



UNITED NATIONS
UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2007
Number 3

GEOLOGICAL AND GEOTHERMAL MAPPING IN SVEIFLUHÁLS AREA, SW-ICELAND

Mohammad Abdelghafoor
Natural Resources Authority
Geology Directorate, Geological Mapping Division
P.O. Box 7, Amman
JORDAN
m_abdelghafoor@yahoo.com

ABSTRACT

Geological and surface hydrothermal alteration mapping was carried out in the Sveifluháls area to the north of the active Krýsuvík geothermal field. The upper Pleistocene interglacial and glacial succession is composed of 9 units including hyaloclastite and basaltic lava flows in addition to the historical lava that covers the northwest part of the study area. The study area is crossed by several extensional faults and fractures with a NE-SW general trend.

The study area exhibits different grades of hydrothermal alteration, including zeolite-calcite and clay alterations. XRD analysis and petrographic studies showed the presence of different types of zeolite, calcite and clay minerals with different grades of alteration. The field relationships between the hydrothermal alteration and the geological setting of the study area imply that the hydrothermal alterations are quite old and structurally controlled. The geothermal map illustrates the distribution of the alterations. They are concentrated on the western side of the main hyaloclastite ridge in the central and southern parts of the study area, indicating that the centre of geothermal activity lies to the southwest of the study area. That corresponds with resistivity maps of the area. This implies that the geothermal system is cooling down and the activity is moving towards its centre.

1. INTRODUCTION

1.1 Background

Iceland was created at the intersection of a mid-oceanic ridge plate boundary and a mantle plume (or a hot spot). The North Atlantic Mid-Oceanic Ridge comes ashore at the Reykjanes Peninsula, in the southwest corner of Iceland, and crosses the country in a northeastward direction. This plate boundary is marked by a zone of volcanic and seismic activity as it slowly diverges, roughly one centimetre per year in each direction.

Iceland's geothermal features are common in the volcanic zone along the tectonic plate boundary. Here, groundwater and sometimes seawater seep into the ground and travel through highly fractured bedrock. The water reaches varying depths where it comes in contact with heat from volcanic sources.

As the water is heated, it ascends through fissures, crevices, and volcanic crust to emerge in hot springs and other geothermal features.

Geothermal areas in Iceland are divided into high-temperature fields and low-temperature fields. High-temperature systems have temperatures of at least 200°C at a depth of one kilometre and are only found in the active volcanic zone along the tectonic plate boundary. Magmatic intrusions provide the main heat source for these systems. Low-temperature systems have temperatures less than 150°C at a depth of one kilometre. The low-temperature areas are fracture dominated and derive their heat from convection within the cooling lithospheric plate.

1.2 Scope of study

Geological exploration is considered to be the first step for any geothermal utilization process of an area and gives an idea about the behaviour of the geothermal system and its evolution during geologic time. The main goal of this study was to carry out surface geological and geothermal mapping in the Sveifluháls area (west of Kleifarvatn lake) by classifying the rock units depending on their petrological characters, mapping the main structural features in the area and outlining the locations of surface geothermal manifestations as well as alterations, in order to figure out the relationship between the geothermal activities and the tectonic setting of the study area.

1.3 Location and accessibility

Sveifluháls area is located on the western rim of Kleifarvatn lake, 25 km to the south of Reykjavík and north of Krýsuvík geothermal field (Figure 1). The area is accessed by taking the road from Reykjavík to Krýsuvík. On reaching the area there are two choices for reaching the Sveifluháls high ridges; either take the western road near the lava field which is an earth road, or take the eastern road near the lake which is a gravel road.

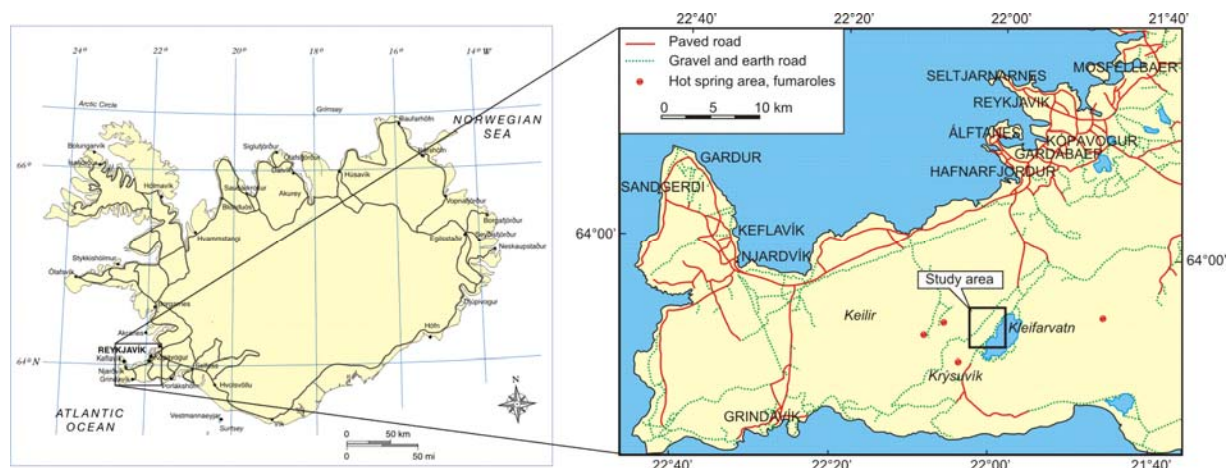


FIGURE 1: Location map of the study area

1.4 Topography and climate

Topographically, the study area could be divided into two main regions (Figure 2). The first includes the northeast lava plains, a relatively flat area with an average elevation of about 200 m a.s.l. The second topographical region features the highly elevated ridges near Kleifarvatn lake, and represents the main part of the study area. The elongated hyaloclastite ridges trend NE-SW, and range in elevation between 160 and 400 m a.s.l.

Since the study area is close to the Atlantic Ocean, it is affected by the Irminger current, which greatly moderates the climate along Iceland's southern and western coasts. The area receives a relatively high mean annual rainfall, between 1200 and 2000 mm per year. Winter is cold with a mean daily temperature in the range between -2 and -4°C. Summers are fairly warm, with a mean monthly temperature of about 8-10°C (The Icelandic Meteorological Office, 2007)

1.5 Methodology

In order to achieve the main goal of this research and verify the relationship between the tectonic setting of the study area and the geothermal alterations, a reconnaissance geological survey was carried out during August and September 2007 using a Garmin-GPS 72 to locate and track the structural lineaments (i.e. faults and fractures) 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 and spot images have been used to trace the aerial extent of the major structures and their distribution within the study area. These photos were super-imposed by topographical maps in order to draw these structures. Several rock samples that show geothermal alteration were collected for XRD and petrographic analytical purposes, in order to figure out the degree of alteration and the mineral assemblages that exist in the hydrothermally altered areas.

1.6 Previous work

Several geological, geophysical and geochemical studies have been carried out in the Krýsuvík geothermal field, including the Sveifluháls area. Previous geological maps were prepared by Imsland (1973), Jónsson (1978) and Saemundsson and Einarsson (1980). Imsland mapped Sveifluháls and classified the rocks there into eight stratigraphic units composed of hyaloclastite, glacial sediments and other volcanic materials, while Jónsson created detailed maps (scale 1:25,000) of the entire Reykjanes Peninsula, but mostly focussed on mapping the Holocene lavas. Saemundsson and Einarsson prepared a more generalized geological map of the Reykjanes Peninsula in the scale 1:250,000, where all the rocks in the study area were classified as a single hyaloclastite unit. Vargas (1992) studied the geological and geothermal situation of the Krýsuvík valley, producing a geological map for the area south of the Kleifarvatn lake.

Arnórsson et al. (1975) carried out an exploration programme consisting of two phases: (1) a surface exploration using geophysical, geological and geochemical methods; and (2) drilling of slim 800-1000 m deep exploratory wells. As part of their study, an electrical resistivity map at 600 m depth was

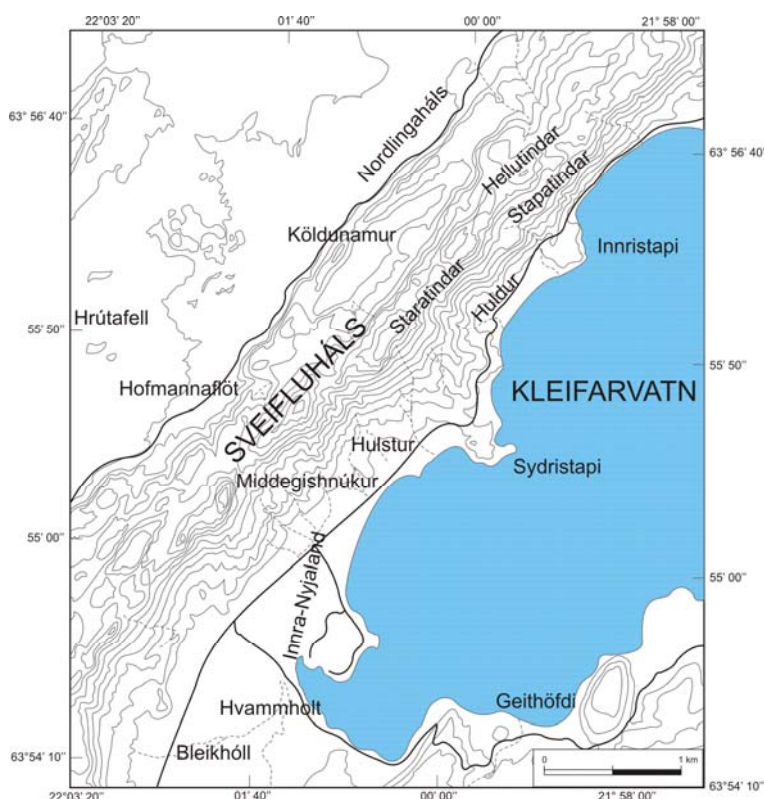


FIGURE 2: Topographic map of the study area

produced that showed the Sveifluhals area with three different resistivity zones: $< 10 \Omega\text{m}$, $10\text{-}30 \Omega\text{m}$ and $30\text{-}50 \Omega\text{m}$.

Arnorrsson (1987) studied the gas chemistry of the Krysuvik geothermal field, particularly in the Sveifluhals area and found that the subsurface temperatures were in the range $290\text{-}300^\circ\text{C}$ when using a CO_2 geothermometer. Einarsson et al. (1991) investigated the youngest lava flows in the Krysuvik area, using radiocarbon dating and tephrochronology to determine the age of the lavas. They suggested that these lavas were formed in an eruption in 1151 AD and named it the Krysuvik Fires.

In an overview report on geothermal investigations, Flovenz et al. (1986) give a resistivity map at 300 m depth that shows a low-resistivity zone ($< 5 \Omega\text{m}$) to the southwest of Koldunamur area. Eysteinnsson (2001) performed TEM resistivity measurements around Trolladyngja and Nupshlidarhals. Five of the subsurface resistivity sections that cross the study area show a low-resistivity layer ($< 6 \Omega\text{m}$) that comes up near the surface in the Koldunamur active area.

Clifton et al. (2003) reported on the surface effects of earthquakes since June 17, 2000, and a part of their study covers the Kleifarvatn area. They concluded that the earthquakes occurred along N-striking right lateral strike-slip faults. A major hydrological effect was the draining of water through an open fissure in the lake bed, lowering the lake level by more than 4 m.

