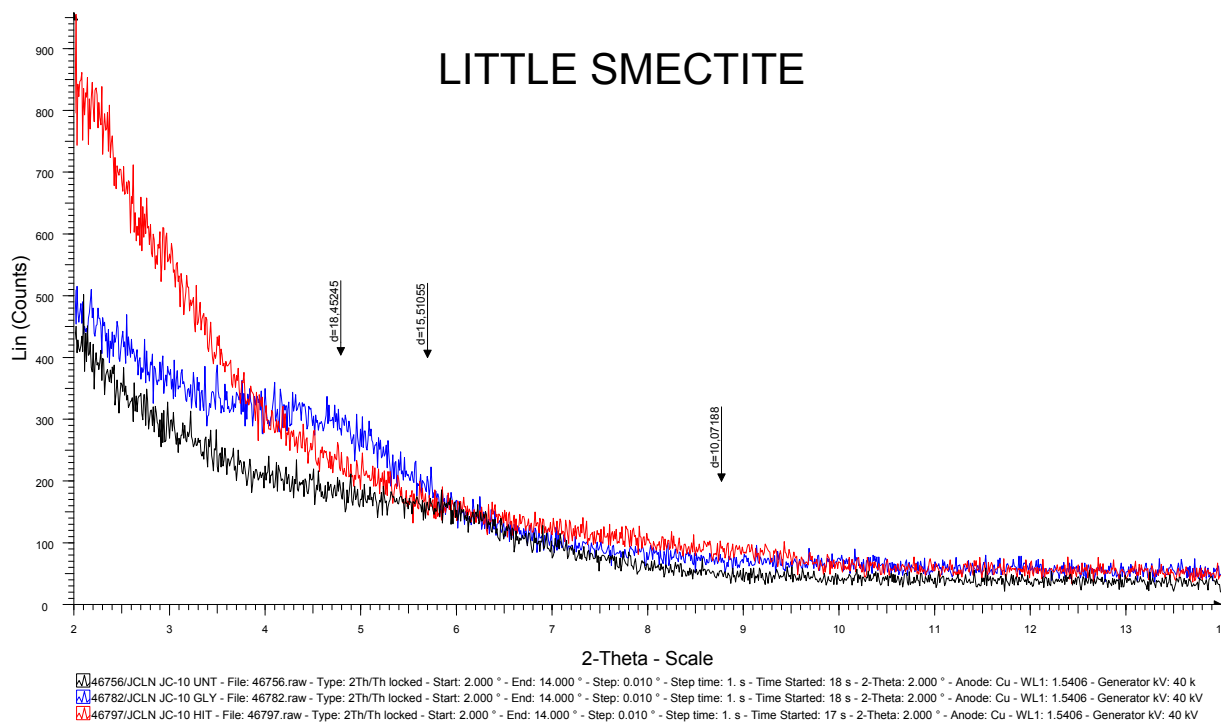


FIGURE 2: XRD analysis of sample JC-10 UNT

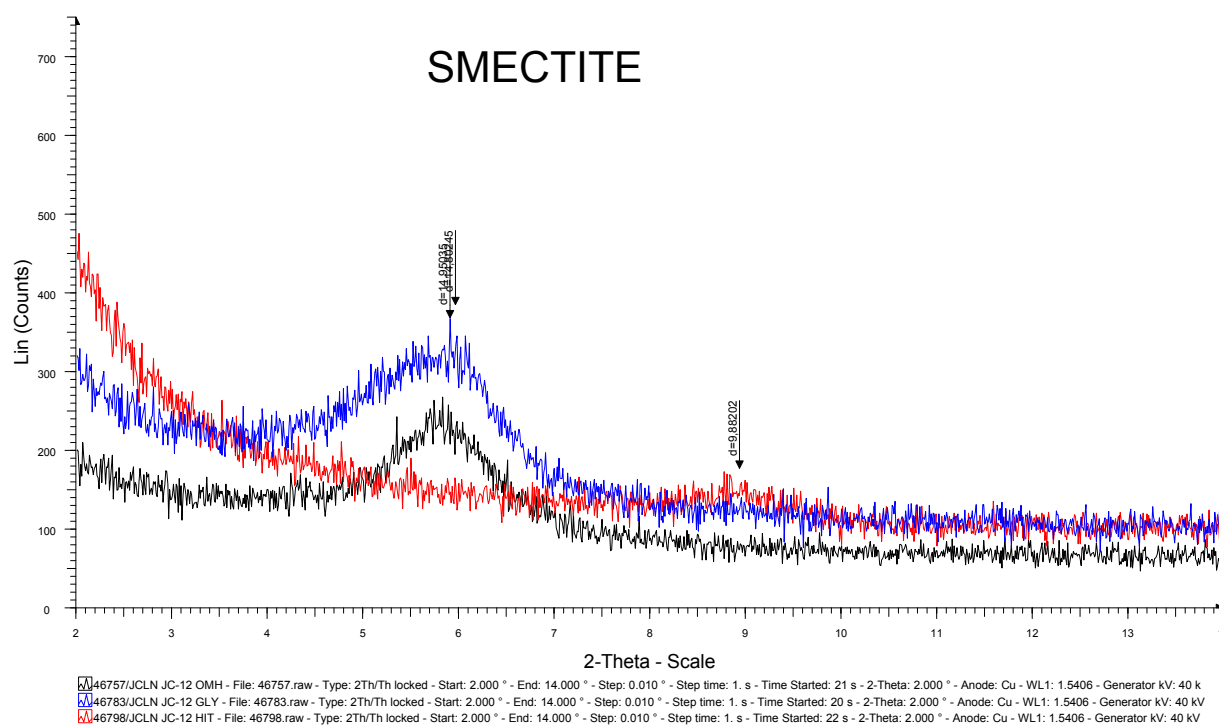


