



BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION IN WELL B-9, NAMAFJALL GEOTHERMAL FIELD, NE-ICELAND

Edward Isabirye

Geological Survey and Mines Department,
Box 9, Entebbe,
UGANDA.

ABSTRACT

A study was made of the drill cuttings from well B-9, a 1312 m deep drillhole in the Bjarnarflag sector of the Namafjall high-temperature area, NE Iceland. The strata which the drillhole dissects consists of fine- to medium-grained basalt below 422 m depth, the top being covered by a succession of fresh-looking basaltic breccia, glassy basalt and tuff, these being referred to as hyaloclastite. Basalt intrusions occur below 500 m. The hydrothermal mineralogy predominantly reflects a high-temperature environment ($>200^{\circ}\text{C}$) although an overlap with an intermediate temperature environment ($150\text{-}200^{\circ}\text{C}$) is present in the upper 700 m of the drillhole. The first hydrothermal event, which involved high-temperature conditions is evidenced by change from lowgrade clays into more coarsely crystalline clays (smectites) with depth and increasing temperature, wairakite, chlorite, prehnite, epidote, albite, actinolite and possibly garnet. The second hydrothermal event so far restricted to the top 700 m is evidenced by the zeolites mordenite and laumontite. An overlap of laumontite (temperature range $100\text{-}200^{\circ}\text{C}$) with wairakite and prehnite ($>200^{\circ}\text{C}$), epidote ($250\text{-}280^{\circ}\text{C}$), occurs at about 434-460 m depth. Both the petrographic observations and XRD analyses over the same depth range confirmed these findings.

1. INTRODUCTION

1.1 Scope of study

The Government of Uganda is presently rehabilitating the existing power generation and distribution installations and studying ways to meet the increasing energy demand by indigenous energy resources. One alternative is geothermal energy.

The author of this report attended the 6 month long UNU Geothermal Training Programme at Orkustofnun - National Energy Authority, Reykjavik, Iceland. The fellowship was a result of a joint geothermal exploration project (UGA/92/002 & UGA/92/E01) by the Government of Uganda and the United Nations through the UNDP, aimed at locating a suitable geothermal reservoir for harnessing geothermal energy. The immediate objective was to establish an active geothermal group within the Geological Survey and Mines Department.

The 26 weeks of the training programme were composed of: 1) Introductory lectures on all the disciplines involved in geothermal exploration, exploitation and utilization (5 weeks); 2) Field excursions to the main geothermal fields of Iceland (2 weeks); 3) Borehole geology specialized course (18 weeks).

The 18 weeks of training in borehole geology included: a) A study of drill cuttings from an 800 m deep well which had just been drilled at Stora Drageyri, W-Iceland; b) A study of well B-9 in the Namafjall high-temperature area, N-Iceland, by:

- 1) Cutting analysis, using binocular stereo-microscope;
- 2) Petrographic analysis of 29 selected thin sections from the drillhole;
- 3) XRD analysis of secondary minerals;
- 4) Field excursion to Hvalfjordur in search of zeolite minerals;
- 5) Visits to Seltjarnarnes, west of Reykjavik where a new low-temperature well for district heating was drilled.

This report describes chiefly the results of the analysis of the drill cuttings from well B-9 in Namafjall which were studied with respect to petrography, mineralogy and the hydrothermal alteration history.

1.2 The Namafjall high-temperature area

The Namafjall geothermal system is located in NE-Iceland, about 5 km northeast of Lake Myvatn (Figure 1). Precisely, the area lies in the active volcanic zone, on the same fissure swarm and about 10 km to the south of the Krafla volcano, forming the tectonic plate boundary known as the Mid-Atlantic Ridge, where it traverses the island. The thermal system is divided into two sectors separated by a hyaloclastite ridge called Namafjall, i.e. Hverarond to the east and Bjarnarflag to the west of Namafjall. Well B-9, which is the subject of the present study lies in the Bjarnarflag sector.

Thermal manifestations on the surface cover some 7 km² and are mainly in the form of steam vents and mud pools. Exploitation of the area started in 1967. So far 12 wells have been drilled into the reservoir with a depth range of 265

to 1996 m. Geothermal steam has been used for electricity production (3 MW_e) for a diatomite factory and a district heating system. In the vicinity of the geothermal area, mostly basaltic rocks are exposed on surface. They consist of basaltic lava flows with very minor acidic components and hyaloclastites as are also observed in the drillholes (Olafsson and Kristmannsdottir, 1989).

The Namafjall and Krafla geothermal systems lie on the same fissure swarm (Armannsson et al., 1987). During the Krafla eruptions of April and September 1977 the Namafjall field was severely affected, and in September 1977 well 4 actually erupted magma (Larsen et al., 1978, Bjornsson et al., 1979), which is

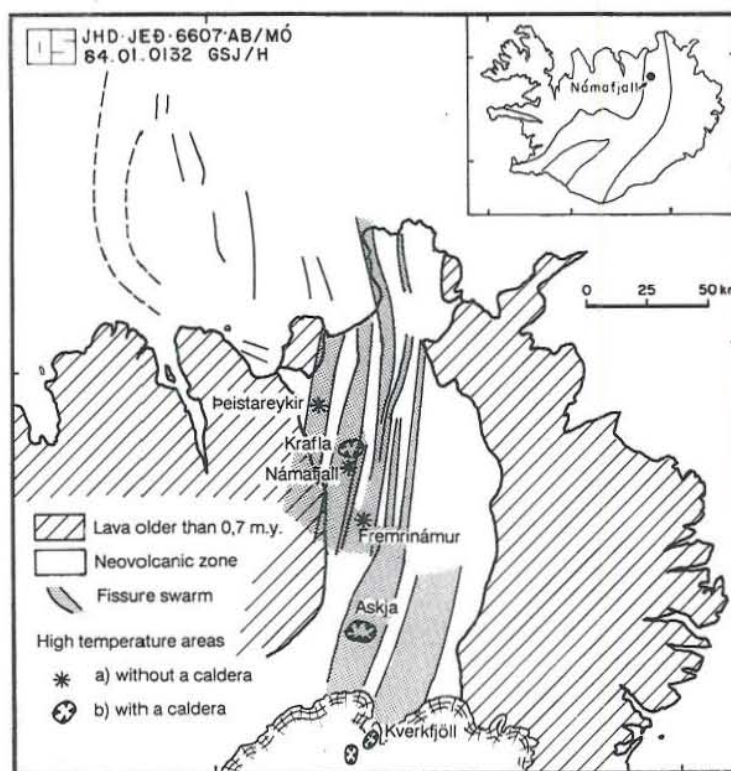


FIGURE 1: The spreading zone of North Iceland and the associated high-temperature areas

September 1977 well 4 actually erupted magma (Larsen et al., 1978, Bjornsson et al., 1979), which is believed to have found its way through a feed at 1036 m depth (Gudmundsson et al., 1989). In September 1977, the lower parts of most of the existing wells collapsed due to tectonic movements.

The sites of all the wells in the Namafjall area are shown in Figure 2 along with the most notable faults, fissures and thermal manifestations. All the tectonic movements during the Krafla eruptions were confined to the area between the Krummagja and Grjotagja faults, and well 2, the only well outside that area during the eruptive episodes, was apparently not affected by this volcanic and tectonic episode.

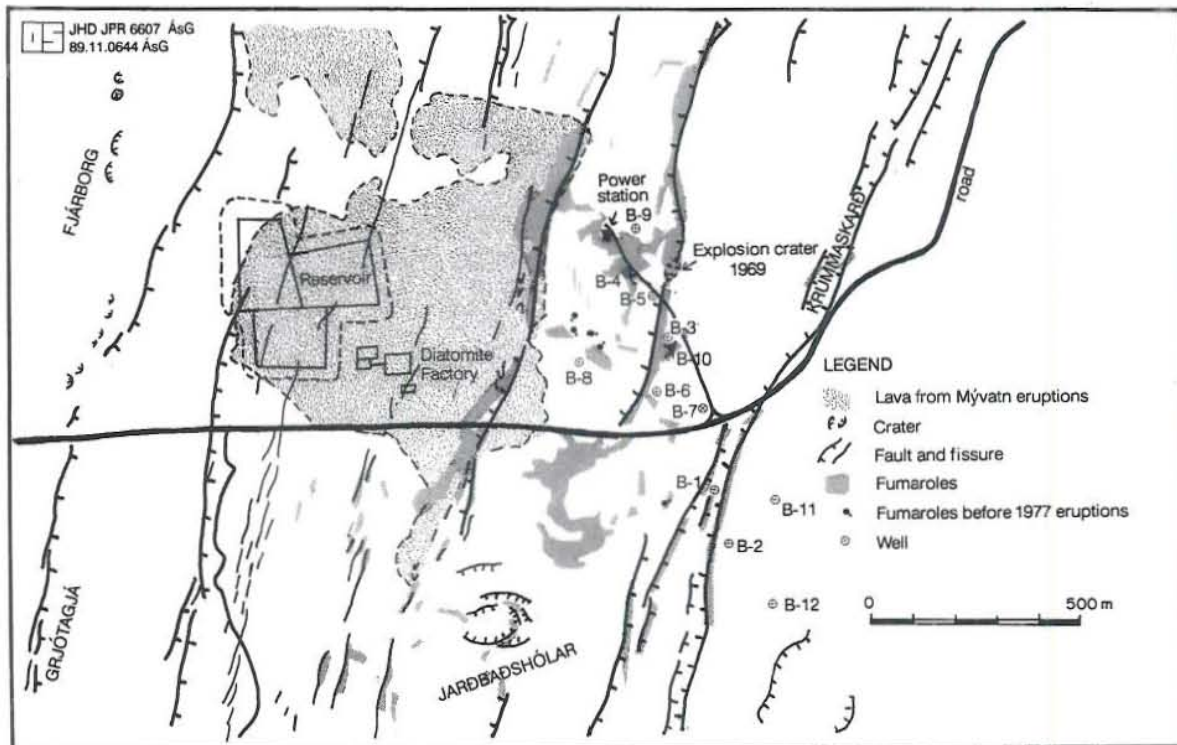


FIGURE 2: Location of wells in the Namafjall sector and the surface geothermal manifestation

1.3 Well B-9

Well B-9 is located approximately 100 m north of well B-4 (Figure 2). It was drilled to 30 m by a percussion drill rig in the fall of 1970 and later with a large drill rig to a total depth of 1312 m. It was cased to 256 m with a 9 $\frac{5}{8}$ " casing and with a liner hanging from the top to 600 m. When the drilling was completed, the well was cased with a liner from 570-819 m but is only slotted at 621-641 m depth. Drilling was smooth down to production casing depth (256 m). Only one circulation loss was monitored at 47 m depth. In the production part, total circulation losses were monitored at 270 and 280 m both of which were cemented off. Circulation losses of 3 and 6 l/s and total loss were monitored at 481, 648 and 1175 m, respectively. Limited information is available on B-9's discharge characteristics. It had a limited discharge and was difficult to keep open at 10 bar-a pressure. The well was used irregularly during the first years. It has been closed since 1974 except for two days in 1984 when it was opened for production measurements. Immediately after drilling, the well was open to bottom. During logging between 1972 and 1974, a blocking was found at 955 m, probably due to a cave-in. It is probable that the well collapsed during discharge, not forgetting that the liner extends only to 819 m. Following the volcanic activity, the well was first logged in 1980. Some irregularities were found at 560 m, possibly the top of the liner and then at 827 m just below the liner. The logging tools finally stopped at 843 m. It is thus evident that the well is about 100 m shallower after the volcanic activity.

Figure 3 shows the selected temperature logs performed in the well since 1970 to present. The first temperature log after drilling to 1312 m is contained therein.

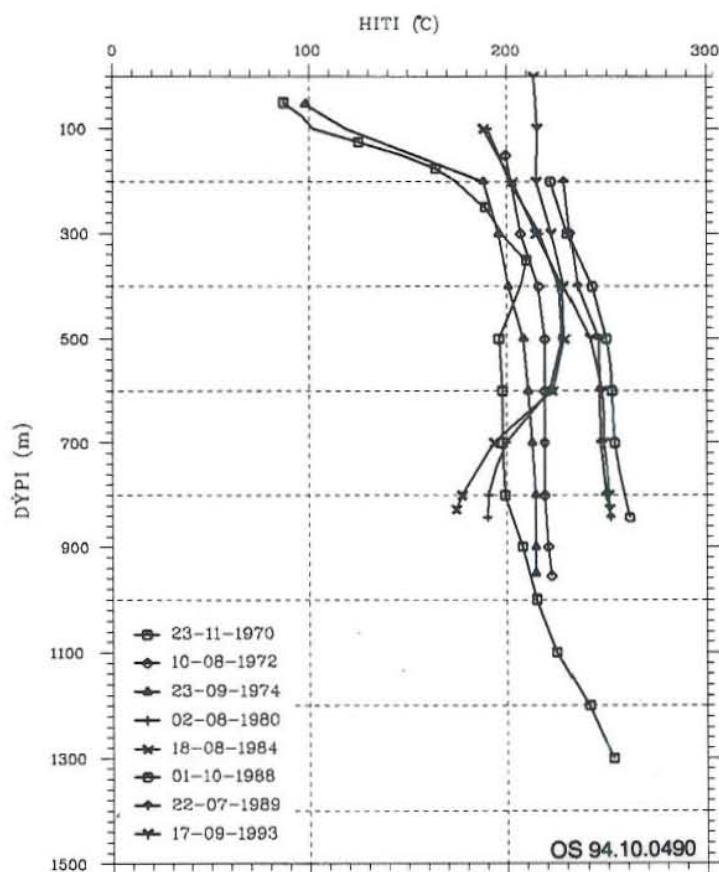


FIGURE 3: Temperature measurements in well B-9, 1970-1993

similar results but a slightly lower overall temperature. The well-head pressure also increased from 9.5 bars in 1980 to 26.0 bars in 1988 and to 28.0 bars in 1989. The pressure in the reservoir, however, has remained relatively constant.

