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GEOTHERMAL EXPLORATION AND GEOLOGICAL MAPPING AT SELTÚN IN KRÝSUVÍK GEOTHERMAL FIELD, REYKJANES PENINSULA, SW-ICELAND

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ABSTRACT

Krýsuvík is one of the high-temperature geothermal areas in the Reykjanes peninsula in southwest Iceland. Seltún is a small field within the Krýsuvík area where the geothermal activity is intense. The geothermal field has not been utilised, but a detailed study of the field has been undertaken. Although this mapping exercise was part of the UNU geothermal training, it was also a contribution to the mapping and study of the area.

Both geology and hydrothermal alteration were mapped, resulting in two separate maps: a geological map and a geothermal map. Surface manifestations were also mapped to delineate upflow zones that could serve as a basis for a geothermal model that could answer questions like that of temperature reversal at around 300 m depth in many wells in the area.

The surface alteration and manifestations were found to be of linear distribution trending in the same direction as the major fault system and fissure swarms. The model suggests structurally controlled upflow zones. The model also suggests a solution to the temperature reversal in many wells in the Krýsuvík area.

1. INTRODUCTION

1.1 General geological and geothermal aspects of Iceland

Iceland is a unique part of the active mid-oceanic ridge system. It is one of a few (if not the only) areas in the world where the mid-oceanic ridge can be observed above sea level. Iceland was formed as a result of a constructive margin of sea floor spreading between the North American plate and the Eurasian plate, and a mantle plume. The plates are spreading at a rate of 2 cm per year. The existence of a mantle plume leads to dynamic uplift of the Icelandic plateau and an increase in volcanic activity. The existence of Iceland is believed to be due to its location on the mantle plume. The plume results in melting of the mantle which gives rise to volcanism (Gudmundsson and Jacoby, 2007).

The exposed volcanic pile is predominantly of basaltic composition (80-85%); while acidic and intermediate rocks constitute about 10%. The basalts themselves have been classified into three main types: the compound flows of olivine tholeiite, simple tholeiite (with little or no olivine) and porphyritic with plagioclase and pyroxene. Olivine tholeiite morphologically gives pahoehoe lava fields, while olivine poor tholeiite gives rise to aa lava fields (Saemundsson, 1979).

Sediments of volcanic origin constitute 5-10% of a typical Tertiary lava pile, but a much higher percentage in Quaternary rocks due to glacial erosion. The active periods of volcanic systems have been found to vary from 300,000 years to over 1 million years. They are preserved as entities in the volcanic pile, indicating that they grew, drifted off towards the margin of the active volcanic zone and then became extinct (Saemundsson, 1979). Active high-temperature geothermal fields are associated with active or dormant volcanic systems found within the active volcanic zone crossing Iceland from southwest to northwest. This explains why the once hot geothermal systems gradually cool within a relatively short lifespan after drifting out of the volcanic zone.

Super positioning and the present configuration of axial rift zones predict that the oldest exposed rocks in Iceland should occur in the furthest northwest, north and east (Figure 1). From radiometric dating, the oldest rocks in the northeast and northwest have been found to have an age range of 13-16 million years, a young age if compared to the oceanic magnetic anomaly (Saemundsson, 1979). This is because samples were only taken from the younger upper piles (top 1000 m). Magnetotellurics in NE-Iceland revealed 8-10 km thickness of the crust in the axial rift zone and up to 20-30 km in the older Tertiary areas east and west of the axial rift zone (Björnsson, 1985).

Like other constructive plate margins, the Mid-Atlantic ridge is characterised by a high heat flow in the crestal region, but with increasing distance symmetrically away from the crest, the mean heat flow falls until it reaches an average level for the oceans (Fridleifsson, 1979).

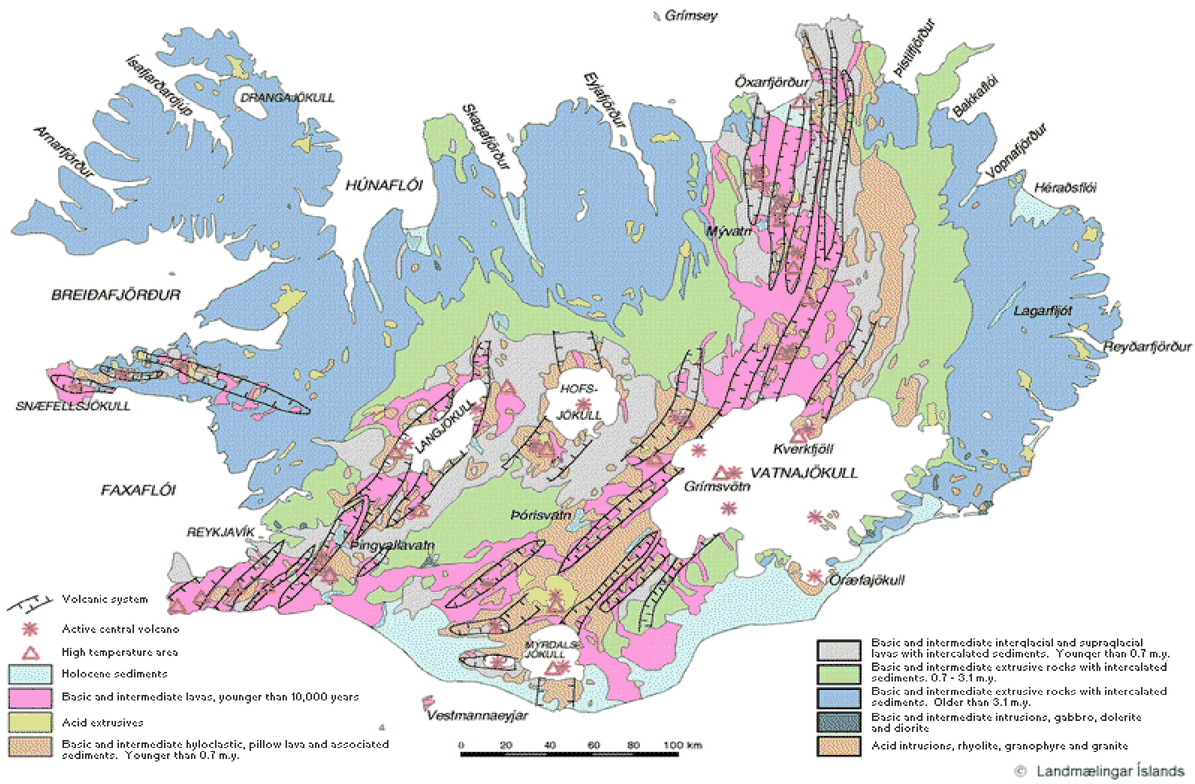

FIGURE 1: Geological map of Iceland (Jóhannsson and Saemundsson, 1999) showing oldest Tertiary rocks, Older Plio-Pleistocene eruptives, Holocene rocks plus other young formations; volcanic systems follow the oceanic ridge (copied from Hollocher, 2007)

1.2 Location and accessibility of Krýsuvík

Krýsuvík is located on the Reykjanes peninsula in SW-Iceland (see Figures 2 and 3). From Reykjavík you find it via the main road to Keflavík (Reykjanesbraut) with a turn left to take the Ásbraut road. Krýsuvík is about 25 km from Reykjavík. Within Krýsuvík, the mapping area was around Seltún and the eastern side of the Sveifluháls ridge (southeast of Lake Kleifarvatn).

1.3 Geological and tectonic setting of Reykjanes peninsula and Krýsuvík

Reykjanes peninsula is elongated, oriented roughly N75ºE (Figure 2) forming an oblique segment of the constructive plate margin. The formation of the peninsula can be explained by the geodynamic processes which are responsible for an anomalously large extrusion rate of magma which has its maximum just south of central Iceland (Jakobsson, 1979). Krýsuvík is one of the five high-temperature geothermal fields on the Reykjanes peninsula. The distribution of thermal manifestations and resistivity surveys indicate an extent of some 40 km^2 (Arnórsson, 1987). The Krýsuvík high-temperature geothermal field itself is divided into at least five subfields, namely: Trölladyngja, Hveradalir-Seltún, Austurengjar, Köldunámur and Sandfell geothermal fields (Ármannsson et al., 1994).

