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Permeability Geology and Hydrothermal Alteration Mineralogy of OW-39A, Olkaria Geothermal Project, Naivasha, Kenya

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ABSTRACT

Well OW-39A is a directional well drilled to the south at azimuth of 180°and inclination of 20°to a measured depth (MD) of 3066 m adjacent to the N-S trending Ololbuttot fissure, which is a N-S trending eruptive fissure. Comprehensive binocular and petrographic analyses of cuttings from the well indicate that the lithology of the well comprises five rock units i.e. pyroclasts, rhyolites, tuffs, basalts, and trachytes and then intrusions of rhyolitic, syenitic, basaltic and granitic composition. Trachyte forms the main reservoir rock and it is the dominant rock below 900 m. These rock units host secondary hydrothermal mineral assemblages which are dependent on temperature, permeability and rock type. Mineral deposition sequences in the well show systematic evolution from low to high temperature conditions with depth, as observed from alteration minerals in veins and vesicles. Five alteration zones were identified: unaltered zone (0-134 m), zeolite- smectite-illite zone (134-578 m), chlorite-illite zone (578-748 m), epidote-chlorite-illite zone (748-896 m) and actinolite-epidote-wollastonite zone(896-3066).Appearance of epidote at 750 m and actinolite at 896 m indicate reached 250°C and 280°C temperature conditions respectively at these depths. Comparison of fluid inclusion analyses, alteration and formation temperature indicate two geothermal episodes; one of a high temperature geothermal system below 700-800 m depth and a recent second phase of cooling. Permeability is observed in the cuttings by the intensity of oxidation, veining, alteration intensity, circulation losses, presence of calcite and abundance of pyrite. Eight feed zones are identified in the well starting from 750 down to 2750 m deduced from the shape of temperature profiles, and their locations correlate with the cutting data as mentioned above. The intermediate feed zone at 1100 and the major feed zone at the 2100 m are considered the dominant ones in the well. Alteration mineral correlation with neighbouring wells of OW-37A and OW-35 suggests that the well is nearer to an up flow zone than the latter. Well OW-39A is a directional well drilled to the south at azimuth of 180°and inclination of 20°to a measured depth (MD) of 3066 m adjacent to the N-S trending Ololbuttot fissure, which is a N-S trending eruptive fissure. Comprehensive binocular and petrographic analyses of cuttings from the well indicate that the lithology of the well comprises five rock units i.e. pyroclasts, rhyolites, tuffs, basalts, and trachytes and then intrusions of rhyolitic, syenitic, basaltic and granitic composition. Trachyte forms the main reservoir rock and it is the dominant rock below 900 m. These rock units host secondary hydrothermal mineral assemblages which are dependent on temperature, permeability and rock type. Mineral deposition sequences in the well show systematic evolution from low to high temperature conditions with depth, as observed from alteration minerals in veins and vesicles. Five alteration zones were identified: unaltered zone (0-134 m), zeolite-smectite-illite zone (134-578 m), chlorite-illite zone (578-748 m), epidote-chlorite-illite zone (748-896 m) and actinolite-epidote-wollastonite zone(896-3066).Appearance of epidote at 750 m and actinolite at 896 m indicate reached 250°C and 280°C temperature conditions respectively at these depths. Comparison of fluid inclusion analyses, alteration and formation temperature indicate two geothermal episodes; one of a high temperature geothermal system below 700-800 m depth and a recent second phase of cooling. Permeability is observed in the cuttings by the intensity of oxidation, veining, alteration intensity, circulation losses, and presence of calcite and abundance of pyrite. Eight feed zones are identified in the well starting from 750 down to 2750 m deduced from the shape of temperature profiles, and their locations correlate with the cutting data as mentioned above. The intermediate feed zone at 1100 and the major feed zone at the 2100 m are considered the dominant ones in the well. Alteration mineral correlation with neighbouring wells of OW-37A and OW-35 suggests that the well is nearer to an up flow zone than the latter while the stratigraphic correlation between the wells reveal the existence of normal faults between OW-39A/OW-37A and OW-37A/OW35.

1. INTRODUCTION

The Greater Olkaria Geothermal Area (GOGA) is situated south west of Lake Naivasha in the eastern arm of the African Rift Valley in Kenya. It is bounded to the north by Eburru complex and to the east and south by the Longonot and Suswa volcanoes, respectively. Olkaria geothermal field is divided into smaller sectors namely East, Northeast, West, South, Domes and Central Olkaria all relative to the position of the Olkaria volcanic centre and for ease of development. Well OW-39A is located in the Olkaria East production field defined by UTM E 0198168, N 9901777 and an elevation of 2158 m.a.s.l. It is a directional well drilled to the south at azimuth of N180°E and inclination of 20° to a measured depth (MD) of 3066 m. The surface, anchor and production casings were set at 50.2, 292, and 750 m respectively. It was designed as a production well with the aim of tapping steam from Ololbutot fissure, which is a N-S trending eruptive fissure, and also to confirm the importance of this structure given the fact that it is associated with the most active surface manifestations in Olkaria.

2. SAMPLING AND ANALITICAL METHODS

2.1 Sampling

Samples of cuttings from well OW-39A were taken at every 2 m interval at the drill site during drilling, but in cases where the sample was too little, up to 4 m depth interval was sampled. Preliminary analysis was done at the rig site by use of a binocular microscope, to enable the geologists and drillers to understand the subsurface geological formations and conditions, which assist in applying the right drilling procedures. Representative samples of the rock units encountered in the well were then selected for detailed laboratory analysis of hydrothermal alteration minerals and fluid inclusion studies.

2.2 Analytical methods

Several methods were used to analyze the cuttings including binocular analysis of the cuttings sampled at the well, petrographic microscope analysis of thin sections, X-ray diffarction diffraction to qualitatively identify individual minerals, especially clays, and fluid inclusion analyis for determination of homogenization temperature of fluids trapped in host mineral in the rock.