2. STRATIGRAPHY

2.1 Introduction

Three main basalt types have been recognized in the field; flows of olivine tholeiite basalt, single flows of tholeiite basalt with little or no olivine, and flows porphyritic in plagioclase and pyroxene. Gradations are common between the three but as a rule they are distinctive enough to provide mappable stratigraphic units. Certain lava types are characteristic for distinct types of lava morphology. Thus, the olivine tholeiite often produce lava shields which are seen in the lava pile as thick pahoehoe flows consisting of numerous thin flow units but are also found as individual flows. The olivine-poor tholeiite is characteristic of fissure erupted aa lavas. Central volcanoes erupt both types but the latter is more abundant forming unusually thin flows, free

The first logs are evidently influenced by cooling during drilling and thus do not show real rock temperature. However, the temperature at 1300 m was higher than 250°C. The temperature logs from 1972 and 1974 only reach 955 m. They show 200-230°C below 300 m. It is thus possible that the temperature was influenced by discharge. Four temperature logs have been run after the start of the volcanic episode. These logs, which reach 800 m only, show that the well cooled markedly below 600 m probably as a result of the volcanism. In 1980, the highest temperature in the well between 300-600 m depth was about 215-225°C while the bottom hole temperature at 843 m was only 175°C. Four years later, the well had heated up by about 15°C at the bottom, while above 600 m, the temperature had remained unchanged since 1980. In the autumn of 1988, well temperature had changed drastically; the highest temperature at the bottom was 260°C while above 600 m the highest temperature was 20-30°C higher than in earlier temperature logs. The temperature logs in 1989 gave

of phenocrysts, possibly erupted in a superheated state. The porphyritic basalts are more often produced from fissures and range among the most voluminous flows erupted in single eruptions (Saemundsson, 1979).

In the present study, the latter group is characteristic in the hyaloclastite formations penetrated by this well as observed in thin sections at 80, 102, 140, and 200 m depth. It becomes unclear in the glass-rich tuff at 302, 380, and 456 m depth. Otherwise the majority of the volcanic succession penetrated by the well appears to be of tholeiite composition with little olivine. However, formations of tholeiitic composition were observed in thin sections at 594, 630, 852, 878, and 910 m but it becomes difficult to categorize those below this depth owing to extensive alteration and disintegration.

The rock formations penetrated usually exhibit a sub-ophitic texture. The plagioclase laths are enclosed in patches of pyroxene, where the latter appear as aggregates and not as single crystals. The iron ore minerals are interstitial which implies later growth. This crystallization habit is characteristic of olivine tholeiite basalt whereas olivine-poor tholeiite is generally fine grained and equigranular with the iron ore minerals more or less evenly distributed within the rock. The plagioclase often displays what is termed "skeletal growth" as a result of quenching (rapid cooling e.g. by ice) of lava as it solidifies. This is typical of eruptions under glaciers resulting in partially crystallized lavas ranging from tuff through breccia to glassy basalts all of which the term "hyaloclastite" is used to describe the succession. This is what is observed in the upper 500 m section of well B-9. Below this depth, the basalts appear to be more crystalline, generally fine- to medium grained with several small dolerite (medium- to coarse grained) intrusions. However, the cuttings are too small in many places and highly altered to accord proper classification but judging from the penetration rate, it appears that the bulk of the formation is hyaloclastite above 800 m. Thin sections at 594 m depth reveal both olivine tholeiite and tholeiite basalt.

Drill cutting samples taken at 2 m depth intervals were studied under a stereo-microscope. Interesting samples were picked out and 29 thin sections made of them for petrographic analysis. Hydrothermal alteration minerals in veins and vesicles were hand-picked under the binocular microscope for identification and classification by the XRD technique. The description of the well's stratigraphy is a result of the author's work and findings and is shown in Section 2.2. Figure 4 shows the detailed geological profile established for the well along with the penetration rate.

2.2 Volcanic succession from the cuttings

<u>Depth</u>	<u>Description</u>
0-32 m	No cuttings.
32-58 m	Fresh porphyritic fine- to medium-grained breccia and fresh basaltic glass. Cutting samples from 38, 46, and 50 m were lacking due to circulation losses. Drillers' records indicate total circulation loss at a depth of 47 m.
58-70 m	Fresh porphyritic medium- to coarse-grained glassy basalt (pillow breccia) and fresh basaltic glass.
70-104 m	Fresh fine- to medium-grained basaltic breccia. The breccia is vesicular. 100 and 102 m lacking. Thin sections at 80 and 120 m show the formation to be of olivine tholeiite composition which is also plagioclase porphyritic.
104-110 m	Fresh porphyritic basaltic tuff.
110-134 m	Fresh porphyritic fine- to medium-grained breccia and fresh basaltic glass.
134-154 m	Fresh porphyritic basaltic tuff. Thin section at 140 m shows olivine tholeiite basalt.
154-160 m	Detrital tuff
160-184 m	Fresh porphyritic basaltic tuff.
184-224 m	Detrital porphyritic basaltic tuff. This could mark a boundary between two formations. Thin section at 200 m reveals olivine tholeiite basalt.

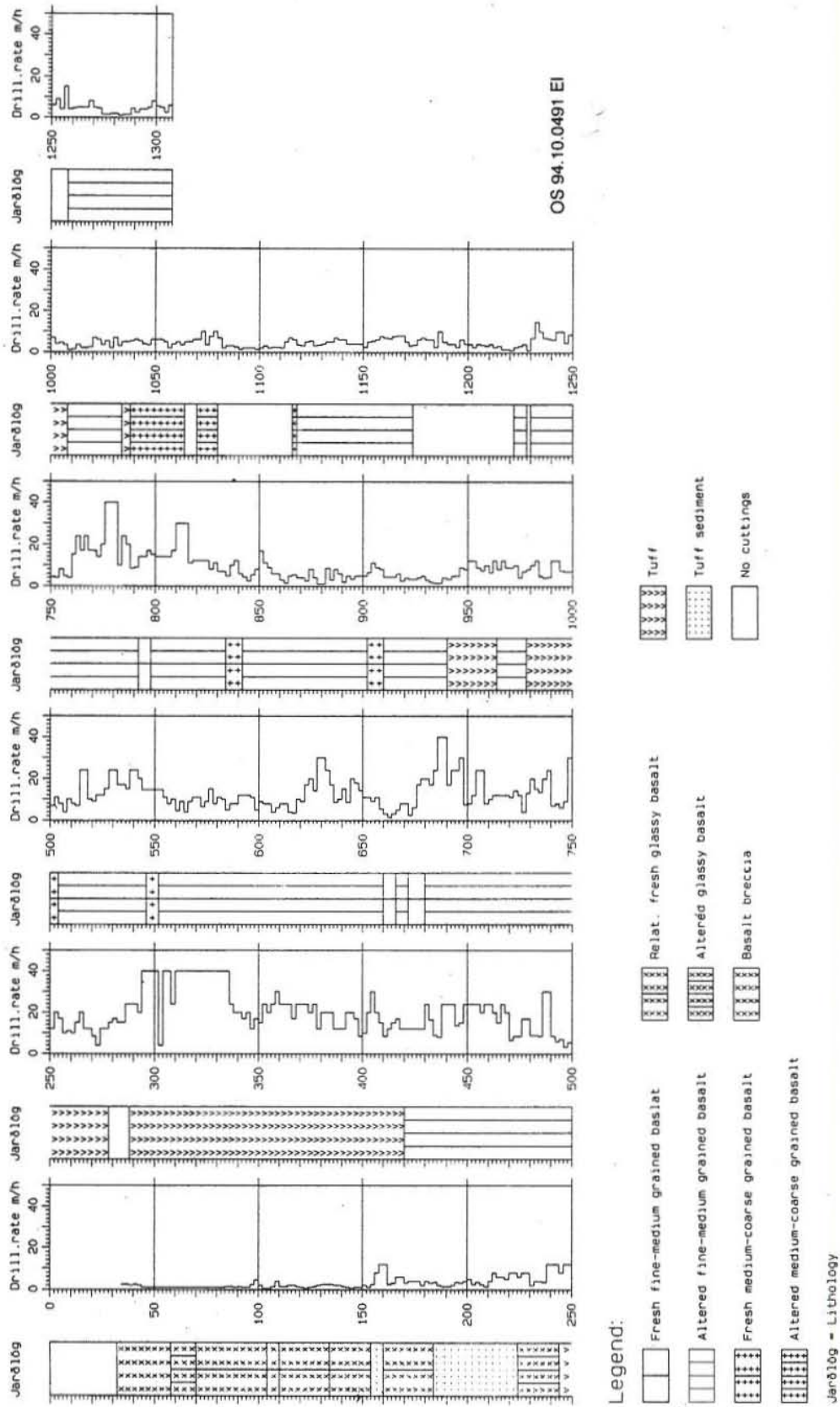


FIGURE 4: Detailed geological profile and penetration rate for well B-9

224-244 m	Slightly altered porphyritic tuff (considered as basalt-rich breccia). Remnants of fresh basaltic glass present.
244-278 m	Mixed rock comprising tuff and fresh fine- to medium-grained basalt (considered as altered tuff). A small tongue of fresh fine- to medium grained basalt exists at 256 m. Circulation losses reported at 270 m. Hydrothermal alteration minerals like pyrite, calcite, quartz and wairakite occur in large quantities at 270 m.
278-288 m	No cuttings. Circulation losses were reported at 280 m.
288-420 m	Altered porphyritic tuff. Whether the formation is of olivine tholeiite or tholeiite composition is difficult to say because the rock is rather more glassy to afford proper classification from the thin sections at 302 and 380 m. Permeability in form of fractures and veins seems to be prominent as indicated from the relative abundance of vein fillings especially between 246 and 380 m. At 274 and 276 m, the formations appear to be thoroughly altered. A light-coloured band of tuff occurs between 336 and 344 m containing excessive quantities of pyrite, calcite, wairakite and quartz could be a highly pyritized wall-rock. The tuff between 346 and 380 m contain a great deal of pyrite as vein material sandwiching calcite, quartz, wairakite and other zeolites.
420-500 m	Altered fine- to medium-grained basalt. Thin section at 456 m shows a more glassy formation but could be olivine tholeiite in composition. A circulation of 3 l/s was encountered at 481 m.
500-504 m	Fresh medium- to coarse-grained basalt (dolerite intrusion).
504-546 m	Altered fine- to medium-grained basalt. Thin sections at 508 and 534 m show the formation to be olivine tholeiite in composition.
546-552 m	Could be an intrusion (see Section 2.3).
552-660 m	Altered fine-grained basalt. Thin section at 560 m indicates it to be olivine tholeiite. However, thin section at 594 m reveals the formation to be a mixture of both sub-ophitic olivine tholeiite and tholeiite basalt. 612-618 m seems to be completely crystallized altered tholeiite basalt, fine- to medium-grained whereas 618-660 m seems to be altered fine-grained basalt. Thin section at 630 m shows the formation to be equigranular tholeiite basalt exhibiting flow structure (parallel arrangement of plagioclase laths).
660-666 m	Could be an intrusion (Section 2.3). A circulation loss of 6 l/s was encountered at 648 m.
666-672 m	Altered fine- to medium-grained basalt.
672-680 m	Could be an intrusion (see Section 2.3).
680-792 m	Altered fine- to medium-grained basalt. Thin sections at 718 and 768 m show the formation to be of olivine tholeiite composition.
792-798 m	Could be an intrusion (see Section 2.3).
798-834 m	Altered fine- to medium-grained basalt. Thin sections at 798 and 828 m indicate olivine tholeiite.
834-842 m	Altered medium- to coarse-grained basalt. Could be an intrusion or a simple basalt flow (see Section 2.3).
842-902 m	Altered fine- to medium-grained basalt. Thin sections at 852 and 878 m shows the formation to be tholeiitic in composition.
902-910 m	Fresh medium to coarse-grained basalt. Could be an intrusion (see Section 2.3).
910-940 m	Altered fine- to medium-grained basalt. Thin sections at 910 m shows it to be tholeiitic in composition.
940-964 m	Altered tuff perhaps of olivine tholeiite composition.
964-978 m	Altered fine- to medium-grained basalt, perhaps similar to the preceding depth interval.
978-1008 m	Altered tuff. Thin section at 984 m shows the formation to be of olivine tholeiite composition.
1008-1034 m	Altered fine- to medium-grained basalt. Thin section at 1026 m indicates olivine tholeiite composition.
1034-1038 m	Altered tuff. Could be of olivine tholeiite composition.

1038-1064 m	Altered medium- to coarse-grained basalt. Samples at 1050 and 1060 m lacking.
1064-1070 m	No cuttings.
1070-1080 m	Altered medium- to coarse-grained basalt. Could be either an altered dolerite intrusion or a normal basalt flow. Thin section at 1070 m shows the formation to be of olivine tholeiitic composition.
1080-1116 m	No cuttings. Thin section at 1098 m shows a coarse-grained rock, most likely of olivine tholeiite composition.
1116-1118 m	Altered medium- to coarse-grained basalt (altered dolerite intrusion).
1118-1174 m	Altered fine- to medium-grained basalt. Thin sections at 1120 and 1160 m exist but owing to the cloudy appearance of the rock constituents perhaps due to extensive alteration, it is difficult to categorize the formation from this depth down to the bottom of the well.
1174-1222 m	No cuttings. Total circulation losses at 1175 m. Main aquifer. Thin section at 1218 m does not reveal much for similar reasons as above.
1222-1228 m	Altered fine- to medium-grained basalt.
1228-1230 m	No cuttings.
1230-1250 m	Altered fine- to medium-grained basalt. Thin section at 1246 m exists but nothing much can be derived from it for the same reasons as above.
1250-1258 m	No cuttings.
1258-1308 m	Altered basalt, fine- to medium-grained. These sections at 1282 and 1300 m do not show the rock type either.