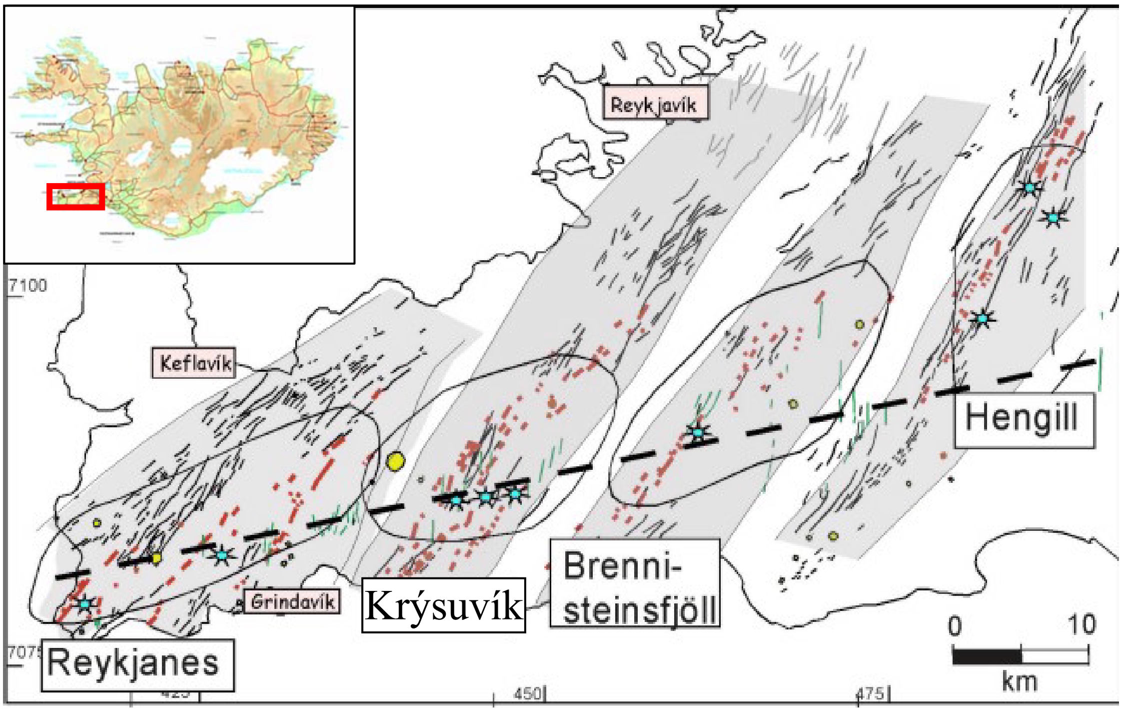

FIGURE 2: Tectonic map of Reykjanes peninsula showing fissure swarms, eruptive fissures, geothermal centres and approximate location of the plate boundary (dashed line) (modified after Clifton, 2007)

The Reykjanes peninsula is characterised by extensive Postglacial lava fields and steep-sided mountains and ridges of pillow lavas, pillow breccias, and hyaloclastites which protrude through the lava fields. The hyaloclastites are of upper Quaternary age from the last glaciations, formed during volcanic eruption in molten water chambers within the ice. The hyaloclastite ridges are striking approximately N40ºE and originate from eruptive fissures. The hyaloclastite ridge of Sveifluháls is believed to have been formed during the last glaciations (Imsland, 1973; Jónsson, 1978). The ridge is reportedly composed of four eruptive formations and was possibly built up during four volcanic episodes (Imsland, 1973), the details of which are presently being explored (supervisors, personal communication).

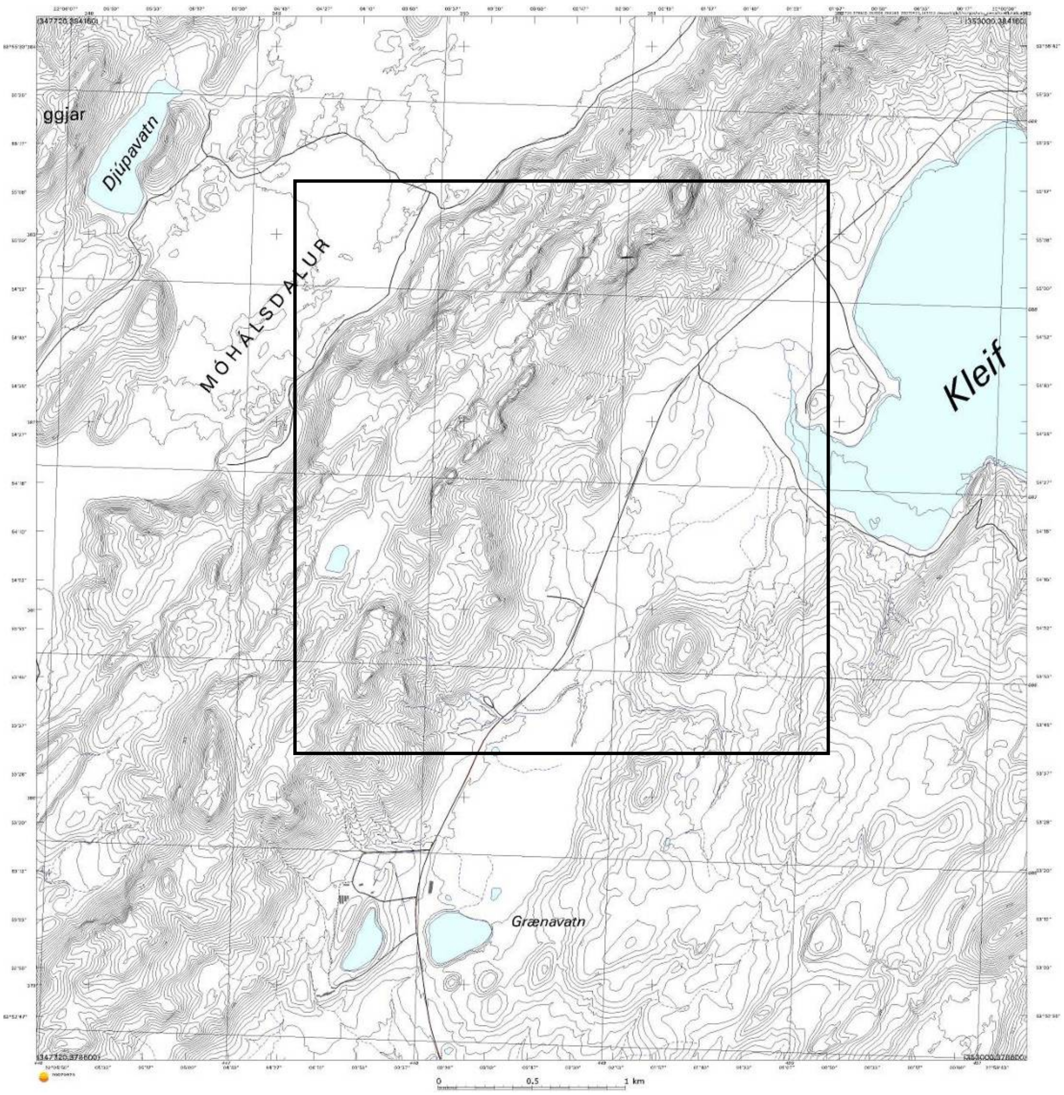

FIGURE 3: Location of the study area in Krýsuvík.

The faults and fissures of the fissure swarm (Figure 2) dissecting Krýsuvík field are much denser within the hyaloclastite ridges than in the younger lava fields in between. This is because of longer exposure of the glacial formations to the tectonic processes than that of the postglacial lava fields. Several explosion craters (maars) occur within Krýsuvík field (Arnórsson, 1987). Only a few volcanic eruptions are reported to have occurred in historical times (the last 1100 years) on the peninsula, including the vicinity of Krýsuvík. There is little doubt that shallow level magma chambers and dense dyke swarms are the heat source in the geothermal system. However, the heat sources have not been located in detail with respect to depth or spatial distribution.

2. PREVIOUS WORK IN KRÝSUVÍK AREA

2.1 Geology and hydrothermal alteration

Before 1950, fifteen to twenty shallow wells were drilled in Krýsuvík as a first phase of exploration to investigate the potential for electricity generation (Ármannsson et al., 1994). The Sveifluháls ridge was first mapped in 1973 and eight hyaloclastite units were mapped (Imsland, 1973). Three exploration wells (H5, H6 and H7) of 3⅜" diameters were drilled in 1971. The drill sites were selected based on geophysical interpretation, geochemistry and data from old wells to delineate temperatures, hydrogen content, hydrothermal alteration and to calibrate resistivity surveys (Arnórsson, 1987).

