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ALTERATION HISTORY IN WELL RV-39, REYKJAVÍK, ICELAND

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ABSTRACT

A variety of hydrothermal minerals have been identified by petrography and X-ray diffraction study to obtain their occurrences. The occurrences of each may be controlled by lithology, temperature, pressure, fluid composition or any combination of these. Minerals may reflect current conditions (mineral at equilibrium), or previous condition (metastable minerals), or they may reflect transition or intermediate phases as the mineralogy adjusts to a new temperature, pressure, compositional environment (unstable, transient minerals).

Some contemporaneous mineral assemblages have been recognized in well RV-39. In RV-39, the mineral assemblages can be divided into 4 groups i.e iron oxides-chalcedony, chlorite-epidote-prehnite, laumontite and thomsonite-chabasite (low-T. zeolite) group. Each mineral group was formed under somewhat varying physical chemical conditions, the implication from these upon the geothermal history is the main topic of the present study.

The hydrothermal history of RV-39 can be divided into an extinct high temperature system and present low temperature system. The high temperature system reached temperatures up to 300°C as represented by chlorite-epidote-prehnite mineral assemblages, and subsequently cooled down to 200°C as seen by the presence of superimposed laumontite zone. Originally the basaltic extrusives were highly porous, while porosity was reduced by mineral precipitation related to the high temperature system. Liquid dominated presently active hydrothermal system ($T < 110°C$) is fed by a relatively hot plume of rising fluid which flows laterally at shallow depth to mix with cold ground water. The present-day water chemistry appears to be in equilibrium with some low temperature minerals i.e chalcedony, chabasite and calcite.

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1. INTRODUCTION

The work described in this report was carried out while the author held a UNU fellowship to attend the UNU Geothermal Training Programme at the National Energy Authority, Iceland, in 1987. It is the result of the author's training in Borehole Geology.

The topic of the work is "Alteration history in well RV-39, Reykjavik, Iceland".

Drill cuttings from the well were studied to obtain information on the secondary mineralization in the geothermal field of Reykjavik. An emphasis is laid on the relative age of the formation of individual minerals to provide information on the alteration history of the geothermal field, as there is a strong relationship between fluid chemistry, temperature and type of secondary mineralization. Chemistry data, drill cuttings and thin sections of RV-39 were made available by National Energy Authority of Iceland (ORKUSTOFNUN).

2. PREVIOUS WORK

Previous geological works have been done intensively in Reykjavik geothermal field in order to obtain a subsurface information through the well prior to the present research.

Drilling in the Reykjavik low-temperature area started as early as 1928. During 1928-1930, 14 shallow wells had been drilled into Reykjavik area to a maximum depth of 250 m. The total output of these wells was 15-20 l/s of 90°C hot water, which was used for domestic heating. After 1950, several deeper wells were drilled while an extensive deep-drilling activity took place between 1959-1963 and 22 wells were drilled in the Reykjavik area to a maximum depth of 3085 m. Altogether 41 deep wells have been drilled to date. The well RV-39 is located in the Ellidaar field, one of three geothermal fields in Reykjavik. The Reykjavik geothermal fields has been described by Tomasson et al. ,1977. The well data had been gathered either from shallow or deep wells which were drilled from 1965 to 1973. The lithological profiles showed three main rock units i.e. basalt lava units (B1, B2, B3, B4, B5), hyaloclastite units (or moberg) (M1, M2, M3), and a dolerite unit. All of which are of Pleistocene age. 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 low-temperature zeolite zones in active low-T areas in Iceland 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.

3. SCIENTIFIC APPROACH AND METHODOLOGY

The work was carried out by collecting detail mineralogical data by petrographic studies under microscope and by XRD-analyses of several samples. Based mainly on the similarity of some minerals and their distribution, grouping is done to present the hydrothermal mineral zones. An attempt is made to sort out the hydrothermal history from studies of time relationships. This include cross-cutting minerals veins, depositional sequences in amygdales and replacement texture.

Reference to the literature is frequently made in order to explain the mineral formation to some extent and the thermodynamic behind it. The study of the hydrothermal history is partly confirmed by downhole measurement and fluid chemistry data.

Pioneering studies were done G.P.L.Walker (1960) on extinct low-temperature zeolite zones in eastern Iceland. Fridleifsson (1983a) has described in detail extinct high-temperature hydrothermal mineralization in south-east Iceland in a eroded volcanic complex. Kristmannsdottir and Tomasson (1978) studied the temperature implication of zeolites in active geothermal areas in Iceland, particularly in the low temperature areas. Studies on some zeolites equilibria e.g. stilbite and laumontite have been described by Liou (1971) and wairakite - analcime by Seki, (1971). Comparison of the present data is also sought to other references e.g. Palmason et al (1979) and Smarasson (1984). Finally important data is used directly from reports on geothermal fields, geological maps and internal reports in ORKUSTOFNUN.

The following mineral temperatures, for instance, are based on the Icelandic experience and can be applied in predicting temperature in well RV-39 (Fridleifsson pers com) :

Minerals	**Temperature**
Low-T zeolite	120°C
Laumontite	120 - 180°C
Wairakite (+ quartz)	200°C
Epidote (+ chlorite)	> 230°C
Actinolite	> 280°C
Garnet	300°C
Hendenbergite	400°C

4. GEOLOGICAL SETTING

The Ellidaar hydrothermal system is one of three apparently separate hydrothermal system within a radius of 6 kilometers from the center of Reykjavik. The others are the Laugarnes and Seltjarnarnes hydrothermal systems. 41 wells (1000-3085 m depth) have been drilled within the Reykjavik area and RV-39 is one of them, located with in the Ellidaar system (Figure 1). The wells in these areas produce from low temperature (<150°C) geothermal water and is mostly used for domestic heating. The water distribution is operated by the Reykjavik Municipal District Heating Service (Hitaveita Reykjavikur).

Geologically, the Ellidaar geothermal field lies just outside of the active volcanic zone in southwestern Iceland (Figure 1). The active volcanic zone is flanked symmetrically by Quaternary volcanics which in turn are flanked by Tertiary volcanics. The strata, which dips towards the volcanic zone, reflects continuous volcanic activity and crustal spreading in this part of the country during at least the last 7 million years (Tomasson et al.,1975). The Reykjavik geothermal systems are situated in Pleistocene rocks ranging in age from about 2.8 to 1.8 million years. Two central volcanoes were active in this region during this period, the Kjalarnes (older) and the Stardalur central volcanoes, which produced relatively young lavas in part of the strata at Ellidaar, dating back to the last interglacial about 70,000 to 100,000 years ago. These are overlain by younger sediments; and one Post-glacial lava flow from the volcanic zone into the Ellidaar valley about 5,000 years ago (Fridleifsson, 1973; Tomasson et al., 1975). The Pleistocene strata is characterized by interlayering series of hyaloclastites and lava flows. The hyaloclastites were formed by sub-aquatic volcanic eruption during glacial period, while the lava flows were formed during interglacial periods. The surface rock were subsequently cut by shallow level dykes and sheets.

