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Geological and Geothermal Mapping in Trolladyngja - Sog Area, SW-Iceland

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ABSTRACT

Geological and hydrothermal alteration mapping was carried out in the Sog area within the Trölladyngja geothermal field on the Reykjanes Peninsula, SW-Iceland.

The bedrock consists mainly of hyaloclastites, erupted subglacially in upper Pleistocene time. They were divided into 5 eruptive units on the basis of different petrography, minor supraglacial basaltic lavas and intercalated sediment. Holocene lava flows cover the east side and the west side of the study area. The hyaloclastites form bulky NE-SW trending ridges, 100-200 m high, and about a kilometer broad leaving sediment traps between them. The Sog valley is one such, about 1.5 km in length. It is filled with clayey sediment, most of it lacustrine, which is overlain by about 10 m of clay interlayered with peat, clearly of Holocene age. A gorge formed in the Holocene drains the Sog-valley towards west with its tributaries. Erosion has cut a valley transversally across the ridge complex and exposed different grades of alteration down into the hyaloclastite rock. The alteration grades reach from an uppermost pale brown rock with palagonite, down into dark brown or blackish rock with smectite as the dominant clay and below it to a greyish green mixed-layer facies of smectite-chlorite. The transition from smectite to mixed layer clays corresponds to at least 180-200°C and a hydrostatic pressure of at least 17 bar at the time of alteration. The hydrothermal alteration zones imply that the alteration took place subsurface.Despite some erosion an ice thickness of at least 100 m would be needed to explain the chlorite-smectite alteration. A late near surface alteration to plastic smectite clay characterizes the filling of the Sog valley.

The only geothermal manifestations in the Sog-valley are minor tepid springs (<20°C) in and near the outlet gorge. One single fumarole occurs in it, and another near its entrance. Both are fault-related. The fumaroles have light-coloured clay, typical of acid surface alteration (kaolinite) and efflorescence minerals of bitter taste around them. In general, it can be stated that the study area with its bright alteration colours has cooled down. It was at the peak of activity probably during last or second last glacial period, before erosion exposed the alteration zones.

1. INTRODUCTION

1.1 The Study Area

The Trölladyngja – Sog area is located about 40 km southwest of Reykjavik, the capital of Iceland, (63°54 30 N – 63°56 30 N and 22°04 30E – 22°06 30 E). Two different roads from Reykjavik can be used to get into the field area. The topographical setting of the study area (Figure 1) is divided into three main parts:

- East and west sides of study area are represented by relatively flat areas or plains, elevated to 150-200 m a.s.l. They are partly covered by basaltic lavas that are a few thousand years old.
- A depression between two hyaloclastite ridges, filled by a hydrothermally altered sedimentary succession.
- Hyaloclastite mountain ridges in the middle of the field area reaching about 300-400 m a.s.l.

The present study are a part of 6-month training at the United Nations University Geothermal Training Programme (UNU-GTP) in Iceland. An important part of the training in geological and geothermal exploration was to create a geological map as well as a geothermal alteration map of the study area, which is the chief aim of the present study.

1.2 Methodology

The main goals of this study were to make geological and geothermal maps of a volcanic field and to find out if some relationship could be established between the tectonic setting and the geothermal alteration of the study area. The geological mapping exercise was carried out from the 15th of July to the 3rd of September, 2008. However, the actual time spent in the field was limited to about 16 days, partly due to weather conditions, as efforts were sometimes hampered by rains. Instruments and tools used to carry out the field work included the following:

1) A Garmin - GPS 72 to locate and track the structural, stratigraphical, and alteration features such as faults, fractures, dykes and stratigraphical boundaries and alteration zonation;

2) Topographic maps, air photos and compass used to trace the aerial extent of the major structures and their strike and dip directions and distribution within the study area;

3) A geological hammer, a metric tape and a hand lens used for field inspection of rock samples and unit thicknesses; and

4) A shovel, and small plastic sample bags to collect fresh samples from the different alteration zones and different rock units for XRD and petrographic studies, in order to figure out the degree of alteration and the mineral assemblages that exist in the hydrothermally altered areas, and also to differentiate between the different rock units or outcrops in the study area.

1.3 Previous work

The study area has been explored intermittently by many geo-scientists over the last few decades. Most of this exploration work was done for geothermal exploration purposes. Reference is made to only a few reports and papers, most of which are written in Icelandic. A regional geological map was published by Orkustofnun after many years of mapping by Jónsson (1978), who mostly was sorting out the sequence of Holocene lavas of the Reykjanes peninsula at large. Later, a geological map on the scale 1:250,000 was published (Saemundsson and Einarsson, 1980). Several geothermal studies have been undertaken, the first important one by Arnórsson et al. (1975). Additional work was done in the early 1980s, including a resistivity survey. A review report on the geothermal knowledge of the Trölladyngja field was published by Orkustofnun in 1986 (Flóvenz et al., 1986). Other works include e.g. reports by several UNU Fellows who have done practical training within the Trölladyngja field in surface and subsurface geology (Muhagaze, 1984; Kifua, 1986); a report on ideas of potential steam production and transmission to an energy park (Ármannsson et al., 1994); borehole drilling reports on wells TR-01 and TR-02 (Fridleifsson et al., 2002; Kristjánsson et. al., 2006; and Mortensen et al., 2006).

The earlier reports (such as by Arnórsson et al., 1975) reported the maximum logged temperature in the Krýsuvík-Trölladyngja area as high as 262°C (in well KR-06 at Trölladyngja). Fournier and Potter (1982) reported the maximum quartz temperature to be 261°C. Arnórsson et al. (1983) reported Na/K temperature as 261°C and Arnórsson (1987) reported gas temperature as high as 285°C. A more recent report from temperature logging in well TR-01 shows values up to 360°C at 2300 m depth (ISOR database). Data from some of these reports is used in the present study to assist with creating a geological-geothermal model of the field area.

2. GENERAL GEOLOGY AND GEOTHERMAL ASPECTS OF ICELAND

2.1 Geological Background

Iceland is located at the junction between the Reykjanes Ridge in the south and the Kolbeinsey Ridge in the north. These ridges represent the submarine segments of the Mid-Atlantic Ridge closest to Iceland. The plate boundary in Iceland is expressed on the surface by narrow belts of active faulting and volcanism, often referred to as rift zones, extending from Reykjanes in the southwest across Iceland before plunging back into the Arctic Ocean at Öxarfjördur in the north (Figure 2). Iceland is also associated with a large mantle plume or hot spot, that has slowly migrated eastwards relative to the ridge axis during the last tens of millions years, and it is this combination of the Mid-Atlantic Ridge and the mantle plume that has created Iceland and controls its rifting and volcanic processes. During the last 20 million years the Icelandic rift zones have migrated stepwise eastwards to keep their positions near the surface expression of the plume, leading to a complicated and changing pattern of rift zones and transform fault zones (Saemundsson, 1986). Lying astride the Mid-Atlantic Ridge, Iceland is an integral part of the global mid-oceanic ridge system (Figure 2). It is the largest supra-marine part of the mid-oceanic ridge system. 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, and has been active during the last 20-25 million years, broadly coinciding with the time-span of active volcanism in Iceland. The rift segment along the Reykjanes Peninsula forms a trans-tensional plate boundary, where the activity is displaced towards east. The western part of Iceland, west of the volcanic zones, belongs to the North American plate and the eastern part to the Eurasian plate, with the oldest rocks outcropping in northwest and in eastern Iceland. The rate of spreading is close to 1 cm/year in each direction (DeMetz et al., 1994).