3. RESULTS

3.1 Lithology

The preliminary geological logs of well OW-39A, were done at the rig site where the samples were analysed using binocular microscope and confirmed later in the laboratory using thin section analysis. The lithological column of the well is composed of unconsolidated pyroclastics forming a thin layer at the top overlying a volcanic sequence consisting of tuffs, trachytes, rhyolites, basalt, and some rhyolitic, basaltic, syenitic and granitic intrusion

3.2 Hydrothermal alteration and mineral distribution

The distribution of hydrothermal minerals (Figure 1) in well OW-39A is described below:

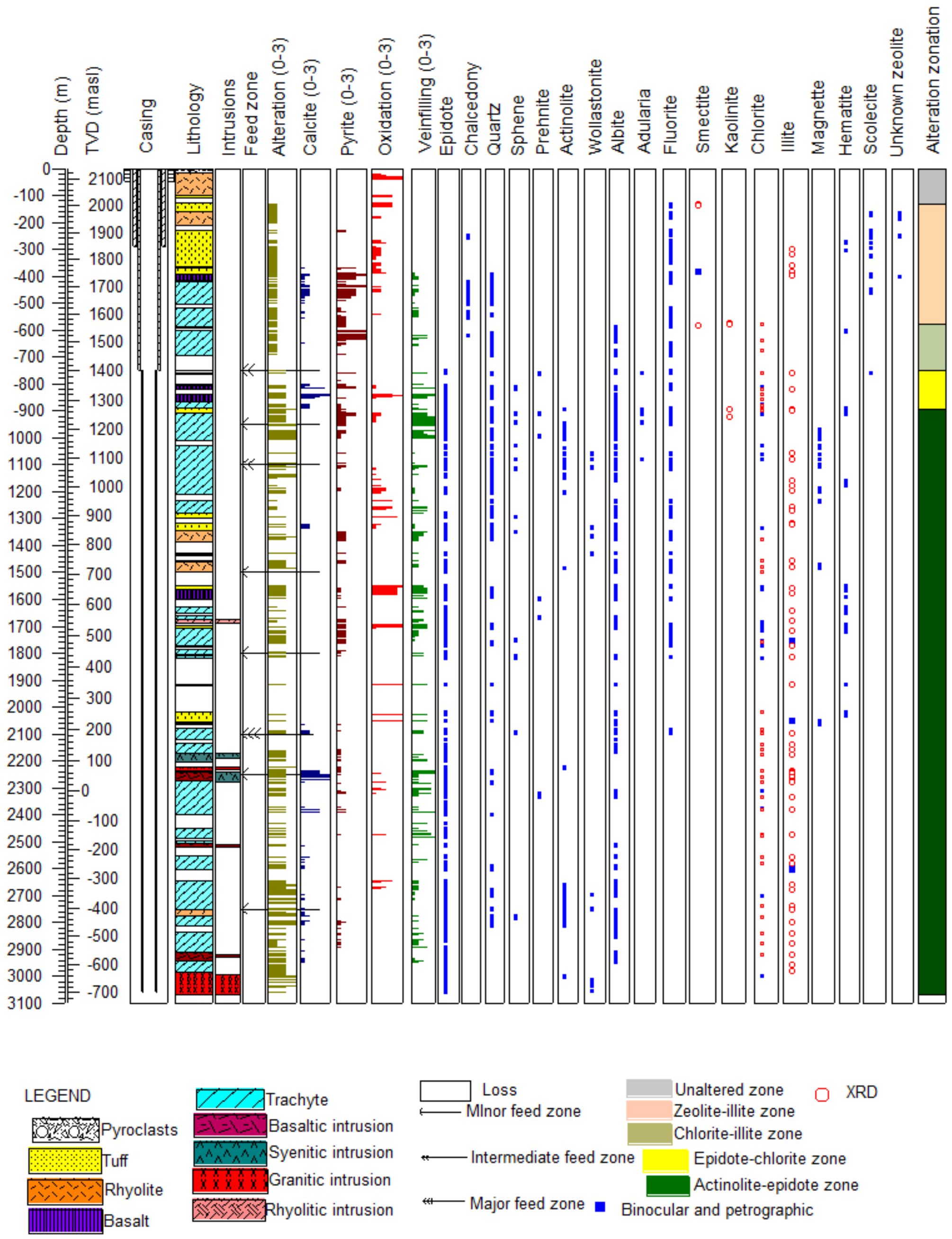

Figure 1: Stratigraphy and distribution of hydrothermal alteration mineralogy of well OW-39A

Haematite: Haematite is observed as silver-grey, brown to reddish brown in colour. Haematite can form in environments associated with colder in-flow that are more oxygen-rich by the oxidation of magnetite or iron-rich minerals in the formation. In this well hematite is observed between 274 and 1568 m and is abundant as silver grey below 900 m.

Magnetite: Magnetite is an iron oxide. The reduction of hematite to magnetite at high temperatures and pressures of 1-2 kbars in the presence of hot water causes the precipitation of stable magnetite from hydrothermal fluid in a hydrothermal system in vesicles and veins (Mathews 1976), while magnetite precipitation can also be associated with intrusions. The oxide is first observed at 968 m as black, to brown black cubic mineral filling in veins and occasionally in vesicles.

Zeolites: Zeolites are distinguished by their shape; mainly fibrous/acicular, tabular/prismatic and granular (Saemundsson and Gunnlaugsson, 2002). The zeolites were observed as white to light brown fibrous and radiating minerals. In this well zeolites occur from 134 m to 460 m. Zeolites are not common and only scolecite was identified.

Chalcedony: Chalcedony is a cryptocrystalline form of silica commonly referred to as amorphous form of silica. It is observed as a translucent white to grey, grey to greyish blue and some were in shades of brown. It is observed in trachyte, basalt and tuffs at the upper parts of the well from 250 m to a depth of about 624 m. Below this depth it becomes unstable and recrystallizes to quartz. It is a low-temperature mineral, observed in the well as filling veins and vesicles, indicating formation temperatures of ~110 to 180°C.

Quartz: Quartz first occurs from 400 m as a secondary mineral and not observed below 2812 m. It is colourless and occurs in euhedral to subhedral crystals. It has conchoidal fracturing, indistinct cleavage, and undulating extinction under the microscope which makes it easily identifiable. It occurs as infilling in both vesicles and veins. The first occurrence of quartz indicates formation temperature greater than 180°C.

Calcite: Calcite occurs intermittently from 250 m and disappears completely below 2950 m. It is abundant between 836 to 850 m in basaltic rock and 2234 to 2264 m in a fractured trachytic rock at the contact with a basaltic intrusion (2240-2276 m). Major aquifer in this well (2100 m) is associated to calcite in trachytic lava indicating that the zone is permeable. Calcite occurs as replacing feldspars and volcanic glass, and also seen as infill in vesicles, fractures and veins. It is abundant in the basaltic formations with minor occurrences in tuffs and trachyte (Browne and Ellis 1970). Relatively high carbon dioxide concentration in solution in the presence of mineral pH buffer causes calcite to form in place of other calcium alumino-silicates. Therefore, calcite formation in this well could be related to carbon dioxide (CO_2) concentrations in the reservoir fluids. Platy calcite was observed in the vesicles as composite crystals formed of numerous paper thin sub-crystals. It was common in the basaltic and trachytic layers between 392 to 750 m and also at 760 m. Its presence in the well indicates possible boiling conditions and high porosity (Browne 1984; Omenda, 1998; Muchemi, 1992; Simmons and Christenson, 1994). Calcite also disappears at temps <300°C (Simmons and Christenson, 1994).

