Report 10, 1992

GEOTHERMAL GEOLOGY: STRATIGRAPHY AND HYDROTHERMAL ALTERATION OF WELL OW-716, OLKARIA GEOTHERMAL AREA, KENYA

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ABSTRACT

The hydrothermal alteration mineralogy for well OW-716 was conducted with several different techniques. Results obtained from the alteration mineralogy indicate temperatures of less than 200°C within the first 500 m depth of the well, with an increase near the boiling curve going down to the well bottom, showing a temperature range in excess of 280°C. Similarly a preliminary fluid inclusion study carried out on the quartz crystals at a depth of 350 m showed temperatures of 180°C which is higher than both alteration and formation temperatures, while at a depth of 2260 m, lower temperatures in the range of 245°C were recorded indicating heating up within the reservoir.

It is possible to correlate the lithological units of well OW-716 with the other neighbouring wells in the field, and the possibility of local structural controls could account for the losses in circulation experienced within wells OW-707 and OW-714.

From the well subsurface geology, the upper part of the well has mostly tuffs and lava flows of a rhyolitic nature, then a succession of thin basaltic units, with tuff intercalations of various compositions; deeper below is mostly trachytes and rhyolite lava rocks with tuff intercalations.

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1. INTRODUCTION

1.1 Location of Olkaria in relation to the Rift Valley

Olkaria geothermal area is located 40 kilometres southwest of Naivasha Town, and about 10 kilometres south of Lake Naivasha in Kenya. Figure 1 shows the location of Olkaria geothermal area within the Kenyan Rift Valley. The field is about 50-80 km^2 in area as defined by the distribution of fumaroles, resistivity surveys and interpretation of the geological structures (Virkir, 1987). The field is roughly circular in shape, about 10 kilometres from east to west, measuring less in the north-south direction.

The NE-Olkaria sector occupies an area of as much as 12 km^2 in extent, and within this a production field of 5 km^2 in area has been delineated by exploration and appraisal drilling.

1.2 Surface features of Olkaria

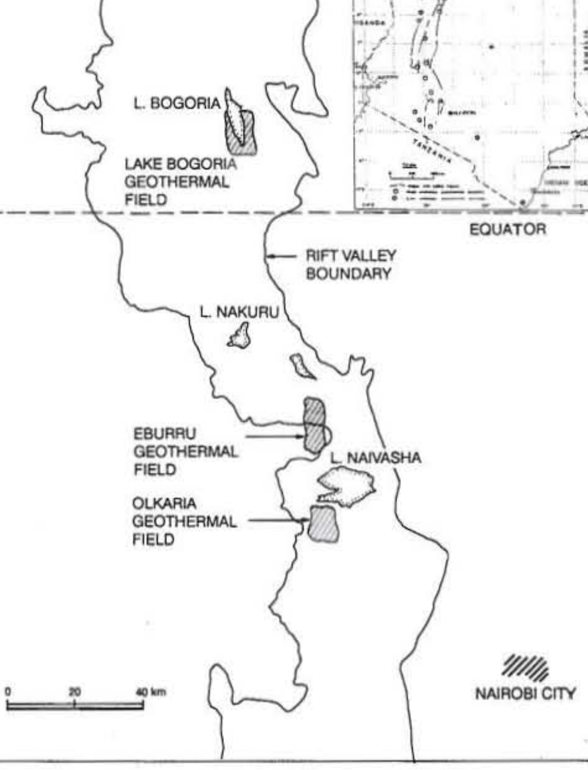

FIGURE 1: Map showing the location of Olkaria geothermal area within the Rift Valley

This field is associated with the Olkaria volcanic centre, and is considered to be bound by the arcuate faults or ring structure which has been interpreted as a caldera. Faults and fractures are prominent in the area. The structure and lithology of Olkaria area was mapped by Naylor (1972) who split this area into two main components, i.e there are those which trend N-S and E-W but there are also inferred faults striking almost NW-SE. These structures are the expected sources for vertical or near-vertical permeable anomalies. Fumaroles are frequently associated with these structures where they lie inside the ring structure but not where they extend beyond it as they often do. According to Naylor (1972), McNitt was the first to propose the ring structure. Distribution of micro-earthquakes and fumaroles also suggested an east-west running fracture just north of Olkaria peak now referred to as the Olkaria fault (Healy, 1972; Hamilton et al., 1972; Odongo, 1981). Figure 2 shows geological structures and well sites in Olkaria.

The reviewed structure of Olkaria area and an outlined structural map by Merz & McLellan - Virkir (1979) supported Naylor's (1972) proposal although the trace of its western margin was thought to be somewhat different from the earlier proposal by Naylor (1972) and hence also the geological setting of the rows of young volcanic vents near Olkaria peak. The eastern part of the Olkaria area has concentrically aligned vents of comendite marking the ring structure but in the west margin was taken to be represented by a series of low hills of arcuate

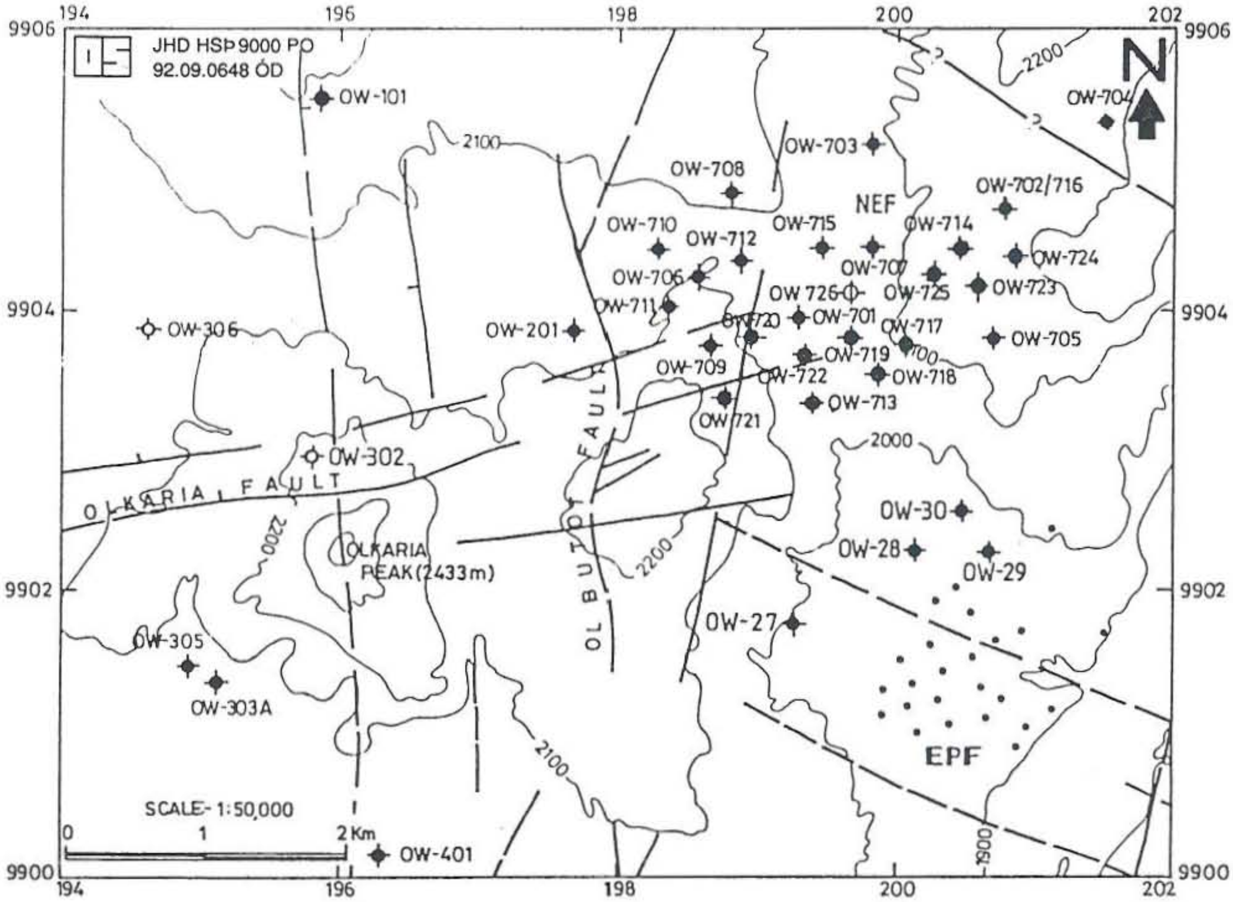

FIGURE 2: Geological structures and well sites in Olkaria

shape enclosing flat depressions. (Merz & McLellan - Virkir, 1979).

Odongo (1981) did not recognise any convincing evidence for a ring structure at Olkaria but emphasized the importance of the north-south and east-west running fractures to the geothermal processes as surface manifestations appeared to be concentrated on them. Odongo (1984) recognised Olkaria, together with Longonot and Eburru, as volcanic centres.

Olkaria area is predominately covered by Quaternary ash and pyroclastics, hence showing poor outcrops. Figure 3 shows geological structures and a N-S belt of peralkaline volcanic rocks, Lake Naivasha Area. Odongo and Muchemi (1985) correlated the known stratigraphy of Olkaria with volcanic rocks to the north and south in the Rift Valley on the escarpments. The main rocks in the area are the trachytes/rhyolites, comendites, tuffs and pyroclastics. The trachytes are the most abundant by volume and the comendites (sodic-rhyolite) are the main outcrops in the area, found in the cliffs of Hell's Gate (Ol Njorowa Gorge) (Odongo and Muchemi, 1985). According to Scott (1980), Olkaria is covered with peralkaline trachytes and comendites. Bosworth et al. (1986) has shown that the Rift Valley of Kenya is divided into three segments or detachment systems which are asymmetric, being characterised by escarpment faults on one side, further evidence of hot spots below the Rift Valley around Lake Nakuru.

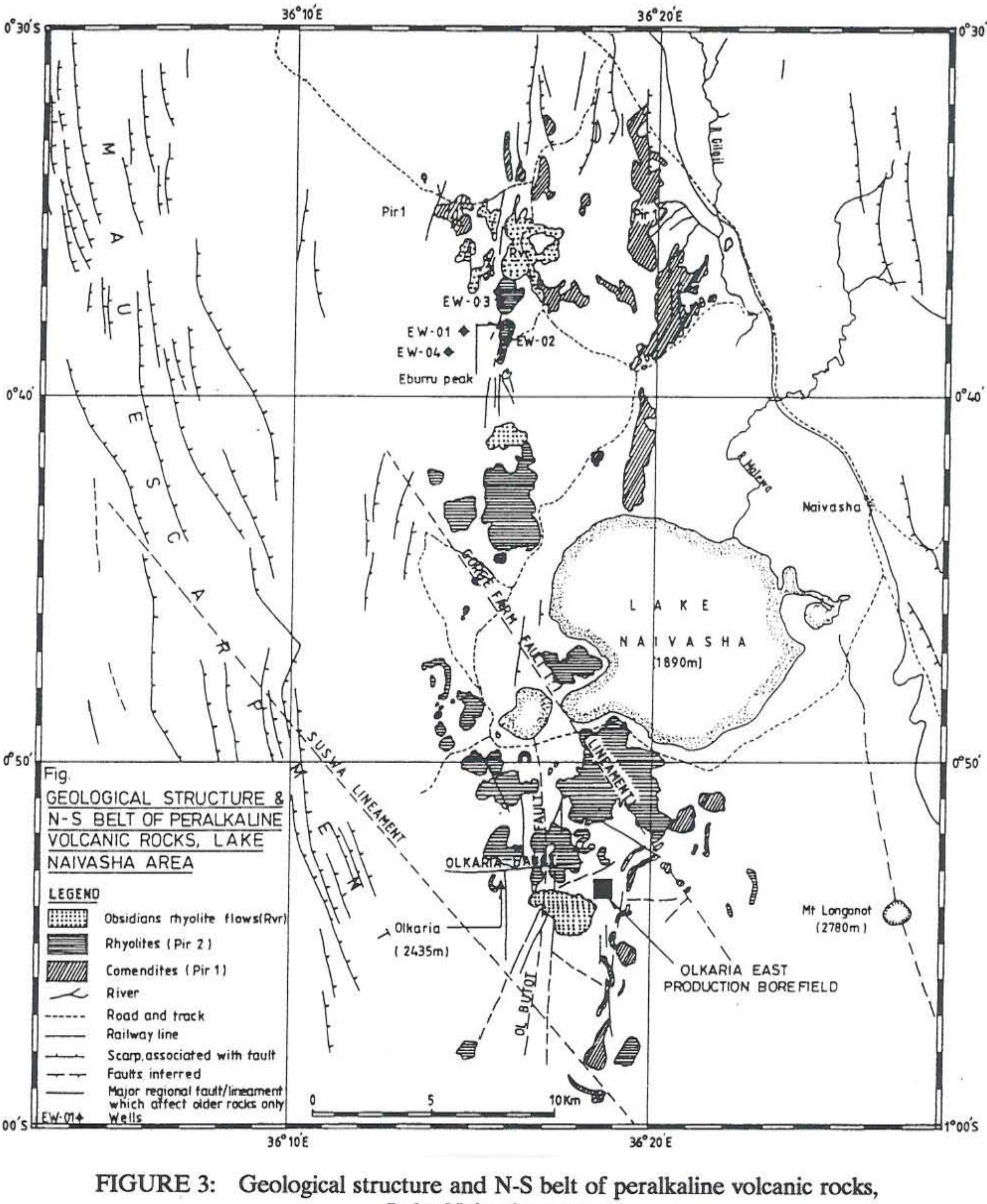

FIGURE 3: Geological structure and N-S belt of peralkaline volcanic rocks, Lake Naivasha area

1.3 Subsurface features

The main rock units are tuffs, rhyolites and basalts which act as cap rocks for the reservoir, and volcanic lavas of rhyolites, trachytic composition and tuffs which form the reservoir rocks. Seismic velocities at Olkaria, as reported by Hamilton et al. (1972), have shown that the volcanic sequence in the Rift Valley overlying the crystalline basement is some 3.5 km thick in comparison with data from Lake Bogoria. Healy (1972) suggested that basaltic rocks may dominate at Olkaria below 1.7 km, whereas acid tuffs and lavas would take their place at higher levels.