5. BOREHOLE GEOLOGY

5.1. Classification of the Rocks

The rock in the wells of the Ellidaar geothermal system, are identified from of their appearance in drill-cuttings. Smarasson (1987) used the following classification : tholeiite basalt (fine to medium grain basalt); olivine-tholeiite basalt (medium to coarse grain basalt); dolerite (coarse grain basaltic and intrusions); glassy basalt (usually pillow lava); basaltic breccia (basalt fragment in glassy matrix); hyaloclastite (basaltic tuff).

Andesite occurs as very fine grained lavas and intrusions of intermediate composition, SiO_2 = 52-66 wt.%, and sediments are composed of conglomerate, tillite and alluvial sediments. This classification scheme also distinguishes between fresh and hydrothermally altered rocks.

Basalt is a term used for basaltic rock types which have SiO_2 content of 45-52 % by weight. It occurs as lavas, and intrusions (sheets, dykes and sills). If the basaltic intrusions cooled slowly, coarse grained rocks resulted (dolerite). It can sometimes be difficult to distinguish between lavas and dykes in drill-cuttings, but one of the main criteria is the appearance of the intrusive rocks, which usually are fresher in appearance than the lavas. This may relate to lower permeability, younger age, or both.

Similarly it is sometimes difficult to decide from the drill-cuttings, whether to group a rock as "glassy basalt" or a "basaltic breccia". The main difference is that the glass in the basaltic breccia is vesicular as this rock type is a mixture of crystalline basalt and basaltic tuff. Cuttings that are partly crystalline and partly glassy rock are more common in basaltic breccias than in glassy basalt. Glassy basalt contains less glass than the basaltic breccia, and may have originated as supercooled lava flows or pillow lavas.

Tuff is a term used for rocks that have cooled rapidly enough to form glass, either from subaerial or subaquatic phreatic extrusions. In the Ellidaar area it is mostly basaltic tuff although intermediate and acid tuffs occurs too. The acid ones are usually found as thin layers interbedded in the basaltic lava pile as sedimentary horizons. The hyaloclastite tuffs commonly occur as heaps, ridges or clastic sediment close to their vents.

Glassy basalt, basaltic breccia and hyalotuff can, if found in a continuous sequence, be classified as a single compound unit and called hyaloclastite formation (moberg formation in Icelandic). The glassy basalt is then believed to be a pillow lava, the basaltic breccia or hyalo-breccia is a mixture of basalt fragments (single fragment or bombs), and the hyalo-tuff is a palagonite tuff (moberg in Icelandic).

Intermediate rocks of the tholeiitic should have a SiO_2 content between 52-66%. They are rare outside the volcanic centers. Intermediate rocks are seldom found in low temperature areas unless the thermal system is located within extinct volcanic centers. This is the situation in Reykjavik, where the geothermal reservoirs occur in a Pleistocene volcanic center that was active about 1 million years ago (Fridleifsson, 1973). Intermediate and acid rocks (SiO_2 > 66%) are abundant below 1500 m in the Laugarnes field (Fridleifsson et al., 1985), and below 1700 m in the Ellidaar field (Smarasson et al., 1984a,b). The intermediate rocks are dark in color and very fine grained and dense, whereas the acid rock are generally yellow or brownish and glassy.

5.2. Stratigraphy of Well RV-39

Following the above terminology, and as seen on Figure 2, the lithology of well RV-39 can be separated into 5 major groups depending upon their composition, texture, and the mechanism of deposition (Smarasson et al., 1984) :

1. Sediments
2. Basalt lava units
3. Hyaloclastite units
4. Dolerite unit
5. Andesite lava unit

The sediments

The sediment formations provide marker horizon or a key for correlation between wells. They were deposited as river or lake deposits while the volcanism was inactive. The formation consist of conglomerate, cemented by clay or sandy materials. They are encountered by drilling at depths of 5-7 m, 23-40 m and 87-94 m.

The basalt lava units

The basalt lava units (units B1 to B6) are predominant in the well and occur at the following depths : 17-23 m, 45-87 m (B1), 94-400 m (B2), 664-887 m (B4), 1037-1764 m (B5), 2050-2095 m (B6). Lava unit B1 (45-87 m) is composed of a relatively fresh coarse grained olivine-tholeiite. It seems to consist of three compound lava flows which are separated by thin sediments. Each of the compound lavas could be 10-15 m thick, whereas each flow unit is much thinner. Lava unit B2 (94-400 m) is characterized by tholeiite lavas and thin intercalation of sediments. These lavas are partly altered. Lava unit B4 (664-887 m) is characterized by fairly altered tholeiite basalt lavas. Thin olivine-tholeiite basalt lavas occur in the lower part of this unit (Smarasson, 1984). Sediments are few. Thin dykes are also found in the lower half in the unit. Lava unit B5 (1037-1764 m) is mainly composed of altered basaltic lavas. They are mostly fine-medium grained tholeiites. Lava unit B6 (2050-2095 m) is the lowermost unit of the well. It is composed of medium-coarse grained altered basaltic lavas.

The hyaloclastite units

The hyaloclastite units mostly covers the depth interval of 400 -664 meter. This is supposed to be a moderately permeable layer covering the hydrothermal system (Tomasson, 1975). This formation is composed of tuffs, basaltic breccias, some sediments and basalts. This unit seems to cover three other sub-units i.e. M1, B3 and M2, found in other wells but not be separable in this well.

The dolerite units

Dolerite unit are composed of several dykes or sheets and found at the following depth : 1727 - 1764 m and 2020 - 2050 m. The dolerite are fairly dense rocks of low permeability which may be the primary reason for the fresh appearance of these rocks.

The andesite lava unit

The andesite unit (1764-1881 m) has been encountered by the drilling about 117 meter thick in the lower part of the well from 1764 - 1881 m depth. It is mainly composed of thick fine grained dark lavas of intermediate chemical composition. Due to higher natural radioactive decay in more acid rocks; natural-gamma ray well logs have proceed useful in identifying the intermediate and acid rocks (Smarasson et al., 1984).

6. HYDROTHERMAL ALTERATION

6.1. Distribution of Hydrothermal Minerals

The distribution of the minerals discussed below is shown on Figure 2 :

Iron oxides are found in the upper part of the well down to 600 meter depth and less abundantly at deeper level. They are mainly formed at the expense of Fe-rich minerals or glass in the basalts redeposited as hydrated Fe-oxides in veins and vesicles. They seem to have been deposited at low temperatures before the hydrothermal system became active. They partly dissolved or altered upon in the later high temperature system, explaining their relative absence in the deeper part of the well.

Chalcedony is found in the cuttings from 80 meter to 600 meter depth. It is abundant in the upper part showing a brownish yellow layering in the bottom of amygdales. Mineralogical examination of time relationships suggests that it belongs to earlier time periods, while the fluid chemistry shows that the present system is equilibrium with chalcedony at temperature of about 100°C (Figure 6).