2.3 Intrusions

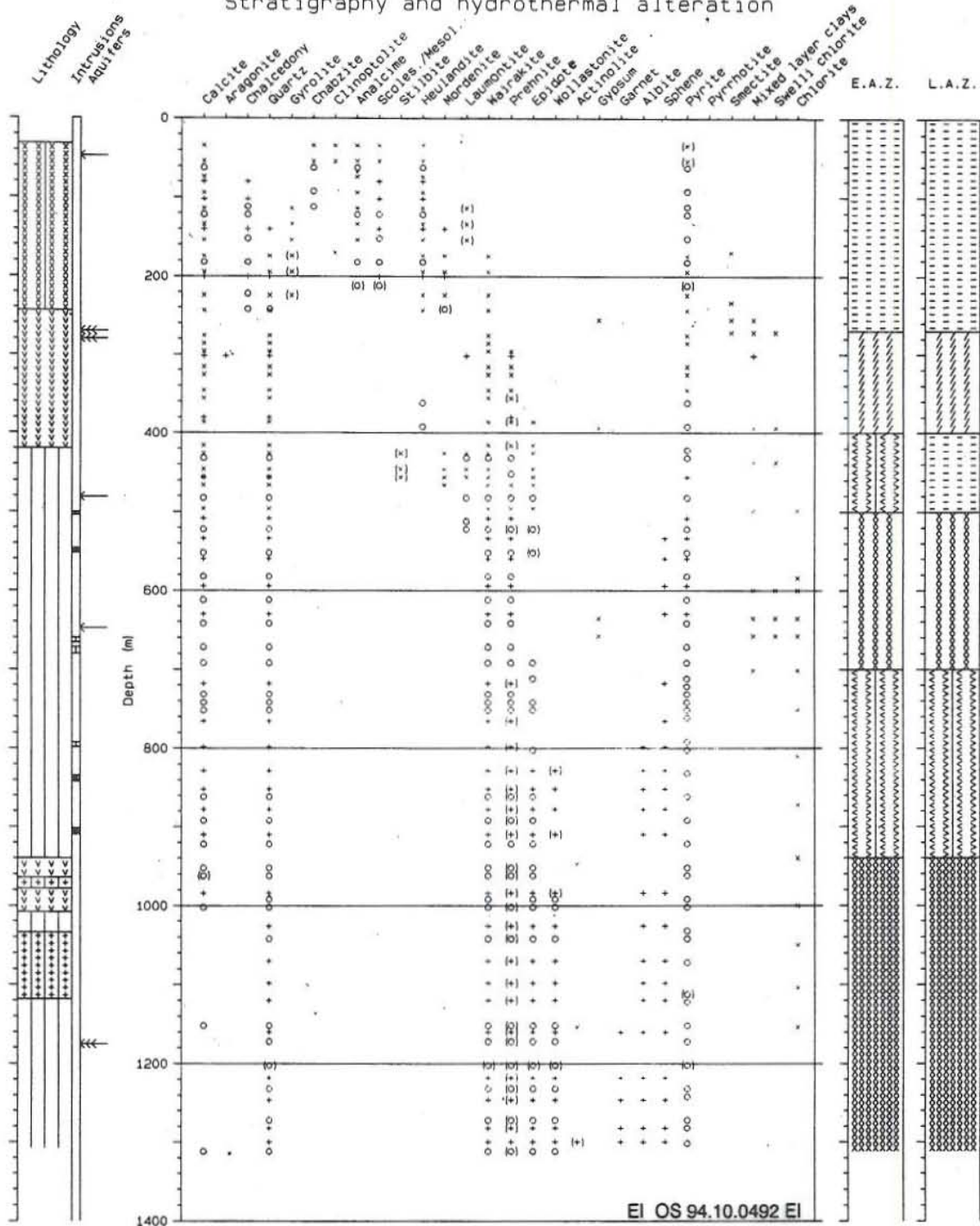
A column of intrusions found in the well is contained in Figure 5. From the volcanic succession made of this well, it is apparent that the majority of the intrusions are medium- to coarse-grained basalts referred to as dolerite. However, fresh-looking, fine- to medium-grained basalts occur at 672-680 and 792-798 m. A medium-grained fresh basalt occurs at 660-666 m. Interestingly, this intrusion is devoid of any alteration mineral. Pyrite, calcite, quartz, wairakite or even clay minerals were not detected at all. It could as well be a fine- to medium-grained basalt but is at least very well crystallized. The intrusions occur both as fresh and altered. This may imply different ages perhaps where the more fresh-looking ones may be presumed to be younger than the more altered ones. Although the absence of secondary minerals may indicate lack of permeability, that hypothesis alone does not seem to hold in this case because first, the aquifer at 648 m may be connected in one way or another to this intrusion. Secondly, this depth interval corresponds to the lowest penetration rate recorded in this section. Instead, it appears to be a typically fresh and young dolerite intrusion which undoubtedly should be of poor permeability in its interior. In addition relatively fresh-looking dolerite intrusions were defined at 500-504, 546-552, 902-910 m depth intervals while altered dolerite intrusions were discerned at 834-842, 1038-1064, 1070-1080 m. At 1116-1118 m and possibly also at 1080-1116 m, where cuttings are lacking, either altered dolerite intrusions or simple medium- to coarse-grained basalt flows may be found (Figure 5). Whatever is the case, intrusions in this well comprise less than 10% of the entire volcanic succession.

3. HYDROTHERMAL ALTERATION

3.1 Analytical techniques

The study of hydrothermal alteration of the formations penetrated by drillhole B-9 involved three main techniques, namely:

NÁMAFJALL WELL B-9
Stratigraphy and hydrothermal alteration



Legend:

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|--------------------------------|-------------------------------|--|
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| | | |
| | | |
| | | |
| | | |
| E.A.Z.: Early alteration zones | L.A.Z.: Late alteration zones | |

FIGURE 5: Secondary mineral distribution and alteration zones in well B-9

- 1) The stereo- (or binocular) microscope;
- 2) The petrographic microscope;
- 3) The X-ray diffractometer.

The **binocular microscope** is an important analytical instrument especially in cutting analysis during drilling. A number of hydrothermal minerals have been found to indicate particular formation temperatures in Iceland. Wairakite, for example has been very useful when determining casing depth especially in high-temperature areas (Gudmundsson, pers. comm.). During the present study the cuttings were studied in great detail by this technique.

A rough estimate of the relative abundances of all the recognizable hydrothermal minerals was made and the numbers 0, 1, 2, 3, and 4 were assigned for comparison purposes. They stand for absent, rare, common, abundant and very abundant, respectively (see Section 3.3 and Figure 6). This nomenclature has been used in this report to emphasize the relative abundances of the minerals as were seen strictly under the binocular microscope. The relative abundance of some selected hydrothermal minerals along with aquifers and a simplified geological section of well B-9 are shown in Figure 6.

The **petrographic microscope** is a useful instrument in the study of drill cuttings in thin section. A microscopic study of drill cuttings is a part of the geological and mineralogical research which aims towards a more thorough geological understanding of geothermal reservoirs. The essential use of this microscope relates to the small size of the secondary minerals formed in the rocks by the action of hydrothermal fluids and their interrelation. In the present study, 29 thin sections of this well selected by A. Gudmundsson were used. The petrographic microscope may thus be used to:

- 1) Confirm (or determine) the rock type as seen in the stereo-microscope;
- 2) Confirm and add to the secondary mineral identification from drill cuttings;
- 3) Study the type of rock replacement mineralogy;
- 4) 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. Included in this group are iron ore minerals which need to be studied in a polished section and reflected light microscopes - not applied in the present study. However, an idea of the relative ore composition can be formed by using an external light source and the reflection properties of the ore, yet in thin sections. In the present study, however, all those minerals suspected to be sulphides appeared isotropic in thin sections. The only ore identified with certainty under the stereo-microscope was pyrite. However, dark spots could also be discerned in the cuttings under the stereo-microscope below 422 m. They ought to be of primary magnetite and/or ilmenite which later alter to sulphides and sphene.

The **X-ray diffractometer** is a very useful instrument in cross-checking observations made under both the stereo- and binocular microscope, especially where zeolites cannot be identified individually. More important though is the accurate identification of clay minerals. In the former case, this technique was employed to prove the presence of wairakite in this well at a depth as shallow as 220 m. Furthermore, XRD confirmed the presence of epidote, prehnite and wairakite together with mordenite and laumontite, at a depth range from 432-520 m. Amygdale and vein infillings were systematically picked where found, at depth ranges 34-70, 70-108, 110-150, 152-224, 226-244, 246-292, 294-318, 320-344, 346-420, 422-464, and 464-492 m. In total, 11 XRD runs were performed on these samples. The last two confirmed the presence of epidote, prehnite, mordenite and laumontite occurring together. Under the stereo-microscope, epidote, mordenite and laumontite were not distinguishable in the thoroughly altered fine- to medium-grained basalt between 462 and 492 m but were indicated by XRD. Traces of laumontite are observed between 494 and 520 m. This state of affairs is of great importance as regards the condition of the geothermal reservoir. The characteristic peaks for these minerals in the 422-464 and 464-492 m depth range are shown in Figure 7. For details see Section 5.

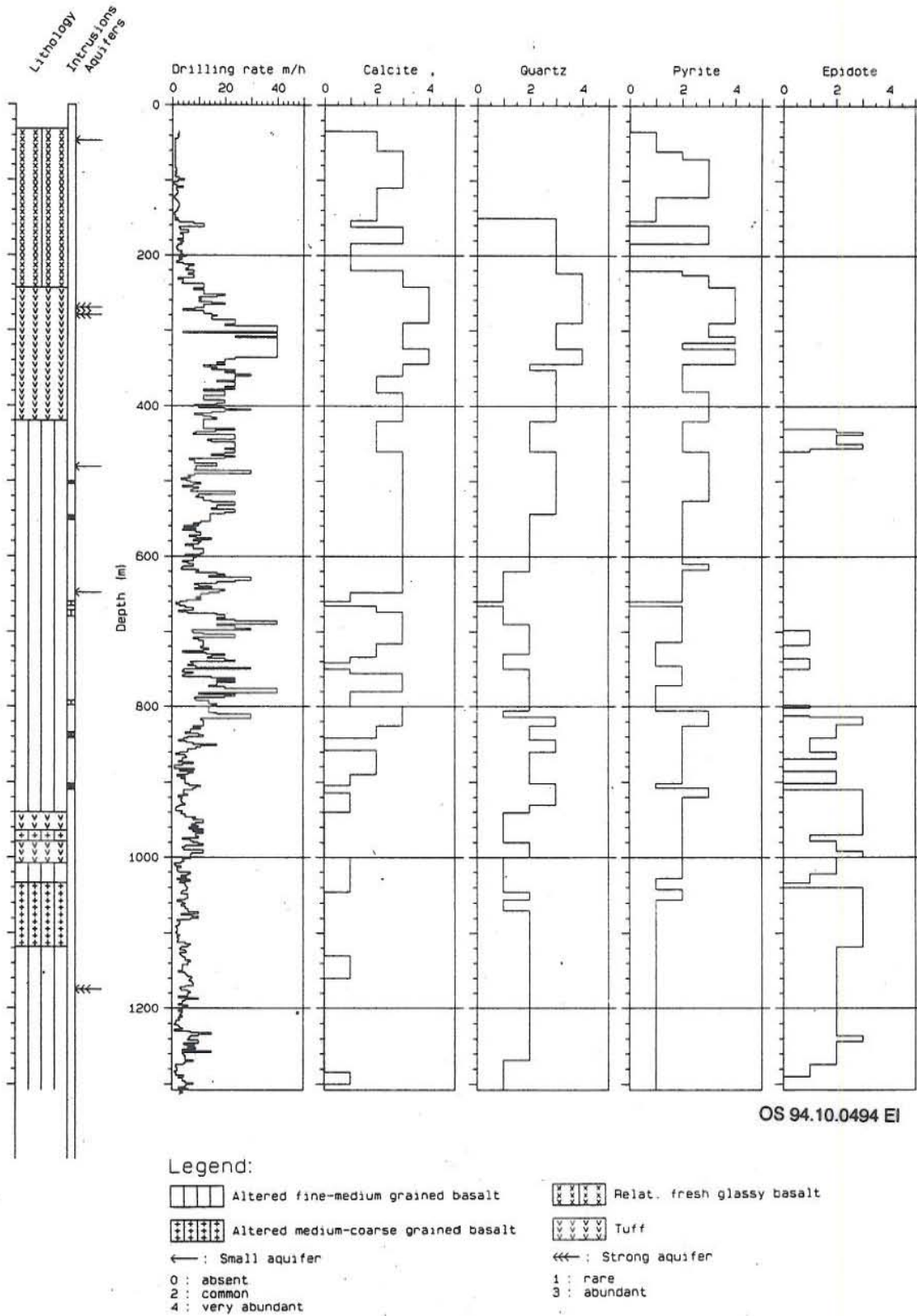
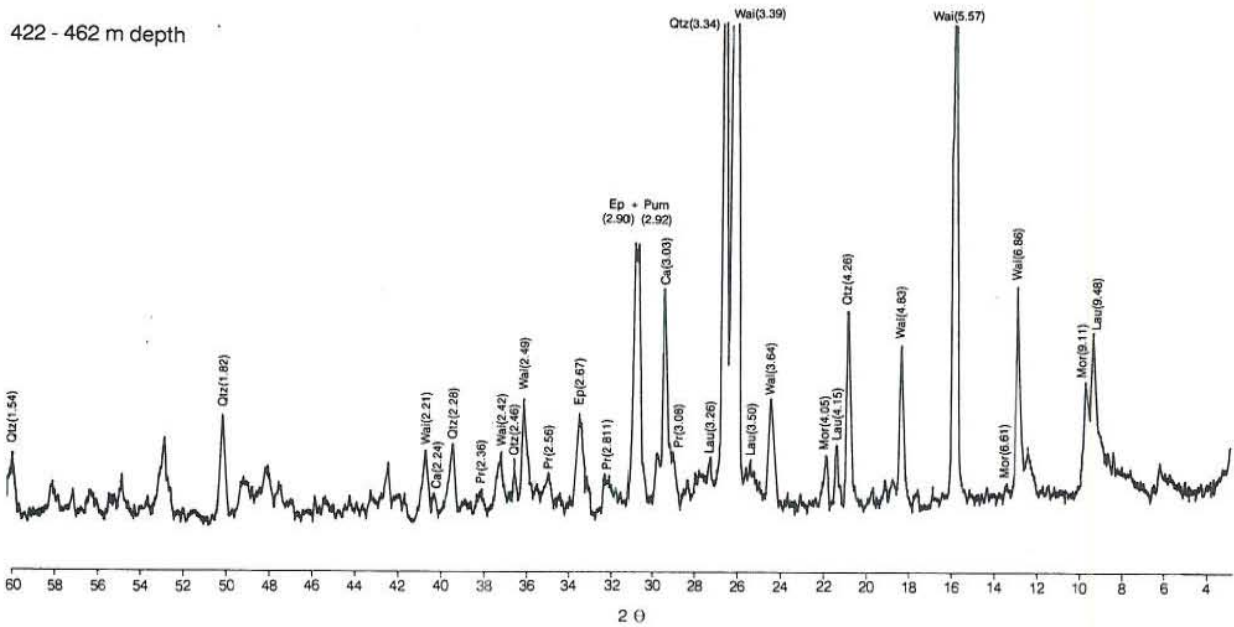


FIGURE 6: Relative abundance of selected alteration minerals in well B-9

422 - 462 m depth



LEGEND: Qtz = Quartz; Wai = Wairakite; Lau = Laumontite; Ca = Calcite; Pr = Prehnite; Mor = Mordenite; Pum = Pumpellyite.