Pyrite: Pyrite occurs as euhedral cubic crystals with shiny brassy yellow lustre. The mineral is first observed at 232 m in the well. Well-formed cubic pyrite crystals were deposited in fractures, vesicles and veins and as disseminations in the groundmass. Abundance of pyrite indicates high activity of sulphur, good permeability and past or present boiling regimes (e.g. Lagat, 1998), hence its abundance in the well was coinciding with the intermediate aquifers at 750 m and1100 m, and also minor aquifer at 950 m indicate good present past permeability and also boiling zones at these depths.

Epidote: Epidote first appears at 748 m and from then crystalline epidote is persistent to the bottom of the well. The mineral is identified from rock cuttings by its yellow to greenish yellow colours. In thin sections it is pleochroic with pale green, pale yellow and greenish brown colours exhibiting high relief with parallel extinction. It is found filling fractures, vesicles, and replacing primary plagioclase and pyroxene and, in most cases, forms mineral associations mainly with quartz, chlorite, calcite, actinolite and prehnite and sometimes pyrite. Presence of well-crystallized epidote indicates temperatures of more than 250°C (e.g. Omenda, 1990; Gylfadóttir et al., 2011).

Albite: Albite forms by the replacement of primary feldspars and plagioclase phenocrysts into hydrothermal albite. It is identified by its colour, whi ch is cloudy white or greyish white, an anisotropic mineral, showing uneven fracturing. It appears as striated, anhedral to subheral crystals. It is observed in the well from 588 m down to the bottom but albite replaces feldspars at temperatures of 180°C and above (Reyes, 2000).

Fluorite: Fluorite is a very common mineral in this well. It is first observed at 134 m and common down to 2750 m. It is identified in petrographic microscope by its very low relief, two perfect cleavages and its pale brown to colourless colour in thin section while it is isotropic under crossed nicols.

Sphene: Sphene is not a common mineral in this well. It is first encountered at 812 m and appears intermittently down to 2786 m, where it disappears completely. It occurs mainly as irregular grains but rarely as clear euhedral crystals having acute rhombic sections. The mineral forms mainly as a result of alteration of Fe-Ti–oxides.

Prehnite: Prehnite is first noted in the well at 758 m. It has a high relief and is colourless in plane polarised light which changes to green yellow and orange in crossed nicols. It is identified by its sheaf like bow-tie texture and strong birefringence. It occurs as vein and vesicle filling in association with epidote and chlorite. Prehnite indicates formation temperatures of about 250°C (Reyes 2000).

Wollastonite: Wollastonite is a rare mineral in this well and appears first at 1058 m. It is white to colourless, sometimes grey, with a distinct crystal habit appearing as fibrous and radiating aggregates. In thin section it is colourless and has moderately high relief. It forms in vesicles in association with epidote and actinolite. Its presence in the well indicates formation temperatures of above 270°C (Reyes 2000).

Actinolite: Actinolite is pale green, green and sometimes dark green in colour and occurs as fibrous, radial crystals and massive to granular aggregates in the groundmass. In thin sections it shows moderate relief with weak pleochroism of pale yellow, deep green blue and pale green colours. The first occurrence of actinolite is at 894 m and from there actinolite is persistent to the bottom of the well. It is observed as filling in vesicles and is sometimes seen in veins. The mineral is formed as a replacement of pyroxenes. In most cases it forms mineral association with quartz, pyrite, wollastonite and epidote. This mineral indicates formation temperatures of above 280°C (e.g. Lagat, 2007; Gylfadóttir et al., 2011).

Clay minerals: Clay minerals are the most common and dominant hydrothermal alteration minerals that are observed in wellOW-39A. They are finely crystalline or metacolloidal and occur as flake-like or dense aggregates of varying types (Pendon, 2006). Their occurrence in a geothermal system are indicators of changes in the chemical environment such as the presence of acidic fluids in a relatively neutral environment while their distribution depends on the ability of fluid to approach equilibrium in host rocks at any scale during the hydrothermal processes (Harvey, 1998) and also as temperature indicators (Kristmannsdóttir, 1979, Franzson, 1998). Four types of clays were identified from the surface to the bottom of the well, based on binocular analysis, petrographic analysis and XRD analysis, and a brief description is given below:

Smectite: Smectite is a low temperature clay and it is observed as fine grained brown to green aggregates recognized by the first order birefringence colour. It is observed at shallow depths and was identified from its characteristic extinction sun feature in thin section (384 m). Its occurrence indicates temperatures of less than 200°C (Franzson, 2013) and also alkaline fluid environment. Smectite is unique in that it swells when ethyl glycol is added to it and when heated it shrinks. In this regard, it shows characteristic peaks of range from 14.78 Å-16.33 Å, 18.37 Å-19.58 Å and 10.50 Å-10.98 Å for air-dried/untreated, glycolated and heated samples respectively.

Kaolinite: Kaolinite is bright green to white in colour, replaces K-feldspar and occurs as a vein and vesicle filling mineral. It is identified from XRD analysis by 7.15 Å for the untreated and glycolated, and completely collapses after being heated to 550°C. It occurs in low intensity alteration below 572 m. Kaolinite is associated with acid alteration and low temperatures up to 180°C (Reyes 2000).

Chlorite: Chlorite is pale green to dark green in cuttings but in thin sections it is pale green and occasionally shows anomalous brown colour. It is fine to coarse grained weakly to non-pleochroic and shows low birefringence. It exhibits small intergranular patches in the shallow depths while at deeper levels it forms radial aggregates. The mineral occurs as a filling in vesicles veins and fractures in association with epidote, quartz and calcite. XRD analyses of chlorite show conspicuous peaks at 7.0-7.2 Å and 14.0-14.5 Å in the untreated, glycolated and oven heated to differentiate it from kaolinite whose peak collapses when heated to 550 C.

Illite: Illite is common clay mineral extensively distributed in this well. It is colourless to brown under petrographic microscope. It is observed as a vein filling and as an alteration product of sanidine. Under XRD analyses, it shows strong peaks of between 9.9 to 10.4 Å in untreated, glycol treated and heated samples. It is first observed at 298 m in XRD analysis. Its appearance indicates temperature above 200°C (Kristmannsdóttir, 1979).