Figure 1: Location of the study area

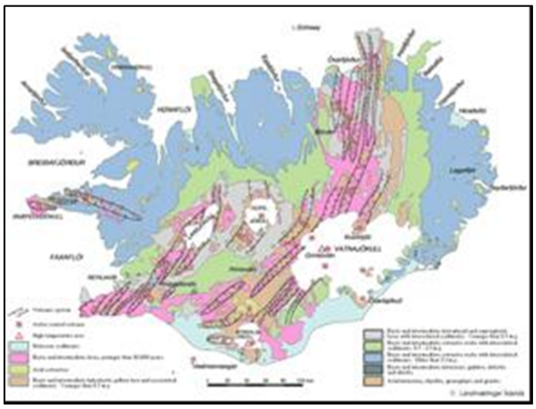

Figure 2: Geological map of Iceland (Jóhannesson and Saemundsson, 1999) showing the three main formations, the oldest Tertiary lava flow formation, the Plio-Pleistocene eruptives influenced by glacial vestiges, and younger formations associated with more recent volcanic activity (< 0.7 My), including Holocene volcanic rocks plus other young formations; the volcanic systems follow the oceanic ridge.

2.2 Geothermal Activity in Iceland

Geothermal activity in Iceland is divided into high temperature and low temperature fields. The high temperature fields are defined by temperatures above 200°C in the uppermost kilometer of the crust and are related to the active volcanic zone along the plate boundary. Geothermal manifestations in high-temperature fields are represented by many fumarolic fields, characterized by the occurrence of fumaroles, mud pools, hot springs and geysers (Figure 3). The low-temperature areas are fracture-dominated and derive their heat from convection within the cooling lithospheric plate. The low-temperature activity is manifested in hot and warm springs, with the highest thermal output along the flanks of the volcanic zones.

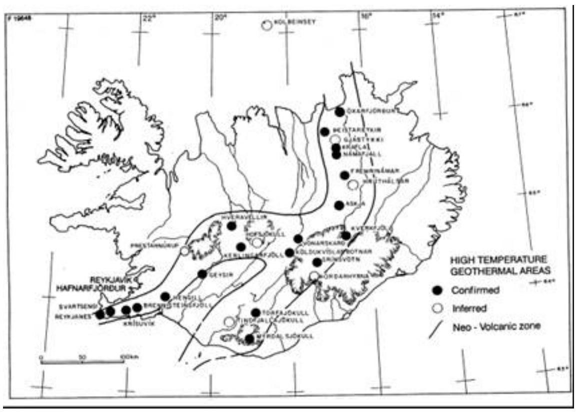

Figure 3: High-temperature geothermal areas in Iceland (Ármannsson et al., 1994)

3. GEOTHERMAL HISTORY OF THE TRÖLLDYNGJA AREA

3.1 Geothermal Exploration of The Trölladyngja-Krýsuvík High-Temperature Area

Several research studies were carried out in the Trölladyngja-Krýsuvík high-temperature area in the 1960s and 1970s (Arnórsson et al., 1975). These included detailed geological, geophysical and geochemical surveys as well as the drilling of some exploration wells in 1971 and 1972. Two of these wells (wells no. 6 and 7), drilled in the study area, have a temperature of about 260°C at 500 m depth and 140°C at ~370 m depth, respectively (Figure 4). Two additional exploration wells (TR-01 and TR-02) were drilled in the Trölladyngja-Sog area between 2002 and 2006, with recorded temperatures shown in Figures 5 and 6.

3.2 Geophysical Studies

Resistivity measurements were done in the area in the 1970s and 1980s (Arnórsson et al., 1975; Flóvenz et al., 1984). A renewed effort was carried out by Eysteinsson et al. (2001). The results are relevant to the present study, for assisting with the geothermal modeling. Figure 7 shows results important for this study. A location map showing the different TEM profiles is seen in Figure 7A. Several cross-sections from this TEM survey cross the study area, two are shown here. Cross-section AV6 (Figure 7B), trends W-E, while SA6 (Figure 7C) trends NWSE. The shape of the high-resistivity core (fossil or active 240°C isotherm) seen in the resistivity cross-sections is, the surface alteration pattern, the tectonic pattern and temperature information from the drill holes within the field area, is used to create a hydrothermal model of the field.

4. GEOLOGICAL MAPPING OF TRÖLLADYNGJA-SOG AREA

Dominant rock units in the Trölladyngja-Sog area are hyaloclastite and postglacial lava flows with subordinate superficial deposits (Jónsson, 1978; Saemundsson and Einarsson, 1980). Figure 8 shows the geological map of the area and Figure 9 a NE-SW cross-section of it.

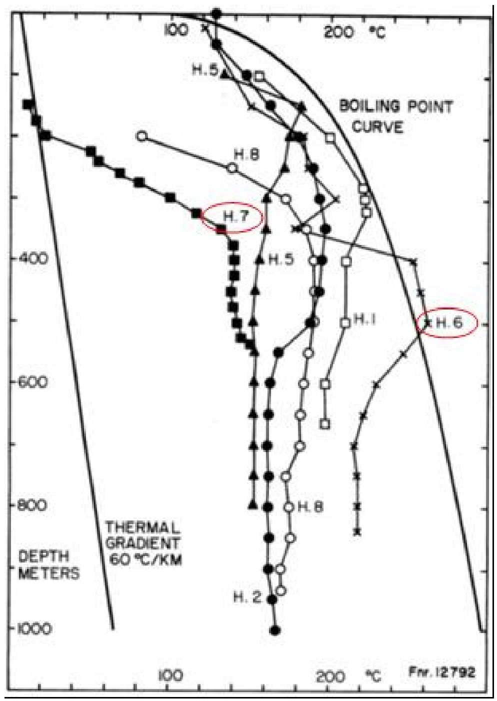

Figure 4: Temperature profiles from deep wells in the Trölladyngja-Krýsuvík high-temperature area, including wells 6 and 7 (Arnórsson, et al., 1975)