464 - 492 m depth

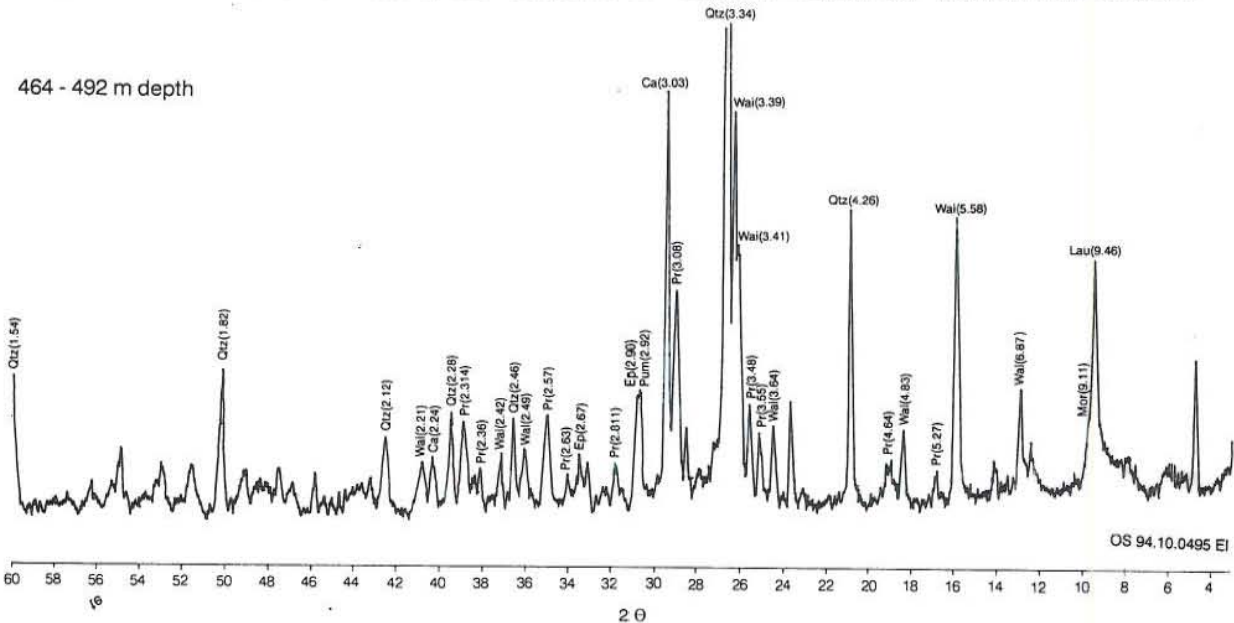


FIGURE 7: Characteristic XRD patterns for some minerals at 422-462 and 464-492 m depth intervals in well B-9

The zeolites identified by this technique were heulandite, clinoptilolite (a variety of heulandite), analcime, laumontite, mordenite, gyrolite, analcime, chabazite, and mesolite. It was also useful in establishing approximately the depth at which analcime disappears and wairakite starts to appear.

While only a fair picture of the different clay minerals can be obtained from both the stereo- and polarizing microscopes especially on the basis of colour and relative grain size, a more accurate identification and classification of them is possible with the help of the XRD. The standard procedure for clay sample preparation is contained in Appendix I. In total, 16 runs were performed and the results are contained in

3.2 Alteration of primary minerals

The degree of preservation of primary textures is a function of formation permeability and the type, abundance, and grain size of primary minerals (Lonker et al., 1993).

Figure 8 shows the alteration state of the primary rock constituents in well B-9. The principal primary constituents of basalts are, olivine, pyroxene, plagioclase feldspars (higher in Ca) and iron ore minerals like magnetite and ilmenite. Under the influence of hydrothermal fluids, these minerals alter to similar and/or different alteration minerals as follows:

- 1) Glass alters mostly to clays, sphene, epidote or calcite;
- 2) Olivine alters to iddingsite or clays, sphene, sulphides or calcite;
- 3) Pyroxene alters mainly to clays. It is, however, relatively resistant to hydrothermal alteration;
- 4) Plagioclase is also relatively resistant to alteration but the first indications of alteration are tiny fractures filled with clay at high temperatures and deeper down albite is seen to replace it. Later on, epidote, sphene and calcite appear. Wairakite is a common replacement mineral of plagioclase phenocrysts;
- 5) Iron ore minerals alter mainly to sphene and sulphides (usually pyrite and pyrrhotite).

In general, the order of decreasing susceptibility to alteration is glass, olivine, plagioclase and pyroxene. In this well, fresh basaltic glass occurs all the way from the top to around 224 m. Calcite and clay minerals are the most common replacement minerals of the glass in this well. Olivine starts to alter by developing diagonal fractures which go into clay minerals which are green in colour. They are normally smectites which then convert to higher clay minerals with increasing temperature and depth of burial. Olivine which had started to alter is clearly seen in the thin sections at 80, 102, 140, and 200 m. From around 250 m, olivine seems to be completely altered. Pyroxenes were observed to develop a cloudy rim at the edges and start to disintegrate at around 1120 m. Replacement of plagioclase phenocrysts with secondary minerals was first noticed in thin sections around 560 m where partial replacement by wairakite was detected. In other instances quartz was seen to replace them. The same was observed in thin sections at 594 and 630 m. Fractures filled with clay minerals especially chlorite were first encountered in a thin section at 718 m. Limited albite was seen in thin sections at 798 m. Extensive albitization was encountered in all thin sections below this depth. Alteration of plagioclase up to 700 m was restricted to phenocrysts only whereas beyond this depth, albitization occurred in the laths. It sounds more logical to refer to the former process as replacement and the latter as alteration. Wairakite is identified by its cross-hatched twinning similar to the polysynthetic twinning of feldspars. Iron ore minerals were first observed to alter to sphene in thin sections at 534 m. It was recognized by a reaction rim at the edges which displayed yellow to red brown colours.

3.3 Distribution of hydrothermal minerals

The hydrothermal mineral assemblage found in this well is shown in Figure 5 and includes calcite, aragonite, chalcedony, quartz, gyrolite, chabazite, clinoptilolite, analcime, scolecite/mesolite, heulandite, mordenite, laumontite, wairakite, prehnite, epidote, pumpellyite (a variety of epidote), wollastonite, actinolite, gypsum, albite, sphene, pyrite, pyrrhotite, clay minerals (namely smectites, mixed layered clays, swelling chlorite and chlorite), and possibly also garnet. Of these, gyrolite, chabazite, clinoptilolite, analcime, scolecite/mesolite, heulandite, mordenite, laumontite and wairakite are the only zeolites identified in this well.

The occurrence and distribution of hydrothermal alteration minerals along with the simplified stratigraphy is shown in Figure 5 while the distribution of the individual minerals is discussed below.

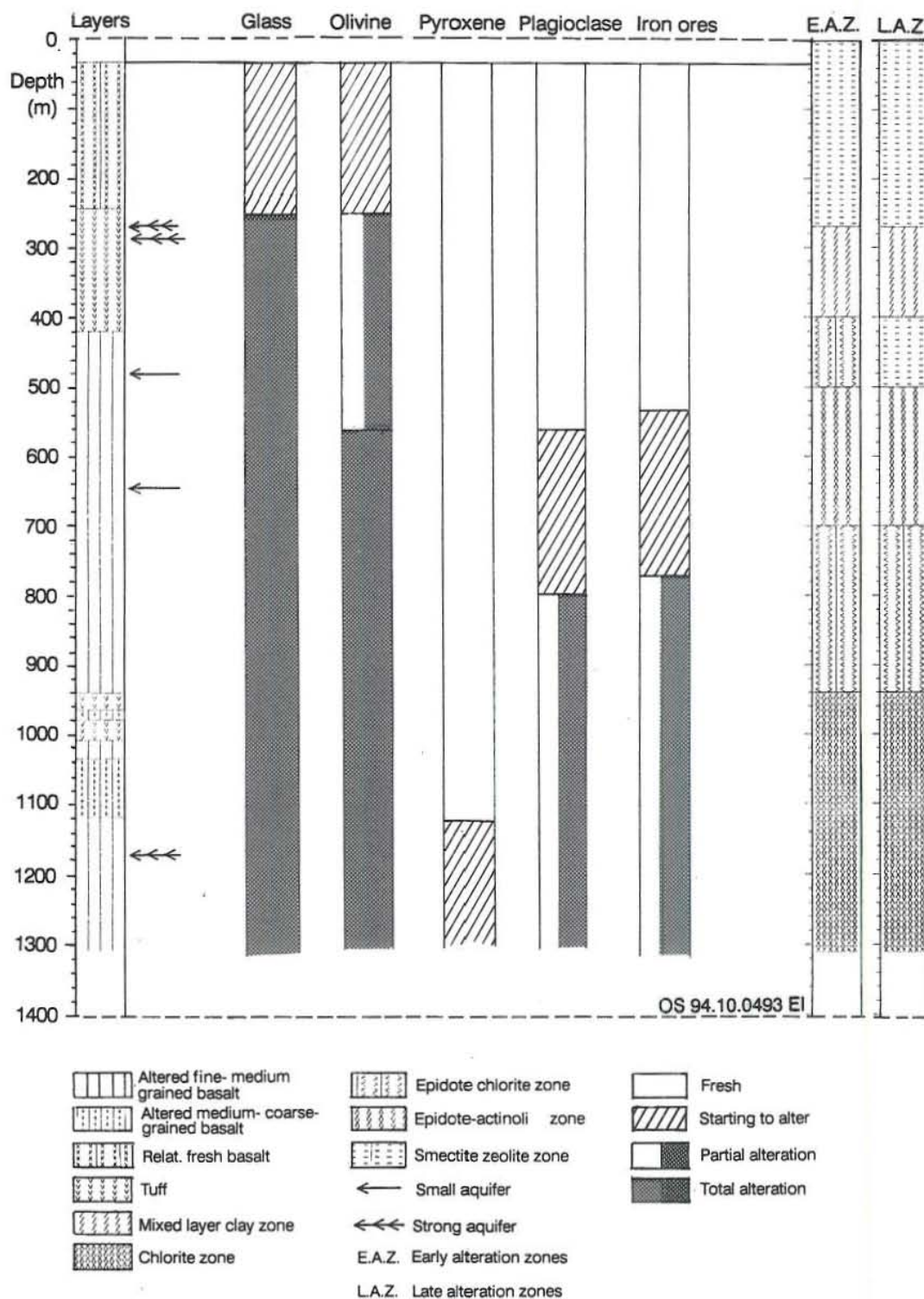


FIGURE 8: Alteration state of primary minerals and glass in well B-9

Calcite is one of the most abundant secondary minerals in this well. It occurs from the top to around 900 m. Its distribution below this depth is rather erratic (Figures 5 and 6). It is rare below 902 m, absent in the fresh medium-grained intrusion at 660-666 m, in the dolerite intrusion at 902-910 m, rare up to 940 m and absent between 942 and 1000 m. It is rare again from 1002-1038 m while it is completely absent from 1040-1120 m. It is important to note that the calcites observed in this well are of two types; normal rhombohedral

calcite and what has been termed platy calcite. For the implications see Section 4. If this hypothesis is true, then both kinds dominate in the upper 400 m of the well with normal calcite dominant in the top 300 m and both kinds occurring between 300 to around 1000 m. Beautiful plates of such calcite are abundant at 396 and 398 m.

The rare occurrence of calcite below 1000 m (Figures 5 and 6) is assumed to be foreign to these depth range, being a result of contamination during drilling otherwise a reoccurrence of calcite would suggest cooling. This assumption is supported by the very abundant occurrence (4) of calcite in the last sample at 1308 m recovered from this well yet no calcite was detected in the second last two samples at 1306 and 1304 m depth. Generally, calcite occurs as open space fillings and as a replacement of the glassy groundmass, primary pyroxene and plagioclase phenocrysts.

Aragonite occurs as very large crystals in thin sections at 302 m depth. It is difficult to distinguish it from calcite in the cuttings, but in thin sections it is identified by its pearly grey (white of the high order) with brighter colours on thin edges and along cracks within the crystal.

Chalcedony was observed in thin sections at 80 m and in the cuttings at 110 and 114 m.

Quartz was first observed in this well in the XRD run for 150-224 m depth interval down to the bottom of the well. In thin sections, it was first observed at 102 m. At deeper levels, quartz is seen to occur before or after calcite in vesicles. It is also seen to replace laumontite perhaps in response to increasing temperature at around 500 m depth. Like epidote, it occurs as small, euhedral prismatic crystals in the upper levels of the well but large crystals are found at deeper levels especially in vugs associated with wairakite.

Gyrolite was only identified through XRD and found at 110 to 150, and at 150 to 224 m but smaller peaks at 22.07 and 11.07 Å occurring in the XRD run for 224-244 m depth interval may also imply its presence there.

Chabazite is restricted to the upper 70 m of this well only distinguished by XRD in the depth range of 34-70 m. In cuttings it is recognized in vesicles down to about 120 m by its euhedral rhombohedral crystals that approach the cube. Characteristic peaks at 4.32 and 2.93 Å distinguish it from the other low-temperature zeolites.

Analcime is found in the well from the top (34-70 m) to around 150 m. Below this depth wairakite seems to predominate. In XRD, it gives characteristic curves at 3.43 and 5.60 Å, the latter being weaker.

Scolecite/Mesolite is similarly restricted to the top 70 m of the well. Peaks at 6.64, 4.44 and 2.89 Å are characteristic for this mineral. Binocular and petrographic analyses indicate its presence down to about 220 m.

Heulandite is the lower temperature zeolite occurring in abundance in this well occurring from 34-244 m. It is recognized in thin sections by its distinct tabular crystals. The predominance of heulandite over stilbite in this well was proved by two XRD runs for vein and amygdale infillings at 34-70 and 70-108 m where heulandite peaks are characteristic. Instead, **clinoptilolite**, a variety of heulandite gives characteristic peaks especially in the top 70 m. If there is any **stilbite**, then it is in trace amounts. Characteristic peaks at 8.95 and 4.65 Å distinguish it from clinoptilolite which exhibits strong peaks at 8.92 and 3.96 Å in decreasing order of intensity.

Mordenite is recorded from 150 to 492 m. It gives the main peak at 9.11 Å but smaller peaks at 13.6, 6.60 and 4.05 Å also occur. It occurs together with laumontite and epidote from 430-492 m.

Laumontite is by far the most widespread zeolite which also happens to be a high-temperature zeolite. It was detected with certainty at 422-462 m (stilbite is questionable here), overlapping there with wairakite, epidote and prehnite between 432 and 460 m. It gives characteristic peaks at 9.44, 4.15 and 3.50 Å. In hand specimen it is a very soft mineral which is easily crushed between two fingers. Epidote is not observed in the cuttings between 464 and 492 m but an XRD run from 464-492 m gives peaks for laumontite as above and a broad peak for epidote and pumpellyite at 2.90 and 2.92 Å respectively. The rock formation here is altered basalt, fine- to medium-grained. Between 494 and 520 m the laumontite is seen to transform to quartz. However, on the basis of crystal structure, it may be possible to transform laumontite into wairakite with increasing temperature (Kristmannsdottir, 1982). This situation was not encountered in the cutting analyses but perhaps the abundant wairakite observed below this depth could in part be a result of such a transformation. For the implications of this seemingly incompatible mineral assemblage, see Section 5.