1.4 Location of well OW-716

Well OW-716 is the sixteenth of the current "700" series that has been drilled for exploration purposes in the North-East sector of Olkaria. This well is located on the edge of the caldera or the ring structure, occupying the former OW-702 position that was abandoned after being drilled to a depth of 1744 m. It lies three kilometres away from the present production field. The well is at an elevation of 2169.6 m a.s.l., having coordinates of east 201384.4 and north 9904080 and is drilled to a depth of 2296 m.

The well design includes casings of 20" set at 52 m, 13 3/8" at 357 m and a production casing of 9 5/8" at 594 m. No major losses of circulation were experienced in the course of drilling. Aerated water and foam were used for drilling. Figure 4 shows the well design.

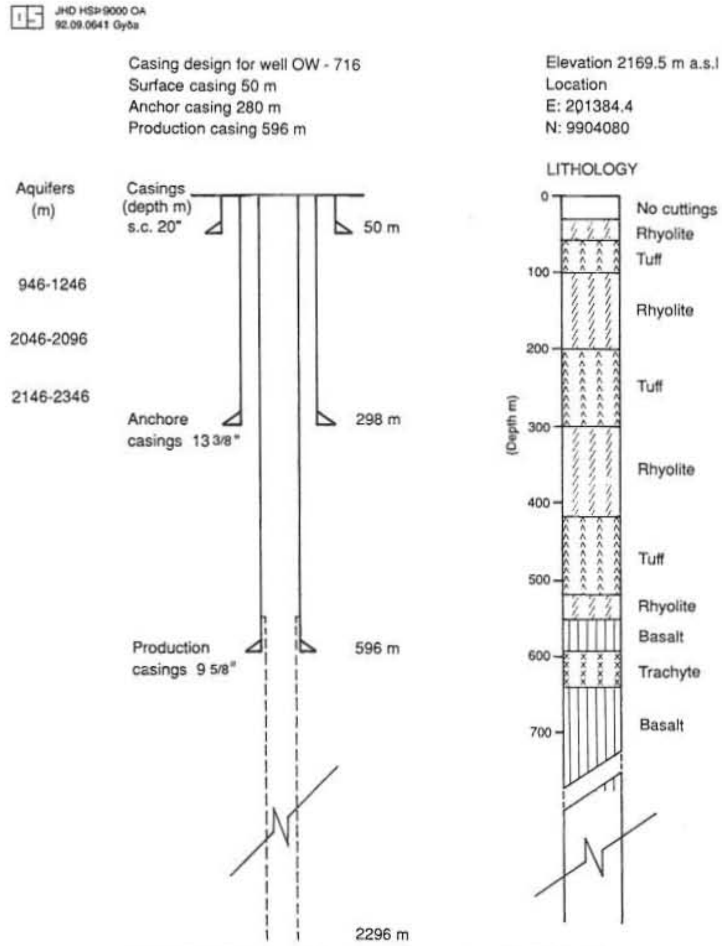

FIGURE 4: Design of well OW-716

2. STRATIGRAPHY

2.1 Analytical methods

The equipment used in the study of this well include binoculars or the stereo microscope used during the preliminary stages of analyzing the cuttings that are recovered from the drilled well. Another method used is the analyses of thin sections prepared from both the cuttings and the cores, through use of the petrographic microscope. The latter method gives more detailed information than the former.

The well OW-716 was drilled to a depth of 2296 m. Two cores were recovered, one at 1701-1703 m and the other one at total depth. Cuttings were collected at regular intervals of 2 m and every sample was analyzed by use of the stereo-microscope. Based on the obtained results, a lithological section was prepared.

2.2 Description of the stratigraphic units

The interpretation of the stratigraphic units is established as shown in Figure 5. It is based on detailed petrography carried out as shown in Appendices I and II. The units penetrated in the well during drilling, were the tuffs and pyroclastics, the lava rocks, i.e the acidic rhyolites, the intermediate trachytes and volcanic basalts. Figure 5 shows the lithology of the well. A generalised stratigraphy of the units penetrated in the well would appear as shown below:

0-500 m	Pyroclastics, tuffs and lava flows mostly of rhyolitic composition.
500-700 m	This part is characterised by basaltic lava flows with minor intercalations of tuffs of various compositions, having lava fragments. The basaltic unit has been described as the cap rock of the reservoir (see Section 1.3).
700-940 m	Lava flows, and extensive tuffs of basaltic and/or intermediate composition characterises this depth interval.
940-1200 m	Rhyolite lava flows with tuff intercalations.
1200-1750 m	Lower trachytes mostly, with rhyolite intercalations. These form the most extensive trachytic unit observed in this well.
> 1750 m	Rhyolitic lava rock unit with other lava rock units of intermediate to basic composition, with tuff interlayering.

The varying rock thickness in the above stratigraphy suggests tectonic disturbances before the deposition of the overlying rhyolite on the lower trachytes. Below is a summary of the individual rock units that were penetrated in the well.

Pyroclastics
The first thirty metres of drilling had no recovery. A correlation with neighbouring well OW-714 shows that this is supposed to be a pyroclastic unit consisting of loess ashy material to be penetrated extending up to the upper contact of the rhyolite. This unit has pumice, obsidian, with quartz and feldspars, stains of iron oxides, loosely compacted, with no alteration. Similarly, at a depth of 2230-2250 metres, the only pyroclastic unit is penetrated in this well.

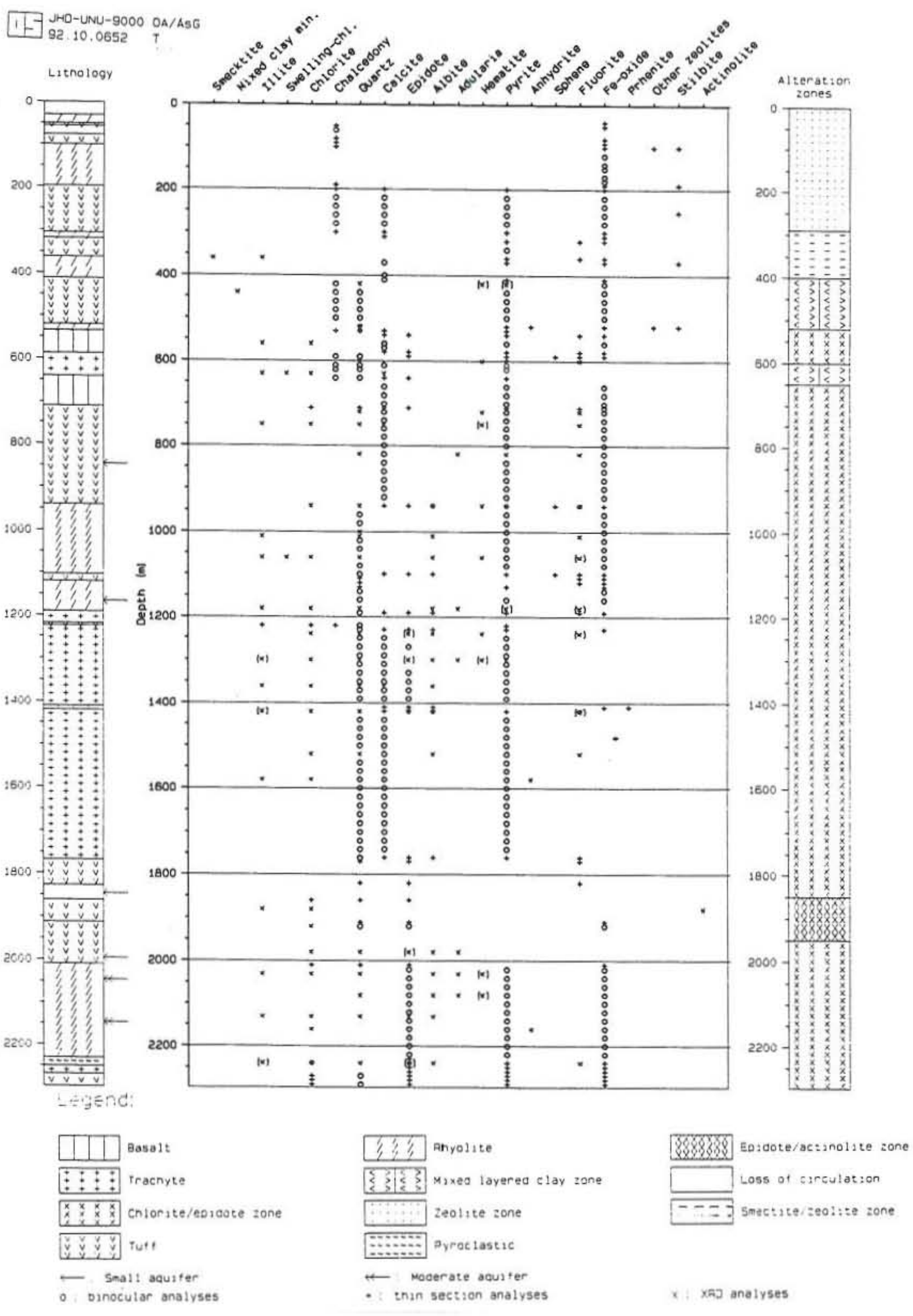

FIGURE 5: Stratigraphy and hydrothermal alteration of well OW-716

Tuffs

At the shallow depth of 50 m, the first ashy tuff was penetrated and continued with interlayering of rhyolites down to 500 m depth. These units are seen occurring in different forms, as interlayering units or within the lava formations. These units are seen spread throughout the well. They occur as welded, showing flow-banding structures; lithics, where they are dominantly made up of heterogeneous lava fragments; silicified, for those seen having mostly silica. Their respective thicknesses vary and the extent of alteration depends upon the composition and depth, i.e. the lithic tuffs have the primary minerals like plagioclase very much altered to clays and oxides, imparting greenish or brown colours; calcite is also noted, replacing the feldspars and making veins; the glassy tuffs are wholly altered.

Rhyolites
First penetrated at a depth of 34 m, they extend down to 420 m, with tuff intercalations. These units shows spherulitic and porphyritic textures, flow-banding structures, riebeckites, hornblende and magnetite. These units show little alteration, except where clays have been noticed. Deeper in the well the rhyolites are medium to coarse grained and do not show the aforesaid type of texture, i.e. the spherulitic one, though with fewer feldspar phenocrysts and quartz crystals. They are felsic and have mostly tuffs as intercalations.

Trachytes
These are penetrated at a depth of 588 m. They are overlain by the basaltic unit, and interlayered with tuffs at deeper levels. They are dark in colour, showing both porphyritic and occasionally trachytic texture in other instances. Trachytes noted within this well are of two types. The upper ones are predominantly "coarsely" porphyritic interlayered with tuffs, basalts and the rhyolites. But the ones observed deeper in the well are "finely" porphyritic interlayered with tuffs, basalts and rhyolites. They show moderate alteration especially of the feldspar phenocrysts to clays and oxides.

Basalts
At a depth of 534 m, a thin basaltic unit was penetrated. This unit shows a dark coloured porphyritic rock, mostly altered. Other basaltic units in the well show similar alteration and texture, and are also interlayered with tuffs, trachytes and rhyolites.

