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BOREHOLE GEOLOGY OF WELL RN-9, REYKJANES, SW-ICELAND

Johnson Mungania,
UNU Geothermal Training Programme,
Grensasvegur 9,
108 Reykjavik,
ICELAND

Permanent address:
The Kenya Power & Lighting Co. LTD,
Olkaria Geothermal Project,
P. O. Box 785,
Naivasha,
KENYA

ABSTRACT

Well Rn-9 is the largest producer in the Reykjanes high temperature geothermal field. Analyses of drill cuttings were done and results used with other downhole measurements to interpret some conditions of the well. Ten probable locations of aquifers have been identified on the basis of circulation loss measurements, temperature profile anomalies, variations in hydrothermal mineral intensity and intensity of veining. The aquifers above 600 m are controlled by permeability along stratigraphic units whereas those below are mostly controlled by permeabilities adjacent to basaltic intrusions. Petrographic and XRD studies of the cuttings show four alteration zones in this well; a smectite-zeolite zone, a mixed layer clay zone, a chlorite belt and a chlorite-epidote zone. Interpreted formation temperatures based upon hydrothermal alteration minerals indicate temperatures of about 110°C at shallow depths of 82 m increasing rapidly to about 200°C at 310 m depth and over 250°C at about 600 m depths. Temperatures of 270°C at about 700 m depth are indicated by occurrence of wollastonite. Disappearance of calcite and presence of garnet indicate temperatures above 290°C at about 1000 m depth. Although the maximum measured temperature in the well is 295°C, occurrence of calcite as the latest deposition about 1100-1250 m depth may indicate lower temperatures at this depth interval. Correlations of occurrence of hydrothermal alteration minerals in the other wells in Reykjanes show that the geothermal system was more extensive in the past, as seen by occurrences of high temperature minerals at shallow and cold parts of some of the wells.

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1. INTRODUCTION

This project is part of a training in geothermal studies. The author was awarded a six months United Nations University Fellowship which was attended in Reykjavik, Iceland. In addition to studies on all aspects of geothermal energy, a specialised training in borehole geology was undertaken which included detailed lectures and practical aspects of borehole data analysis and interpretation. This report was compiled from cuttings analysis of well Rn-9, Reykjanes, Iceland.

1.1 The Reykjanes high-temperature field

The Reykjanes geothermal field is located at the tip of the Reykjanes peninsula in SW-Iceland. This marks the locality where the Mid-Atlantic Ridge emerges above sea level (Figure 1). An ENE-WSW trending seismic zone underlies the area at a depth of about 2 km (Bjornsson et al., 1970), and is interpreted to be marking the plate boundary. The crust above 2 km depth is characterised by NE-SW trending volcanic fissure swarms which describe a right stepping en echelon structure over the area. The geothermal activity within the peninsula is associated with the localities where the fissure swarms intersect the underlying seismic zone. Seismological studies (Palmason, 1971) show existence of four different geophysical layers representing the crust below Reykjanes which is about 8.5 km thick.

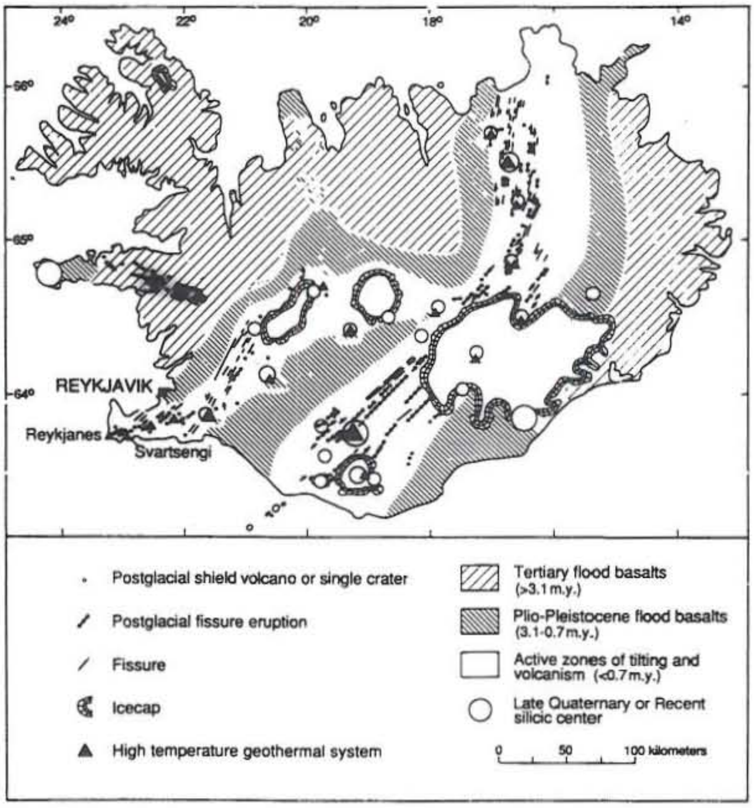

FIGURE 1: The volcanic zone of Iceland and the location of the Reykjanes high-temperature field (Lonker et al., 1993)

Exploration in Reykjanes geothermal area started in the early fifties and the first well was drilled in 1956. Geological maps and surface exploration surveys followed in 1960s (Lindal and Ludviksson, 1969). In 1968 and 1969, six wells were drilled to explore the extent of the field. Well Rn-8, which was drilled in 1969 with a purpose of deep exploration as well as to study chemistry and other properties of the reservoir, was successful. A geothermal model was constructed in 1971 for the Reykjanes reservoir based on available data (Bjornsson et al., 1971).

Well Rn-9 was drilled in 1983 about 200 m south of well Rn-8 as a replacement well. It was sited at a location where there was reasonable assurance of hitting permeability for production. Figure 2 shows the location of wells in the Reykjanes field and Table 1 lists the boreholes and their conditions. The last two wells, Rn-8 and Rn-9, are good producers and supply a salt extraction plant located in the field with brine and steam. Salt (NaCl) is extracted from the hot (280°C) geothermal brine.

Surface geology of the Reykjanes field and the surroundings is shown on Figure 2. The rocks include hyaloclastites (which consist of pillow lavas, tuff and breccia, which result from eruptions under glacial conditions), post glacial shield volcanic lavas and the youngest being fissure erupted lavas. All the rocks are basaltic by composition. Some faults and fissures are clear on the surface (Figure 2), more may be buried under the accumulative volcanics.

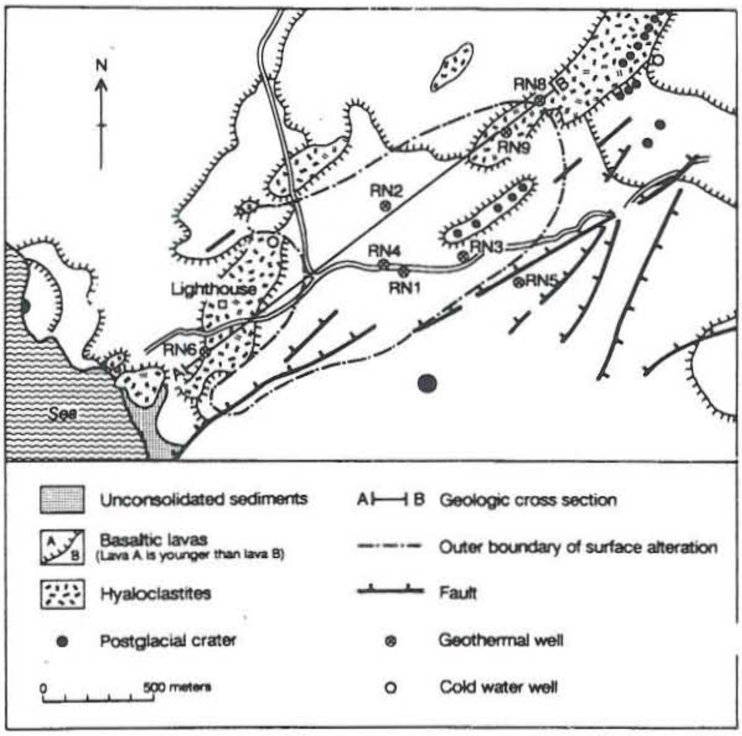

FIGURE 2: Surface geology of the Reykjanes geothermal field (Lonker et al., 1993)

Figure 3 shows the resistivity map of the Reykjanes field. The very low resistivities are associated with the chemistry of subsurface water with sea water component expressed in the high salinity. The 3 Ωm contour line is interpreted to show the extent of the thermal plume. This encloses an area of about 1 km^2 (Bjornsson et al., 1970).

TABLE 1: Status of wells in the Reykjanes high-temperature field

Well no.	Date (year)	Depth (m)	Casing (m)	T_{max} (°C)	Total flow (kg/s)	Steam flow* (kg/s)	Remarks
1	1956	162	12	-	-	-	Collapsed
2	1968	300	43	225	26	1.7	
3	1968	1166	242	-	-	-	Collapsed
4	1968	1036	245	250	19	3.5	Out of order
5	1969	112	41	-	-	-	Drilling abandoned
6	1969	572	222	-	-	-	Cold
7	1969	70	38	-	-	-	Cold
8	1969	1754	297	298	67	21	Connected to plant
9	1983	1445	529	295		181**	Connected to plant

* at 6 bar, ** at 21 bar

High heat flow in the Reykjanes area heats the saline ground water causing a convection. Since the water table here is at the same elevation as ground water surrounding the system, the pressure within the system is lower, allowing saline sea water to flow into the system to replace what is lost at the surface by geothermal activity. A pressure difference of about 10 atmospheres was measured at a depth of 1700 m (Tomasson and Kristmannsdottir, 1972).

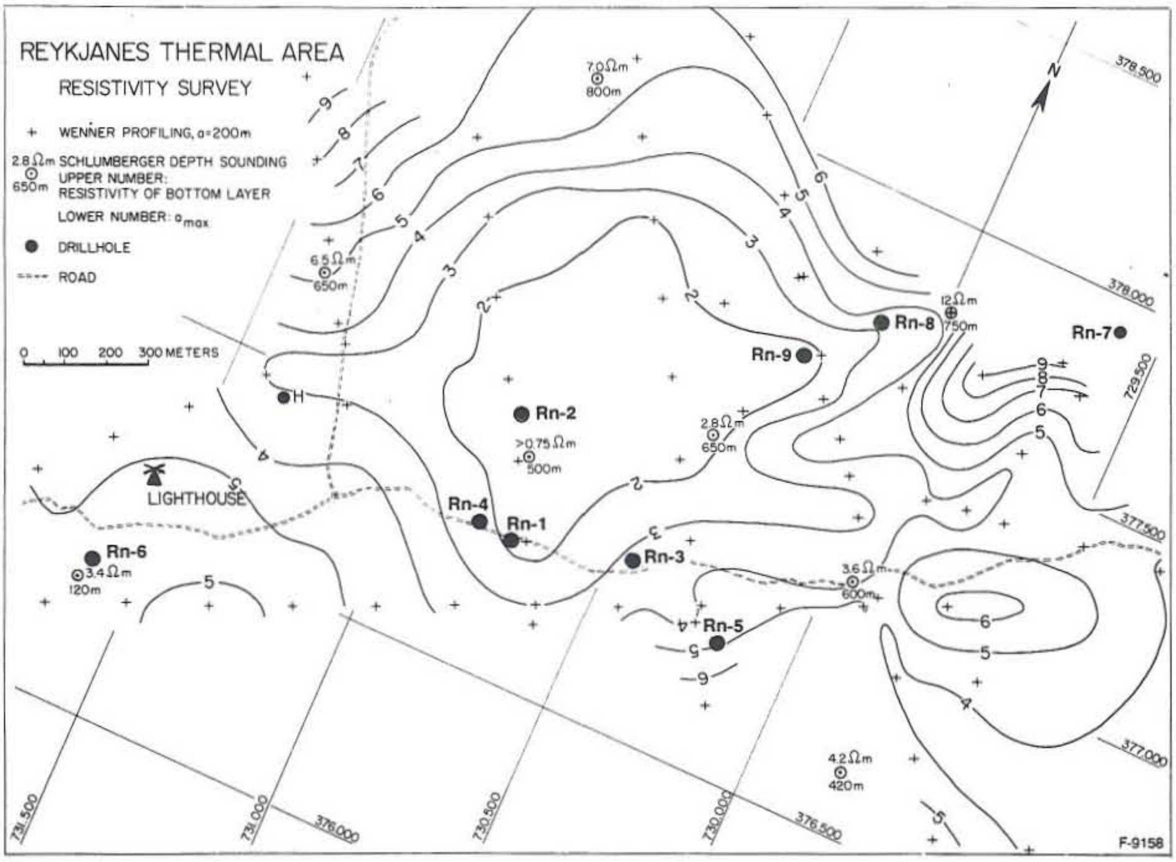

FIGURE 3: Resistivity map of the Reykjanes high-temperature field (mod. after Björnsson et al., 1970)

Chemical characteristics of geothermal fluids in high-temperature systems are governed by chemical composition of the recharge, type of rock it interacts with and temperatures in the system. In Reykjanes, the recharge is by influx of sea water into a high-temperature system through permeable volcanics. A comparison of Reykjanes geothermal water with sea water is shown in Table 2. Generally, the geothermal brine is enriched with NaCl by about 1.6 times, Na^+ and Ca^{2+} by about 5 to 6 times. Mg^{2+} and SO_4^{2+} are reduced by about 30 times. The difference in chemistry between the geothermal brine and the sea water is due to the non-complex water-rock interactions and flashing of the geothermal fluids (Arnorsson, 1974)

1.2 Scope of investigation

The most direct way of studying the subsurface geology of a field is by making downhole measurements and studying samples from a drilled well. Measurements done during drilling e.g. circulation losses and penetration rates and those taken after the completion of the well are important in determining various geological aspects of the well. Variations in lithological units, physical characteristics like formation permeabilities, temperatures in the well, etc. may be determined from these measurements. These parameters together with cuttings analysis are used to locate aquifers and characterize the reservoir of the field.