2. GENERAL GEOLOGY

Iceland lies astride the Mid-Atlantic Ridge and is an integral part of the global mid-oceanic ridge system. It is the largest part of the mid-oceanic ridge system above sea level. Iceland developed on the Mid-Atlantic Ridge as a landmass between the submarine Reykjanes Ridge to the southwest and the Kolbeinsey Ridge to the north that has been active during the last 20-25 million years, broadly coinciding with the time-span of active volcanism in Iceland. 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. It has grown by rifting and crust accretion through volcanism along the axial rift zone, the volcanic zones, which in terms of the plate tectonic framework mark the boundary between the Eurasian and North American plates. 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 the northwest and eastern Iceland. There are also rocks of similar age in Western Iceland and in the centre of northern Iceland, caused by movements of the hot spot and the volcanic zones, due to rift jumps associated with the continuous movement of the mantle plume. The rate of spreading is calculated as 1 cm in each direction per year (e.g. Gudmundsson, 2007 and references therein).

2.1 Geological background of Iceland

Iceland is built almost exclusively of volcanic rocks, predominantly basalts. Silicic and intermediate rocks, rhyolites, dacites and andesites constitute about 10% and sediments another 10% (Saemundsson and Gunnlaugsson, 2002). Icelandic rocks can be divided into four main formations (Figure 3a):

- The Upper Tertiary plateau basalt formation;
- The Upper Pliocene and Lower Pleistocene grey basalt formation;
- The Upper Pleistocene palagonite (Hyaloclastite) moberg 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.

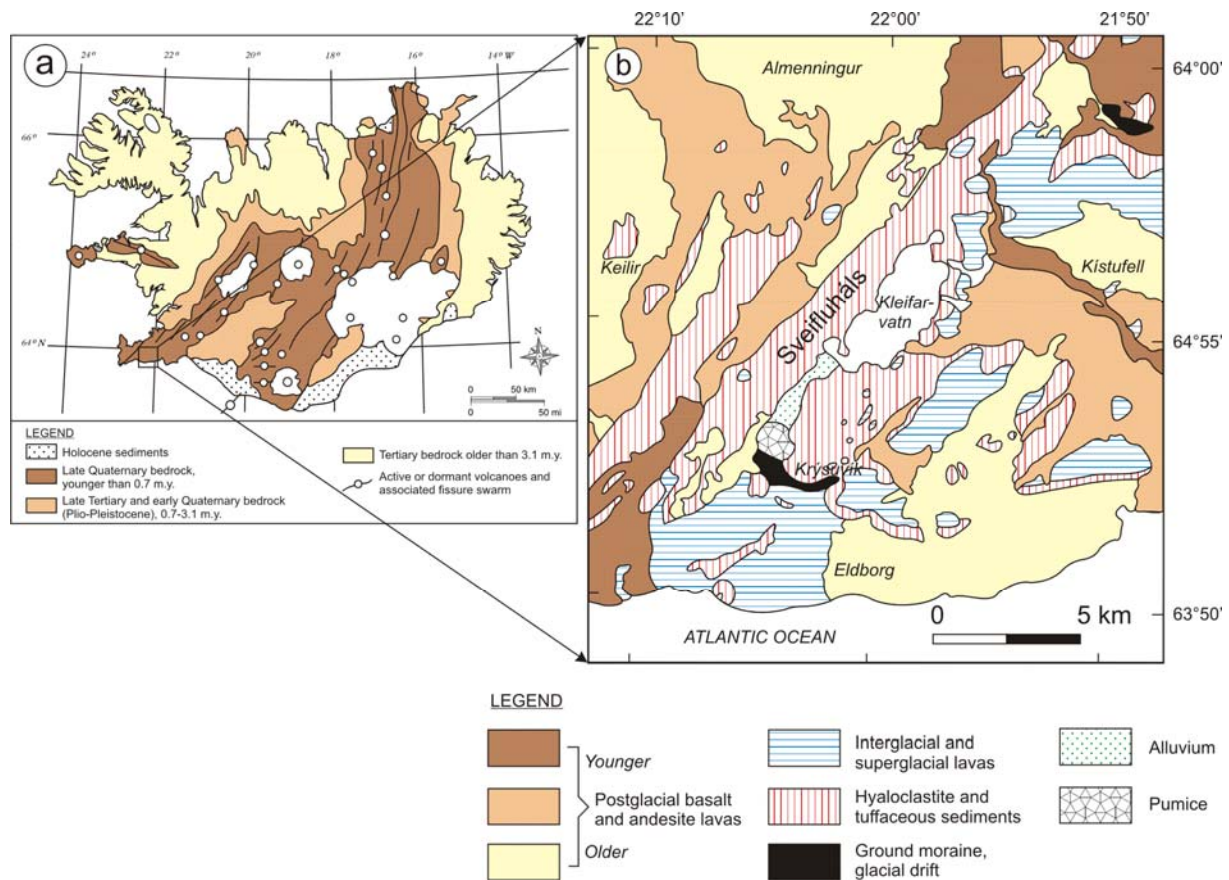


FIGURE 3: a) Simplified geological map of Iceland (courtesy Nordic Volcanological Institute);
 b) Regional geological map of Kleifarvatn lake and the surrounding areas
 (redrawn from Saemundsson and Einarsson, 1980)

The Tertiary basalt formation comprises east and southeast Iceland, the main part of west Iceland and western part of north Iceland, altogether about half the country's area. In east Iceland, basaltic lava flows, mainly tholeiitic, form 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 fine-grained granite (granophyre) occur, especially within the eroded ruins of differentiated central volcanoes. 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 the Middle Miocene and much younger than the basalts in Britain, Greenland and the Faroe Islands. In the Tertiary Icelandic basalts, lava vesicles are usually filled with minerals such as rock crystal, jasper and chalcedony, or with zeolites. Zeolites from Teigarhorn in Berufjörður are found in museums all over the world. The Helgustadir mine in Reydarfjörður remained the world's main supplier of the transparent Iceland spar (optical calcite) for centuries.

Intercalated between the plateau basalts, especially in northwest Iceland, are plant-bearing sediments and thin layers of lignites. Species found include beech, maple, vine, liriiodendron 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).

The Pleistocene rocks are confined mainly to a broad SW-NE trending zone between the Tertiary plateau basalt areas, and are also exposed on the peninsulas Tjörnes, Snæfellsnes and Skagi. The Pleistocene rocks are divided into two formations and the limit between them is the last magnetic reversal, occurring about 700,000 years ago (Gudmundsson, 2007). In the Pleistocene formation there are three main facies:

1. Interglacial basalt lava flows which are generally grey in colour and of coarser texture than the Tertiary ones. The grey basalt formation, where the interglacial basalt layers remain dominating facies, is mainly exposed along the inner border of the Tertiary basalt areas and in the central part of south Iceland.
2. Subglacially formed pillow lavas, breccias and brownish tuffs, known as palagonite (móberg), and rich in hydrated and otherwise altered basaltic volcanic glass. The share of silicic and intermediary rocks in the Pleistocene formation is similar to that in the Tertiary rocks. The main rhyolitic massifs are the Torfajökull and Kerlingarfjöll volcanic centres.
3. Glacial, fluvial, lacustrine and marine sediments that are interbedded between lava flows. The thickest series of marine strata are found on the Tjörnes peninsula in north Iceland, where the arrival of Pacific molluscs commenced about 3 million years ago, after the first opening of the Bering Strait.

Stratigraphic studies indicate about fourteen 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 mountain ash 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: 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. They consist of a shield volcano resting on an accumulation of pillow lavas and palagonite tuffs and breccias. The lava shields were formed by subaerial outflow of lava when the accumulations had grown high enough to protrude through the ice cover. The prototype of such table mountains is Herdubreid (1,682 m), north of Vatnajökull (Gudmundsson, 2007).

2.2 Regional geology of Reykjanes Peninsula

The Reykjanes Peninsula, SW-Iceland, is the on-land continuation of the Reykjanes Ridge section of the Mid-Atlantic Ridge. Volcanism takes place mainly within four fissure systems (Jakobsson, 1972; Pálmason and Saemundsson, 1974) (Figure 4). Several rock units of different ages and lithologies cover the Reykjanes Peninsula including postglacial basaltic lavas, interglacial and superglacial lavas,

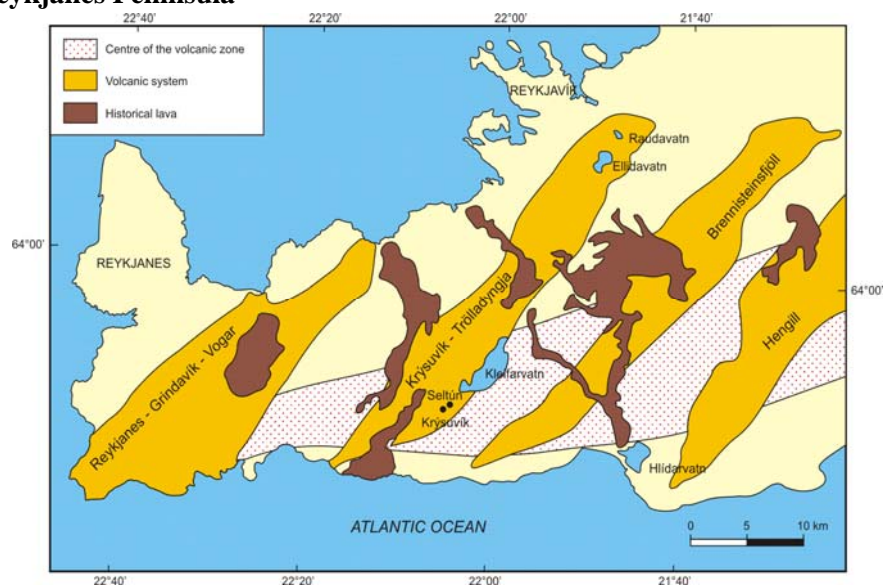


FIGURE 4: Distribution of the main volcanic systems on Reykjanes Peninsula (modified from Jakobsson, 1972)

and hyaloclastite and tuffaceous sediments beside other glacial and recent sediments (Figure 3b).

A high degree of obliquity between the ridge axis at $\sim N90^\circ E$ and the plate spreading direction of $\sim N110^\circ E$ induces a right-stepping, en-echelon arrangement of the fissure systems (Figures 4 and 5). The only occurrence of acid lavas on the Reykjanes Peninsula is at the Hengill volcanic system, the most northeasterly fissure system (Saemundson, 1995).