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 similar in pattern to other high-temperature fields (Gíslason, 1973).

TABLE 1: Alteration zones in Krýsuvík (from Kamah, 1996)

Alteration zone	Temperature range (°C)	Depth (m)
Smectite-zeolite	< 200	140
Mixed-layer clays	200 – 230	Up to 380
Chlorite	>230	737
Chlorite-epidote	240-260	To 1220

Temperature reversal was reported in most wells below 800 m depth (Arnórsson et al., 1975). This phenomenon is spread over a wide area. Maximum temperatures were reported at 200-500 m depths. Proper upflow zones were not found. The deepest exploration well was only 1220 m.

In 1996, studies were made on well KR-2 (1220 m deep) located in Krýsuvík (Kamah, 1996). Study of the drill cuttings showed that upper Pleistocene strata are mostly composed of hyaloclastite units with thinner intervening basaltic lava units of interglacial age. Table 1 shows alteration zones seen in the well.

2.2 Geochemistry

During the 1970 - 1972 exploration survey, four exploration wells were drilled to a depth of 800-1000 m and other two wells to a depth of 1000- 1200 m. This was necessary because the pillow breccias out of which steam emerged did not allow the collection of uncontaminated steam samples for proper geochemical studies (Arnórsson, 1987). The concentration of carbon dioxide in fumarole steam was reported to be in the range between 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 is believed to be due to contamination from air. 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 two reasons: 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 (Arnórsson, 1987). In 1975, Arnórsson et al. reported that the bed rock was intensely altered by acid surface leaching. Alkaline water springs presenting a flashed water fraction of 'deep water' do not exist in the area.

Thermal waters from wells in the Krýsuvík high-temperature geothermal field display a large variation in dissolved solids, unlike in other areas where hot water chemistry is very homogeneous (Arnórsson et al., 1975). Percolation of sea water into the reservoir rock has been reported on the Reykjanes peninsula. It is said to be more predominant to the west than the east because of high permeability of the bedrock (pillow lavas and pillow breccias). Geothermometry on gas from fumaroles in Sveifluháls (298°C) and from well KR-9 (288°C) suggests the reservoir temperature may be close to 300°C (Ármannsson and Thórhallsson, 1996, Bjarnason, 2000).

2.3 Geophysics

Extensive geophysical work has reportedly been done in the Krýsuvík area. Low resistivity (10 Ωm) was found in areas where the surface had been strongly altered by acid leaching (Arnórsson et al., 1975). This contrasted with high resistivity in the Postglacial lavas (>1000 Ωm). At a few hundred metres depth, the resistivity was found to be low, 5-10 Ωm in a large area.

Presently, older geophysical surveys are being reviewed and new methods like TEM, MT and gravity methods have been added. The preliminary results show a large low-resistivity anomaly characterising the entire Krýsuvík area at a shallow depth, underlain by a high-resistivity anomaly (Eysteinsson, 2001), associated with high-temperature alteration.

3. GEOLOGICAL MAPPING

3.1 Methodology

The location of the study area is shown in Figure 3. A geological map was made of this area as well as a geothermal map. The geological map includes the main lithological units and tectonics. The boundaries of the different lithological units were tracked in the field using GPS (GARMIN GPS 12 XL). Structures such as craters and faults were mapped in the same way. Where the terrain would not allow tracking, points were taken along the structure or boundary and later joined in the office when editing the map. In such cases, notes were taken while in the field, and sketches made to give the picture. Numerous photographs of interesting features were also taken.

The GPS data was downloaded to the computer using software called MapSource and then edited. Next the data was processed using ARCINFO and ARCGIS and different tracks and points were plotted onto a map. The plotted map was then edited manually to make different boundaries (to form regions) and put in all the structures. Later, the map was digitised to produce a geological map (Figure 4). While in the field, samples were studied macroscopically using hand lenses to distinguish between different lithological units. Although some sampling was done, no detailed petrological studies were made. The hand samples were only used for consultation and the classification of rocks with the supervisor.

3.2 Geology

3.2.1 Hyaloclastite units

The main field that was mapped is within the southern part of the Sveifluháls ridge. The field is covered with two hyaloclastite units which are taken as the basement formation within the area mapped. However, within these units different lithofacies could be observed. Pillows and pillow breccias were common in the young hyaloclastite unit 2. The older hyaloclastite unit 1 contained fine-grained tuffs, less clastic materials and contained a lot of sedimentary structures. However, some sedimentary structures were not limited to the older hyaloclastite unit 1; they also occurred in the younger unit at a few places with a higher degree of sorting (Figure 5). In the northern part of the area where the older unit is more exposed, pillow dykes were observed to cross cut the older hyaloclastite unit. The pillows were exceptionally porphyritic with plagioclase.

The pillows encountered in the area contained a lot of concentric vesicles, implying a low thickness of ice or water under which they were formed. The thin glaciers or water gives lower hydrostatic pressures which results in low-density pillows with a lot of vesicles. However, this is geothermally advantageous. Highly vesicular pillows give good geothermal reservoirs because of increased porosity coupled with good permeability. Some of the pillows had necks on the main pillows, formed as a result of lava flowing through a small opening out of the pillow, forming a secondary pillow on the main pillow. Most of the glassy hyaloclastites were found to be weathered to brown palagonites, especially at lower altitudes, possibly due to longer exposure to weathering conditions. At higher altitudes (near the eruptive fissure), especially where steep slopes occur, the hyaloclastites seemed fresher.

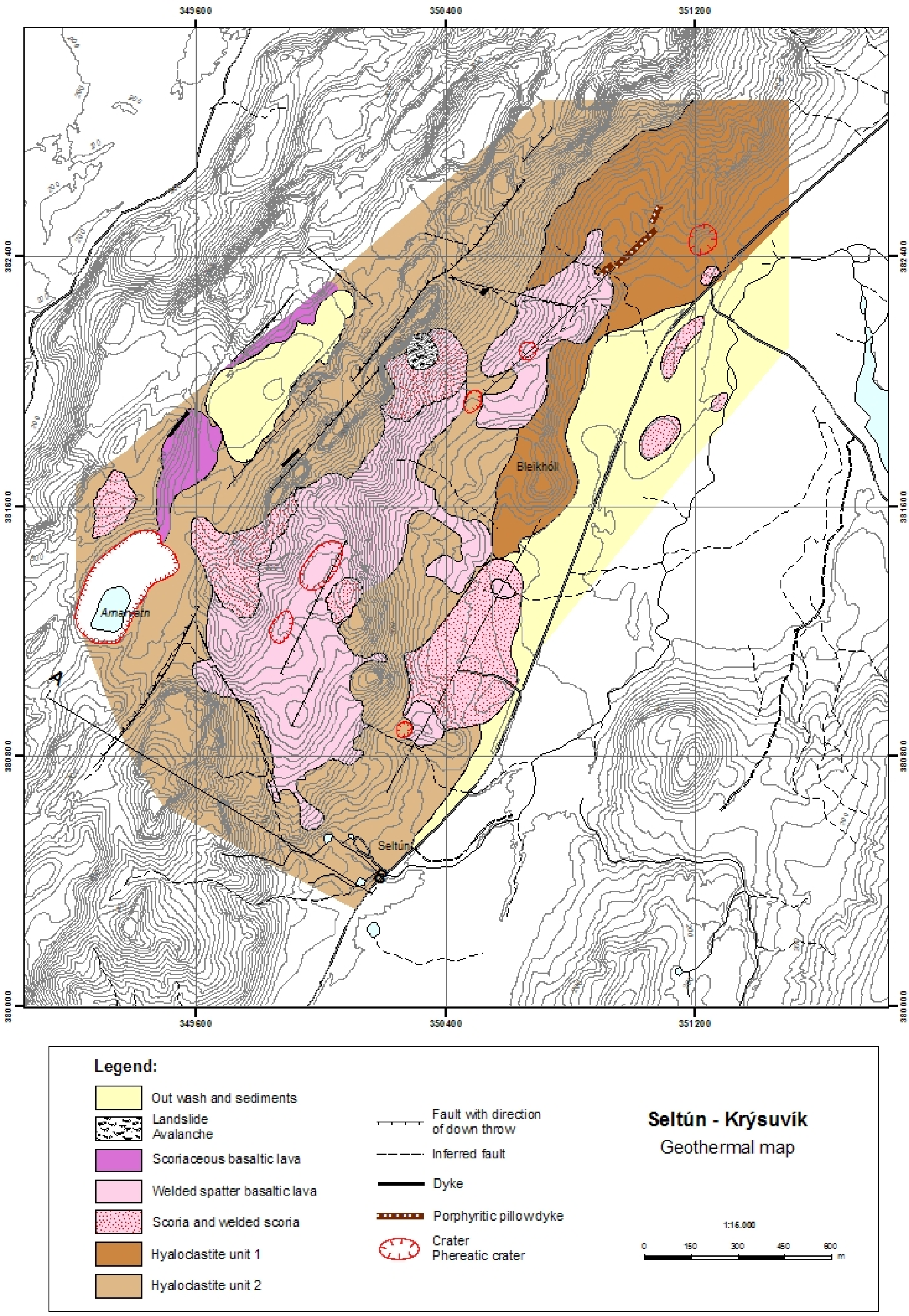

FIGURE 4: Geological map of Seltún – Krýsuvík area

FIGURE 5: Sorting in sedimentary hyaloclastite tuff.

