HYDROTHERMAL ALTERATION IN BOREHOLE RV-40, REYKJAVIK, ICELAND

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#### ABSTRACT

A study is made of the hydrothermal alteration mineralogy found in well RV-40, a 2191 m deep well in the Laugarnes field, a part of the Reykjavik low-temperature area.

The Quaternary (Plio-Pleistocene) strata which the drillhole dissects consists of fine to coarse-grained basaltic lavas, hyaloclastites, dolerite intrusions, basaltic andesites and basaltic breccias.

The hydrothermal mineralogical data is complex and involves both minerals which are associated with low- as well as high-temperature environments. A comprehensive study of cross-cutting vein relationships and infilling sequences reveals that the strata have suffered at least three hydrothermal events.

The first hydrothermal event, which involved low-temperature conditions, is evidenced by jasper, iron oxides, pyrite, smectite and swelling chlorite.

The second hydrothermal event, by far the most conspicuous, is evidenced by chlorite, epidote, prehnite, albite, garnet and ferrosalite. This event can further be divided into three sub-events.

The third hydrothermal event implies a return of lowtemperature conditions, and is evidenced by zeolites, clay minerals and anhydrite. It is believed to be associated with the prevailing thermal conditions of the low-temperature area in Reykjavik.



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#### 1 INTRODUCTION

#### 1.1 Scope of work

This report is a part of the author's training at the UNU Geothermal Training Programme in Iceland. The 24 weeks of the training programme were composed of: (1) General lectures on geothermal sciences (4 weeks); (2) Field excursions to the main geothermal fields in Iceland (2 weeks); (3) Borehole geology specialized course (18 weeks).

The 18 weeks of training in borehole geology included: a) A study of 74 thin sections from borehole RV-40 in the Reykjavik low-temperature area; b) An XRD-study of mineral separates from borehole RV-40; c) An electron-microprobe study of selected minerals; d) A training in cutting analysis at a drill rig in the Nesjavellir high-temperature field (1 week); e) A field excursion to an extinct and deeply eroded high-temperature area in the Geitafell Central Volcano, SE-Iceland (1 week); f) A field excercise in mapping of mineral veins in the Vesturhorn intrusion, SE-Iceland (1 week); g) Writing of this report (6 weeks).

This report chiefly describes the study of the drill cuttings from borehole RV-40 in Reykjavik, which were studied with respect to the petrography, the mineralogy, and the hydrothermal alteration history.

# 1.2 The Reykjavik low-temperature area

The Reykjavik low-temperature area in SW-Iceland rests within rocks of Quaternary age (Fig. 1-a). The geothermal area is separated into 3 hydrothermal systems, i.e. the Laugarnes-,the Ellidaar-, and the Seltjarnarnes fields (Fig. 1-b). The Laugarnes field is located in the central part of Reykjavik.

Drilling in the Laugarnes area started as early as 1928. During 1928-1930, 14 shallow drillholes were sunk into the Thvottalaugar field to a maxium depth of 246 m. The total output of these wells was 15-20 1/s of 90°C hot water, which was used for domestic heating. Prior to this drilling the Thvottalaugar hot springs yielded some 5-10 1/s of 88°C hot water, which was used for cloth-washing by the local people. After 1950, several deeper wells were drilled in the neighbourhood, while an extensive deep-drilling activity took place between 1959-1963, when 22 wells were drilled in the Laugarnes field. These wells, however, are located several hundred meter west of the Thvottalaugar hot spring field, close to which the newest drillhole, RV-40, is located.

The geothermal field is covered by approximately 30 m thick coarse-grained olivine-tholeite lava flows of late Pleistocene age, resting on interglacial sediments, up to 60 m thick. Below this cover, the stratigraphy is characterized by basalt lava flows intercalated by volcanic hyaloclastites and morainic sediments (Thorsteinsson and Eliasson, 1970; Tomasson et al., 1975).

Kristmannsdottir and Tomasson (1978) reported that the zeolite distribution within all the geothermal fields in Reykjavik closely related to the prevailing rock temperatures. With increasing depth and temperature the zeolite zones in Reykjavik are indexed by the following zeolites:

chabasite; mesolite/scolecite; stilbite; laumontite

These zeolite zones are superimposed upon a hydrothermal alteration related to a former high-temperature hydrothermal system, of which both epidote and prehnite are among the characteristic minerals. Other minerals like clay minerals, for instance, are either related to this old high-temperature hydrothermal system, or formed by the more recent low-temperature geothermal activity.

#### 2 STRATIGRAPHY

#### 2.1 The drilling history

Well RV-40 was drilled from February 20th to the 26th of March, 1984. The drillhole is 2191 m depth, with a 9 5/8" production casing down to 295 m depth. Minor losses of circulating cooling water was detected during drilling; approximately 2 1/s at 430 m depth, and approximately 1 1/s at 1350 m depth. After series of pressure build-up tests, with and without the use of injection packers, the well's transmissivity improved - the apparent well yield being 10-12 1/s with about 70 m drawdown. The induced aquifers appear to be sited at 340 m, 1060 m and 1550 m depth (Tomasson et al., 1984)

#### 2.2 The lithology of RV-40

Due to the exclusive use of rotary drill bits only rockcuttings are available from the well. The cutting samples were collected at 2 m interval, and then studied under a stereo-microscope. A preliminary, but detailed stratigraphic profile of drillhole RV-40 was published in April 1984(Tulinius et al., 1984; Tomasson et al., 1984). This stratigraphic profile is shown in Fig. 2. The following description of the stratigraphy is a shortened translation from these preliminary reports.

0-33 m depth. Glacial sediments occur in the uppermost part of the drillhole. The sediments are layered and range in grain size from silt to gravels.