Hydrothermal alterations of rocks have a strong relationship with the activity of a geothermal system. Mineral formations depend on temperature, formation permeability and composition of the fluids. Hydrothermal mineral assemblages are used to determine the possible ranges of temperatures which may have affected the formations. Changes of formation temperatures by cooling or warming up may be indicated by new mineral assemblages overprinting on the old ones.

TABLE 2: Comparison of the chemistry of the Reykjanes well Rn-9 thermal waters and sea water (Fridleifsson, 1981)

Component	Well Rn-9	Sea water
Temperature (°C)	295	-
SiO_2	584	6.0
B	-	-
Na^+	9120	10,470
K^+	1387	380
Ca^{2+}	1475	398
Mg^{2+}	0.87	1250
CO_2 (total)	1842	100
SO_4^{2-}	17.8	2630
H_2S (total)	58.1	-
Cl^-	17,634	18,800
F^-	0.15	1.26
Dissolved solids	30,272	33,900
H_2	0.14	

Clays are of particular importance because they show structural transformation at some given temperatures. Determination of hydrothermal minerals in the rock samples is done using binocular and petrographic microscope and X-ray diffraction for identification of clays. These simple but effective methods were used to study well Rn-9 samples for this project.

All the background information regarding geology, hydrogeology and other aspects about Reykjanes area have been referred from existing litterature. Cuttings analysis data of well Rn-9 from Franzson et al., (1983) is incorporated. Also thin section analysis and XRD data on clay analysis by Tomasson and Kristmannsdottir (1972) and Kristmannsdottir (1971), respectively, for other wells of Reykjanes field are used in correlations.

2. WELL STRATIGRAPHY AND OTHER DOWNHOLE DATA FOR WELL RN-9

Well Rn-9 was drilled between April 11th and May 6th 1983. The well was drilled to a depth of 1445 m. A 13 ⅝" production casing was set at 524.6 m and 12 ½" slotted liners put to the bottom. Figure 4 shows the drilling plan and the drilling progress of well Rn-9 plotted together.

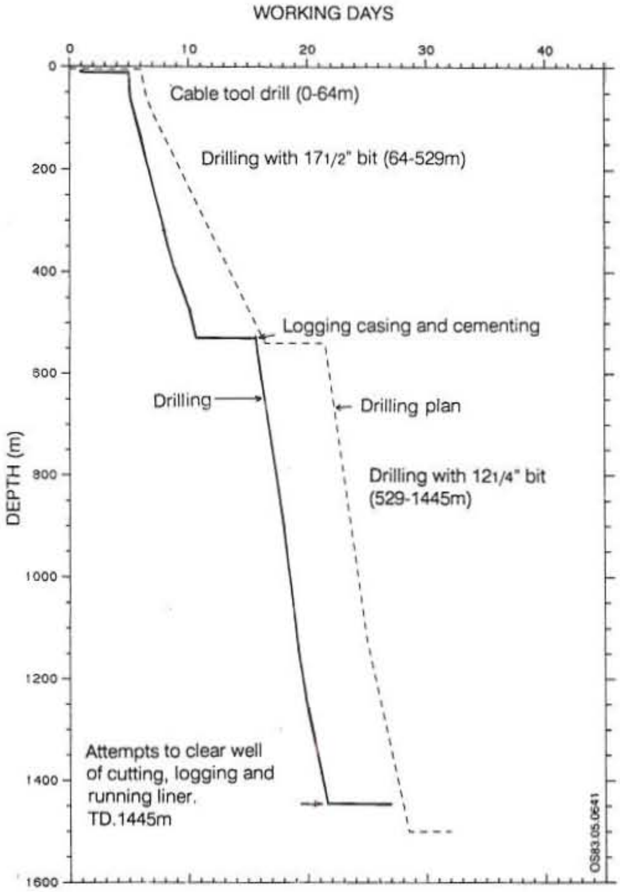

FIGURE 4: Drilling of well Rn-9 (Franzson et al., 1983)

2.1 Stratigraphy column

All the rock units cut by well Rn-9 are volcanics. The lithological column plotted together with some drilling and geophysical logs is shown in Appendix I. The various rock units vary in texture rather than chemical composition. In the upper 800 m, hyaloclastite units are dominant (≈ 70%). In the lower part, basaltic lavas are dominant (≈ 80%). Few intrusives have been cut by this well. Correction for cuttings travel time in the well has been done for the lithological section shown in Appendix I. The following are descriptions of the various stratigraphic units as given by Franzson et al., (1983) based upon cuttings analysis:

0-206 m - Hyaloclastite. Hyaloclastite tuff is dominant in the upper part but basalt and breccia layers exist in the bottom part.

206-278 m - Basalt. A total of seven basalt layers were identified, probably lava flows.

278-335 m - Hyaloclastite. Two tuff layers and one of basalt are found above 300 m, overlying a thick (>30 m) tuff sediment.

335-381 m - Basalt. Two almost equally thick basalt layers were identified divided by an approx. 4 m thick layer of tuff sediment.

381-587 m - Hyaloclastite. A homogenous glassy tuff layer is dominant to about 500 m with a tuff sediment and a glassy basalt below.

587-708 m - Basalt. At this depth range at least seven basalt layers are found, and are interpreted as being lava flows. Thin hyaloclastite layers are found in the middle of the series.

708-829 m - Hyaloclastite. Hyaloclastite tuff is dominant almost to the depth of 800 m where a glassy basalt comes in, probably pillow lava.

829-1054 m - Basalt. About 12 lava layers exist at this depth range with few thin hyaloclastite layers in the middle. Between 940-964, 972-977, 979-981 and 995-999 m, it is likely that the well cuts basalt intrusions.

1054-1092 m - Hyaloclastite. Tuff is the most noticeable lithological unit here with one interstratified layer of glassy basalt.

1092-1143 m - Basalt. Four separate basalt layers are noticed of which two are probable intrusions i.e. at 1092-1110 m and 1136-1143 m.

1143-1215 m - Hyaloclastite. A large part of the lithology at this depth range is tuff sediment except the hyaloclastite breccia found from the depth of 1100-1195 m

1215-1326 m - Basalt. A total of eleven basalt layers were found at this depth range. It is probable that six of them are intrusions, i.e. at 1243-1252, 1252-1262, 1268-1278, 1281-1281, 1285-1299 and 1305-1326 m. The basalt intrusions are characterized by their relatively fresh cuttings, dense without any vesicles. The well logs can also be used to identify the locations of intrusives, they show low penetration rates and slightly higher resistivities. Their neutron-neutron responses are similar to basalt lavas.

1326-1344 m - Hyaloclastite. Hyaloclastite is dominant at this depth range.

1344-1445 m - No samples recovered. Although no samples were recovered from this depth range due to total loss of circulation, a look at the geophysical logs shows that the hyaloclastite mentioned above may be continuous to a depth of about 1404 m with a 3 m thick basalt layer at 1366-1370 m and another one between 1393-1395 m. A basalt layer comes in at 1412 m and is possibly continuous to the well bottom.

2.2 Well logs

Some of the measurements taken during drilling are very useful for borehole geology evaluations. These include the penetration rate and loss and gain zones of the circulating drilling fluids. Appendix I shows the plot of penetration log along with other downhole data. Although no obvious rate of penetration is found for a given rock type, the log is good especially in marking the contact locations of various units. The circulation losses recorded were used to locate some of the aquifers (shown later in Figure 9).

Some **geophysical logs** are available for this well and are shown in Appendix I. Although measurements for the different parameters have a response to different conditions in the well, the apparently most interesting of these logs as regards geology is the neutron-neutron log. The log is quite good in discriminating between more dense basalts and glassy hyaloclastites. The following general characteristics of the curve for various rock types are observed:

a) Hyaloclastites (include here pillow basalts, pillow breccia and glassy tuff) have characteristically lower readings of about 600 API-nu with small variations of ±50.
b) Fresh basaltic lava flows generally have higher values of about 1150 API-nu with wider variations of about ±100, thus a very rough peaked curve.
c) The intrusives do not show any distinguishing characteristics from lava layers on the neutron-neutron log. However, the penetration rate shows relatively low values at depth ranges where intrusives are suspected due to other analyses.

In some cases a unit may show some intermediate characteristics due to textural variations (e.g. due to brecciation etc.). The resistivity log is characterised by generally low values because of the high salinity of the reservoir fluids. However, the values are even lower in hyaloclastites as compared to basalt layers (Appendix I). This is probably due to higher porosity and alteration of the former.

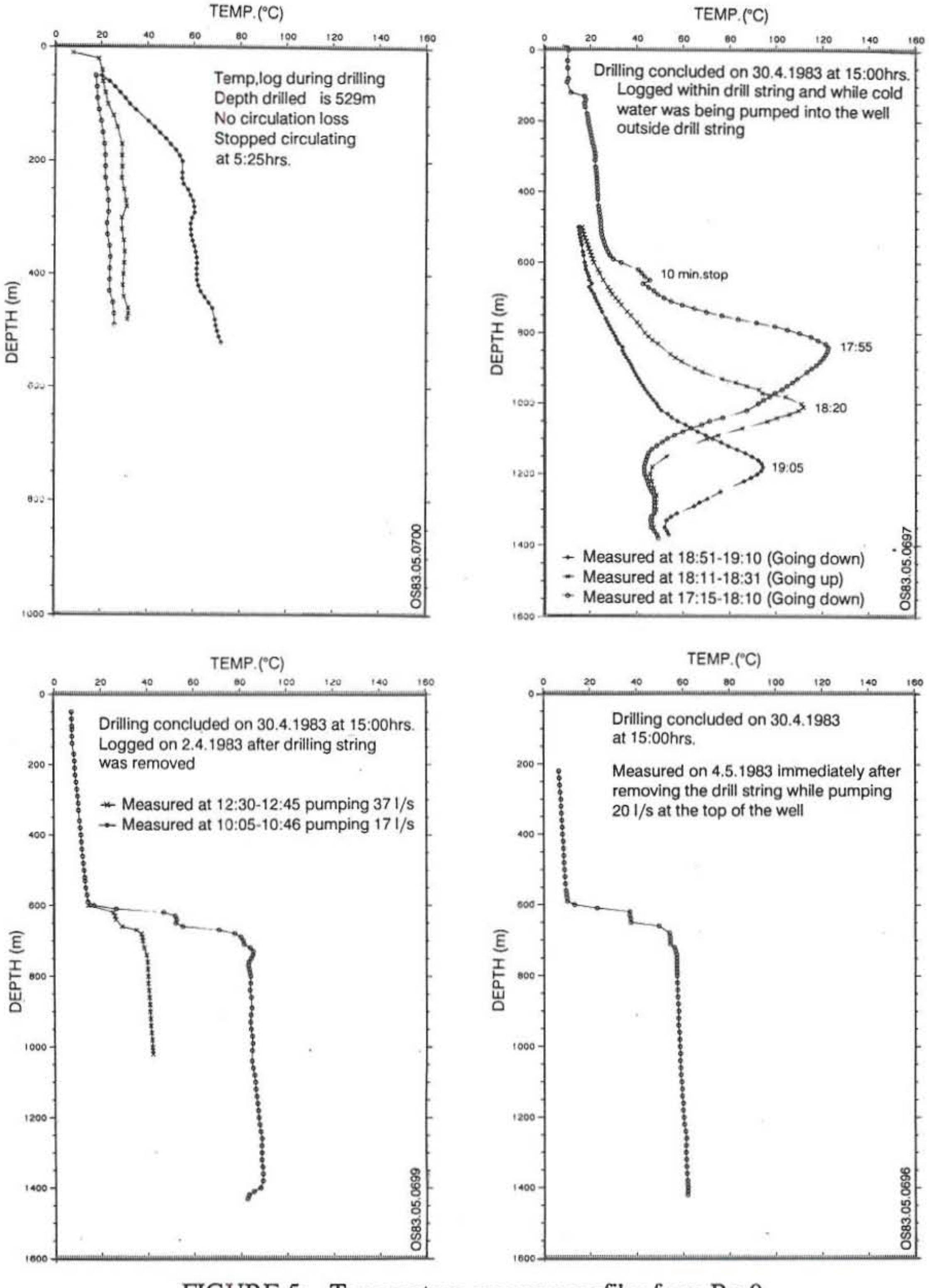

FIGURE 5: Temperature recovery profiles from Rn-9 (Franzson et al., 1983)

Although the **temperature logs** during drilling do not show the true rock temperature, they are very important in determining possible locations of feeder zones. Recovery curves are most valuable because they show where disturbances on the formation temperatures have been caused by drilling fluids (Stefansson and Steingrimsson, 1980). The modes of disturbances and the rates at which they die away relate to the permeability of the zones affected, temperatures and condition of fluids in these zones.

