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BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL OW-30, OLKARIA GEOTHERMAL FIELD, KENYA

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ABSTRACT

This report presents data from the geological well logging of OW-30 in the East producing field, Olkaria. Sampling of the cuttings was fairly good as most of the drilled depth of 1596 m had good circulation returns except for the depth intervals 50-196, 202-268, 840-920, and 1122-1354 m where total circulation losses were experienced. The rock types penetrated include pyroclastics, tuffs, rhyolites, trachytes and basalts. The upper part of the well is mainly tuffs and rhyolitic lava flows blanketed by loose unconsolidated pyroclastics. Basaltic to intermediate lavas with tuff intercalations make up most of the well, with trachytes dominating at deeper levels. Hydrothermal alteration mineral assemblages indicate a high temperature area, with certain depths showing evidence of cooling probably due to incursion of cold fluids. Four hydrothermal alteration zones are present in this well and are represented by the first appearance of the index minerals representing each zone. They are the smectite-zeolite, the mixed-layer clays, the illite-chlorite and the chlorite-epidote zones representing temperatures less than 200, 200-230, 230-250, and over 250°C, respectively. Appearance of garnet at 1354 m and disappearance of calcite at 1410 m indicates a temperature of over 280°C. Completion and temperature recovery tests show major permeability at around 600-700, 900-1050 and 1300-1400 m, and probably at the well bottom.

1. INTRODUCTION

1.1 General information

The Olkaria geothermal field is situated southwest of Lake Naivasha in the eastern arm of the African Rift Valley in Kenya (Figure 1). The field is divided into small fields namely East, Northeast, West, and Central Olkaria all relative to the position of the Olkaria volcanic centre. The Olkaria East field is fully developed with a 45 MW_e power station in operation, the Northeast field is in the final stage of development awaiting the construction of a 64 MW_e power plant while the other fields are still under exploration.

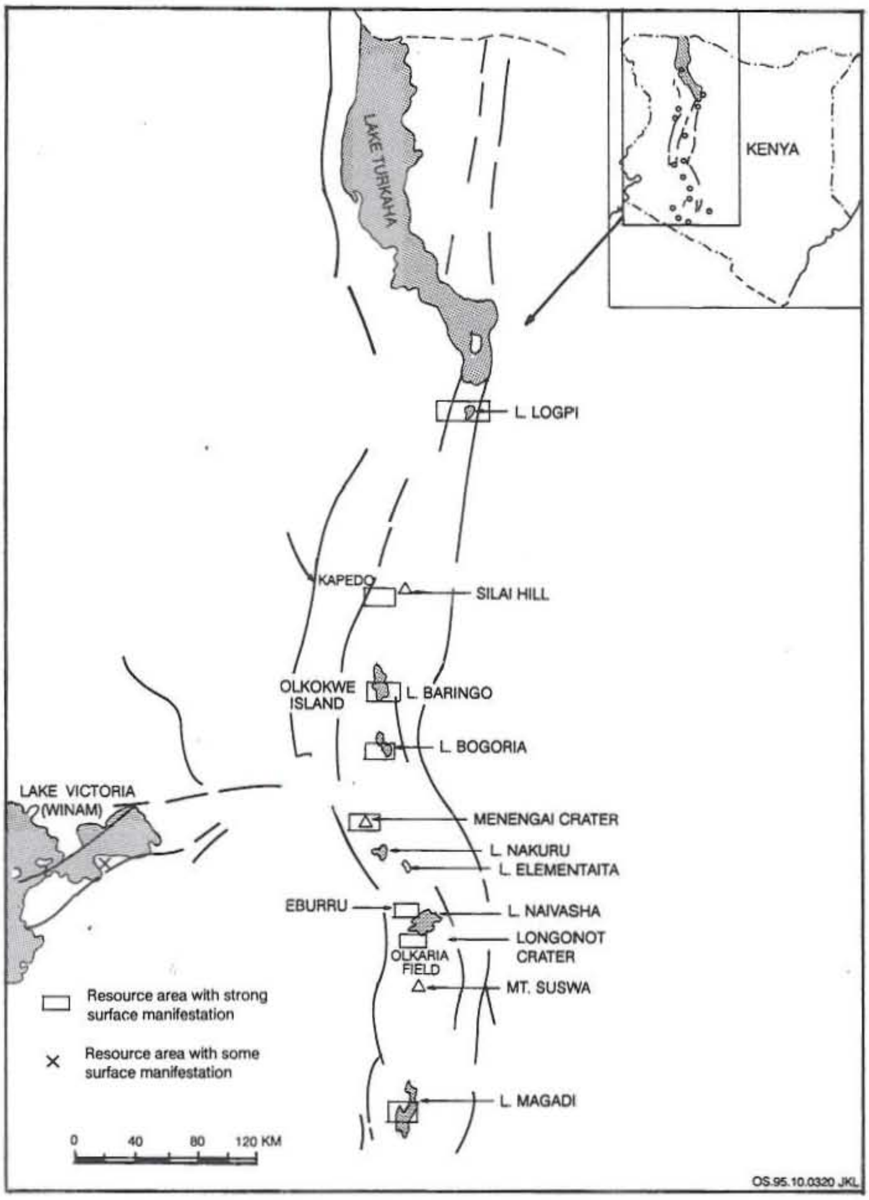

FIGURE 1: Map showing the location of the Olkaria geothermal field within the Rift Valley in Kenya

1.2 Geological setting

Olkaria geothermal field is associated with the Olkaria volcanic centre which is bound by a northeasterly trending belt of volcanism and substantial normal faulting along the floor of the western Rift Valley. Field mapping by Naylor (1972) identified Olkaria as a remnant of an old caldera complex, subsequently cut by N-S normal rift faulting that produced the loci for later eruptions of rhyolitic and pumiceous domes now exposed in Olnjorowa gorge. His proposal was supported by Mertz and McLellan-Virkir (1979) who reviewed the structure of Olkaria. However, the trace of the western margin and the geological vents setting of the rows of young volcanic centre near Olkaria peak was thought to be somewhat different from the earlier proposal by Naylor. The eastern part of the field has concentrically aligned vents of comendites marking the ring structure but in the western margin was taken to be represented by a series of low hills of arcuate shape enclosing flat depressions.

The area is generally covered by a young Quaternary ejecta believed to have originated from Longonot and Suswa volcanoes. Altered and warm grounds are extensive in this area, with the present manifestations showing a close association with the dominant N-S structures in Olkaria central and ENE-WSW Olkaria fault zone. Figure 2 shows the geological structures and N-S belt of peralkaline volcanic rocks around the area. The main rock units are tuffs, rhyolites and basalts which act as the cap rock for the reservoir and volcanic lavas of rhyolites, trachytes and tuffs which form the reservoir rock. Volcanic sequences in the Rift Valley overlying the crystalline basement are about 3.5 km thick based on seismic velocities by Hamilton et al. 1972 compared with data from Lake Bogoria. According to Healy, 1972, Basaltic rocks dominate below 1.7 km at Olkaria, whereas acid tuffs and lavas dominate above.