33-42 m depth. Fresh fine grained tholeiitic basalt.

42-105 m depth. Tholeiitic lavas of variable porosity. The more porous ones are typically more extensively altered. Thin sediments intervene these lavas.

105-226 m depth. The basaltic lavas in this depth interval vary in modal composition from hyalocrystalline to holocrystalline rocks and in granularity from fine to coarse grained basalts. Often the denser and coarsergrained basalts have relatively fresh appearance and may represent intrusions. The same applies to the denser part of the finer-grained basalts. Intrusive rocks thus appear to dominate this part of the well.

226-300 m depth. Dolerite intrusions. The extent of hydrothermal alteration varies. These rocks are probably fractured to some extent judging from the increased amount of secondary mineral precipitates in some of the samples.

300-460 m depth. An intrusion ranging in grain size from dolerite to gabbro. The extent of alteration varies between the samples, but where it is most intense the primary pyroxene has almost disappeared. In the lower part of this depth interval several finer-grained basalt layers appear.

460-615 m depth. Altered hyaloclastite intercalated by a number of basaltic layers which could mostly be of an intrusive nature. Hydrothermal alteration is widespread in the hyaloclastite and the more vesicular basalt. The earliest finding of epidote is at 540 m depth, but from 580 m downwards epidote occurs in all samples. The percentage of epidote in samples may be high, partly reflecting the palaeopermeability, as epidote is a common vein and amygdale mineral.

615-755 m depth. Medium grained basaltic lavas, interbedded by thick hyaloclastite beds. Some of the lavas are quite amygdaloidal.

755-865 m depth. Hyaloclastite interbedded by several altered tholeiite layers, and some medium-coarse grained basaltic intrusions. The tholeiite layers are most likely a part of the hyaloclastite formation.

865-1067 m depth. Most of the basaltic layers in this depth interval are fairly dense but hydrothermally altered tholeiite lavas. The relatively fresh medium-coarse grained basalt, however, probably represent intrusive rocks in addition to the dolerite intrusion which is shown at the base of this depth interval.

1067-1215 m depth. Hyaloclastite formation characterizes this depth interval. The coarser grained basalts shown on the profile probably represent intrusions, while the finer-grained basalts are amygdaloidal lavas, especially those below 1140 m depth.

1215-1260 m depth. Vesicular, altered tholeiite basalt lavas characterize this depth interval.

1260-1302 m depth. Basalt-rich hyaloclastite, including a few thin dykes. The lower part of the formation could possibly be built of scoriaceous lavas.

1302-1478 m depth. Altered amygdaloidal tholeiite lavas are the dominant rock type in the upper part of this interval. The medium to coarse-grained basalt between 1425-1438 m could be of olivine-tholeiitic composition. The other coarse grained rocks and the dolerite layers show less altered appearance and could all be of an intrusive nature.

1478-1744 m depth. The next 266 m interval is grouped as a separate unit within this well, characterized by rocks of intermediate chemical composition, as deduced from the radioactive gamma log. Under the stereo-microscope, dark and often extremely fine-grained rocks are common. These could be basaltic andesite to icelandite in composition, but the distinction from the dark and commonly fine-grained tholeiite in rock-cuttings is virtually impossible without the aid of thin-section and chemical analyses. These rocks are thus shown as fine-grained basalt in preliminary stratigraphic column, but as intermediate in the simplified section used in Fig. 4.

1744-1780 m depth. Altered basaltic breccia dominates this part of the well, but two thin dolerite layers are also seen.

1780-1854 m depth. Altered medium to coarse-grained lavas with scoriaceous intercalations dominates this interval. Two dolerite layers are shown near its base.

1854-1890 m depth. Mostly basaltic breccia.

1890-1952 m depth. A lava sequence similar to that between 1780-1854 m depth. The central portion of the lavas are usually coarser grained than the marginal facies. The lavas are extensively altered.

1952-2020 m depth. Basaltic breccias dominate this depth interval, but several fine-grained dense basalt layers are also found and some 8 dolerite intrusions. Higher resistivity was measured in these basaltic layers by resistivity log.

2020-2191 m depth. Fine-grained and dense basaltic layers are the dominant rock type down to 2150 m depth, below which basaltic breccias become more common. In addition, three dolerite intrusions are shown in the section and one 6 m thick tuffaceous bed is shown (2104-2110 m). This layer is light coloured and unlike other layers in the lower part of the drillhole, and might thus possibly be of value as a marker bed.

#### 3 HYDROTHERMAL ALTERATION

The present study of the hydrothermal alteration of the rocks cut by drillhole RV-40 has chiefly involved a microscopic study of 74 thin sections. The mineral identification has been supported by an XRD-study of selected mineral samples taken from the rock cuttings.

Most of the 74 thin sections studied were selected by Mr. J. Tomasson who established the stratigraphic profile of the upper 1650 m of the drillhole. The stratigraphic column of the remaining 541 m (1650-2191 m) was established by Dr. G.O. Fridleifsson. This stratigraphic profile is shown in Fig. 2, where the depth location of the selected thin sections is also given. The simplified geological profile used in Fig. 4 was provided by Dr. G.O. Fridleifsson.

#### 3.1 Petrographic analyses

A microscopic study of drill cuttings is a part of the geological and mineralogical researches which aim towards a thorough understanding of hydrothermal reservoirs. The essential use of microscopes relates to the small grain size of the secondary materials formed in the rocks by the action of the percolating hydrothermal fluids. The polarizing microscope may thus be used:

- To confirm (or determine) the petrographic analyses of the drill cuttings by the stereoscopic microscope.
- (2) To confirm the secondary mineral identification from drill cuttings, otherwise studied in a stereoscopic microscope. (This chiefly applies to those secondary minerals which form mineral veins and amygdales).
- (3) To study the type of rock replacement mineralogy.

