

## **Appraising a Geothermal Field Using Hydrothermal Alteration Mineralogy: a Case Study of the East of Olkaria Domes Geothermal Field; Olkaria, Kenya**

Irene Ronoh

Kenya Electricity Generating Company LTD, P. O. Box 785-20117 Naivasha, Kenya

E-mail: ironoh@kengen.co.ke

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### **ABSTRACT**

Hydrothermal alteration minerals have been used successfully to observe the changes in a geothermal reservoir. The temperature dependent minerals are used as indicators to determine the entrance into the reservoir and the production casing depths. The alteration intensity shows the quantity of fluid flow through the rock and can be used as an indication of porosity and/or permeability. Drilling in the Olkaria Domes geothermal field is currently ongoing to explore and appraise the field as the boundaries to the geothermal reservoir are still unknown. Four geothermal wells OW-919, OW- 914A, OW-916 and OW-912B were drilled in Olkaria Domes field. The wells were drilled to gather steam for the 140 MW power project and to appraise the field to the east and southeast trending. The wells were drilled to an average depth of 3000 m and all encountered a high temperature system with alteration mineralogy indicating a reservoir temperature of above 250°C. All wells apart from OW-912B discharged during testing. Rock types identified in the wells include pyroclastics, rhyolites, tuffs, trachytes and basalts. Intrusions in the wells were of rhyolitic, basaltic and syenitic compositions occurring as dykes from as shallow as 520 m depth in well OW-916. Hydrothermal alteration indicates that the geothermal system is grading from low to high temperature with increasing depth. However, certain wells show an evidence of cooling probably due to cold fluids incursion in the well. The wells display an evolution history indicated by the deposition of minerals like zeolites, opal and chalcedony with their stable temperatures of below 150°C at shallower depths. This eventually grades into a zone dominated by minerals like quartz, wairakite, chlorite, epidote, prehnite, wollastonite and actinolite which are stable above 180°C occurring deeper in the wells. Epidote was first noted in well OW-916 at 556 m depth and occurred deeper in OW-912B at 950 m depth. Alteration mineral assemblages identified in the wells include: smectite-zeolite, zeolite-illite, chlorite-illite, epidote-chlorite-illite and actinolite-epidote-chlorite-illite zone. From the assessment of hydrothermal mineralogy, it is evident that well OW-916 is located at or near the upflow zone of the Olkaria Domes geothermal field and the resource is deeper towards wells OW-912B. Well OW-919 is tapping the resource at 800 m but is cooled down below 1000m deep. This well shows outflow characteristics with the extent to the east of the field remaining unknown. This paper therefore discusses the successful use of hydrothermal alteration mineralogy in mapping the geothermal resource in the Olkaria Domes field and to evaluate it for further production.

### **INTRODUCTION**

The Kenyan Rift forms part of the extensive East African Rift system that runs from Lake Turkana in the north and south to Lake Natron in northern Tanzania. The tectonic activity in the rift has resulted in formation of normal (dip-slip) faults and numerous Quaternary volcanoes. These Quaternary volcanoes are associated with the geothermal activity and represent fourteen prospects identified along the rift. They are categorized into low-temperature and high temperature fields and most of them are undergoing exploration phase with drilling only underway in the central and southern part of the Kenya Rift valley, (Figure 1).

The Greater Olkaria Geothermal Field is one of the geothermal fields in Kenya currently under full exploitation, with a present production capacity of about 207MWe. The Greater Olkaria Geothermal Area (GOGA) is located within the Greater Olkaria Volcanic Complex. It is subdivided into seven fields for geothermal development purposes namely: Olkaria East (Olkaria I), Olkaria Northeast (Olkaria II), Olkaria Central, Olkaria Northwest, Olkaria Southwest (Olkaria III), Olkaria Southeast and Olkaria Domes (Olkaria IV). These are named in relation to the Olkaria Hill (Figure 2).

Drilling in the Olkaria Domes geothermal field is ongoing to gather steam for the Olkaria IV and V power plants. Furthermore, to appraise the field to the east towards the Longonot geothermal prospect. This paper is therefore meant to;

- Identify the rocks penetrated by wells OW-919, OW-914A, OW-916 and OW-912B in the east of the field and thereby gain knowledge on the stratigraphy and the structures encountered by wells drilled to the east of the Olkaria Domes geothermal field;
- Identify the hydrothermal alteration mineralogy found in the field and to obtain a better understanding of the water rock interaction processes occurring in this active hydrothermal system;
- Observe the temporal relationships in the wells to provide clues about the past and present conditions of Olkaria Domes reservoir;
- Determine the general location of the wells with respect to the upflow, outflow and the marginal zones of the system.