3.3 Hydrothermal alteration mineral zonation

Hydrothermal minerals are known to form at specific temperatures in a geothermal system. (Browne, 1978, 1984; Omenda 1998). The distribution of the hydrothermal minerals with depth in well OW-39A is dependent on temperature. In this well the mineralization pattern shows five distinct zones as shown in Table 1. The top zone is the unaltered zone (0-134m) and has no alteration related to geothermal activity, suggesting the temperatures were <40°C. The second zone (zeolite –smectite-illite zone) extends from 134-578 m. This is the lowest grade mineral alteration zone indicating temperature range of 40-200°C. The upper boundary of this zone coincides with the first occurrence of zeolites at about 134 m. The third zone (Chlorite- illite zone) occurs between 580 to 748 m and is characterised by high oxidation in the upper parts at 600-640 m depth. The upper boundary is marked by the first appearance of chlorite in the XRD analysis at 578 m suggesting the formation temperatures could be above 230°C. The fourth zone (epidote-chlorite-illite) extends from 748-896 m. It is characterised by abundance of epidote, suggesting that alteration temperatures above 250°C. Other minerals present in this zone include albite, sphene, quartz, chlorite, illite and calcite. The fifth zone extends from 896 m to bottom of the well. It is marked by first appearance of actinolite at 896 m indicating temperatures above 280°C below this depth. It characterised by mineral assemblage of actinolite, wollastonite, epidote and prehnite. Other minerals in this zone include pyrite, calcite, fluorite, chlorite, illite, and oxides.

TABLE 1. Alteration mineral zones in well OW-39A

Depth (m)	Alteration	Temp range (°C)
0-134	Unaltered	<40
134-580	Zeolite-smectite-illite	40-200
580-748	Chlorite-illite	200-230
748-896	Epidote-chlorite-illite	250-280
896-3066	Actinolite-epidote-wollastonite	>280

3.4 Alteration mineral correlation with neighbouring OW-37A and OW-35

Isograds give a general picture of the temperature distribution in a geothermal system as they delineate the first appearance of an index mineral. A cross section of alteration temperature extending from the SW at well OW-39A, through OW-37A and to OW-35 in the NW (Figure 2) has been plotted. First appearance of index minerals have been plotted (Figure 3) in all the three wells and five distinct alteration zones have been identified in all the three wells. The top zone (unaltered zone) is quite thin in all the wells. Zeolites-smectite-illite zone appears at 2004 m.a.s.l in OW-39A, 1919 m.a.s.l. in OW-37A and 1768 m.a.s.l in OW-35. This zone is thicker in OW-39A and OW-37A and thinner in OW-35. Chlorite-illite zone is appear at 1560 m.a.s.l in OW-39A, 1388 m.a.s.l OW-37A and 1768 m.a.s.l. in OW-35. This zone is thicker in OW-37A and OW-35 but thinner in OW-39A. First appearance of chlorite at these depths indicates alteration temperature above 230°C. First appearance of epidote is in basaltic lava at 1390 m.a.s.l in OW-39A, in trachytic lava at 845 m.a.s.l in OW-37A and in tuff at 1288 m.a.s.l. in OW-35 indicating that the alteration temperatures at these depths in the wells is above 250°C. This temperature (250°C) is shallower in OW-39A and OW-35 while deeper in OW-37A. The epidote zone is thinner in OW-39A and thicker in OW-35. Actinolite first appears in OW-39A at 1242 m.a.s.l, OW-37A at 467 m.a.s.l. and in OW-35 at 342 m.a.s.l. The plots indicate this zone is shallowest in OW-39A indicating hotter shallow depth of alteration temperatures above 280°C. The correlation indicates the elevation of the hydrothermal alteration in the area around OW-39A implying the proximity of up flow zone. Formation and alteration temperature are within the range in OW-37A and OW-35 but in OW-39A the formation and alteration temperature are reverse of the other, that is alteration temperatures indicates the proximity of up flow while current formation temperature indicate marked cooling of the same structure. This might indicate a flow reversal of a specific permeability structure from a geothermal outflow to an inflow of cooler inflow into the geothermal system.

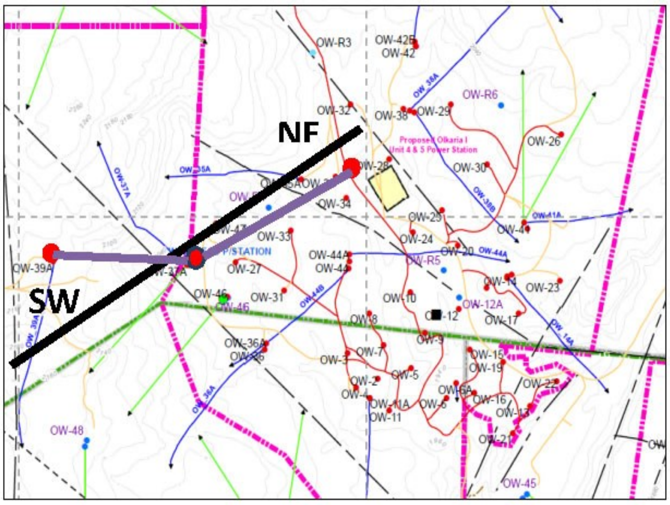

Figure 2: Showing cross cutting of correlation direction between wells OW-39A, OW-37A and OW-35A.

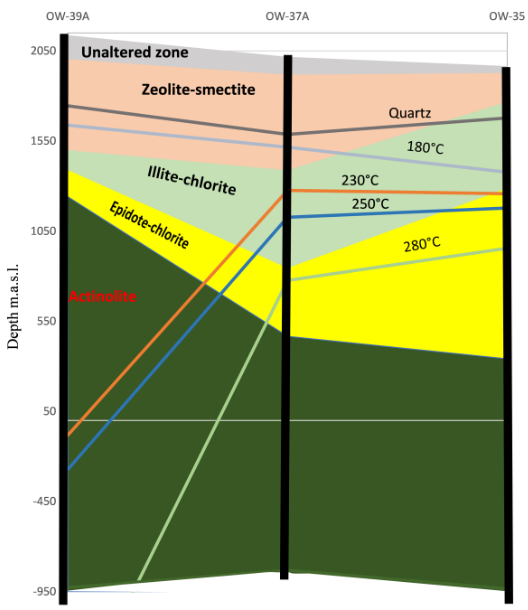

Figure 3: Alteration mineral correlation bewtween well OW-39A, OW-37A and OW-35.