3.2.2 Spatter welded lava and scoria

In the study area spatter welded lava and scoria are common. This lava is considered to be of either late glacial age or early Holocene age. The spatter debris came from a line of craters mapped in the area. The distribution of the youngest volcanic units is of importance with respect to the distribution of hydrothermal manifestations as the younger volcanic units may be linked to an active heat source at depth. Similarly, young dykes and faults create flow paths for hydrothermal fluids.

The spatter basaltic lavas are all porphyritic with plagioclase phenocrystals. In some hand samples, olivine was also observed. In some cases scoria was found welded to the basaltic spatter lavas, with the latter forming two layers, at the bottom and at the top. These lavas were deposited on older hyaloclastites (Figure 6). Because the lavas were very hot they caused the host hyaloclastites to be heated and oxidised to a reddish brown material (Figure 7). Although the basalts were generally massive, in some places they are scoraceous and highly vesicular. Ejecta from craters at lower altitudes east of the area contained debris of highly altered clayey materials, implying that the eruption occurred in an already altered ground.

3.2.3 Outwash and sediments

At the eastern side of the area mapped lies a valley - the Krýsuvík valley. The valley floor is covered with outwash and soil. Because it is flat, aeolian and fluvial material has been deposited. The provenance of all these materials is from the tuffaceous hyaloclastites, palagonites and some spatter debris. Sedimentary sequences, tillites and other depositions of glacial origin have been reported from within the sedimentary fill of the valley (Vargas, 1992). Some loose materials were also mapped on the southeast side of the mapped area. They are deposited in a flat basin within a fault-formed graben.

FIGURE 6: Spatter lava on top of brown palagonitised hyaloclastite.

FIGURE 7: Heated hyaloclastite because of hot spatter lava (lava at top, oxidised layer in middle, fresh layer at the bottom)

3.3 Structures and tectonics in Seltún-Krýsuvík area

Mapping of structures, lineaments and tectonics is important when carrying out geological and geothermal surveys as they are very useful for making proper interpretations for later geothermal mapping. Such structures can throw light on possible zones of upflow and outflow, hence useful in the formulation of a geothermal model.

3.3.1 Faults and lineaments

Although several lineaments and faults striking northwest-southeast were mapped in the area of study, most of the faults mapped strike roughly N40ºE which is the regional trend of faults, lineaments and eruptive fissures. The Sveifluháls ridge, which hosts most of the area mapped, also trends northeast (meaning the eruptive fissure responsible for the formation of the ridge has the same trend).

FIGURE 8: Fault with downthrow to the west, strike N40°E

Many of the mapped faults involve some displacement to either direction. The amount of displacement is usually hard to determine because most them have been highly eroded (Figure 8). However, in one of them the displacement was on the order of about 30-50 m along the Sveifluháls ridge. On the southwest side of the mapped area, there is downthrow along two parallel faults giving rise to a graben near the phreatic crater east of the area. Open fractures, in which there is no displacement, were encountered within the fault zones.

3.3.2 Dykes

Basaltic dykes are common and those which seemed long enough were tracked (Figure 9). Although a few of them are porphyritic with plagioclases, most of these dykes are aphyric. Some are very finely grained and very dense while others were light and vesicular. Most of them show a chilled margin. The hyaloclastite was already cold when the dykes intruded. In most cases they caused some alteration in the host rock along the contact.

FIGURE 9: Basaltic dyke striking N40°E

In addition to normal dykes, sedimentary and mud dykes were also mapped in a few places. These were formed where open fractures had formed which were later filled with fine material like tuff. The mud dykes are thus believed to be fractures that opened up in small basins of mud within the hyaloclastites and the mud sank into them. These are common at higher altitudes along the ridge near the eruptive fissure. Feeder dykes with the same material as the hyaloclastites were also seen.

3.3.3 Phreatic craters

When carrying out geothermal mapping it is important to map all craters. They are always indicative of a possible source of heat for the geothermal system. The phreatic craters mapped in this area are along zones of weakness. This is clearly indicated by their linear distribution near faults. They are responsible for the welded lavas and spatter debris or scoria. They are Postglacial, i.e. of Holocene age. One of the craters mapped is west of the area. It is now filled with water to form Lake Arnarvatn (see Figure 4). The spatter debris was thrown several tens of metres, but for lighter materials (light scoria) the influence of wind direction is paramount. It was observed that eruptions of the same episode from different craters have their scoria thrown in the same direction. In the case of the mapped area, all the scoria was thrown northwest or west. This may be used as a tool to tell if the different craters are of the same or different eruptive episodes.

3.3.4 Landslides

Landslides are common in areas with unstable steep slopes. The Sveifluháls ridge is characterised by very steep slopes. Because of this, landslides (big enough to be mapped) were mapped in the area. An example can be seen at the central northern part of the area (see geological map, Figure 4). They are usually triggered by earthquakes, which are common in this area. The area is even more prone to landslides if it is completely altered to clays. The clays, with some precipitation, will 'lubricate' the movement of an unstable landmass down slope. The landslide shown on the map is younger than the most recent eruption (from a phreatic crater). This is evidenced by the fact that it covered the scoria from the crater, implying it occurred later.

4. GEOTHERMAL MAPPING IN SELTÚN

Mapping of geothermal surface manifestations is very important in the exploration of geothermal resources. Information obtained from this kind of work can be used to formulate a tentative geothermal reservoir model for the geothermal resource. Such a model may then be used as guidance in subsequent exploratory work such as geophysical surveys and exploration drilling.

4.1 Methodology

Weak and intense ground alterations seen in the field were mapped using GPS. Other geothermal features like warm springs, mud pots, travertine, and fumaroles were also plotted using GPS. The data was then downloaded using MapSource software. It was later processed by ARCGIS and printed out on a map which was edited manually for digitising to produce a geothermal map (Figure 10). Old boreholes were not neglected during mapping. Retrieved data on them can be useful in revealing information about subsurface geology and hydrothermal alteration.

Hot grounds were mapped by tracking isotherms around them using a GPS. A 50°C isotherm was tracked while using a thermometer to measure the ground temperature to enclose an area which is hotter than 50°C. The thermometer is a rod, about one metre in length, mounted with a sensor at one end. The other end has a cable which can be connected to a digital meter which records the temperature. During measurements, the thermometer rod was inserted into the ground to a depth of 12-15 cm. Similarly, a 15°C isotherm was tracked around the 50°C isotherm to enclose areas whose temperatures were between 15 and 50°C. These tracks were similarly downloaded.

Sampling was also carried out to understand the type of alteration minerals and what kind of alteration was found in the Seltún-Krýsuvík area. The clay and alteration mineral samples were analysed using a XRD machine. Dilute hydrochloric acid was used to distinguish between samples with calcite (travertine) or silica. The treatment of samples before XRD analysis was as follows:

A sufficient quantity of sample was ground in a mortar and transferred onto a sample holder made from synthetic quartz and placed in the sample holding compartment of the X-ray instrument. The equipment employed was a Philips PW1710 diffractometer with Ni-filtered Cu k-alpha radiation. Data was checked for aberrant values, background patterns were subtracted and smoothed and the subtracted patterns appended and displayed with the untreated patterns. Comparative data for crystalline mineral phases were retrieved from the PDF-2 data-base from ICDD, using DiffracPlus software from Bruker AXS.