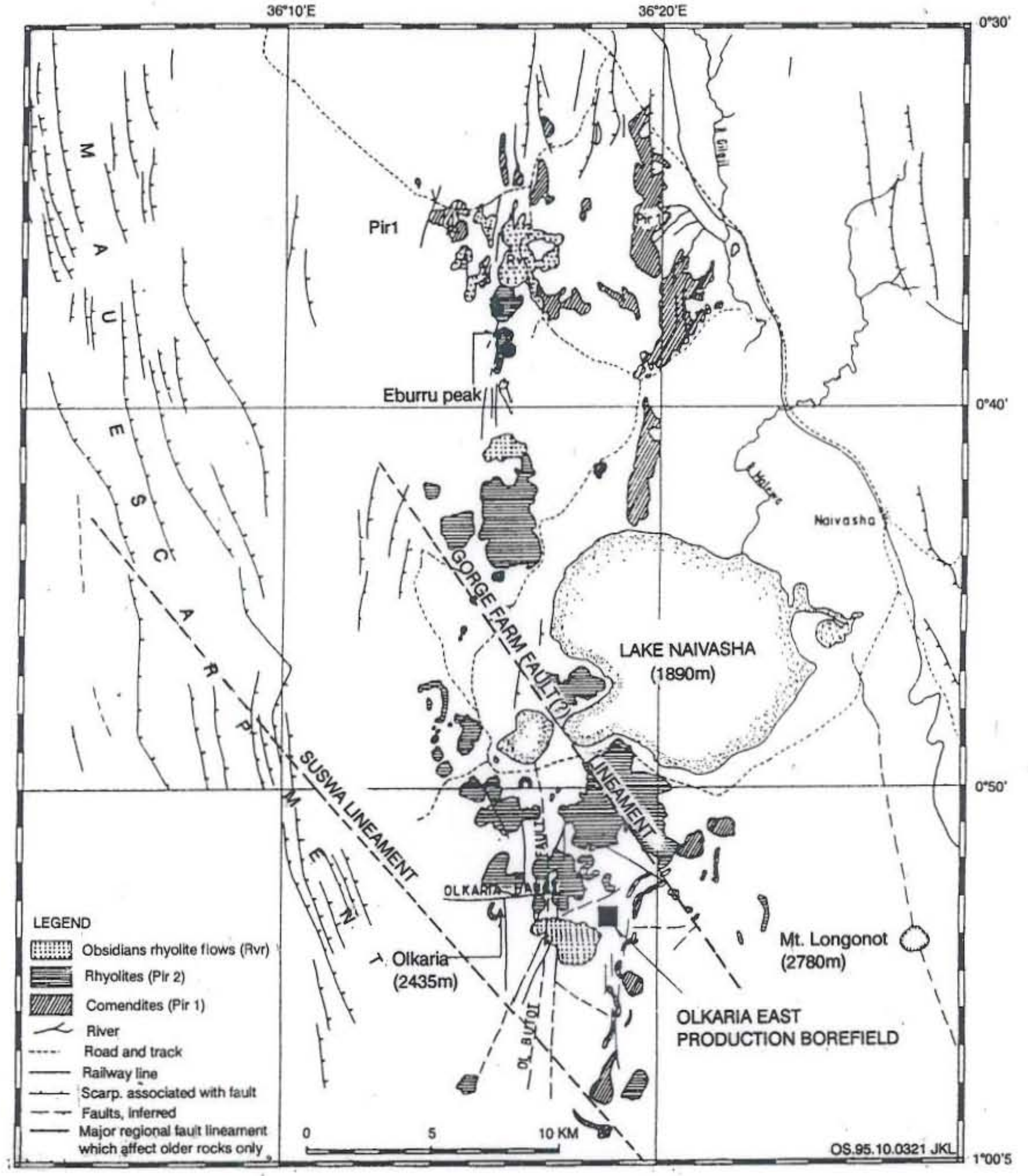

FIGURE 2: Geological structure and the N-S belt of peralkaline volcanic rocks around Lake Naivasha area

1.3 Well OW-30

Well OW-30 was the 30th well to be drilled in the East production field (Figure 3). The well was drilled to a depth of 1596 m (362.6 m a.s.l.) and is situated at 9902587.19 N, 200488.24 E at an elevation of 1959 m a.s.l. The surface, the anchor and the production casings were set at 50.2, 245, and 602 m respectively. This well together with about five others was drilled as a make-up well to gather for the steam decline in the already connected wells to maintain the maximum rated capacity of 45 MW_e in the plant.

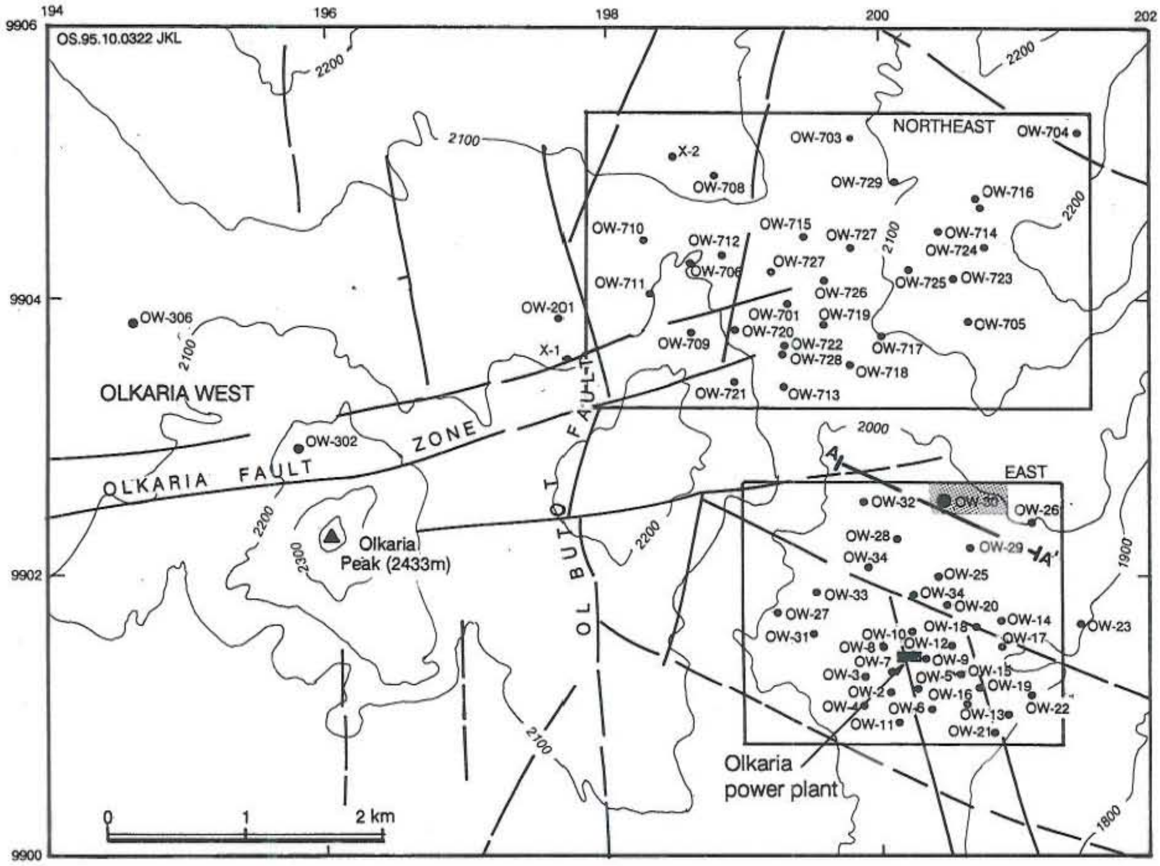

FIGURE 3: Location of well OW-30 in the Olkaria East production field; location of lithological cross-section A-A' (Figure 8) is also shown

2. STRATIGRAPHY

The rocks encountered in this well are mainly lavas. Pyroclastics occur at shallow depths, while basalts, trachytes and rhyolites often with tuff intercalations usually dominate below, to 1122 m. Trachytes with thin tuff layers at 1410 and 1550 m make up the rest of the well. A detailed petrography of the cuttings from the well is outlined in Appendix I. Below is a brief description of each of the units encountered.

Pyroclastics
Loose unconsolidated pyroclastics form the upper 44 m of the well. They are yellowish to brown glassy pumiceous rock fragments with hair like fibres of glass forming discontinuous laminations probably caused by extreme compaction and welding of the original pumiceous fragments. The tuffaceous nature of the fragments is shown by the erratic and disconnected orientation of the flow lines. The rock unit shows slight alteration to clays and some particles exhibit evidence of oxidation. The top few metres are made up mainly of superficial sediments.

Tuffs
Tuffs are encountered in most parts of this well occurring as thin layers intercalating other rock units, except at 638-840 m where they occur in a thick formation. They occur in two varieties; the vitric and the lithic tuffs are variable in colour from purplish grey to greenish yellow depending on the composition of the rock. The former type is glassy and pumiceous with secondary silica infilling the pumiceous

vesicles whereas the latter is mainly made up of lithics of basaltic and trachytic lavas cemented in ashy matrix with calcite deposition. Hydrothermally altered tuffs are bleached to various shades of light grey to almost white or light greenish yellow. Alteration in this rock type varies with depth.

Rhyolites
They are white, brown to pale grey in colour. They are first penetrated at 44 m and occur alternating with other rocks to 1122 m. The shallow rhyolites are more glassy, have low phenocryst content and show low angle flow banding. The deeper ones are felsitic to porphyritic, quartz forming small phenocrysts with k-feldspars. The rock type in general is not affected much by hydrothermal alteration and shows fresh phenocrysts of andesine, quartz as well as magnetite set in hyptocrystalline groundmass.