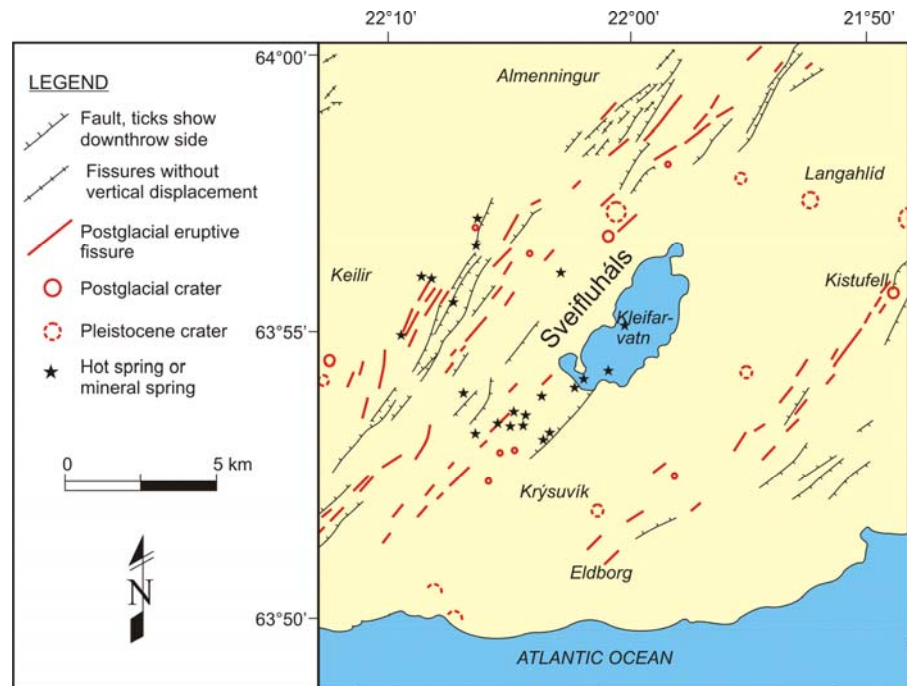


FIGURE 5: Regional tectonic map of the Kleifarvatn lake and surrounding areas (redrawn from Saemundsson and Einarsson, 1980)

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 by spreading-direction parallel fractures, producing alteration which varies from “spotting” of the basalt to complete replacement by clay minerals. There are four main geothermal fields on the Reykjanes Peninsula (Arnórsson, 1978), which show a decrease in fluid salinity with distance from the southwest margin of the area. This may result from decreasing seawater contribution to the geothermal fluids, or a decrease in the evaporation rate of the fluid (Sveinbjörnsdóttir et al., 1986).

Sub-glacial eruptions in Iceland are associated with contained melt-water lakes (which may increase the meteoric contribution to hydrothermal systems), and result in pillow mounds and associated hyaloclastite aprons; the latter are commonly altered to palagonite (e.g. Gee et al., 1998). Eruptive episodes have taken place at intervals of roughly 1000 years on the Reykjanes Peninsula, and the more recent subaerial events have successively infilled volcanic topography formed during glacial periods (Pálmason, 1980; 1986)

2.3 Geophysical prospecting

Based on a geophysical study by Eysteinnsson (2001), several TEM resistivity subsurface sections have been produced covering the area west and south of Sveifluháls. Four cross-sections are presented here to show the resistivity structure beneath the study area (Figure 6).

The first cross-section (AV8), which trends E-W, shows a relative rise in the low-resistivity cap near the active area of Köldunámur but sinks to deeper levels to the west. Below is a high-resistivity core thought to be associated with high-temperature alteration. The second cross-section (NA5), which trends NE-SW and lies to the west of the main hyaloclastite ridge, shows a similar low-resistivity cap (above a high-resistivity core) rising close to the surface at Köldunámur, continuing at the same level for 5 km to the south before sinking to a deeper level. Along the other two cross-sections, SA8 and SA9, which trend NW-SE, the low-resistivity layer approaches the surface on the west side of the hyaloclastite ridge, and continues eastward. High resistivity is seen below.

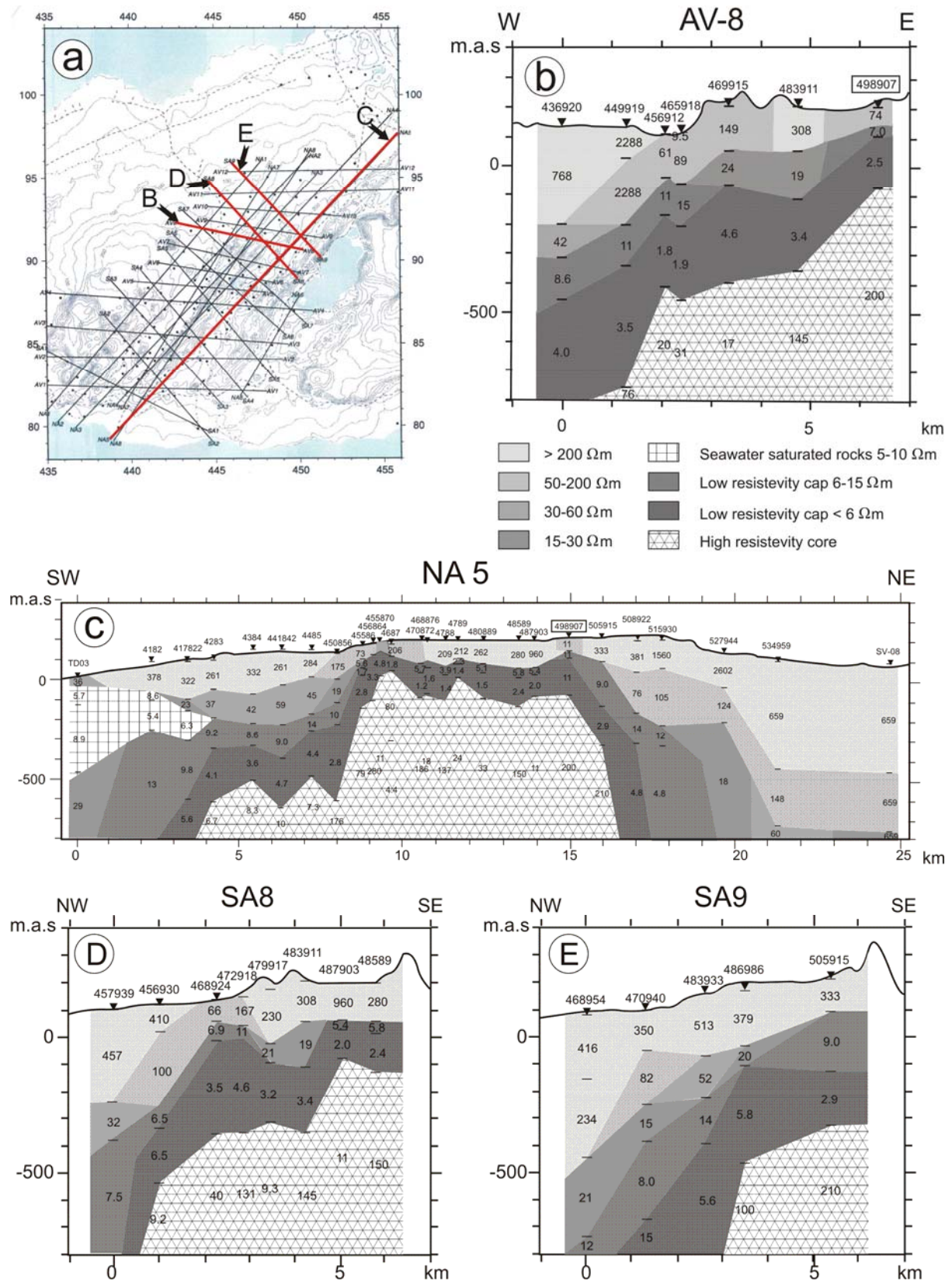


FIGURE 6: Resistivity structures in Sveifluhals area; A) Location map showing the distribution of the TEM soundings and the resistivity cross-sections; B, C, D and E) Resistivity cross-sections AV8, NA5, SA8 and SA9, respectively (compiled from Eysteinnsson, 2001)

3. GEOLOGICAL MAPPING OF SVEIFLUHÁLS AREA

A reconnaissance geological survey was carried out during August and September, 2007 covering the hyaloclastite ridges west of Kleifarvatn lake. During this survey several rock units of the hyaloclastite rocks with different lithofacies including pillow breccias, tuff, scoria and other volcanic materials were identified, and many structural features were mapped, including faults and fractures. Some of these structures were tracked directly in the field using the GPS, while others were delineated from aerial photos. A topographical map of scale 1:10,000 was used for the original drafting of the geological map (Figure 7).

3.1 Rock classification (lithological units)

Sveifluháls area is considered a typical hyaloclastite ridge that formed under ice, where during the last glaciation the ice thickness over the area has been calculated to be about 300 m (Arnórsson et al., 1975). Jones (1970) described the formation process of such hyaloclastite ridges (Figure 8) which gives, in later stages, table mountains; that stage appears to the south of the study area, while in the study area the hyaloclastite ridges contain pillow lava, pillow breccia and hyaloclastite tuff and few outcrops of basaltic lava to the south of Hofmannaföt area.

3.1.1 Hyaloclastite rocks

Hyaloclastite rocks are considered to be the main component of Sveifluháls area, where they are presented in the form of parallel elongated ridges trending NNE-SSW. Several hyaloclastite units were recognized in the study area. These are:

Móberg 0: The oldest hyaloclastite in the area crops out on the northeast side of the main ridge. It is comprised mainly of tuff with lithic fragments of aphyric basalt. It is not significantly altered, only palagonitized. There are small lenses of sheet-like intrusions of aphyric basalt in the tuff, probably co-genetic with the tuff. A small outcrop of porphyritic basalt sits on top of this unit.

Basalt 1: The oldest basaltic lava in the area can be found northwest and southwest of the main hyaloclastite ridge. This unit consists of gray fine-grained basalt lava at the top and pillow breccias in the base with large phenocrysts of plagioclase (Figure 9). Generally, this unit is fresh without any geothermal alteration. The southernmost outcrop of this unit, which represents the highest exposure, exhibits a very thinly bedded altered basalt with a relatively high percentage of scoriaceous material, which indicates that the source of this unit lies in the south.

Móberg A: It crops out at Hofmannaföt area and continues to the south. This unit is characterized by greyish colour and non-porphyritic texture beside its smooth slopes due to the presence of geothermally altered clay especially at the Hofmannaföt area.

Móberg B: This unit starts cropping out to the south of the Hofmannaföt area and continues to the south. It consists of dark gray hyaloclastite with coarse grained non-porphyritic tuffaceous material, and it shows some regional alteration. In the north it is seen to overlie móberg A and probably also móberg C. Its position in the sequence is not clear, but from the freshness and rough exposures of the ridge it compares best with móberg F.

Móberg C: A highly oxidized reddish brown hyaloclastite unit crops out to the southeast of móberg A and continues several kilometres to the south. This unit shows a localized clay alteration, and is composed mainly of tuffaceous materials with aphyric volcanic clasts.

Basalt 2: Chain of small outcrops on the top of móberg C composed of remnants of basaltic lava. It is characterized by a light coloured appearance with a grey fresh surface; flow lamination is pronounced.