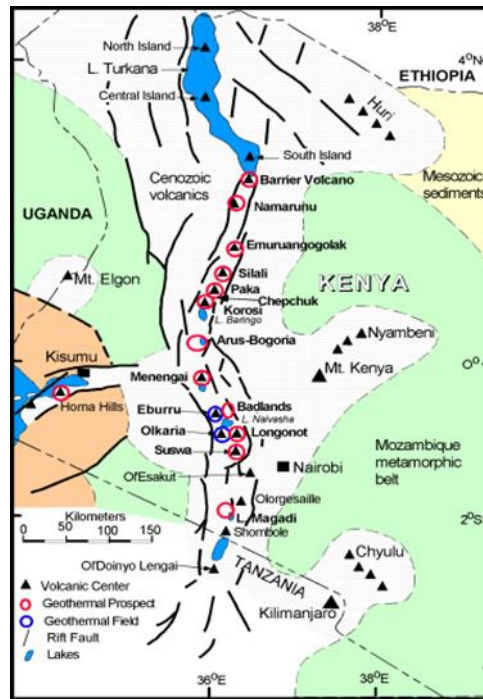


Figure 1: Map showing geothermal prospects in the Kenyan Rift with Olkaria field shown by the arrow (modified from Mariita, 2009)

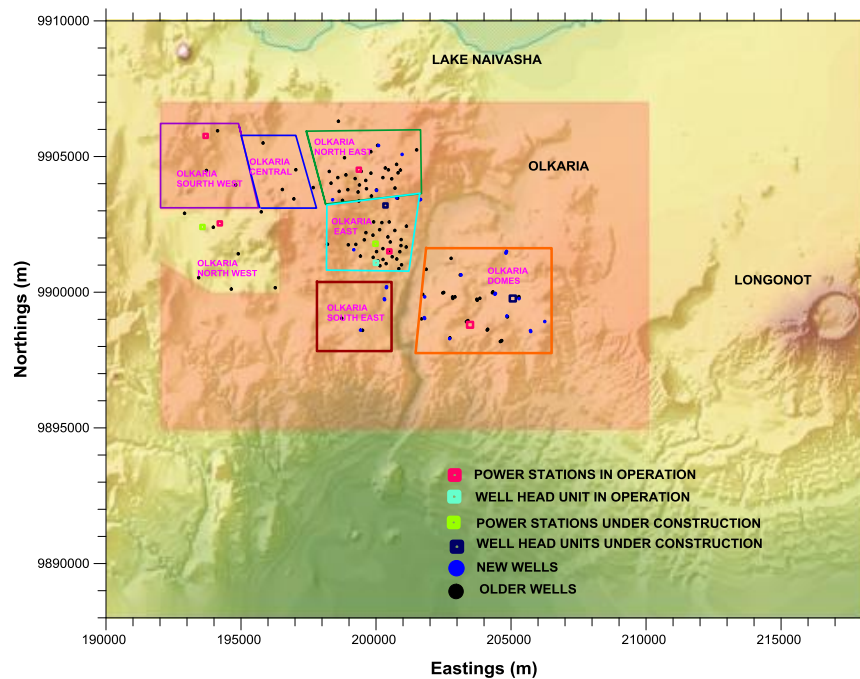
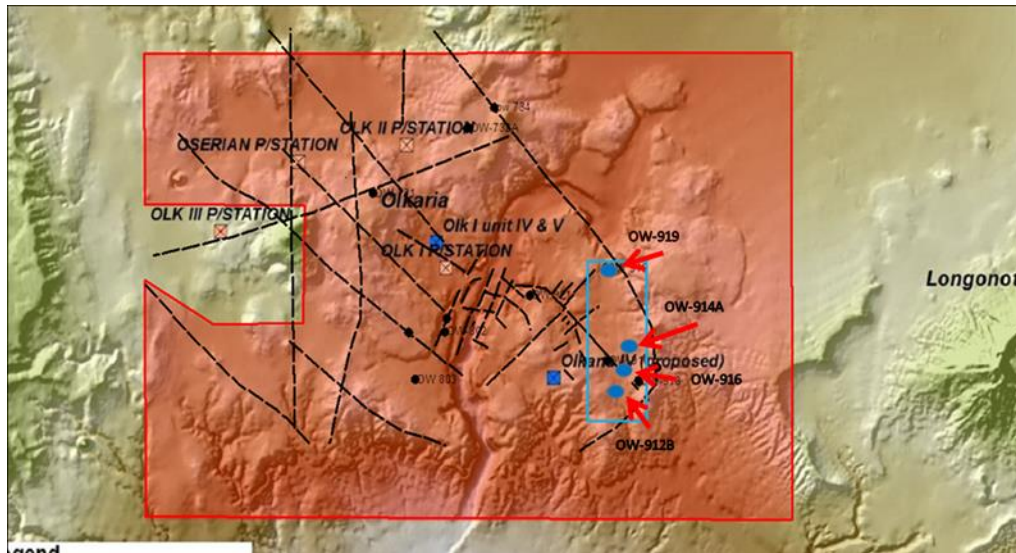