Trachytes
Trachytes are less abundant lava flows at shallow depth, but form thick formations in the deeper parts of the well. The rock is grey to brown, strongly porphyritic with large phenocrysts of sanidine set in fine-grained groundmass consisting of closely packed microlites, lath like in shape exhibiting flow structure. The sanidines are well formed showing good crystal outlines appearing somewhat elongated rectangles and nearly all showing simple twining. The rock shows a varying degree of alteration at various depths. Pyroxenes and amphiboles are the mafics present in the rock unit.

Basalts
Basalts are the least common rocks in this well, occurring at 480-576 m with a thin tuff intercalation at 530 m. The rock is dark grey to greenish grey depending on the intensity of alteration. It is porphyritic with plagioclase feldspars and olivines, the groundmass consisting of tiny lathlike plagioclase feldspars. Vesicles are rare with calcite, sometimes epidote and clays infilling the vugs. Most olivine phenocrysts show slight alteration along the cracks in the mineral, but some are completely altered such that its presence is only revealed by the outline of the alteration product.

3. HYDROTHERMAL ALTERATION

3.1 Analytical methods

The analyses of hydrothermal alteration minerals is done in three ways; by use of a stereo or binocular microscope, petrographic microscope and the X-ray diffractometer. The initial identification is by use of stereo or binocular microscope usually at the drill site. Cuttings are collected at an interval of 2 m during drilling and each sample is analysed. The rock type, some alteration minerals and their abundance, and the stratigraphic boundary is identified by this method. The petrographic microscope is used to confirm the rock type and the hydrothermal minerals, additional minerals not observed by the binoculars and to study the mineralogical evolution in the rock. The X-ray diffractometer is important in identifying individual minerals particularly clays and zeolites. Procedures for preparing samples for XRD analysis are shown in Appendix II and the XRD results for OW-30 in Appendix III.

3.2 Alteration of primary minerals

Most of the primary rock forming minerals are unstable in a geothermal environment and are therefore susceptible to replacement by new minerals that are either stable or at least metastable under the new conditions. Feldspars, pyroxenes, and the iron oxides show a greater resistance to alteration compared to glass and olivine. Albite, epidote, sphene and prehnite are observed to partly replace plagioclase below 540 m. Glass shows little alteration at shallow depths but is completely altered down the well whereas quartz apparently shows no alteration at all. Olivine shows alteration to oxides. It occurs in anhedral crystals with polygonal outlines and in phenocrysts in the basalts. In most cases it is completely altered and its presence is revealed by the outline of the alteration product. Table 1 below summarizes the order of replacement of the primary minerals and their alteration products in this well.

TABLE 1: Order of replacement of primary minerals and their alteration products (mod. from Browne, 1984a)

Primary minerals	Order of replacement	Replacement products
Volcanic glass	1	Zeolites, quartz, calcite, clays
Pyroxenes, amphiboles, olivines	2	Chlorite, illite, quartz, pyrite, calcite
Ca-plagioclase	3	Calcite, albite, adularia, quartz, chlorite, illite, montmorillonite, epidote, sphene
Sanidine, orthoclase, microcline	4	Adularia
Iron oxides	5	Pyrite, sphene, secondary oxides

3.3 Distribution of hydrothermal alteration minerals

The distribution of alteration minerals and their analytical methods are shown in Figure 4. A brief description of each of the minerals is outlined below.

Calcite
Calcite is a very common alteration mineral in this well. It is encountered in trachytes at 268-332 m then in basalts and tuffs at 480-616 m and becomes abundant in the range 932-1410 m in all the rock types encountered, occurring in platy crystals and sometimes as fine aggregates. It forms at varying temperatures and hence the reason for its wide distribution. It replaces primary plagioclase usually in association with epidote as observed in trachytes at 1030 m and tuffs at 1070 m. It also fills interstices and veinlets of fractured rocks. Its disappearance below 1410 m implies a temperature in excess of 270°C (Kristmannsdóttir, 1978; Browne, 1984a) a situation valid in Icelandic wells.

Chalcedony
Chalcedony is encountered at 450 m where it occurs as a secondary mineral in spherulitic cavity linings in association with quartz. The mineral is colourless to pale brown in thin section. Its occurrence usually indicates temperatures below 180°C and above it quartz forms.

Quartz
As an alteration, quartz mostly occurs in veins and cavities. It is widespread, first seen at 268 m in a vein and again with chalcedony at 450 m and then persisting down to the bottom of the well. It occurs sometimes in association with epidote and calcite. Like the primary quartz, the hydrothermal quartz apparently shows no subsequent alteration.

Zeolite
Zeolites are observed first in tuff at 196 m and also in a trachyte at 388 m. The types found are acicular, radiating crystals, probably mesolite, scolecite or natrolite and occur in cavities associated with calcite.

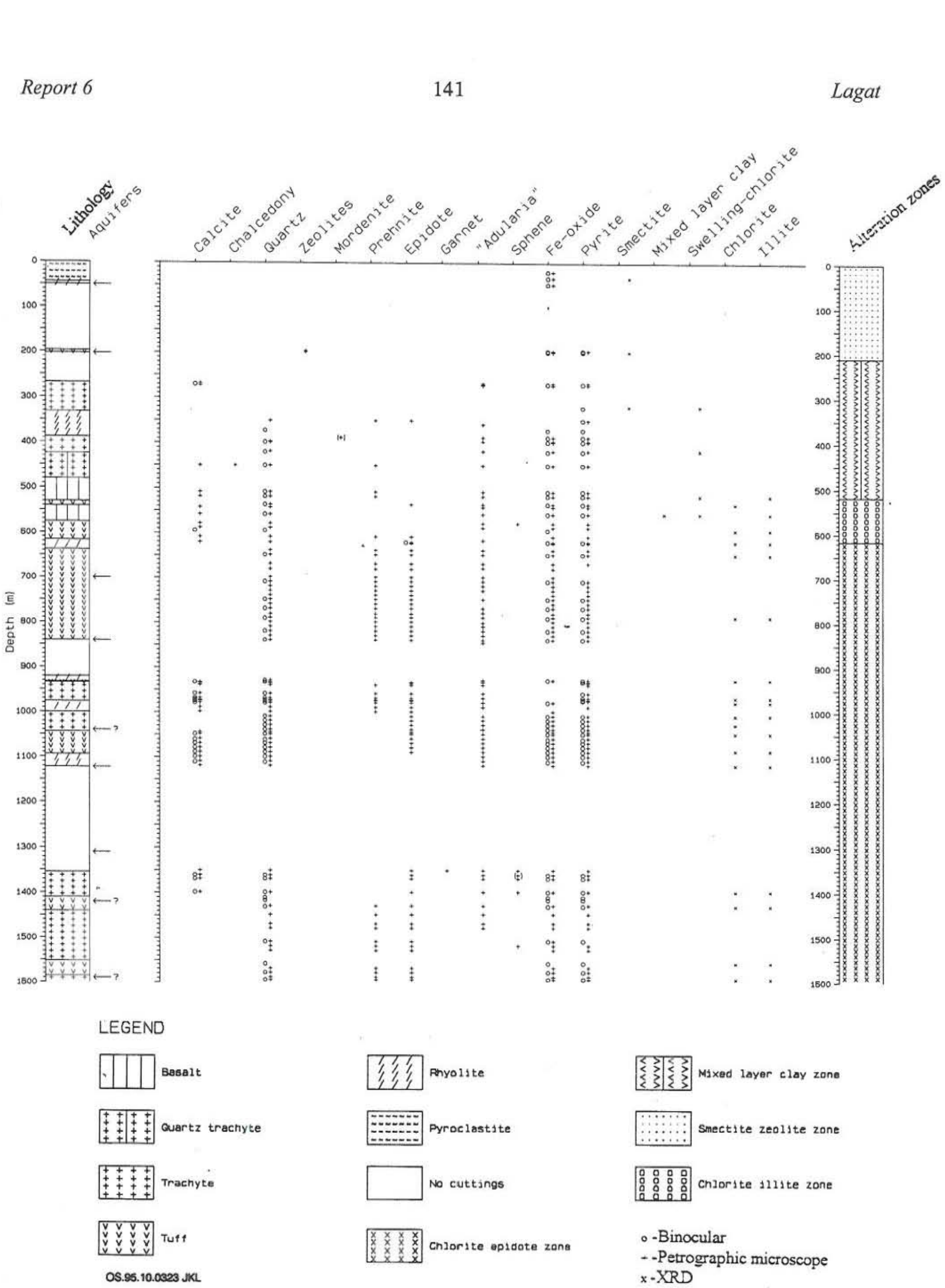

FIGURE 4: Lithology, aquifers, analytical methods and distribution of hydrothermal alteration minerals and alteration zones in well OW-30

The sensitivity of zeolites to temperatures below 110°C was effectively described from drill holes in low-enthalpy reservoirs of Iceland (Kristmannsdóttir, 1978) who reports mesolite to occur below 70°C. Therefore, probably cooling might have occurred at this depth at the time of its formation, and this could be attributed to colder groundwater.