Jasper/Opal are positively identified in the cuttings from 80 meter to 600 meter depth. The reddish brown appearance of microcrystalline silica appears as cavity fillings, sometimes form a tiny layer settled on the floor of the amygdales (Figure 5). These three minerals above seem to have formed simultaneously in previous environment.

Clay I is identified petrographically by its relative appearance and relationship with other minerals in thin sections. It forms a greenish almost anisotropic layer spotted with yellowish tints. It belongs to the older high.T system and spreads sporadically through all thin section of RV-39.

Chlorite is found in close relationship with clay I through the well. Petrographically, it appears as the first inside walls of amygdales or fractures. It is yellowish green and shows parallel extinction to crystal cleavages. It forms through alteration of Fe-Mg rich minerals, especially cryptocrystalline or glassy minerals which were easily altered while the high T system was active. The distribution of chlorite (Figure 2) was based on microscopic study only. Compared to other wells nearby chlorite occurs at shallower depth in RV-39 than other wells. Therefore an XRD-study on the upper boundary of chlorite is needed.

Prehnite is only found in some thin sections between 600-1000 meter and from 1500 meter down to the bottom of the well. 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 as well as after epidote, which may imply a time overlap between the two minerals.

Pyrite is sporadically found in all drill-cuttings, more abundantly in the upper part of the well, and is easily distinguished because of its cubic form and metallic luster.

Calcite I is abundant from 400 meter down to the bottom of the well, both in veins and also in amygdales. Calcite is common at all depths at rock temperatures up to 280°C (Fridleifsson pers com). It has formed both in the older system and the presently active system, Calcite like quartz is a replacement mineral of primary plagioclase, interstitial matrices and volcanic glass. It is also precipitated directly from hydrothermal fluids while cooling took place in the system.

Quartz is present below 600 meter depth and is commonly formed in veins and as an amygdale mineral. Quartz is often associated with minerals like pyrite, calcite, zeolite group, epidote and chlorite. Quartz seems to have been formed in the older high-T hydrothermal system and metastable in the present condition.

Albite is a common replacement mineral of primary plagioclase in RV-39 and often in association with porous-amygdale rich rock which shown epidote inside the amygdales. Albite is observed at rock temperatures exceeding about 220°C, but is more common at rock temperatures near to 300°C (Kristmannsdottir, 1979).

Zeolites. The zeolites identified are : wairakite, laumontite, mordenite, analcime, heulandite, stilbite, scolecite, mesolite, thomsonite and chabasite (Figure 2). The occurrences of most of these zeolites are dependent on the rock temperature. Wairakite occurs sparsely in thin sections from 616 m, 1132 m, 1152 m and 1540 m depth and is believed to be formed at T > 200°C. Laumontite is abundant at all depths below 450 meter. It is believed to be formed at T.range of 120-180°C. Heulandite occurs sparsely in thin sections from of 495 m, 616 m, 718 m depth. Scolecite is found to form prior to the above mentioned zeolites at 495 m to 544 m, down to 618 m and in the deeper part at 902 m and 1210 m depth. Stilbite is found at 512 m to 570 m depth, and positively identified at 900 m to 1100 m, and occurs at 1260 m to 1330 m. Mesolite which is only found at 1039 m in thin section. Chabasite and thomsonite are abundant at depth between 70 m to 500 m depth as decreasing in abundance down to 1000 meter. Mordenite is identified by XRD at 1210 m and 1450 m depth in the present study.

Epidote is easily identified in the stereoscopic microscope due to its greenish yellow color and acicular form. In well RV-39 it is found below 1030 meter depth and down to bottom. The usually euhedral epidote has a widespread occurrence, commonly radiating in amygdale, and either single in veins or in some mineral assemblage. It also occurs as a replacement mineral for primary feldspar and volcanic glass. Epidote is metastable in the present-day low-temperature water (T=103°C) in the Ellidaar system, and supposed to be formed at temperatures above 230°C.

Clay II is identified petrographically using the mineral relationship method. It is rarely interlayered and more darker green in colour, and anisotropic. It has grown centrally inside minerals growth and amygdales. It is found in association with low-temperature minerals, such as calcite II, chabasite and thomsonite.

Calcite II is also identified by the time relationship method and is associated with those above explained minerals (clay II). Ionic activity calculated from present fluid chemistry confirms that calcite may be precipitated from slightly oversaturated condition (Figure 4).

7. FLUID COMPOSITION

The geothermal fluids in most of Iceland's active systems are of meteoric origin with low salinities (Palmason et al., 1979). One chemical analysis is available from well RV-39, sampled March 12th, 1987, (Gunnlaugsson pers com). The analysis has been calculated by using 'Watch3' program to obtain the ionic activity of each element in the deep water. The well is full of water and no flashing has taken place, the aquifer temperature is 103.5°C; then will be obtained the chemical components in deep water and solubility product of each mineral as seen on Table 1 and 2. But some minerals containing aluminum/iron oxides, e.g. zeolites group could not be calculated (displayed as 99.999) due to lack of the analytical data. Chalcedony geothermometer is much closer to the measured temperature shown that at 101.5°C the water is oversaturation in calcite and chalcedony (Figure 4). Calcite and chalcedony are favorably precipitated in the present alkaline ($CO2$ = 20.2 ppm) water which has pH = 9.51, salinity (Cl=22.4 ppm) and 15.4 ppm of sulphate content supporting the solubility of silica in the water. The evidence for the precipitation of those minerals is confirmed by mineralogical examination and identified by calcite II and chalcedony (Figure 5). The other low-temperature minerals which may be formed in the present geothermal fluid in RV-39 are chabasite and thomsonite.

In present condition, the aquifer of well RV-39 is dominated by hot water while the fourth period of hydrothermal minerals is being precipitated.

8. ALTERATION HISTORY

In RV-39 four distinct stages of alteration and mineralization are recognized (Figure 6). The first one of these represents a time period of a low-temperature geothermal system, characterized by the deposition of jasper, iron oxide, opal, chalcedony and low-temperature clay minerals. The minerals precipitating during this period indicated a fossil system which was formed soon after volcanic deposition upon rise in the geothermal gradient.

The second time period involves prograde alteration of primary minerals and open-space mineralization, the extent of alteration increasing with depth. This period is represented the chlorite-epidote-prehnite hydrothermal zone below 1 Km depth, indicating that temperatures up to 300°C were reached by the extinct system in well RV-39. Some relicts of the minerals from the first period are sometimes seen within mineral assemblages of the second period.

When the system cool down, a third period of mineralization appears forming a laumontite zone. The system cooled down from about 200°C to about 120°C in a water phase. This zone was superimposed by zeolites.