3.5 Stratigraphic correlation

Correlation of the lithology along a cross cutting shown in figure 2 above from the SW at well OW-39A, through OW-37A and to OW-35 in the NW of the three wells shows same type of rocks(Figure 4) which have also been observed in other Olkaria wells (Musonye, 2012;Mwangi, 2012; Ronoh, 2012; and Njathi, 2012). The top formation is composed of pyroclastic rock, which is very thin in OW-39A but thicker, in OW-37A and OW-35 indicating it could have been a flow forming thicker layers in the low lying areas of OW-37A and OW-35. These pyroclasts overlie rhyolitic lavas in all the wells with subsequent layers of tuff, trachyte and basalt. Tuffs are common rocks in the three wells above 800 m intercalating with basalt, rhyolite and trachyte, and this could indicate that this area experienced phreatic episodes of eruptions in the past. Basalt occurs in the three wells with a thickness less than 50 m. Trachytes dominate the bottom depths in all the wells below 900 m, 750 m and 700 m in wells OW-39A, OW-37A and OW-35 respectively intercalating with tuffs, rhyolite, basalts and minor intrusions. This could indicate the onset of the Plateau Comparison of fluid inclusion, formation and alteration temperatures of well OW-39A was done by plotting the formation temperature, mineral alteration temperatures and fluid inclusion data as shown in figure 6. Comparison between formation and alteration temperature in a well is an important tool in determining the present geothermal condition of the well, hence can indicate whether the well is cooling down, heating up or in equilibrium. In this well alteration temperatures at 270, 392, 580, 748 and 896 m are 130, 180, 230, 250 and 280°C respectively. The formation temperatures at 270, 392, 580, 748 and 896 m are 100, 150, 195, 205 and 210°C respectively. The alteration temperatures at 270, 392, 580, 748 and 896m are 30, 30, 45, 60 and 70°C respectively higher than the formation temperature indicating that the well is cooling. This difference increases with depth.trachytes in these wells. The intrusions are only encountered in well OW-39A and well OW-35. Basaltic and granitic intrusions occur only in OW-39A, whereas rhyolitic and syenitic intrusions occur in both wells (OW-39A and OW35). There are no intrusions encountered in OW-37A. The occurrence of the intrusions in specific wells could probably imply these intrusions are dykes. As has been discussed by earlier researchers on the subsurface geology of Olkaria (Browne, 1984; Leach and Muchemi, 1987; Muchemi, 1992; Omenda, 1998), basaltic lava flow coincides with the cap rock of the reservoir and has been used as a marker horizon as it is widespread. The basaltic lava used as maker horizon and encountered at 808 m, in OW-39A, 640 m in OW-37A and OW-35 show slightly variable depths of occurrence and may imply minor faulting. This therefore reveals a possible existence of a fault between OW-39A and OW-37A with the down throw towards OW-39A. The other fault could exist between OW-37A and OW-35 with the down throw towards OW-35 (Figure 4).

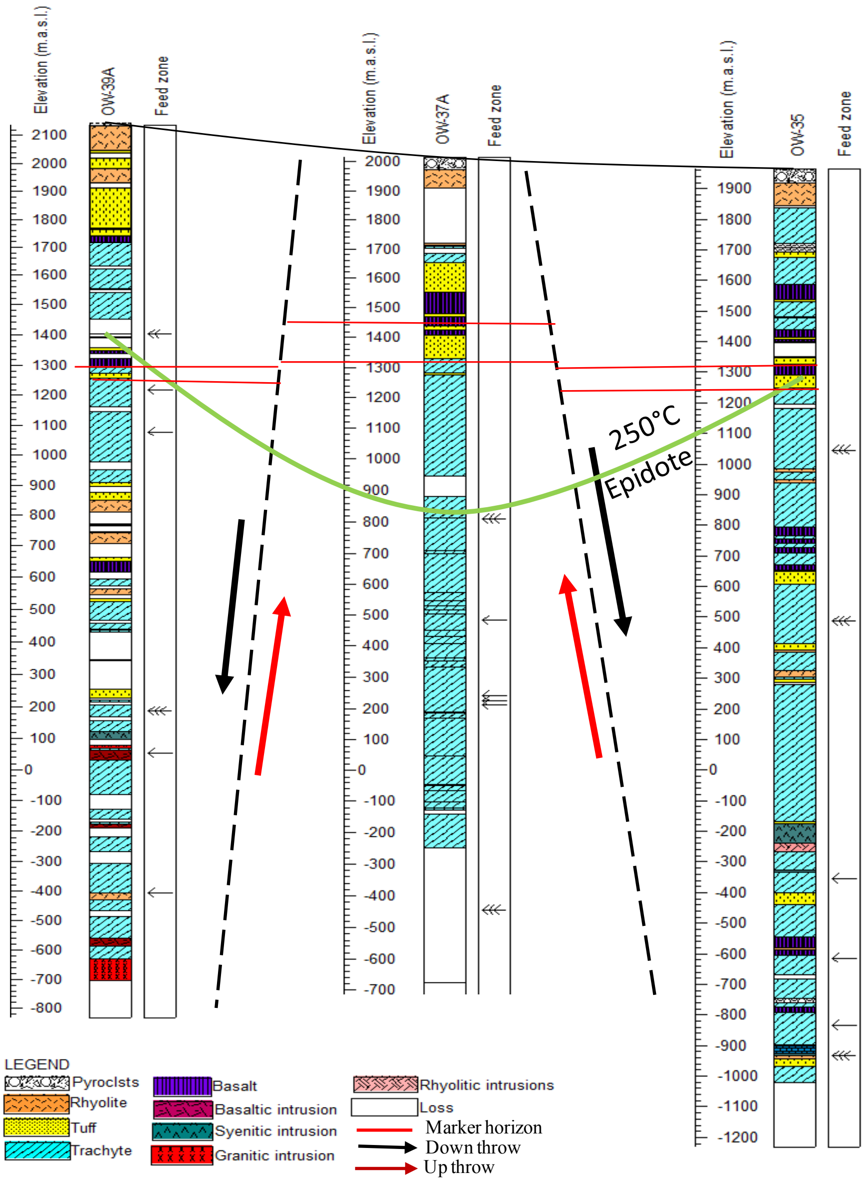

Figure 4: Stratigraphic correlation between OW-39A, OW-37A and OW-35.