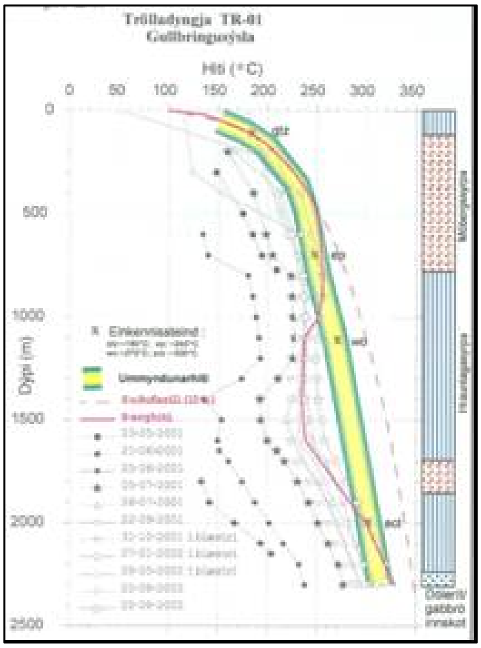

Figure 5: Temperature profiles of well TR-01 in Trölladyngja area (Fridleifsson et. al., 2002)

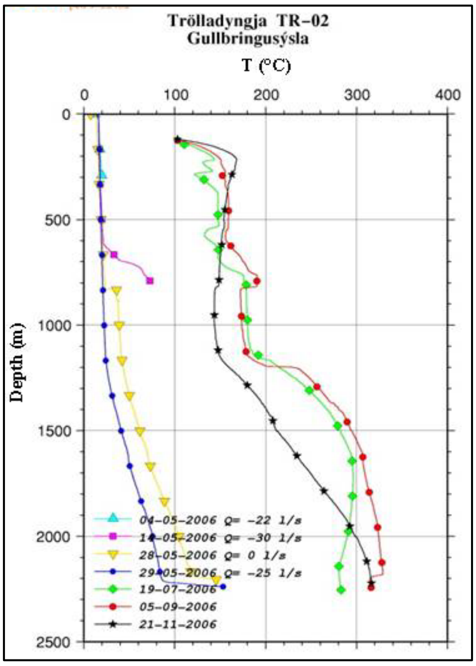

Figure 6: Temperature profiles of well TR-02 in Trölladyngja area (ISOR-database)

4.1 The Bedrock Units

The bedrock of the area consists of NE-SW trending hyaloclastite ridges. They are the most prominent geological feature of the area. They consist of fragmented basalt erupted within the confines of a glacier where the material piled up rather than spread out as basaltic lavas do. The ridges are each several kilometers long, about one kilometer wide and about 200 m high above the surroundings. They consist for the most part of breccia and tuff, collectively called hyaloclastite. The main formation phases of the ridges are well documented (Jones, 1969) including pillow lava, breccia, hyaloclastite tuff and subaerial lava. All these rock facies occur in the study area, the breccia and tuff facies being dominant.

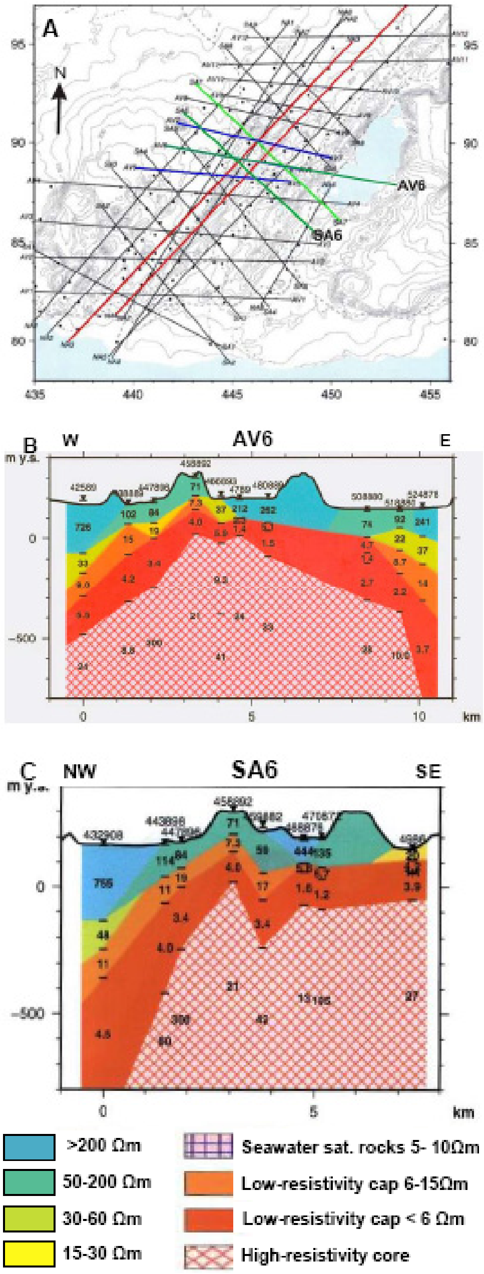

Figure 7: Resistivity measurements in Trölladyngja-Sog area, a) Location map showing the distribution of the TEM soundings; b) Cross-section AV6, with a W-E trend through the Trölladyngja-Sog area; and c) Cross-section SA6 trending NW-SE; the cross-section show resistivity structures associated with the geothermal upflow

The pillow lava represents the initial effusive phase under deep melt water and it tends to pile up around the volcanic orifice. The pillow breccia phase then follows, consisting primarily of porous lava lumps and only subordinate dense pillow fragments. As the eruption continues in progressively shallower water, conditions become more explosive in nature (phreatic activity), evidenced by the formation of a bedded tuff. As the volcanic piles emerge above the melt-water level, the subaqueous eruption pattern changes to a subaerial pattern with the eruption of pyroclastics and lava flows which cap the hyaloclastite ridge or the table mountain. In the Trölladyngja-Sog area, ridges of hyaloclastite tuffs and associated breccias dominate and pillow lava is subordinate. In one case within the Graenadyngja ridge, a poorly developed lava cap is seen, suggesting the emergence above the confined water level within the surrounding glacier.