The fourth period is the present-day hot water system ranging in temperature from 80°C to 120°C. The water in RV-39 is largely supplied from an aquifer at about 1030 m depth which coincides with the deepest appearance of chabasite. The measured temperature shows a negative gradient below this main aquifer. The present hot water system forms a mushroom shape reservoir which was intercepted by RV-39 at 1030 m. Chemically, the present water is saturated with respect to chalcedony which is formed at temperatures of less than 120°C, but data in the phase equilibria on the chabasite-thomsonite assemblages are lacking.

The age relationships of the hydrothermal minerals can be seen clearly on Figure 5 and 6. Figure 6 shows the older minerals on the left side shifting to younger minerals on the right side.

The alteration history of RV-39 is fairly similar to the alteration history of well RV-40 in the Laugarnes field (Yaowanoiyothin, 1984), which the temperatures in the fossil Ellidaar high-T system have not risen as high as in the Laugarnes field.

9. DISCUSSIONS

The iron oxides was formed on the older system which are affected by cold ground water on the upper part of the well. They were attend because of later high temperature activity at deeper levels.

The present study is able to state that the formation of chalcedony may have been continuous from the beginning of the system until the present time.

Various silica minerals (chalcedony, quartz, jasper) are much independent on a temperature changing, and/or environmental changing perform as metastable minerals. Using these minerals as indicator for investigating a hydrothermal history may give a useful interpretation. In low-temperature of less than 150°C, microcrystalline quartz is favor precipitated, on contrary, crystalline quartz at high-temperature seem to be implied in well RV-39.

10. CONCLUSIONS

The study of the hydrothermal evolution of secondary minerals shows that the hydrothermal activity of the system cut by well RV-39 can be separated into 4 time periods, all of which were in water dominated system.

The first period indicated a fossil low-T system during which various amorphous minerals phases like jasper, opal, chalcedony and iron oxides were precipitated in a rather cold groundwater.
The high-T hydrothermal system became active, presumably in relation to intrusive activity in a neighbouring central volcano complex while an evidence for higher temperature than 300°C has not been found in the rocks intersected by well RV-39. The peak of the high temperature activity was represented by the chlorite-epidote-prehnite zone during the second hydrothermal mineralizing period.

The third period of the system indicated a decreasing temperature from 200°C down to 120°C, which resulted in the formation of laumontite within epidote zone between 1000-2095 m.
The fourth time period of the system reflects the present-day condition, and is best seen in the upper part of the well. A temperature of 103.5°C hot water on the wellhead is mainly supplied from 1030 m depth which is also the deeper limit of chabasite occurrence. Chemical analysis shows the hot water to be slightly alkaline and near saturation with respect to calcite and chalcedony at present, while thermodynamic data on the zeolite equilibria are lacking.

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Table 1: Analysis result of water chemistry in well RV-39

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8703125086                        RV-39 Ellidaar

PROGRAM WATCH2.

WATER SAMPLE (PPM)                STEAM SAMPLE

PH/DEG.C          9.51/20.5       GAS (VOL.%)                      REFERENCE TEMP.        DEGREES C    103.5 (MEASURED)
SIO2            114.50            CO2
NA               48.00            H2S                              SAMPLING PRESSURE      BARS ABS.
K                 1.01            H2                               DISCHARGE ENTHALPY      MJOUL/KG
CA                1.95            O2                               DISCHARGE                KG/SEC.    41.5
MG                .004            CH4
CO2              20.20            N2                               MEASURED TEMPERATURE DEGREES C      103.5
SO4              15.40                                             RESISTIVITY/TEMP.    OHMM/DEG.C        .0/  .0
H2S                .40                                             EH/TEMP.               MV/DEG.C      .000/  .0
CL               22.40
F                  .62            LITERS GAS PER KG
DISS.SOLIDS        .00            CONDENSATE/DEG.C                    MEASURED DOWNHOLE TEMP.    FLUID INFLOW
AL               .0000                                                  DEGREES C/METERS        DEPTH (METERS)
B                .0000
FE               .0000            CONDENSATE (PPM)                          .0        .0              .0
NH3              .0000            PH/DEG.C                                  .0        .0              .0
                                  CO2                                       .0        .0              .0
                                  H2S                                       .0        .0              .0
                                  NA                                        .0        .0              .0
                                                                            .0        .0              .0
                                                                            .0        .0              .0
                                                                            .0        .0              .0
                                  CONDENSATE WITH NAOH (PPM)                .0        .0              .0
                                  CO2                                       .0        .0              .0
                                  H2S                                       .0        .0              .0

 IONIC STRENGTH =    .00238      IONIC BALANCE :   CATIONS (MOL.EQ.) .00219252
                                                   ANIONS  (MOL.EQ.) .00202017
                                                   DIFFERENCE    (%)       8.18

                                                       DEEP STEAM (PPM)            GAS PRESSURES (BARS ABS.)
 DEEP WATER (PPM)
                                                                                   CO2        .486E-03
 SIO2        114.51        CO2          20.20          CO2             .00         H2S        .633E-05
 NA           48.00        H2S            .40          H2S             .00         H2         .000E+00
 K             1.01        H2             .00          H2              .00         O2         .000E+00
 CA            1.95        O2             .00          O2              .00         CH4        .000E+00
 MG            .004        CH4            .00          CH4             .00         N2         .000E+00
 SO4          15.40        N2             .00          N2              .00         NH3        .000E+00
 CL           22.40        NH3            .00          NH3             .00         H2O        .115E+01
 F              .62                                                                TOTAL      .115E+01
 DISS.S.        .00
 AL           .0000
 B            .0000                                    H2O (%)                .00
 FE           .0000                                    BOILING PORTION        .00
```

Table 2 : Result of ionic activity and solubility product using "WATCH 3".

```
==========================================================================================

ACTIVITY COEFFICIENTS IN DEEP WATER
H+           .943     KSO4-        .940     FE++         .783     FECL+        .939
OH-          .938     F-           .938     FE+++        .591     AL+++        .591
H3SIO4-      .939     CL-          .938     FEOH+        .940     ALOH++       .782
H2SIO4--     .782     NA+          .939     FE(OH)3-     .940     AL(OH)2+     .940
H2BO3-       .937     K+           .938     FE(OH)4--    .781     AL(OH)4-     .939
HCO3-        .939     CA++         .783     FEOH++       .781     ALSO4+       .939
CO3--        .779     MG++         .789     FE(OH)2+     .940     AL(SO4)2-    .939
HS-          .938     CAHCO3+      .941     FE(OH)4-     .940     ALF++        .782
S--          .781     MGHCO3+      .939     FESO4+       .940     ALF2+        .940
HSO4-        .939     CAOH+        .941     FECL++       .781     ALF4-        .939
SO4--        .778     MGOH+        .941     FECL2+       .940     ALF5--       .779
NASO4-       .940     NH4+         .937     FECL4-       .939     ALF6---      .570