Figure 5 shows the temperature profiles during heating up of the well. Such curves give a lot of information on the state of the reservoir. However, the immediate obvious interpretations for geological interest are the possible locations of aquifer zones. Therefore, possible aquifer zones may lie within the intervals 390-450, 610-700, 1000-1060 and 1200 m and below, based upon generalised temperature profiles. A detailed aquifer analysis is presented later which relies quite a lot on the temperature profiles.

3. HYDROTHERMAL ALTERATION OF WELL RN-9

3.1 Analytical methods

Geothermal borehole geology revolves around the use of hydrothermal alteration mineral assemblages to interpret temperature and permeability conditions of the formations penetrated by the well. The most important data when studying borehole geology of a well are subsurface rock samples. Core samples are the best, but in the absence of core (as in the case of Rn-9), drill cuttings are used for analytical work. Other downhole measurements like geophysical logs (temperature, caliper logs etc) and drilling logs (like circulation losses and penetration rate) are used with cuttings examination results to make further interpretations of the subsurface conditions about the well. Examination of cuttings was done under reflection (binocular) microscope and 97 thin section of cuttings samples, covering the whole range of drilled depth, were analyzed under petrographic microscope. X-ray diffractometry method (Appendix I) was used for identification of clays in 20 samples selected for this well (Appendix II).

3.2 Alteration of primary minerals

Most of the rocks encountered in this well are volcanics. A good proportion of their composition is glassy because of fast cooling on eruption. Except at the middle parts of thicker lava flows, most of the rocks have some glass which shows varying degrees of alteration. The amount of clay from primary glass alteration is higher in hyaloclastite rock units. Alteration of the glass in the shallower depths is to olive greenish montimorillonite clay and sometimes brownish clays. Also, fine grains of calcite in clays and reddish oxides replacing glass are observed in samples from shallow (36 m) depths.

There is no progressive alteration of olivine and pyroxene with depth recognized, however some intensely altered lava units are occasionally encountered in the well e.g. between 400-500 m. Olivine is commonly replaced by clays in the altered basalts and only the original structures like the irregular cracks of the crystal can be used to infer that the original crystal was an olivine. Pyroxenes also show partial alteration to clays, especially in altered lava units.

Plagioclase feldspars are relatively unaltered in most parts of the well. However, there are some localities where they have altered to clays, calcite, epidote, quartz and sometimes partially displaced by albite. Partial alteration of some plagioclase crystals to clays is observed even at shallow depth samples (82 m) of the more altered units. Between 400-500 m, few samples show replacement of plagioclase by both clays and little calcite. Pronounced replacement of plagioclase by albite is seen in samples from about 800 m and becomes very common in 1268 m samples. Some samples from 1268 m and below 1300 m show growth of epidote and chlorite in plagioclase crystals. Also some tiny quartz grains may be the product of plagioclase alteration. This is observed in some samples from 1268 m and below.

3.3 Distribution of hydrothermal alteration minerals

A range of hydrothermal minerals is found in rocks of this well varying from low temperature zeolites to high-temperature minerals, like epidote. Figure 6 shows a plot of distribution of some of the minerals which could be readily identified.

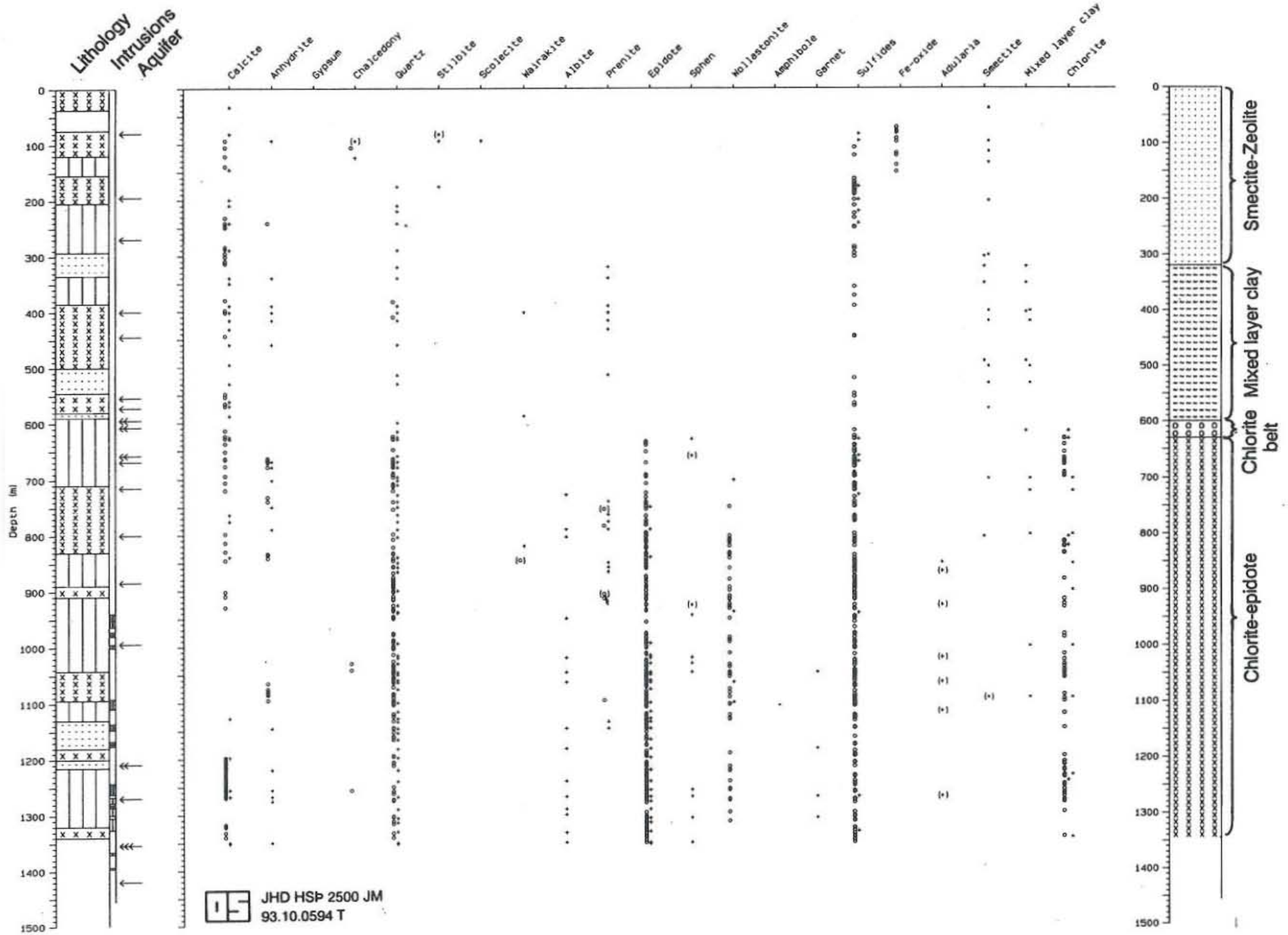

FIGURE 6: Distribution of hydrothermal alteration minerals in Rn-9

Description of occurrence and distribution of individual minerals in well Rn-9 is as follows:

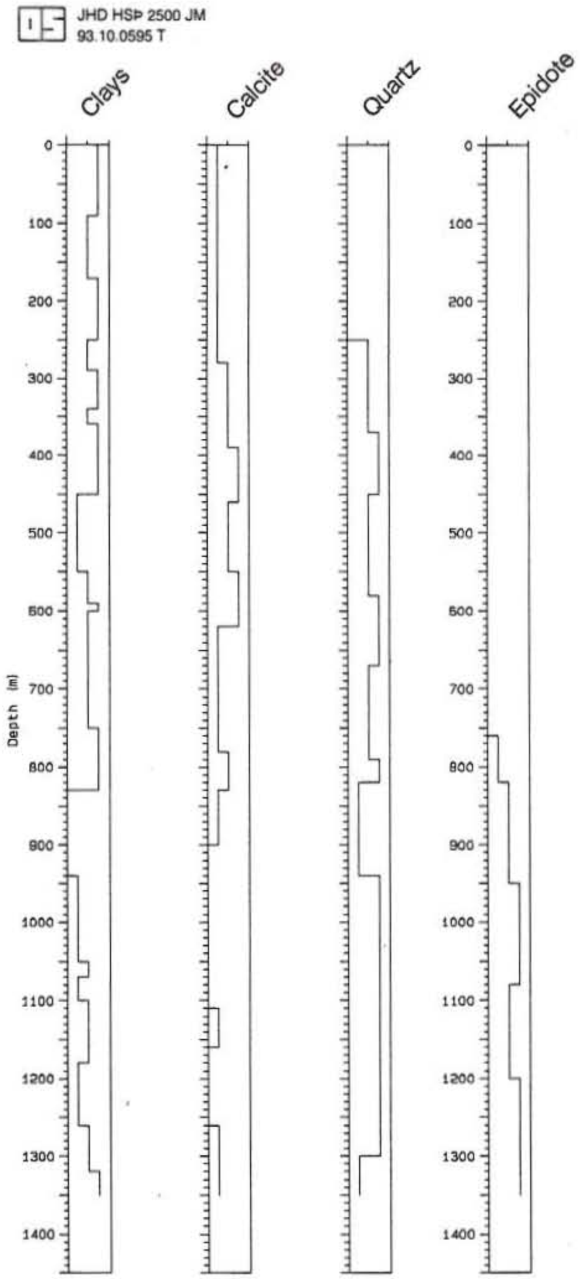

FIGURE 7: Relative abundance of common alteration minerals in Rn-9

Calcite is well spread in the well in varying quantities. It is first seen at a depth of 150 m. It is very abundant at around 400 m and 600 m. Very little calcite occurs between 800 m and 1100 m. However, it re-occurs again at 1150-1270 m depth range and again a little around 1320-1350 m. It is most widespread as very fine grains as alteration of primary minerals intermixed with clays. In the zones mentioned above, calcite crystals occur in veins and vugs with quartz, anhydrite and sometimes prehnite.

Anhydrite is found in the well mainly as a vein infilling, first occurring around 310 m depth and becoming very abundant between 400-450 m. It is also found in veins at around 800-900 m and below 1300 m. Zones of relatively intense anhydrite deposition probably mark localities at which incursions of sea water into the geothermal system occurred (Tomasson and Kristmannsdottir, 1972).

Quartz is a very widespread hydrothermal mineral in the well. It first appears at 190 m depth in filling openings. Well formed crystals start appearing at 270 m depth. Sporadic increases of quartz veins correspond with increases of other mineral veins as seen in Figure 7. It occurs in veins with all other deposition minerals such as calcite, wollastonite and almost always present where there is epidote. Quartz seems to be one of the most widespread alteration minerals. It sometimes occurs in earlier phases of mineral deposition as well as later ones. Instances of quartz veins cutting other quartz veins are observed in some samples (Table 3).

Zeolites are only present in the shallower parts of this well. The depth at which they occur in abundance is in a sample from 82 m depth. The zeolites in this sample are probably **stilbite** and **scolecite**. Lesser amounts of stilbite are observed in a sample from about 178 m. **Wairakite** was found in samples from 400, 616 and 820 m. It occurs as a vein infilling with calcite and prehnite.

Prehnite is first encountered just below 300 m as a deposition in veins. It is very abundant in 400-450 m depth range. Some veins containing prehnite are also found around 800 and 1260 m (and below). Most of the prehnite found in the cuttings is of older phase of hydrothermal deposition as can be seen in Table 3 showing the mineral deposition sequences.

TABLE 3: Sequences of mineral deposition in veins in Rn9
(for samples where any order is determinable)

Depth (m)	Deposition sequence	Remarks
390	Clays ⇒ Calcite	Latest phase calcite
402	Calcite ⇒ Quartz	
416	Prehnite ⇒ Quartz+Anhydrite	Prehnite is an older phase of deposition,
462	Prehnite ⇒ Calcite	incursion of sea water into the system
460	Calcite ⇒ Quartz	causing deposition of anhydrite; then later
486	Clays ⇒ Calcite	deposition of calcite
	Clays ⇒ Calcite	
628	Clays ⇒ Quartz	
680	Clays ⇒ Quartz	
710	Clays ⇒ Quartz	
764	Clays ⇒ Quartz	
800	Epidote ⇒ Wollastonite	Wollastonite postdates most of the minerals
938	Clay ⇒ Quartz+Wollastonite	
996	Quartz ⇒ Epidote	
1016	Quartz ⇒ Epidote	
1050	Clays ⇒ Quartz ⇒ Epidote	
1090	Quartz+Epidote ⇒ Wollastonite	
1146	Prehnite ⇒ Quartz ⇒ Calcite	
1154	Quartz across Quartz	Several generations of quartz (ab. 1154 m)
1220	Clays ⇒ Epi+Pyr ⇒ Epi ⇒ Wollast	
1256	Clays ⇒ Epidote	
1268	Clays ⇒ Quartz ⇒ Pyr ⇒ Calcite	Occurrence of late phase calcite at this depth
1312	Quartz+Epidote ⇒ Wollast	is difficult to interpret.