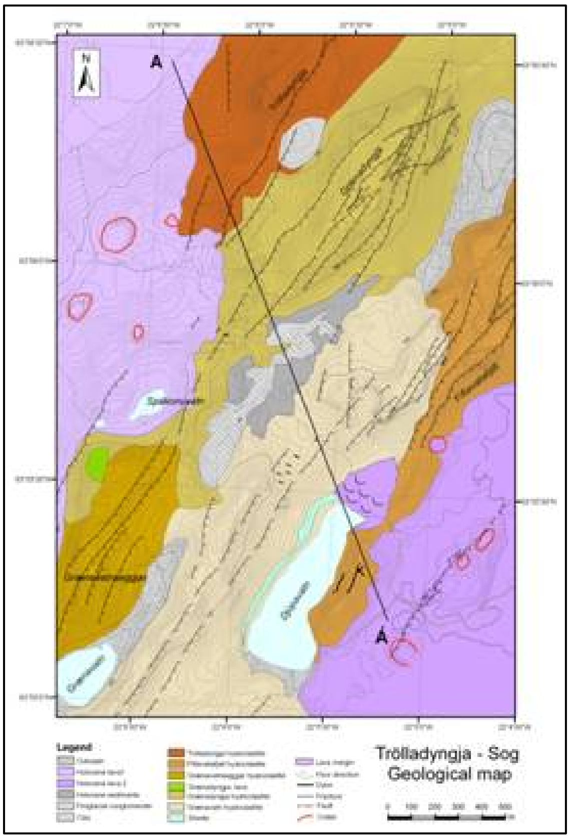

Figure 8: Geological map of the study area

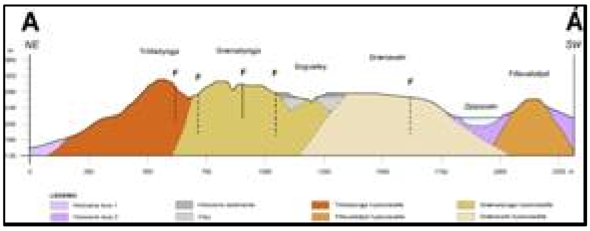

Figure 9: Geological cross-section of the study area; location is shown in Figure 8

Five eruptive hyaloclastite units were mapped on the basis of rock type, superposition criteria and morphology (Figure 8). Their true age is unknown. The only useful criterion for age estimate is a different degree of smoothing by erosion, the ridges being serrated and steep when young. It is suggested here as a working hypothesis that the ridges were erupted during the second last (Saalian) and last (Weischelian) glacial periods. No interglacial lavas are known to support this, however. It would mean that the oldest ridges might be somewhere about 150,000~200,000 years.

The oldest bedrock units are the hyaloclastite ridges of Units 1 (Graenavatn) and 2 (Graenadyngja). They are of rather smooth morphology and quite deep lows have been eroded across them east and west of Sog. The Sog-valley, a 1 km long depression, separates the two ridges. It formed mainly as a result of the ridges being piled up on both sides. The sediments of the Sog valley indicate that the narrow outlet gorge leading west from Sog was eroded in the Holocene.

Unit 1 – Graenavatn: The Graenavatn ridge is low in its north-eastern part growing higher to the southwest where it is overlain by the flank of the younger Unit 4 ridge, the contact being very irregular. On the west side a yellowish silty sediment separates between the Graenavatn ridge and the overlying Unit 2 (Graenadyngja). The saddle between Sog and Djúpavatn is eroded into the Graenavatn ridge. There a high degree of alteration and a multitude of dykes and veins of basalt are exposed at the ridge axis. The ridge continues to the southwest and passes east of Lake Graenavatn as a fairly steep and faulted structure. Petrographically the rock of the Graenavatn ridge is aphyric basalt, mostly a breccia, rich in matrix tuff. The lithics occur both as porous lumps and as dense fragments always very fine grained. Olivine is very minor or absent. The rock might thus be classified as a tholeiite.

Unit 2 – Graenadyngja: Graenadyngja forms a very prominent ridge north of Sog. It is lowest at Sog and a gully has been eroded through it there draining the Sog-valley towards west. It gains in height again southwest of the Sog entrance and extends to Lake Spákonuvatn. There it is overlain by the hyaloclastite of Unit 3 (Graenavatnseggjar). Occurrences of yellowish, silty sediment mark the separation between the two units. Breccia, rich in tuff matrix, dominates over bedded hyaloclastite tuff facies. Lithics are aphyric, mostly porous, primary lava lumps. Broken angular fragments of larger lava pods or pillows occur also. The lithics are of aphyric basalt. Graenadyngja has all four main facies of a hyaloclastite ridge exposed as well as the transition zone from subglacial to subaerial eruption. A small outcrop of pillow lava is found in the deepest part of the outflow gorge near the median zone of the ridge. The breccia and tuff facies forms the main bulk of the ridge, well exposed on the upper slopes and variously intertwined. Dykes and veins occur in the lowest part of the breccia near the axis of the ridge. Locally piles of bedded tuff are found on the upper slopes of the ridge. A second set of dykes and sheets are found below the crest on the southwest-side of the ridge, also of aphyric basalt. They are followed upwards by reddish scoria and remnants of a lava cover at the crest, indicating transition to supraglacial eruption. A lava remnant is found also east of Spákonuvatn overlapped from the east by Unit 3 hyaloclastite. Graenadyngja is considered an important unit concerning the geothermal system. The most intense and varied alteration occur there as well as the only active fumaroles of the Sog area. The name Graenadyngja refers to the green colour of vegetation in contrast to the other ridges which are mostly barren. Although it is mostly of low grade it has reduced the permeability of the hyaloclastite to such a degree that rain water does not soak into the ground immediately but is retained partly in the surface layers.

Unit 3 – Eggjar: The Eggjar ridge (shortening for Graenavatnseggjar) forms the morphological continuation of Graenadyngja to the southwest. It is a separate unit, however, overlying it. It differs slightly in petrography from Graenadyngja, the rock being sparsely porphyritic in plagioclase and olivine, particularly the lower part of it. A sediment separating the two units was mentioned and also the superposition of Eggjar-hyaloclastite on the lava cover of Graenadyngja. Only the north-eastern most part of the Eggjar ridge extends into the study area west of southern Sog. It is composed there mainly of hyaloclastite tuff, the breccia facies becoming dominant further southwest as the ridge gains in volume and height. The hyaloclastite of Eggjar looks fresh apart from palagonitization which is ubiquitous in these rocks and unrelated to geothermal activity. However, nearest to Sog smectite may have formed more abundantly, as can be judged from the darker colour and softer feel under the hammer.

Unit 4 – Fíflavallafjall: This unit crops out in the eastern part of the study area. It overlies Unit 1 in the west and south and is bordered on the east by Holocene lavas northeast of Lake Djúpavatn. Unit 4 rocks are sparsely porphyritic in plagioclase with phenocrysts up to 4-6 mm. Fíflavallafjall forms a very prominent ridge northeast of the study area but it is meager where underlain by Unit 1 which gains in height south-westwards. The contact between the two units is sharp but very irregular due to the uneven underlying surface of Unit 1. The rock of Unit 4 is mostly breccia, rich in tuff matrix and it is fresh apart from palagonitization. Lithics are both primary lava lumps and angular fragments of broken lava inclusions. The difference in alteration between Unit 1 and Unit 4 is abrupt, indicating cooling of the geothermal system before Unit 4 was erupted.