Wairakite, the Ca analogue of analcime was originally recorded in tuffaceous sandstones and breccia, vitric tuff and ignimbrite which had been altered by alkaline hydrothermal fluids associated with geothermal steam in New Zealand; the actual occurrence was at a depth where the observed temperature range was from 200 to 250°C (Steiner, 1955).

It is recognized in cuttings first by its cloudy appearance due to the high abundance of fluid inclusions. This is actually the case in the upper parts of the well. At greater depth, characteristic igloo-like crystals occur. In thin section it is recognized by its characteristic cross-thatched twinning comparable to the polysynthetic twinning in plagioclase. In the XRD, wairakite was first detected between 150 and 224 m, most probably occurring just below 200 m as it becomes abundant in the 224-244 m and the subsequent runs. Characteristic peaks at 3.39 and 3.41 Å, both of which are very strong, distinguish it from analcime, its Na analogue.

Prehnite was first recorded in XRD runs for 294-318 and 320-344 m, questionable between 346-420 m and abundant in 464-492 m runs and perhaps down to the bottom of the well, although the XRD run for 422-462 m depth interval gives a very small peak at 3.08 Å. A big peak is, however, registered for it in the 464-492 m run. In the cuttings, three crystals of it were picked from 432 m for XRD analysis. It is especially abundant in 482 m. In the cuttings it is recognized at 380 m by its pale green, platy crystals with a reniform habit usually filling large vugs. In thin sections, it is recognized by its bow-tie structure. The small size of the cuttings in the lower section of the well render the recognition of this mineral in drill cuttings difficult.

Epidote occurs sporadically in the upper 800 m, first recorded by the binocular microscope and XRD between 430 and 460 m as already pointed out above, where it ranges from common to abundant (Figure 6). It is rare between 700 and 716 m and from 736-750 m perhaps in response to lower porosity and permeability of the formations here. It wavers between common and abundant from 816 m to around 1270 m becoming rare to the bottom of the well, furthermore underscoring the low porosity and permeability of these formations. It is identified in the stereo-microscope by its yellowish-green colour and acicular euhedral crystals. In thin sections it is colourless to yellowish-green and somewhat pleochroic. The grain size and degree of crystallinity of the epidote was seen to increase with depth. In the upper section it forms minute granules filling vesicles and vugs; at greater depth it was seen to occur as bright yellowish-green crystals in stellate masses associated with quartz, chlorite and prehnite (Mehegan et al., 1982). Replacement of plagioclase phenocrysts by epidote is common too. Epidote is seen to occur at greater depth than prehnite in this well (Figure 5). This is similar to the situation observed in the Krafla wells (Gudmundsson, pers. comm.).

XRD runs for these minerals at 422-462 and 464-492 m depth intervals (Figure 7) revealed the presence of **pumpellyite**, a variety of epidote (Moorehouse, 1964). The broad peaks at 2.90 and 2.92 Å, both of which are strong, distinguish these minerals. In thin sections, pumpellyite is strongly pleochroic from colourless to intensely green and ranges in form from fan-shaped aggregates to thin prismatic crystals. The strong pleochroism, distinct habit, and anomalous colours allow pumpellyite to be optically distinguished from coexisting chlorite variants (Viereck et al., 1982). The latter authors considered pumpellyite to be a variety of chlorite but this is found not to be the case. Instead, Moorehouse (1964) agrees with Deer et al. (1963).

Wollastonite first appears in this well at around 1000 m depth. In thin sections, it was first recorded at 1026 m. It is identified by its colourless and fibrous aggregate form radiating outwards in close association with epidote and possibly garnet.

Actinolite was detected by XRD technique together with chlorite at 948 and 1154 m (Gudmundsson, 1993).

Gypsum was detected by XRD clay mineral analyses at 256, 272, 394, 636, and 658 m (Appendix II).

Garnet was very difficult to discern in thin sections as the rock was thoroughly disintegrated to accord fair observations but given the occurrence of high-temperature minerals like wollastonite and actinolite from around 950 m down to the bottom, the presence of garnet cannot be ruled out. According to Figure 5, it is expected from a depth of 1160 m down to the bottom of the well.

Albite was observed to partially alter plagioclase in all thin sections from 798 m to the bottom of the well. It was recognized by its lower refractive index than balsam and was distinguished from wairakite by the latter's cross-hatched twinning. In Tertiary sections, albitization occurs sporadically in plagioclase from approximately the same depth as chlorite becomes the dominant sheet-silicate (Kristmannsdottir, 1982). A comparison of the alteration state of plagioclase with respect to depth shows partial alteration starting from 780 m which is not far from the 752 m depth in the clay mineral analysis (Appendix II) where chlorite starts to be the dominant sheet-silicate. This is similar to the situation observed in Nesjavellir high-temperature field (e.g. Franzson, 1994). Likewise, in the present study, abundant sphene is seen altering the primary ore minerals around the same depth as chlorite becomes the dominant sheet-silicate in both fields (Figure 5 and Appendix II).

Pyrite is widely distributed in this well ranging from rare to very abundant (Figures 5 and 6). The relative abundance of pyrite has been used to infer the permeability of a rock formation, whereby its high abundance implies greater permeability. In this well, therefore, pyrite was found to be rare in the upper 70 m of the well, perhaps in relation to temperature but becomes abundant to 124 m. It is rare again below this depth to the upper boundary of the small detrital tuff layer at 154 m and most probably common at the lower boundary of 184 m. Its relative distribution in the detrital tuff layer between 184 and 224 m cannot be estimated with certainty but it becomes very abundant from 224-280 m. In the latter depth range, the pyrite, on top of its brass yellow reflections and perfect cubic form, occurs as exceptionally large crystals encountered nowhere else in the well. Similar pyrite occurs between 310-344 m where calcite, wairakite and quartz are similarly very abundant. Below about 720 m, pyrite occurs as small crystals, appearing more or less as tiny specks disseminated more within the rock. It wavers between rare and common below 1040 m to the bottom of the well, otherwise it is also found as an open space filling coming earlier or later than calcite and zeolites. **Pyrrhotite** is inferred to occur together with pyrite but was difficult to distinguish clearly from the latter in the binocular and petrographic microscope.

The **sheet silicates** found in this well include smectites predominantly saponite, mixed layer clays, swelling chlorite (or correncite) and chlorite. They are among the dominant alteration minerals especially in hyaloclastite formations like the ones penetrated by this well. A detailed study of clay minerals as well, as their relation to other alteration minerals can be very useful in the interpretation of the thermal history of a geothermal area (Kristmannsdottir, 1978; Elders et al., 1979; Reyes, 1990). Sixteen samples were selected for analysis, all limited to the top 940 m. The results are shown in Appendix II.

Smectites are the only clays found down to around 234 m. They, however, occur also down to about 272 m. In the stereo-microscope, they appear as brownish-green, poorly-crystallized masses lining openings. In thin sections, they appear brownish, with low birefringence. On the XRD, they have peaks occurring between 13.4-15 Å (constant humidity at 35%), expanding to about 17 Å on treatment with glycol and collapsing to about 10 Å (9.93) or completely disappearing on heating to 550-600°C. Typical peaks for smectites at 170 and 234 m are shown in Figure 9. In this case, no peak was obtained for 234 m on heating.

Mixed layer clays (MLC) found in this well are mainly interlayered smectite-chlorite. In thin sections, they are brown to yellowish with low birefringence. They generally show variable optical properties owing to their transitional nature. They give peaks between 15-17 Å (for constant humidity), expanding to 29-31 Å on treatment with glycol and collapse to 12-14 Å on heating to 550-600°C. In this well, peaks between 29-31 Å were obtained for both glycolated and constant humidity samples with no defined peak (collapsed) on heating at least in all cases. The mixed layer clays are identified in samples from 256-702 m (Appendix II). Typical peaks for mixed layer clays at 394 and 498 m depth are shown in Figure 9.

Swelling chlorite (or corrensite), another variety of chlorite occurs in this well. It has peaks at 14.47 Å (for constant humidity), swells to 15.49 Å with glycol and drops to 14.72 Å when heated to 550-600°C as at 394 m. It was identified in 272, 394, 438, 600, 636, and 658 m samples. Typical peaks for swelling chlorite at 658 m depth are shown in Figure 9.

Chlorites are found both as infillings and as replacement minerals for ferromagnesian minerals in the deeper and hotter parts of the well. In the stereo-microscope, they are identified by their light-greenish colour and coarse-grained nature. They are equally pale-greenish with very low birefringence in thin sections. They are characterized by peaks at 14.2-14.5 Å (constant humidity) with another at 7-8 Å all of which remain unchanged with glycolation and heating to 550-600°C. Chlorite is first recorded in the sample at 498 m and to the bottom of the well. Typical peaks for chlorite at 752 and 872 m depth are shown in Figure 9.

3.4 Hydrothermal mineral zonation and alteration zones in B-9

The degree of hydrothermal alteration and amount of hydrothermal minerals formed in a geothermal reservoir depend largely on the following parameters: 1) The type and permeability of the rock; 2) the temperature and chemical composition of the fluid and 3) the duration of the geothermal activity; the latter being related to the age of magmatic activity (Kristmannsdottir, 1978; Elders et al., 1979; Browne, 1984; and Reyes, 1990).

According to Browne (1984) the minerals commonly used as geothermometers are the zeolites, clays, epidote and amphiboles. In Icelandic geothermal fields, most zeolites are common before 100°C and disappear before 200°C (stilbite, heulandite, mordenite). Laumontite replaces other zeolites at 100-120°C. However, in the present study mordenite is observed together with laumontite down to 492 m (Figure 5 and 7) and should disappear a little before laumontite does (at about 520 m). This suggests that it can withstand temperatures of over 150°C. This is in agreement with observations made elsewhere in Icelandic geothermal fields e.g. in Nesjavellir high-temperature field (Franzson, 1994).

Wairakite, just as in Cerro Prieto, Mexico, starts appearing at 180°C and is recorded up to 300°C (Kristmannsdottir, 1978; and Elders et al., 1979). On the other hand, in New Zealand, wairakite is identified at temperatures between 200-250°C (Steiner, 1955). In the present study, quartz appears a little earlier than wairakite where the former indicates a temperature of 180°C suggesting that wairakite first appears at a higher temperature than quartz. Therefore, 200°C is reasonable. Interestingly these two minerals tend to plot nearest to the boiling curve (see Figure 10) and since boiling in this part of the reservoir is not unusual, then these estimates are not far from the actual temperature values. However, it should be noted that these minerals are fossil at this depth and belong to the period responsible for the generation of epidote and prehnite in the 400-500 m depth interval in this well.

Chlorites in New Zealand geothermal fields are common minerals and have a wide range in composition and are therefore not used as geothermometers. In the present study, chlorite was found to occur alone at 584 m bounded by a mixture of chlorite and mixed layer clays at 498 m and chlorite, mixed layer clays and swelling chlorite at 600 m and below. It only becomes dominant beyond 700 m as at 752 m (Appendix II). Therefore, the chlorite recorded at 584 m seems to represent the conditions (230-250°C) that prevailed at this depth in

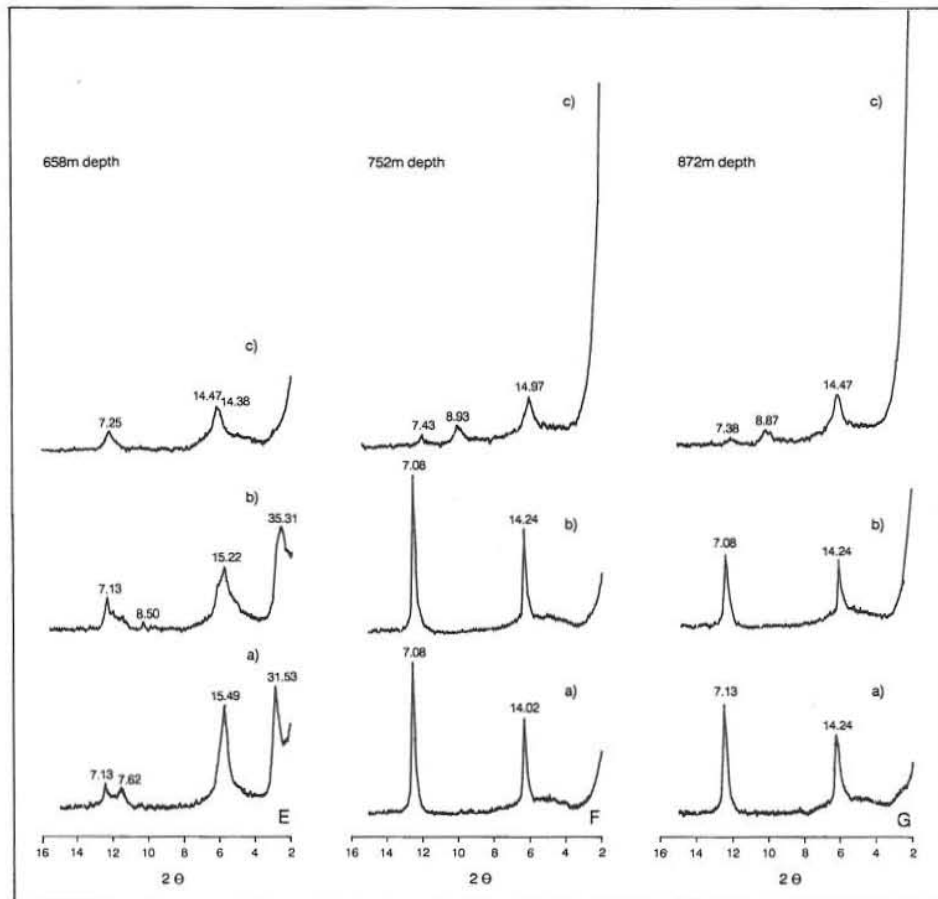
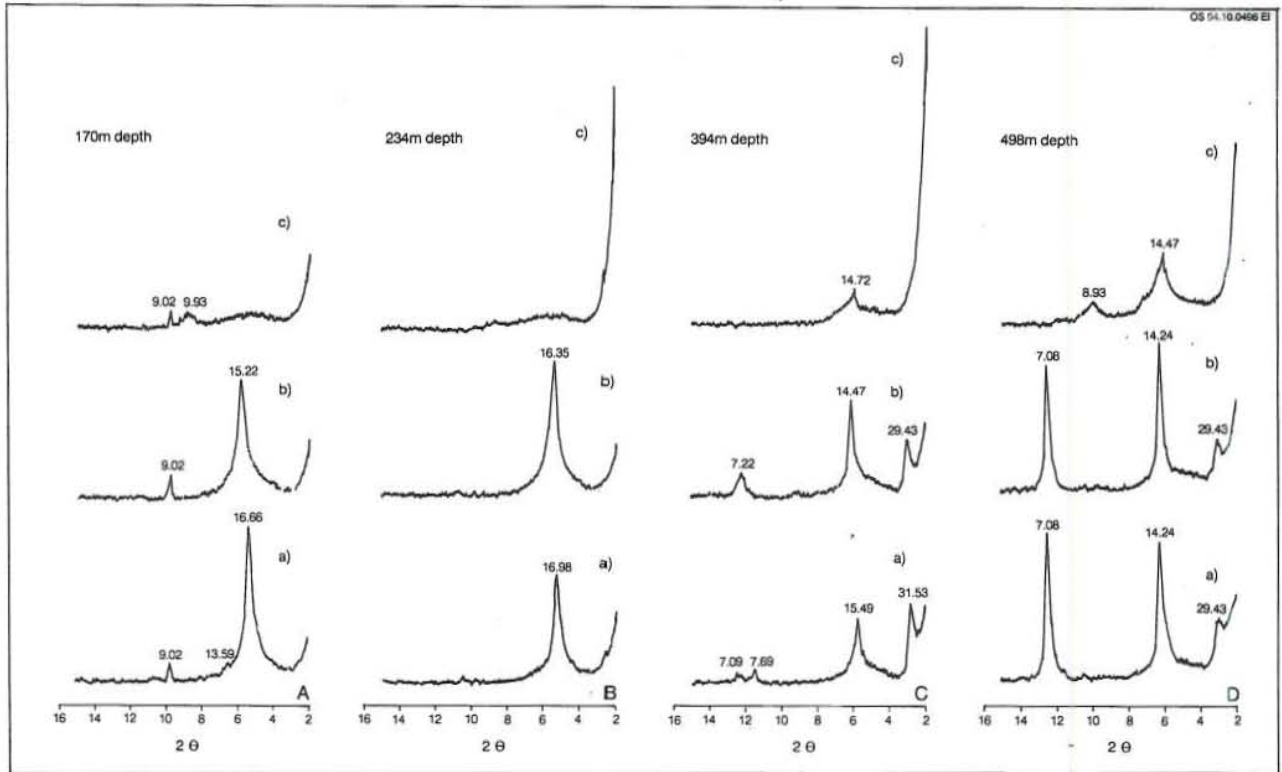