Epidote is first noticed in cuttings from 634 m depth. It becomes very abundant between 850-1100 m. It also occurs abundantly below 1200 m to the well bottom. It occurs as deposition in veins and also as a product of plagioclase alteration at deeper parts of the well (e.g. samples from 1040 and 1268 m). In this well it occurs mainly intergrown with quartz crystals.

Wollastonite first occurs in a sample from 700 m and is abundant in samples from 938 m depth. Other cuttings samples bearing wollastonite are from 1100 and 1268 m depths. It is found in veins and vesicles, mainly with quartz. In most of the veins where it occurs with other minerals, it is the last to be deposited (Table 3).

Although pyrite is the most abundant, other **Sulphides** such as chalcopyrite and sphalerite are also present. Pyrite occurs almost throughout the well as small disseminated mineral grains in the rock. In some depth zones, it is more concentrated and occurs in veins. This includes 80-200, 600-700, around 1000 and below 1200 m depth ranges. An attempt was made to locate feeders using intensity of pyrite mineralisation based upon mineral grains count in sample cuttings (Figure 9, see later). The shallower (<200 m) sulphide deposition zone is assumed to be due to mixing of cold oxygen rich surface waters with hot reduced thermal waters from below.

Clays are present in all parts of this well. They occur both as a product of alteration of primary minerals and as a secondary deposition in vesicles and veins. The proportion of clay minerals at a given depth depends on the rock type (mainly the original proportion of glass in the rock).

Hyaloclastites have more clay content than coarser lava units. Appendix III shows the XRD results for clay identification in samples from selected depths. Distribution of various clays with depth is described below.

Smectites are the only clays to the depth of 300 m. In thin section, they appear as brownish, low birefringence with variable refractive index. They occur as poorly crystallized masses lining openings. They are identified on the XRD traces by their peaks occurring at 13.4-14 Å (constant humidity ≈ 35%), expanding to about 17 Å on treatment with glycol and collapsing to about 10 Å on heating to 550-600°C. Typical peaks for a sample from 36 m depth bearing smectites are shown in Appendix III. Smectites are also found with other clays in samples down to 800 m depth (Appendix III).

Mixed layer clays found in this well are mainly interlayered smectite-chlorite. In thin section, they are brown to yellowish with low birefringence. Mixed layer clays are transitional, hence, their optical properties vary. They are identified on the XRD traces by broad peaks around 14-17 Å (for constant humidity), expanding to 31 Å on saturation with glycol and collapse to 12-14 Å on heating to 550-600°C. An example of results for a sample bearing mixed layer clays from 400 m depth is shown in Appendix IV. The mixed layer clays are identified (with XRD) in samples between 400 and 500 m, also occurring at 700-800 and some around 1000 and 1100 m depths (Figure 6 and Appendix III).

Chlorites are found both as infilling and replacing ferromagnesian minerals at deeper parts of the well. They are identified (with XRD) in samples from 700 m, although they are suspected to occur as shallow as 600 m (in thin section samples). This variety of clays occurs down to the well bottom. Chlorites are pale greenish and have very low birefringence under microscope. They are characterised by peaks occurring at 14-15 Å (constant humidity) and remaining unchanged for glycolated and heating to 550-600°C. Typical peaks for chlorite clays are shown in Appendix IV for a sample from 1342 m depth.

Several **other alteration minerals** exist in this well; **Albite** was found in samples at 800 m and below occurring as a replacement of plagioclases. The albitization of plagioclase feldspars is most common in samples of altered units below 1300 m depth. **Sphene** is first observed in samples from 660 m as alteration of mainly opaque mineral grains and magnetite. It continues to occur sporadically with main occurrences being in the altered hyaloclastite unit at 1140-1190 m depth range. **Garnet** was found in samples from 1046, 1180, 1268 and 1310 m. Lonker et al., (1993) also reported some at depth range of 1050-1350 m in this well, occurring as poorly formed clusters with epidote, calcite, anhydrite and chlorite. It is identified by its high refractive index and isotropic optics. **Adularia** probably occurs at 938 m depth and several vein samples from 1064 m depth also have adularia and quartz deposits.

3.4 Alteration minerals zonation

Alteration mineral assemblages are useful in determining hydrothermal conditions and temperatures which exist at different depths in the well. Occurrences of some minerals whose temperature of formation is known are used to infer possible formation temperatures. It should be noted, however, that some of the minerals may be representing fossil conditions, thus past formation temperatures. Some geothermal alteration zonations for basaltic rocks in Iceland have been described by several authors e.g. Kristmannsdottir and Tomasson (1974). Four alteration zones are interpreted for well Rn-9 (Figure 6). These are: Smectite-zeolite zone, mixed layer clay zone, a chlorite belt and chlorite-epidote zone.

The **smectite-zeolite zone** extends to about 310 m from the surface. Abundance of zeolite in sample from 82 m indicates temperature of up to 100°C at this shallow depth. Entry of mixed layer clay (310 m) and prehnite (350 m) suggest temperatures ≥200°C.

A **mixed layer clay zone,** mainly interlayered smectite-chlorite starts occurring in samples at 310 m depth. Intense occurrence of prehnite between 400-500 m depth implies temperatures exceeding 200°C. Gradual transformation of smectites to chlorites occurs between 200 and 230°C. This occurs possibly between 310 and 600 m in this well where most of the smectite is transformed into chlorites.

A narrow belt defined by occurrence of **chlorite** clays without epidote exists within 600-617 m depth interval (Figure 6). This possibly defines temperatures of 220-250°C.

A **chlorite-epidote zone** is far better defined by epidote, which first starts appearing in samples from 617 m depth. Epidote becomes very abundant in the rock below 800 m depth. Constant and continuous occurrence of epidote indicates temperatures of ≥250°C. Higher temperatures in this zone, possibly 270°C and above are indicated by presence of wollastonite at about 700 m depth. Garnet occurrence at 1040 m and below is indicative of even higher temperatures at deeper parts of the well.

3.5 Temperatures

Figure 8 shows the temperature ranges at various depths as interpreted from the different hydrothermal mineral assemblages. Measured temperatures based upon a temperature profile taken on 8/3/1992, about nine years after the well was drilled, are assumed to represent temperatures close to formation temperatures. This is plotted together with hydrothermal mineral temperatures (Figure 8). The progressive alteration with depth is apparent from the variation in alteration mineral assemblages encountered at different depths. Occurrence of zeolites at less than 200 m indicate temperatures of about 100°C at these shallow depths. Quartz deposits start occurring at about 190 m indicating possible temperatures of

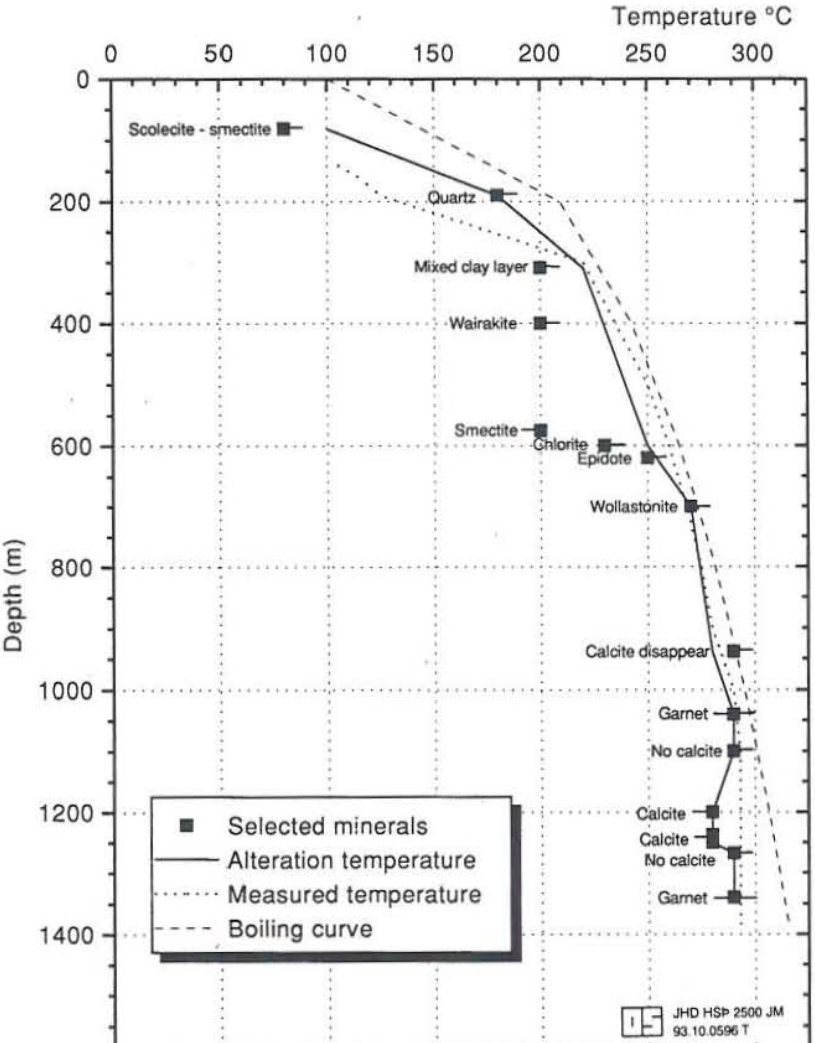

FIGURE 8: Plot of hydrothermal assemblage interpreted temperatures in well Rn-9

about 180°C. Temperatures of about 200°C at depths of 310 m are indicated by entry of mixed layer clay. Wairakite occurrence at 400 m indicate that temperatures may exceed 200 m at this depth, however, reoccurrence of smectite without presence of mixed layer clay at 575 m may indicate lower temperatures (≤200°C) at this depth. At 600 m depth, occurrence of chlorite clays, and epidote at 617 m depth indicate temperatures about 230 and 250°C respectively. Occurrence of wollastonite at about 700 m indicates temperatures of about 270°C. Within a section between 800 and about 1100 m, calcite disappears, which may imply temperatures above 290°C. Garnet occurrence from 1040 m may imply high temperatures (≥290°C). However re-entry of calcite as a late deposition (Table 3) around 1150 to about 1250 m shows possibly lower temperatures (≤280°C) at these depths. Some prehnite and anhydrite is also found at a depth of 1268 m with calcite and very abundant epidote. These may be fossil and possibly concentrated here due to higher permeabilities in the lower parts of the well. Measured temperatures of 295°C in this part of the well (around 1200 m) are much higher than calcite and possibly a colder zone may be existing here but masked by stronger and hotter feeders from the well bottom. Presence of garnet in the samples from 1046 m and below are indicative of quite high temperatures. Lonker et al., (1993), based upon analysis of the composition of a garnet from Reykjanes, suggest that such andradite rich garnet would form at temperatures below 350°C. They suggested temperatures of 320-330°C for garnet occurrence in well Rn-9.

3.6 Alteration history

For the purposes of interpretation of the present thermal system around the well, it is important to consider the alteration mineral assemblages in relation to their relative times of deposition. This is because only the minerals that are closest in time relation to the present system may be used to interpret the conditions in the system. Studies of veins crosscutting and sequences of deposition of various minerals in openings are useful in determining the relative time of their deposition. Table 3 shows some of the recorded deposition sequences in samples from various depths.

From observations shown in the table, the following broad suggestion may be made; Calcite and quartz are the latest major phase of deposition in the 300-500 m and 1100-1250 m depth ranges, older major phases of deposition are represented by prehnite and clays. Quartz veins are the latest deposition mineral around 600-700 m but were preceded by clays. Below 800 m depth to well bottom, the alteration mineral deposition sequences may be generalised as;

Clays → Clays+Prehnite → Epidote → Epidote+Quartz → Wollastonite (in places).

It can be seen here that deposition of wollastonite is later than other minerals. In a few cases, it is found intergrown with quartz.

4. AQUIFERS

4.1 Aquifers in Rn-9

The term aquifer implies permeable zone or zones and may be represented by several feeders (Stefansson and Steingrimsson, 1980). Diagnostic characteristics of feeders include loss of circulation during drilling, anomalous temperatures during well heating up period and variations in hydrothermal mineral occurrence. Other measurements including pressure measurements may be used to locate feed zones. Variations in alteration intensity in the well may also be associated with permeability differences. Sharp increases in pyrite deposition and increase in intensity of vein fillings by prehnite, anhydrite and calcite between 400-550 m is also seen in other wells; in well Rn-8 at 300-500 m, in Rn-4 at 500-600 m. The increased intensity of the alteration minerals in this zone may indicate that the aquifer here has been very active in the past. Concentration of well formed anhydrite indicate probable localities of earlier incursion by salty saline fluids. High concentration of calcite deposition indicates change of pH caused by boiling in an aquifer (Tomasson and Kristmannsdottir, 1974).