Unit 5 – Trölladyngja: This unit crops out at the northern margin of the study area forming the Trölladyngja mountain, a NE-SW trending ridge, 2.5 km long and 200 m high. It does not reach south of the Sog stream. The rock is highly porphyritic in plagioclase, the phenocrysts being mostly 0.4-0.7mm in size. Trölladyngja is made up mainly of breccia and tuff which is yellowish brown and fresh apart from palagonitization. Lava sheets occur intercalated with tuff in the crestal part of the ridge indicating intermittent subaerial phases of the eruption. Geothermal alteration has not affected the Trölladyngja ridge in the study area except in the extreme SW. There it is of the low-grade type. That part of the geothermal system had cooled down before covering by a Holocene welded scoria layer.

Holocene lavas and pyroclastics: Unit 4 (Fíflavallafjall) and Unit 5 (Trölladyngja) are considered to be youngest of the hyaloclastite ridges, probably late Weischelian in age. This is concluded from the fact that Holocene eruptive fissures follow the trace of those two ridges but are absent from the others in between, except marginal to one of them. It is thus considered that the Holocene volcanic activity is a continuation of a pattern that started in late Pleistocene time.

The lavas which are basaltic were excluded from this study apart from the marginal part of them where they or cogenetic pyroclastic material bank against the hyaloclastite rock. The youngest flow was erupted east and northeast of the area in the 12^{th} century (Jóhannesson and Einarsson, 1988) whereas the youngest flow in the west was erupted about 2000 years ago (Saemundsson, pers. comm.). In the west the Holocene eruptives are a layer of loose scoria covering the western slope of Unit 2 (Graenadyngja) south of the stream from Sog. To the north of the stream the scoria is welded, forming a coherent sheet draping the lower slopes of the Graenadyngja and Trölladyngja ridges. The margins of the scoria deposit were tracked by GPS from Trölladyngja in the north to south of Spákonuvatn (Figure 8). In the east of the study area lava was erupted from a fissure east and northeast of Lake Djúpavatn. Flows and spatter from it drape the lowest part of the Graenavatn ridge and a flow covers the outwash flat northeast of the Lake (Jónsson, 1978).

4.2 Dykes, Sheets and Plugs

Basaltic dykes and sheets are common in the hyaloclastite rocks. Most of them are of the same rock type as the hyaloclastite into which they intruded and are thus considered co-intruded with formation of the ridges. Dyke rocks of a different type occur also. Such dykes are distinctive in the case of olivine rich rock. They were found among the intrusions into the axis of the Graenadyngja ridge west of Sog-valley. The thickness of the dykes rarely exceeds 1 m. The thinnest of them are just veins, a few tens of centimeters thick with a rather irregular trend. The dykes strike N20°E, N16°E and N70°E in the Fíflavallafjall ridge. The dip of these dykes ranges from about 45-60° to vertical. Some of the dykes have a persistent northeasterly strike for several tens to over 100 m. Dykes striking north-south also occur. Some of the dykes were considered to be feeder dykes of the breccia or its lava cover. They are the longest and occur in the crestal area of the ridges. Such were seen in Fíflavallafjall, Graenadyngja and Eggjar. Examples of plugs or larger bodies of lithic basalts were found in the crestal area of Unit 1, 2 and 4. The largest of these occurs in Unit 1 northeast of Graenavatn. It is about 20-30 m in diameter, elongated NE-SW. Intrusive sheets are most abundant high up in Graenadyngja and Eggjar. They are near horizontal and commonly 1-2 m thick. They are regarded as off-shots from the axial feeder system, probably contributing to lateral growth of the breccia pile. The intrusive rocks were not mapped in detail and only a few are shown on the map (Figure 8).

4.3 Sog Sediment and Its Deposition

Holocene sediments were not included in this study. They are mainly talus and outwash infills in depressions between the ridges. The main depressions of that kind are between the Graenadyngja/Eggjar ridges in the west and The Fíflavallafjall/Graenavatn ridges in the east. The Sog-valley plays here a special role being filled mostly with clay (Figure 10). A conglomerate was deposited locally between Trölladyngja and Graenadyngja. The sediment occurrences are shown on the map (Figure 8).

4.4 Tectonics and Structure

The tectonics of the study area is controlled by the regional tectonics of the Reykjanes peninsula and more specifically by the western volcano-tectonic range of the Krýsuvík volcanic centre, called Vesturháls. The main structural feature of NE-SW trending ridges in Vesturháls is bordered on both sides by a number of Holocene crater rows which run parallel. Assuming a dyke feeder underneath the crests of the hyaloclastite ridges, these together form 1.5-2 km broad system of volcanic fissures. Numerous NE-SW trending normal faults were mapped in the study area. Their throws are commonly in the range of 10-20 m. They define a graben structure along the axis of Graenadyngja. Some of the faults are seen to continue into the surrounding lavas with lesser throws. Large faults (Figure 11) run along the top of the Eggjar and Graenadyngja ridges forming a jumble of blocks and joints splaying off from the main trend. At Graenadyngja several 100 m long splays trend 50°E across the crestal region. A north-south fault with insignificant throw was found in the northern part of the Graenavatn ridge (Unit 1). It was the only one found in the area that might correspond to the transcurrent strike slip system, but striations or indication of lateral shift was not observed.

5. GEOTHERMAL MAPPING OF THE TRÖLLADYNGJA-SOG AREA

The study area is a part of one of the active volcanic and geothermal areas of the Reykjanes Peninsula. Geothermal manifestations include fumaroles, mud pools, warm springs and warm grounds. Figure 12 shows a map of geothermal manifestations and alteration in the study area.

Classification into high-, medium- and low-grade alteration intensities has been deployed. Intensity here is a measure of how completely a rock has been changed into clay and towards chlorite before exhumed by erosion. A rock completely changed into clay is highly altered, that containing some clay is medium altered, and that containing traces of clay is slightly altered. Appendix I shows XRD analyses of clay samples from the Sog area.

Figure 10: Holocene sediments (red polygons) and grayish to bluish alteration (yellow polygon) around the Sog valley

Figure 11: NE-SW trending fault in Graenadyngja hyaloclastite (unit 2)

5.1 Geothermal Manifestations

Thermal activity occurs sporadically as fumaroles and hot ground on the western slope of Vesturháls and immediately west of it. The main activity is concentrated in an east west zone extending westwards from Sog. Our study area involves the easternmost part of this zone with the Sog valley down to Djúpavatn adjoining it as an extinct continuation. A main objective of the study was mapping, classifying and interpreting the geothermal features of the area. The geothermal manifestations included warm springs, fumaroles and hot ground and related active alteration as well as cold, areal alteration and its zonation from high- to low-temperature conditions. A structural control of the thermal features was looked for. The findings are shown on the geothermal map (Figure 12).