3.6 Fluid inclusion geothermometry

Fluid inclusions analyses in well OW-39A were done in quartz crystals. Fluid inclusion homogenization temperatures give the entrapment temperature of a fluid in a mineral (Roedder, 1984). This temperature, combined with other geochemical techniques, constrains potential sources and migration pathways and assists in deciphering the thermal history of a geothermal system. The homogenization temperatures (T_h) of the inclusions were measured in quartz crystals picked from 812 m depth and the results are presented in figure 5. The T_h values ranged from 210-285°C in the quartz apparently from two populations. The lower T_h value range is 210-215°C while the higher one ranges from 280-285°C. The lower range T_h values appear to be formed in healed fractures in the crystal and may have formed at a later stage than the higher ones which appeared more primary in nature. The high values may therefore be an earlier phase thus indicating that cooling has taken place in the geothermal system at this location.

3.7 Comparison of measured, hydrothermal and fluid inclusion temperature for well OW-39A

The homogenization temperature (T_h) values at 812 m in the well ranged from 210-285°C in the quartz as discussed above. The formation temperature at this depth is 208°C. The lowest T_h value range is 210-215°C while the highest is 280-285°C. These measurements indicate the inclusions with lower T_h range 210-215°C) is near equilibrium with the current formation temperatures whereas the high temperature range inclusions are far above the formation temperature. The formation temperature at 812 m is 208°C indicating that the lower T_h range is in equilibrium with the current formation temperature whereas the highest T_h range is far above the formation temperature. The two sets of T_h temperature reveal two geothermal history of the well whereby at one time elevated temperature existed succeeded by cooling. In this discussion we assume that the measured temperature conforms to the formation temperature.

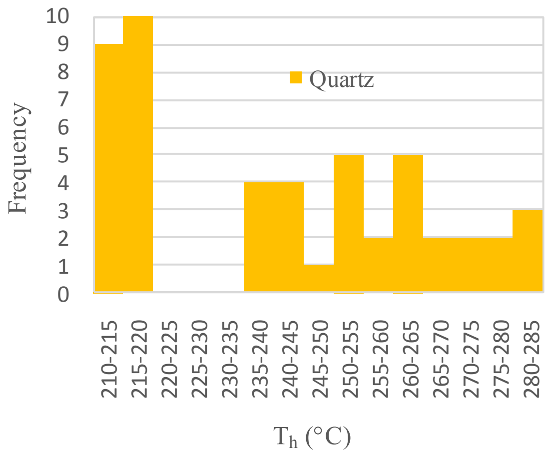

Figure 5: Histogram showing temperature and distribution of fluid inclusion.

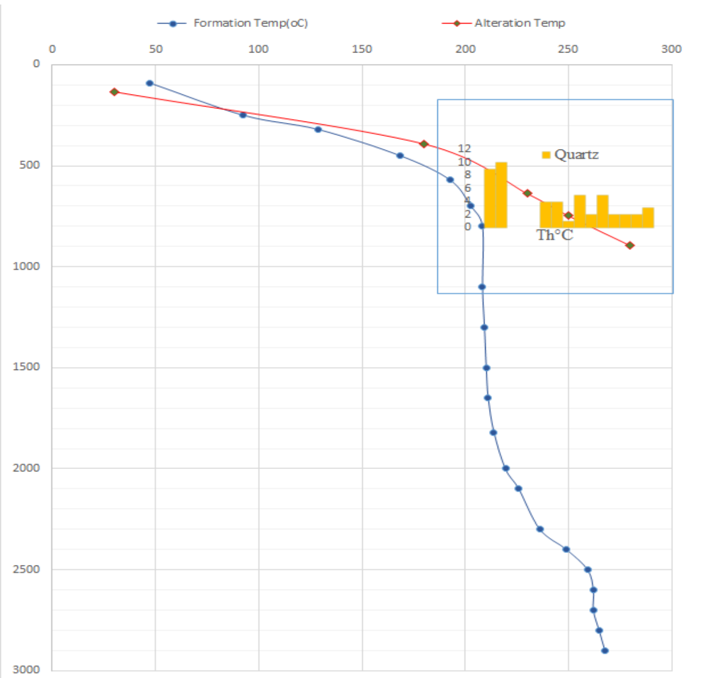

Figure 6: Showing comparison between fluid inclusion, alteration temperature and formation temperature for OW-39A

3.8 Aquifers and permeable zones

The main sources of permeability in the Greater Olkaria volcanic complex are lithological contacts, intrusive boundaries and major faults and fractures (Lagat, 2004; Gylfadóttiret al.2011). Permeable and feed zones in well OW-39A were identified and interpreted by monitoring loss of circulation fluid during drilling, hydrothermal alteration mineralogy patterns, changes in circulating fluid temperature and temperature recovery tests (Figure 7). The temperature logs and alteration intensity reveal that the well is highly permeable above 2250 m. The feed zones in this well are identified in the production zone and are classified as major minor and intermediate. Five minor aquifers occurring at 950, 1500, 1800, 2250 and 2750 m are marked by high intensity of alteration fracturing and loss of returns. Two intermediate aquifers occur at 750 and 1100 m. At 750 m it is marked by loss of circulation and high intensity of alteration while at 1100 m is defined by high alteration intensity, veining and fracturing. The major aquifer at 2100 m is marked by lithological contact between intrusions, loss of circulation and fracturing.