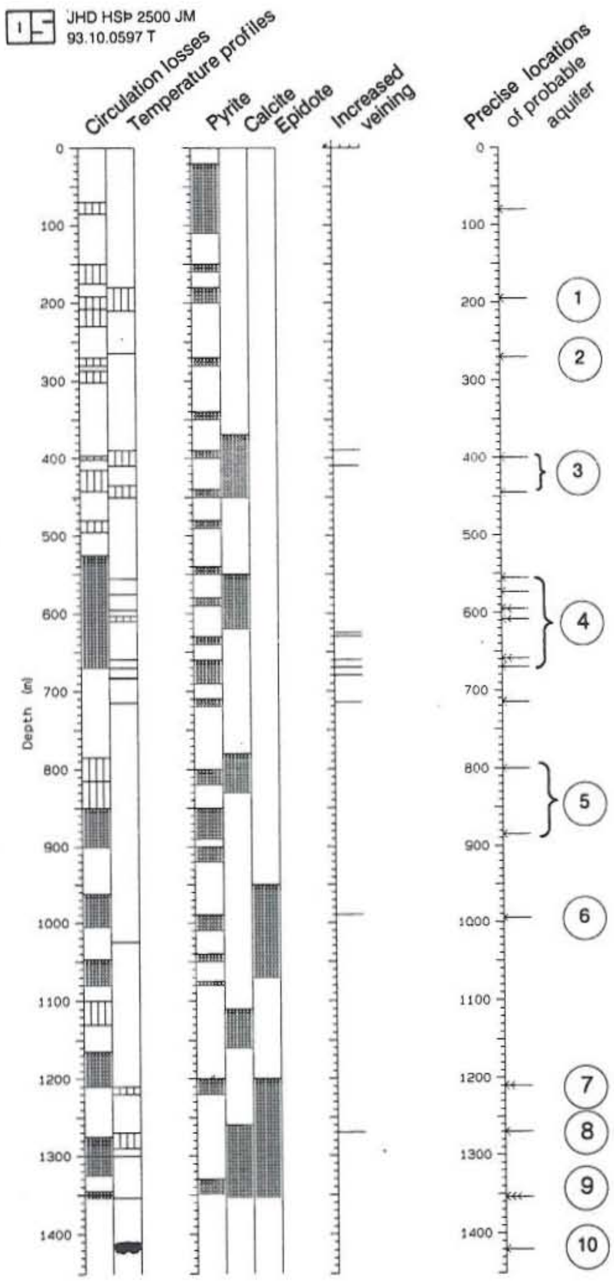

FIGURE 9: Detailed analysis for precise feeder locations in Rn-9

The descriptions above refer to the general observations on hydrothermal alteration minerals useful as aquifer indicators in the well. A detailed analysis of all information was made to locate, as precisely as possible, individual feeder zones in the well. Figure 9 shows tabulation of analysis results for different aspects of feeder zones. The major feeders in this well are located at 600, 660, 1190, 1270 and possibly at about 1344 m. Other small feeder zones exist in the well at 190, 265, 400, 800 and 980 m. The major feeders are characterized by high circulation losses (exceeding 3 l/s), temperature anomalies and intense hydrothermal alteration accompanied by veining (Figure 9). The smaller feeders may show some of these anomalies; for instance, the zone at about 400 m is marked by intense alteration mineral deposition and veining. However, only some weak anomalies are seen at that depth range on the temperature profile. This is possibly a site of an earlier active aquifer whose permeability is diminishing due to hydrothermal mineral infillings. The feeders at about 800 and 980 m do not show up on the temperature profiles. This may be due to the existence of stronger feeders above (at about 600-700 m) whose waters were flowing downwards into the well during the time of temperature logs hence, masking those below them. The general relationship between stratigraphy and the probable location of feeders may be described as follows: Feeder (1) may be located along a stratigraphic unit, probably within the basalt and breccia found at around 200 m (see description of stratigraphy). Feeder (2) is located at the bottom of basalt unit layers about 275 m. Feeders (3) at around 400 m are probably controlled by the upper boundary of the hyaloclastite. Thin section samples from here show a lot of veining in essentially glassy (tuffaceous) rock cuttings. The feeders (4) around 600-700 m are located within a thick lava unit extending from 585 m to 710 m. At least the top most feeder is located at the top parts of the lava unit. Aquifers (5), (6) and (8) are located within a fresh basalt unit in which some basalt intrusions are found. Although no samples are present from the depths at which feeders (9) and (10) are located, from geophysical logs it is possible to see that they may be correlated with locations of probable basalt intrusions.

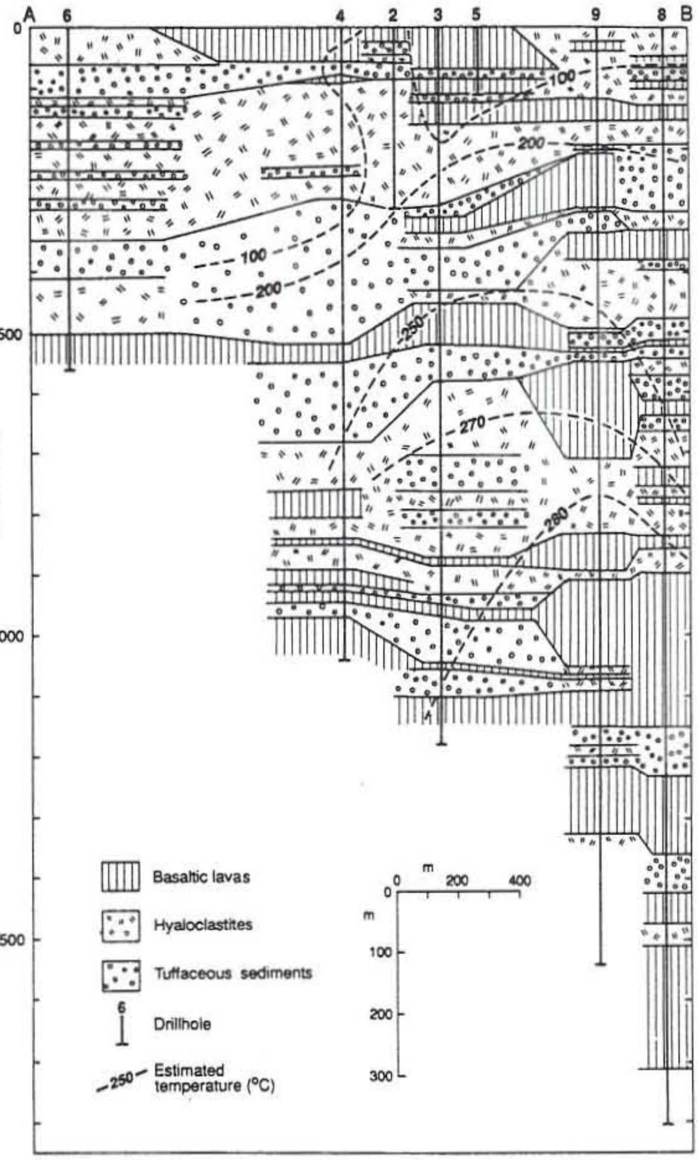

FIGURE 10: Cross section of lithological correlation and temperature isotherms in Reykjanes (Lonker et al., 1993)

It should be noted that the usage of any of the parameters shown on Figure 9 to locate feeders is not limitless. For instance, although loss of circulation is almost a sure way of identifying a permeable zone, opening of a permeable zone anywhere in the well during drilling may be wrongly associated with permeability at the depth which the bit has reached at the time of loss. Temperature profiles are very useful, however, internal flows inside the well may cause smaller feeders to be masked by larger ones. Variations in alteration intensities are very useful; sulphide deposition generally shows an increase adjacent to a feeder zone. Sometimes an extensive pyrite deposition is caused by drop of pH when cold (oxygen rich) percolating surface waters meet with hot geothermal fluids. Such an extensive zone of pyrite deposition may infer the cap rock. The extensive pyrite zone in this well extending from a shallow depth (30 m) to about 120 m possibly represents the upper limits of a geothermal system in this locality. Increases in intensities of other minerals, calcite and quartz, especially in veins correlate quite well with aquifer zones.

4.1 Correlation of well Rn-9 with other Reykjanes wells

Figure 10 shows a cross section across Reykjanes field based upon data from most of the boreholes. The stratigraphy of the area comprises hyaloclastites, basaltic lavas and few tuffaceous sediments. The upper 1000 m are dominated by hyaloclastite units and subaerial lava flows increase at levels below. Most of the major units can be correlated across the wells.

Figure 11 shows distribution of the common hydrothermal minerals in the other wells in the Reykjanes field. Occurrence and distribution of hydrothermal minerals in other wells is referred from Tomasson and Kristmannsdottir (1972).

Progressive alteration with depth is also observed in other wells. Zeolites occur at shallow depths and higher temperature minerals like epidote occur at deeper levels (below 500 m). A correlation of common alteration minerals, gives a picture of how deep these alteration minerals exist in this field. Thickness of the zone with occurrence of smectite and zeolite seems to be very shallow around wells 4, 2 and 3 but becoming thicker towards wells 8 and 6. This possibly implies elevated temperatures at shallower depths around wells 9, 2 and possibly 3.

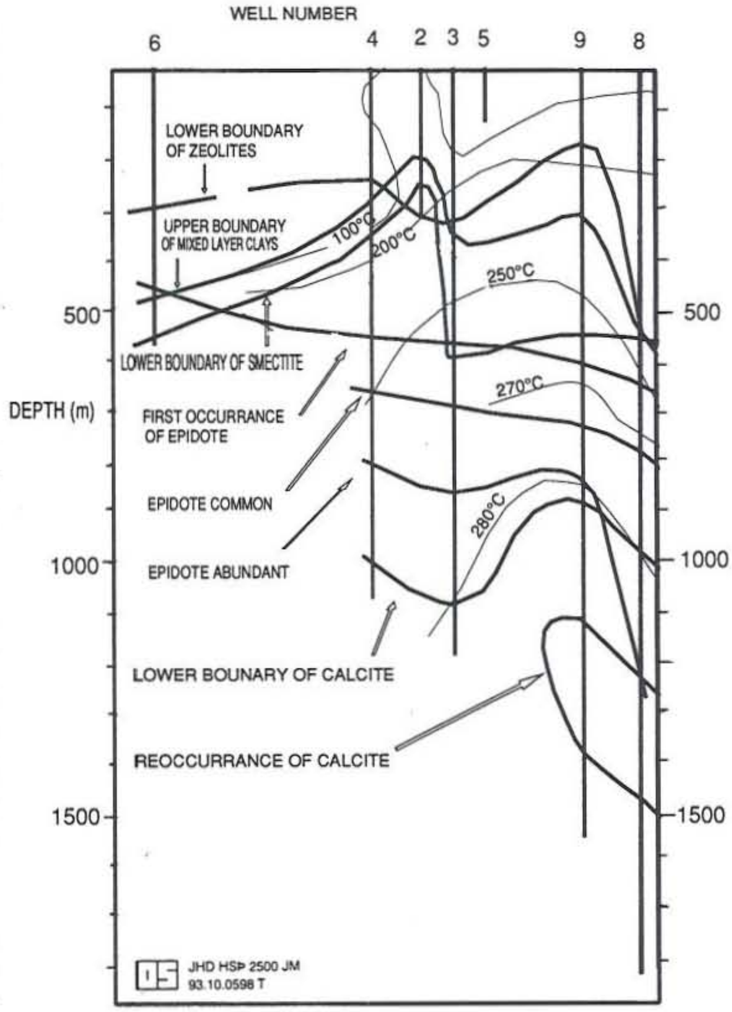

FIGURE 11: Correlation of some hydrothermal alteration mineral occurrences in Reykjanes wells

Isotherms of measured temperatures in the wells are included in the cross section diagram (Figure 11). They indicate that the shallowest high temperatures are around well Rn-9. However, at well 6 epidote is found at even shallower depths (≈ 450 m), and that implies that the system was quite extensive towards southwest in the past.

5. DISCUSSION

From the available data, it was possible to look at various aspects of the alteration in well Rn-9. Some alteration zones and deposition sequences of hydrothermal minerals have been observed. This has been used with the drilling and temperature logs to interpret the locations of aquifers in the well. Finally the hydrothermal alteration of the well was compared to other wells in the Reykjanes field.

Drilling logs, particularly the circulation loss ones, were used to delineate probable permeable zones. These are compared to the record of zones showing anomalous alteration intensities (e.g. sulphide deposition) and increased veining. It is found that most of them show some anomalies in some or all of these aspects. Temperature profiles were similarly used to locate probable aquifer zones. A plot of the interpreted locations of the feeders against the stratigraphic column shows that some are located at the bottom and top parts of lava units, while others are located within thick basalt units, in particular near to where basaltic intrusives have been identified. Sites of intense veining like around 400, 600, 1000 and 1270 m are correlated to the locations of possible aquifers.