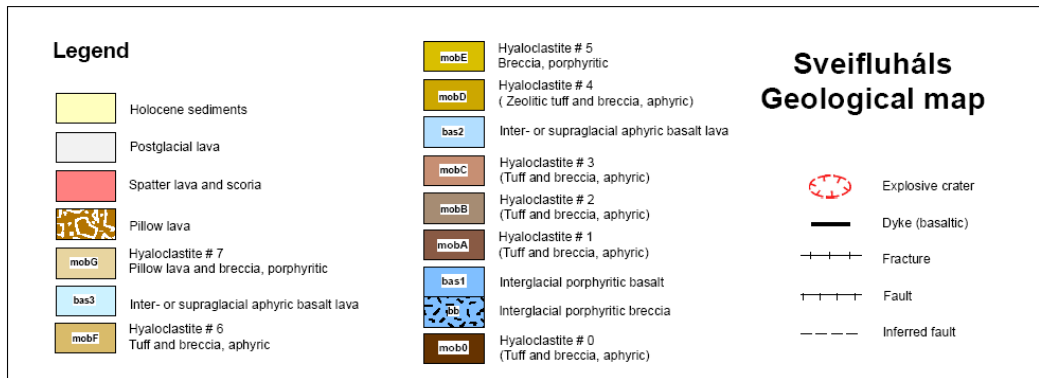
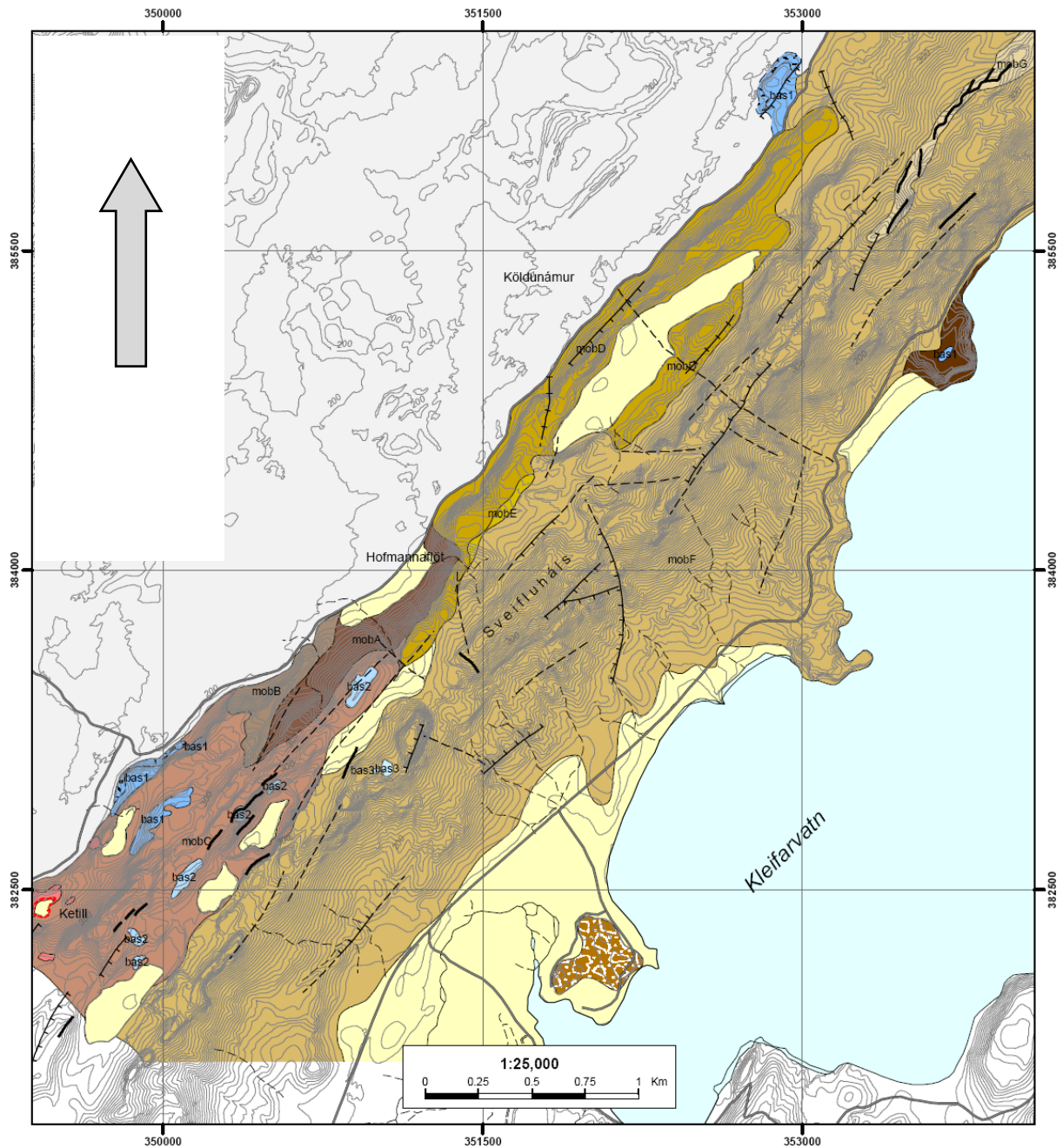


FIGURE 7: Geological map of the study area

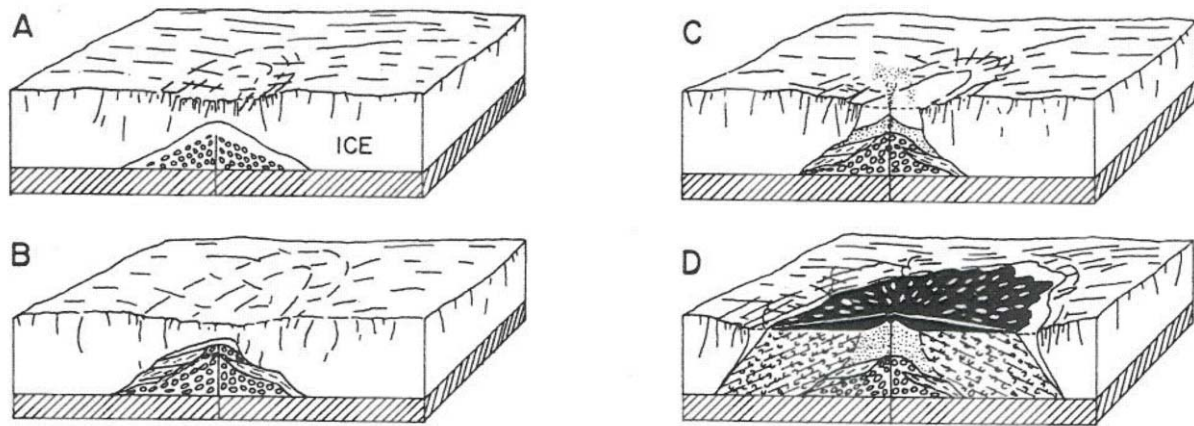


FIGURE 8: Growth of a mono-genetic volcano; A: A pile of lava forms in deep melt-water lake; B: Slumping on the flanks of the pillow lava pile produces the pillow breccia; C: Hyaloclastite tuffs are erupted under shallow water; D: A lava cap progresses across its own delta of foreset bedded breccias (from Jones, 1969)

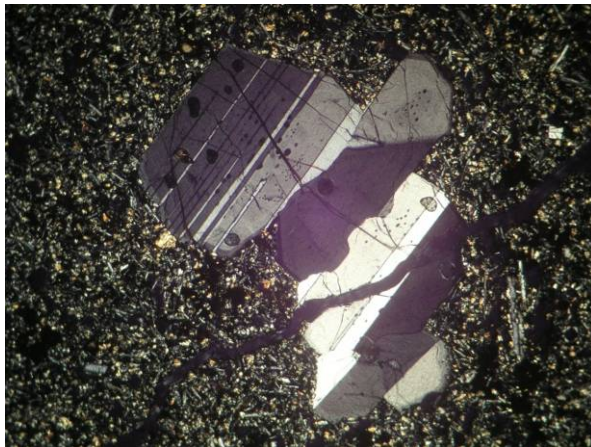


FIGURE 9: Plagioclase phenocryst inside microcrystalline olivine-pyroxene matrix of basalt 1



FIGURE 10: Interglacial basalt on top of móberg F
The palagonitization process of the original volcanic glassy material. The clastic material inside the tuff and the pillow breccia is composed of aphyric fine-grained basalt with occasional plagioclase phenocrysts. A small outcrop of interglacial basaltic lava (basalt 3) overlies this unit directly to the south of the highest mountain in the study area (Figure 10). The unit is the freshest (least altered) of the hyaloclastites to the west of Sveifluháls.

This unit is composed of fine-grained aphyric basalt highly altered and oxidized. It can be found directly to the west of the highest mountain in the study area and continues to the south.

Móberg D: Gray zeolitic hyaloclastite which starts cropping out directly to the north of the basaltic lava of basalt 2. Dipping to the northeast, it overlies móberg C in a sequence of three units (móberg B, móberg C and basalt 2) in a small gully to the south of Hofmannaf্লöt area. This unit is composed of tuffaceous hyaloclastite with aphyric volcanic clasts and it is characterized by the prominent presence of zeolite within the volcanic glass of this unit. It continues to the north but there it becomes less zeolitic.

Móberg E: This porphyritic hyaloclastite unit can be found as a thin layer dipping to the southeast on the eastern slope of móberg D at Hofmannaf্লöt area. This unit is composed of dark gray tuffaceous hyaloclastite, characterized by the presence of plagioclase phenocrysts within the volcanic glass and lithic fragments.

Móberg F: This is the main hyaloclastite unit in the study area. This unit consists of a wide diversity of lithofacies such as pillow basalt, pillow breccia and tuffaceous material, but the main distinguishing feature of it is the reddish brown colour of the tuff, which arises from the

Móberg G: The youngest hyaloclastite unit in the study area is found in the northern parts composed of porphyritic breccia and coarse grained tuff and shows a dark fresh colour. The pillow breccia in this unit is composed of fine-grained massive basalt. Several dykes of fine-grained gray basalt were noticed in this unit.

3.1.2 Historical lava

The northwest part of the study area is covered by a historical lava erupted during the so called Krýsuvík Fires 1151 AD based on ^{14}C dates, tephrochronology studies and historical records (Jóhannesson and Einarsson, 1988). The eruption took place within the Trölladyngja fissure swarm. The total length of the eruptive fissure is about 25 km, but there is a gap in its central part. Krýsuvík Fires created four main lava flows: Ögmundarhraun, Kapelluhraun, Laekjarvellir and Mávahlídar (Einarsson et al., 1991). According to a petrological study by Gunnlaugsson (1973), the lavas are olivine tholeiites in composition. Close to the craters the flows are thin pahoehoe flows, but as they flowed further they became more viscous and formed aa flows.

The lava flows of the Krýsuvík Fires cover an area of 36.5 km^2 and the estimated volume is 0.22 km^3 (Einarsson et al., 1991). The general trend of the Krýsuvík Fires fissure is $\text{N}45^\circ\text{E}$, but west of Krýsuvík the fissure displays a more easterly trend which, further north, breaks up into short segments and shifts en-echelon northwards until it resumes a northeasterly trend. This N-S trending anomaly coincides with the narrow seismic zone which extends from the South Iceland Seismic Zone west along the central part of the Reykjanes Peninsula (Jóhannesson, 1989).

3.1.3 The basaltic dykes

Several dykes have been mapped in the study area, especially in the northern parts where they cut hyaloclastite unit 8 to produce the porphyritic hyaloclastite unit 9 (Figure 11). Some of these dykes are considered to be feeder dykes, as they have considerable length and width ($\sim 70 \text{ cm}$). In some places they are surrounded by pillow breccias.

Generally, the dykes in the study area trend NE-SW. The northern dykes are composed of fine-grained basalt with phenocrysts of plagioclase, indicating that they are the source of *móberg G*, while the dykes in the southern part of the study area are aphyric basalt. In some cases they appear in light colours due to weathering of the basalt.



FIGURE 11: The dyke swarm in the northern part of the study area

3.1.4 Explosive craters and scorias

One explosive crater was mapped in the south west part of the study area, located at the Ketill area on the western rim of the hyaloclastite ridge where it is surrounded by dark red scoriaceous materials and spatter lava from the northern, southern and western sides of the crater, while the eastern side is bounded by the hyaloclastite *móberg C*. It was noticed that the spatter lava flows on the inner face of the western side, indicating that the source is located in the east. Local exposure of the scoriaceous materials could be found on the eastern rim of the hyaloclastite ridge along one of the faults, surrounded by hyaloclastite unit 8 (Figure 12).