CHEMICAL COMPONENTS IN DEEP WATER (PPM AND LOG MOLE)
H+ (ACT.)      .00   -8.363    MG++          .00   -6.861     FE(OH)3      .00    .000
OH-           2.61   -3.815    NACL          .02   -6.564     FE(OH)4-     .00    .000
H4SIO4      142.54   -2.829    KCL           .00   -8.884     FECL+        .00    .000
H3SIO4-      39.19   -3.385    NASO4-        .14   -5.941     FECL2        .00    .000
H2SIO4--       .11   -5.921    KSO4-         .01   -7.178     FECL++       .00    .000
NAH3SIO4      1.12   -5.022    CASO4         .19   -5.853     FECL2+       .00    .000
H3BO3          .00     .000    MGSO4         .00   -7.780     FECL3        .00    .000
H2BO3-         .00     .000    CACO3         .25   -5.595     FECL4-       .00    .000
H2CO3          .29   -5.326    MGCO3         .00   -8.631     FESO4        .00    .000
HCO3-        26.94   -3.355    CAHCO3+       .13   -5.877     FESO4+       .00    .000
CO3--          .53   -5.050    MGHCO3+       .00   -8.978     AL+++        .00    .000
H2S            .01   -6.745    CAOH+         .01   -6.689     ALOH++       .00    .000
HS-            .38   -4.939    MGOH+         .00   -8.171     AL(OH)2+     .00    .000
S--            .00  -12.539    NH4OH         .00     .000     AL(OH)3      .00    .000
H2SO4          .00  -19.482    NH4+          .00     .000     AL(OH)4-     .00    .000
HSO4-          .00   -9.209    FE++          .00     .000     ALSO4+       .00    .000
SO4--        15.15   -3.802    FE+++         .00     .000     AL(SO4)2-    .00    .000
HF             .00   -9.005    FEOH+         .00     .000     ALF++        .00    .000
F-             .62   -4.486    FE(OH)2       .00     .000     ALF2+        .00    .000
CL-          22.39   -3.200    FE(OH)3-      .00     .000     ALF3         .00    .000
NA+          47.75   -2.683    FE(OH)4--     .00     .000     ALF4-        .00    .000
K+            1.01   -4.589    FE(OH)++      .00     .000     ALF5--       .00    .000
CA++          1.73   -4.365    FE(OH)2+      .00     .000     ALF6---      .00    .000

IONIC STRENGTH =   .00232      IONIC BALANCE :  CATIONS (MOL.EQ.) .00219087
                                                ANIONS  (MOL.EQ.) .00201796
                                                DIFFERENCE   (%)       8.22

CHEMICAL GEOTHERMOMETERS DEGREES C              1000/T DEGREES KELVIN =  2.65

QUARTZ       125.2
CHALCEDONY   101.5
NAK           75.9

OXIDATION POTENTIAL (VOLTS) :     EH H2S=  -.463    EH CH4= 99.999    EH H2= 99.999    EH NH3= 99.999

LOG SOLUBILITY PRODUCTS OF MINERALS IN DEEP WATER
                TEOR.     CALC.                       TEOR.     CALC.                     TEOR.     CALC.
ADULARIA      -17.087    99.999    ALBITE LOW       -16.362    99.999    ANALCIME       -13.107    99.999
ANHYDRITE .    -5.656    -8.382    CALCITE           -9.499    -9.629    CHALCEDONY      -2.813    -2.829
MG-CHLORITE   -80.215    99.999    FLUORITE         -10.533   -13.499    GOETHITE        -4.544    99.999
LAUMONTITE    -27.020    99.999    MICROCLINE       -18.439    99.999    MAGNETITE      -29.436    99.999
CA-MONTMOR.   -84.728    99.999    K-MONTMOR.       -41.196    99.999    MG-MONTMOR.    -85.894    99.999
NA-MONTMOR.   -41.219    99.999    MUSCOVITE        -20.948    99.999    PREHNITE       -36.666    99.999
PYRRHOTITE    -98.057    99.999    PYRITE          -144.462    99.999    QUARTZ          -3.065    -2.829
WAIRAKITE     -24.623    99.999    WOLLASTONITE      10.718     9.425    ZOISITE        -35.812    99.999
EPIDOTE       -43.320    99.999    MARCASITE       -121.239    99.999
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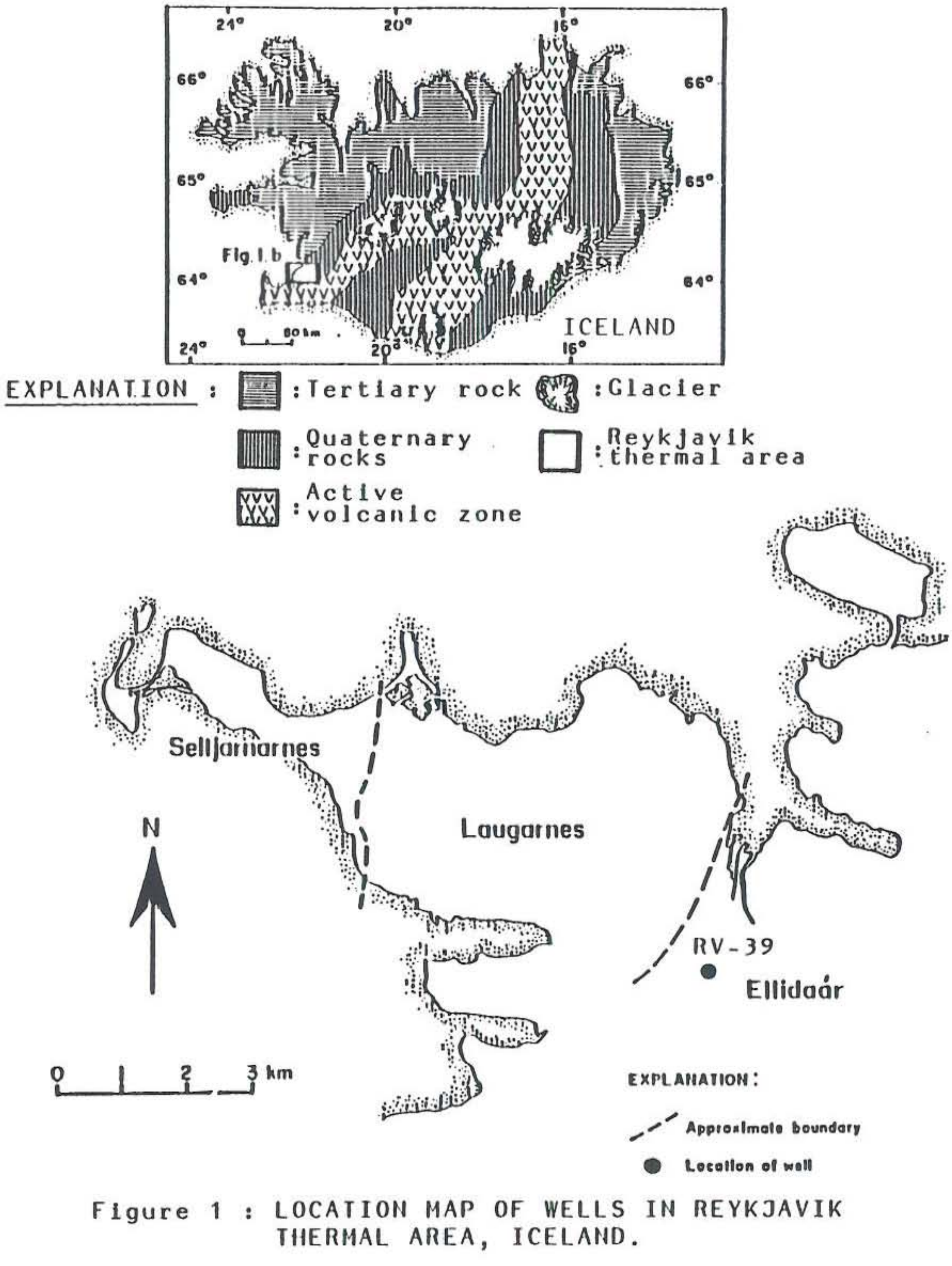