Hydrothermal alteration in Rn-9 shows progressive zonation with depth which has been interpreted to represent the following possible formation temperatures; smectite-zeolite (200°C) at 310 m depth, mixed layer clays (200-230°C) to 600 m, chlorite belt (230-250°C) to 617 m and chlorite-epidote (≥250°C) below 617 m. Other minerals like wollastonite have been used to interpret possible formation temperatures of 270°C at 700 m and above 290°C at 1040 m from appearance of garnet. Deposition sequence of hydrothermal minerals in vesicles show that the latest mineral in most parts of the well may be in equilibrium with the formation temperatures. However, occurrence of some late deposition of calcite in some samples from 1100 m to about 1250 m depth may indicate possible cooler horizons in this part of the well.

In relation to other wells, most of the stratigraphy can be correlated in other wells. Furthermore occurrences of hydrothermal alteration assemblages can be correlated across the wells (Figure 11); smectite and zeolite occur at shallow depths in the field. Epidote is encountered deeper (>500 m) in most wells with chlorites. Garnet is also reported for the adjacent well Rn-8 at depths below 1400 m (Lonker et al., 1993). The deeper zone with calcite depositions is also seen in Rn-8 at 1200 and about 1430 m. Cross sections with measured temperature isotherms plotted (Figures 10 and 11) show that Rn-9 is located in the hottest part of the field compared with other wells. However, high-temperature minerals like epidote and chlorites are found in shallower but cooler parts of other wells (e.g. Rn-6 and Rn-4) indicating the system may have been extensively active in the past.

6. CONCLUSIONS

1. The rocks cut by well Rn-9 are all volcanics of basaltic composition, they comprise mainly hyaloclastites and basalt lavas. Minor basalt intrusions are also present.

2. About ten groups of feeders are identified in the well. Some of the feeders occurring at depths shallower than 900 m are probably controlled by permeability along stratigraphic units whereas some of those below 900 m are possibly controlled by permeability along basaltic intrusions.

3. Four alteration zones are identified in the depth penetrated by the well; smectite-zeolite, mixed layer zone, a chlorite belt and chlorite-epidote zone.

4. Hydrothermal alteration mineral temperatures probably represent the present formation temperatures. Therefore, the minerals are in equilibrium with formation temperature in most parts of the well except between 1100-1250 m depth range where possible cooling may be occurring.

5. The activity of the geothermal system may have been more extensive towards south in the past.

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I am indebted to my family who had to do with my absence from home for the six months of my study in Iceland.

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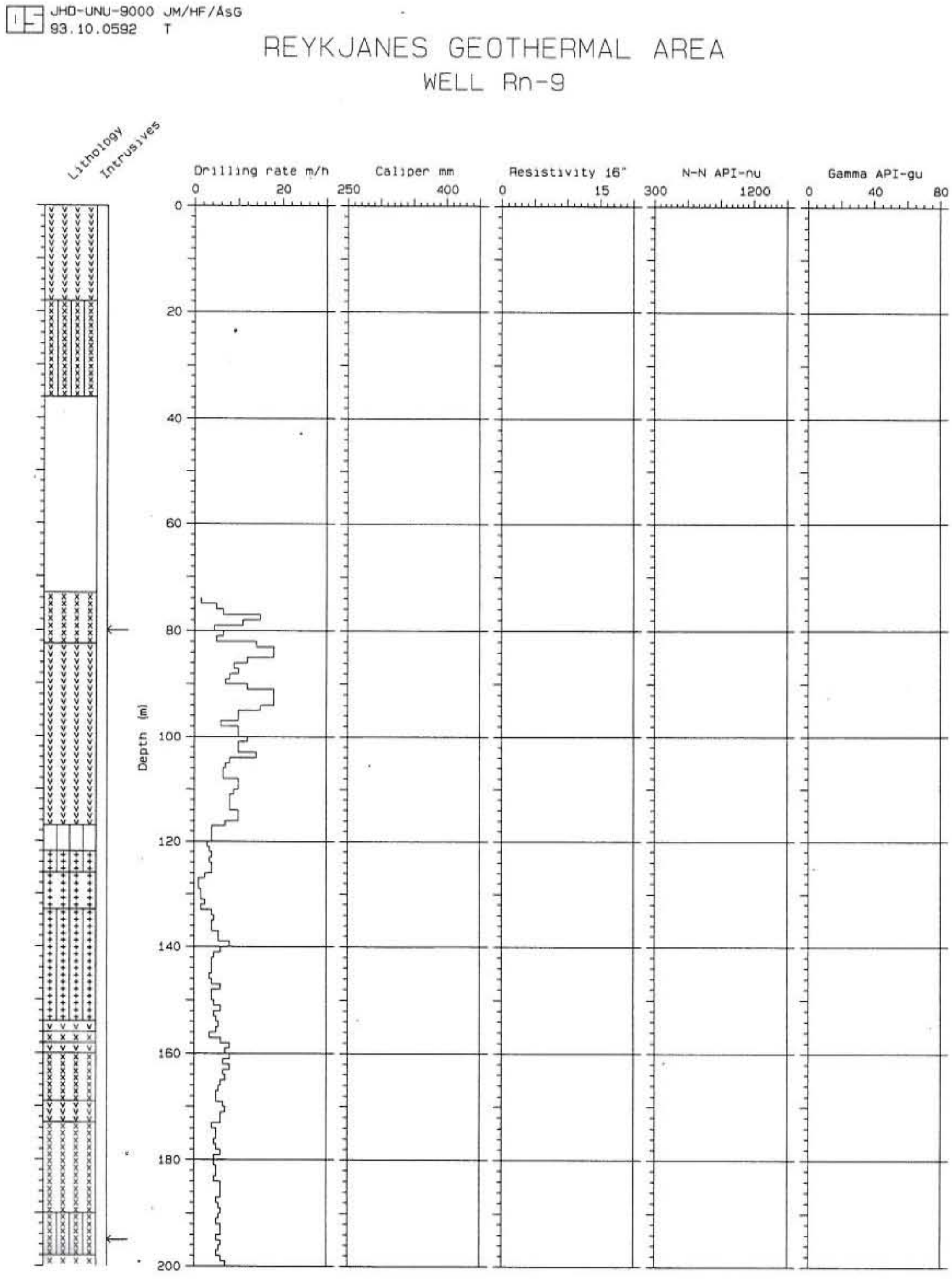
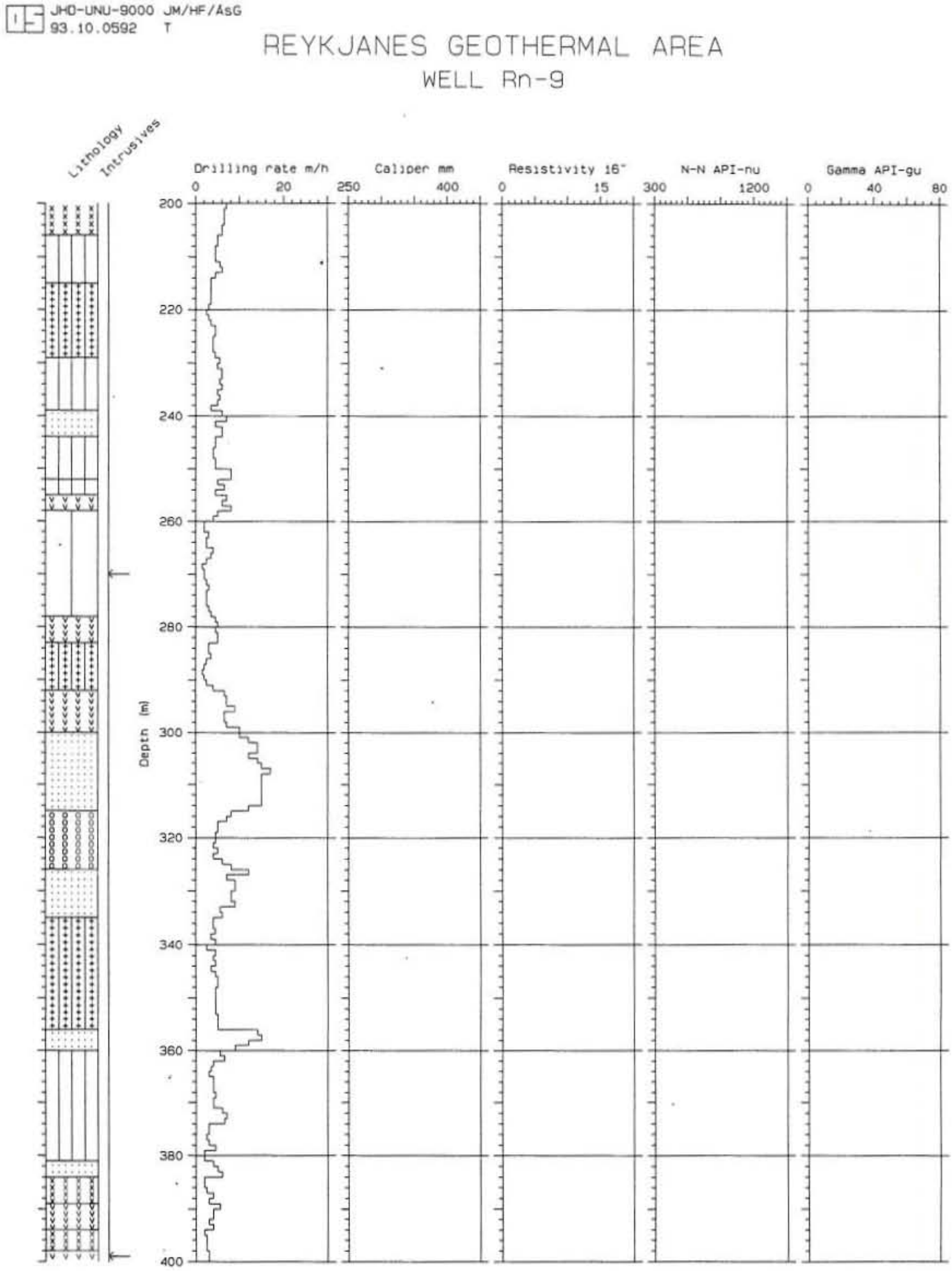
APPENDIX I: Detailed stratigraphy and geophysical logs of Rn-9

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REYKJANES GEOTHERMAL AREA
WELL Rn-9
Lithology
Intrusives
Drilling rate m/h
Caliper mm
Resistivity 16"
N-N API-nu
Gamma API-gu
Depth (m)
0
20
250
400
0
15
300
1200
0
40
80
200
220
240
260
280
300
320
340
360
380
400