2.3 Correlation to neighbouring wells

Figure 6 shows the correlation of wells OW-707, OW-714, OW-716. The above stratigraphic units within this well have been correlated with the neighbouring wells in the field. Obtained results from wells OW-707 and OW-714 were used for a cross-section as shown in Figure 6. The total losses of circulation experienced in the upper part of well OW-707 and lower part of OW-714 resulted in the correlation relying mostly on what is observed from well OW-716. In well OW-716 there is a close matching correlation in those units that could be established. The generalised stratigraphy from this correlation looks like this: the first 500 m shows tuffs and rhyolites, from there down to about 700 m are basalt lavas with tuffs interlayering, acting as caprocks in the area. The reservoir extends, therefore, from the bottom of the caprock to the deeper part of the well. Thus, tuffs and rhyolites characterise the upper part, trachytes dominate the middle part with thin basaltic units as seen at 1410-1420 m, similarly for OW-707. The lower part is rhyolite and intermediate/basic rocks with tuffs interlayering (see Appendices). The deeper the penetration of the well, one would expect various lavas and tuff interlayering, though the presence of acidic rock formation would not be dominant with depth as reported by Hamilton et al. (1972).

2.4 Concluding remarks

It is possible from the penetrated rock units within these wells to build up stratigraphic units within this field, subsequently draw correlations of wells, and map out probable subsurface

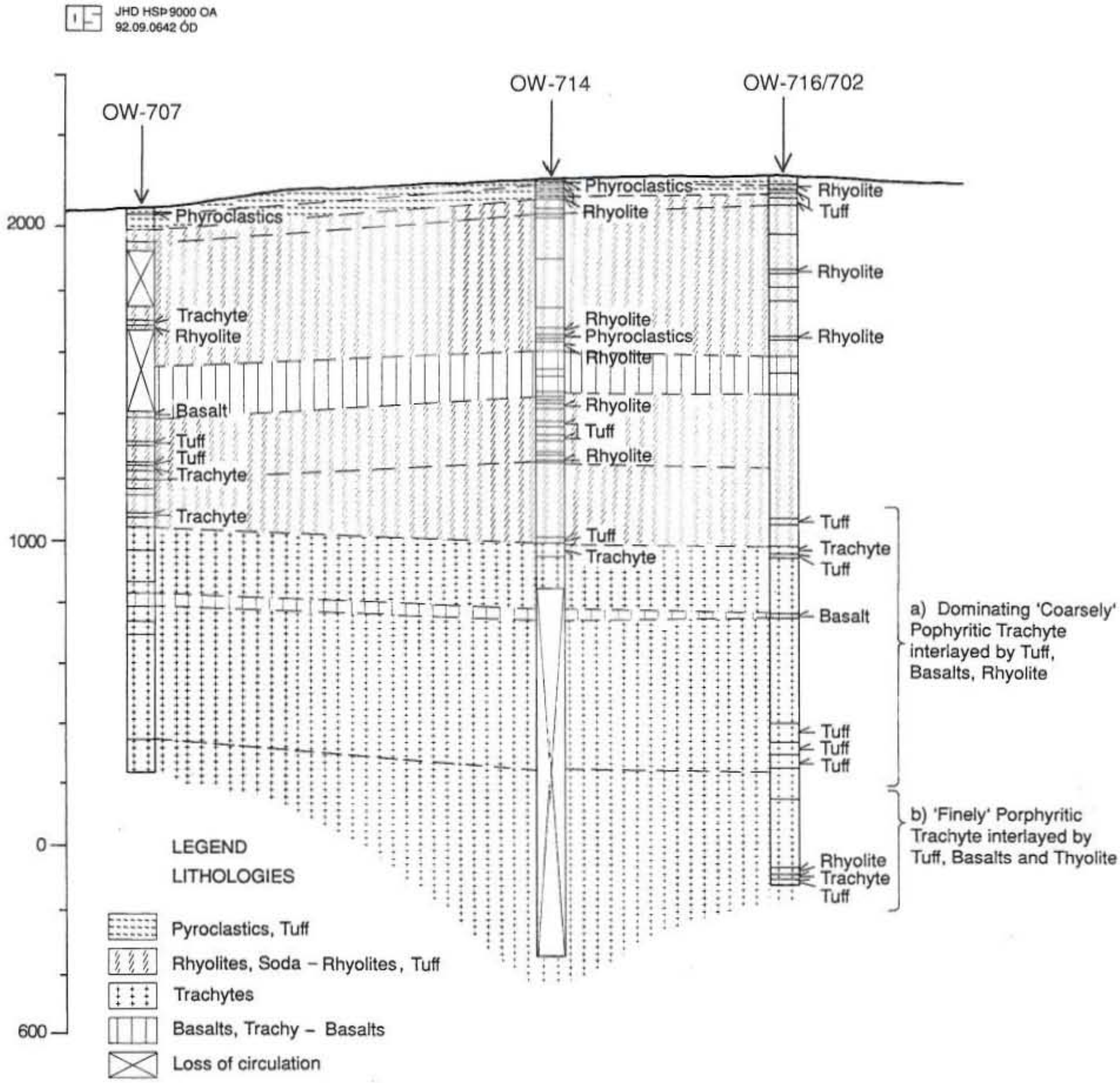

FIGURE 6: Stratigraphic correlation of wells OW-707, OW-714 and OW-716

geological structures within the field. The extensive circulation losses experienced in the top part of well OW-707 and the blind drilling in well OW-714 at the bottom could be explained in terms of probable local structural controls like fracturing or brecciation within these wells. These can be verified from the well logs.

3. HYDROTHERMAL ALTERATION

3.1 Analytical techniques

The use of different analytical methods is very important in giving detailed information on the well. The binocular microscope, the petrographic microscope for cuttings and thin section analyses, respectively, have already been mentioned under analytical methods. Nevertheless, a brief look at individual methods, merits and limitations shall be outlined.

a) Binoculars
As drilling of the well goes on, the recovered samples are analyzed by use of the binocular microscope. This method assists in determining the formation boundaries, recognition of permeable, fracture or breccia zones. But the textures and specific depth of origin of the samples cannot be determined from this method of analysis.

b) Petrographic microscope
This is one method of analysis which gives quite conclusive results both from the cores or cuttings that are made into thin sections. The optical properties, textural and microstructural relationship of the minerals, i.e clays or other mineral assemblages can be determined by use of this method. One major drawback is in determination of the type of clay or even oxide observed at certain depths.

c) X-ray diffractometer
Another very useful method normally used is the XRD. An X-Ray Diffractometer (XRD) is an extremely useful instrument in the identification of minerals and can be used, under some circumstances, to provide quantitative information. It is especially good for identifying particular clays, oxides and zeolite minerals. However, one problem for this method is to discriminate between primary or secondary minerals, as in the case of feldspars, quartz or amphiboles.

A routine observation method for clay minerals is used based on

a) a constant humidity;
b) glycol saturation;
c) heating to 550-600°C.

3.2 Alteration of primary minerals

In the tuffaceous units, clays and calcite are the most common replacement primary minerals and in other instances albite and quartz. In the rhyolites, especially at shallow depths, the pyroxenes and feldspars show little or no alteration at all, though at deeper levels, they are mostly altered. Primary quartz is resistant to alteration but there are instances where it is seen spotted with clay minerals. Glass, olivine and feldspars are more susceptible to alteration, especially to clays and oxides. The trachytes show sanidine phenocrysts altering into albite, plagioclase feldspars are altering into clays, and in other cases calcite has been noted to be replacing plagioclase. Hence, the alteration of the primary minerals in this well can be summarised: glass is the most altered of the volcanic products whereas quartz shows a smaller degree of alteration. The intensive alteration noted within the basaltic units, especially of olivine, plagioclase to oxides and clays, is noteworthy. This observation agrees with the Olkaria East Field, that alteration is only partial and not pervasive as noted by Browne (1984a).

3.3 Distribution of hydrothermal alteration minerals in well OW-716

An assemblage of the hydrothermal alteration minerals that have been observed within this well include: chalcedony, anhydrite, hematite, calcite, epidote, flourite, amphiboles, adularia, pyrite, prehnite, albite, mordenite, sphene, quartz, stilbite, scolecite; and the clays are illite, smectites, chlorite, mixed layer clays. The occurrence and the distribution is discussed under individual minerals. Figure 5 shows the stratigraphy and hydrothermal alteration of well OW-716, whereas Figure 7 shows the mineral abundance of selected hydrothermal minerals with depth (see also the table for clays in Appendix III).

3.3.1 Alteration minerals

Smectite
These are clays which are common for low temperatures, and they include clays like montmorillonite, saponite, beidellite, etc. Smectite occurrence is independent of the rock type. In this well the scarcity of enough samples at the shallower depths made it difficult to determine the exact location at which smectite was first encountered.

The only confirming sample was at a depth of 350 m, which upon analysis gave the peaks for these clays. Figure 8a shows the results obtained from the X-ray diffraction method and the smectite peaks as observed a) at constant humidity, b) in glycol saturation and c) after heating to 550-600°C.

On the other hand, the thin section shows green to brown colours changing to yellowish-green colour, green in polarised light. Smectite here is seen replacing glass, other primary minerals like feldspars and/or the ferromagnesian-bearing minerals, and occurring as infillings in both voids and fractures.

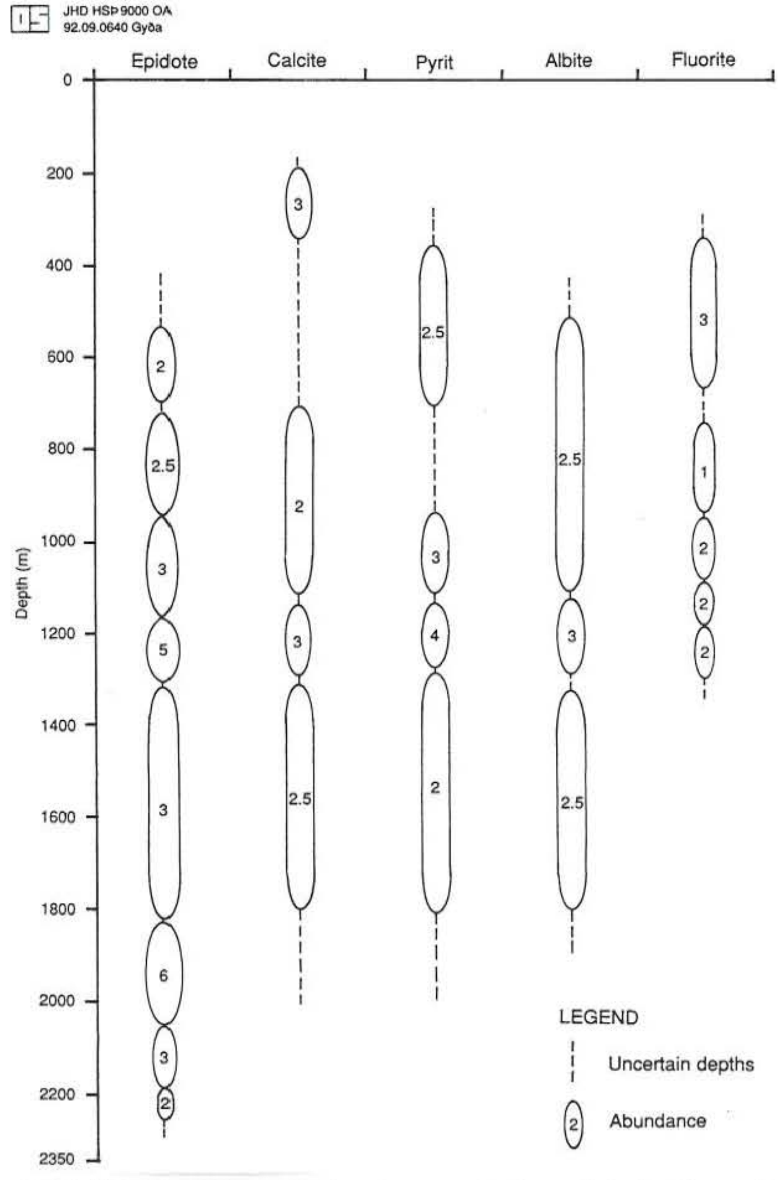

FIGURE 7: Mineral abundance of selected hydrothermal minerals with depth in OW-716

Mixed layer clays
Clays showing interstratified layers are referred to as mixed layers. These kind of layers are taken