5.2 Fumaroles, Warm Springs and Hot Ground

Two active fumaroles occur in the study area. The main one is a 30 m long row of fumaroles and boiling mud pots trending NE-SW just south of the entrance to the Sog-gully. Hot ground is found 200 m further southwest, also a linear feature with temperatures of 60-70°C where hottest. The fumarole and hot ground are located within a layer of scoria erupted from a crater row about 100 m to the west. Connection with a southeast-throwing fault is clear. It is visible on the hill northeast of Spákonuvatn, but less obvious at the fumarole.

The second fumarole is a single feature in the south wall of the Sog gully. It forms a clayey mound of bright colours, about 4 m in diameter (Figure 13). It emits steam and gas and droplets of water at boiling temperature. There are precipitates of white and yellow efflorescence sulphate minerals of bitter taste. These are soluble and disappear in rainy periods. A prominent, southeast-throwing fault in the western slope of Graenadyngja runs some 30 m east of the fumarole. A connection is thought likely.

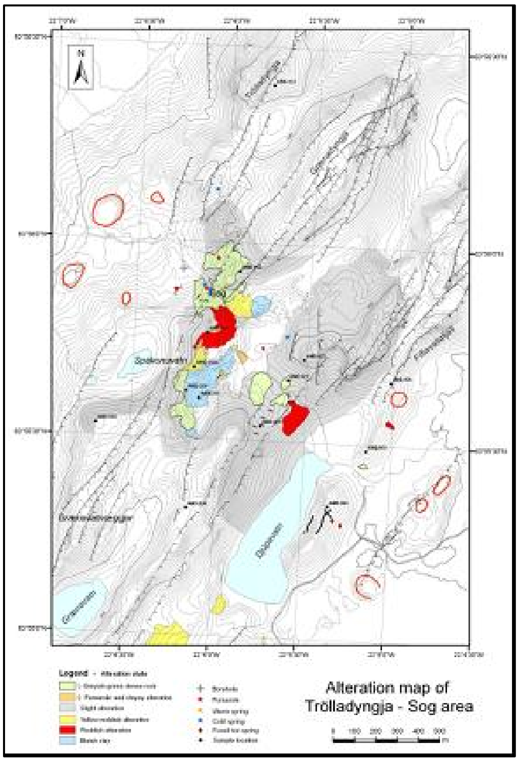

Figure 12: Geothermal map of the study area showing the relationship between the distribution of hydrothermal alteration zones, geothermal manifestations and the tectonic settings

Figure 13: An active fumarole in the Sog area

A few lukewarm springs occur in steep stream cuts in the south wall of the Sog gorge, just east of the fumarole. Their temperature was 14-16°C. They emerge from a thin layer of scree and are considered local groundwater, heated from a hot or warm body of rock which must exist underground in the Sog area. Their occurrence is probably related also to the same fault as the fumarole.

5.3 Extinct Holocene Thermal Features

An extinct hydrothermal explosion crater is found southeast of the Sog-valley. It is elliptical in shape, about 50 m long, elongated NE-SW. It is open to the northeast. The bottom is covered by a bog and mud washed in from the sides. The inward slope of the crater consists of clay where seen underneath a vegetation cover. A small deposit of sinter overlies the clay at the lowest north-eastern rim. X-ray and hydrochloric acid test showed it to be travertine. The crater is well preserved and is doubtless of Holocene age. It is related to a NW-throwing fault clearly to be seen northeast of Sog but in the valley it is smoothed out by its sediment fill. Remnants of a second Holocene fumarole were found on the same fault trend 250 m further northeast. This is a small outcrop of reddish clay, traceable for some 25 m from northeast to southwest. It disappears beneath a thin soil cover to the northeast, formed after the activity died out. No traces of former steam outlets or mud pools were seen.

5.4 Alteration

There are three types of geothermal alteration to be seen at the surface in the area:

1. One type is a zoned subsurface alteration now exposed due to erosion which has removed overlying rocks to a considerable degree;

2. A second type consists of plastic clay. It is thought to be of shallow level subsurface origin;

3. The third type of alteration occurs around active fumaroles and hot ground and such that have cooled down. It is typical of surface and near-surface conditions.

The different types and grades of alteration are defined on the basis of temperature dependant alteration minerals and intensity.

The main constituent of the hyaloclastite rocks of the area is basaltic glass which is unstable in the presence of water, also at ambient temperature. A characteristic alteration of the glass is palagonitization, a mechanism involving leaching and cementing of the glassy rock and oxidation of ferrous iron to ferric iron (Jakobsson, 1979). This causes the typical brownish colour of these rocks, in fact that of whole mountains.

5.4.1 Subsurface Deep to Shallow Level Alteration

Altered rocks exhumed by erosion are widespread in the basement rocks of the Sog valley and around it. The alteration was divided into three types according to the intensity of the alteration:

- The highest grade of alteration is characterized by the hyaloclastite rock attaining a fairly tough habit (a hammer is needed to break it) and a greenish grey colour. X-ray analyses showed it to consist of mixed-layer smectite-chlorite. This alteration facies constitutes a part of the ridges between the entrance of Sog-valley in the west (Graenadyngja) and the Graenavatn-ridge in the east to where it slopes down to Djúpavatn (Figure 8). It coincides with a multitude of irregular minor intrusions of basalt in the median zone of both ridges. Crystals of quartz occur in vugs. In the high temperature systems of Iceland, quartz begins to form as temperatures approach 200°C (Fridleifsson, pers. com.). Accordingly, finding these together with the presence of mixed-layer clays is suggestive of formation temperatures close to or above 200°C. Mixed-layered clays of smectite-chlorite suggest 200-240°C formation temperature (Kristmannsdóttir, 1979) (Figure 14 and Figure 1 in Appendix I). Some quartz crystals occur within these sites of alteration. Figures 1-3 in Appendix I show examples of XRD analyses of high-grade alteration.

- Medium-grade alteration follows upwards and sideways of the high grade alteration. Here, the hyaloclastite rock is blackish to dark brown. This is a type where the glass of the rock has been altered to smectite, as is well known from elsewhere in Iceland (Saemundsson, pers. comm.). An X-ray analysis was not done in our case.

Low-grade alteration follows above the medium-grade alteration with less altered hyaloclastite rock. Here the constituents of the original rock are well preserved but infillings of zeolites and calcite occur. Of zeolites, chabazite and thomsonite were identified (by hand lens and in thin section) possibly scolecite also occurs. Thin sections show a partial alteration of the larger glass grains to brownish palagonite and smectite. The low grade alteration is widespread involving a large part of Graenadyngja and most of the Graenavatn ridge northeast and southwest of Sog. Figures 14 and 15 show examples of low-grade alteration.