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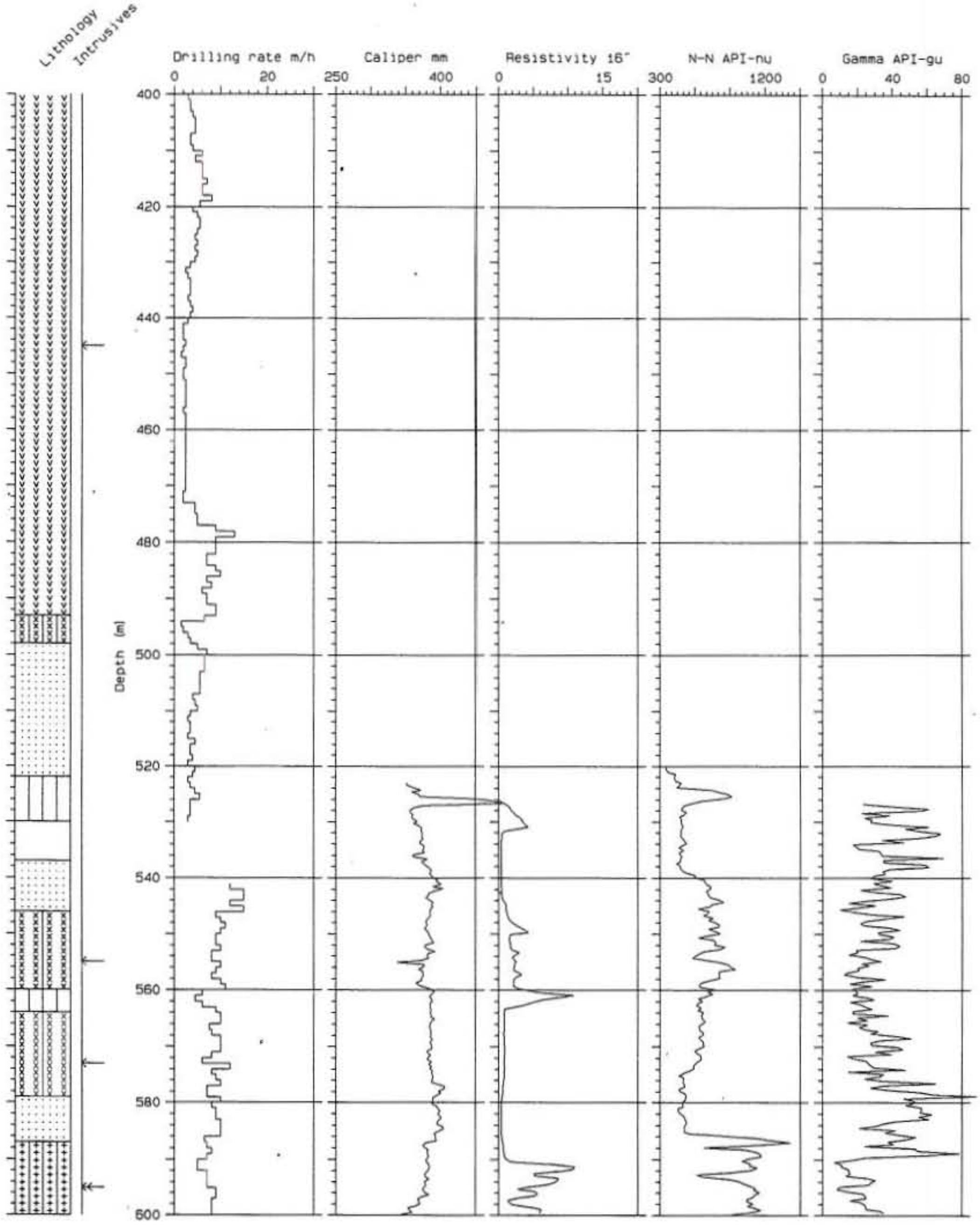
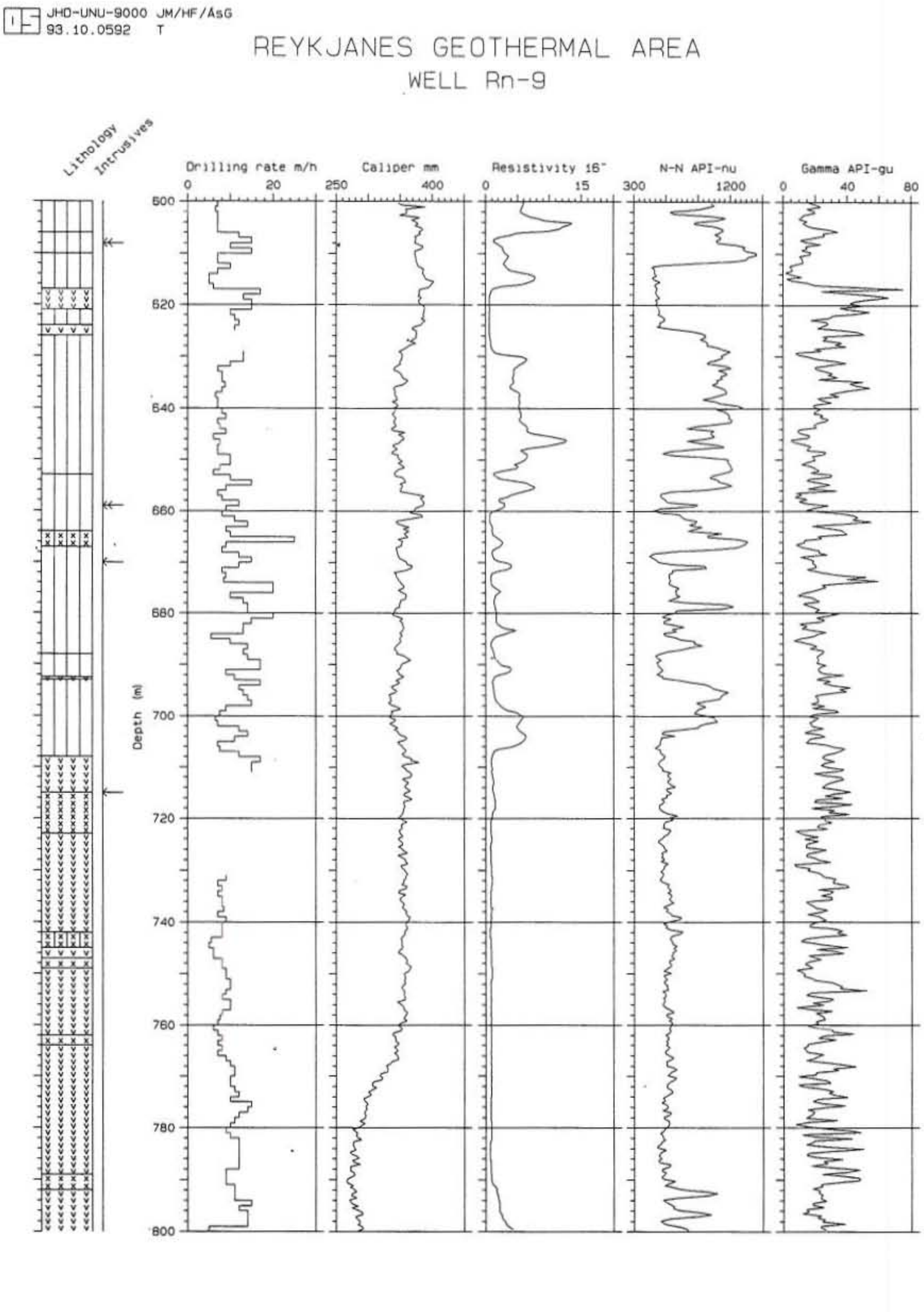
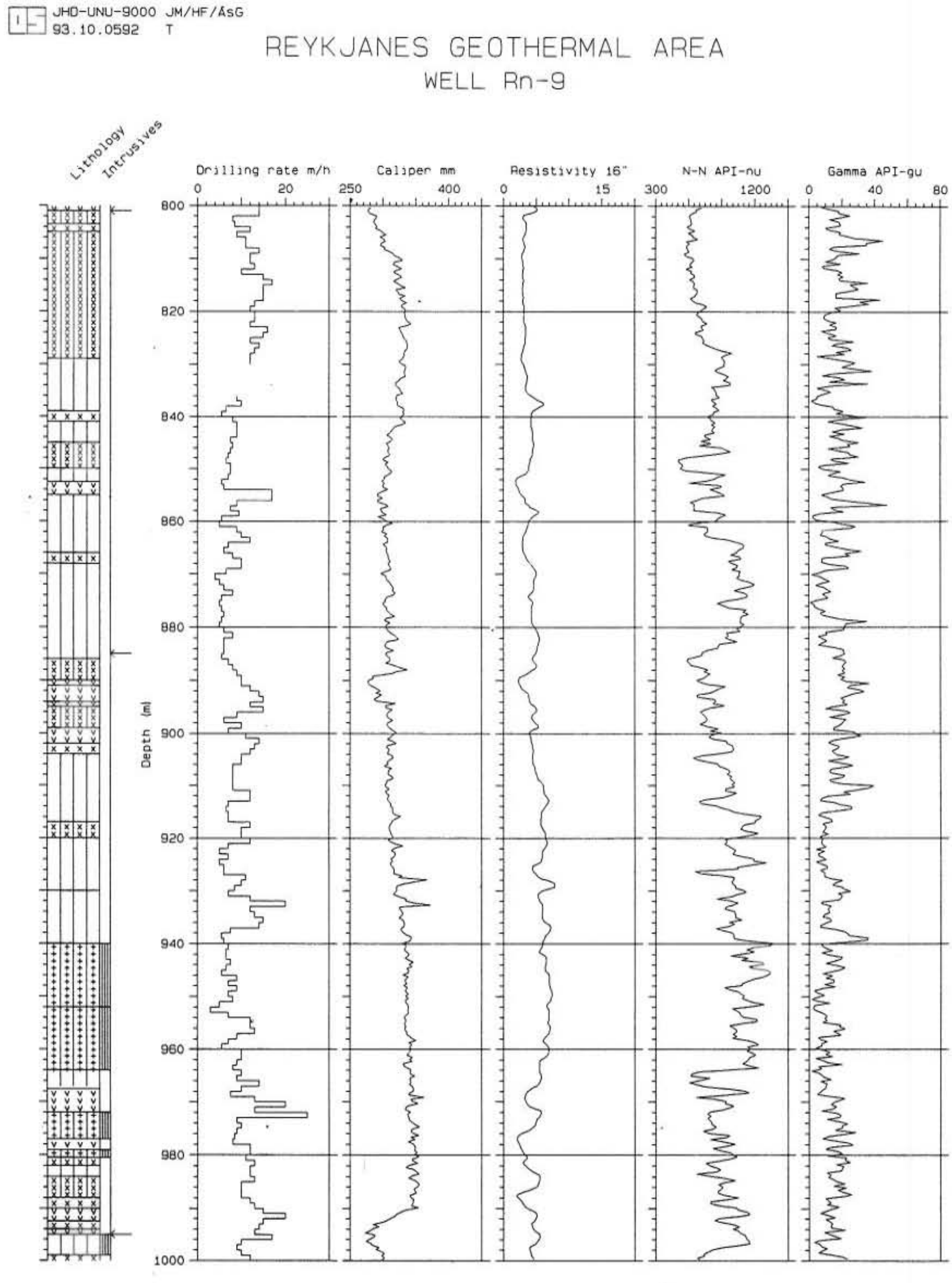
REYKJANES GEOTHERMAL AREA
WELL Rn-9