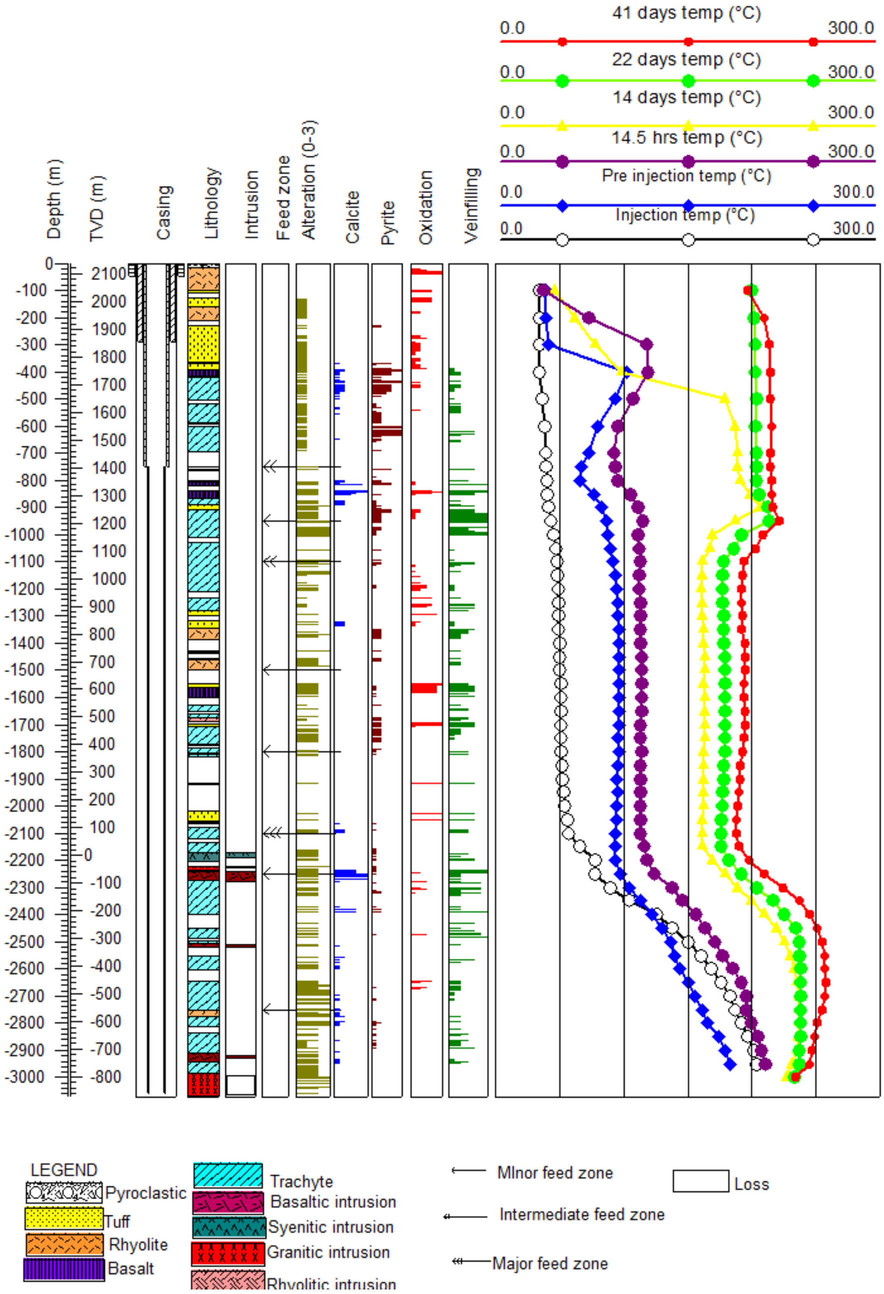

Figure 7: Permeable and feed zones in OW-39A in relation to the geological evidence and the recovery and circulation fluid temperature measurements

4. DISCUSSION AND INTERPRETATION

The lithology of OW-39A was interpreted by analysis of the drill cuttings from the well using binocular and petrographic microscopes. From these analysis five main rock types namely pyroclastics, tuffs, rhyolites, basalts and trachytes are encountered in the well. Pyroclastic rocks form the uppermost 14 m the underlying rhyolites extend to 98 m and correspond to the Olkaria commendites. Rhyolitic tuffs and basalts dominate the upper 400 m of the stratigraphic column of the well representing the Upper Olkaria volcanics, while Plateau trachytes is dominant at depth and form the main reservoir formation

Hydrothermal alteration minerals are observed in the veins, vugs and vesicles and as a replacement of primary minerals. Their distribution in active geothermal fields depends on the ability of fluid to approach equilibrium in host rocks at any scale during the hydrothermal processes. In this well the appearance of smectite (134m, 384 m) and kaolinite (572 m) indicate temperatures of less than 200°C whereas kaolinite indicate the presence of acidic fluids. Illite and chlorite are the dominant clay mineral in this well appearing to well bottom.

The study of the hydrothermal distribution pattern shows five distinct alteration zones with the first appearance of index minerals coinciding with the upper boundary of each zone. These are: the unaltered zone (0-134 m) that has no alteration related to geothermal activity suggesting temperatures of <40°C. The second zone (zeolite-smectite zone) that extends from 134 to 578 m is the lowest grade mineral alteration zone indicating alteration temperatures of <200°C. It is characterised by high oxidation and abundant zeolites. The third zone (chlorite-illite zone), which is marked by the first appearance of chlorite occurs between 578 and 748 m. The zone is fractured as evidenced in the veining and is characterised by abundance of pyrite and calcite suggesting the zone is highly permeable. Epidote-chlorite-illite is the fourth zone extending from 748 to 896 m. The top depth is marked by first appearance of epidote and it is characterised by high oxidation, veining, high intensity of alteration, abundance of pyrite and calcite indicating that the zone is also highly permeable. The appearance of epidote in this zone indicates that the alteration temperature at 748 m and below could be above 250^{o}C. Other minerals present in this zone include albite, prehnite, sphene, quartz, chlorite, illite, fluorite, pyrite, calcite and oxides. The fifth zone extends from 896 m to bottom of the well. It is marked by first appearance of actinolite at 896 m indicating temperatures above 280°C below this depth. It is characterised by the mineral assemblage of actinolite, wollastonite, epidote and prehnite. Other minerals in this zone include pyrite, calcite, fluorite, chlorite, illite, and oxides. The absence of actinolite for a long interval between 1488 to 2210 m in the well could indicate the absence favourable conditions such as high temperature for the formation of actinolite.

Alteration mineral correlation between OW-39A, OW-37A and OW-35 (Figure 3) indicate that chlorite-illite zone is thinner in OW-39A whereas it is thicker in OW-37A and OW-35 implying higher alteration temperature gradient with depth in OW-39A. Epidote occurs at shallower depth in OW-39A (1390 m.a.s.l.) and OW-35 (1288 m.a.s.l.) but deeper in OW-37A (845 m.a.s.l.). This zone is thicker in OW-35 than in the other two wells. Actinolite appears at shallowest depth in OW-39A and deeper in OW-35A hence actinolite zone is thicker in OW-39A. The plots indicate this zone is shallowest in OW-39A indicating higher alteration temperatures at shallow depth, which may be caused by an up flow zone and higher permeability around OW-39A. Formation and alteration temperatures are within the range, i.e almost at equilibrium in OW-37A and OW-35 but in OW-39A formation and alteration temperature are reversed indicating elevation of the geothermal system in the vicinity to this well, while current formation temperature indicate a reversal in temperature probably due to later cold water inflow and mixing. That is alteration temperatures indicate a previous up flow zone in vicinity to this well, while current formation temperature indicate a reversal in temperature probably due to cold water inflow and mixing

Taking into consideration the topographic correction between the wells, True vertical depth with reference to the elevation of each well was used. Basalt layer s in the three wells was used as a marker horizon, when carrying out analyses of drill cuttings, to infer buried faults in this area Stratigraphic correlation of the basalt layers between the three wells indicate the possible existence of normal faults between OW-39A/OW-37A and OW-37A/OW35 with downthrows towards OW-39A and OW-35 respectively. Also the appearance of dominant trachyte below 900, 750 and 700 m in wells OW-39A, OW-37A and OW 35 respectively correlates well with the probable existence of the normal faults as shown in figure 4, and hence conforms to an observation made by Lagat (2004).