(4) To study in detail the mineralogical evolution as seen from cross-cutting relationships, sequential infilling of amygdales, and textural features like partial pseudomorphism of early secondary minerals by later minerals.

Some minerals cannot be identified under the polarizing microscope. Amongst those are the ore minerals which need to be studied in polished section and reflected light microscopes, - not applied in the present study. In general, however, an idea of the apparent ore composition can be gathered by using an external light source and the reflection properties of the ore, yet in thin section. This method coupled to a study of the cutting samples in a stereoscopic microscope is widely used to get a rough idea of the ore composition, while more detailed methods are used for accuracy. In the present study, however, this method was applied, showing the sulfides, for instance, to be composed of pyrite only as other sulphides were not positively identified.

More accurate methods were applied for a detailed identification of the clay minerals and zeolites, which were studied by using an X-ray diffractometer. One sample, containing a potential hedenbergitic pyroxene, was studied further for chemical composition by using an electron microprobe.

Most of the secondary minerals which were identified are shown in Fig. 4. These include: opaline silica and jasper, quartz, calcite, aragonite, undefined iron oxides, pyrite, zeolites (laumontite, stilbite, wairakite and mordenite) epidote, chlorite, swelling chlorite, smectite, albite, prehnite, garnet, ferrosalite. Orther minerals which occur less abundantly, like micas and anhydrite, are also shown in Fig. 4 and mentioned in the text. The mineral distribution with depth is described in section 3.4.

# 3.2 The X-ray diffraction analyses

34 samples of drill-cuttings were prepared for XRD-analyses of clay minerals, while 18 zeolite-bearing samples were hand-picked from the cuttings for an XRD-identification. The sample preparation methods are described in Appendix I.

Fig. 4. shows the mineral distribution with depth, and the analytical method used in identification is also indicated (see also Appendies II and III for identification flowchart and table of the analyses).

#### 3.3 Electron microprobe analyses

Few grains of secondary mineral assemblages, apparently containing hedenbergitic pyroxene, were collected from the rock cuttings between 1604-1612 m depth. The apparent hedenbergitic pyroxene had previously been found in a thin section from 1608 m depth, and also at shallower depth, in a thin section from 1556 m.

A polished thin section was made of the composite sample above, to confirm the optical idendification by studying the mineral chemistry in an electron microprobe.

The result from the chemical study is shown in Table 1 (analyses 1-4), confirming the optical identification. The hedenbergitic pyroxene is located in the ferrosalite field as shown in Fig. 3. In Table 1 (analyses 5-8) a comparison is made with representative analyses of amygdale pyroxenes from gabbro contact aureoles in the Geitafell Central Volcano (Fridleifsson, 1983).

The ferrosalite (a part of the hedenbergite solid solution series) from drillhole RV-40 forms assemblages with epidote, quartz and laumontite with or without garnet. With respect to mineralogical evolution it seems likely that the ferrosalite-epidote-garnet assemblage was formed earlier than laumontite. It further seems likely, that the ferrosalite was formed by contact metamorphism from some neighbouring heat source, while a relationship to an intrusive rock (as seen from the stratigraphic section) is not obvious.

#### 3.4 The mineral distribution

The mineral distribution is shown in Fig. 4, while the individual minerals are discussed below.

Jasper is found in all thin sections from 608 m depth to the bottom of the well. It occurs abundantly in the thin sections from 608-744 m depth. The reddish brown jasper, composed of microcrystalline quartz, has only been found as cavity fillings. In one case, i.e. in the sample from 1870 m depth, jasper forms a layer at one wall of an amygdale, like it had settled on the floor of the amygdale.

Quartz is present at all depths. It occurs sporadically between 116-490 m, but abundantly below that depth. It is common as a vein and an amygdale mineral, and is commonly associated with minerals like calcite, iron oxides, pyrite, zeolites, epidote, and chlorite.

Calcite like quartz, is rare in the upper part of the well, but common below 490 m depth down the drillhole. It has a widespread occurrence mode like quartz, and is found in veins, amygdales and as a replacement mineral of primary plagioclase, interstitial matrices and volcanic glasses.

Aragonite is found with calcite in 12 samples below 490 m depth, while its distinction from calcite is somewhat difficult in thin sections and thus requires either a good axial figure (as it is biaxial, -ve, with small 2V) or an XRD-analysis. In the present study, aragonite was only identified under the microscope.

Pyrite is found throughout the drillhole. By using the reflection property of pyrite, it is easily recognized by its bright yellow reflection in addition to its cubic form (see also section 3.1). Pyrite is an alteration product of the primary Fe-Ti oxides and glass and is also found in

veins and amygdales. A distinction between pyrite and marcasite is very difficult, if possible, by the method applied.

The secondary iron oxides show reddish brown color in thin sections and have either grown in a botryoidal fashion or irregularly. The iron oxides are either found in veins or in amygdales and have a continuous distribution down the well.

Laumontite is the most dominant zeolite in this borehole, and has a continuous distribution from 298 m depth down the well. Other zeolites may be present, but their optical identification is commonly difficult due to small grain size. In a section from 1604-1612 m depth, for example, a late zeolite was formed in a crack in an earlier and slightly altered laumontite. The identification of all the other zeolites shown in Fig.4 was thus done by the XRD-method, while circumstancial evidences, like the one above, were used in establishing the evolutionary sequence.

Epidote is easily identified in the stereoscopic microscope due to its yellow color and acicular form. Therefore, its first occurrence in the Icelandic geothermal fields is usually reported in the preliminary report, like in RV-40, where it occurs at 544 m depth, and then continuously from 580 m downwards (Tomasson et al., 1984). In the thin sections it occurs commonly from 1206 m down the drillhole. The usually euhedral epidote has a widespread occurrence, commonly radiating in lava vescicles, in veins with or without an association with other minerals, and as a replacement mineral after both primary feldspar and volcanic glass.