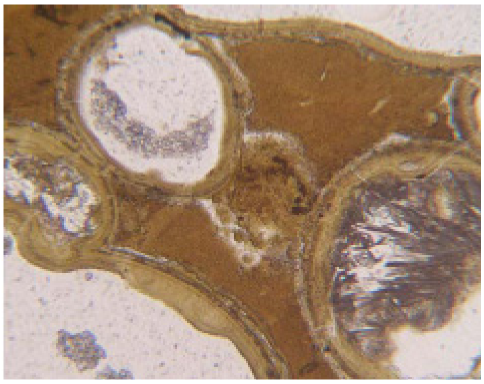

Figure 14: Alteration bands around volcanic glass fragments under PPL (unit1)

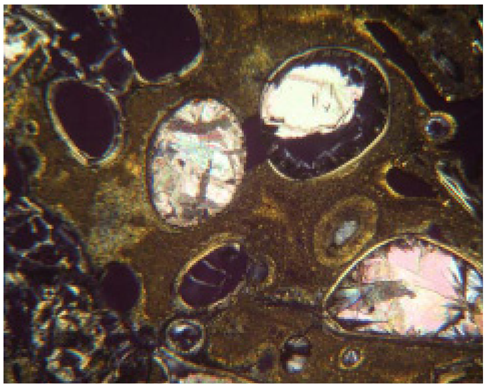

Figure 15: Radial zeolite under XPl within the groundmass of hydrothermally altered clays in unit 4 (Sample AMD.003)

5.4.2 Near Surface Alteration

The second type of alteration includes soft, plastic clays exposed in the lowest eastern slope of the Graenadyngja ridge down to the Sog-valley, banking against and partly overlying the high grade mixed-layer greenish facies. Smectite is the only clay found within this alteration zone. Although, nothing is left of the original mineral assemblage of the rock, layering is distinct, indicating that the original rock was a bedded hyaloclastite tuff. The clay shows a variety of light colours near the surface but when dug into the colour is uniformly bluish gray underneath. The surface colouring thus must be due to oxidation by surface water. The clay facies rock is intersected by up to 20 cm thick veins of aragonite trending irregularly. They probably indicate flow paths from the time of alteration. In the west and south the plastic clay facies is seen to grade upwards into medium- to low-grade facies alteration and locally the boundary between the clay and slightly altered rock is sharp.

An interesting relationship can be interpreted from the lack of mixed-layer clays within the highly altered sedimentary basin at about the same elevation as the adjacent hyaloclastite ridges containing mixed-layer clays (Fridleifsson, pers. comm.). The most likely cause for this difference suggests there may be an age difference in the two types of clays, the mixed-layer clays being formed earlier, during a peak in the glacial burden of the field (either of Saalian or Weischelian age), whereas the clays within the sedimentary basin may have formed during a shallower water or ice-free period in late Saalian or late Weischelian time. More detailed sampling and XRD analyses of the lowest outcrops within the sediment should be undertaken before too rigid an interpretation of this hydrothermal condition is suggested.

In the main tributary of the Sog-stream coming from north, the plastic clay is overlain by a less altered conglomerate devoid of vein fillings.

5.4.3 Surface Alteration

Surface alteration occurs around two active fumaroles and mud pots. Closest to them the ground has been altered to light-coloured clay with streaks of mostly reddish brown or blackish colouring. The clay was not determined by X-ray but is presumed to be kaolinite as is the rule in the acid water of sulphurous springs. Disseminated pyrite and sulphurous efflorescence minerals occur. The drill pad of TR-2 is just below the main fumarole. It was cut into Holocene talus, altered to red-stained clay.

Patches of whitish clay, probably kaolinite, are found locally along the trace of a NE-SW fault in eastern Sog. A hydrothermal explosion crater in the southwest of the fault is a clear sign of activity in the Holocene but the feature is cold now. The crater is surrounded by the same type of clay indicating former fumarolic activity.

5.4.4 Interpretation of Alteration Zoning

Interpretation of the alteration sequence in Sog is rather straight forward as regards the high- to low-grade facies of the main body of the rock sequence. It was all brought about under alkaline conditions well down in a geothermal system. The mixed-layer alteration containing quartz would indicate a formation temperature of about 200°C. This would have required about 18-20 bar pressure according to the boiling point curve. However, it is unlikely that erosion amounts to 200 m or more of rock in this area so the confining agent to make such pressure conditions possible must have been ice during glacial time. Erosion followed, leveling the two ridges west and east of the Sog-valley to form the lows between the Sog-entrance and Djúpavatn. The lowest grade alteration of palagonitization some smectite and zeolites would suggest a temperature of about 40-60°C (Fridleifsson, pers. comm.).

The plastic clay facies is more difficult to interpret. It seems to have formed under somewhat different conditions from those which prevailed during the zonation type alteration. The clay being smectite, an alkaline and probably a near-surface environment is needed, however. It is tentatively suggested that this situation of a lower pressure level came about after reduction in size of the thermal area and after thinning or disappearance of the ice. The reduction in areal extent of the thermal field to persist only in the Sog Valley might have been a corollary of the nearby large hydro-volcanic explosion craters of Djúpavatn and Spákonuvatn which would have drained the upper part of the geothermal system thus seriously affecting surface activity. Conditions for eruptions of this kind come about in a boiling geothermal reservoir if the hydrostatic pressure is suddenly released as can happen during a rapid glacial melting (Saemundsson, 1991).

5.4.5 Comparison of Alteration Facies to Resistivity and Borehole Temperatures

Resistivity cross-section AV6 (Figure 7B), trending W-E, shows a relatively sharp rise in a low resistivity layer (1.5-8 Ωm) as the Trölladyngja high-temperature field is approached from the west. Below the low-resistivity cap, a high-resistivity core (cross-hatched) is found to exist with resistivity values of 30-300 Ωm (Eysteinsson, 2001). Comparison studies between borehole alteration data and the resistivity data show a correlation between the resistivity structures and the mineral alteration zones. The high-resistivity core has been found to correspond to chlorite alteration, roughly delineating a fossil (or active) isotherm of 240°C.

The other cross-section, SA6 (Figure 7C), trends NW-SE. It shows a resistive core enveloped by a low-resistivity layer (dark/red), with the low-resistivity cap rising from northeast to southwest, reaching the highest elevation at site no. 458892 (200 m a.s.l.). This point seems to be located below the most intensive surface alteration in the Sog area. The boundary between the two marks the transition from dominantly clays (smectite, mixed-layer clays) to chlorite and epidote. In terms of temperature this means about 240°C. A geothermal reservoir near boiling would require a water depth of at least 400 m to get that temperature. The present surface is only at about 150 m above the smectite / mixed layer transition. This supports the idea of a confining agent such as ice to provide conditions for the necessary hydrostatic pressure for 240°C at such shallow level.