Prehnite
The occurrence of prehnite is sporadic, first encountered at 332 m, but found down to the bottom of the well. It replaces the groundmass in basalts and trachytes, sometimes infilling veinlets usually in association with quartz. In thin section, it forms fan shaped and spherulitic aggregates showing polysynthetic twinning. Locally, it shows a "bow-tie" structure and a wavy extinction. Prehnite is usually stable at a temperature above 220°C (Browne, 1984) and Steiner (1977) puts the figure at over 200°C in Wairakei field. Its presence therefore is an indication of high temperatures.

Epidote
It is first encountered along with prehnite at 332-388 m and from 530 m to the bottom of the well, becoming abundant at 932-1000 m in association with quartz and calcite. It occurs as; a replacement mineral replacing plagioclases, an alteration product of silicic groundmass and with quartz filling vesicles and veinlets and linings of walls of fractures. It forms granular to columnar aggregates in more or less distinct elongate crystals and gives the rock a yellowish green colouration when abundant. Epidote is a mineral of intermediate alteration zone and its appearance indicates a temperature above 250°C (Browne, 1984b), though Steiner, (1977) suggests crystalline epidote forms in Wairakei geothermal field at temperatures above 235°C.

Garnet
Garnet was only observed in trachytes at 1354 m. It is extremely rare and occurs in euhedral crystals, has high refractive indices and is completely isotropic. Presence of garnet indicates a formation temperature of well over 320°C (Browne 1993). However, in Iceland, garnet normally indicates temperatures over 270°C and that temperature boundary is used there.

Sphene
It is first observed in trachytes below 1354 m occurring in clear euhedral crystals having an acute rhombic cross-section and also in irregular grains. In thin section it is almost colourless to neutral but pale yellow in cross polars (XPL). It is a product of alteration of magnetite and other opaque minerals.

Iron oxide
Oxides were observed virtually throughout the well, with intensities varying with depth. They are reddish brown in colour occurring as replacement of less stable iron oxides. Their presence in large quantities indicates that the rock may have at one time been in contact with oxygen-rich ground water.

Pyrite
Pyrite is widespread but not an abundant mineral except in a trachyte at 388-424 m where it is found in relatively large amounts. It is first observed at 196 m after the circulation loss and appears virtually down the well. It replaces magnetite, disseminated in altered groundmass and filling veinlets and lining walls of fractured rocks. It occurs as euhedral cubic crystals and sometimes in irregular grains. Where it replaces the oxides, pyrite cubes commonly enclose brownish iron oxide relics. Presence of pyrite in large quantities may indicate good permeability as was observed in the aquifers at 1040 and 1420 m respectively.

Smectite
It is observed by XRD peaks at 34 m and after the circulation loss at 198 m. In thin section, it appears brownish, has low birefringence and occurs as crystallised mass lining vesicles. It is identified by the peak occurring at 15.8 Å in constant humidity of 35%, 18.6 Å when treated with glycol and collapses to 10 Å when heated to about 550°C. It was not identified below about 400 m depth.

Mixed layer clay
This is an interstratified layer of illite-swelling chlorite and smectite-illite-chlorite occurring at about 200-600 m. It is identified in XRD by the broad peak at 14-17 Å when untreated, about 30 Å when glycolated and collapsing to 12-14 Å when oven heated. It is dark green, coarse grained and occurs as infilling vesicles. In thin section, it is a brown to yellowish mineral with weak birefringence.

Swelling chlorite
It is identified by its ability to swell when treated with glycol. It was found in samples at 320-596 m in the mixed layer clay zone. It shows a peak at 14.11 Å in the untreated sample, swells to 17.32 Å when glycolated and contracts back to 14.48 Å when oven heated at about 550°C. It was not detected below 600 m depth. Typical swelling-chlorite peaks are shown in Figure 5b.

Chlorite
It is distinguished by its conspicuous peaks at 7-7.2 Å and 14-14.5 Å in the untreated, glycolated and the oven heated samples. It was first observed at 536 m occurring as infilling and replacement of ferromagnesian minerals, and was detected in XRD down to the bottom of the well. In the binocular microscope it is greenish in colour, very fine-grained and lines vesicles whereas in thin section it appears pale greenish and shows a rather weak birefringence. A typical XRD sample for chlorite is shown in Figure 5c.

Illite
Illite was first detected by XRD at 518 m occurring with swelling-chlorite in the mixed layer clay zone, and thereafter appearing to the bottom of the well. Illite shows very distinct peaks at approximately 10 Å and does not change when treated with glycol and when heated to over 550°C. It occurs partly as a replacement of k-feldspars. Typical illite peaks are shown occurring with swelling-chlorite in Figures 5b and c.

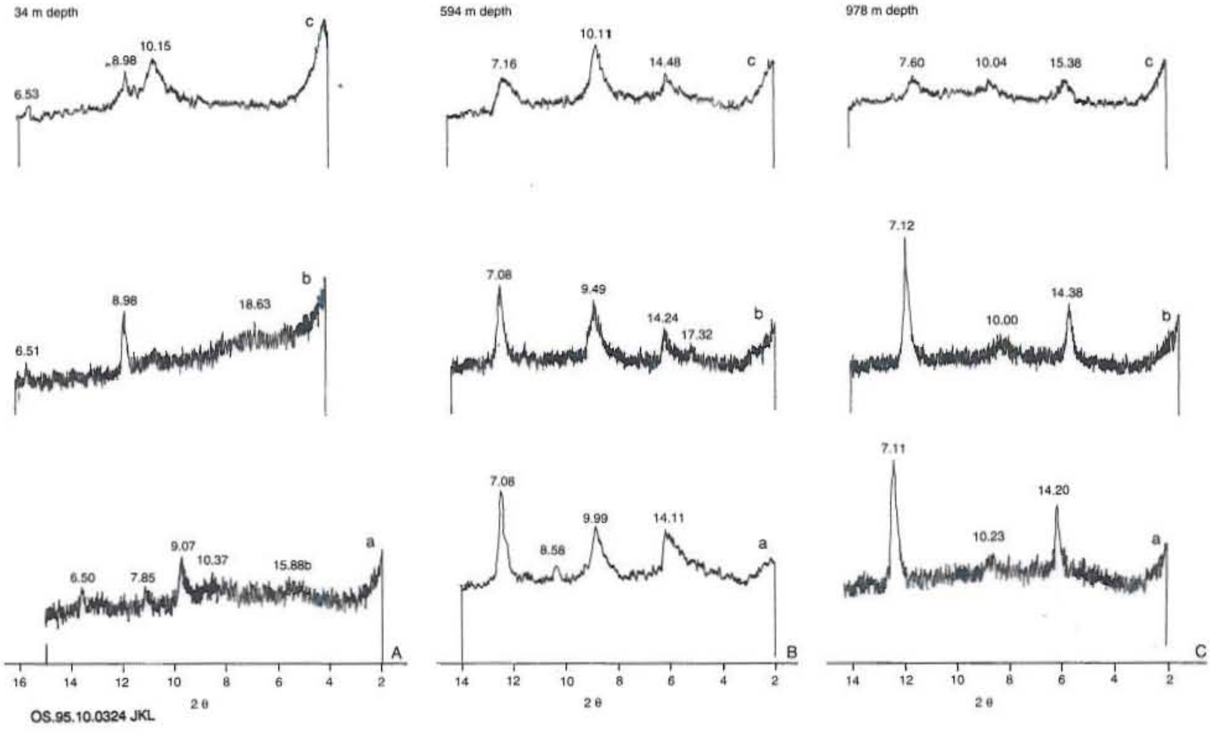

FIGURE 5: XRD characteristic patterns for clays in well OW-30; the letters A,B and C represent untreated, glycolated and oven heated analyses respectively

Adularia
It is first seen in thin section at 576 m. It occurs in pseudo-orthorhombic, is usually diamond shaped and found as a replacement of plagioclase or primary k-feldspars and occasionally in veins and cavities. Where it replaces plagioclase or primary k-feldspars, there is near isochemical transformation to an optically and structurally different phase of adularia.