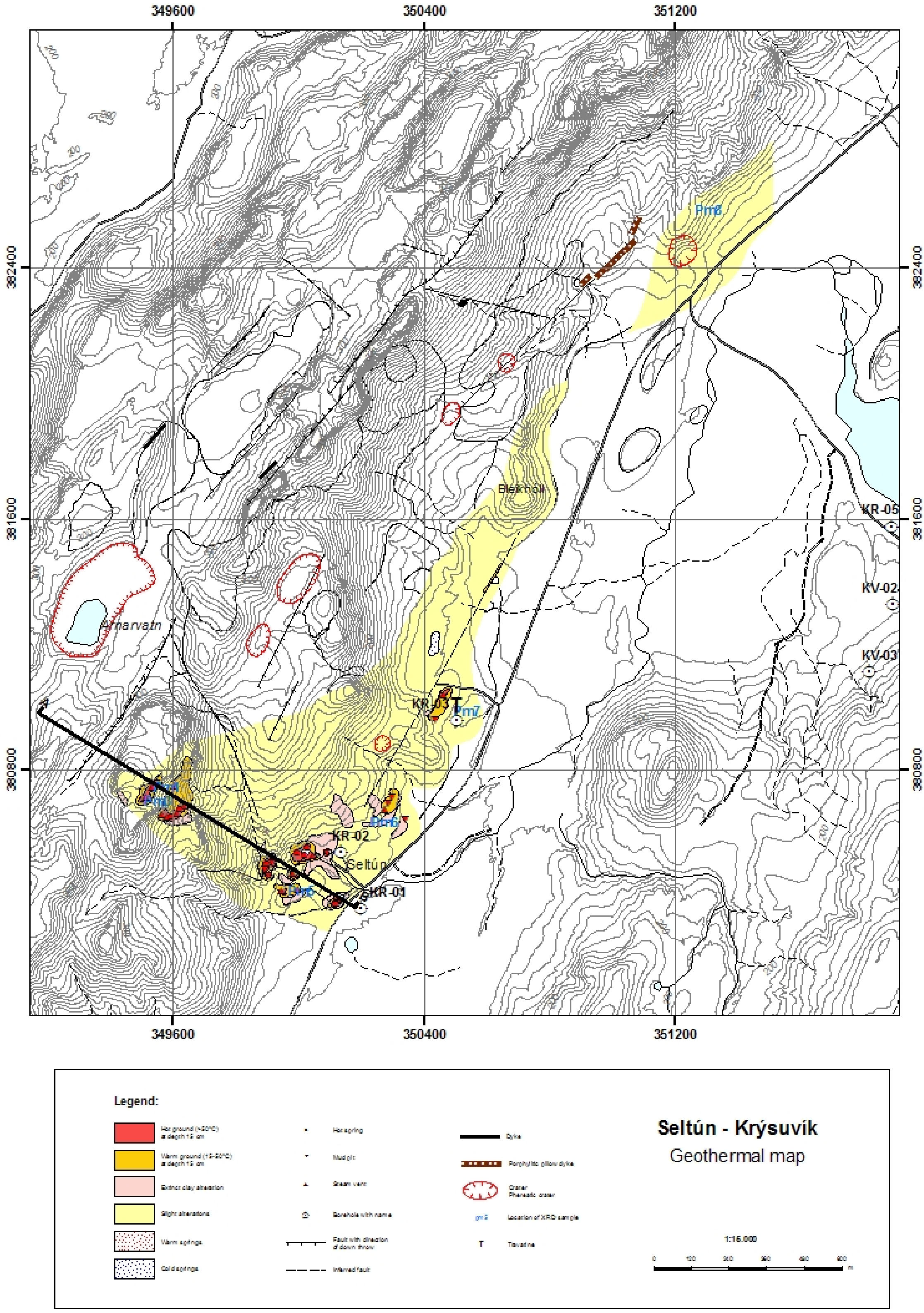

FIGURE 10: Geothermal map of Seltún - Krýsuvík

4.2 Surface alteration

The alteration in the area ranged from very weak to very intense. Analysis of clay samples (like samples PM 03 and PM 05) by XRD indicated that the most common clay type is kaolinitic clays (see Appendix I for XRD curves). This confirms the fact that alteration in the area of study is acidic. Kaolin seldom forms in alkaline environments, confirming that the Krýsuvík area has undergone acid leaching of the rocks. Alkaline environments are usually characterised by smectite clays. The clays ranged in colour from white to dirty white and brown. Some clay was stained to red colours due to the presence of iron oxides (like sample PM 05). In active and highly altered areas sulphur was commonly found, but where the system was cooling it seemed to be oxidising, too. However, results of XRD analysis for sample PM 06, which looked like sulphur getting whitened, showed the presence of amorphous silica (opal), titanium oxide (anatase) and a bigger percentage of sulphur. Both silica and sulphur are commonly considered to be found in high-temperature geothermal areas.

FIGURE 11: Hyaloclastite tuff which was altered with calcite

In weakly altered areas zeolites were the common minerals. In some samples, calcite was found to be a secondary mineral, seemingly replacing some glass grains in the hyaloclastite and tuffs. A lot of calcite was found to be deposited in fractures (Figure 11) within hyaloclastite tuffs and pillow hyaloclastites. Analysis of samples from these deposition minerals indicated that the calcite contained aragonite as well (see Appendix 1 for XRD curve of sample PM 01). The rate of alteration seemed to be faster in glassy hyaloclastites than in the massive basalts or pillows. Glass easily gets altered just as it easily weathers to palagonite.

Samples were collected from the weakly altered area and one of them (PM 08) was analysed with XRD. It was found to contain phillipsite, calcite, analcime and possibly cowlesite (zeolite) and clay. Traces of plagioclase were also detected (Appendix I).

Gradation of colours within the original material caused by alteration was observed. Colours ranged from pale brown, reddish brown, and brick red to white depending on the degree of alteration. Efflorescent minerals (sulphur salts) were encountered. They occur at the periphery of very hot grounds. These salts are sour and soluble in water. When it rains, they tend to disappear because they dissolve (K. Saemundsson, pers. comm.). The efflorescent minerals are listed in Table 2.

TABLE 2: Efflorescent alteration minerals (soluble sulphur salt)

Mineral	Colour
Pickeringite	Yellow or orange
Halotricchyte	White
Brocantite	Green

The first two types of minerals in Table 2, Pickeringite and Halotrichyte, were more common in the mapped area than the Brocantite. Weak alteration was also seen along dykes and fractures. The occurrence of alteration along dykes clearly indicates they are of a younger phase and intruded an already cold existing rock. This is supported by the presence of chilled margins in the dykes. The hydrothermal alteration was distributed more to the eastern side of the mapped area than to the west, especially northwards. However, in the southern part of the mapped area, the alteration area seems to widen, extending further west.

4.3 Hot ground

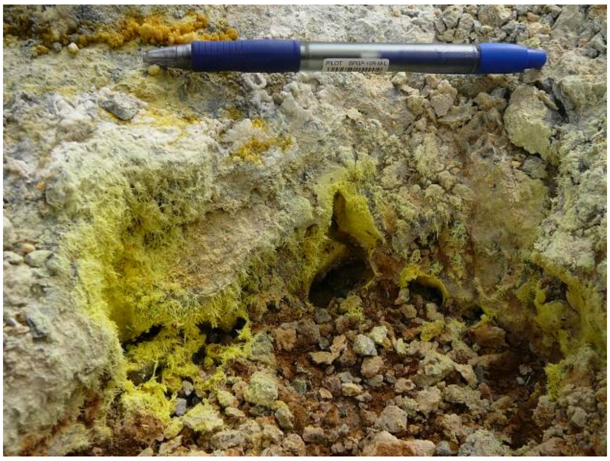

FIGURE 12: Sulphur needles in a solfatara, completely altered with lots of steam vents.

The hot grounds were mapped with a 50° and a 15°C isotherm with the former enclosing areas hotter than 50°C and the latter enclosing an area warmer than 15°C. Most of the area enclosed by the 50°C isotherm was observed to be completely altered to clays and, in most cases, it was active with fumaroles, mud pots, boiling springs and sulphur. Such spots with a lot of sulphur and steam vents are sometimes referred to as solfataras (Figure 12). Highest temperatures measured in different hot grounds were in the range of 60-95°C at a depth of 12-15 cm. The distribution of vegetation, especially moss, can give a rough picture of the temperature distribution within hot ground. In the area, there was a plant with yellow flowers which was noted to be only distributed in areas within 15°C isotherms or close to that.