FIGURE 9: Characteristic XRD patterns for clay samples in well B-9

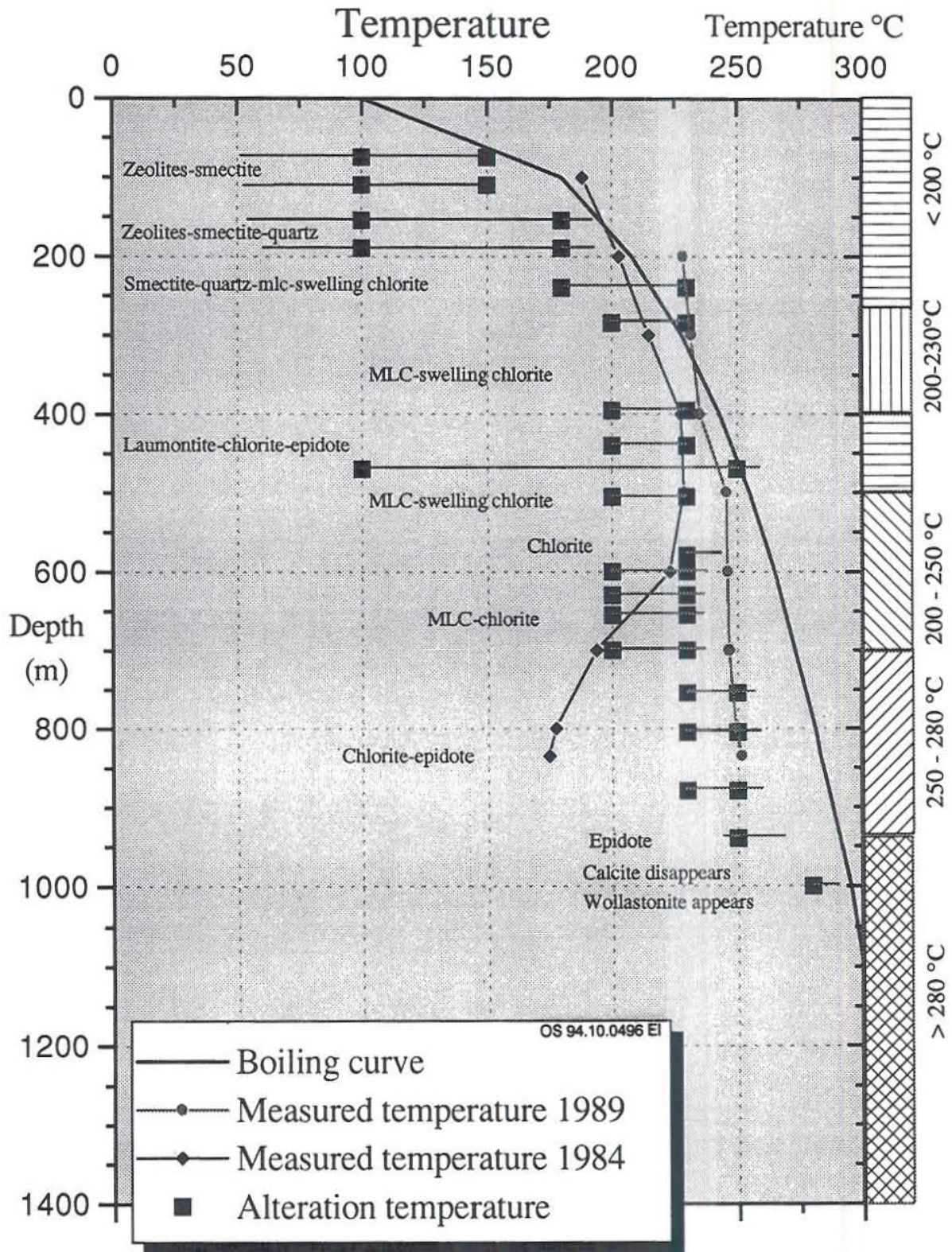


FIGURE 10: Correlation of alteration mineral temperatures and measured temperatures in well B-9

the past. If it was the reverse case, then the other lower temperature minerals like gypsum at 636 and 658 m would be non-existent. Likewise, the chlorite found occurring together with the mixed layer clays and swelling chlorite between 600 and 700 m could be representing such conditions. Mixed layer clays of smectite and chlorite are dominant at 200-230°C. This conforms to what was found in the present study where on top of the mixed layer clays composed of smectites and chlorite, the temperatures measured in this part of the well (in the 300-700 m depth intervals as in Figure 3) in 1972 and 1974, did not exceed 220-230°C. Although the temperature logs may have been influenced by discharge, they appear to represent the conditions prevailing in this part of the reservoir at the time of drilling the well (see Figure 3). Therefore, as chlorite is the dominant sheet silicate mineral from around 750 m, it suggests that the rock temperatures were >230°C even before the most recent volcanic activity in the area. Smectites are recorded at depth where rock temperatures are above 200°C (see Figure 3 and Appendix II). In New Zealand, clays such as montmorillonite (a type of smectite) are stable at about 140°C and illite above 220°C.

Among the minerals that occur at higher temperatures ($\geq 250^\circ\text{C}$), epidote seems to be the most reliable and consistent temperature guide. In Icelandic active geothermal fields, epidote occurs sporadically at 230-250°C but it appears in abundance at rock temperatures above 250°C. Therefore, the epidote observed in the 400-500 m depth interval should represent temperatures of $\geq 250^\circ\text{C}$ and the abundant epidote starting from 816 m a minimum of 250°C. From the curve in Figure 10, calcite is seen to disappear at the same depth wollastonite first appears (1000 m) which corresponds to a temperature of around 280°C. These conditions ought to have existed in this part of the reservoir at any one time in its history. According to Browne (1984), epidote first appears in many fields at 250°C and the lithology does not influence its formation. Variations regarding prehnite are seen in New Zealand where it appears at temperatures greater than 220°C. In Cerro Prieto, Mexico it occurs on the contrary, at higher temperatures than 300°C. This probably is due to the difference in the pH and calcium contents of the geothermal fluids. In the present study, prehnite is observed at a shallower depth than epidote (see Figure 5 and Section 3.3). Taking a depth of first occurrence say 300 m in this well, corresponds to a temperature of about 225°C which is not very different from 220°C as observed in New Zealand. Furthermore, this temperature lies on the boiling curve, suggesting boiling conditions at this depth at any one time. Recall also that platy calcite was first recorded from 300 m downwards together with the normal rhombohedral calcite furthermore underscoring the logic of boiling conditions in this part of the reservoir some time in the past.

The intensity and type of alteration usually reveals the degree of permeability, past or present. Minerals such as adularia and albite are often related to permeable zones, especially if they are present individually in association with quartz and calcite (e.g. at Tongonan, Philippines and in all New Zealand geothermal fields). This relationship is only valid if these minerals occur in veins and fractures (Browne, 1984). If they are, however, altering plagioclase, this relationship does not hold. However, from the present study, it is evident that plagioclase suffers two kinds of change by hydrothermal fluids namely: replacement by any other mineral through dissolution and alteration by albitization. The former was observed in the phenocrysts whereas the latter was restricted to the laths only (see Section 3.2). In view of this therefore, whether plagioclase disappears by replacement or alteration, the permeability of the formation may or may not be reduced considerably through self-sealing. It all depends on the chemical structure of the new mineral. Both these processes seem to be characteristic of Icelandic geothermal fields where replacement is earlier than albitization with respect to both depth and temperature. Worth noting also is that where extensive albitization was observed to occur in this well (at a depth greater than 1000 m), calcite was near to disappearing or completely absent, implying temperatures of $>270^\circ\text{C}$ (Kristmannsdottir, 1982). Otherwise the albitization of plagioclase occurs within a wide range of temperatures (Reyes, 1990). It has been observed that in zones where both albite and adularia occur together, the permeability of the rock tends to decrease through self-sealing. Therefore, the former relationship ought to be used with care.

The original mineralogy of the rock seems to have a minor effect on the type of mineral assemblage in permeable zones and where temperatures exceed 250°C. It is controlled mostly by the porosity/permeability.

However, there seems to arise a contradiction here. For instance the association minerals such as albite, quartz, epidote, chlorite, adularia, pyrite and illite occur in different geological environments suggesting that the original mineralogy has some influence on the secondary minerals produced. It is seen in andesitic rocks (Philippines and Indonesia), in rhyolites (New Zealand), alkaline lavas (Kenya) and sediments (Cerro Prieto). K-micas and K-feldspars are relatively rare in Icelandic geothermal fields and adularia less frequent than found elsewhere (e.g. Fridleifsson, 1984).

The occurrence of analcime may be related to the composition of the rock. For instance in Icelandic geothermal fields, the appearance of individual zeolites is influenced by rock composition where analcime is less common in quartz tholeiites than in olivine tholeiites (Walker, 1960). Instead zeolites such as mordenite, heulandite and laumontite are found in all areas. Browne (1984) also mentions that zeolites such as analcime mainly form in intermediate-acidic rocks. Concerning these factors, temperature and permeability of a system can then be inferred by the assemblage of hydrothermal alteration minerals. In the present study, analcime though very similar to wairakite in appearance, was precisely detected by XRD in the 34-70 m depth range up to around 150 m (see Section 3.3 and Figure 5). Although the rock here is olivine tholeiite and porphyritic in plagioclase too, it is not observed in large quantities. Instead, it appears to be more sensitive to temperature and permeability of the rock.

In active geothermal fields (New Zealand, Cerro Prieto, Iceland and Philippines), alteration zones were derived by empirical data found between rock temperatures and secondary minerals. For example, in Iceland, different alteration zones were obtained regarding the formation of smectites, mixed layer clays and chlorite than found elsewhere. The temperature ranges for these zones are 0-200, 200-230, and 230-250°C, respectively (Figure 11). A similar scheme was employed in creating Figure 10. In New Zealand other alteration zones with respect to temperature have been developed. For instance, smectites, mixed layer clays (smectite/illite) and illite give temperature ranges of 0-140, 140-220, and >220°C, respectively. These empirical relationships as well as the indicative minerals of temperature and permeability can be applied to other geothermal systems. Nevertheless, it is important that each area develops its own local zonation of hydrothermal alteration mineralogy vs. temperature relationship.

A correlation of alteration zones with rock temperature in active high-temperature areas in Iceland is shown in Figure 11. Also shown are the index minerals and mineralogical changes characterizing each alteration zone (slightly modified from Palmason et al., 1979).

A minimum of five alteration zones can be recognized in well B-9 (Figure 5). They are the smectite-zeolite, mixed layer clay-swelling chlorite, mixed layer clay-swelling chlorite-chlorite, chlorite-epidote and epidote-actinolite zones. As already noted, overlapping in these zones is not unusual. Therefore, two of such figures have been drawn. For example, the chlorite zone in Figure 5 is contained within the mixed layer clay-swelling chlorite-chlorite zone. The smectite-zeolite zone extends to around 270 m with a laumontite-chlorite-epidote zone at 400-500 m sandwiched between two mixed layer clay-swelling chlorite zones (200-230°C) above and a mixed layer clay-swelling chlorite-chlorite (200-230°C) zone below. The mixed layer clay-swelling chlorite zone extends from about 250 to about 400 m but is again recorded from 500-700 m overlapping with the mixed layer clay-swelling chlorite-chlorite zone over the same depth range. For this reason, a temperature range of 200-230°C has been assigned for this belt while a range of 200-250°C is assigned to the laumontite-chlorite-epidote zone above. A chlorite-epidote belt extends from 700-940 m (250-280°C). The abundant occurrence of epidote in this well from 940 m and the first appearance of actinolite at 948 m (Gudmundsson, 1993) to the bottom can be considered to represent the epidote-actinolite belt ($\geq 280^\circ\text{C}$).

The extensive occurrence of mixed layers and swelling chlorite from 272-498 m and then from 600-700 m may be interpreted to indicate the vulnerability of this upper part of the reservoir to varying hydrothermal regimes with respect to temperature of the hydrothermal fluid circulating through the system. Recall that circulation losses of 3 and 6 l/s were monitored at 481 and 648 m, respectively, which may correspond to

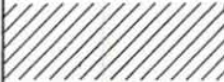
Rock Temperature °C	Alteration zones	Index minerals	Mineralogical Characteristics	Regional Metamorphic Facies
50	I	Chabazite Smectite Scolecite Stilbite Laumontite	Low temperature zeolites and smectite forms	Zeolite Facies
100			Low temperature zeolites → laumontite	
150			Smectite interlayered	
200	II	Wairakite Mixed-layer clay minerals	Laumontite → wairakite Smectite → mixed-layer clay minerals	
250	III	Chlorite Epidote	Mixed-layer clay minerals → chlorite Epidote—continuous occurrence	
300	IV	Chlorite Actinolite	Actinolite forms Plagioclase commonly albitized	

FIGURE 11: Correlation of alteration zones in tholeiite basalts with increasing temperature in active geothermal areas (slightly mod. from Palmason et al., 1979)

aquifers feeding this well with cooler waters than before. As a consequence of this, two alteration mineral assemblages appear to occur in this section of the well, where one is older than the other. Thus, the epidote and chlorite zones occurring in this section are relict today, with the zeolites mordenite and laumontite representing the true condition at this depth at least before the recent volcanic activity in the area. The mixed layer clays and swelling chlorite being transitional here. The alteration minerals and the expected temperature ranges for their stability are shown in Figure 10.