3.4 Alteration minerals zonation

Hydrothermal conditions found in the reservoir could easily be inferred from a closer look at the hydrothermal mineral assemblages. Occurrence of alteration minerals, whose formation temperatures are known, are useful as geothermometers to predict formation temperatures, although some minerals may represent past conditions. In this well the hydrothermal minerals used to determine the zonations are smectite, zeolites, swelling-chlorite, mixed layer clays, chlorite, illite and epidote. Each zone is characterized by a definite assemblage of hydrothermal minerals and is defined by the first appearance of its index mineral. There are roughly four alteration zones, though there could be a possibility of one or two more zones. The zones are shown in Figure 4 and below is a brief description of each of the zones.

Smectite-zeolite zone
This zone extends from the surface of the well to about 202 m. Presence of circulation losses at 50-198 and at 202-268 m makes it difficult to determine the exact boundary of the zone. This zone is marked by the presence of smectite and zeolites and the temperature range is less than 200°C.

Mixed layer clays zone
It is made up of an assemblage of swelling-chlorite, chlorite and mixed layer clays. It ranges from 202 to 518 m when illite starts to appear, and characterises a temperature interval of about 200-230°C. In Icelandic geothermal fields mixed layer clays are present where measured temperatures are in the range of 200-230°C (Kristmannsdóttir, 1978).

Illite-chlorite zone
This zone is marked by the appearance of illite and chlorite and ranges from 518 to 616 m. It represents a temperature range of 230-250°C. Illites and chlorites are found to occur in a wide temperature range, however, chlorites show a distinct temperature range in basalts. Chlorite occurs in basalts in Icelandic fields only above 230°C (Kristmannsdóttir, 1978) and this seems to be the case in Olkaria though in dominantly intermediate to acid rocks.

Chlorite-epidote zone
It is defined by the appearance of both epidote and chlorite at 616 m, and persists to the bottom of the well. It represents a temperature of over 250°C. The appearance of garnet at 1354 m, and the disappearance of calcite at 1410 m reveals a temperature of well over 280°C.

3.5 Correlation of hydrothermal alteration temperatures and measured temperatures

Figure 6 is a plot of the alteration temperatures, calculated boiling temperatures and the measured temperatures (assumed to be close to formation temperature after 95 days heating). The top 200 m are represented by smectites and zeolites and this shows a formation temperature of less than 180°C. Slight cooling might have occurred at around 388 m due to the presence of mordenite with formation temperatures of about 50-150°C. Drastic increase in temperature with depth at 400-600 m, as shown by the temperature profile run after 1 hours heating conforms well with the hydrothermal mineralogy within the same depth. Higher formation temperatures of about 200-260°C represented by swelling chlorite, chlorite and epidote at 488-1354 m in the mixed layer clays, the illite-chlorite and part of the chlorite-epidote zone could be seen. Presence of garnet at 1354 m and the disappearance of calcite at 1410 m indicates formation temperatures of well over 280°C.

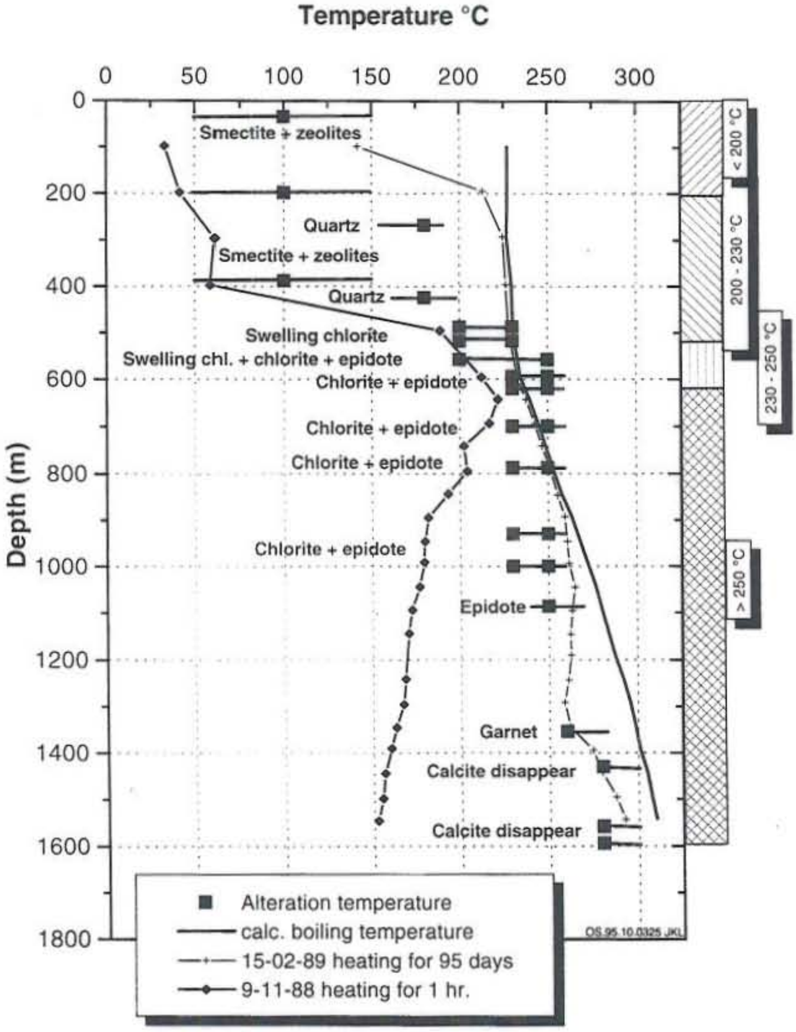

FIGURE 6: Correlation of hydrothermal alteration, measured and calculated temperatures in well OW-30

3.6 Veins

Veinlets in well OW-30 vary in width from microscopic to several millimetres and are usually common near fissure zones. The intensity of veining varies with depth. They are most common in basalts and trachytes and less common in rhyolites and tuffs. The common vein filling minerals are calcite, quartz, pyrite, epidote and clays but prehnite is also found sporadically. Vein filling minerals are temperature dependent and more often two or more minerals infill the same vein. Calcite, quartz and occasionally epidote are the most common vein filling minerals found virtually throughout the well.

3.7 Mineralogical evolution

Evidence from vein forming minerals crosscutting and depositional sequences in vesicles give an indication of the mineralogical evolution in a well. In this well vesicle and vein fillings were, however, extremely rare making it quite difficult to give a generalised mineralogical evolution. However, from the veins and vesicles observed, calcite and quartz seem to be the latest to be deposited followed by clays in the top 500 m. Below 500 m, quartz, calcite and epidote seem to be the latest phase preceded by clays.

4. AQUIFERS

Figure 7 shows the downhole temperature profiles, abundance of selected hydrothermal alteration minerals and the position of aquifers in well OW-30. From the above data, a total of 9 aquifers could be located and are labelled aquifer 1 to aquifer 9 from the top to the bottom of the well. The position of aquifers marked by total circulation losses may not be accurate since the opening up of a well can occur