Figure 2: Location map of Olkaria Geothermal area showing production fields

## 2. GEOLOGICAL SETTING

Olkaria geothermal field is associated with Olkaria Volcanic centre, a Quaternary volcano that is situated in the Central Kenya Rift part of the East African Rift (Strecker et al., 1990). The surface geology of the Olkaria Volcanic Complex is covered by ash falls from Mt. Longonot and Suswa and numerous comendite and pantellerite lavas. Four fault systems characterize the field and are associated with fluid movement. These include ENE-WSW, NW-SE, N-S, E-W structures and they are all defined as normal faults through the correlation of lithology and alteration mineralogy zones. These include, but not limited to, the Ololbutot fault, Olkaria fault, Olkaria fracture, Gorge farm fault, Ring fault structure and Ol Njorowa Gorge. Surface mapping by Naylor (1972) identified the Olkaria area as the remnants of an old caldera complex. This was subsequently cut by north-south normal rift faulting that provided the loci for later eruptions of rhyolitic and pumice domes now exposed in the Ol Njorowa Gorge. Later volcanic activity

associated with Olkaria volcano and the Ololbutot fault zone produced rhyolitic and pumiceous obsidian flows. Areas of altered and warm ground are extensive throughout the Olkaria area. This together with present surface manifestations show a close association with the dominant N-S structures (in the central Olkaria area), the ENE/WSW Olkaria fault zone and the ring domes (figure 3).



**Figure 3: Structural map of Olkaria Geothermal field. Boundary of the study area and wells marked blue.**

From the surface to depth of about 1400 m.a.s.l, the Olkaria Volcanic Complex is covered by Quaternary comendites and pantellerite. It is overlaid by an extensive cover of pyroclastic fall from Longonot and Suswa. The youngest lava flow being Ololbutot lava flow which is dated about  $180 \pm 50$  years BP (Clarke et al. 1990). Below these, the dominant rocks are trachytes with thin basaltic flows and tuffs. The lower trachytes and tuffs are possibly part of the older Tertiary volcanics which form the volcanic basement of the Central Rift. At depth, acidic intrusives have been reported in some wells in Domes, North East, East and South East fields.

### 3. OLKARIA DOMES PRODUCTION FIELD

Olkaria Domes field lies to the east of the Olkaria East field (Figure 2). It is bound approximately by the Hell's Gate National Park, Ol Njorowa gorge to the west and a ring of domes to the north and south (Mungania, 1999). Detailed surface exploration was conducted in the area in 1992/93, which led to the development of a basic working model, from which recommendations for drilling of exploration wells were made. Drilling in Olkaria Domes field began in 1998 with the first three exploration wells, namely: OW-901, OW-902 and OW-903. The wells encountered a high-temperature system and they discharged on testing. Appraisal drilling began in 2007 with six deviated wells being drilled to a depth of about 2800 m. As of April 2014, forty (40) wells have been drilled in the Domes field and the data from these wells have aided in updating the conceptual model of the Greater Olkaria Geothermal Area.