The sheet-silicates analysed from this borehole chiefly include chlorite, swelling chlorite and smectite. In addition biotite has been found, as well as iddingsite and a poorly defined olivine pseudomorph, formerly termed bowlingite, but apparently composed of a mixture of a sheet-silicate and an iron oxide. Due to the sparse occurrence of these additional minerals, they could not be determined by XRD-analyses.

Due to the small grain size of clay minerals it is usually impossible to distinguish between the clay types in thin sections. However, there is commonly both a colour difference (from reddish brown to deep green) and a difference in birefringence (from abnormal 1st order yellow to anomalous blue) which can be used for a crude distinction between the smectites and chlorites, while a detailed distinction between the clay minerals is done by XRDanalyses. The common clay minerals occur everywhere within the rocks, i.e. in amygdales, veins, at clevage- and parting planes of the primary minerals, or show more widespread replacement of the primary minerals. Usually the volcanic glass is more or less replaced by clay minerals, particularly at deeper levels. With respect to evolution of the hydrothermal system an evidence is preserved in the implying at least two depositional episodes of rocks chlorite, one being older than the formation of epidote the other being later (discussed further in section 3.6)

The biotite is an alteration product of the primary ferromagnesian minerals and has a limited distribution, only found in thin section from 422, 560, 608, and 1566 m depths.

Albite is a common secondary mineral in RV-40 and is always found as a replacement mineral of primary feldspar, often in association with epidote.

Prehnite is only found in some thin sections between 624 m down to 1158 m depth, but in most sections below that depth (see Fig. 4). The prehnite commonly shows a bow-tie structure and occurs both in veins and amygdales. The age relationship between epidote and prehnite seems to imply that prehnite may be formed prior to as well as after epidote. This probably implies a time overlap as shown in Fig. 5 (see also section 3.6).

Garnet has only been found in 5 samples (Fig. 4), in association with some or all of the following minerals: epidote, pyrite, prehnite, quartz, laumontite, and appears to have formed in veins as well as in amygdales. In two cases, hedenbergitic pyroxene is added to this assemblage, i.e. in the thin sections from 1556 m and 1608 m depths.

The ferrosalite occurs in veins in both cases, where it forms an assemblage with laumontite and epidote, with or without garnet. The chemical composition of it shown in Table 1.

Anhydrite was found in one sample only, i.e. at 1466 m depth. The anhydrite grows as small euhedral crystals embedded in mineral veins, which are composed of quartz, zeolites, and pyrite.

## 3.5 The mineral zonation

By looking at Fig. 4, several mineral zones may be recognized. One of these, commonly mapped in high-temperature fields, is the chlorite/epidote-zone. The upper boundary of this zone, marked by the first appearance of epidote in the presence of chlorite, is at 540 m in RV-40 (Fig. 4). This boundary has been set at approximately 230°C in hightemperature fields (Kristmannsdottir, 1979). As seen from the evolutionary sequence in Fig. 5 (see also section 3.6) this mineral zone relates to former high-temperature activity in the Laugarnes field.

Other mineral zones may also be mentioned. Above the chlorite/epidote-zone, two fossil clay mineral zones could be present. These, however, may be difficult to distinguish from the later smectite/zeolite zones. By viewing the zeolite and clay mineral distribution in Fig. 4, however, smectite is only found in a few samples below 600 m depth, while laumontite is by far the most common zeolite from about 300 m depth to the bottom of the well. Therefore the distribution of these minerals does not appear to be related. It further seems evident from the present data that only a laumontite zone could be established for RV-40. According to the mineralogical evolution (section 3.6) it is of a low-temperature origin. Kristmannsdottir and Tomasson (1978) set the lower temperature limit for this zone at 110°C.

A temperature profile measured in the middle of August, 1984, nearly 5 months after completion of drilling, is with the mineralogical distribution in Fig. 4. The shown profile may not be fully representative of the prevailing rock temperature, as the borehole does not seem to have recovered yet from the drilling operation during which great quantities of cooling water were pumped into the formations (H.Tulinius, pers.comm.).

# 3.6 The mineral evolution

Amongst the geological features which are used to unravel the mineral evolution of the hydrothermal system are cross-cutting veins and amygdale infilling sequences, as mentioned in section 3.1. Due to the exclusive use of rotary drill bits, however, most of the macroscopic veinamygdale textures, providing information on the and time-relationships, are lost, while bits and pieces of such information are left for the drillhole geologist to sort out. During the thin section study, a note was made to those textural features providing some form of time related information. Much of this information, however, is incomplete, i.e. provides only a part of the evolutionary history. The result from this part of the study is shown in Fig. 5.

Fig. 5 shows the apparent mineralogical evolution of the Laugarnes low-temperature field as seen from the study of the thin sections from RV-40. The presentation is considerably simplified, e.g. as no particular depth is implied for the diagram. As seen from Fig. 4, for instance, epidote only occurs below 544 m depth, while smectite is more or less confined to depths above 600 m. The presentation in Fig. 5 thus involves some interpretation, but is meant to show a generalized picture of the hydrothermal evolution of the Laugarnes system at some depth within the chlorite-/epidote-zone. Interpretations, however, are kept at as implied by the usage of solid- and dotted minimum, lines. As an example, a clear evidence for the two growth periods of the chlorite exists, i.e. that chlorite was formed both prior- and past the epidote development (Fig. 5). In other cases, the formation time of the

minerals may not be known in detail, as shown by the dashed lines, while it is clear that the minerals were formed during the longer time periods. In addition to this, brackets are used to show that the development of a few minerals was of localized occurence only.