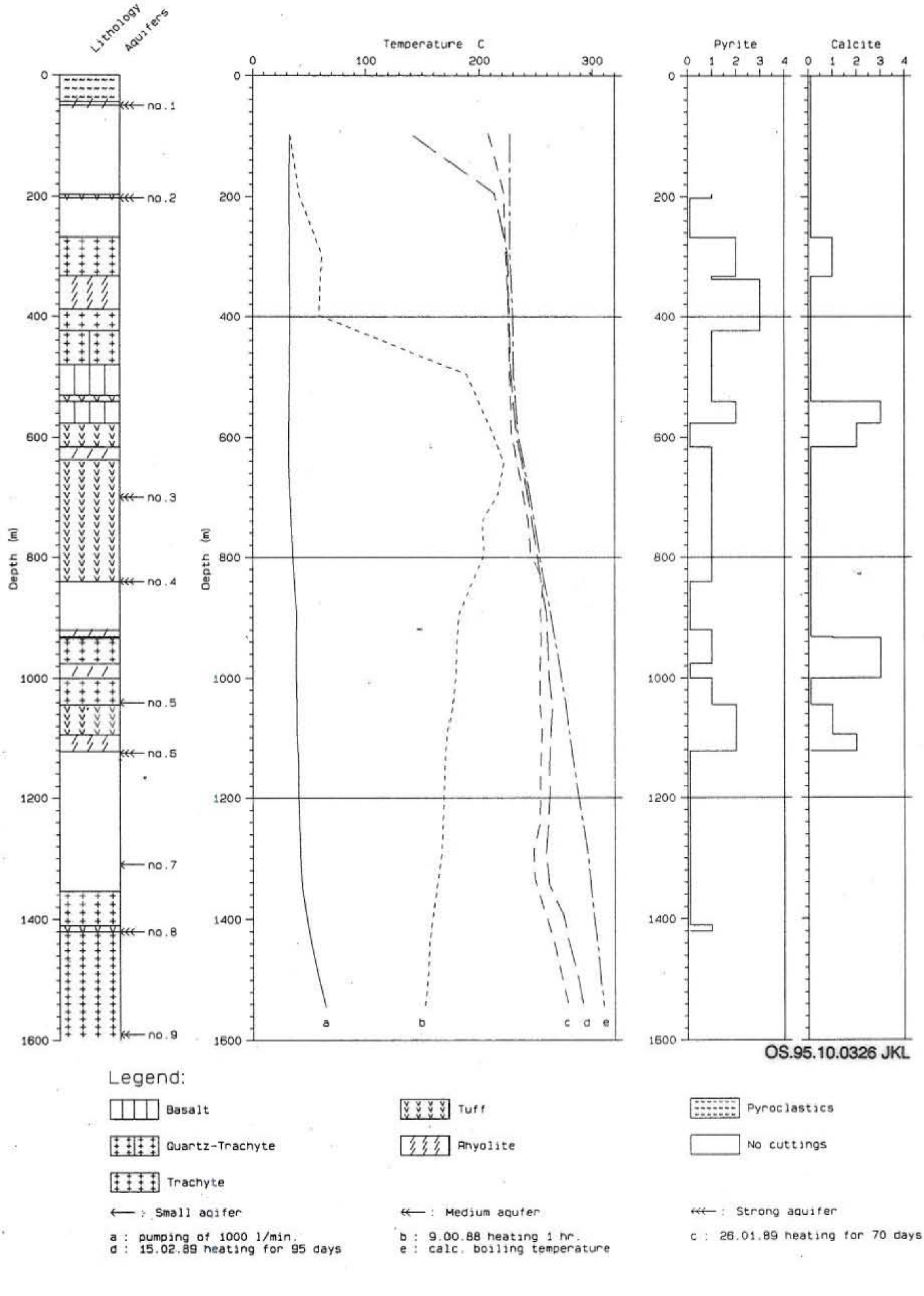

FIGURE 7: Stratigraphy, temperature profiles, selected hydrothermal alteration minerals and position of aquifers in well OJ-30; the numbers 0, 1, 2, 3 and 4 represent relative abundance of alteration minerals

any time and the loss could be at a different depth and not necessarily the particular depth the loss is experienced. Those marked by temperature profiles are relatively accurate but may have an error of 10 m.

- **Aquifers 1 and 2** were recorded at 50 and 202 m and are marked by total loss of circulation. The temperature profiles run after several days heating showed a relative increase in temperature with depth affirming flow of water in the reservoir.

- **Aquifer 3** is located at around 700 m in a tuffaceous rock and is shown by the temperature profiles run while pumping 1000 l/min., and by a temperature low in the log, run after heating for one hour. The profile run while pumping showed a break in the temperature curve increase in temperature with depth while a run after 1 hour´s heating showed some cooling around that depth revealing that there had been a flow of cooler circulating water into the aquifer.

- **Aquifer 4** is at 840 m depth and is also marked by a loss in circulation.

- **Aquifer 5** was recorded at around 1040 m in the boundary between a trachytic and tuffaceous formations and may be related to that stratigraphic boundary. An increase in abundance of pyrite deposition below the aquifer was also observed. Alteration of feldspar phenocrysts showed some relation to the location of the aquifer; intense alteration at the aquifer and a gradual decrease away from it.

- **Aquifer 6** is located at 1122 m and is also marked by a loss of circulation.

- **Aquifer 7** is in a circulation loss zone and was recorded at around 1310 m. It is marked by a break in the temperature curve where a drastic increase in temperature with depth occurs.

- **Aquifer 8** was recorded at around 1420 m in a tuff formation, close to the stratigraphic boundary with trachyte. An increase in pyrite deposition was noted in this aquifer. Aquifers 7 and 8 are perhaps the major aquifers in this well.

- **Aquifer 9** was recorded at the well bottom at around 1590 m, close to the boundary between the tuff and the trachyte. This was determined by the rapid heating up of the well at that depth as shown by the temperature profile curves. From the above observations it can be inferred that some relationship exists between the aquifers and the stratigraphic boundaries, alteration of feldspars and pyrite deposition.

5. STRATIGRAPHIC CORRELATION WITH OTHER WELLS

An attempt was made to correlate the stratigraphy of OW-30 with its neighbouring wells OW-29 and OW-32 along line A-A' shown in Figure 3. Figure 8 is the stratigraphic cross-section in the NW-SE direction close to the wells. Loss of circulation at the top part of wells OW-29 and OW-30 hinders a clear correlation from about 50 to 250 m. A correlation between all three wells is very difficult down to about 400 m where basalts could be observed in all the three wells. A possible fault displacement of about 100 m is present between wells OW-30 and OW-32 and this may be attributed to the NNW-SSE tectonic line observed on the structural map passing between the two wells. A thick tuff formation with a rhyolitic intercalation in wells OW-30 and OW-32 is observed in all three wells from about 600-940 m. At around 1000-1200 m lavas of trachytic to rhyolitic compositions with occasional tuff intercalations dominate.

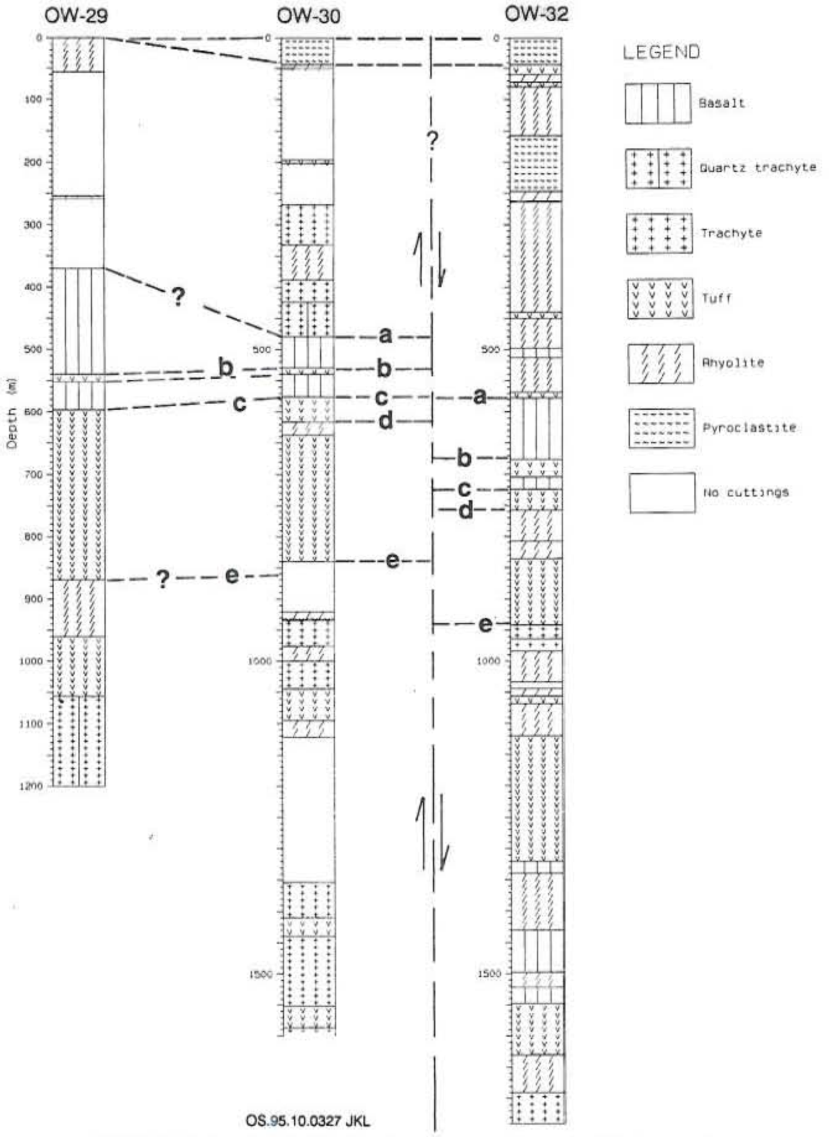

FIGURE 8: Lithological cross-section A-A' through well OW-30 and its neighbouring wells OW-29 and OW-32, location is shown in Figure 3