Most of the hot grounds mapped were found to be in hyaloclastite tuffs, breccias and pillows. At lower altitudes, the hot grounds were located in scree, outwash and sediments. The continued deposition of sediments by wind and surface runoff into the valley keeps on covering the hot altered grounds, making them look weak (if activity is not so strong) and covering the clays. Where cold streams traverse hot grounds, the 15°C isotherm tends to be too close to the 50°C isotherm because of the cooling effect of cold water from the stream.

4.4 Fumaroles and steam vents

The steam vents and fumaroles in this field were of varying strength in activity. The activity also depends on the amount of rainfall and the availability of water. It was observed that the fumaroles at lower altitude were strong and steam-dominated while at higher altitudes they were weak in terms of steam production. The reasoning is that following precipitation, the water percolates and tends to be more available at lower altitudes than at higher altitudes. Surface runoff and streams also tends to avail water to hot grounds at lower altitudes.

Steam vents and fumaroles, especially weak ones, were observed to be linearly distributed in some places, following fractures. In addition to steam, other gases are also produced. Those gases that are easy to recognise, like hydrogen sulphide, could easily be identified by the characteristic smell.

4.5 Mud pots

Mud pots were only mapped at lower altitudes, especially at Seltún. The kaolinitic clay forms grey slurry that keeps on spitting with a sound like thick porridge boiling in a pot. The clay material is mainly kaolinite, suggesting alteration by acid leaching.

In these mud pots, temperatures up to 95°C were measured. To the north, the mud pots seem to be dying out. However, when it rains intensely, all mud pots get filled with water and then act as boiling pools. The activity of springs and mud pots is dependent on precipitation (Figures 13 and 14). This indicates that most of the water is meteoric water and no deep waters are being discharged.

FIGURE 13: Mud pot at Seltún during August

FIGURE 14: The same pool (as in Figure 13) in September, now full of water.

4.6 Boiling springs

Like mud pots, boiling springs were also encountered at lower altitudes, especially at Seltún. The source of water, as previously mentioned, is not deep, but rather surface water. At Seltún some water channels flow from down ridges and pour into the hot altered grounds. In one of the channels, temperature was measured upstream and found to be 12ºC but downstream, after leaving the active area, it was found to have a temperature of 42ºC. Some of the boiling springs are strong, throwing water up to 0.3 m. The highest temperature measured was 97ºC at 20 cm depth but increased to 110°C at deeper levels.

4.7 Warm and cold springs

These were few. One warm spring and one cold spring were mapped on the east or northeast side of the area. These were found in the area where geothermal activity is seemingly decreasing. In the warm spring, the temperature measured was in the range of 32-34ºC. Warm water flows out of the ground at a few spots in a linear fashion. Along this fracture there is a linear anomalous soil temperature of 15-20ºC. This area was mapped and looks like a line of warm ground. The measured temperature in the coldest spring was in the range of 14.5-14.7 °C.

4.8 Silica sinters and travertine

No silica sinters were seen in the mapped area. However, travertine was seen at one point where it had been buried in outwash and then mixed with soil. The 'sedimentary' or layering in this material could be traced by looking at the sides of a pit where aggregates or scoria were being excavated (site where sample PM 07 was picked).

5. GEOTHERMAL MODEL AND DISCUSSION

In building up a model, a stratigraphic column from well KR-2 was used (Figure 15). Other wells in the area such as KR-1, KR-3 and KR-8 were used to understand the geologic distribution of the subsurface from which isotherms were plotted into the model. High temperatures approach the surface east of Seltún, but in the west, high temperatures seemed to be at greater depth. The subsurface geology is an alternating series of hyaloclastite and basaltic lava, indicating glacial-interglacial periods (Figure 15). Alteration zones in the subsurface ranging from zeolites to chlorite-epidote were also plotted in the model, based on well data.

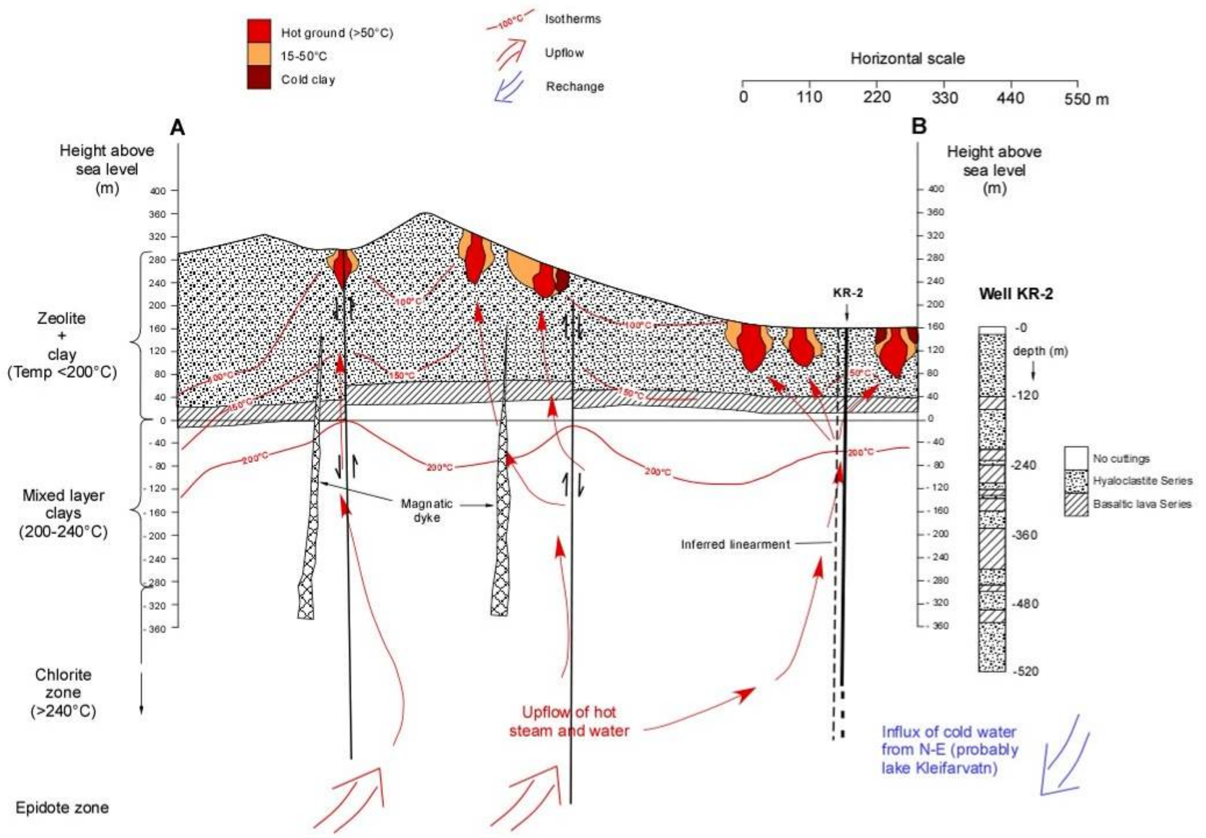

FIGURE 15: Geothermal model for the Seltún-Krýsuvík area

Hot grounds, fumaroles and other surface manifestations are located near sub vertical to vertical faults or fractures. Upflow zones are, therefore, structurally controlled. Recharge seems to be due to an inflow of cold water from the northeast, probably from Lake Kleifarvatn (Figure 15). The fractures in the lake seem to take water at great depth which is then heated and rises in the upflow zones. Because of this inflow, the geothermal system may be cooling down from the north, where cold alteration alone was mapped, especially at Bleikhóll (Figure 10).

The linear distribution of alteration (Figure 10) shows a NE-SW trend and the distribution of fumaroles and hot ground along faults and lineaments with the same trend might promote the idea of directional drilling in a NW-SE direction so that more fissures could be penetrated. This could solve the problem of temperature reversal in many vertical wells in Krýsuvík. The model also suggests that the explosion craters in the area are associated with magmatic dykes, thus being a possible source of heat in the geothermal system.

6. CONCLUSIONS

- The NE-SW linear distribution of alteration and warm ground trending in the same direction as the main fracture system suggests the geothermal system is structurally controlled.
- The geothermal system is seemingly cooling down due to clay alterations and the deposition of secondary minerals which reduce porosity and permeability.
- There is no doubt that the numerous phreatic craters in the area of study indicate the presence of a magmatic chamber at some depth, responsible for these explosive eruptions.

- The numerous fissure systems are responsible for the recharge of the system from precipitation, and for outflow zones.