The mineral formation sequences, shown in Fig. 5, can be grouped into three main time periods, as shown at the top of the diagram. The first one of these represents a time period of a low-temperature geothermal system, characterized by the deposition of jasper, iron oxides, pyrite, and low-temperature clay minerals.

The second time period represents the formerly active high-temperature system, which can be divided into three sub-periods (2.1, 2.2, and 2.3). As seen in the diagram most of the characteristic high-temperature minerals, except for epidote, were already being formed during period 2.1. The formation of epidote and albite was added to the mineral assemblages during the second sub-period. Of localized occurrence during this period was the formation of ferrosalite and garnet, the formation of which presumably relates to local heat sources (see earlier discussion). Sub-period 2.2 thus seems to represent the peak period of the high-temperature activity. The cooling period of the high-temperature system appears to be represented by sub-period 2.3.

The third period represents the evolution of the present-day low-temperature system. The zeolite formation characterizes this period. Of some interest is the finding of anhydrite at 1466 m depth, which apparently formed relatively early with laumontite during time period 3.

The result from the present study on the hydrothermal evolution of the Laugarnes field is comparable with the results from well RV-38 in the same field (Fridleifsson, 1982, and pers.comm.). The formation time of the relatively rare anhydrite, for instance (see Figs. 4 and 5), is in both wells found to be of fairly late origin.

# 4 CONCLUSIONS

The main conclusions of this hydrothermal study of the rocks penetrated by drillhole RV-40 in the Thvottalaugar field of the Laugarnes area are as follows:

- A. The study of the hydrothermal evolution of the secondary minerals shows that the evolution of the system can be separated into three major formation periods. The first of these is characterized by a fossil low-temperature alteration; the second by an extinct high-temperature alteration, and the third by the presently active low-temperature system.
- B. The second formation period can be divided into three subperiods, 2.1, 2.2 and 2.3. The formation period 2.2 appears to represent the maxima of the extinct hightemperature activity, as seen by the presence of ferrosalite and garnet. These minerals have not been found earlier within the Reykjavik geothermal fields, but are known from both active and extinct high-temperature fields in Iceland, and appear to be formed within contact zones of local heat sources.
- C. The development of zeolites characterizes thethird formation period, which is in closest time relation to the present-day geothermal activity. The laumontite is the most common zeolite found in the well from 300 m depth to the bottom of the well, while the other zeolites are rare. There is some circumstancial evidence, however, that laumontite may not be forming today, as some other zeolite appears to be formed in altered laumontite, even at deep levels.

#### ACKNOWLEDGEMENTS

I would like to thank the staff of the United Nations University, Geothermal Training Programme in Iceland under the direction of Dr.Ingvar Birgir Fridleifsson for the good study conditions and for his kind co-operation.

The author is greatly indebeted to Dr. Gudmundur Omar Fridleifsson, Dr. Arny Erla Sveinbjornsdottir and Dr. Hjalti Franzson, supervisors of the present report, for their great advice and help towards my understanding of borehole geology and for their careful reading and constructive criticism of the mannuscript.

Thanks are expressed to Vigdis Hardardottir for her help during the XRD studies and to Dr. Karl Gronvold for his help during the electron microprobe studies.

Special thanks are also due to Mr. Ingvar Magnusson for helping me to made Fig. 2. and 4. and also the staff of the drawing office for drafting the remaining figures.

Finally, I wish to express my thanks to Mr. Sigurjon Asbjornsson for his help during my stay in Iceland and for editing this report.

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Fig. 4

DRILLHOLE RV-40, distribution of secondary minerals, temperature profile and simplified geological section