6. DISCUSSION

Total circulation loss and an absence of marker units that are distinctive and widespread made it quite difficult to correlate the stratigraphy properly with the neighbouring wells. No clear correlation could be observed to about 480 m, where basalts could be seen in all the wells. A downthrow displacement of about 100 m shown by the basaltic unit of the same thickness appearing at 480-576 m in OW-30 and at 578-676 m in OW-32 implies that a fault may be present between OW-32 and OW-30. However, if the fault observed in the structural map passing through the Olkaria east field in roughly NNW-SSE direction is extrapolated northwards it passes between the two wells possibly indicating that the displacement is actually caused by that fault. A thick tuff layer at around 600-850 m in wells OW-29 and OW-30 is also seen to occur at around 700-940 m in OW-32 with a rhyolitic intercalation in both wells OW-30 and OW-32. The bottom part of all the wells is composed mainly of trachyte with occasionally thin tuff intercalations. A closer correlation study between the wells is, however, needed before the fault displacement can be confirmed.

Hydrothermal alteration in this well shows progressive zonation with depth. The four zones represent progressively increasing formation temperatures and can be assorted into the following zones, smectite-zeolite (0-202 m), mixed layer clays (202-518 m), illite-chlorite (518-616 m) and chlorite-epidote (616-1594 m) zones representing ≤200, 200-230, 230-250, and over 250°C respectively. All the above temperatures are obtained from various geothermal fields around the world with more or less the same hydrothermal conditions and known mineral stabilities. Smectites are stable at temperatures of about 50-170°C (Reyes, 1990), then a transitional smectite-illite state persists to about 220°C before completely being transformed into illites. Epidote appears at temperatures over 240°C, and with chlorite persisting to relatively high temperatures of over 340°C.

Only major aquifers could be located from the available data. In all, 9 aquifers could be indicated from circulation losses, temperature logs and alteration data. Alteration of primary feldspars also showed some relationship with the position of aquifers where it increased to a near complete alteration, near aquifers but remained relatively fresh away from the aquifer. A good example of this is observed in aquifer 5 where there was a gradual increase in the intensity of alteration of feldspars before the aquifer, intense to nearly complete alteration at the aquifer and a gradual decrease below the aquifer. Marked difference in alteration of cuttings (others completely altered while others are relatively fresh) recovered from the same formation, especially within the basalts implies that fluids may be flowing in a lateral flow probably along narrow channels rather than perversively through the reservoir rock. Presence of narrow veins is consistent with the above definition.

7. CONCLUSIONS

1. The lithology of OW-30 agrees fairly well with the model of east Olkaria field in which the rocks below about 150 m consist of subhorizontal intercalated rhyolite, trachyte and basalt plus occasional thin tuffs of similar composition. Below 1200 m trachytic lavas in relatively thick formations occur with relatively thin tuff intercalations.

2. Measured temperatures in the well correspond closely with the temperatures indicated by alteration mineralogy (based on hydrothermal alteration mineral temperatures from different fields around the world where their stability is known).

3. Based on temperature logs, total circulation loss and alteration mineralogy, 9 aquifers were recorded at 50, 202, 700, 840, 1040, 1122, 1310, 1420 and 1590 m respectively.

4. There are four alteration zones defined by the alteration mineral assemblages. The zones are smectite-zeolites (0-202 m), mixed layer clays (202-518 m), illite-chlorite (518-616 m) and chlorite-epidote (616-1594 m) zones representing ≤200, 200-230, 230-250, and >250°C respectively.

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APPENDIX I: DETAILED PETROGRAPHY OF CUTTINGS FROM OW-30

Numbers assigned to hydrothermal alteration minerals indicate relative abundance on the scale 1 to 4.

0-44 m **Pyroclastics.** Yellowish to light brown glassy pumiceous rock with hair-like fibres of glass (Pelee´s hair). Oxidation to rusty brown oxides observed in the glassy groundmass. The glassy material shows compacted flow texture, a characteristic of acidic flow. Dark obsidian particles also observed. Slight alteration to clays. Alteration minerals: Clays 2, Oxides 2.

44-50 m **Rhyolite.** Cream coloured highly silicious rock showing slight alteration to clays. Phenocrysts of quartz and feldspars present in the glassy groundmass. The oxides show slight oxidation to reddish brown stains. Alteration minerals: Clays 2, Oxides 1.

50-196.5 m **Loss of circulation.**

196.5-202 m **Tuff.** Yellowish to light green rock with tiny pyrite dissemination showing oxidation. The glassy part of the rock has probably fibrous zeolite crystals forming at the sides. Glass is altered to greenish clays. Alteration minerals: Clays 3, Oxides 1, Pyrite 1, Quartz 3, Zeolites (?).

202-268 m **Loss of circulation.**

268-332 m **Trachyte.** Gray fine-grained rock with large feldspar phenocrysts. The rock is partially altered to dark green clays and has tiny pyrite disseminations. Slightly oxidised. Has quartz in vesicles. Alteration minerals: Quartz 1, Calcite 1, Clays 2, Oxides 1, Pyrite 2, Quartz 2.

332-388 m **Rhyolite.** Light grey highly siliceous coarse crystalline rock. Feldspar porphyritic and the oxides show intense oxidation. Has pyrite disseminations and quartz occurs infilling veins. Low alteration intensity. Quartz and chalcedony observed in veins. Alteration minerals: Chalcedony 1, Clays 2, Epidote 2, Prehnite 1, Pyrite 1.

388-424 m **Trachyte.** Dark gray, fine-grained feldspar porphyritic cuttings. Has high pyrite content in the groundmass and some particles show strong oxidation. Microfractures with clay infilling evident. The crystals show a clear trachoid texture. Alteration minerals: Clays 2, Oxide 3, Pyrite 3, Zeolite (mordenite?).

424-480 m **Quartz trachyte.** Gray highly siliceous rock showing slight oxidation to brown colour. Quartz infilling veinlets. Slightly altered to clays and has pyrite disseminations in the silicic groundmass. Alteration minerals: Clays 2, Oxides 2, Pyrite 1, Quartz 1.

480-530 m **Basalt.** Dark grey medium grained lava rock. Has plenty of euhedral platy calcite and quartz crystals in the groundmass. Its feldspar porphyritic and the mafics show slight alteration to greenish clays. Pyrite cubes occur in the groundmass. Alteration minerals: Calcite 4, Clays 2, Oxides 2, Prehnite 1, Pyrite 1, Quartz 2.

530-540 m **Tuff.** Whitish to brown rock altered to dark green clays. The brown cuttings show intense oxidation and have tiny pyrite disseminations. The whitish cuttings are bleached, a characteristic of hydrothermal alteration. Alteration minerals: Clays 2, Epidote 1, Oxides 3, Pyrite 1, Quartz 2.

540-576 m **Basalt.** Dark grey medium grained highly oxidised cuttings. Has large feldspar phenocrysts in a glassy groundmass. The rock is fractured with veins of calcite and quartz. It is slightly altered to smectites which occur as lining in vesicles. Pyrite occur as tiny cubes while occur olivine in altered subhedral crystals. Alteration minerals: Calcite 3, Clays 3, Oxides 4, Pyrite 2, Quartz 3.

576-616 m **Tuff.** Light green to grey rock showing mild light green alteration to very fine-grained clay lining vesicles. Pyrite is disseminated on the groundmass and the mafics show brown oxidation. Quartz and calcite infilling veinlets. Alteration minerals: Calcite 2, Clays 3, Epidote 2, Oxide 1, Prehnite 1, Quartz 2.

616-638 m **Rhyolite.** Brownish grey highly silicious rock with tiny disseminations of mafic minerals showing slight oxidation. Low alteration intensity. Alteration minerals: Clays 2, Epidote 1, Oxide 2, Pyrite 1.

638-840 m **Tuff.** Grey to dirty brown fine-grained highly glassy rock with pyrite disseminations. It is highly fractured with quartz and clays infilling veins. Alteration minerals: Clays 3, Epidote 2, Oxide 3 Prehnite 1, Pyrite 1, Quartz 2.