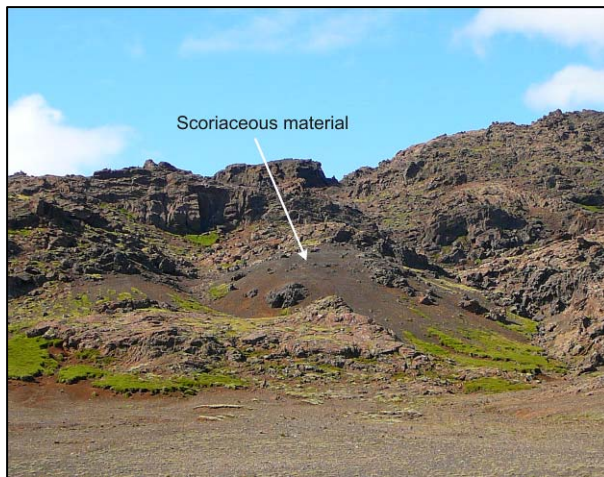


FIGURE 12: Local outcrop of the scoriaceous materials to the east of the hyaloclastite ridge



FIGURE 13: Normal fault in the northern part of the study area

3.1.5 Geological history of the area

It is obvious from the stratigraphic sequence that the study area went through three glacial-interglacial cycles. The first cycle is represented by the oldest rock units in the study area móberg 0 and basalt 1, which is followed by a glacial period to form hyaloclastites móberg A, B and C. After that, the area was influenced by an interglacial period and the basaltic lava of basalt 2 was formed. Hyaloclastite units móberg D, E and F were formed in a glacial environment that was followed by the formation of the basaltic lava on top of móberg F in an interglacial environment. The youngest hyaloclastite unit (móberg G) was formed in a glacial period. After that the area was exposed to the Holocene geological processes that formed the Holocene sediments and the historical lava to the west.

3.2 Tectonic setting of the study area (structural elements)

Sveifluháls area is a NE-SW elongated ridge on the volcanic axis of the Reykjanes Peninsula, within the plate boundary zone. The most significant structural element in the area is a NE-SW orientated fissure swarm, which controls the major part of the volcanic features and constitutes the regional structural frame for the study area. The study area is crossed by many extensional (normal) faults (Figure 13). The main trend of these faults is N30-40°E with variable downthrow, while the other minor trends are NW-SE and E-W.

Three joint trend analyses have been made in different parts of the study area (Figure 14) in order to figure out the major stresses of the area. These analyses showed different trend angles (Az).

The opposing plate movement on either side of the Reykjanes Peninsula causes a shear stress along the peninsula. This brings about

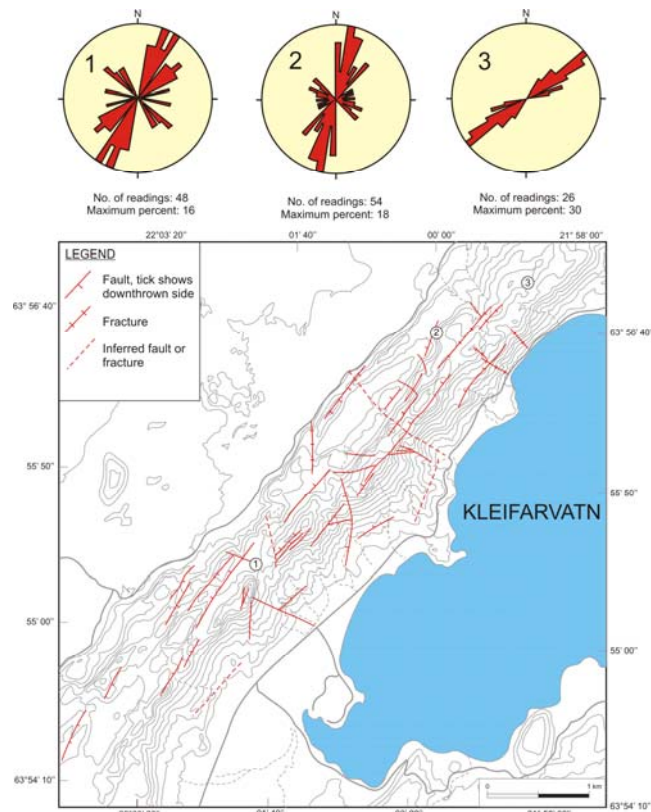


Figure 14: Structural map of the study area

an extensional en-echelon arrangement. Vargas (1992) studied the stress state for the Krýsuvík and Sveifluháls areas according to an en-echelon model with simple shear strain. He found that the maximum release direction is oriented at Az 125 to the seismic shear zone direction. This maximum release would cause the formation of en-echelon extensional fissures perpendicular to it (Az 35), which appears clearly in the joints in Group 1, taken in the main hyaloclastite, móberg F. Vargas also mentioned that the maximum compression axis would be oriented perpendicular to it (Az 35), and it would cause the formation of conjugate couple of strike-slip faults, each set being oriented at 30° to each side of the maximum compression axis. This means (at Az 5 and 65, respectively), that Az 5 appears clearly in group 2, which was measured within the hyaloclastite of Móberg D, whereas Az 65 demonstrated by group 3, was measured within the hyaloclastite of Móberg F. In the same study, Vargas (1992) matched the focal mechanism and the shear stress model and selected fault planes at Krýsuvík and the Sveifluháls area and he found that the Az 5 matches the right-lateral fault character, while Az 65 corresponds to left-lateral character, and Az 35 corresponds to a graben character.

4. GEOTHERMAL MAPPING OF SVEIFLUHÁLS AREA

The Sveifluháls area is considered to be the inactive part of the Krýsuvík geothermal field. Despite that, this area has been affected by geothermal activities in the past. This can be seen clearly from the geothermally altered rocks in the area. So, in order to determine the distribution of the altered zones and the degree of alteration (Figure 15), geothermal mapping was carried out. Hence, the altered areas could be outlined. Samples were taken in the altered areas to figure out the mineral assemblages.

4.1 Geothermal manifestations

The geothermal manifestations in the study area are represented by one small active area near Köldunámur (Cold Mines). This area is located to the west of the hyaloclastite ridge within the historic lava and cannot be seen from the road. It is surrounded by very rough aa lava. This active area is represented by three steam vents with temperatures ranging between 94 and 96°C (Figure 16). The steam vent area is surrounded by hard geothermally altered ground, which makes temperature measurements quite difficult. Overall the results showed that both the 15°C and the 50°C isolines were very close to the centre of activity.

Two samples were taken from the altered ground to find the geothermal minerals that exist in this area. The first sample was pretty homogeneous and nearly pure sulphur (Figure 17). Kaolinite is typical for surface alteration under acid conditions (low pH). The second sample represented amorphous opal, common in active low-temperature areas, with a small amount of kaolinite being present in the sample (Figure 18).

4.2 Rock alteration and geothermal mineral assemblages

Although the hyaloclastite part of the study area is inactive at the present time, the rocks comprise different grades of hydrothermal alteration, which indicates geothermal activity in the past. Hydrothermal surface alteration, hot or cold, indicates the presence of a hydrothermal system beneath. Therefore, mapping surface alteration is useful in delineating a hydrothermal system. The alteration intensity increases with increasing activity. By distinguishing between unaltered rocks (fresh or weathered) and slightly hydrothermally altered rocks, one can make a distinction between some hydrothermal activity and intense hydrothermal activity.

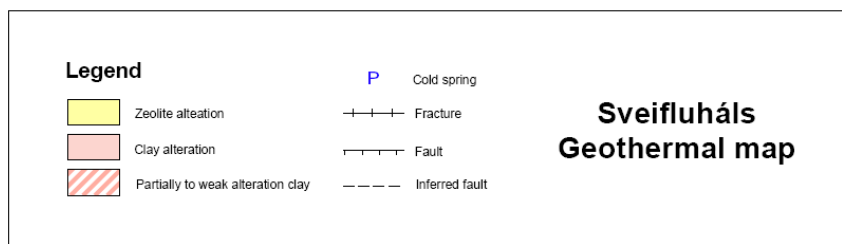
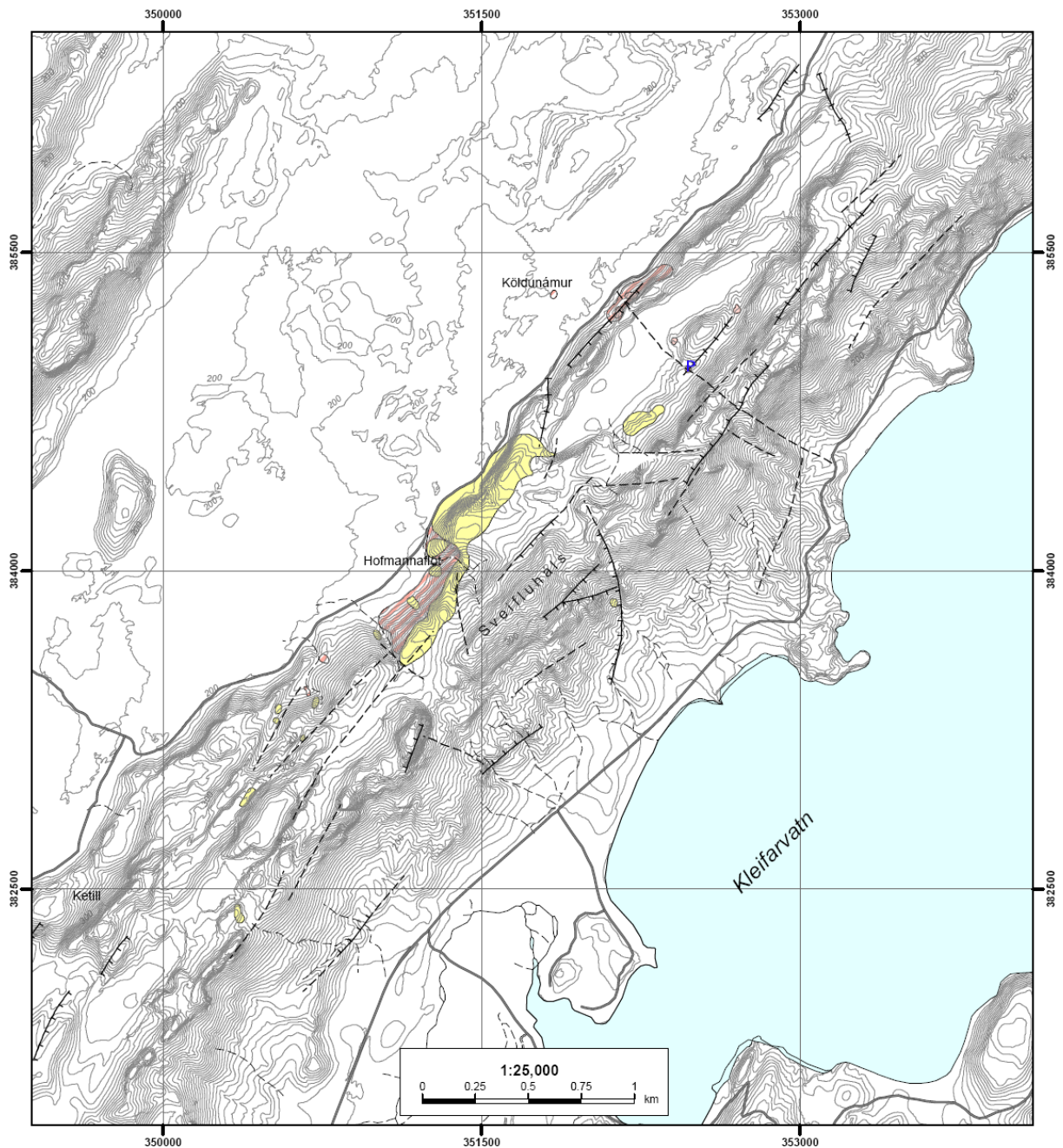


FIGURE 15: Geothermal map of the study area showing the relationship between the structural patterns and the distribution of the hydrothermal alteration zones

Generally, the surface geothermal alterations in the study area are found to be most intense on the west and southwest sides of the hyaloclastite ridge. Local hydrothermal alteration zones are found in other parts of the study area. During the field work, two major types of hydrothermal alteration were recognized: zeolite-calcite alteration and clay alteration.