Si02 50.69 Ti02 0.08 Al203 1.04 Cr203 0.01 Fe0 16.75 Mn0 0.92 Mg0 7.45 Ca0 21.92 Na20 0.33 Total 99.19 Si 1.9875 Ti 0.0024 Al 0.0481 Cr 0.0005 Fe+2 0.5492 Mn 0.0306 Mg 0.4354 Ca 0.9210 Na 0.0250 Total 3.9997	51.15 0.09 1.02 0.00 16.02 0.92 7.79 21.83 0.34 999.16	51.18 0.06 1.70 0.00 16.40 0.83 7.31 22.47 0.32 99.64	51.70 0.02 1.12 0.00 17.43 0.55 6.32 23.58 0.27	51.68 n.d. 0.13 18.08 0.62 7.02 23.72 n.d.	50.54 n.d. 1.36 n.d. 21.99 0.62 4.73 22.07 n.d.	50.26 n.d. 0.12 23.48 0.76 3.50 23.12 n.d.	51.96 n.d. 0.39 0.13 15.05 0.41 8.67 23.97 0.26
Si 1.9875 Ti 0.003 Mn0 0.92 Mg0 7.45 CaO 21.92 Na20 0.33 Total 99.19 Si 1.9875 Ti 0.0024 Al 0.0481 Cr 0.0005 Fe+2 0.5492 Mn 0.0306 Mg 0.4354 Ca 0.9210 Na 0.0250 Total 3.9997	0.09 1.02 0.00 16.02 0.92 7.79 2.1.83 0.34 9.99.16	0.06 1.70 0.00 16.40 0.83 7.31 22.47 0.32	0.02 1.12 0.00 17.43 0.55 6.32 23.58 0.27 100.99	n.d. n.d. 0.13 18.08 0.62 7.02 23.72 n.d.	n.d. 1.36 n.d. 21.99 0.62 4.73 22.07 n.d.	n.d. n.d. 0.12 23.48 0.76 3.50 23.12 n.d.	n.d. 0.39 0.13 15.05 0.41 8.67 23.97 0.26
Si   1.04     Cr203   0.01     Fe0*   16.75     MnO   0.92     MgO   7.45     CaO   21.92     Na2O   0.33     Fotal   99.19     Si   1.9875     Si   0.024     Al   0.0481     Cr   0.5492     Mn   0.0306     Mg   0.4354     Ca   0.9210     Na   0.0250     Total   3.9997	1.02 0.00 16.02 0.92 7.79 2 21.83 0.34	1.70 0.00 16.40 0.83 7.31 22.47 0.32	1.12 0.00 17.43 0.55 6.32 23.58 0.27	n.d. 0.13 18.08 0.62 7.02 23.72 n.d.	1.36 n.d. 21.99 0.62 4.73 22.07 n.d.	n.d. 0.12 23.48 0.76 3.50 23.12 n.d.	0.39 0.13 15.05 0.41 8.67 23.97 0.26
Si   1.9875     Si   1.9875     Si   1.9875     Si   0.013     Fotal   99.19     Si   1.9875     Si   0.033     Fotal   99.19     Si   0.033     Fotal   99.19     Si   0.024     Al   0.0481     Cr   0.5492     Mn   0.0306     Mg   0.4354     Ca   0.9210     Na   0.0250     Total   3.9997	0.00 16.02 0.92 7.79 2 21.83 0.34	0.00 16.40 0.83 7.31 22.47 0.32 99.64	0.00 17.43 0.55 6.32 23.58 0.27	0.13 18.08 0.62 7.02 23.72 n.d.	n.d. 21.99 0.62 4.73 22.07 n.d.	0.12 23.48 0.76 3.50 23.12 n.d.	0.39 0.13 15.05 0.41 8.67 23.97 0.26
Si 1.9875 Total 99.19 Si 1.9875 Si 1.9875 Si 0.0024 Al 0.0481 Cr 0.0005 Fe+2 0.5492 Mn 0.0306 Mg 0.4354 Ca 0.9210 Na 0.0250 Total 3.9997	16.02 0.92 7.79 2 21.83 0.34	16.40 0.83 7.31 22.47 0.32 99.64	17.43 0.55 6.32 23.58 0.27	18.08 0.62 7.02 23.72 n.d.	21.99 0.62 4.73 22.07 n.d.	23.48 0.76 3.50 23.12 n.d.	15.05 0.41 8.67 23.97 0.26
Inco   0.92     Inco   7.45     Inco   21.92     Inco   0.33     Inco   0.9210     Inco   0.924     Al   0.0250     Inco   0.9210     Na   0.0250     Inco   3.9997	0.92 7.79 2 21.83 0.34	0.83 7.31 22.47 0.32 99.64	0.55 6.32 23.58 0.27	0.62 7.02 23.72 n.d.	0.62 4.73 22.07 n.d.	0.76 3.50 23.12 n.d.	0.41 8.67 23.97 0.26
Info   0.92     Info   7.45     Info   21.92     Info   0.33     Info   0.919     Info   0.0024     Info   0.0005     Info   0.0005     Info   0.0306     Info   0.9210     Info   0.0250     Info   0.0250     Info   3.9997	7.79 2 21.83 0.34 9 99.16	7.31 22.47 0.32 99.64	6.32 23.58 0.27	7.02 23.72 n.d.	4.73 22.07 n.d.	3.50 23.12 n.d.	8.67 23.97 0.26
Si   1.92     Va2O   0.33     Fotal   99.19     Si   1.9875     Si   0.0024     Al   0.0481     Cr   0.5492     Mag   0.4354     Ca   0.9210     Na   0.0250     Fotal   3.9997	2 21.83 0.34 9 99.16	22.47 0.32 99.64	23.58 0.27 100.99	23.72 n.d.	22.07 n.d.	23.12 n.d.	23.97
Al 0.0481 Cr 0.0306 Cr 0.0005 Cr 0.0005 Cr 0.0481 Cr 0.0005 Cr 0.0306 Mg 0.4354 Ca 0.9210 Na 0.0250 Fotal 3.9997	999.16	99.64	0.27	n.d.	n.d.	n.d.	0.26
Si 1.9875 Si 1.9875 Si 0.0024 Si 0.0024 Si 0.0005 Se+2 0.5492 Se+2 0.5492 Se+2 0.5492 Se 0.4354 Se 0.9210 Sa 0.0250 So 0.13.9997	99.16	99.64	100.99	101.24	n.u.	n.d.	0.20
Si 1.9875   Si 0.0024   Si 0.00481   Cr 0.0005   Se+2 0.5492   An 0.0306   Ag 0.4354   Ca 0.9210   Va 0.0250   Fotal 3.9997	99.16	99.64	100.99	101.24			
i 1.9875 i 0.0024 i 0.0481 r 0.0005 ie+2 0.5492 in 0.0306 ig 0.4354 ia 0.9210 ia 0.0250 'otal 3.9997					101.30	101.24	100.84
i 1.9875 i 0.0024 i 0.0481 r 0.0005 e+2 0.5492 in 0.0306 g 0.4354 a 0.9210 a 0.0250		Catio	ns based	on 6 Oxyg	gens		
1 0.0024 1 0.0481 r 0.0005 e+2 0.5492 in 0.0306 ig 0.4354 a 0.9210 ia 0.0250 		1.993	4 1.99	34 2.000	0 1.981	1.998	1.992
1 0.0481 0.0005 e+2 0.5492 1 0.0306 1 0.0306 1 0.4354 2 0.9210 1 0.0250 1 0.0250 1 0.0250	0.0026	0.001	9 0.00	46 -	-	-	-
r 0.0005 e+2 0.5492 in 0.0306 ig 0.4354 ca 0.9210 la 0.0250 Cotal 3.9997	0.0465	0.049	1 0.05	09 -	0.063	-	0.018
re+2 0.5492 In 0.0306 Ig 0.4354 Ca 0.9210 Ia 0.0250 Cotal 3.9997	0.0000	0.000	0 0.00	00 0.00	4 -	0.004	0.004
In 0.0306 Ig 0.4354 a 0.9210 Ia 0.0250 Potal 3.9997	0.5229	0.534	1 0.56	21 0.58	5 0.721	0.781	0.483
fig 0.4354 2a 0.9210 1a 0.0250 Potal 3.9997	0.0305	0.027	4 0.01	81 0.020	0.021	0.026	0.014
a 0.9210 a 0.0250 Otal 3.9997	4 0.4531	0.424	3 0.36	36 0.40	5 0.276	0.208	0.496
la 0.0250 Cotal 3.9997	0.9129	0.937	8 0.97	42 0.98	4 0.927	0.985	0.985
otal 3.9997	0.0256	0.024	4 0.02	- 00	-	-	0.020
	7 3.9901	3.992	4 3.98	69 3.998	3.989	4.002	4.013
a 47.57	47.56	48.76	50.81	49.3	47.7	49.2	49.8
lg 22.49	23.61	22.06	18.93	20.3	14.2	10.4	25.1
re+Mn 29.94	4 28.83	29.19	30.26	30.4	38.1	40.4	25.1