840-920 m **Loss of circulation.**

920-932 m **Rhyolite.** Grey fine-grained rock with high silica content and large feldspar phenocrysts. The oxides show intense oxidation. Quartz in veinlets. Alteration minerals: Clays 3, Oxides 2, Pyrite 1, Quartz 3.

932-934 m **Tuff.** Light grey to green thin tuff layer showing slight alteration to clays. Quartz occurs with epidote and calcite in veins. Alteration minerals: Calcite 1, Clays 3, Epidote 2, Pyrite 1, Quartz 3.

934-976 m **Trachyte.** Grey to brown fine-grained feldspar porphyritic rock with high silica content. It is highly altered to light green clays. The mafics are highly oxidised probably related to a permeable zone where the oxides may have at some stage come in contact with oxygen rich groundwater. Calcite and quartz in veinlets, and pyrite disseminated in the groundmass. Alteration minerals: Calcite 3, Clays 4, Epidote 2, Prehnite 1, Pyrite 1, Quartz 3.

976-1000 m **Rhyolite.** Grey fine-grained highly silicious rock with oxides showing mild oxidation. The rocks show low alteration intensity and have quartz and calcite in veinlets. In thin section it shows clear spherulitic texture and intergrowth of quartz and feldspar crystals. Epidote occurs along with quartz. Alteration minerals: Calcite 3, Clays 2, Epidote 2, Oxides 2, Prehnite 1, Quartz 3.

1000-1044 m **Trachyte.** Dark grey very fine-grained rock with a relatively high silica content. The rock is altered to greenish clays and shows slight oxidation to rusty brown colour. Quartz occurs in tiny microveins whereas pyrite is disseminated in the groundmass. Alteration minerals: Clays 2, Epidote 1, Oxides 1, Pyrite 1, Quartz 3.

1044-1094 m **Tuff.** Light grey to light green rock showing mild alteration. Rusty stains, a product of oxidation is evident. It is highly glassy and has quartz, calcite and occasionally epidote in veins. Pyrite mineralization also evident. Alteration minerals: Calcite 1, Clays 3, Oxides 3, Epidote 1, Pyrite 2, Quartz 2.

1094-1122 m **Rhyolite.** Grey silicious rock with mafics exhibiting brown oxidation. Has quartz and calcite in veins. Pyrite seen replacing ferromagnesian minerals and also filling veinlets. Alteration minerals: Calcite 2, Clays 4, Oxides 2, Pyrite 2, Quartz 2.

1122-1354 m **Loss of circulation.**

1354-1410 m **Trachyte.** Grey to brown highly siliceous lava rock with large quartz phenocrysts and small feldspar laths. Mafics show brown oxidation whereas glass shows alteration to greenish clays. Epidote alteration of feldspars evident. Calcite was also observed to replace the feldspars. In thin section clear sphene crystals and small rare garnet crystals are seen. Alteration minerals: Calcite 1, Clays 2, Epidote 2, Garnet 1, Oxides 2, Pyrite 2, Sphene 2, Quartz 2.

1410-1440 m **Tuff.** Chocolate brown highly fractured thin tuff intercalation with a high degree of alteration. Alteration minerals: Clays 5, Oxides 2, Pyrite 1, Quartz 1.

1440-1550 m **Trachyte.** Grey fine-grained feldspar porphyritic rock with tiny pyrite disseminations. In thin section the rock shows large sanidine phenocrysts with tiny groundmass microlites of feldspars showing flow texture, a characteristic of trachytic texture. Epidote seen occurring with quartz mainly in veins. Alteration minerals: Clays 3, Epidote 2, Oxides 2, Prehnite 1, Pyrite 1, Quartz 2.

1550-1586 m **Tuff.** Brown tuffaceous highly altered rock. The oxides show a high degree of alteration. Alteration minerals: Clays 5, Oxides 2, Pyrite 1, Quartz 1.

1586-1596 m **Trachyte.** Grey fine-grained feldspar porphyritic rock with tiny pyrite disseminations. In thin section the rock shows large sanidine phenocrysts with tiny groundmass, microlites of feldspars showing flow texture. Epidote occurs mainly with quartz in veins. Alteration minerals: Clays 3, Epidote 2, Oxides 2, Prehnite 1, Pyrite 1, Quartz 2.

APPENDIX II: Procedure for preparing clay samples for XRD analysis

1. Into a clean test tube place approximately two teaspoonfuls of drill cuttings. Wash the dust with distilled water and fill the tube to approximately two-third, full distilled water. Place the tubes in a mechanical shaker for 6-12 hours depending on the intensity of alteration of the cuttings.

2. Allow the particles 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 approximately 10 drops on a labelled glass plate, avoiding making the film very thick. Make a duplicate of each sample and let them dry at room temperature overnight.

3. Place one sample in a desiccator containing glycol ($C_2H_6O_2$) solution and the other set in a desiccator containing hydrated calcium chloride ($CaCl_2H_2O$). Store at room temperature for at least 24 hours. Thicker samples need a longer time, at least 48 hours.

4. Run both sets of samples in the range 2-14° on the XRD machine.

5. Place one set of samples (usually the glycolated one) on an asbestos plate and insert in a pre-heated oven. Heat the samples at 500-550°C for one hour making sure the oven temperatures do **not** exceed 600°C. When samples are cool repeat procedure No. 4.

APPENDIX III: XRD results for well OW-30

Depth (m)	Untreated d (Å)	Glycolated d (Å)	Heated d (Å)	Probable minerals
34	6.50, 7.85, 9.07, 10.37, 15.88b	6.51, 8.98, 18.63b	6.53, 8.98, 10.15	Smectite
198	6.53, 8.98	6.53, 8.98, 16.67b	6.50, 8.98, 10.04	Smectite
320	6.59, 8.55, 14.52	6.51, 8.47, 14.77	6.51, 8.43	Swelling-chlorite
368	6.44, 8.47	6.53, 8.45	6.49, 8.42	Feldspars (?)
418	6.44, 7.17, 8.55, 14.15b	6.54, 7.11, 8.47, 16.98	6.41, 8.51, 13.80	Swelling-chlorite
518	7.11, 9.99, 14.48	6.49, 7.19, 10.09, 16.98	6.44, 9.99, 14.20b	Swelling-chlorite, Illite
536	6.38, 7.11, 14.62	6.37, 7.11, 14.15	6.39, 7.44, 15.12	Chlorite
558	7.22, 9.99, 14.97	7.28, 10.11, 17.05	6.53, 10.04, 14.94b	Swelling-chlorite, Illite
594	7.08, 8.58, 9.99, 14.11	7.08, 9.99, 14.24, 17.32	7.16, 10.11, 14.48	Swelling-chlorite, Illite
620	7.11, 14.15,	7.11, 14.15	10.12, 14.87	Chlorite
648	7.06, 10.16, 14.38	7.17, 10.09, 14.62	7.10, 10.22, 14.24	Illite, Chlorite
788	6.40, 7.11, 10.16	7.07, 10.06	8.50, 9.99	Illite, Chlorite
928	7.10, 10.16, 14.29	7.07, 10.09, 14.15	7.47, 10.10	Illite, Chlorite
968	7.11, 8.53, 10.13	7.11, 8.56, 13.06	10.11	Illite, Chlorite (?)
978	7.11, 10.23, 14.20	7.12, 10.06, 14.38	7.60, 10.04, 14.98	Illite, Chlorite
1008	7.11, 10.07, 14.23	7.11, 10.06, 14.24	No peak	Illite, Chlorite
1028	7.11, 14.38	7.16, 14.48	7.48	Chlorite
1048	7.11, 14.34	7.10, 14.38	7.49, 14.97	Chlorite
1086	7.11, 10.11, 14.11	7.12, 10.04, 14.24	7.66, 10.20, 15.23	Illite, Chlorite
1118	7.16, 10.11, 14.43	7.11, 10.06, 14.38	7.54, 10.11, 15.17	Illite, Chlorite
1398	7.09, 10.11, 14.15	7.11, 10.04, 14.33	7.47, 10.11, 15.12	Illite, Chlorite
1430	7.11, 10.00, 11.41, 14.24	7.13, 10.11, 11.75, 14.24	7.53, 9.99, 15.22	Illite, Chlorite
1558	7.11, 10.11, 14.43	7.13, 10.22, 14.38	7.61, 10.09, 15.33	Illite, Chlorite,
1594	7.09, 10.11, 14.43	7.10, 10.11, 14.38	7.54, 10.01	Illite, Chlorite