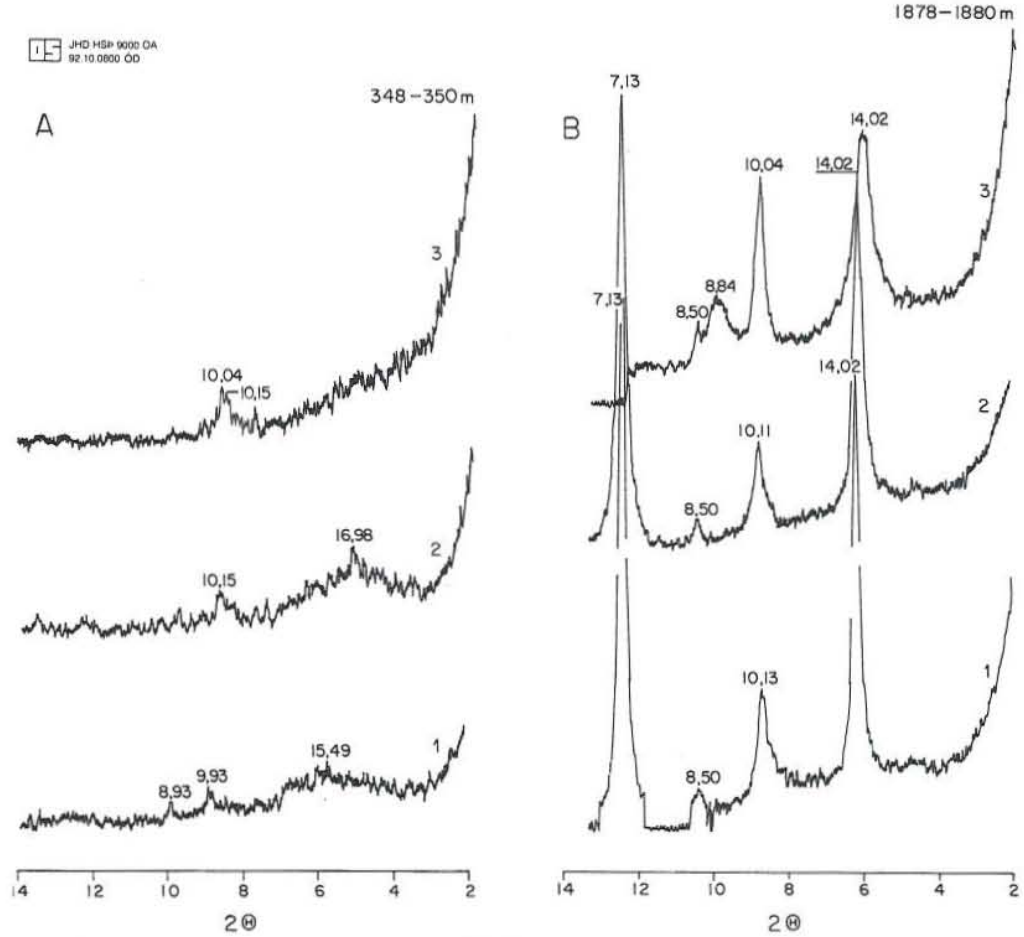

FIGURE 8: XRD-clay analysis of samples from 350 m and 1880 m depth

to combine the existence of smectite-illite, smectite-chlorite and smectite-illite-chlorite. In this well at a depth of 438-440 m, analyzed samples gave rise to the respective peaks as 16.66 Å (broad) when treated with calcium chloride; 17.65 Å (broad) in glycol saturated and 23.98 Å and 16.35 Å (broad) when heated to 550-600°C. These were results from the X-ray diffraction.

Illite

Mostly seen along with the chlorite (interstratified) (Figure 8b), illite clays always show a very distinct or characteristic peak of close to 10 Å. The peaks do not show much change upon glycol saturation or even on heating to 600°C. Illite clays are mostly common in the potassium-rich rock types.

Confusion reigns where the sericite replaces mica in reference. Of course this is applied to low temperature, colourless clay aggregates of layer lattice minerals, possibly intermediate between micas and the clay minerals (Whitten and Brooks, 1972).

Swelling chlorites

The samples at 628 m were treated with calcium chloride, glycol saturated and heated to 600°C. The following results were obtained: 7.64 Å; 7.13 Å and 18.79-13.18 Å; and 18.79-13.18 Å, respectively. Similar results were also obtained at a depth of 1058-1060 m. All these lead to the swelling chlorite conclusion. At 1060 m, the presence of an aquifer has been observed.

Chlorites
Chlorite clays normally form at the expense of the primary ferromagnesian minerals or glass or the deposits in the vesicles and veins from the Fe-Mg rich fluids. In the thin section study, chlorite clays are normally seen as minute radiating aggregates though they are best distinguished by the X-ray diffractometer method.

From the thin section study, they show moderate pleochroism, from yellow to green colours, having low birefringence. In this well the first recorded presence of the chlorite clays was from cuttings at a depth of 518 m. Consequently, chlorite has been seen to stretch clear down to the well bottom, occasionally appearing with illite.

Chalcedony
Thin section petrography shows the first appearance at a depth of 50 m. Subsequently seen at 250 and at 350 m, chalcedony is seen to be deposited within the zeolite vein in a sequence that was observed at a depth of 250 m, so that the zeolites are older than the chalcedony and the clays are the youngest.

Quartz
Seen mostly occurring in veins and cavities. The first appearance was at a depth of 518 m along with chalcedony in the vesicles, and consequently seen persisting to the well bottom.

Calcite
Occurs sporadically within the well, and marks the most abundant of the hydrothermal alteration minerals. First noted as shallow as 200 m, it is observed as infilling in veins, and replacement of primary plagioclase; it is also seen forming calcite veins as a result of alteration of primary feldspars, and is widely distributed within the chlorite-epidote zone. The disappearance of calcite at a depth of 1800 m depth is in agreement with the increase in temperature in the range of >280°C, a valid situation observed in Icelandic fields (Asgrimur Gudmundsson, pers. com.).

Epidote
The first epidote was observed from the thin section petrography at a depth of 588 m, and most abundantly from 1200 m, throughout the chlorite-epidote zone within the lower part of the well. The first occurrence of epidote indicates temperatures of ≥230°C and appears scarce until at temperatures in excess of 250°C where it is very abundant. The core recovered at the well bottom does not show the presence of epidote but the cuttings show it extends as deep as 2270 m.

Albite
Occurs as a replacement mineral of the primary feldspars i.e plagioclase and K-feldspars. It first appears at 588 m within the trachytic unit and is subsequently seen in the trachytes and basaltic units.

Adularia
The first appearance is at a depth of 820 m within the cavities. It also occurs as a replacement of K-feldspars, although the crystals were too fine to discriminate against other feldspars.

Hematite
Was detected by the XRD method. First confirmed at 600 m . The presence of this mineral is a result of the replacement of the less stable iron oxides like magnetite/ilmenite.

Pyrite
Was observed as shallow as 300 m, and extends as deep as 1800 m. It is seen occurring both in

veins, in disseminated form, with good cubes at 710-738 m. This could be a good indication of the probable active and fossil permeability in the well.

Anhydrite
This was seen at a depth of 518 m. Anhydrite is deposited as a result of the alteration of calcic plagioclase-bearing minerals.

Sphene
First noted at a depth of 600 m. It occurs mostly as infilling in: veins, vesicles, cracks and in feldspars. Seen forming zones with epidote, and opaque oxides.

Flourite
Has higher affinity for acidic rocks. Its first appearance is within the rhyolite unit at 300 m. It consequently shows scattered distribution down the well.

Zeolites
First observed at a shallow depth of 100 m. There are three types that were noticed within this well, scolecite and mordenite, showing their fibrous nature of occurrence, and stilbite in its typical almost parallel extinction in thin section, seen mostly within the veins. They occur along with the chalcedony and secondary quartz, but the zeolites show older generation than the quartz and the clays.

Prehnite
Observed at a depth of 1410 m. This is the only depth at which this mineral was observed within this well.

Actinolite (Amphibole)
It was observed at a depth of 1880 m, using the XRD method, with three peaks indicating the presence of this mineral (Figure 8b). This could be due to the feldspar phenocrysts altering to clays which grade to amphibole (actinolite + riebeckite + hornblende) with depth.

3.3.2 Alteration zones

Alteration mineralogy is important in determining the hydrothermal conditions present in the well/reservoir, and similarly can be used to reflect the past temperatures that existed at all depth levels. A brief outlook of these zones is outlined below in the text, but detailed mineral assemblage with their relative abundances can be obtained from the appendices. Alteration zones observed herein include; zeolite, smectite-zeolite, mixed layer clays, chlorite-epidote and actinolite-epidote zones.

Factors affecting the formation of the hydrothermal minerals are temperature, pressure, the rock type, permeability, the fluid chemical composition and the duration of activity (Browne, 1984a). The temperature and permeability form the alteration mineralogy, whereas the pressure has a minor effect on the formation or the deposition of hydrothermal alteration of minerals, except by the governing maximum fluid temperatures in the open geothermal system which can result in boiling, hence, affecting mineral deposition within the rock formation.

Minerals are formed within the pressure-temperature composition field. Most of them are temperature sensitive, amongst them zeolites and the clays. Others have a wide range of temperature formation, thus, precipitation is more dependent on the changes of pH values, gas content of the fluids and boiling.

The alteration zones in this well have been built up based on the basis of hydrothermal distribution and clay mineralogy with emphasis put on the clay mineralogy data obtained from the analyses which were performed on the X-ray diffractometer. The samples from the shallow depths showed very little presence of clay formation until a depth of 350 m was reached. The results obtained from this exercise are tabulated and attached to this report in Appendix III. Individual zones are discussed in the order of changes in mineral assemblages from the top to the bottom of the well: smectite, mixed layer clays, chlorites and illite adopted there as an accepted division of alteration zones. Table 1 shows the alteration zones in well OW-716.

TABLE 1: Alteration zones in OW-716 and corresponding temperature ranges

Alteration zones	Temperature range (°C)
Zeolites (no clays)	<110
Smectite-zeolite	<200
Mixed layer clays	>200, <230
Chlorite-epidote	>230, <280
Epidote-actinolite	>280

Zeolite zone
Observed from the top part of the well to almost 300 m. The low temperature zeolites like mordenite and stilbite were seen. Further down stilbite still persists and scolecite is seen occurring. A temperature range of up to 110°C is expected. (also see distribution of hydrothermal minerals).

Smectite-zeolite
At 350 m, though the zeolites are still observed, the first appearance of smectite is noted here. This zone is expected to sustain the minerals up to 200°C.

Mixed layer clays
Includes an assemblage of smectite-illite, smectite-chlorite and smectite-illite-chlorite. This is at a depth of 440 m. It is suggested that a gradual transformation of smectite, rich in iron and magnesium, into chlorite occurs at temperatures of 200-230°C.

Chlorite-epidote
Epidote was first noted at a depth of 520 m. This is the most extended zone within this well, stretching far down to the well bottom, though overlapping with the amphibole/actinolite-epidote zone at 1870 m. This zone characterises high alteration temperature in the range of >230-280°C until the first appearance of actinolite.

Actinolite (amphibole) -epidote
Actinolite was identified at a depth of 1870 m on the basis of the results obtained from the XRD analyses. The appearance of this zone is an indication of alteration temperature in excess of 280°C. This is one observation which holds true, as evidenced from the disappearance of the calcite at this depth. The lower limit of this zone should not be restricted to what is observed from the alteration zone, because the measured temperature is seen to increase with depth.

3.4 Practical use of hydrothermal mineralogy

The practical applications of hydrothermal mineralogy are of great importance in geothermal areas. Minerals that depend upon temperature, permeability, composition of the fluids are used to interpret the development of the reservoir conditions. It is well known that hydrothermal minerals are temperature dependant and form mineral assemblages. Cooling and warming up periods inside the geothermal systems may form new mineral assemblages which may overprint the older ones.

Widespread chlorite minerals in active geothermal fields show a great range in composition, which is temperature related. However, Kristmannsdottir (1975) has shown that smectites from Reykjanes, Iceland are present as a discrete phase where temperatures are below 200°C, and become randomly interlayered with the chlorite where temperatures are between 200 and 230°C, but above 230°C chlorite is the only clay mineral present (Kristmannsdottir, 1975). A similar situation is not true for the New Zealand geothermal fields (Browne, 1984b). The chemistry of the rocks also determines the deposition of the minerals in Iceland where the rocks are predominantly basalts with low silica zeolites, as compared to mordenite, common in rhyolitic fields (Browne, 1984a). The occurrence of adularia has been used to denote permeable zones (Browne, 1978).

The formation of zeolites is strongly temperature dependent and because of this their identity is a useful guide to their deposition temperature. There is a range of zeolites that occur at low temperatures (<110°C) best seen in low temperature areas in Iceland (Kristmannsdottir and Tomasson, 1978). Among the high temperature minerals, epidote seems to be the most reliable and consistent temperature guide, first appearing at 230°C in many fields, and subsequently observed to show a random distribution of occurrence irrespective of the lithology of the host rock.

Some minerals such as pyrite and related sulphides give valuable information about the fracture pattern in the reservoir, and are, therefore, indirect indicators of permeability. Other minerals like illite seem to be more related to the composition of the rock, rather than restricted temperature ranges. In well OW-716, illite was first identified at 350 m depth and is observed in every alteration zone and furthermore seems to be an indicator of the potassium/sodium content of the rock.