TABLE 1 The chemical composition of ferrosalite.

# APPENDIX I

### The preparation methods for X-ray diffraction analyses

The preparation of the clay minerals for analyses as done in Iceland is as follows (Hardardottir, 1984):

- (1) Approximately 2 teaspoons of drill cuttings are placed in a test tube, which is filled up to 3/4 with distilled water. First the sample is cleaned and then the clay minerals are separated from the sample by placing the tube horizontally into shakers for 5-6 hours.
- (2) The tube is now placed on a table for 2-3 hours, after which a few ml of water (with suspended clays) is taken from the tube by a pipette. 3-4 drops of this sample are put on a glassplate, enough to cover it by a thin sample film. To avoid cracking of the sample during heating the sample is kept as thin as possible. The sample is now dried slowly by an evaporation, usually overnight. Once dried the sample is stored for ca. 24 hours in a dessicator containing CaCl<sub>2</sub>.
- (3) Now the "untreated" but oriented sample of clay minerals on the glassplate is ready for the first XRD-run.
- (4) In the first run the sample is driven from 2-17 degrees on the goniometer which is sufficient for the clay identification.
- (5) After the first run, the sample is stored in a dessicator containing a glycol solution ( $C_{2H602}$ ) and stored for a minimum of 24 hours at room temperature.
- (6) The glycol-saturated sample is then taken for a second run in the X-ray diffractometer and again driven from 2-17 degrees.
- (7) The sample is now placed on an asbestos plate for heating. It is important to write down the location of each samples on the asbestos plate as all types of

conventional marking will disappear during the heating of the sample. Next the abestos plate is put into a preheated oven (550-600°C), and heated for 1 hour. After cooling the sample slowly it is ready for the third run in the XRD.

(8) The third XRD-run is identical to the former two, i.e. from 2-17 degrees.

The result from the three XRD-runs above is then compared, providing the information necessary for most clay mineral identifications. The identification methods are described to some extent in Appendix 2.

The preparation method for the XRD-analyses of the zeolitebearing samples, as well as for many other crystallized alteration minerals is following:

- The sample is first crushed in an agate mortar containing acetone.
- (2) Next the powdery sample is placed on a glass-window in an aluminium sample-holder, ready for the XRD-run.
- (3) The X-ray diffractometer is driven from 2-60 degrees, which is sufficient for most samples.

Once the 20 values are known, they are converted to d-spacing values by the use of convertion tables. The peak-intensity values are then estimated, the highest 3-4 peakes are used to identify the minerals; either by the aid of XRD-standard diagrams, kept at the NEA XRD-laboratory, or in the case of unknown minerals, standard XRD search-manuals are applied. APPENDIX II

FLOW CHART FOR INDENTIFICATION OF SHEET SILICATES (Tomasson et al. 1977)

Untreated sample with 35 % relative moisture (D-SPACING)	<pre>* Sample saturated * with ethylen * glycol * (D-SPACING) *</pre>	<pre>* Sample heated to * 600£C for 2 hrs. * * (D-SPACING)</pre>	* 1 * *	inerals
13.6-14.6	* Unchanged	* Unchanged	*	1
	* 16.2-16.4 *	* No peak	*	2
	*	* 9.6-9.8	*	3
	*	* 13.5-14	*	4
	* 15.2-15.9	* No peak	*	5
	*	* 12-13	*	6
	*	* 9.7 to 13.2	*	7
	*	* 9.8	*	8
	* 13-16	* No peak	*	9
	*	* 9.8	*	10
	* 13-14	* 13.2-13.6	*	11
12.8-13.2	* Unchanged *	* Unchanged *	*	12
	*	* No peak	*	13

Explanation

1 = chlorite 2 = smectite 3 = smectite 4 = swelling chlorite 5 = mixed layer clay minerals 6 = mixed layer smectite-chlorite-illite 7 = mixed layer chlorite-illite-smectite 8 = mixed layer, badly crystallized and irregular 10 = badly crystallized smectite or vermiculite with small amounts of illite 11 = mixed layer clay minerals and chlorite 12 = mixed layer chlorite-illite 13 = mixed layer chlorite-illite, badly crystallized