FIGURE 3: XRD analysis of sample JC-12 OMH

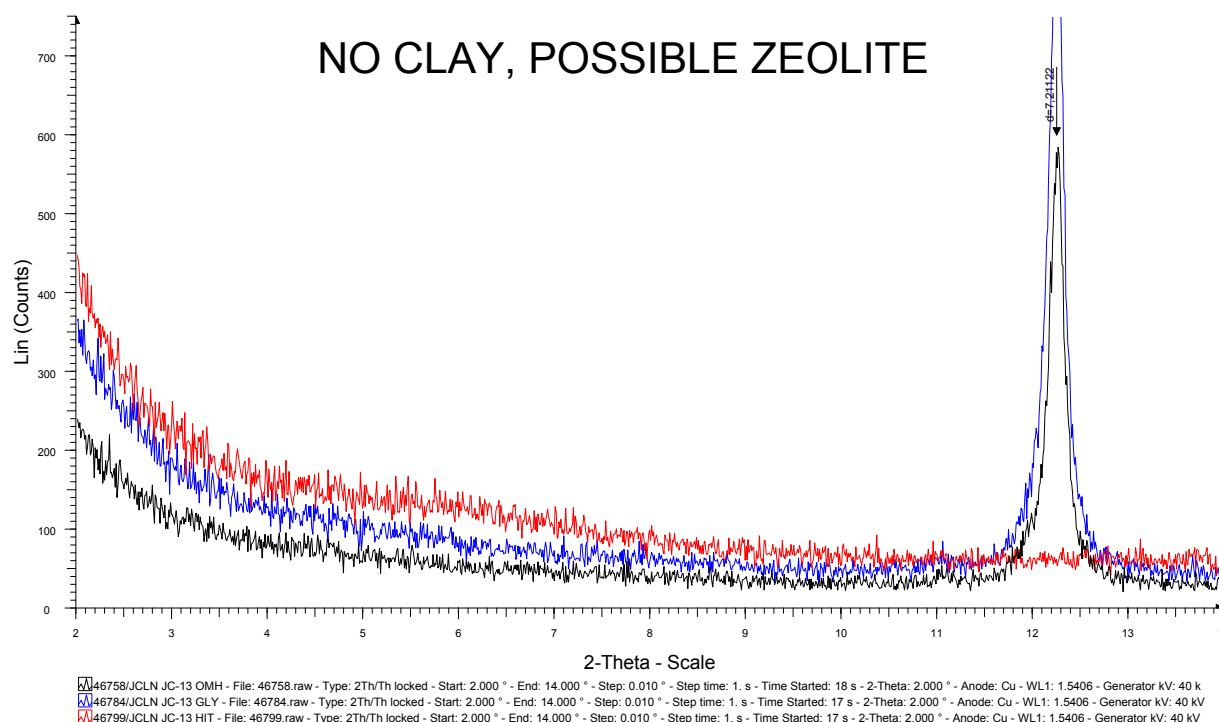


FIGURE 4: XRD analysis of sample JC-13 OMH

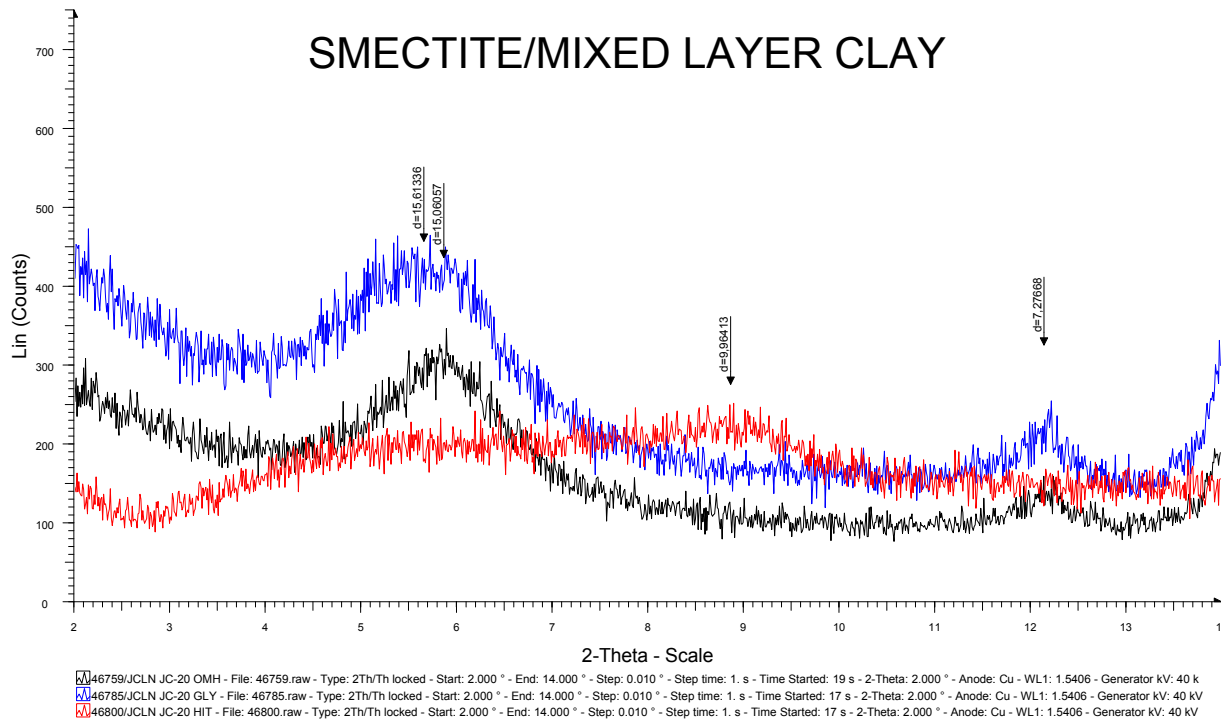