### 4. BOREHOLE GEOLOGY

#### 4.1 Lithostratigraphic correlation

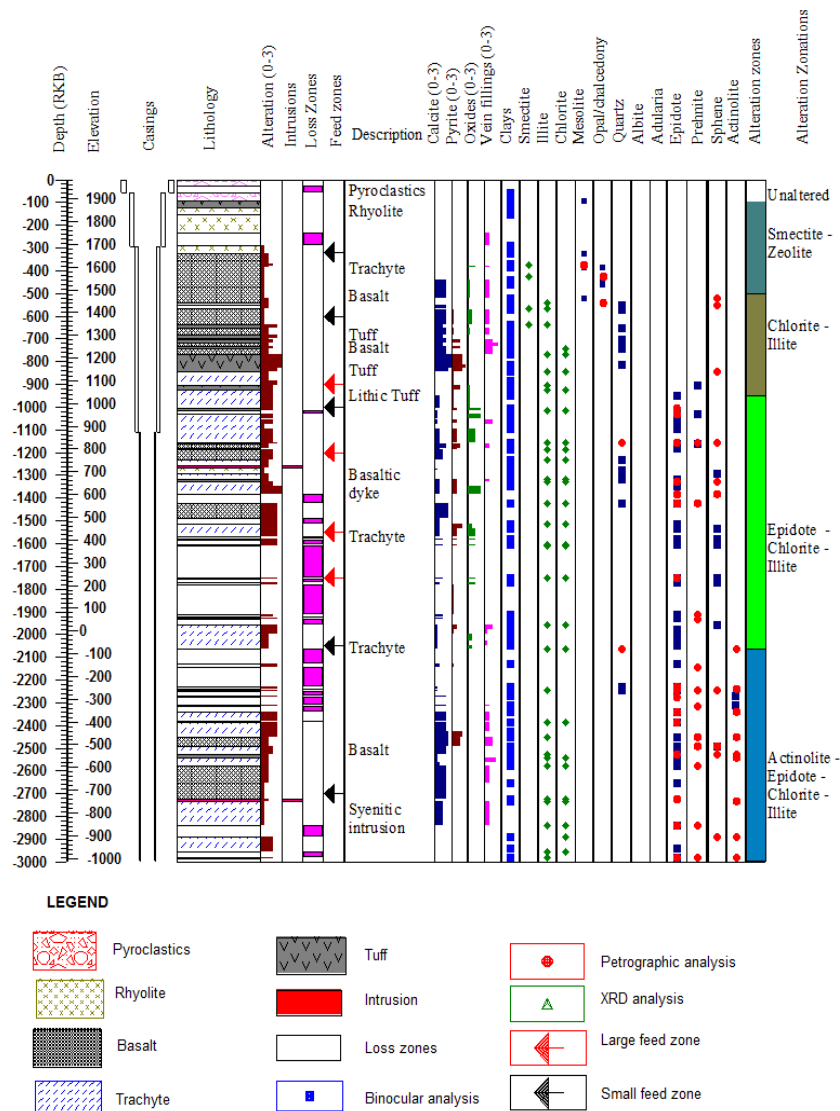
Wells OW-919, OW-914A, OW-916 and OW-912B in the east of the Olkaria geothermal field assume the general stratigraphy of the Greater Olkaria geothermal area. OW-919 with an elevation of 1983 m.a.s.l was drilled to 2998 m, OW-914A with an elevation of 2009 m.a.s.l was drilled to 2996 m, OW-916 with an elevation of 2035 m.a.s.l was drilled to 3000m and OW-912B with an elevation of 2073 m.a.s.l was drilled to 2998 with the wells varying in lithology as described below;

#### Pyroclastics

Wells in the Domes field show a varying thickness of pyroclastic rocks with the unit appearing thicker eastwards. These wells have a pyroclastic cover of up to 100 m.b.g.l with well OW-919 showing a highly oxidized rock unit indicating cold groundwater interaction with the formation. They are composed mainly of unconsolidated volcanic glass, feldspar and quartz crystals, lithic fragments, obsidian and rare amphibole and pyroxene crystals. The pyroclastics show extensive alteration of the volcanic glass to clays, iron oxides, silica and sulphur deposit (Figure 4).

#### Rhyolites

The rhyolites of Olkaria Domes are mainly comenditic and tend to vary from glassy to porphyritic. They display a spherulitic texture with occasional flow banding. They generally occur at shallow depths though intermittent lava flows are also noted at depth. In wells OW-919, OW-914A and OW-916, the formation occurs between 100 m and 368 m, while in OW-912B it occurs between 102 m and 548 m. Thinner units of rhyolites are noted below 1000 m.b.g.l and appear interlayered with other rock units. They vary in crystallinity, texture and intensity of alteration.