- The geology mapped in the area ranges from subglacial hyaloclastites to eruptive aerial formations of ejecta, spatter lavas and debris. The hyaloclastites consist of pillows, tuffs and pillow breccias. Two hyaloclastite units were mapped: older unit and a younger one. The older unit is more tuffaceous with less clastic materials and shows more sedimentary structures. The young unit is more clastic. Both units are very glassy.

- Tectonically, most lineaments, fissures and faults strike NE-SW which is the regional trend of zones of weakness and eruptive fissures.

- Based on mapping, directional drilling in the geothermal field with a NW-SE orientation is recommended.

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APPENDIX I: XRD curves for mineral analysis of samples

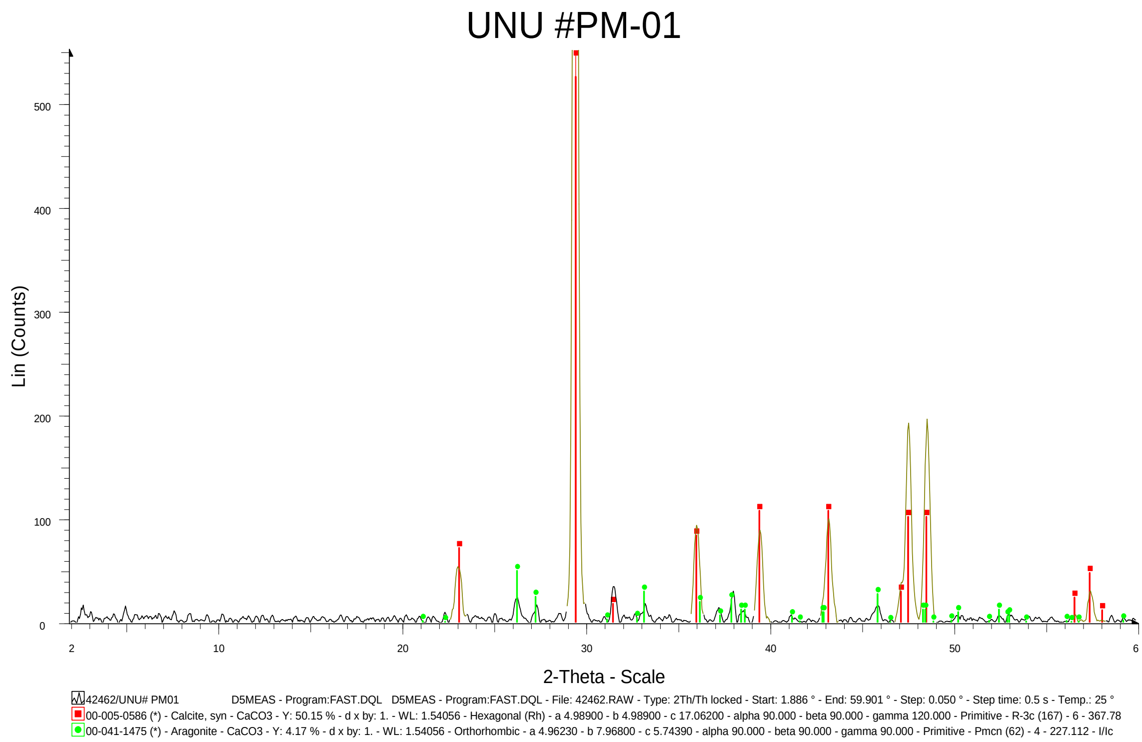

FIGURE 1: Sample PM 01 which was found to be almost pure calcite, but traces of aragonite were detected.