Figure 1 : LOCATION MAP OF WELLS IN REYKJAVIK THERMAL AREA, ICELAND.

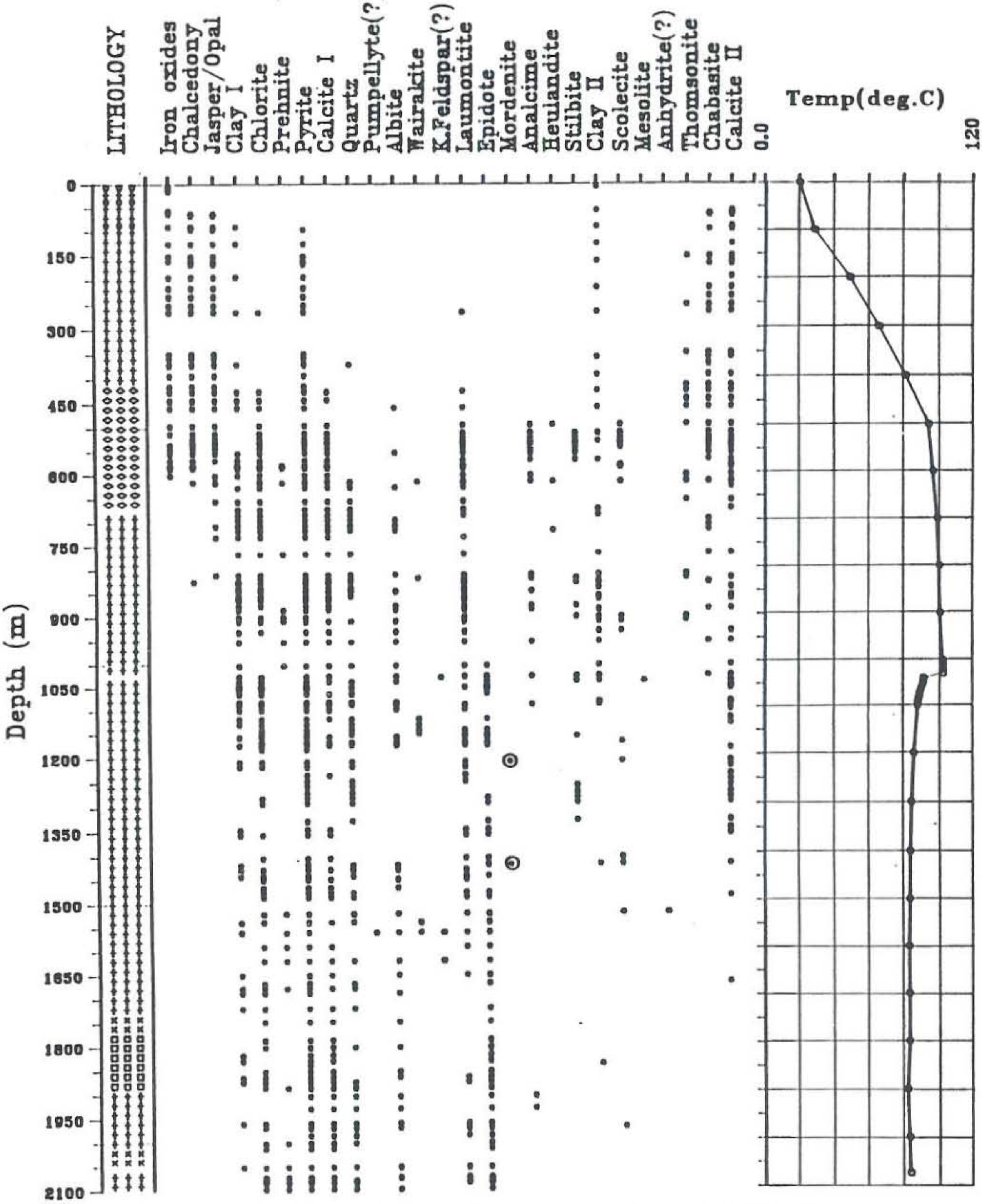


Figure 2 : Hydrothermal minerals in well RV-39.

┼┼┼	Basalt lava unit	○○○	Sediments
◇◇◇	Hyaloclastite unit	•	Thin section
×××	Dolerite unit	⦿	XRD-method
▫▫▫	Andesite lava unit		