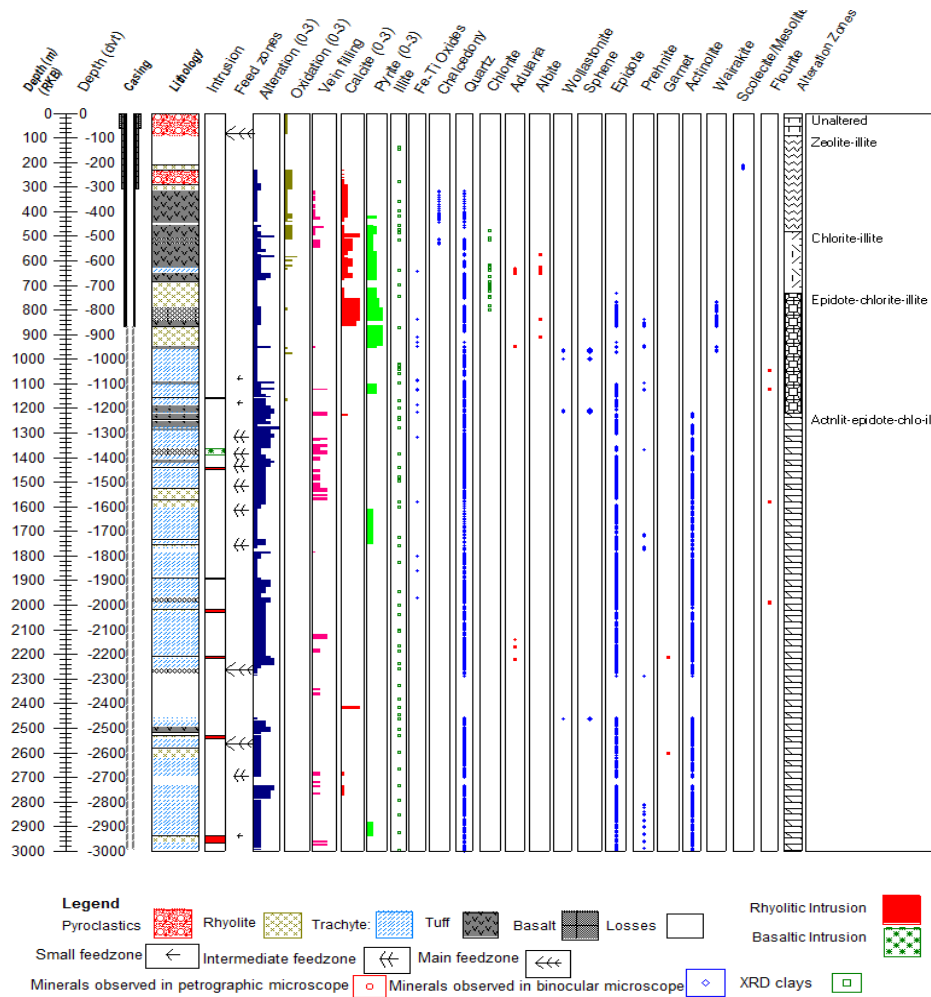
**Figure 4: Distribution of alteration minerals in well OW-919**

#### Tuffs

They occur as intercalation with other formation such as rhyolites basalts and trachytes. They range in colour from greenish to grey to brown with varying composition and texture. Lithic and homogenous variations occur. The variation could be due to different eruption episodes in Olkaria and the adjacent volcanoes; Longonot and Suswa. Permeability of these units is relatively high thus act as feeder zones. They vary in thickness from 10 to 100 m and observed shallower in well OW-914A at 312 m, and occur as thin units to a depth of 2540 m, (Figure 5). However, they occur deeper in well OW-919 at 638 m, (Figure 4).

#### Basalts

Basaltic rocks are generally dark grey to brown and depict holocrystalline groundmass composed of calcic-plagioclase, anhedral clinopyroxene and FeTi-oxide. Alteration of olivine gives it a reddish tinge but the plagioclases and pyroxenes appear slightly altered. Basalts in wells OW-919, OW-914A, OW-916 and OW-912B are encountered at an average depth of 400 m. They form the geothermal cap rock due to its high intensity of alteration to impermeable clay minerals. At deeper depth, the lower temperature clay minerals are easily altered to high temperature clays such as illite, chlorite and epidote.



**Figure 5: Distribution of alteration minerals in well OW-914A (Source: Musonye, 2012)**

### Trachytes

Trachytes are dominant rock in most wells in the Olkaria Domes. They occur in these wells from 554 m to bottom depth, (figure 4) forming stratigraphic sequences with rhyolite, basalt and tuff. The units vary depending on colour, texture and intensity of alteration. The shallower stratigraphic units appear greyish to brown in colour. They are fine to medium grained and consist of phenocrysts of sanidine and FeTi-oxide. They are found out to be the dominant geothermal reservoir rocks in most of Olkaria fields.

### Intrusives

Notable intrusions are of basaltic or rhyolitic compositions of varying scales. They range in thickness from 4m to 30m and have been encountered from as shallow as 520 m in well OW-916. Basaltic intrusions occur between 1258 m and 1266 m in OW-919, 1364 m to 1388 m in well OW-914A and between 520 m and 544 m in OW-916. Rhyolitic intrusions are found as thin units below 1154 m (figure 4).