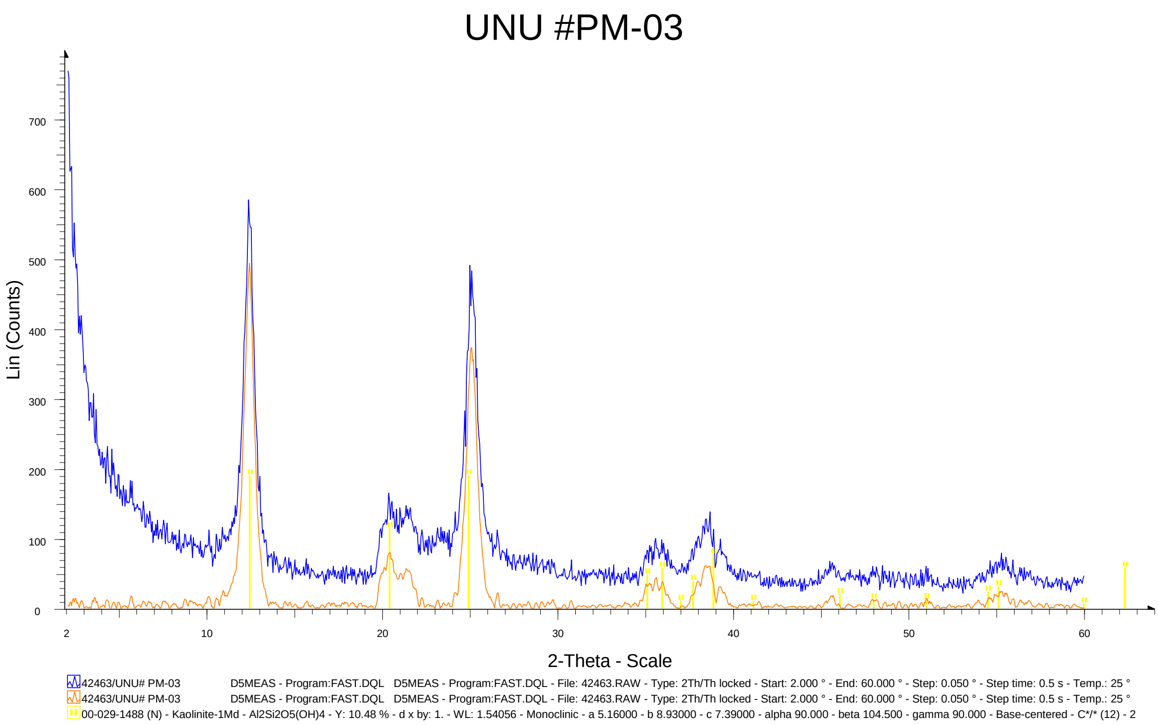

FIGURE 2: Sample PM 03 which was found to be pure kaolinite

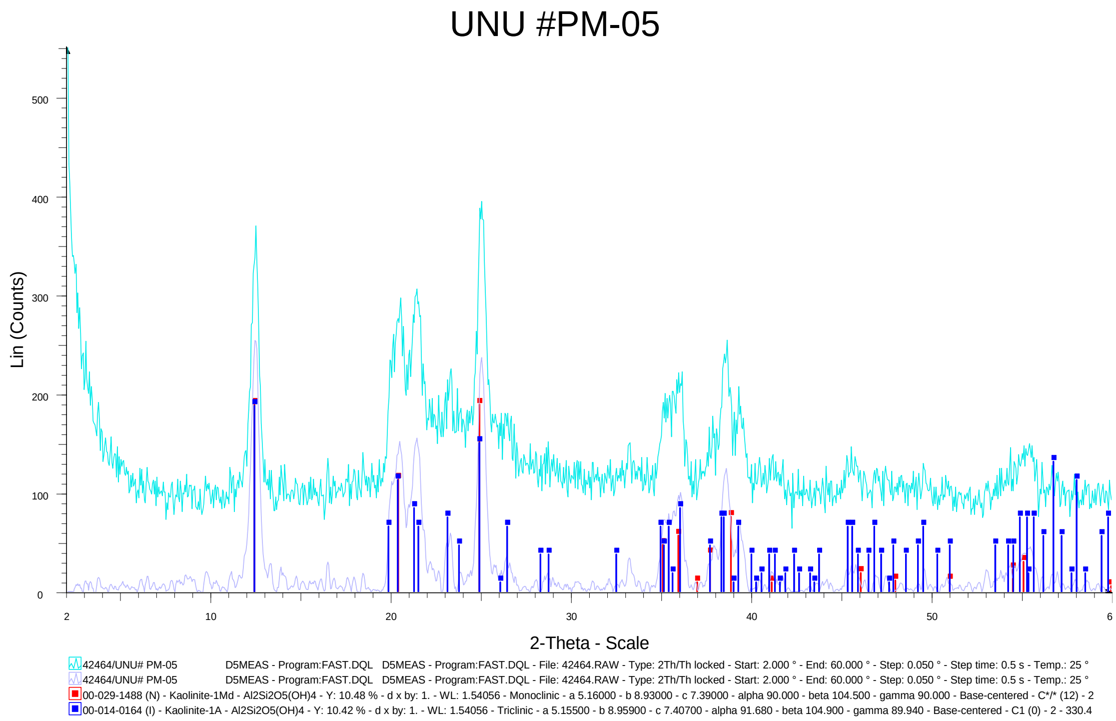

FIGURE 3: Sample PM 05 which was kaolinitic clay stained by iron and thus red

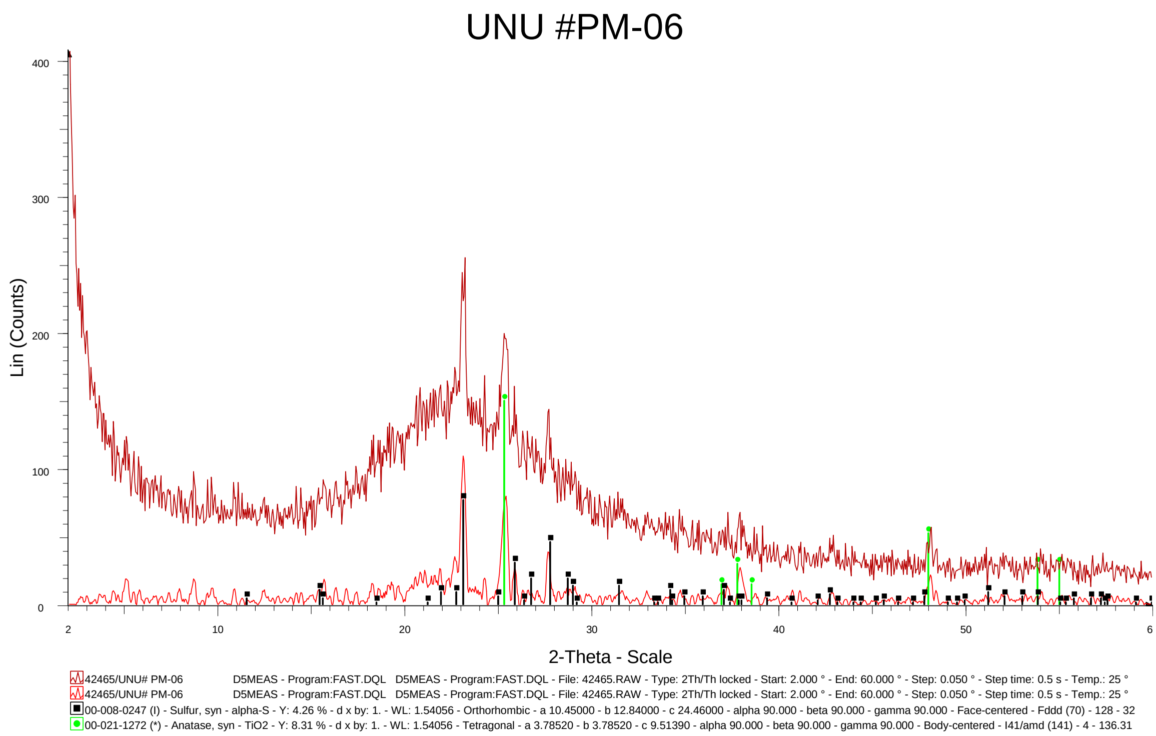

FIGURE 4: Sample PM 06 was found to contain amorphous silica (opal) with titanium dioxide (anatase) and a big % of sulphur.

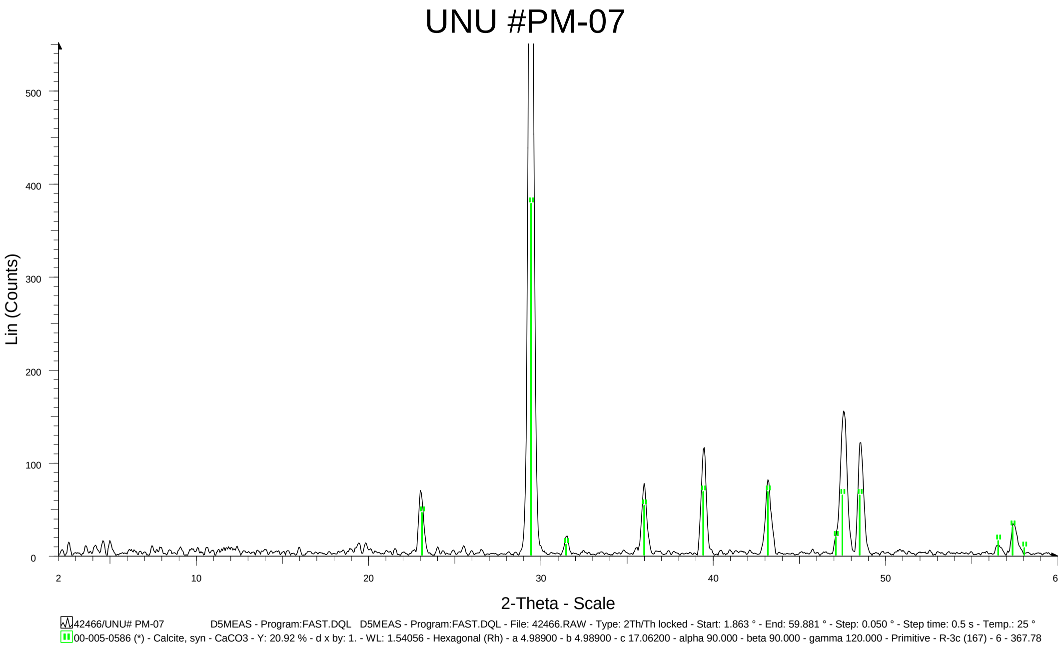

FIGURE 5: Sample PM 07 which was found to be pure calcite.

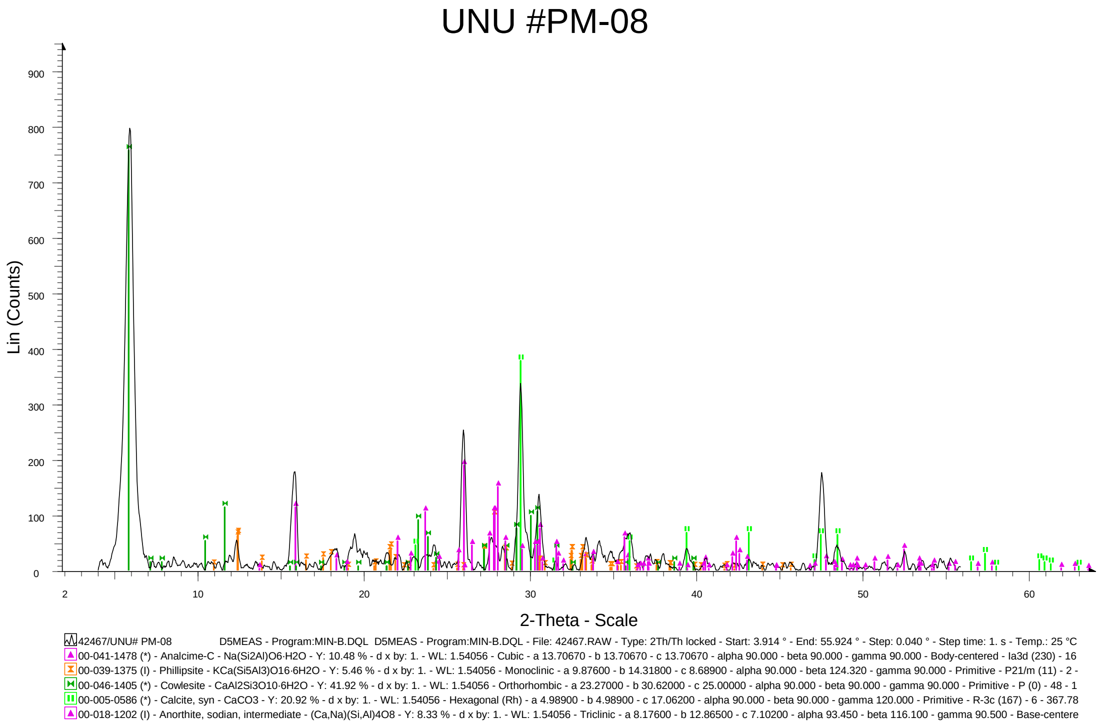

FIGURE 6: The weakly altered sample contained phillipsite, calcite, analcime and possibly cowlesite (zeolite) or clay; also traces of plagioclase