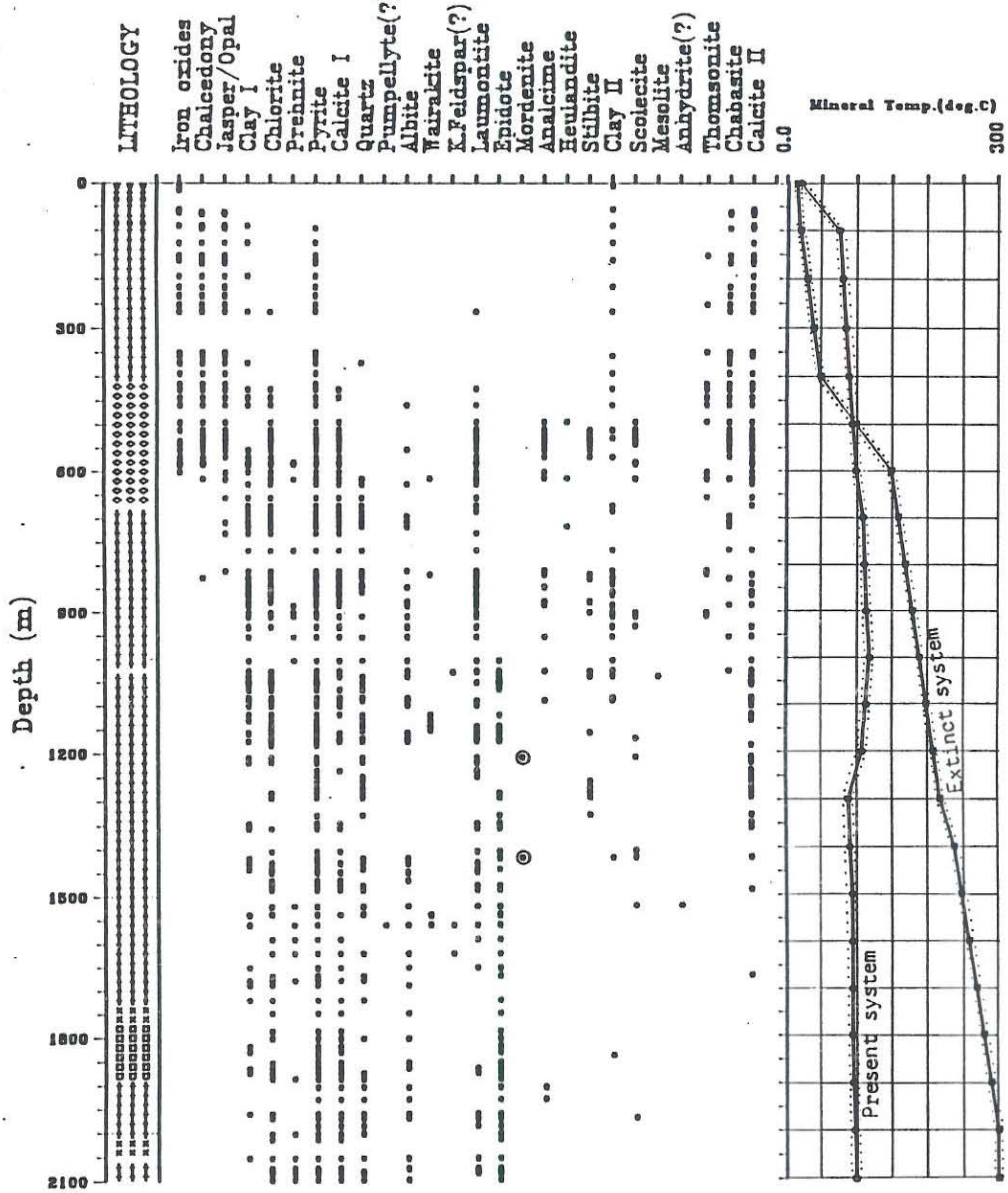


Figure 3 : Mineral temperatures show two hydrothermal system influenced in well RV-39.

┼┼┼ Basalt lava unit
◊◊◊ Hyaloclastite unit
xxx Dolerite unit
▭▭▭ Andesite lava unit
○○○ Sediments
• Thin section
⊕. XRD-method

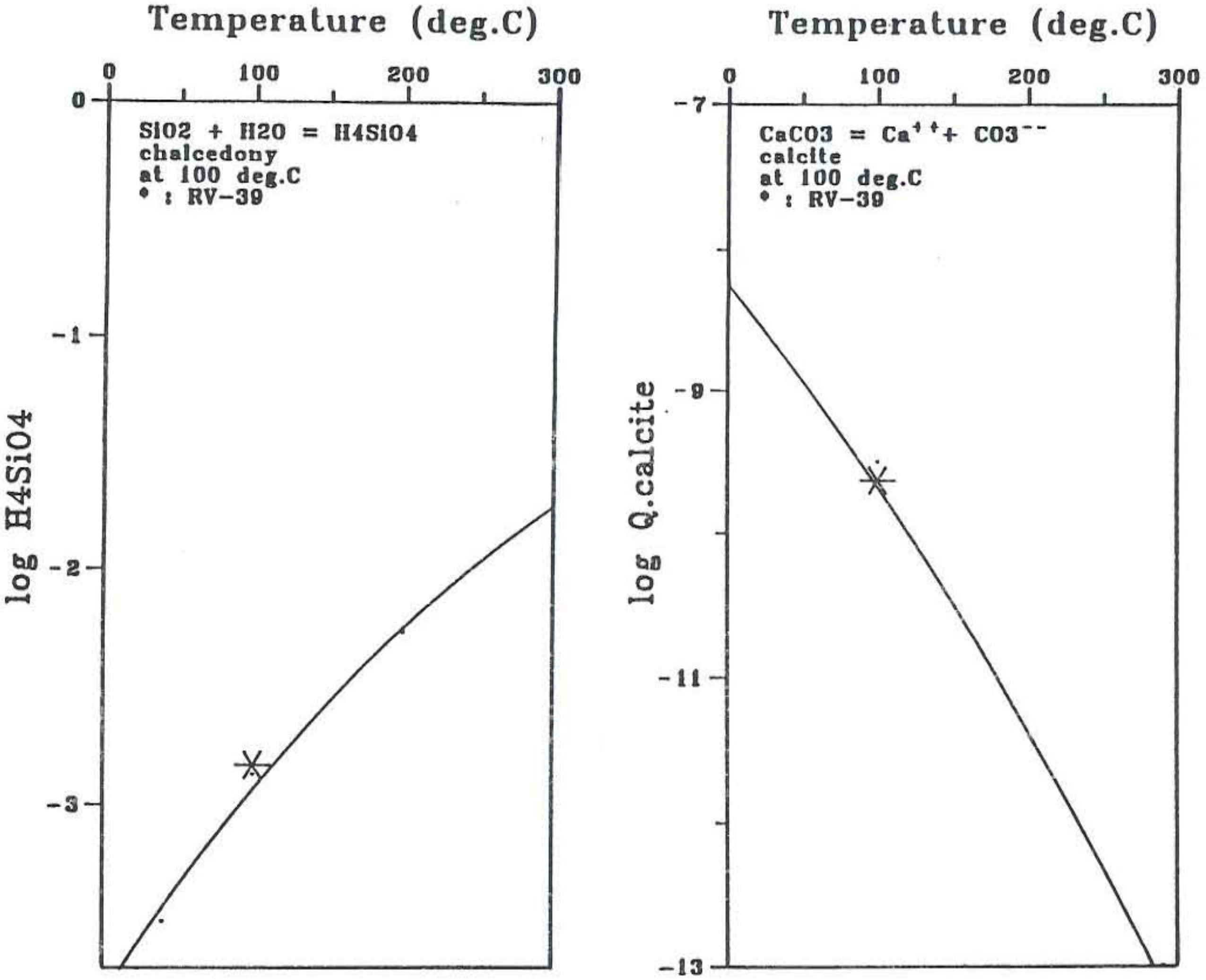
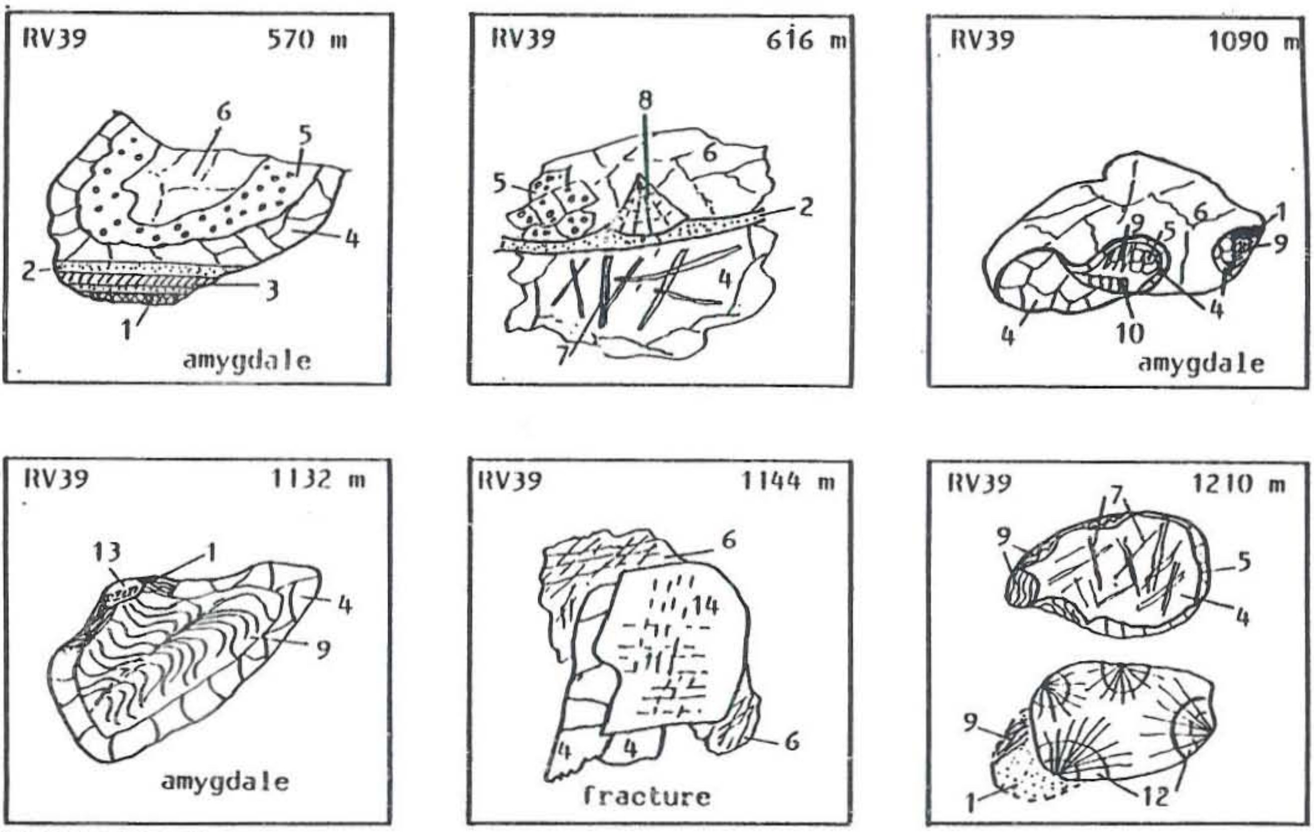