4.2.1 Zeolite-calcite alteration

This alteration is found in the form of white mineralization that fills the pores within the volcanic glass. The hyaloclastite rocks of móberg D show an extensive zeolite alteration in different localities starting from the western slopes at Hofmannaflöt area, continuing further to the north along the eastern side of the large basin to the east of the Köldunámur area.



FIGURE 16: The active geothermal area at Köldunámur

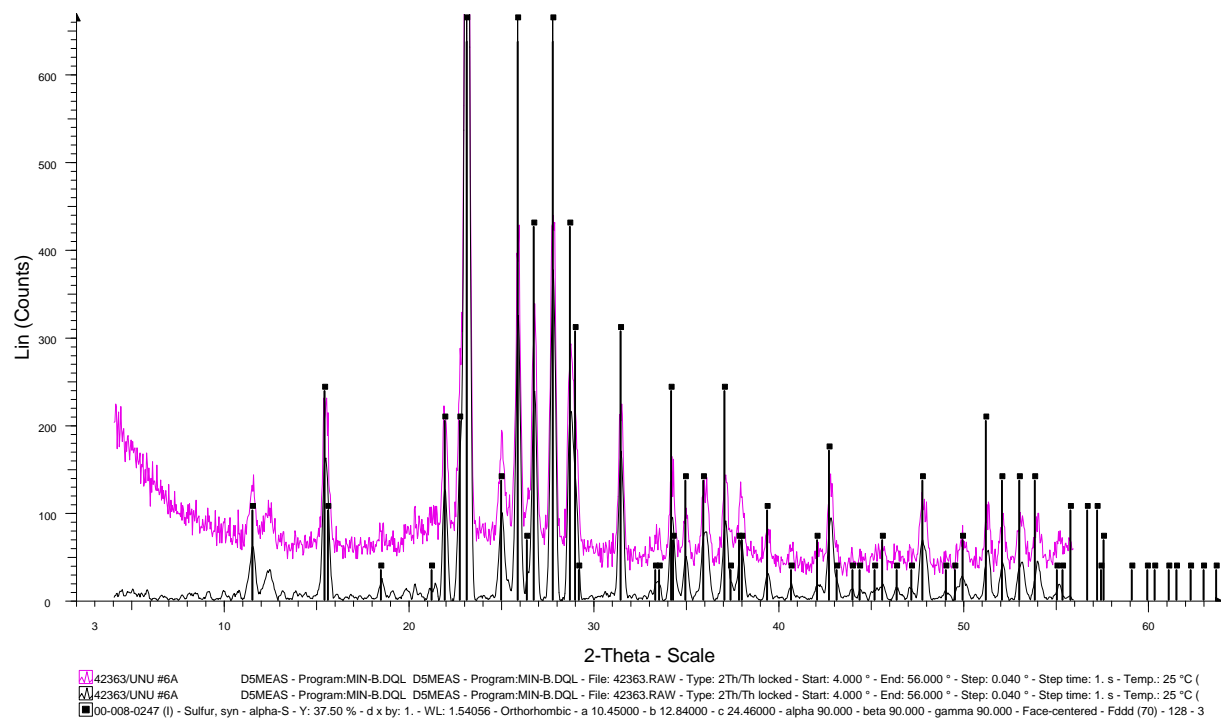


FIGURE 17: XRD analysis of sample no. 1 from the active Köldunámur area; the upper curve represents the untreated patterns, while in the lower one aberrant values have been subtracted and patterns made smooth

The petrographic analysis of different samples taken from a zeolite altered hyaloclastite at Hofmannaflöt area shows different types of zeolite minerals such as radial zeolite, chabacite, philipsite and analcime (Figure 19). Beside zeolite, the presence of calcite was noticed, which under the microscope appears in its distinctive fractured surface. This could be tested in the field using HCl.

It is obvious from the petrographic study that the alteration went through a multistage process, where the growth of zeolite crystals took place before that of the calcite crystals. This could be explained by chemical changes in the water that reacted with the volcanic glass.

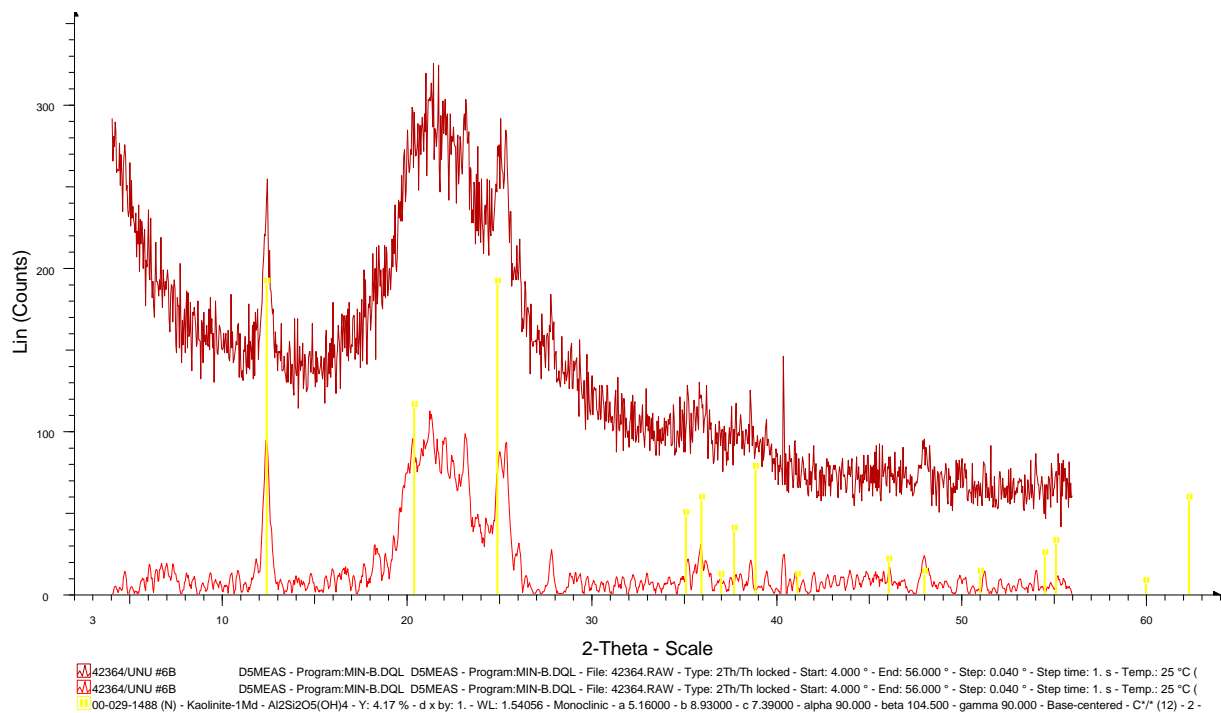


FIGURE 18: XRD analysis of sample no. 2 from the active Köldunámur area, showing the kaolinite peaks at different 2λ values

An XRD analysis was done on a sample of hydrothermally altered hyaloclastite, where the volcanic glass was cemented by zeolite and calcite. The analysis shows three types of zeolites in addition to the presence of calcite (Figure 20).

4.2.2 Clay alteration

Two types of clay alteration could be recognized in the study area:

Weak-partial clay alteration is found within the hyaloclastite glass, where the outer rims of the volcanic glass grains have turned into clay after one or two stages of palagonatization. It could be seen clearly under the microscope as bands of brown colour surrounding the light glass fragment (Figure 21). Notice the outer bands around the volcanic glass, which represent the multi-stages of palagonatization, then inside there is a layer of brown clay around the original volcanic glass fragment. This alteration is distributed all around the area especially on the western side of the hyaloclastite ridge.

Extinct (high-grade) clay alteration is less common than the previous grade, and can be found at two sites (besides the alteration at Köldunámur fumaroles), on the western slopes near the Köldunámur area, where the light coloured clayish alteration is surrounded by weakly altered hyaloclastite (Figure 22). The other area is Hofmannafllöt; the alteration there is characterized by brownish yellow coloured soft material due to the iron oxidation of the hyaloclastite rocks.

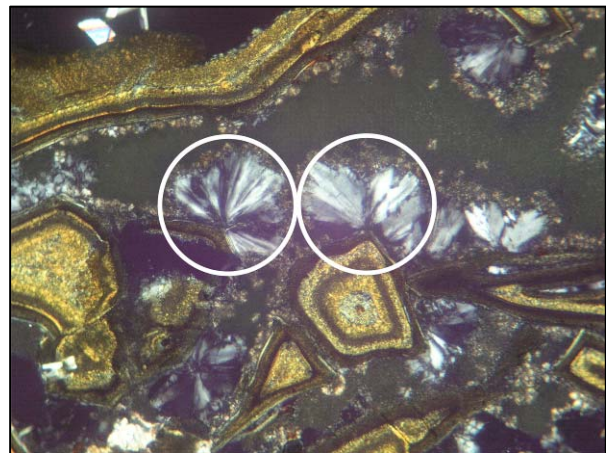


Figure 19: Radial zeolite under XPL within the groundmass of a hydrothermally altered sample from Hofmannafllöt area