FIGURE 5: XRD analysis of sample JC-20 OMH

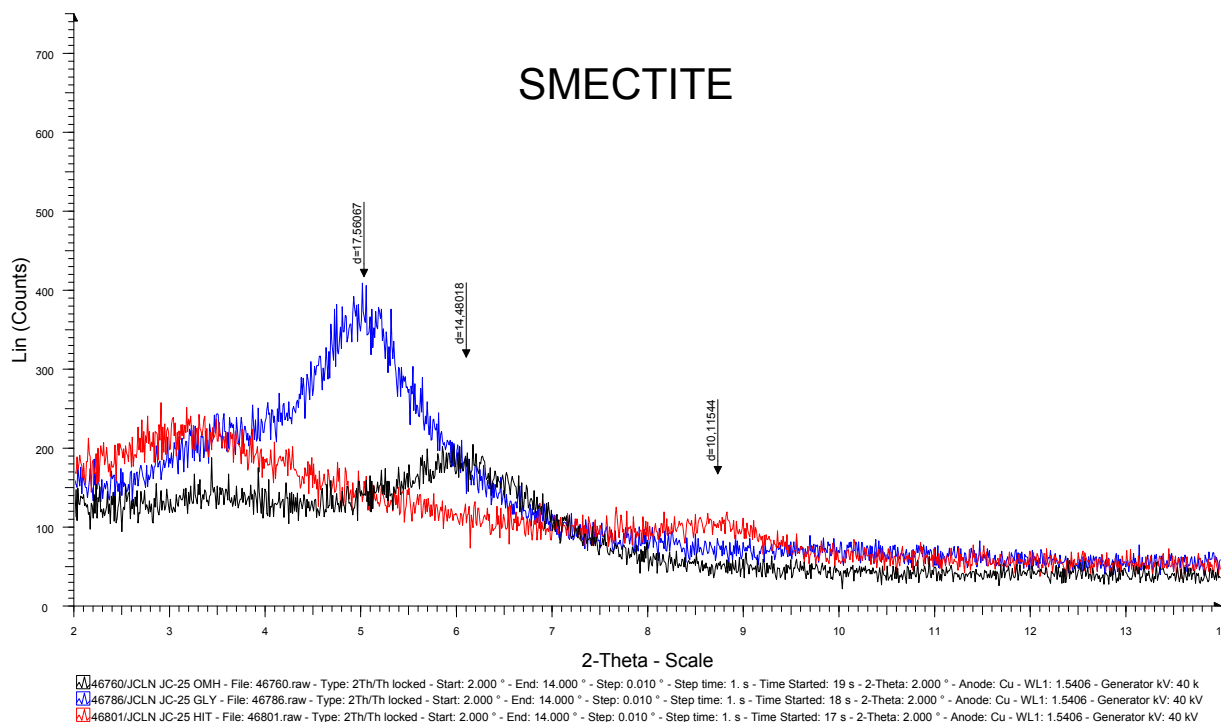


FIGURE 6: XRD Analysis of sample JC-25 OMH