Figures 4 and 6 show temperature logs from borehole TR-2 west of Sog and H-7 east of Djúpavatn. Alteration zoning was studied only in the case of TR-2. The transition from smectite to the mixed layer facies correlates tolerably well with the observed alteration at western Sog (Figure 12), suggesting a much higher hydrostatic pressure to attain the necessary temperature than is possible at the present time. From the diagram it is also evident that the geothermal system has cooled to a depth of some 1200 m since the time of peak thermal activity.

6. CONCLUSIONS

The Sog area is located within the Krýsuvík-Trölladyngja volcanic system, which is one of four main volcanic systems within the Reykjanes peninsula. The study area is covered by upper Pleistocene and Holocene volcanic rocks which consist of at least two cycles of interglacial-glacial sequences. The interglacial periods are characterized by the formation of basaltic lavas and sediments, while the glacial periods are characterized by the formation of five units of hyaloclastite rocks that have different lithofacies such as pillow lava, pillow breccias and tuff, and vary between porphyritic and aphyric.

Several normal faults and fissures, trending N20°-40°E, occur within the field area, in addition to minor fractures. Most dykes crossing the study area strike in a NE-SW direction.

Three types of alteration were mapped. A zoned alteration reaching chlorite-smectite facies is most widespread. It formed at a maximum temperature of about 200°C. A near-surface alteration to soft smectite clay affected later deposited tuffs in the closed basin of Sog. Two fumaroles occur within the field area with local alteration to kaolinite around them. The hydrothermal activity seems to have decreased considerably since Weischelian or Saalian time. Present day fumarolic activity as well as recently active fumarole sites along some of the faults are relatively subordinate to what was in the past. Nevertheless, deep drill holes within the Trölladyngja field show temperatures of up to 360°C at 2300 m depth. So the question remains as to whether a useable geothermal resource still exists within the field.

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APPENDIX I: XRD ANALYSIS OF SAMPLES FROM THE SOG AREA

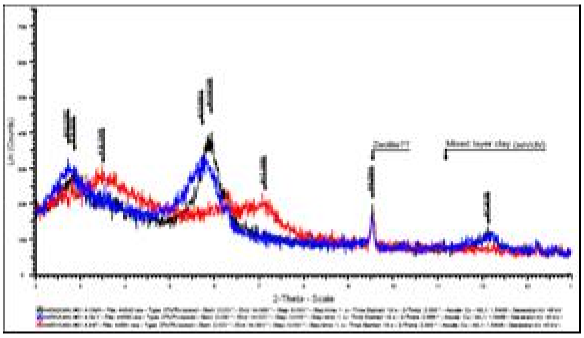

Figure 1: XRD analysis of sample AMD.021

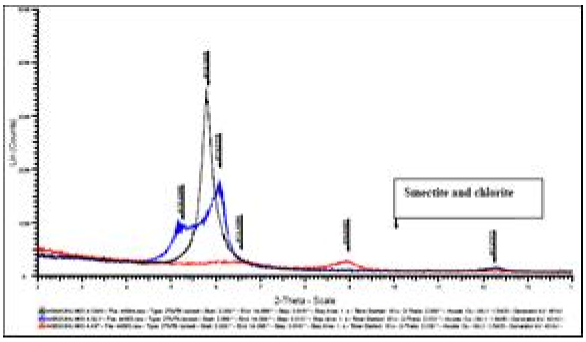

Figure 2: XRD analysis of sample AMD.028

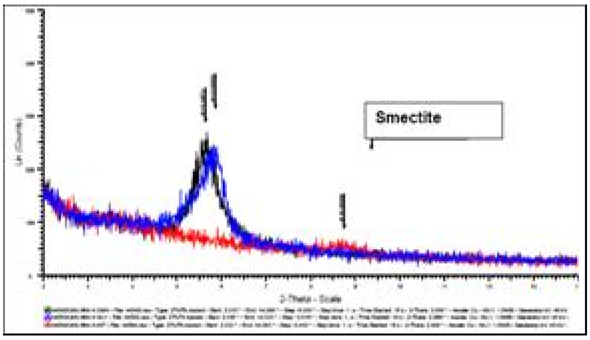

Figure 3: XRD analysis of sample AMD.029

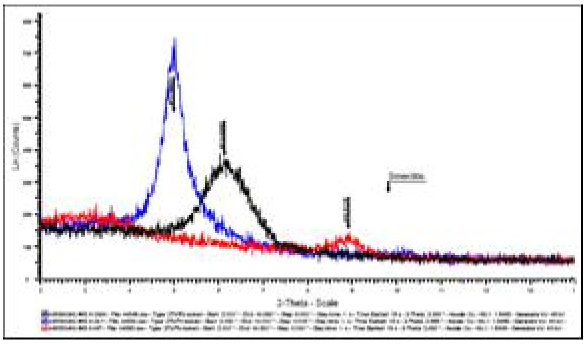

Figure 4: XRD analysis of sample AMD.030a

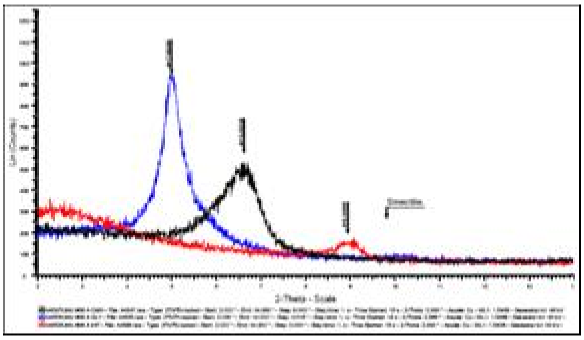

Figure 5: XRD analysis of sample AMD.030b

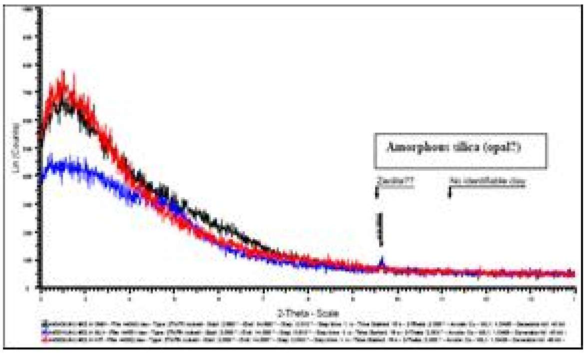

Figure 6: XRD analysis of sample AMD.031