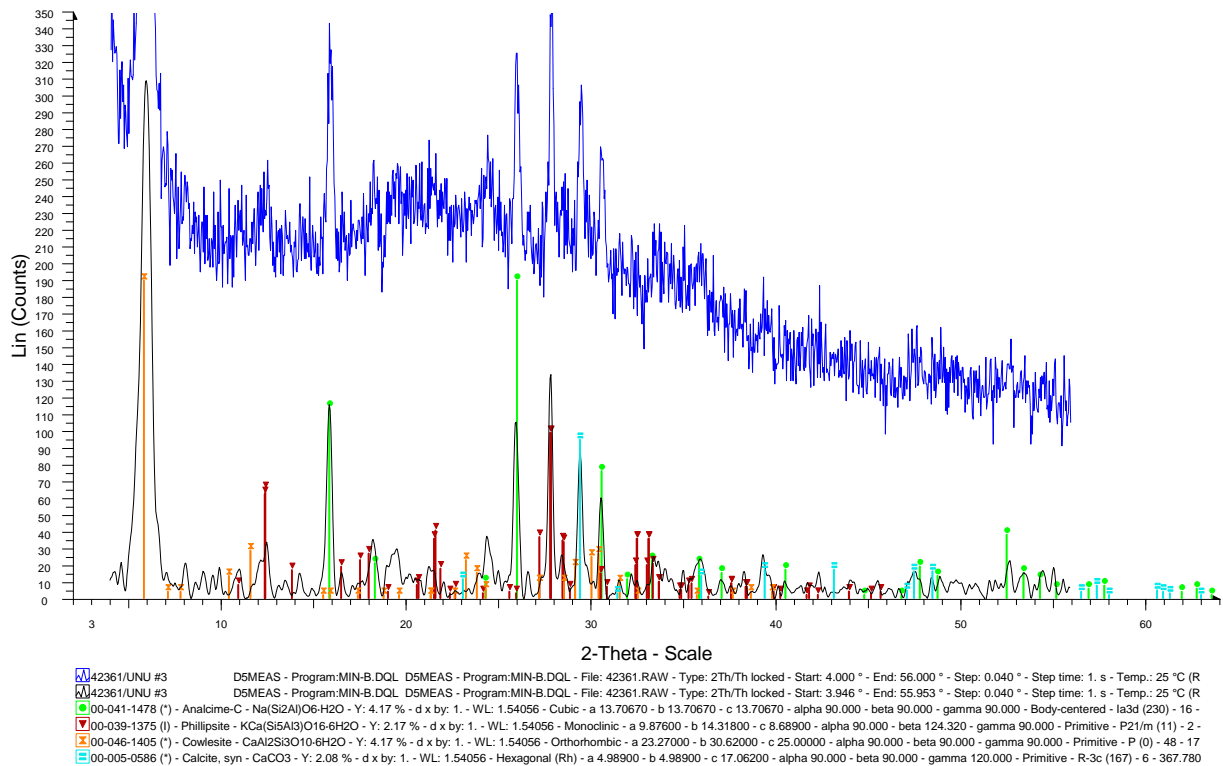


FIGURE 20: XRD analysis of sample no. 3 from the zeolite-calcite alteration zone at Hofmannaföt area

The alteration at the Hofmannaföt area may be older than the alteration at the Köldunámur area, as the clay minerals look fresher and less oxidized. A clay sample from the alteration zone near the Köldunámur area was analyzed by XRD to determine the type of clay; it was shown to be kaolinite (Figure 23).

In the north within the large basin, there are a few local clay alteration zones aligned on a fault trending N30°E, where two cold springs emerge along the same fault, indicating that there is a clay layer in the subsurface that acts as a cap and prevents the water from seeping into the ground.

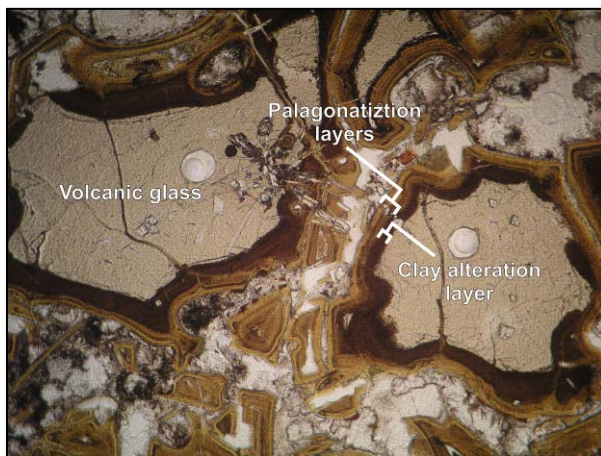


FIGURE 21: The alteration bands around volcanic glass fragments under PPL (hyaloclastite móberg D)



FIGURE 22: Extinct clay alteration on the western slopes near Köldunámur

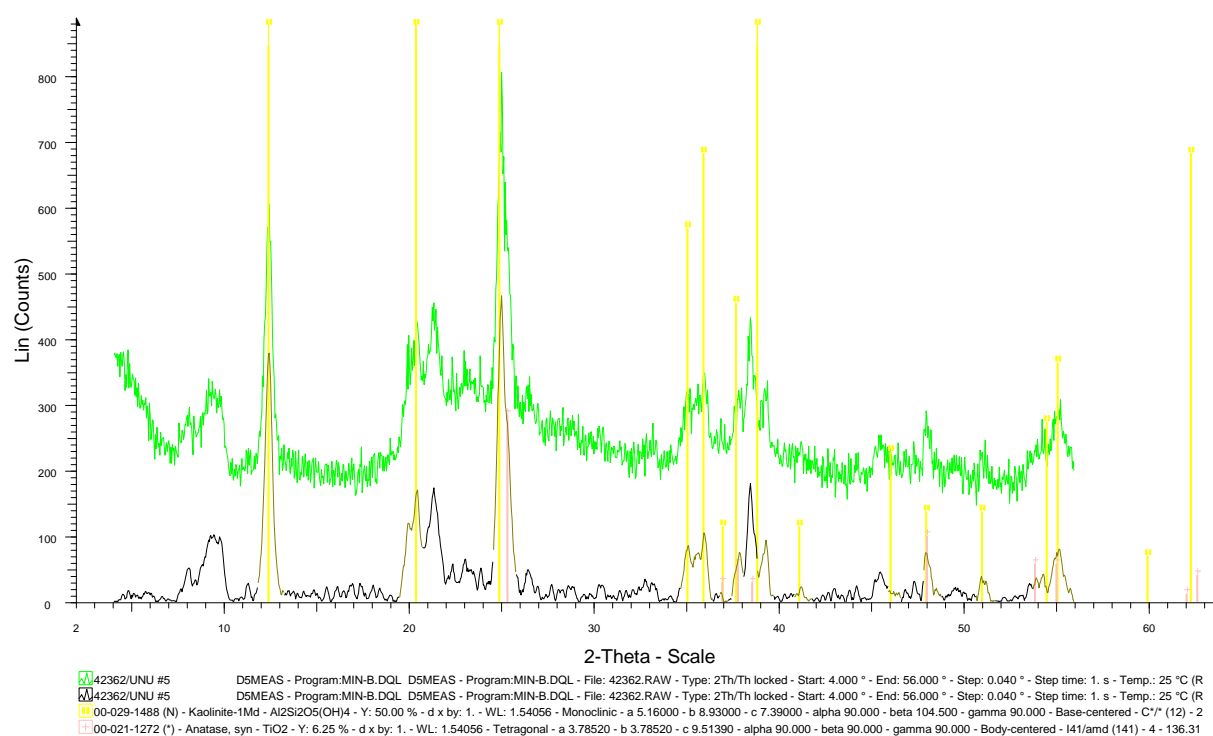


FIGURE 23: XRD analysis of sample no. 4 from the clay alteration zone near Köldunámur

5. CONCLUSIONS AND RECOMMENDATIONS

The Sveifluháls area is located within the Krýsuvík-Trölladyngja volcanic system, which is one of four main volcanic systems on the Reykjanes Peninsula. The study area is covered by upper Pleistocene volcanic rocks, which consist of three cycles of interglacial-glacial sequences. The interglacial periods are characterized by the formation of basaltic lava, which varies between porphyritic and aphyric, while the glacial periods are characterized by the formation of seven units of hyaloclastite rocks that have different lithofacies, such as pillow lava, pillow breccias and tuff.

The study area is crossed by several normal faults trending N30-35°E, which arise from the extensional forces of the divergent plate boundary that stretches along the Reykjanes Peninsula. The joint trend analyses show the presence of three main groups: the first one is Az 35 which corresponds to the main extensional trend; the second is Az 5 which corresponds to right-lateral faults; the third is Az 65 which is related to left-lateral strike-slip faults. A few normal faults were mapped in the study area trending N100°-130°E.

The study area is considered to be within the inactive part of the Krýsuvík-Trölladyngja geothermal system, even though it exhibits many hydrothermal alterations and the presence of one active geothermal manifestation near the Köldunámur area. The latter is represented by three steam vents with some small deposits of sulphur and clay minerals. The hydrothermal alterations in the study area are classified into two main groups, zeolite-calcite and clay alterations. The geothermal map illustrates the distribution of the alterations, being concentrated on the western side of the main hyaloclastite ridge in the central and southern parts of the study area, indicating that the centre of geothermal activity lies to the southwest of the study area. This corresponds with the resistivity maps by Eysteinnsson (2001) and implies that the geothermal activity is cooling down and the active system is moving toward its centre.

It could be noticed from the geothermal map that the geothermal alterations have the same trend as that of the faults in the study area. Some of these alterations are associated with faults such as the clay alteration on the western slopes near the Köldunámur area, and the alteration inside the large basin in the northern part of the study area.

It was noticed in the field that the geothermal alteration is quite old, as can be clearly seen in the Hofmannafllöt area, where alteration affected the older units (móberg A and D), while the younger units (móberg E and F) were not affected.

The temperature profile of borehole KR-08, which is located about 2 km southwest of section E-F (Figure 24), is inverted. This indicates lateral flow from an upflow some distance away, most likely to the east or north, in the area of surface alteration. The temperature profile may also give an indication of what the thermal situation might be in the study area further to the north. The hot zone in the profile is interpreted as being about 200°C or more, with a possible lateral flow.

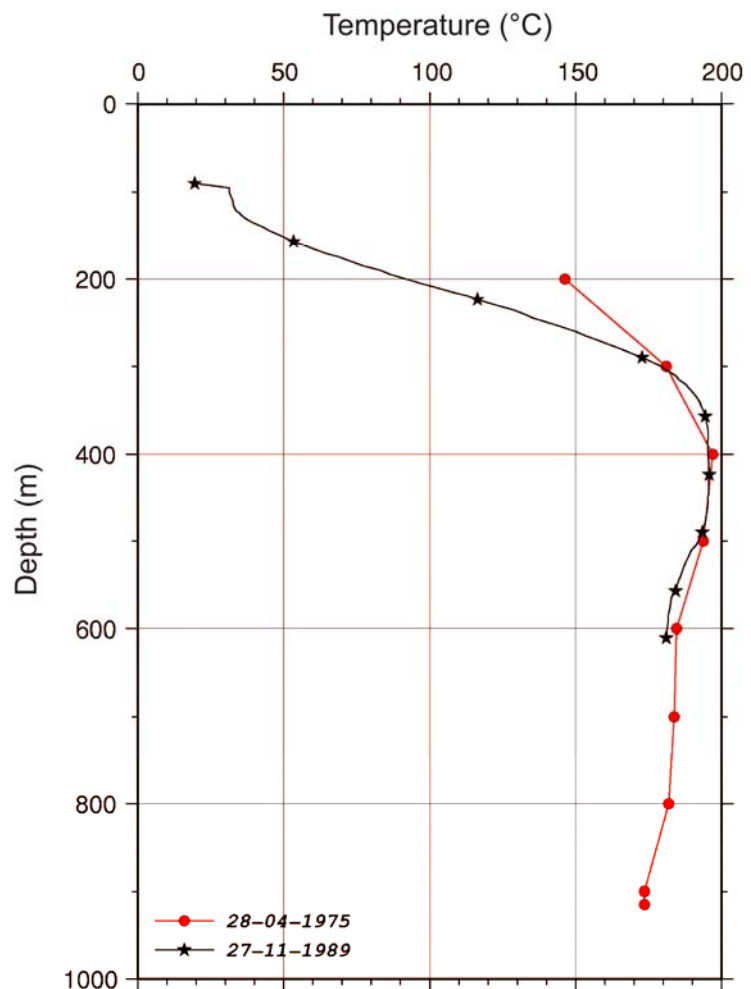


FIGURE 24: Temperature profiles from well KR-08 to the south of the study area (ISOR, 2007)

The geothermal model of the study area (Figure 25) implies the presence of a heat source to the west that is responsible for all geothermal alterations on the western rim of the hyaloclastite ridge. This model also shows that the heat source is found at deeper levels, to the south and east, which can also be seen from the resistivity profiles in Figure 6.