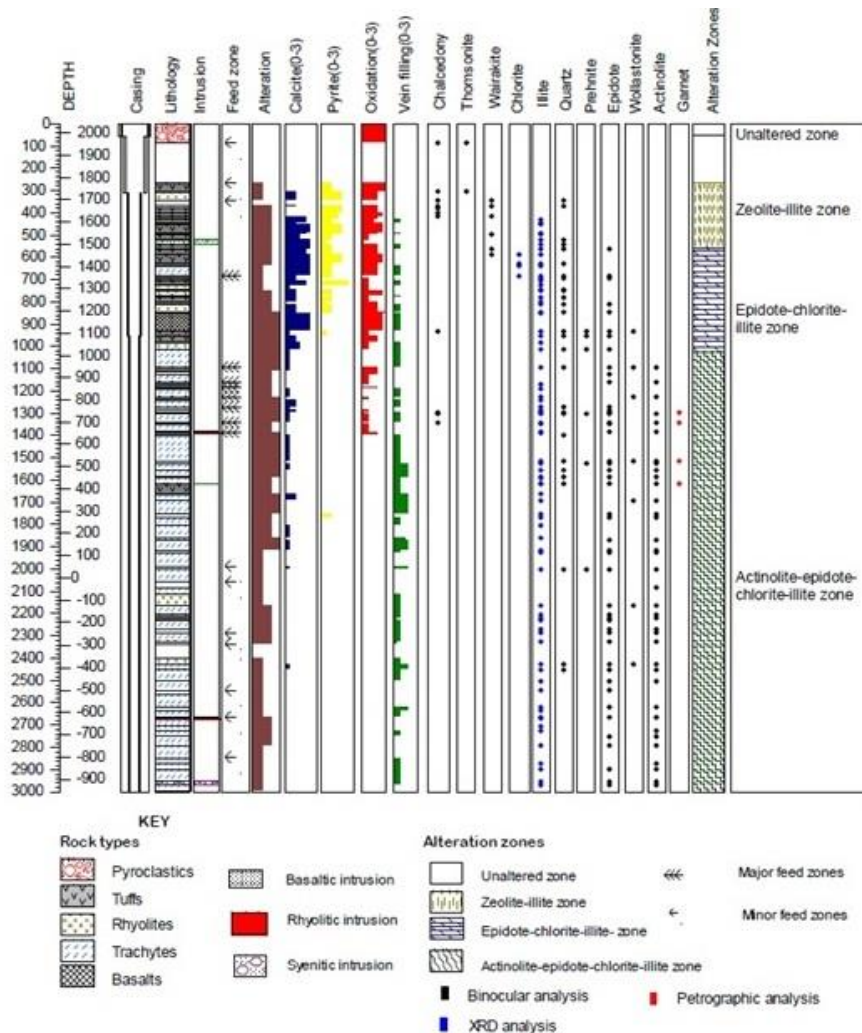
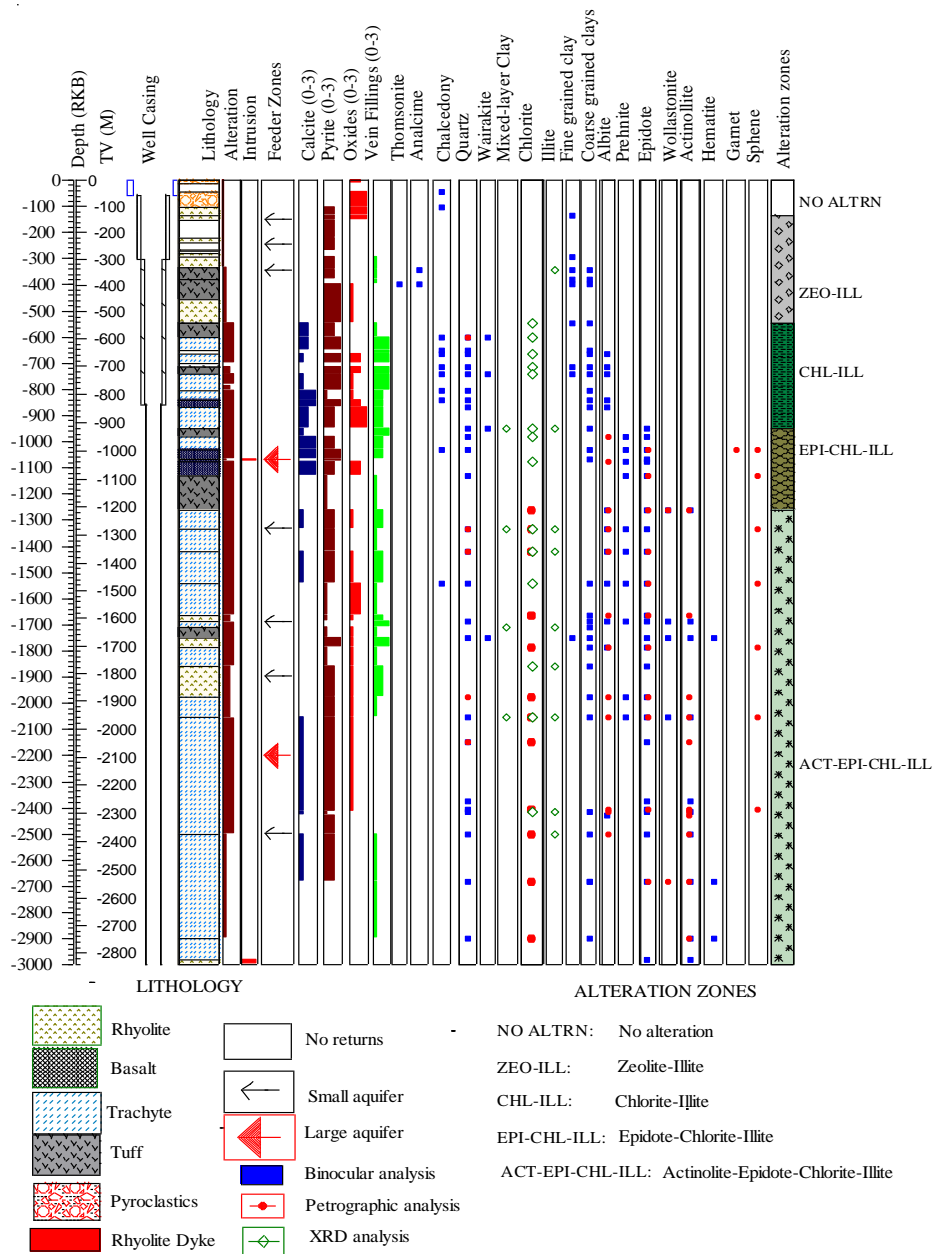