# APPENDIX III. XRD-DATA OF THE SHEET SILICATES (100)=INTENSITY OF PEAK =100, B.=BROAD PEAK

DEPTH(M.)	UNTREATED (D-spacing)	GLYCOL (D-spacing)	HEATED MINERALS (D-spacing)
150	16.351(100)B., 8.3702(14)	16.850(100)B., 8.4986(8)	9.883(32)B. SMECTITE
202	16.054(100)B., 8.3387(10)	16.351(100)B., 8.3387(15)	9.8172(50) SMECTITE
252	14.916(82)B., 7.4932(6.5)	16.915(56), 15.881(40)B.	9.839(21) SMECTITE MIXED LAYER CLAY
342	15.938(100)B.	16.723(100)B., 8.4986(8)	9.972(32) SMECTITE
394	16.054(100)B., 8.3544(6)	16.535(100)B., 8.4986(4)	9.9273(23) SMECTITE
412	15.172(80)B.,	16.786(100)B., 8.4179(12)	9.7739(34) SMECTITE
490	15.491(52)B.,	16.850(61)B.	9.8172(15) SMECTITE
514	14.717(100)B., 7.1897(40)B.	16.172(62)B., 7.2366(20)	14.335(20), SMECTITE 9.883(7) SWELLING CHLORITE
544	15.768(50), 9.5012(12), 7.1665(13)	16.113(65), 9.4404(6), 7.155(14)	13.885(4), SMECTITE 9.8172(10)SWELLING CHLORITE?
560	16.597(100)B., 8.5478(8), 7.2454(14)	16.786(70), 8.4179(6), 7.6483(2)	14.152(12)B., SMECTITE 9.9273(18) SWELLING CHLORITE?
608	14.717(100)B., 7.2249(100)B.	14.717(100)B., 7.2014(100)B.	13.885(100)B., CHLORITE 7.1897(33)
624	14.717(100)B., 7.1897(100)B.	14.967(100)B., 7.2484(100)B.	14.062(60)B., CHLORITE 7.1897(100)
692	14.717(55), 7.1897(100)B.,	14.717(45)B., 7.155(100)B.,	13.929(100)B., CHLORITE 7.1781(25)
712	14.524(38)B., 7.1897(100)B.,	14.717(34)B., 7.1665(100)B.	14.062(44), CHLORITE , 7.1897(20)
738	14.717(40)B., 7.1781(60)B.,	14.717(37)B., 7.2014(60)	14.1975(45), CHLORITE 8.6648(12), 7.1665(20)
744	14.524(48), 7.155(100)B.,	15.491(30)B., 7.1781(100)B.	14.062(38), SWELLING CHLORITE , 7.1781(45) CHLORITE
814	14.767(33)B., 7.1435(58)	15.277(30)B., 7.1781(53)	14.107(15), SWELLING CHLORITE 8.5149(8), 7.1781(44)
874	14.476(13)B., 9.5628(8), 7.1665(45)	14.429(12)B., 9.5012(7), 7.1665(40)	14.197(15), CHLORITE 7.0978(10)

936	16 351(5)	14 717(10)B	7 1897(8)	CHLOPITE?
	7.132(21)	7.155(20)	/.105/(0)	CHEORITE
952	15.017(14),	15.172(10),	NO PEAK	SWELLING CHLORITE?
	/.109/(10)	/.109/(15)		
1066	14.476(8),	14.476(5),	NO PEAK	CHLORITE?
	/.1205(12)	/.1205(10)		
1158	14.967(12)B.,	15.437(10)B.,	14.107(6),	SWELLING CHLORITE
	9.5012(7),	9.5012(7),	8.5809(9),	
	/.1/01(25)	/.1/81(20)	7.2366(5)	
1182	14.476(8),	14.335(22),	14.335(3),	CHLORITE?
	7.132(11)	9.4003(6),	7.132(8)	
		/.132(10)		
1314	14.289(25),	14.335(22),	14.234(18),	CHLORITE
	7.132(40)	7.1205(48)	7.2484(12)	
1386	14.289(10).	14.289(10).	14.289(10).	CHLORITE
112-170-F61F2	7.132(20)	7.1205(22)	7.2366(15)	्याप्रकृत्व व्याप्त व्याप्त <b>व्याप्त व्याप्त</b>
1466	14 717(27)	14 524(27)	14 717(38)	CHI OD 175
1400	7.1435(58)	7.1435(63)	7.3081(14)	CULORITE
1496	14 476(20)	14 212/12\5	14 476465	
1486	14.4/6(30), 7.132(30)	7.1435(19)	14.4/6(6)	CHLORITE
1540	14.524(20),	14.429(20),	14.243(10)	CHLORITE
	/.132(60)	7.132(10)	7.1665(37)	
1696	15.224(14)B.	16.597(5).	14.243(13)	SWELLING CHLORITE
	7.0978(22)	14.717(6),		CHLORITE
		7.132(20)		
1730	14.382(12).	14.382(10),	14.289(10).	CHLORITE
	9.5012(14),	9.5012(16),	8.5975(8),	a and the second s
	7.132(25)	7.132(25)	7.2603(5)	
1780	16.660(22)	16.473(20),	14.017(30)B	SWELLING CHLORITE
	15.546(22)B.,	15.491(25)B.,	7.1665(15)	CHLORITE
	14.476(35),	14.574(18),		
	7.1435(65)	7.132(60)		
1864	14.335(23),	14.476(24),	14.243(14),	CHLORITE
	7.1205(50)	7.132(45)	7.132(36)	
1880	15.824(40)B	16.786(46)8	14.243(10)	SMECTITE
1000	7.1550(30)	7.1665(20)	9.9273(9),	SWELLING CHLORITE
			8.5809(3)	
1970	14,476(25).	16.85(15).	14.243(34).	SWELLING CHLORITE
	7.1435(66)	14.476(25),	7.1665(23)	CHLORITE
		7 1897(57)		