4. FLUID INCLUSIONS

4.1 Method

First, after preparation of the samples, they were examined thoroughly under the microscope, to identify inclusions and then decide upon their origin and reliability. The areas were sketched in detail for use while the sample was at the heating microscope stage. Figure 9 shows a quartz crystal with cleavage planes and inclusions with their measured temperatures.

Slow and careful heating was done to determine which inclusions homogenised first. These measurements were necessary to discriminate against the low and high temperature inclusions. It was possible to tell whether the homogenisation temperature (T_h) had been reached from the time taken for the resurfacing of the vapour bubble. Summarily, it is difficult to determine the exact T_h, as the very small vapour bubble commonly "hides" in a dark part of the inclusion. Use of a moveable fibre optic light source can help to alleviate this problem.

The heating studies of the fluid inclusion is done such that overheating is avoided, lest the inclusions become stretched, which might give wrong results. The detailed procedure for the preparation of fluid inclusion and the criteria used is given in Appendix IV.

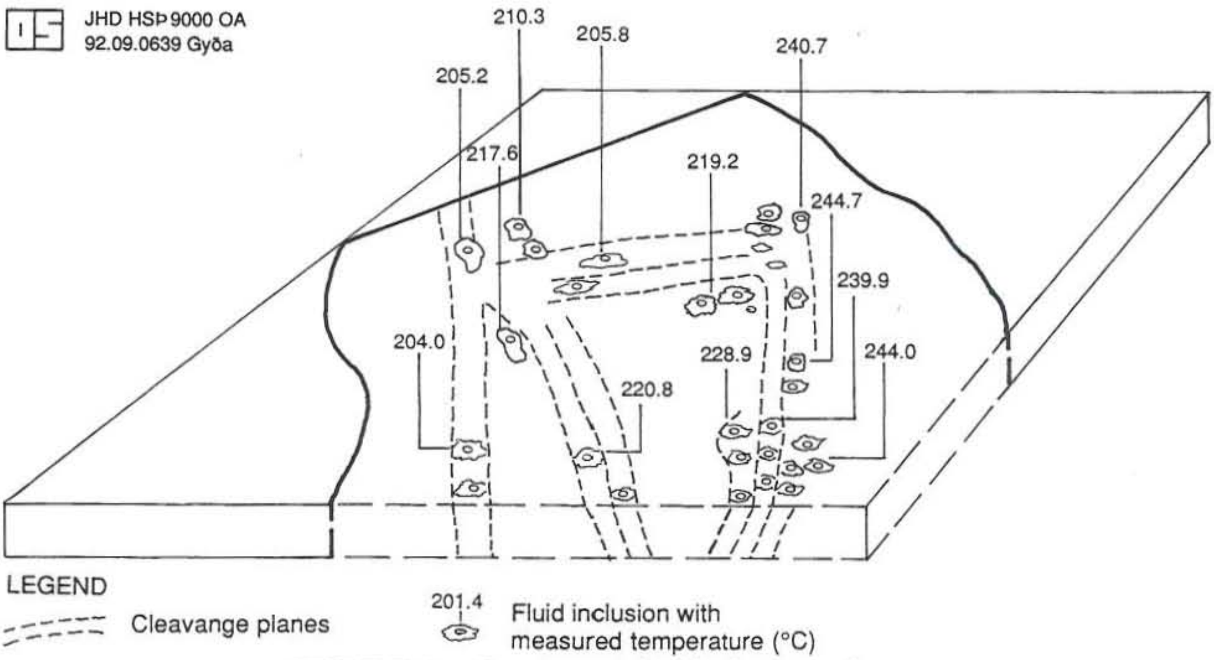

FIGURE 9: Quartz crystal with cleavage planes and inclusions with their measured temperatures

4.2 Selection of the samples

For the study of quartz crystals in this well, samples were picked from depths of 350 and 2258-2260 m. For better fluid inclusion study, i.e. to get good results, the samples obtained from the cores tend to give better results because of the precise depth at which the samples are collected, and the environment from which the sample is collected can be determined with minimal bias. Samples from the drilled cuttings are not as reliable as those from the cores, especially in establishing the true depth at which the sample is obtained. Picking an individual crystal from the

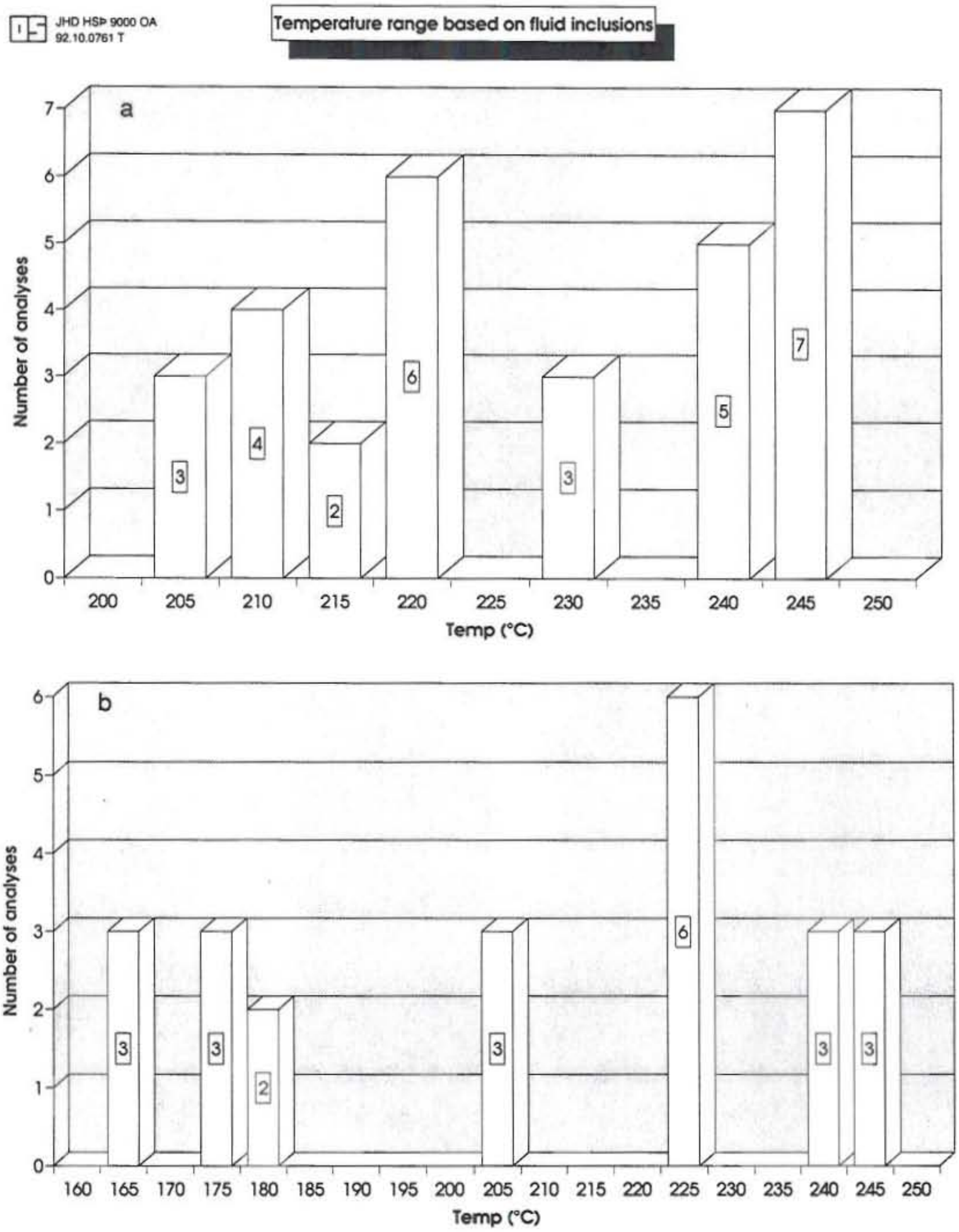

FIGURE 10: Histograms for crystals showing the temperature range based on fluid inclusions

cuttings may be impossible in some cases. The latter situation was the one I experienced in the course of running this study. Nevertheless, despite all these shortcomings, the obtained results reflect a good picture of whatever could be happening within the well, and possibly of the field/reservoir scenario.

4.3 Constraint of fluid inclusion data interpretation

The determination of the origin and the reliability of the subsequently obtained results from the study, and the lack of enough samples to study and compare, comprised another set back. The sudden disappearance of the vapour bubbles and their "hiding" habit in the dark part of the inclusion makes it difficult to reach a consensus T_h. There was uncertainty in determining and establishing the cleavage planes; different temperature results obtained from what, otherwise, could be taken for inclusions in the same plane were misleading. From all these, it necessitated repeat analyses and averaging of them to establish each measurement. Figure 10a and b show histograms for crystals, with temperature ranges based on fluid inclusion analyses.

4.4 Comparison between measured temperature and alteration temperature

The measured temperatures obtained from this study have shown that at a 350 m depth the 180°C obtained is above the results of the measured rock formation temperatures and thus, there is a probable cooling effect at the top of the well. On the contrary, at the deeper level of 2260 m where the other measurements were taken, the obtained maximum temperature of 245°C is much lower than both the direct downhole measurements and evaluated temperatures obtained; one possible explanation is that the field is heating up at deeper levels.

From this study a number of observations have led to the following deductions:

i) The inclusions that were observed in these crystals are of secondary origin in nature, i.e as deduced from the criteria in Appendix IV.

ii) There is a possibility of a cooling effect at the top of the well, whereas at deeper levels the well must be heating up (assuming that these crystals were obtained from these mentioned depths).

iii) The handicap of not being very specific about the depth of sample origin is bound to give misleading interpretation in so far as the T_h of these crystals are concerned.

5. AQUIFERS

Well OW-716 was drilled at an elevation of 2196.5 m a.s.l. Three probable aquifer zones were observed from the well test measurements at different elevations: 1050-1350 (820-1120 m depth), 200-250 m a.s.l. (1920-1970 m depth) and 50-120 m b.s.l. (2220-2290 m depth) (see Figure 5). The subsurface geology here indicates the presence of aquifers in the rhyolites and tuffs. Such an observation is more strongly related to layering of volcanic pile rather than to faults/fractures, although small, but still the structural aspect is registered. The biggest aquifers in the well are shown as double arrows in Figure 5. A similar scenario is also observed within the Olkaria East field (Merz & McLellan-Virkir, 1984).

The fact that the penetrated volcanic piles in the field appear to be sub-horizontal is suggestive that structural features do have an effect, at least as observed within this well, even though it could not be a principal (compared to the bulk volcanic piles) role within the observed local tectonic/stratigraphic set-up of the area.

6. TEMPERATURES

6.1 Alteration temperatures compared to measured temperatures

Figure 11 shows both the rock formation temperature and the alteration temperature plotted from the observed alteration mineralogy within Olkaria well OW-716. Several runs of temperature were carried out in well OW-716. To establish the formation temperature, two runs were selected. The main part of the temperature profile from 2nd October '90 down to a 2000 m depth is adopted here as approximately formation temperature. Below 2000 m depth, the temperature runs for 14th November '90 could be taken to represent the formation temperature.