Figure 6: Distribution of alteration minerals in well OW-916 (Source: Wanjohi, 2012)

#### 4.2 Hydrothermal alteration

The interaction of geothermal fluids with rocks under favourable conditions leads to changes in the compositions of both fluids and the rocks. The mineralogy, color and texture of the rocks are then altered as a result of either heating or cooling. The primary minerals are replaced by the secondary minerals because there has been a change in the prevailing conditions subjected to the rock. The main primary minerals in wells OW-919, OW-914A, OW-916 and OW-912B include glass, olivine, sanidine, plagioclases, pyroxenes and opaques in order of their susceptibility to alteration, glass being the most unstable.

The main hydrothermal minerals in the Olkaria Domes field are zeolites, fine to coarse grained clays, albite, actinolite, calcite, chlorite, chalcedony, epidote, prehnite, hematite, illite, adularia, secondary Fe-Ti oxides, pyrite, titanite (sphene) and quartz. Mineral associations in vesicles are common and consist of two or more of the following minerals; illite, chlorite, quartz, calcite, epidote and pyrite with the paragenetic sequence varying with depth and temperature. Their distribution in well OW-919, OW-914A, OW-916 and OW-912B is summarized in figures 4, 5, 6, 7.



**Figure 7: Distribution of alteration minerals in well OW-912B (Source: Ronoh, 2012)**

#### 4.3 Distribution of hydrothermal minerals

The main alteration minerals found in wells OW-919, OW-914A, OW-916 and OW-912B are calcite, pyrite, zeolites, clays (smectite, illite and chlorite), chalcedony, albite, adularia, quartz, epidote, prehnite, wollastonite, garnet and actinolite. The distribution of the alteration minerals in these wells are discussed below;

*Calcite*; is abundant in well OW-919 from depth 442 m to 1100 m while in wells OW-914A and OW-916 calcite occur sporadically from 266 m to 800 m mostly observed in basalts and tuffs due to high porosities in the lava. In well OW-912B, it is observed from 792 m to 1260 m with platy calcite noted between 980 m and 1100 m.