JHD-UNU-9000 JM/HF/ÁsG
93.10.0592 T
REYKJANES GEOTHERMAL AREA
WELL Rn-9
Lithology
Intrusives
Drilling rate m/h
Caliper mm
Resistivity 16"
N-N API-nu
Gamma API-gu
Depth (m)
600
620
640
660
680
700
720
740
760
780
800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Resistivity 16"
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Gamma API-gu
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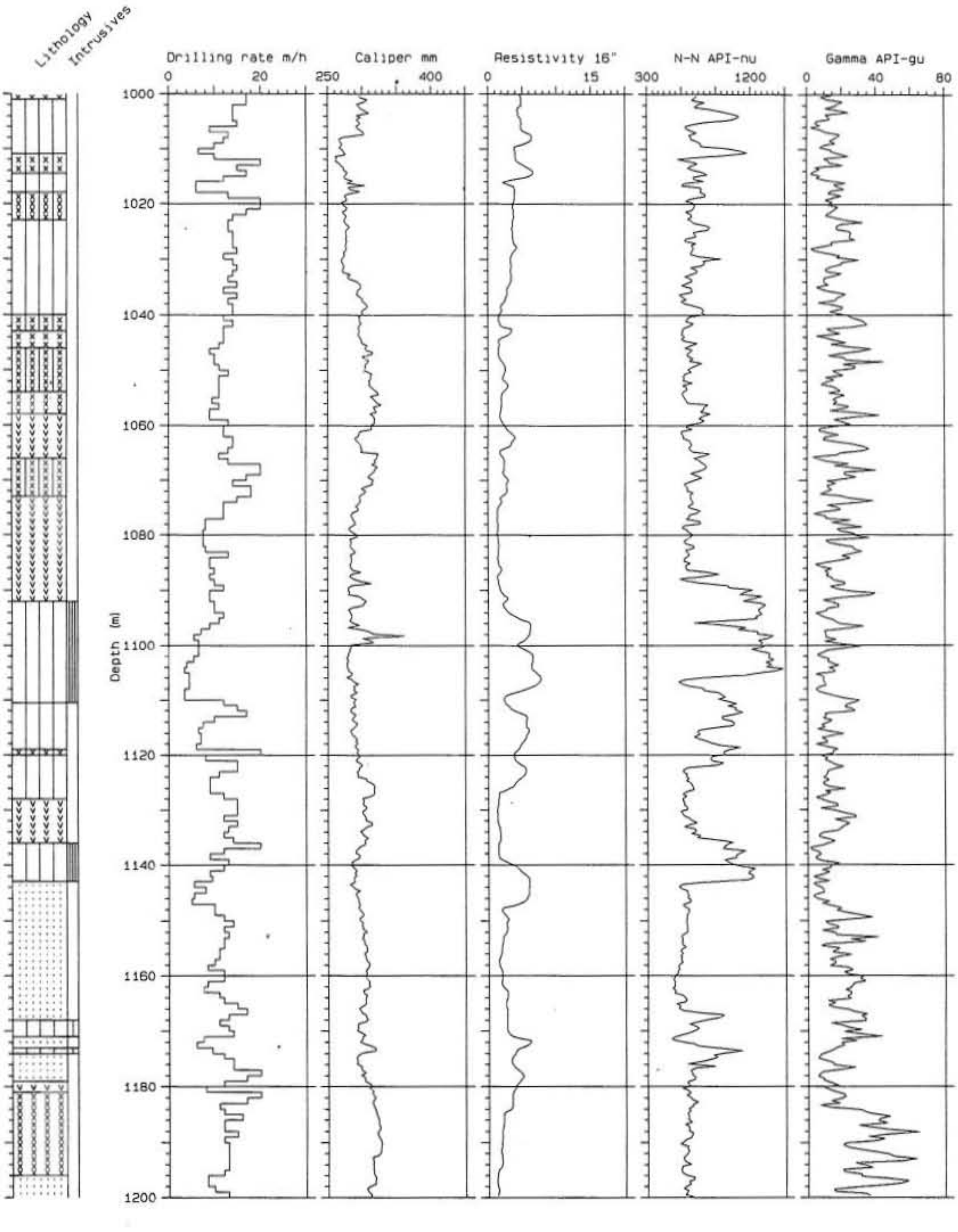
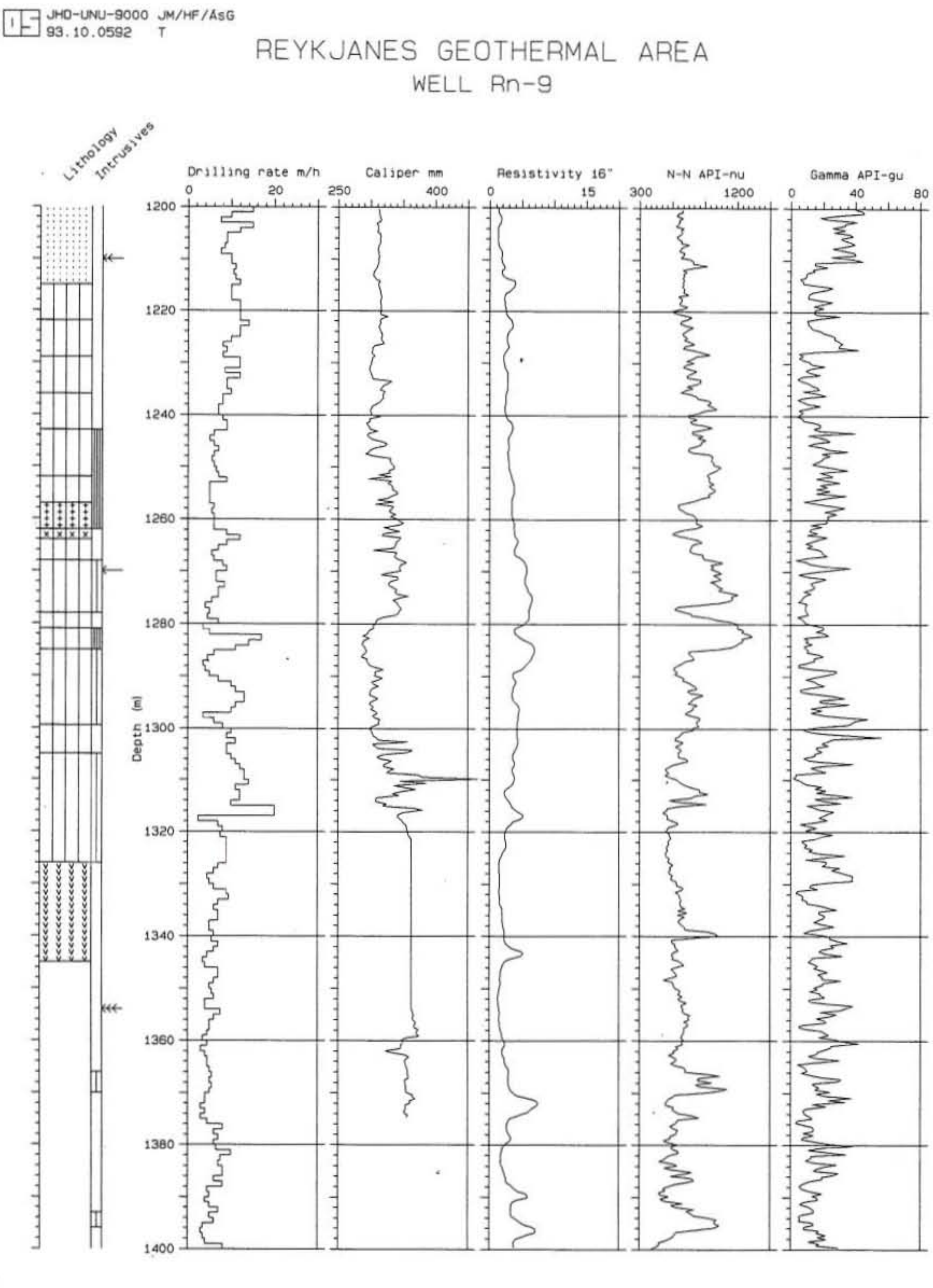
WELL Rn-9

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WELL Rn-9
Lithology
Intrusives
Drilling rate m/h
0
20
Caliper mm
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400
Resistivity 16"
0
15
N-N API-nu
300
1200
Gamma API-gu
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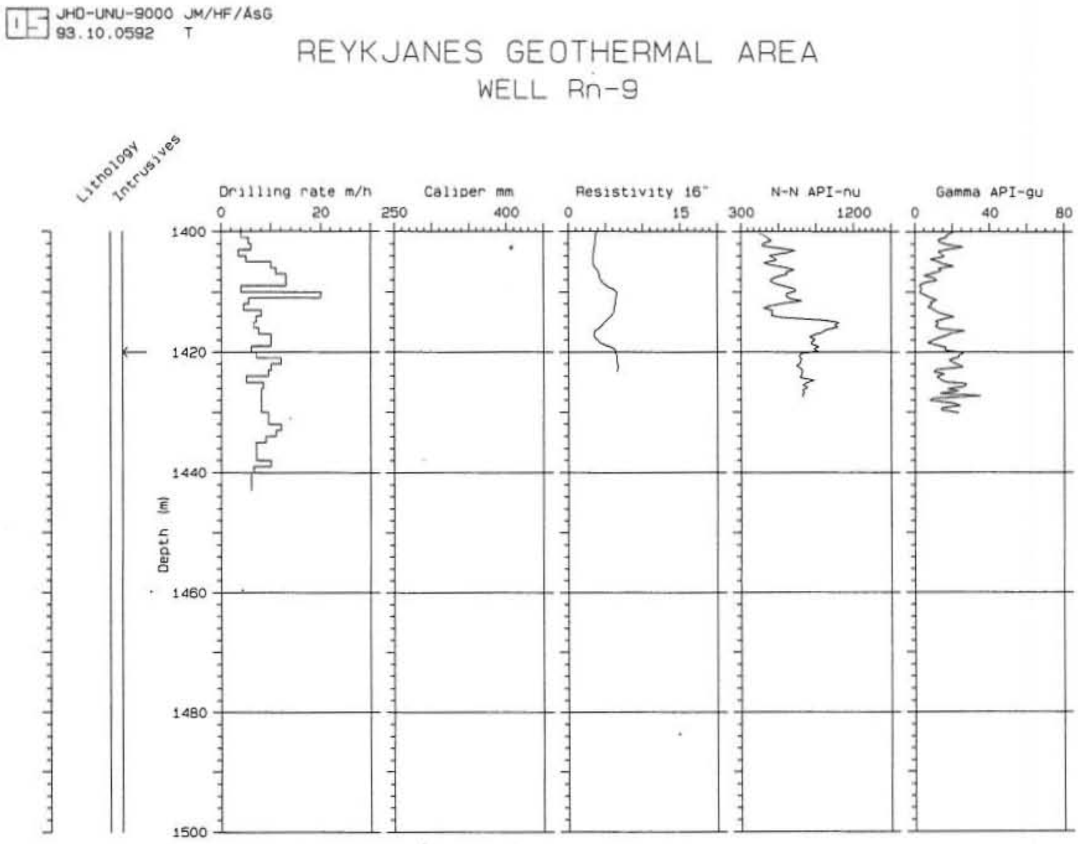
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Drilling rate m/h
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Depth (m)
1460
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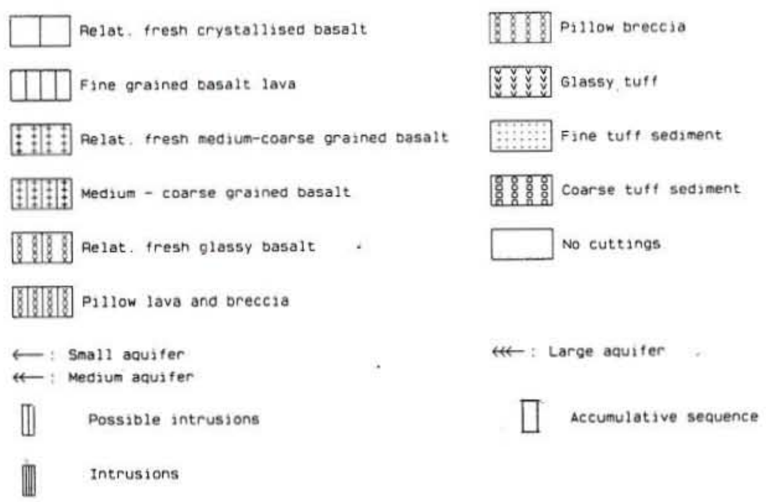
1500

Legend:


Relat. fresh crystallised basalt
Fine grained basalt lava
Relat. fresh medium-coarse grained basalt
Medium - coarse grained basalt
Relat. fresh glassy basalt
Pillow lava and breccia
Pillow breccia
Glassy tuff
Fine tuff sediment
Coarse tuff sediment
No cuttings
Small aquifer
Medium aquifer
Large aquifer
Possible intrusions
Accumulative sequence
Intrusions

APPENDIX II: Procedure for preparation of samples for clay mineral analysis with XRD

1. Place approximately two teaspoonfuls of drill cuttings into a glass tube, wash out dust with distilled water. Fill the tubes 2/3 full with distilled water and plug with rubber stoppers. Place the tubes in a mechanical shaker for 4-8 hours, depending on the alteration grade of the samples.

2. Allow particles to settle for 1-2 hours, until particles finer than approximately 4 microns are left in the suspension. Pipette few ml from each tube and place approximately 10 drops on a labelled glass plate, avoid having the samples very thick. Make a duplicate for each sample. Let them dry at room temperatures overnight.

3. Place one set of samples in a desiccator containing glycol ($C_2H_6O_2$) solution and the other set in a desiccator containing $CaCl_22H_2O$. Store at room temperature for at least 24 hours. Thick samples will need longer time in the desiccator, at least 48 hours.

4. Run both sets of samples from 2-15° on the XRD machine.

5. Place one set of samples (usually the glycol saturated one) on an asbestos plate and heat in a preheated oven, 550-600°C, for one hour. Oven temperature must not exceed 600°C. Exact location of individual samples on the asbestos plate must be known before heating because labelling will disappear during heating process. Cool samples reasonably before further treatment.

6. Run the samples from 2-15° on the XRD machine.

APPENDIX III: XRD results for well Rn-9 samples

Depth (m)	Treated with $CaCl_2$ Lines d (Å)	Glycol saturated Lines d (Å)	Heated to 550-600°C Lines d (Å)	Probable minerals
36	13.39	16.99 8.49	9.94	Smectites
96	15.5 8.51 7.70	17.31 8.55 7.69 5.64	9.83 4.84	Smectites, gypsum
114	13.38 7.56 9.11	16.98 9.11 7.70 5.82	9.82	Smectites, gypsum
134	15.22 13.6 8.5	16.98 8.43 5.60	9,83	Smectites
202	13.39	16.67 13.60 8.35	9.82	Smectites
300	13.60 16.07	16.98 8.43	9.83	Smectites
400	13.6 9.21	16.98 31.55 8.43 7.69 7.07(?)	9.83 12.45 22.63(?)	Smectites, mixed layer clays
418	13.60 30.46 9.34 7.08	16.66 31.55 8.43 7.82(B)	9.81 12.27	Smectites, mixed layer clays
500	13.39 29.45 9.11 7.07(?)	16.67 31.52 8.42 5.57	9.83 12.27(?)	Smectites, mixed layer clays
530	13.6 7.08 10.4(?)	16.7 8.43 31.55(?)	9.83	Smectites
575	16.43 14.3	16.99 8.43 9.43	9.83 14.7(?B)	Smectites
700	14.29 16.36 30.36 7.14 8.50 7.62	15.50 16.98 31.55 7.14 7.70 8.43	13.60(B) 23.88 9.94 8.43	Mixed layer clays, smectite, chlorite, swelling chlorite
722	14.49 29.45 7.13 9.11	14.02 7.13 9.28 29.45	14.73	Chlorite, mixed layer clays
800	14.3 30.4 7.08 9.3	16.92 31.55 15.5 7.19 8.50 7.75	13.6 23.25 9.83 8.42	Mixed layer clays, chlorite, smectite, swelling chlorite
852	14.49 7.70 7.19	14.06 7.08 7.62	14.97	Chlorite, gypsum
900	14.26 7.63 7.14	14.47 7.13 7.63	14.29 8.84(?)	Chlorite, gypsum
1000	14.49 7.14 30.43	14.38 7.08 30.46 8.42(?)	14.24 9.03 8.42	Chlorite, mixed layer clays
1092	14.03 7.08 9.41 29.45 8.50	14.49 16.99 31.52 7.13 9.46 15.24 8.50 7.75	14.23 9.41	Chlorite, mixed layer clays, smectite(?), swelling chlorite
1230	14.47 7,14	14.49 7.14	14.47 8.93	Chlorite
1342	14.29 7.14 7.70	14.38 7.14 7.70	14.49	Chlorite

APPENDIX IV: XRD peaks for smectite, mixed layer clay and chlorite