5.2 Recommendations

- It is highly recommended to carry out a detailed geological and geothermal study of the hyaloclastite ridge for better understanding of the history of the area, especially the eastern part of this ridge.
- Drilling of one or two exploration wells near the Köldunámur and Hofmannafllöt areas (to at least 500 m depth) should be carried out in order to get below a possible inversion zone.

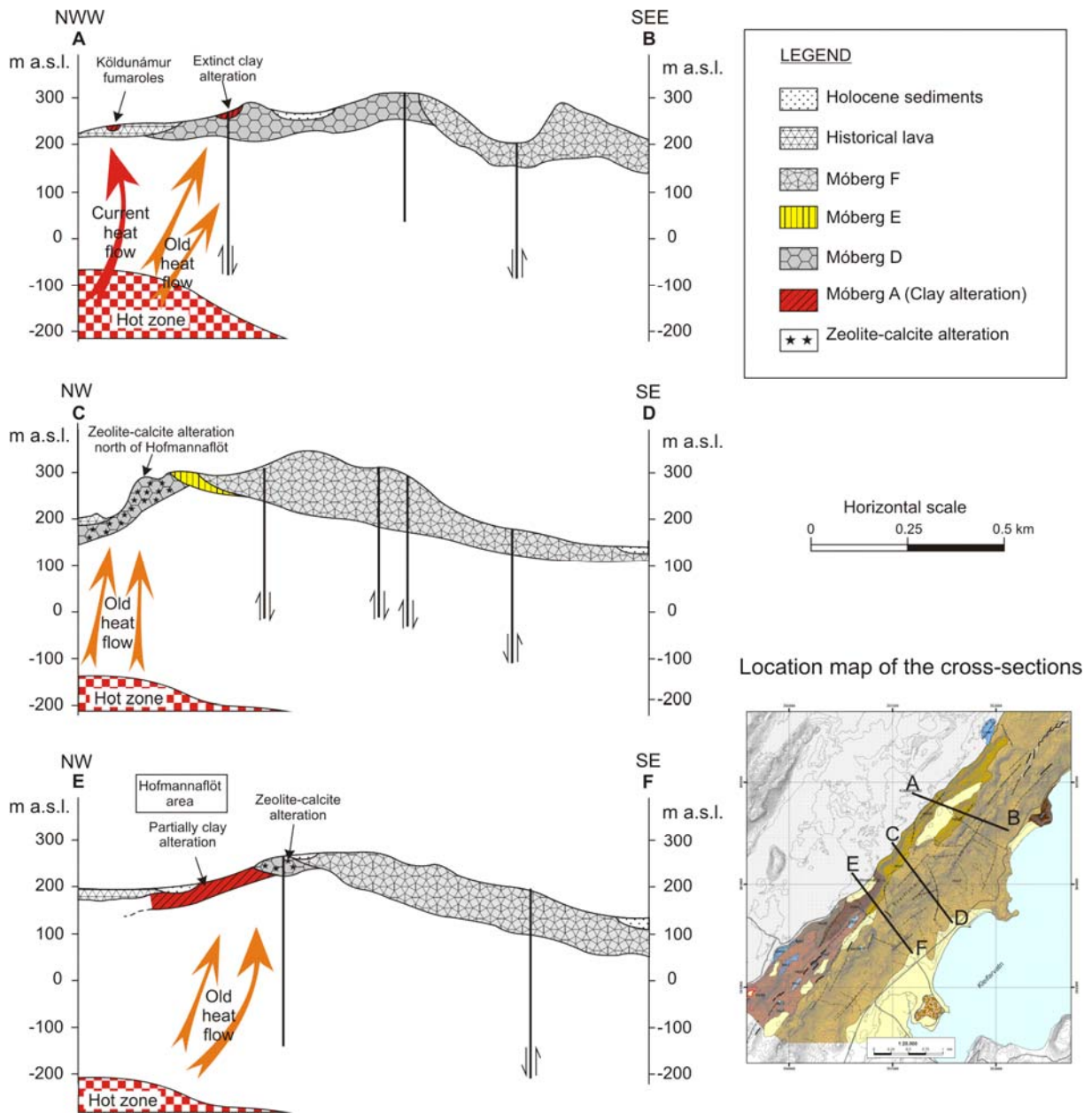


FIGURE 25: Sections outlining the geothermal model of the study area in Sveifluhals

ACKNOWLEDGEMENTS

I would like to express my deep appreciation to Dr. Ingvar B. Fridleifsson, director of the UNU-GTP, for giving me the opportunity to attend this training course and for his guidance throughout the whole training period. My gratitude is extended to Mr. Lúdvík S. Georgsson for his advice and care that eased the growing pains in the critical stage of my study. Grateful thanks are extended to Dr. Ali Swarieh, the head of the Geological Mapping Division, NRA, Jordan, for his continued support. And I am grateful to the UNU-GTP staff, Ms. Thórhildur Ísberg and Dorthe H. Holm for their continuous help during this course.

I owe a considerable debt to Dr. Gudmundur Fridleifsson, my advisor, for stimulating my interest in volcanology; he also taught me to seek out the flows in arguments and argue logically. I would also

like to thank him for fruitful discussion throughout the work, constructive criticism and continuous encouragement. I am grateful to my co-advisors Dr. Kristján Saemundsson and Mr. Sigurdur Kristinsson and the geological staff members at ISOR, particularly Haukur Jóhannsson, for their assistance in the field, valuable discussion and constructive criticism of my study. Special thanks go to Ms. Guðrún S. Jónsdóttir and Mr. Skúli Víkingsson for their help in digitizing the geological data. Many thanks to Dr. Hjalti Franzson for his help in the petrographic study.

I would like to express my sincere thanks for those who share and stand by me throughout my life. Great thanks are due to my parents, brothers, sisters and friends for their help, continuous support and encouragement.

REFERENCES

- Arnórsson, S., 1978: Major element chemistry of the geothermal sea-water at Reykjanes and Svartsengi, Iceland. *Mineralogical Magazine*, 42, 209-220.
- Arnórsson, S., 1987: Gas chemistry of the Krísuvík geothermal field, Iceland, with special reference to evaluation of steam condensation in upflow zones. *Jökull*, 37, 31-48.
- Arnórsson, S., Björnsson, A. and Gíslason, G., 1975: *Systematic exploration of the Krísuvík high-temperature area, Reykjanes Peninsula, Iceland*. Orkustofnun, Reykjavík, report OS-JHD-7528, 20 pp.
- Clifton, A., Pagli, C., Jónsdóttir, J., Eythórsdóttir, K. and Vogfjörð, K., 2003: Surface effects of triggered fault slip on Reykjanes Peninsula, SW Iceland. *Tectonophysics*, 369, 145-154.
- Einarsson, S., and Jóhannesson, H., Sveinbjörnsdóttir, Á., 1991: Age of the Kapelluhraun and Hellnahraun lava flows, Reykjanes Peninsula, South Iceland. *Jökull*, 41, 61-80.
- Eysteinnsson, H., 2001: *Resistivity measurements around Trölladyngja and Núpshlíðarháls, Reykjanes Peninsula*. Orkustofnun, Reykjavík, report OS-2001/038 (in Icelandic), 110 pp.
- Flóvenz, Ó.G., Fridleifsson, G.Ó., Johnsen, G.V., Kristmannsdóttir, H., Georgsson, L.S., Einarsson, S., Thórhallsson, S., and Jónsson, S.L., 1986: *Vatnsleysa-Trölladyngja, freshwater and geothermal investigation. 3 Geothermal exploration*. Orkustofnun, Reykjavík, report OS-86032/JHD-10 B, 39-92.
- Gee, M., Thirlwall, M., Taylor, R., Lowry, D. and Murton, B., 1998: Crustal processes: Major controls on Reykjanes Peninsula lava chemistry, SW-Iceland. *J. of Petrography*, 39, 819-839.
- Gudmundsson, Á., 2007: *Living earth - Outline of the geology of Iceland*. Mál og Menning Publishers, Reykjavík, 408 pp.
- Gunnlaugsson, E., 1973: Lavas in the Krísuvík area. University of Iceland, BSc thesis (in Icelandic), 26 pp + 18 figs and 12 tables.
- Imsland, P., 1973: *The geology of Sveifluháls*. University of Iceland, BSc thesis (in Icelandic), 87 pp.
- ISOR, 2007: *Well KR-08 temperature profile*. ISOR, data bank, unpublished.
- Jakobsson, S., 1972: Chemistry and distribution pattern of recent basaltic rocks in Iceland. *Lithos*, 5, 365-386.

- Jóhannesson, H., 1989: The geology of the Reykjanes Peninsula. In: Egilsson, K. (editor), *The nature of the southern Reykjanes Peninsula*. Náttúrufræðistofnun Íslands, Reykjavík (in Icelandic), 13-22.
- Jóhannesson, H., and Einarsson, S., 1988: Krísuvík Fires I. The age of Ögmundarhraun lava and the Medieval tephra layer. *Jökull*, 38, 71-87.
- Jones, J.G., 1969: *Intraglacial volcanoes of the Laugarvatn region, Southwest Iceland, I*. *Q.J. Geol. Soc. Lond.*, 124, 197-211.
- Jónsson, J., 1978: *A geological map of the Reykjanes Peninsula*. Orkustofnun, Reykjavík, report OS/JHD 7831 (in Icelandic), 333 pp and maps.
- Pálmason, G., 1980: A continuum model of crustal generation in Iceland: kinematic aspects. *J. of Geophysics*, 47, 7-18.
- Pálmason, G., 1986: Model of crustal formation in Iceland, and application to submarine mid-ocean ridges. In: Vogt, P. & Tucholke, B. (eds), *The western North Atlantic Region*. Geological Society of America, Boulder, CO., 87-97.
- Pálmason, G., and Saemundsson, K., 1974: Iceland in relation to the Mid-Atlantic Ridge. *Annual Review of Earth and Planetary Sciences*, 2, 25-50.
- Saemundsson, K., 1995: *Geological map of the Hengill area, 1:25,000*. Orkustofnun, Reykjavík.
- Saemundsson, K., and Einarsson, S., 1980: *Geological map of Iceland, sheet 3, SW-Iceland* (2nd edition). Museum of Natural History and the Iceland, Geodetic Survey, Reykjavík.
- Saemundsson, K., and Gunnlaugsson, E., 2002: *Icelandic rocks and minerals*. Mál og Menning Publishers, Reykjavík, 233 pp.
- Sveinbjörnsdóttir, A., Coleman, M., and Yardley, B., 1986: Origin and history of hydrothermal fluids of the Reykjanes and Krafla geothermal fields, Iceland. *Contributions to Mineralogy and Petrology*, 94, 99-109.
- The Icelandic Meteorological Office, 2007: *Weather information*. The Icelandic Meteorological Office, web page: <http://andvari.vedur.is>.
- Vargas, J., 1992: *Geology and geothermal considerations of Krísuvík valley, Reykjanes Peninsula, Iceland*. UNU-GTP, Iceland, report 13, 35 pp.