The homogenization temperature (T_h) values analysed from fluid inclusions in a quartz vein from 812 m in well OW-39A ranged from 210-285°C, but form two populations; the lower T_h value range is 210-220°C while the higher one is 235-285°C. For comparison the measured (formation) temperature at this depth is 208°C. Inclusions in the healed fractures had T_h range of 210-220°C representing the current condition while the primary ones had T_h range of 235-285°C. These measurements indicate that the inclusions with lower T_h range (210-220°C) is near equilibrium with the current formation temperatures whereas the high temperature range (235-285°C) inclusions are far above the formation temperature but in equilibrium with the alteration temperature. The wide range in T_h temperature, reveal two geothermal phases in the proximity of the well whereby the temperature has been higher than 280°C at one point in time, but has since cooled to ~210°C. Alteration temperature is far above the formation temperature below 392 m (Figure 6) indicating the reservoir is cooling below this depth.

Permeability in OW-39A is very high as it is characterised by high fracturing, veining, intensity of alteration and circulation losses. The presence of calcite and abundance of pyrite in this well indicates high past or present permeability. The well also shows high oxidation indicating there were channels/fractures of oxygen rich fluid flow in the rocks. Aquifer information is determined through analysis of temperature logs run during and after the completion of the well. Circulation losses/gains also play an important part in positioning of the aquifers as well as alteration data. The aquifers in well OW-39A were determined from temperature logs and are mainly associated with high intensity of alteration, lithological boundaries and fractures and highly fractured rocks. Two intermediate aquifers occur at 750 and 1100 m. At 750 m it is marked by loss of circulation and high intensity of alteration, while at 1100 m (in trachyte) it is defined by high alteration intensity, veining and fracturing. From the interpretation of the temperature profile, this aquifer (1100 m) could be a channel of cold fluids into the well. A major aquifer at 2100 m is associated with an intrusion of syenitic composition, but fracturing is observed at the intrusion contact. In OW-37A major aquifers are noted in trachyte at 1250 m and it is marked by circulation losses, fracturing and high intensity of alteration and at 2600 m it is marked by loss of circulation. In OW-35, three major aquifers are identified. At 980 and 1480 m the aquifers are marked by high intensity of alteration, abundance of pyrite, oxidation and veining while at 2900 m the aquifer is marked by fracturing intrusive, veining and lithological contact between rhyolite and syenitic intrusion.

OW-39A was drilled directionally to the south adjacent to Olobutot fault which is a N-S trending eruptive fissure which erupted approximately 180±50 yrs (Clarke et al., 1990). Gylfadóttiret al., 2011, noted that this fault appears to represent a long term groundwater flow structure breaking through the hydrological barrier that the Olkaria region forms south of Lake Naivasha. Permeability connected to groundwater systems can also shape the alignment of the thermal reservoir, as is postulated as causing the separation between e.g. Olkaria West and East (Ololbutot fissure). Observations made from oxidation trends, veining and temperature logs in well OW-39A indicate that the well is highly fractured and that these fractures act as groundwater flow channels in the rock formations. Also the reversal in alteration (through fluid inclusion analysis) and formation temperatures

(Figure 6) observed in the well indicate that the fluid flow in the area around the well has been reversed using same geothermal structure implying an old hot geothermal structure reversed to a "cold geothermal barrier", which has resulted in cooling of OW-39A. Observations made from hydrothermal alteration mineralogy and mineral deposition sequence do not show temperature reversal hence signs of cooling are not evident. This could then probably imply the cooling of area around the well is a recent event.

5. CONCLUSION

The lithology of well OW-39A is composed of pyroclastics, tuffs, rhyolites, basalts, trachytes and

minor basaltic, rhyolitic, syenitic and granitic intrusion. The rock types conform to the general geology of Olkaria.

The thick (~80 m apparent thickness) granitic intrusion could be originating from a deeper granitic body which may be a heat source.

Stratigraphic correlation of wells OW-39A, OW-37A and OW-35 indicate the possibility of existence of a normal fault between OW-39A and OW-37A, and OW-37A and OW-35

Hydrothermal alteration mineral assemblages and their distribution in the well are mainly controlled by temperature, rock type, fluid composition and permeability. Low temperature minerals are found in the upper part while high temperature minerals reside in the deeper part.

Five alteration zones were identified, based on hydrothermal mineral assemblages. These include; unaltered zone (0-134 m), zeolite-smectite-illite zone (134-578 m), Chlorte-illite zone (578-748 m) epidote-chlorite zone (748-896 m) and actinolite-epidote-wollastonite zone (896-3066 m).

Temperature profile monitoring and geological evidence indicate well OW-39A is highly permeable above 2250 m

Aquifers in this well show close association with circulation losses, fractured formations, lithological contacts between formations and intrusions at depth. High past and present permeability in this well is indicated by the high abundance of pyrite and calcite, high alteration intensity, high oxidation, fracturing and high occurrence of veins. High oxidation in this well may also indicate groundwater flow in the fractures in the area around the well.

Comparison between fluid inclusion, alteration, and formation temperature indicate evidence of two geothermal phases in the proximity of the well; the first phase of elevated temperatures succeeded by a cooling a phase.- hence the well is cooling

Alteration zones in OW-39A shows a marked elevation compared to the neighbouring wells of OW-37A and OW-35 suggesting that the well is nearer to an up flow zone than the latter. However, a comparison of the formation temperatures of the same wells show much lower temperatures in OW-39A than the others, indicating that the up flow channel in the proximity of the well may now be acting as an inflow of cooler fluids from outside of the geothermal system. An assumption is made that the measured temperatures in the well is the same as the formation temperatures.

Observations made from hydrothermal alteration mineralogy and mineral deposition sequence do not show temperature reversal hence signs of cooling are not evident. This could then probably imply the cooling of area around the well is a recent event possibly younger than the Ololbutot eruptive fissure.

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