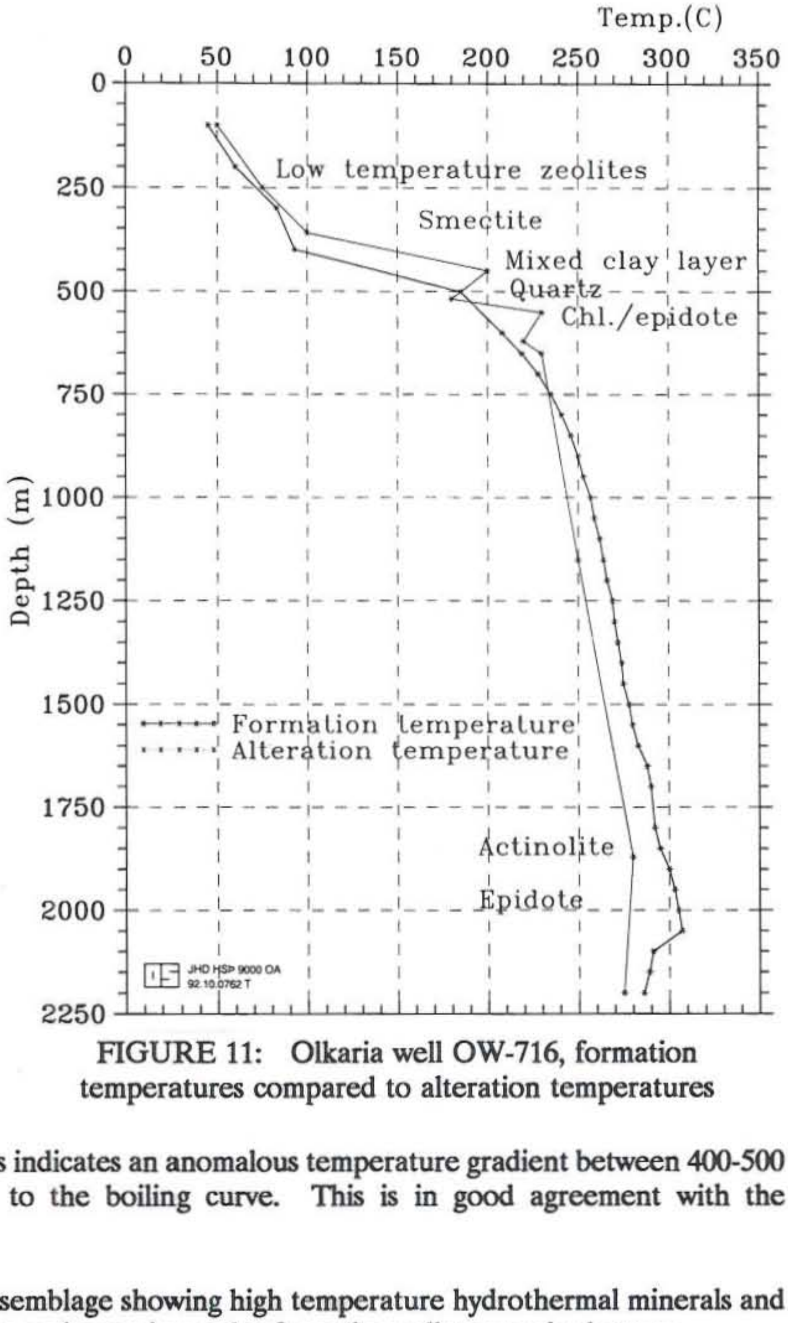

FIGURE 11: Olkaria well OW-716, formation temperatures compared to alteration temperatures

Figure 11 shows estimated rock formation temperature compiled from the loggings and alteration temperature plotted from the observed hydrothermal minerals within the well. The profiles establish the same trend though with small variations. Close to the upper boundaries of the basalt unit at 500 m depth, which is taken to be the caprock, the temperature increases close to 100°C in a 50-100 m interval. This indicates an anomalous temperature gradient between 400-500 m depth, but below it is close to the boiling curve. This is in good agreement with the hydrothermal alteration.

Thus, an alteration mineralogy assemblage showing high temperature hydrothermal minerals and alteration zones is encountered in an increasing order from the well top to the bottom.

6.2 Distribution of temperature in the well field

Figure 12 shows the temperature distribution for NE-Olkaria at the elevations 1250, 1075, 750 and 500 m a.s.l. using information from all the wells within the field. Several well profiles in the field can be used to map the temperature distribution at certain depth levels as observed from the above mentioned figures.

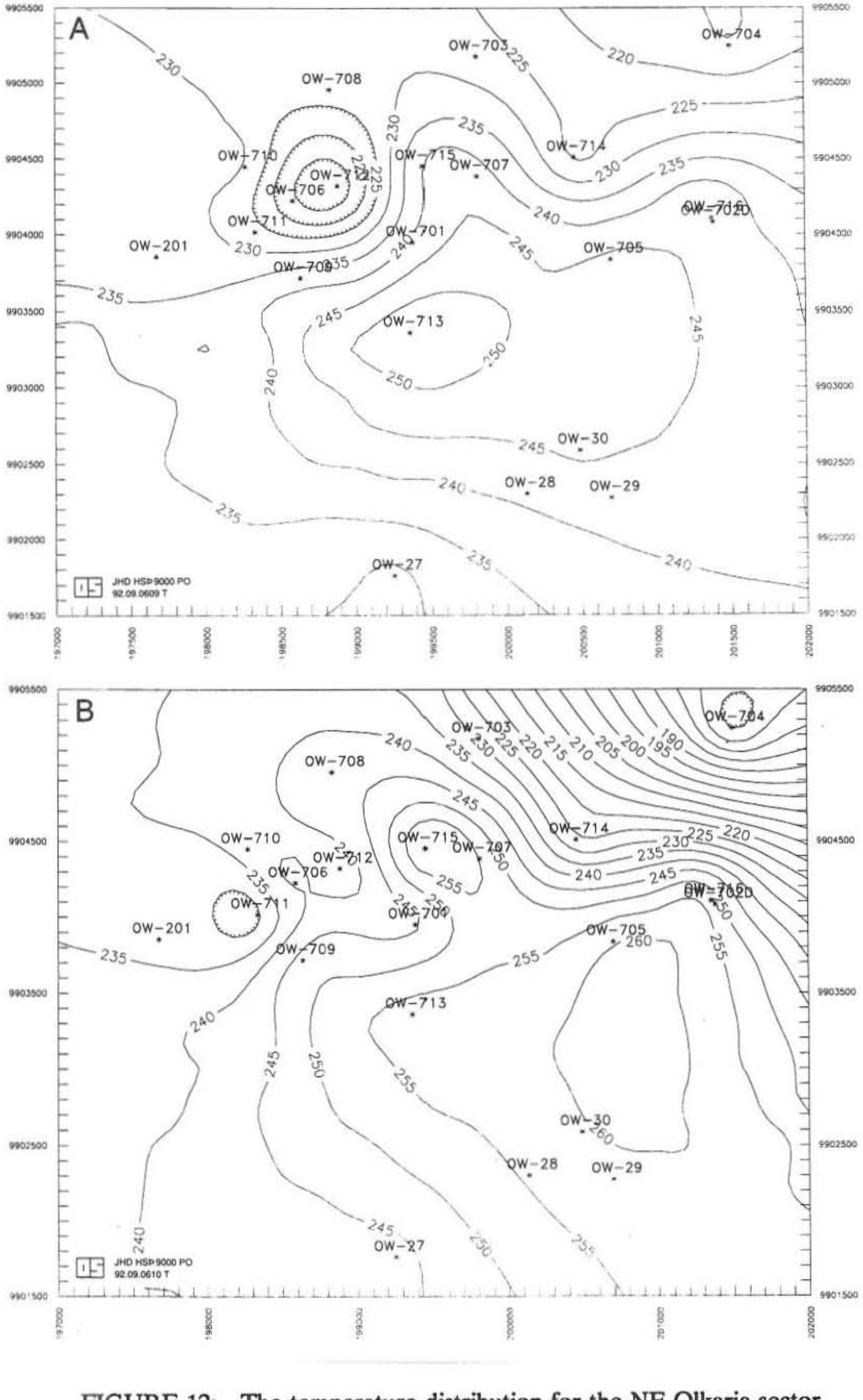

FIGURE 12: The temperature distribution for the NE-Olkaria sector a) at 1250 m a.s.l.; b) at 1075 m a.s.l.

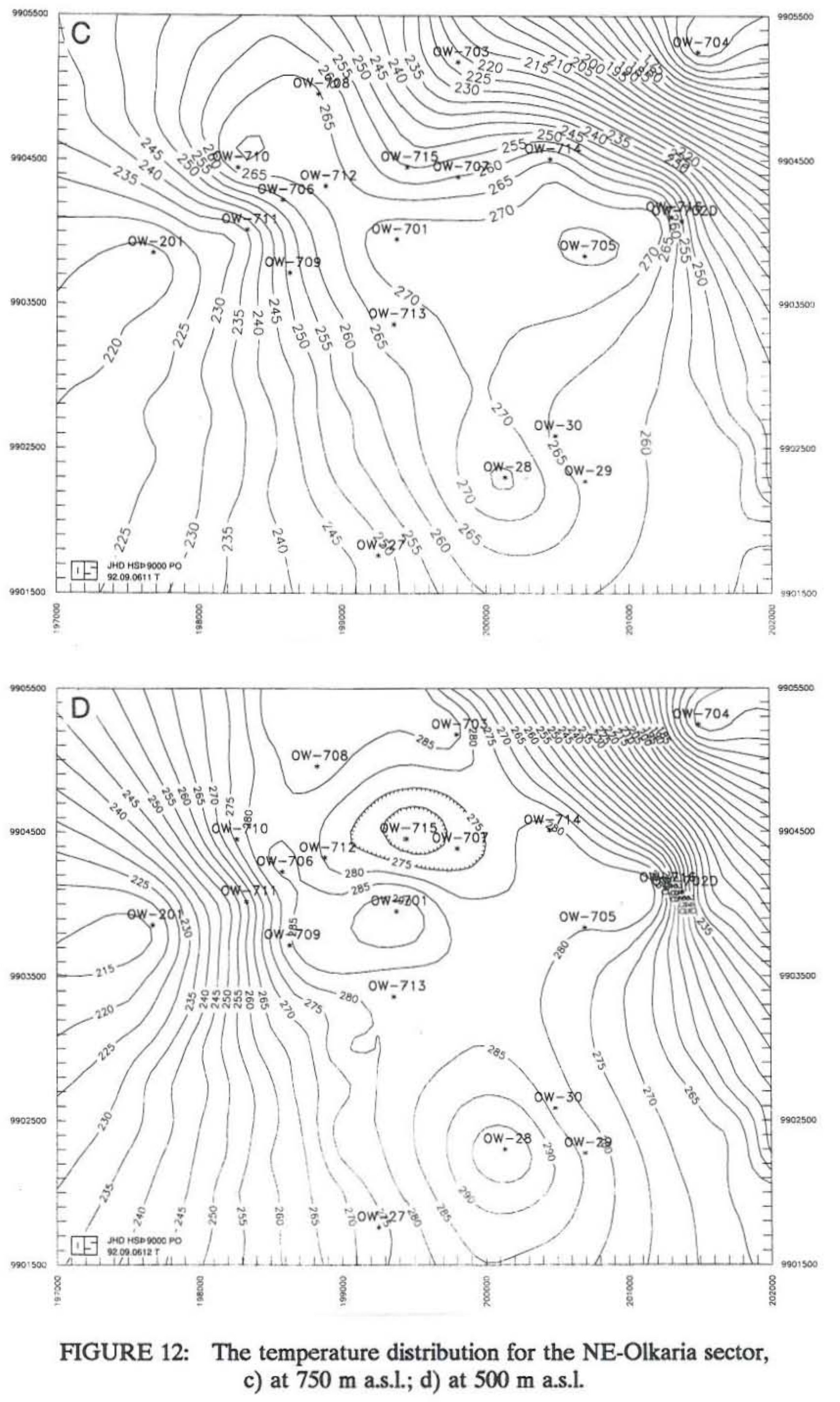

FIGURE 12: The temperature distribution for the NE-Olkaria sector, c) at 750 m a.s.l.; d) at 500 m a.s.l.

Figure 12a shows maximum temperature in the field of 250°C at an elevation of 1250 m a.s.l. (920 m depth), but in the well it is 240-245°C. The distribution pattern shows an east-west lineament, which is one of the main tectonic features in the area (Figure 2).

Figure 12b shows maximum temperature in the field at 260°C at an elevation of 1075 m a.s.l. (1095 m depth), but it shows 250°C in the well. The contour lines show a steep cooling gradient north of the well, but on the other side it is rather flat. The east-west trend is still characteristic but the southern part of the field shows a slight bend towards a north-south trend.

Figure 12c shows maximum temperature in the field of 275°C and 260°C in the well at 750 m a.s.l. (1420 m depth). The contour lines show a different trend than before. The two main tectonic trends, therefore, come out here. The E-W trend is dominant in the northeast part, where the cooling gradient is steepest.

Figure 12d shows maximum temperature in the field of 295°C and 270°C in the well at 500 m a.s.l. (1670 m depth), the N-S trend is principal with almost no effect of the E-W trend being witnessed.

The generalised deduction here is that there is a temperature increase with depth and the establishment of a strong correlation with the main tectonic features of the area. An east-west lineament characterizes the uppermost part, but north-south the lower one.

7. DISCUSSION

A total of twenty seven wells have already been drilled in the NE-Olkaria sector, tested and shown to have a power equivalent of 70 MW_e electricity.

From the rocks penetrated, i.e. the pyroclastics and tuffs, the rhyolites, trachytes and basalts, it has been possible to build up stratigraphic units within well OW-716 that have been used to correlate with the neighbouring wells, where sample recoveries were poor. These also make it possible to deduce that the rock units within the Olkaria North - East field and the neighbouring present borefield show a closer correlating match. Alteration observed within this well shows that the pyroclastics and tuffs are extensively altered, with the rhyolites that were penetrated at the shallow depths of the well showing abundant primary pyroxenes and amphiboles with almost no alteration. Two types of trachytes were observed. The one at the top shows predominantly "coarsely" porphyritic texture, interlayered by tuffs, rhyolites and basalts. At deeper levels is the "finely" porphyritic trachytes interlayered by tuffs, rhyolites and basalts. But most extensively altered lavas are noted where the formation is jointed, fractured or even brecciated (see appendices).