A comparison with the selected temperature logs in Figure 3 reveals three main events:

- 1) The first two logs (1970 and 1972) show the situation in the well shortly after and long after drilling. The 1970 temperature log still shows some disturbance effects due to the drilling fluids, the log for 1972 is taken to represent the formation temperature just before the start of the volcanic activity in the area. The alteration mineral assemblage found in the upper 800 m of the well is in agreement with these temperatures except for chlorite, epidote and prehnite in the 400-500 m depth interval where these minerals are evidently fossil.
- 2) The temperature logs for 1980 and 1984 reflect a disturbance in the reservoir caused by a pressure drop following the volcanic activity. The aquifer responsible for this seems to be the one at 648 m depth and to some extent the one at 481 m. Otherwise a constant temperature of about 230°C is reflected in both logs from 400 to 500 m suggesting that this part of the reservoir is warming up and should be near to the true formation temperature. A situation similar to this was observed in well B-4 (drilled in 1968) which is just 100 m south of B-9 where, even after the magma intrusion into it in September 1977, the only feed at 638 m depth which remained productive registered a temperature of 200°C as compared to a temperature of 260°C measured in 1971 (Tole et al., 1993).
- 3) The temperature logs produced long after the volcanic episode in 1988, '89 and '93 clearly show the

section from 500 to 800 m in B-9 to be warming up where temperatures of up to 250°C are registered. This is further augmented by the groundwater chemistry studies within the Namafjall geothermal system (Olafsson and Kristmannsdottir, 1989) following the volcanic episode in the area between 1975 and 1984 which suggest warming up of the area inside the major faults. The high temperatures recorded in '88, '89 and '93 put the geothermal fluid in the well at all depths at the boiling point-depth curve (BPD). A lowering in the pressure in the reservoir, say due to tectonic movements, can incite boiling in the area resulting in increased surface geothermal activity as proposed by Olafsson and Kristmannsdottir (1989). The high values indicated in the upper 500 m of the well are due to bleeding of the well. The increased proportion of the steam fraction of the total discharge monitored in July 1984 may be a consequence of boiling in the well due to increased heat supply to the reservoir.

The question here is whether these temperatures will be maintained for a good period of time to reduce the transitional mineral assemblage composed of MLC and swelling chlorite extending from 270-700 m.

3.5 Mineral evolution

The depositional sequence observed in the well from the study of thin sections reveals the sequence starting with clay minerals followed by a zeolite or calcite in veins and clay minerals, calcite and/or aragonite and quartz in vesicles in the upper 500 m of the well. Sometimes, pyrite comes in after the clay minerals. Below this depth, quartz comes in after calcite while it is also not unusual to find vesicles filled with clay minerals and calcite alone or quartz instead of calcite or clay minerals alone. Vesicles having the sequence chlorite-quartz-wairakite occur at 630 m although chlorite-quartz sequences dominate downwards.

4. AQUIFERS

The data sets that can be very useful in aquifer indication include among others: 1) The circulation losses monitored during drilling; 2) The temperature logs performed during and shortly after drilling; 3) The geological structure penetrated by the drillhole as established by the binocular microscope and a comparison with the penetration rate; 4) The alteration mineral assemblage as established by the petrographic and binocular microscope; 5) The most probable formation temperature as can be deduced from the subsequent logs performed after the completion of the well. The results from above can then be compared to the alteration mineral assemblage to establish whether equilibrium exists between the minerals and the temperature of the formation. This, however, may be an indirect method to locate which aquifer is responsible for this. The location of probable aquifers (feed points) in well B-9 along with the relative abundance of selected hydrothermal minerals are shown in Figure 6.

Below is a list of the aquifers penetrated by well B-9 with the first three cased off. As already noted in section 1.3, drilling was smooth with circulation losses recorded at 47, 270, 280 (total circulation loss), 481, 648, and 1175 m (3 l/s, 6 l/s and total circulation loss, respectively).

It should be emphasized here that the assumption is being made that the drop in water level (implying circulation loss) is instantaneously monitored by the drillers as the probable aquifer is being penetrated so that the depth at which such changes are noted are absolute ones.

Aquifer 1 occurs around 47 m which may coincide with the ground water table. Total circulation loss was reported. It may be connected to some boundary along accumulative units of the fresh hyaloclastite formation (i.e. horizontal permeability) occurring at this depth. The temperature log of 07.11.1970 starts from around 800 m but the one for 23.11.1970 shows a temperature of >50°C (Figure 3). The alteration mineral

assemblage observed in this part consists essentially of low-temperature zeolites namely chabazite and mesolite and to a lesser extent analcime and heulandite both of which extend beyond 100 m. The relative abundance of minerals like pyrite which are good indicators of permeability is insignificant (rare as in Figure 6) perhaps due to the temperature at such shallow depth. Calcite occurs both as vein and amygdale fillings.

Aquifer 2 occurs around 270 m where a total circulation loss was monitored. Like the one above, it seems to be connected to some kind of accumulative units within the altered tuff in this region. The aquifer may actually be the top boundary of a scoria zone separating two tuff layers. The temperature log for 23.11.1970 indicates temperatures of just under 200°C, enough to form quartz which is very abundant in this region. However, if there has been no appreciable cooling in this zone, the abundant wairakite occurring here suggests past temperatures of >200°C. In this zone, wairakite occurs as cloudy masses due to the abundant fluid inclusions contained in the crystals.

Aquifer 3 occurs around 280 m where another total circulation loss was encountered. This aquifer is not very different from aquifer 2 above as they are quite close to each other. Likewise, it seems to be connected to some boundary marking the lower end of the scoria zone. It may actually be a reopening of the one at 270 m above. The temperatures recorded at this depth are quite similar to those at 270 m and likewise the alteration mineralogy. It is worth noting here that in spite of the very abundant alteration mineral assemblage recorded between 290 and 340 m, no aquifer is indicated around here, implying self-sealing in this depth range and so the mineral assemblage is fossil. These aquifers were cased off and so do not contribute to the flow of this well.

Aquifer 4 occurs around 481 m where a circulation loss of 3 l/s was recorded. It seems to be connected to some boundary between the basaltic layers at this depth which may, in turn, be in some connection with the small fresh dolerite intrusion between 500 and 504 m, most likely a small dyke inclined slightly from vertical. The temperature log of 23.11.1970 shows a decrease in temperature from 210°C at 375 m to about 195°C at 500 m. The alteration mineral assemblage comprising of laumontite, wairakite, quartz, calcite mixed layer clays and possibly swelling chlorite but is evidently not in equilibrium with epidote, prehnite and chlorite. The plausible explanation for this being that the latter group of minerals is relict. Calcite, quartz and pyrite are abundant here and so may be close to self-sealing as can be observed from the small circulation loss recorded.

Aquifer 5 occurs around 648 m depth where a circulation loss of 6 l/s was registered. This aquifer seems to contribute most to the flow of this well but unfortunately it appears to be in hydraulic connection with some kind of fissure feeding it with colder water as the temperature logs for 1980 and 1984 seem to suggest. The aquifer appears to be connected to a boundary between fresh medium-grained basalt intrusions at 660-666 m and another fresh fine- to medium-grained basalt at 672-680 m. At this depth pyrite, calcite and quartz are abundant indicating good permeability.

Aquifer 6 occurs at 1175 m where a total circulation loss was recorded. This aquifer is connected to some accumulative units of highly altered fine- to medium-grained basalt. The temperature log performed in the well on 23.11.1970, before the collapse of the bottom part, indicates a bottom hole temperature of 250°C even if the effects of the drilling fluids are still evident in this log. However, since the bottom of the well is normally the least cooled during drilling, provided that no circulation losses have been recorded there, it follows therefore that the formation temperature at the bottom of this well was well over 250°C. The alteration mineral assemblage observed in the lower 300 m of the well seems to be in equilibrium with the would-be measured temperature. Calcite becomes insignificant in Icelandic geothermal fields when temperatures exceed 270°C (Kristmannsdottir, 1982), its continued absence from 1000 m in this well suggests that this aquifer was feeding water of such a temperature or more. The mineral assemblage of epidote agrees with these temperatures but actinolite recorded at 948 and 1154 m (Gudmundsson et al., 1989) and wollastonite observed in thin sections from 1000 m to the bottom during the current study suggests that

temperatures reached $\geq 280^{\circ}\text{C}$ in this part of the reservoir in the past.

It should be noted also that registering total circulation loss does not necessarily imply a very strong aquifer, which will dictate the flow of the well. This is not always the case as the hydrostatic pressure due to the drilling fluid in the column is extremely high at such great depth and can easily drive all the cuttings into any weak point existing at depth where also the lithostatic pressure due to the overburden is equally high.

Given the poor history of this well owing partly to the extensive collapse of the bottom shortly after drilling, together with others elsewhere in the field after the volcanic episode in the area between 1975 and 1984, poor casing design and discharge characteristics (see Section 1.3), nothing much is known about the aquifer at 1175 m. However, from the alteration mineral assemblage deduced from petrographic, binocular and XRD analyses, epidote and actinolite occur below 940 m depth constituting the epidote-actinolite belt, it is clear that a temperature of $\geq 280^{\circ}\text{C}$ prevailed at one time in this part of the reservoir. Whether this situation is prevalent today is a matter of debate, but the situation appears to be as discussed above. If there is any cooling due to boiling, it has not reached a level as to warrant the reappearance of calcite.

5. DISCUSSION

An attempt to discuss the situation prevalent in the reservoir in general and the well in particular with respect to hydrothermal alteration mineralogy, makes use of the established facts obtained from the IRDP drillhole in eastern Iceland (e.g. Kristmannsdottir, 1982). A drillhole was completed to a depth of 1920 m at Reydarfjordur, eastern Iceland by coring. Overall core recovery was 99.7% hence providing excellent opportunity for the various researchers attached to the project to study the Icelandic crust in greater detail. With respect to Icelandic geothermal waters only, the relationship between alteration zones and temperature is shown in Figure 11.

The scheme is based, firstly, on the changing sequences of zeolite species; secondly, on the sheet silicate transformations; and thirdly, on first appearance of a few temperature-dependent minerals. Included in the latter group are epidote and actinolite. Those three groups (zeolites, sheet-silicates, and other minerals) show different behaviour during alteration and therefore serve different purposes in the interpretation of thermal evolution. The transformation from one sheet-silicate to another requires only minor rearrangements within the crystal structure, and these happen rather quickly and easily if the permeability is high and the temperature adequate. Most transformations of one zeolite to another require a breakdown and rearrangement of the crystal structure. The formation of zeolites is highly dependent upon CO_2 partial pressure at any time of the evolution as well as permeability and temperature. The minimum temperature for formation of laumontite is relatively well known from alteration studies and experimental runs (Liou, 1971).

The retrograde transformation of laumontite into any of the low-temperature zeolites is not considered to be quick or easy. Laumontite transforms into wairakite in conditions of steep geothermal gradient. The retrograde transformation of wairakite into laumontite is assumed to be relatively quick and easy, as their crystal structures are not so different. This has not been observed to happen in the present study at least. Epidote and actinolite are important in the third group of alteration minerals. Both must be completely broken down before transformation into any other mineral can occur. Thus, they appear commonly as relics of high-temperature activity. Their presence implies that at some time in the evolutionary history, the temperature has reached 250 and 280°C , respectively. Therefore, on the basis of these facts, it becomes difficult to argue how epidote, laumontite, mordenite and prehnite can occur together, given the fact that laumontite can only exist in the temperature range $100\text{-}200^{\circ}\text{C}$ whereas prehnite and wairakite exist strictly above 200°C with epidote occurring above 250°C , unless we are to assume that laumontite can exist up to 250°C which ought to be impossible. The temperature logs obtained both from 1970-1974 and 1980-1989

also suggest a temperature between 200 and 250°C between 200 and 500 m. In any case, even if it were possible to transform laumontite into wairakite in conditions of steep geothermal gradient the perseverance of laumontite and mordenite in the 400-500 m depth interval suggests that the temperature in this part of the reservoir was less than 200°C at least before the volcanic activity in the area. However, replacement of laumontite by quartz was observed between 492 and 520 m. Therefore, near-equilibrium conditions between secondary minerals and geothermal water seem to exist with respect to mordenite, laumontite, wairakite, MLCs and quartz but there are clearly dis-equilibrium conditions with chlorite, prehnite and epidote here, yet the condition of permeability is satisfied as some aquifers occur around the same depth. This may suggest that this aquifer was feeding cooler water (180-200°C) for some years as was observed during the volcanic episodes in the area from 1975 to 1984. Such activities appear to create a transient behaviour in the geothermal system. This further suggests that the temperature logs may be indicating the situation of the well just before and after the volcanic episodes in this area as suggested elsewhere (Tole et al., 1993).

The situation observed in well B-4 (Tole et al., 1993) seems to be the same as in B-9. However, a marked difference exists between these two wells especially if the temperature logs after completion of drilling are compared. While the feeder at 638 m in well B-4 remained productive even after the magma intrusion through the well, and its temperature was considered to be close to 260°C, as indicated by downhole temperature measurements carried out in 1971, the temperature measured for well B-9 on 23.11.1970 shows a constant temperature of just under 200°C in the depth interval 500-800 m. Therefore, while the temperature reversals registered for these wells in 1984 may be due to disturbed conditions in the reservoir around these two wells, the situation in well B-9 seems to suggest that the lower temperature conditions had been existing around this depth interval for quite some time. This is strongly supported by the clay mineral assemblage which exhibits a complex collection of chlorite, mixed layer clays, swelling chlorite and even gypsum from 498-702 m (see Appendix I). Epidote is similarly recorded sporadically between 700-816 m perhaps due to poor primary porosity and permeability but may suggest higher temperatures of >250°C in the past and is, therefore, relict up to the time of drilling the well. If not, then it may be suggested that the mixed layer clays have been preserved at those temperatures.