Figure 4 : Ionic activity and solubility product diagram of RV-39 deep water at 100°C.



EXPLANATION :
1: clayI 2: chalcedony 3: jasper 4: quartz 5: laumontite 6: calciteII
7: mordenite 8: thomsonite 9: chlorite 10: epidote 11: prehnite
12: scolecite 13: albite 14: wairakite

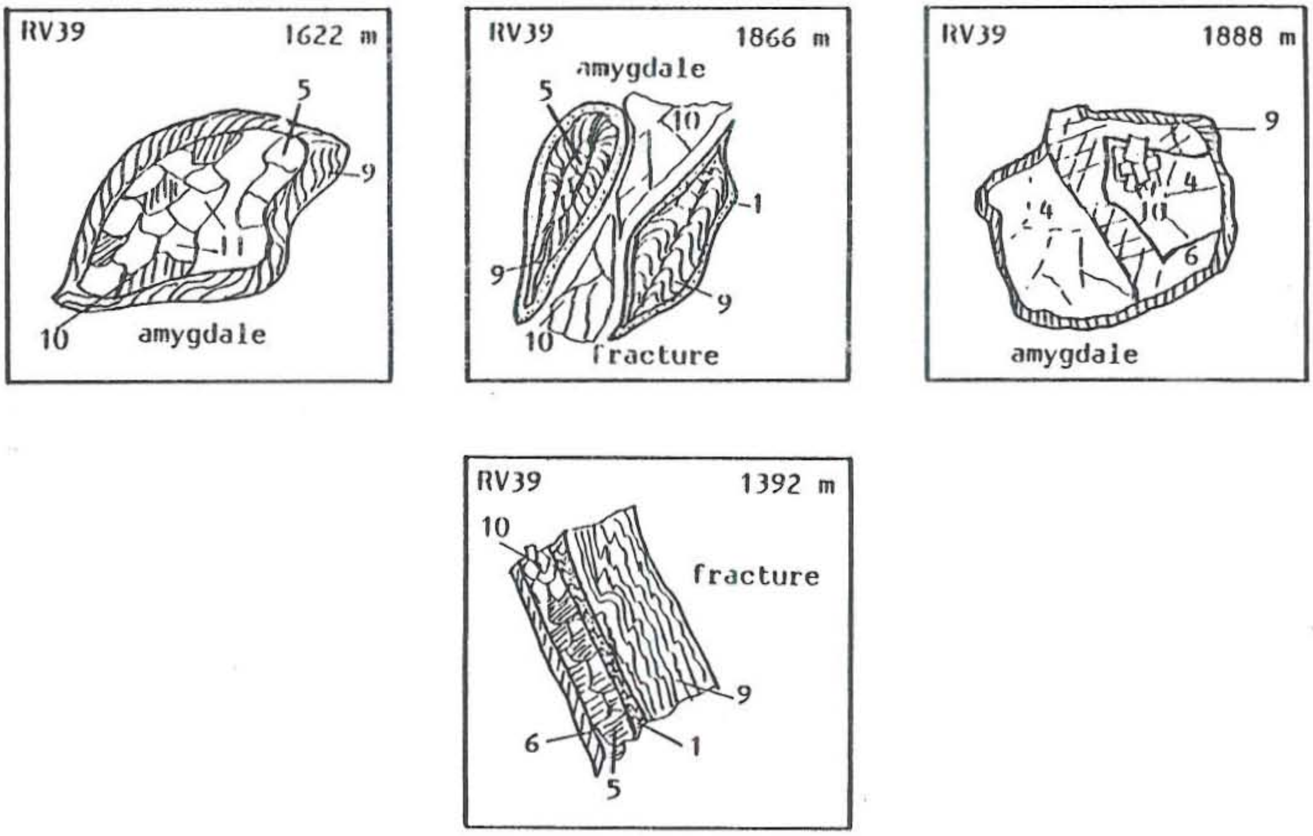


Figure 5: Cross cutting relationship of veins and depositional sequence in amygdale / fracture, in RV39

Figure 6 : The secondary mineral evolution in well RV-39.