Figure 2 shows the geological structures and well sites in Olkaria. Olkaria fault is seen trending in an ENE direction. The wells in the field lying within the vicinity of this fault have been observed (tested) to be good producers. This structural control indicates that this fault acts as a conduit or an upflow zone for the hot fluids, and similarly an expected increase in vertical permeability. Permeability in this well and further extended to this field - North East, has been found to be controlled both structurally, as already exemplified, and also lithologically. The layering of the volcanic piles, the nature of the rock, i.e whether the rock is vesicular or not, all contribute largely to an extent or the magnitude of permeability in well OW-716; similar observation can be used for other wells lying within the same proximity/ field as a whole. It has already been observed (from the stratigraphy and well correlation) that the strata is mostly sub-horizontal ; implying an effect of structural control (tectonic), and the aquifer locations within the well have also been observed to be not associated with any loss of circulation. It is not unusual to deduce, therefore, that the aquifer locations are connected with the lithology more than the structures, at least for this well, though it may not necessarily be true for the other wells within the field. Due to limited lateral extent of individual geological units , and also the fact that permeability is sometimes associated with the cooling joints in lavas developed by contraction, sometimes with contacts between lava flows, porous tuffs or even brecciated zones, it is in order to note that there is no generalised correlation between the permeability, lithology and depth.

Figure 7 shows the distribution and relative abundance of some of the hydrothermal minerals and alteration/formation temperatures observed in this well. The mineral assemblage indicates the well has experienced temperatures of almost 300°C. The alteration mineral zones match closely with depth which could imply a closer relationship of the mineralogy with the present measured reservoir temperature within the well. The abundant occurrence of epidote at 1250 m, the appearance of amphibole/actinolite at 1870 m, along with the disappearance of calcite at that depth are indications of temperature rise of >280°C with depth.

Figures 12a, b, c and d show NE-Olkaria temperatures at different elevations for all wells and indicate that well OW-716, which is located on the edge of the inferred arcuate fractures, marks the boundary of the field in the north and north - east directions. Temperatures are noted to drop drastically in well OW-704 at all levels (observed elevations), thus, implying that it lies outside the reservoir.

The temperature distribution pattern may indicate a strong upflow zone connected to the main trend of the Rift Valley. At upper levels the east-west trend is dominant, further confirming the steep cooling gradient observed earlier as the boundary of the caldera or the ring structure. Data obtained from the reservoir measurement tests in the location of aquifer zones within this well, suggest the presence of bigger feeder zones in the well at the deeper levels. Therefore these data supports strongly the evidence for the flow pattern being closely linked with the tectonic features observed on the surface.

Thin section petrography has shown a mineralogical evolution, suggestive of the zeolites observed in the well, being of two types i.e scolecite older than stilbite; they are of older generation than the chalcedony/quartz (secondary) and these are seen altering to clays which are coarse-grained. The thin sections at 250 m depth show the zeolites deposited in the veins, subsequently cross-cut by the other vein bearing chalcedony but of younger generation. At 350 m the chalcedony is seen deposited within the zeolite vein further suggesting what was observed at 250 m. The alteration zone here could indicate a possible smectite-zeolite-illite type of composition.

CONCLUSIONS

i) The rocks penetrated in this well show similar lithology (i.e they are volcanics) with the other drilled wells in the field. The stratigraphic units may not be necessarily of the same thickness, but still show a good correlation.

ii) Tuffs and pyroclastics are more in bulk, most altered of the formations that were penetrated.

iii) Permeability in this well is both structurally and lithologically controlled, with the latter being more prominent because of bulk. Permeability may not necessarily be directly correlated/linked with lithology and depth.

iv) The alteration and measured temperatures show good agreement, indicating highest temperatures in excess of 280°C at the deeper levels of the well.

v) Results obtained from the fluid inclusion study suggest a probable cooling effect at the upper part of the well and show the reverse at deeper levels.

vi) Structural controls as observed from the temperature profiles at different elevations indicate the presence of strong effect on the field of the E-W trending faults/fractures at higher elevations whereas the N-S are more pronounced at lower depths.

ACKNOWLEDGEMENTS

I extend my gratitude to the government of Iceland and the United Nations University, both for financial assistance and the privilege accorded me to attend this Geothermal Training Programme course, the Icelandic National Energy Authority (Orkustofnun) who provided the teaching and technical expertise, and of course Kenya Power Company who granted me the sabbatical leave.

Special thanks are due to the United Nations University, Geothermal Training Programme Director Dr. Ingvar Birgir Fridleifsson, Mr. Ludvik S. Georgsson, for their motivation and guidance throughout this study period. My deepest and sincere appreciation to my supervisor, Mr. Asgrimur Gudmundsson, who untiringly was always available to assist me, Dr. Hjalti Franzson for his assistance in the fluid inclusion study and Mr. Magnus Asgeir Sigurgeirsson for guidance and assistance in the X-ray diffractometer analyses.

My indebtedness to my dear and beloved family members, Abagonga, for their sacrifice both spiritually or otherwise. Many thanks to all friends and acquaintances I have encountered in the course of my stay.

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APPENDIX I: Detailed petrography of cuttings from well OW-716

Depth in m	Lithology, description and observed alteration minerals
0 - 34	Loss of circulation
34 - 51	*Rhyolite.* Light brown in colour, fine grained, massive rock, highly siliceous, vitreous and vesiculated, infilled by secondary quartz. Rock shows strongly flow-banded structures. Has quartz crystals and feldspar phenocrysts in the groundmass, deep blue coloured minerals, possibly low temperature amphiboles-riebeckites (?) and fresh pyroxenes-aegirine-augites. Less intensity of oxidation is observed. Observed alteration minerals (relative abundance): Quartz (5), oxides (4) and clays (2).
51 - 56	*Ashy tuff.* Very fine grained leucocratic ashy tuff, bearing abundant flakes of micaceous clays (white in colour) possibly sericite, zone doesn't show much oxidation. Observed alteration minerals: Micas (sericite) (4), silica (5).
56 - 76	Loss of circulation
76 - 100	*Tuff.* Mixed cuttings, bearing lithic rock fragments, show grey to brown and green colours depending upon the alteration. Presence of welded tuffs, pumiceous and obsidian cuttings, rhyolitic and trachytic rock fragments also evident. Various types of textures are seen in these fragments. From the thin section analysis, adularia, stilbite as zeolites is noted. Observed alteration minerals: Quartz (4), clays (3), oxides (2), silica (2), adularia (1), stilbite (1).
100 - 198	*Rhyolite.* Grey in colour, shows a massive texture, very siliceous groundmass. Obsidian and quartz are present. Spherulitic texture is evident, with a little bit of oxidation at depth. Observed alteration minerals: Quartz (4), silica (3), oxides (1).
198 - 306	*Tuff.* Greyish to greenish coloured mixed cuttings bearing obsidian and pumiceous fragments, lava rock fragments are present too. First encounter of calcite as well as pyrite in the well at this depth. Observed alteration minerals: Quartz (4), calcite (2), pyrite (1), oxides (2), silica (chalcedony) (2).
306 - 318	*Rhyolite.* Thin unit of rhyolitic cuttings grey in colour, shows flow-banded structures. It is mixed with some tuff material and spherulitic texture is noted. Feldspars are seen altering to clays and oxides. The rock is vesiculated and infilled by silica, quartz crystals and calcite present. Observed alteration minerals: Quartz (4), oxides (3), calcite (2), clays (2).

Depth in m	Lithology, description and observed alteration minerals
318 - 362	*Tuff (breccia zone?).* Altered rock, looks brecciated, greenish colour due to clays and mixed with tuff cuttings. Presence of these contortions suggest a possible volcanic breccia. Flourite and pyrite present. Observed alteration minerals: Pyrite (3), clays (2), flourite (1), oxides (2), quartz (3).
362 - 412	*Rhyolite.* Grey in colour, fine grained, highly siliceous rock, feldspars phenocrysts and quartz crystals in the groundmass. Presence of clays is noted, pyroxenes seen look fresh and infillings of silica, pyrite, and clays are noted. Observed alteration minerals: Pyrite (2), clays (2), silica (3), oxides (2).
412 - 520	*Silicified tuff.* Leucocratic, highly siliceous, vesiculated and infilled by clays and pyrite. Otherwise the rock is massive, has also pumiceous cuttings, feldspars in the lithic fragments show much alteration to oxides and clays. Unit shows evidence of fracturing, silica and and pyrite seen as infillings. Observed alteration minerals: Pyrite (3), clays (2), silica (3), quartz (3), oxides (2).
520 -534	*Rhyolite.* Grey coloured rhyolite rock cuttings, fine grained, massive and shows flow-banded structures. Little intensity of alteration is noted, granular quartz crystals growth in the vugs, veins are infilled by silica, pyrite and calcite are also observed. Observed alteration minerals: Pyrite (2), quartz (3), silica (3), calcite (2), clays (2).
534 - 588	*Basalt.* Dark basaltic cuttings mixed with tuff and rhyolitic material. The rock is fine grained, porphyritic in texture. Presence of clays (green coloured) is evident, epidote and flourite is present. Alteration minerals: Epidote (2), flourite (2), oxides (4), clays (3).
588 - 640	*Trachyte.* Dark grey coloured trachyte rock mixed with tuff material. It is massive, fine grained, showing feldspars alteration to clays and oxides. Epidote, pyrite and sphene are present. Observed alteration minerals: Clays (3), epidote (2), flourite (2), pyrite (2), sphene (2).
640 - 710	*Basalt.* Dark coloured, fine grained, porphyritic texture and has also tuffaceous cuttings. It shows much alteration of feldspars to clays and oxides, albitisation seen, calcite is present in veins and also occurring independently. Observed alteration minerals: Clays (2), epidote (3), pyrite (2), calcite (2).
710 - 940	*Basalt (with tuff intercalations).* Mixed cuttings of basaltic lava rock with tuffaceous material. This unit shows high alteration to clays and oxides, calcite, pyrite, and possibly micaceous clays are present. It has also fracture fillings, chlorite clays, quartz, glass, and calcite seen replacing plagioclase phenocrysts. Observed alteration minerals: Clays (4), epidote (2), pyrite (3), calcite (3), flourite (2).

Depth in m	Lithology, description and observed alteration minerals
940 - 1104	*Rhyolite.* Grey and massive rock, fine grained, and porphyritic in texture. The groundmass is highly siliceous, flow-banded structures present and shows feldspars altering to albite. Highly pleochroic mineral is seen, possibly hornblende. Flourite, sphene, epidote, calcite and dessiminated pyrite are present. Some of these minerals occur in vugs as well. Observed alteration minerals: Epidote (3), calcite (3), sphene (2), albite (3), flourite (3), pyrite (3), quartz (4).
1104 - 1120	*Tuff (silicified).* Thin unit of highly siliceous cuttings, with clays and little oxides. Observed alteration minerals: Clays (2), oxides (2), flourite (1).
1120 - 1190	*Rhyolite.* Grey coloured, massive rock, highly siliceous with vitreous groundmass. Secondary quartz in vugs. Cuttings of obsidian and more alteration at depth. Observed alteration minerals: Pyrite (3), quartz (4), clays (3), oxides (2).
1190 - 1218	*Trachyte.* Dark grey, massive rock, fractured, showing porphyritic texture. Feldspar phenocrysts in the groundmass altering to clays and oxides. Calcite, flourite, epidote noted and the rock has high clay content. Observed alteration minerals: Epidote (5), flourite (2), pyrite (3), calcite (3), oxides (4), albite (4).
1218 - 1224	*Tuff (silicified).* Thin siliceous unit of mostly secondary quartz, pyrite and clays. Observed alteration minerals: Silica (3), pyrite (3), clays (2).
1224 - 1410	*Trachyte.* Similar unit as the one at 1190-1218 m, still showing fracturing and veins. Silica, pyrite and epidote are present. Observed alteration minerals: Epidote (3), albite (3), calcite (2), clays (3), oxides (4).
1410 - 1420	*Basalt.* Highly altered rock, dark coloured and fractured. It has calcite, silica, much oxidation leading to clays and obsidian. The first appearance of prehnite is noted here. Observed alteration minerals: Epidote (3), calcite (3), prehnite (2), albite (3), oxides (3), clays (4).
1420 - 1768	*Trachyte.* Grey coloured trachyte rock, showing fracturing and oxidation. Intense pyritisation noted in this unit and siliceous material cuttings, albite, flourite, calcite noted. Observed alteration minerals: Pyrite (4), epidote (3), albite (3), calcite (3), flourite (1).