Arnorsson (1977) monitored the chemical composition of water and steam from wells at Namafjall during the period 1970-1976 and observed significant changes. As a result of these changes quartz equilibrium and Na-K-Ca geothermometry temperatures decreased with time for some wells, particularly the shallowest, well 5. This decline was accounted for by cooling in the producing aquifers by boiling and partial re-equilibration as the boiling water moved towards the wells. Temperature logging after drilling indicated that temperatures in the reservoir followed the boiling point curve with depth.

Latest temperature logs in well B-11 performed in September 1994 have revealed inflow temperature into the well of less than 150°C via an aquifer at round 600 m. This has been interpreted to be downflow from the upper aquifers downwards during shut-in because of decreasing pressure in the well and surroundings (Bjornsson, pers. comm.). While this cannot be disputed the occurrence of lower temperature alteration mineral assemblages in the upper 800 m especially in B-9 may suggest a thermal breakthrough into this part of the field due to influx of cold water over a period of time. Whether this applies to the rest of the field is hard to say but similarly incompatible mineral assemblages are observed in other wells too. For example, well B-10 has a laumontite-chlorite zone at 560 m depth, well B-6 has a smectite-chlorite zone at 540 m depth and some others in the field but is of limited extent in these wells (e.g. Gudmundsson, 1993).

Given this trend of affairs and from the mineral assemblage observed in well B-9, it is apparent that the aquifers above at 481 and 648 m have been behaving rather abnormally in response to the volcanic episodes in Krafla not only during 1975-1984 but throughout geologic time of their existence, given the fact that several volcanic episodes have been dated in the area. As a consequence, transient cooling episodes take place and an inflow of cooler fluids in the upper 800 m may explain the presence of lower temperature mineral assemblages at these depth overshadowing a fossil mineral assemblage which is clearly related to the

first hydrothermal event that generated epidote at 400-500 m.

Therefore, equilibrium between the temperature in the reservoir and the mineral assemblage can only be expected at deeper levels than the ones so far penetrated by this well. Otherwise disequilibrium is characteristic of this part of the reservoir as for now at least. Therefore, the alteration mineral assemblage, except the lowermost like chabazite, mesolite and gyrolite, seem to belong to both hydrothermal events which implies that if there is cooling in the well and the reservoir as such, then it is restricted to the upper 800 m for now. A plot of the temperatures indicated by the logs from 1988, '89 and '93 (Figure 3) on the boiling point-depth (BPD) curve suggests a temperature range of 246-250°C over the same depth interval which is sufficient for the formation of epidote and prehnite and equally sufficient to convert all the laumontite to quartz and/or wairakite (if possible) which is observed not to be the case today. Platy calcite is first seen at 394 m (Section 3.3) which corresponds to about 220°C on the boiling point-depth curve suggesting boiling conditions at this depth at any one time in history of the reservoir. Since this is the kind of calcite that predominates below 500 m, it can be inferred that the reservoir had been boiling frequently in the past at such shallow depth before cooler water found its way into this part of the reservoir to push the boiling depth to below 800 m as it is today.

A comparison of the alteration mineral temperatures derived for well B-9 with the typical temperature profiles for the three well fields at Krafla (Figure 12) shows that this part of the reservoir behaved like the Sudurhlidar field (boiling system) in the glacial periods but may have been analogous to the Leirbotnar field at the time of drilling. The volcanic activity in the area from 1975-1984 shows the system to be similar to the former, but since volcanic activity is not unusual in the area, the author is of the view that the Leirbotnar field characteristics prevail in the reservoir, the others being of temporary nature. This pegs a time limit as to when the fissure swarms were formed which undoubtedly should be earlier than the time of formation of the

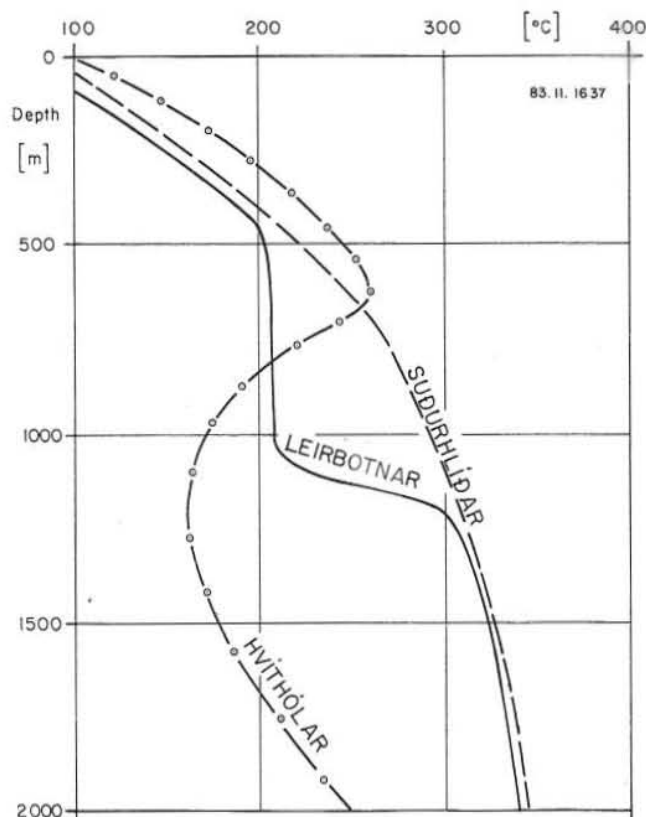


FIGURE 12: Typical temperature profiles for the three well fields in Krafla

first epidote. Since then it has been behaving as conduits for both waters as to whichever is available in response to the ground movements in the area.

The first occurrence of epidote in Icelandic geothermal wells is commonly below 500 m depth with only a few exceptions. Notable of these wells are K-14 in Krafla, R-6 in Reykjanes, and H-6 in Hveragerdi. Therefore, the author concludes that well B-9 is the latest entrant to this unique group of wells. The most plausible explanation being that the epidote at this depth belongs to the glacial periods when the hydrostatic pressure in the reservoir was most likely being controlled by the water table within the glacier and not the current water table after the last glaciation. This implies a minimum age of about 10,000 years. Included in this group of minerals are platy calcite, prehnite, some of the wairakite and wollastonite. Actinolite was detected in XRD for clay minerals at 948 m depth (Gudmundsson, 1993). Possibly also, garnet occurs in this field. Obviously the formation of some of these minerals deeper

down in the well and reservoir cannot be disputed as long as the temperature can allow it. It is thus most likely that the aquifers at 481 and 648 m have been acting as feeders for both waters as to whichever is available and not only during recent volcanic episodes but through the geological time of their existence. If this logic is to be borrowed then it may be inferred that this situation has been operating in this field in more or less a rhythmic fashion bearing in mind that it lies on the same fissure swarm as Krafla.

6. CONCLUSIONS

The main conclusions that can be drawn from the study of well B-9 are as follows:

- 1) A comparison of well B-9 with the other wells in the field shows that it is located nearest the major upflow zone into the field.
- 2) The early occurrence of epidote in this well (above 500 m) can only be explained by saying that geothermal activity in the area started during the glacial times. Therefore, the minimum age is not less than 10,000 years which happens to be the end of the last glaciation. At that time the hydrostatic pressure in the reservoir was being controlled by the water table within the glacier. A maximum age of about 100,000 years, i.e. when the Krafla caldera started forming is attached. In B-9 in Namafjall and KJ-14 in Krafla the first occurrence of epidote is nearly at the same depth. This suggests that these two geothermal systems, although 10 km apart, are of about the same age. Other wells in the same group are R-6 in Reykjanes and H-6 in Hveragerdi.
- 3) The aquifers at 481 and 648 m are feeding the well with much cooler water than the ones at 270 and 280 m which were cased off. The aquifer at 648 m has been controlling the flow in the reservoir to some extent. The aquifer at 638 m in well B-4 seems to be in hydraulic connection with it by virtue of their near-same depth of occurrence. The most plausible explanation for this is that they are in connection with some fracture or fissure which is acting as a conduit for both geothermal water and cold ground water as to whichever is available and when. This appears to have been going on like this for quite a long time to generate the wide zone of transitional mineral assemblage of mixed layer clays and swelling chlorite recorded between 270-700 m depth interval. This is similarly responsible for the low-temperature mineral assemblage composing of laumontite and mordenite occurring together with epidote and the other high-temperature minerals in the upper 500 m of this part of the reservoir.
- 4) The mineral assemblage below 800 m seems to be in agreement with the measured temperatures. A slight lowering consequent upon boiling in the reservoir is suggested. They, however, plot at or near the boiling point-depth curve. Wollastonite and actinolite minerals appear to belong to the first high-temperature system that produced epidote at shallow depth. If wollastonite, actinolite and garnet are forming today, it should be occurring at a greater depth than so far penetrated by the well. However, the cooling has not been appreciable enough for calcite to reappear, implying that the temperature in this lower section of the reservoir is still $>270^{\circ}\text{C}$.

ACKNOWLEDGEMENTS

The author is greatly indebted to the UNDP in collaboration with the government of Uganda, for sponsoring the course and granting sabbatical leave, respectively. My heartfelt thanks go to the Director of the UNU Geothermal Training Programme, Dr. Ingvar Birgir Fridleifsson for the excellent organisation of the training programme. To Mr. Ludvik S. Georgsson and Ms. Margret Westlund for their timely response to all enquiries

pertaining to the programme.

Special thanks go to Dr. Hjalti Franzson and Mr. Asgrimur Gudmundsson, my supervisors for their untiring efforts and willingness to model a true borehole geologist. To Mr. Magnus A. Sigurgeirsson for his exemplary knowledge of clay mineral analysis and to Ms. Gudrun Sverrisdottir for her unconditional assistance with the XRD. Ms. Helga B. Sveinbjornsdottir in drawing office is specially thanked for drawing the figures. My heartfelt thanks are due to the entire staff of Orkustofnun, lecturers and the others alike viz-a-viz the people of Iceland whose cooperation in various ways made my stay in Iceland an exciting and memorable one.

Lastly to my wife, Jacinta, my ever inquisitive daughter, Gloria and my son, Innocent who seems not to know what is happening around him, my endless thanks for being a great spiritual guide.

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APPENDIX I: Preparation of sample minerals for analysis by the XRD technique

The preparation of samples with hydrothermal alteration and clay minerals for identification and classification is done as follows:

Procedure A:

1. Hand pick grain filling either vesicles or veins from the cuttings under the binocular microscope. This can be done continuously at specific depth ranges to be able to follow the appearance and disappearance of some minerals.
2. Crush the samples in an agate bowl to a grain size of 5-10 microns. Acetone is added to prevent loss of sample while powdering.
3. Fill an appropriate sample holder for the XRD with the powder.
4. Run the sample from 3-60°.

This technique was used to distinguish between the different zeolites in well B-9 and the accurate start of occurrence of minerals like prehnite and wairakite.

Procedure B: Preparation of samples for clay mineral analysis

1. Place approximately two teaspoonfuls of drill cuttings into a glass tube, wash out dust with distilled water. Fill the tubes 2/3 with distilled water and plug with rubber stoppers. Place the tubes in a mechanical shaker for 4-8 hrs, depending on the alteration grade of the samples.
2. Allow to settle for 1-2 hours, until particles finer than approximately 4 microns are left in suspension. Pipette a few millilitres from each tube and place about 10 drops on a labelled glass plate. Avoid having the samples thick. Make a duplicate of each sample and let them to dry at room temperature overnight.
3. Place one set of samples in a desiccator containing Glycol ($C_2O_6O_2$) solution and the other set in a desiccator containing $CaCl_2 \cdot 2H_2O$. Store at room temperature for at least 24 hours. Thick samples will need a longer time in the desiccator, at least 48 hours.
4. Run both sets of samples from 2-15° on the XRD.
5. Place one set of the samples (normally the glycolated one) on an asbestos plate and heat in a preheated oven at 550-600°C. Oven temperature MUST not exceed 600°C. The exact location of individual samples on the asbestos plate must be known before heating because labelling will disappear during the heating process. Cool the samples sufficiently before further treatment.
6. Run the samples from 2-15° on the XRD.

APPENDIX II: XRD results for well B-9 clay samples

Depth m	Treated with CaCl ₂ Lines d Å	Glycol-saturated Lines d Å	Heated, 550-600°C Lines d Å	Probable minerals
170	15.22, 9.02	16.66, 13.59, 9.02	9.93, 9.02	Smectites, clinoptilolite
234	16.35	16.98, 8.49	collapsed	Smectites
256	16.35, 30.44, 14.97, 14.62, 7.56, 7.19	16.98, 31.53, 15.49, 7.62	13.93, 9.93	Smectites, mixed layer clays, gypsum
272	15.22, 30.44, 18.39, 9.48, 7.62	15.49, 31.53, 9.48, 7.02	18.79, 14.72, 14.24, 9.40	Smectites, mixed layer clays, swelling chlorite
394	14.47, 29.43, 7.22	15.49, 31.53, 7.69, 7.09	14.72	Swelling chlorite, mixed layer clays, gypsum
438	14.47, 29.43, 9.46, 7.14	15.22, 30.44, 9.40, 7.13	14.47, 14.24, 8.93	Mixed layer clays, swelling chlorite
498	14.24, 29.43, 7.08	14.24, 29.43, 7.08	14.47, 8.93	Chlorite, mixed layer clays
584	14.24, 7.13	14.47, 14.24, 7.09	14.47, 8.93	Chlorite
600	14.24, 30.44, 7.13	14.38, 31.53, 7.13	14.24, 14.97, 7.13, 7.19	Chlorite, mixed layer clays, swelling chlorite
636	14.24, 15.22, 31.53, 7.13, 8.50	14.24, 15.22, 31.53, 7.08, 7.62	14.38, 7.19	Chlorite, mixed layer clays, swelling chlorite, gypsum
658	15.22, 33.44, 35.31, 7.13, 8.50	15.49, 31.53, 7.13, 7.62	14.47, 14.38, 7.25	Chlorite, mixed layer clays, swelling chlorite, gypsum
702	14.24, 30.44, 32.69, 7.13	14.24, 30.87, 7.08	14.72, 14.97, 8.93, 7.43, 7.31	Chlorite, mixed layer clays
752	14.24, 7.08	14.02, 7.08	14.72, 14.97, 8.93, 8.84, 7.43	Chlorite
810	14.24, 7.08	14.06, 7.08	14.87, 8.84, 7.37	Chlorite
872	14.24, 7.08	14.24, 7.13	14.47, 8.87, 7.38	Chlorite
940	14.24, 7.08	14.24, 7.08	14.72, 15.22	Chlorite

XRD analyses for clay minerals done at 948, 1000, 1050, 1104, and 1154 m depth (Gudmundsson et al., 1989), indicate chlorite, chlorite/prehnite (?), chlorite, chlorite and chlorite/amphibole, respectively. The amphibole here being actinolite.