Depth in m	Lithology, description and observed alteration minerals
1768 - 1828	*Tuff (lithic).* Mixed cuttings of tuffaceous material, bearing lithic fragments of trachytic and rhyolitic rock material. The unit is also fairly siliceous, altered feldspars and obsidian present. There were, however, zones with loss of circulation at 1792 and 1828-1862 m. Observed alteration minerals: epidote (2), clays (3), quartz (3), flourite (1).
1862 - 1912	*Tuff (silicified).* Leucocratic cuttings of mostly secondary quartz in massive rock. It has also clays which are green in colour, epidote and micaceous clays are seen. Evidence of fracturing and alteration noted. Observed alteration minerals: Epidote (6), clays (5), quartz (3).
1912 - 2010	*Tuff (lithic).* Dark grey mixed cuttings of tuffaceous rock and lava rock fragments. Welded lithic tuffs and clays are seen. High degree of oxidation is observed and silica content is increasing at depth. Observed alteration minerals: Epidote (3), clays (4), oxides (4), silica (3), quartz (3).
2010 -2230	*Rhyolite.* Grey coloured rhyolitic rock cuttings, mixed with siliceous material. Generally, the rock is fine grained, massive, showing possible fracturing and intensive oxidation. Epidote is still present. Observed alteration minerals: Epidote (3), clays (2), oxides (2), silica (4), quartz (4).
2230 - 2250	*Pyroclastics.* Highly mixed cuttings, mostly of pyroclastics. Epidote, pyrite, quartz and silica are seen. Observed alteration minerals: Clays (4), oxides (3), epidote (2), pyrite (2), quartz (2).
2250 - 2268	*Trachyte / rhyolite.* Altered lava rock, looks brownish in colour due to the presence of the oxides and clays. The rock is porphyritic in texture, fairly mafic and the zone seems fractured. Epidote and pyrite are noted. Observed alteration minerals: Epidote (2), pyrite (2), oxides (3), clays (2), silica (3).
2268 - 2296	*Tuff (lithic).* Mixed up unit bearing mostly tuffaceous material, which seems to be fractured and veins are infilled by silica, epidote (though less), clays and granular quartz. Lava rock fragments of both rhyolite and trachyte seen present. Observed alteration minerals: Oxides (4), clays (3), quartz (2), epidote (2), silica (3).

APPENDIX II: Detailed petrography of cores from well OW-716

Depth in m	Lithology, description and observed alteration minerals
1701 - 1703	*Trachyte.* Dark grey coloured lava rock, hard compact, fractured though the fractures are tight and have already been infilled by silica and clays. The core shows highly porphyritic texture. The rock is a trachyte and the thin section shows feldspar laths in the groundmass alignment to give a trachytic typical kind of texture. Sanidine phenocrysts are seen also altering to clays and oxides mostly, albite formation is also noted. Noteworthy alteration is the albite formation and clays as well as oxides. Observed alteration minerals (relative abundance): Clays (4), silica (2), Fe-oxides (3), albite (3).
2296	*Rhyolite.* Grey coloured, fine grained, moderately altered rock, showing feldspar cristolites-laths, aligned to give flow-banded structures. The rock has vesicles which have been infilled by granular quartz crystals. Much of the alteration has given rise to clays and oxides. Texturally, the rock can be taken for a trachyte but it looks still more of a rhyolite. Observed alteration minerals: Quartz (4), clays (4), Fe- oxides (3), silica (3).

APPENDIX III: X-ray identification of clay minerals

The procedures below, a and b outline the stepwise order followed in the preparation of samples for the hydrothermal alteration individual and clay groups of minerals, respectively.

Procedure a:

1. By use of the binocular microscope, handpick the grains from the drilled cuttings.

2. Powderize the samples in an agate bowl to a recommended value of 5-10 μm. To prevent the escape of powder during grinding, use of acetone is necessary.

3. Fill the sample holder with powder to be investigated.

4. Run the samples at 3-35° on the XRD machine.

Procedure b:

1. Place approximately two teaspoons of drilled cuttings into a glass tube, wash out all the dust with distilled water. Fill the tubes 3/4 full with distilled water and plug them with rubber stoppers. Place the tubes into the shaker for 5-6 hrs.

2. Let the particles settle for 2-3 hrs. (for large particles to deposit). Pipette a few ml from each tube and place 3-4 drops on a labelled glass plate, let them dry overnight in a desiccator containing $CaCl_2$ to maintain constant humidity.

3. Make a duplicate of each sample and place the duplicates in a desiccator containing glycol solution, store for 24 hrs at room temperature.

4. Run samples (and duplicates) from 2-17° on the XRD machine.

5. Place samples (not duplicates) on asbestos plate, label separately and place them in preheated oven 550-600°C, heat for one hr. (oven temperature must not exceed 600°C) cool the sample reasonably.

6. Run these samples from 2-17° on the XRD machine.

TABLE: X-ray identification of clay minerals in samples from well OW-716

Depth (m)	Treated with $CaCl_2$ lines d Å	Glycol saturated lines d Å	Heated, 550-600°C lines d Å	Probable minerals
308-310	14.01b, 6.50			Clays?
348-350	15.49, 9.93, 8.53	16.98, 10.15	10.04, 10.15	Smectite, illite
418-420	17.65b, 6.50?	16.58b	no peak	Clays?
438-440	16.66b	17.65b	23.98, 16.35b	Mixed layers clays
518-520	18.09, 14.48, 7.62, 7.13	17.31, 13.18, 7.13	14.48, 7.49	Chlorites, swelling chlorites
558-560	14.24, 7.07	14.47, 10.15, 8.58, 7.13	18.01b, 10.01, 7.49, 16.98b	Chlorites
628-630	7.64, 7.19, 6.60	(18.79-13.18) 7.13	18.79, 13.18	Chlorites?, swelling chl.
754-756	14.02, 10.18, 7.13, 4.70	14.48, 9.93, 7.13	14.48, 9.99, 7.89	Chlorites illites
938-940	14.48, 7.13	14.48, 7.13	14.47, 7.56	Chlorites
1058-1060	14.24, 7.13	14.48, 7.13	14.97, 7.50	Chlorites
1180-1190	14.24, 7.08	14.02, 7.08	15.77, 7.56	Chlorites
1358-1360	14.48, 12.10, 7.13	23.86, 14.48 7.13	14.48b, 7.44	Chlorites
1418-1420	14.02, 10.04, 7.13	14.19, 10.04 7.13	14.48, 10.02, 7.43	Chlorites, illites
1578-1580	14.02, 11.94, 10.15, 9.95, 7.13	14.19, 11.94, 9.93, 10.13, 7.13	12.27, 10.01, 7.43	Chlorites, illites
1878-1880	14.02, 10.13, 8.50*, 7.13	14.02, 10.11, 8.50*, 7.13	14.02, 10.04, 8.84, 8.50*	Chlorites, illites, amphiboles*
1918-1920	14.02, 7.13	14.02, 7.13	7.13, 14.47	Chlorites
2028-2030	14.02, 10.04, 7.13	14.02, 10.04, 7.13	12.10, 10.04, 7.13	Chlorites, illites
2158-2160	10.04, 7.13	10.04, 7.13	10.04	Chlorites?, illites
2240-2242	14.02, 10.04 7.13	14.02, 10.04, 7.13	14.02, 7.37, 7.13	Chlorites, illites

APPENDIX IV: Procedure for studying fluid inclusions

Fluid inclusions

The detailed procedure for the preparation of fluid inclusion and the criteria used is described below in detail:

Procedure for preparation of fluid inclusion thin sections

The procedure which was used in the preparation of the thin sections for the study of the fluid inclusions, is systematically described below in the successive steps followed. Three Quartz crystals were picked randomly from the drilled cuttings at a depth of 350 metres and the other two from depths of between 2258-2260 metres. Any problems whatsoever that might have been encountered shall be discussed or detailed out in the text.

1. Mount the samples or the crystals on a clean thin section slide glass using Canada Balsam or any other available mounting media.
2. Using Grit 600 (Silicon Carbide Powder) polish the specimen to about 0.1 mm thickness.
3. Wash the specimen on the polishing cloth and spray (aerosol spray) the specimen in two stages viz: with the 6 micron and secondly with 1/4 micron sprays, to polish the surface.
4. Heat the specimen on a hot electric plate to about 120°C, to dissolve the mounting medium, turn the specimen onto the other side and repeat the same procedure as before.
5. Using the thin section microscope, check for the right thickness, then, try and determine the probable cleavage planes of the fluid inclusions in the specimen, their orientation, thickness and respective positions.
6. If the results are satisfactory, then wash the thin section(s) in acetone, in order to get the crystals off the slide and also to clean it from any possible impurities.
7. Now the sample is ready to be mounted on the heating stage microscope for measurements.

Crystals growing in a fluid medium trap minute quantities of the fluid as inclusions in the crystal structure. From these inclusions the temperatures, pressure, density and composition of the fluid at the time of entrapment and subsequent modifications may be determined. The study of fluid inclusions is thoroughly presented by Roedder (1984).

In the course of carrying out this exercise, a number of setbacks were encountered which limited the exhaustive and more or less conclusive laboratory exercise to be performed (as discussed under subtopic: Selection of samples and difficulty of precise depth) hence, limiting the author to only one method of determining Homogenization Temperature (T_h) of the inclusions.

The study of the fluid inclusions here is discussed systematically, under the following subtopics:

1. Method(s) of analyses i.e temperature of freezing or melting (T_m) and temperature of homogenization (T_h), and their application in the study of primary, secondary or pseudo-secondary fluid inclusions.
2. Selection of samples and the difficulty in ascertaining the depths from which these samples were picked.
3. Measurements of the fluid inclusions.
4. Conclusions.

Method of analyses

The methodology applied to the study of the fluid inclusions depends upon the temperatures that have to be determined, thus, whether one is to determine homogenization temperature (T_h) or the melting temperature (T_m) of the fluid inclusions.

In the following text the author wishes to detail the method of study in the course of analyses. The homogenization temperature (T_h) method was preferred due to time limitation. Much of the published fluid inclusion studies deal with determination of temperature of trapping (T_t also known as "temperature of formation"). These determinations are normally made using the homogenization method by watching the inclusion phases homogenize while heating under the microscope.

Homogenization method as commonly used on the inclusions of liquid plus vapour is based on a number of assumptions (Roedder, 1984).

1. The fluid trapped when the inclusion was sealed was a single homogenous phase: A single inclusion does not give adequate information but where many inclusions show apparently the same phase ratio, then we presume that a homogenous fluid was trapped. A distinction should be made before thermometric data is interpreted, as to whether a homogenous or heterogenous fluid was trapped.

2. The cavity in which the fluid is trapped does not change in volume after sealing, although change does occur; several mechanisms include crystallization on the walls or in the fluid itself, thermal contraction of the host mineral on cooling and dilational change from external or internal pressure. It is assumed that such a mechanism can cause gross inaccuracies in T_h (Roedder, 1984).

3. Nothing is added or lost from the inclusion after sealing: Though leakage rarely occurs, it could be common in the rocks that have been crushed or otherwise deformed or in which very high pressure gradients have been set up, i.e near surface dyke(s).

4. Pressure effect is insignificant: Pressure is of concern only in that it controls the fluid density; hence corrections are necessary to add to T_h to get T_t if a fluid inclusion is trapped from a homogenous fluid along the boiling curve.

5. The origin of the inclusion is known: Inclusions only give information about their environments of formation, i.e primary ones indicate enclosing mineral conditions, whereas secondary ones later conditions.

From the above assumptions, it is evident enough that every single one of these assumptions has its own limitations.

Before any measurements were carried out, it was logical to consider upon what basis or criteria the exercise was supposed to be based. Considering procedure number 5 of thin section preparation, mentioned earlier on, the nature of the inclusions tends to show much more of a secondary origin than the other probable origins. Hence, it is noteworthy to discuss the criteria related to the secondary origin as outlined here below:

Empirical criteria for the secondary origin of fluid inclusions

1. Occurrence as planar groups outlining healed fractures(cleavage or otherwise) that come to the surface of crystal (note that movement of inclusions during recrystallization can cause dispersion.

2. Very thin and flat; process of necking down (but note that necking down may occur either during temperature decline or isothermally, in primary, secondary, or pseudosecondary inclusions).

3. Occurrence within a plane that differs compositionally from the rest of the crystal, e.g., in the cathodoluminescence.

4. Primary inclusions with filling representative of secondary conditions:

    A. Located on (the) secondary healed fracture; hence, presumably refilled with later fluids.

    B. Decrepitated and reheeled after exposure to higher temperatures or lower external pressures than at time of trapping; new filling may have original composition but lower density.

5. Temperature of homogenization (T_h) far below that of adjacent presumed primary inclusions in the same growth zone (on the basis that low-T_h early primaries would be decrepitated by a much hotter later stage of growth; note, however, that late stage primaries and pseudosecondaries can be at any lower temperature, and that barring decrepitation, primary inclusions can show an increase in T_h with the stage of formation).