*Pyrite*; Pyrite depicts thermal fluid pathways and its occurrence can be used to infer permeability in a well. Direct pyrite deposition indicates low ratio of  $H_2S/H_2$  partial pressures in the fluid (Mungania, 1992). In wells OW-914A and OW-916, pyrite is observed in abundance from 200 m to 850 m and occurs intermittently to bottom hole. OW-919 and OW-912B shows minor occurrence of pyrite in veins and vesicles from 400 m to the bottom of the well.

*Zeolites*; are rare in the wells but are observed in shallower depths and indicate low temperatures in the reservoir. Thomsonite, chabazite, mesolite and analcime dominate the upper 500 m in the wells while wairakite is intermittently noted below 600 m.

*Quartz*; appears to be deposited after clay and replaces chalcedony in some depths. Secondary quartz forms at a wide range of temperatures but first at temperatures of approximately 180°C. First appearance of quartz occurs at 300 m in well OW-916, at 318 m in well OW-914A, at 650 m in well OW-912B and in well OW-919, quartz is first seen at 554m and is found sporadically upto 2250 m.

*Prehnite*; first appearance is shallower at well OW-914A at 836 m and occurs deeper in well OW-919 at 904 m. It is formed at temperatures above 240°C and is associated with quartz, epidote, chlorite and illite.

*Epidote*; appears to be filling fractures, vesicles, and occurs as a replacement of primary plagioclase and pyroxene. First appearance of epidote is noted at 556 m in well OW-916 (figure 6) and occurs deeper in well OW-919 at 950 m (figure 4) forming mineral associations with mainly quartz, prehnite, chlorite and actinolite. Occurrence of epidote indicates temperatures of above 250°C.

*Wollastonite*; was first observed at 914 m in well OW-916 and at 1260 m in well OW-912B. It is absent in wells OW-914A and well OW-919. It is associated with quartz, epidote, prehnite and actinolite. The first appearance of wollastonite marks a temperature of 270°C.

*Actinolite*; is observed at shallower depth in well OW-916 from 1030 m to bottom. It is observed at 1218m at well OW-914A, 1276 m at well OW-912B and deeper in well OW-919 appearing at 2064 m. It appears both as a replacement of clinopyroxenes and vesicle fillings forming sequences with quartz and clays. It occur in association with chlorite, prehnite and epidote and denotes temperatures of over 280°C.

*Garnet*; is rare in these wells. It was noted in contacts of intrusions with the host rock due to elevated temperatures. In wells OW-914A, OW-916 and 912B, garnet is noted at 2208 m, 1290 m and at 1046 m respectively and is associated with rhyolitic intrusions. However, garnet is absent in well OW-919, (figure 4). It denotes reservoir temperature of about 300°C, (Bird et al., 1984).

#### 4.4 Hydrothermal mineral zonation

Five mineral alteration zones are identified in the well and these are systematically zoned with respect to increasing temperature and depth. By using binocular, petrographic and XRD analysis the following alteration mineral zones could be identified. The five mineral assemblages include; smectite-zeolite zone, zeolite-illite zone, chlorite-illite zone, epidote-chlorite-illite zone and actinolite-epidote-chlorite-illite zone. The upper few hundred meters represent the unaltered zone with well OW-912B having the unaltered formations from surface to 136 m while wells OW-914A, OW-916 and OW-919 occurring to a depth of 100 m. Below the unaltered zone is the zeolite-illite layer which is noted to depth of 550 m. Other minerals occurring in this zone include opal/chalcedony and smectite. The chlorite-illite zone is shallower in well OW-914A at 480 m and deeper in well OW-912B at 548 m. It is associated with the appearance of secondary quartz, albite and adularia. Epidote-chlorite-illite zone is present in all the wells and is noted at 556 m at well OW-916 and occur to the bottom of the well. The actinolite-epidote-chlorite-illite zone is associated with the occurrence of wollastonite, prehnite, and garnet. It is encountered shallower in well OW-916 at 1030 m, at 1214 m in well OW-914A, at 1260 m in well OW-912B and deeper at 2064 m in well OW-919.

#### 4.5 Measured and hydrothermal alteration temperatures

A correlation between measured, hydrothermal alteration and the boiling point curves can infer the temperature conditions of a particular geothermal system. Common hydrothermal alteration minerals are used as geothermometers in the Olkaria Domes and their stability temperature ranges as estimated from measured temperatures. A comparison between the alteration, measured and calculated boiling point temperatures of well OW-919 (Figure 9) indicates that stable conditions have been constant in the well between 800 and 900 m. This is manifested where the well shows near boiling conditions. However, the reservoir below 1000 m has undergone some cooling and shows a temperature inversion below 900 m. Quartz (stable above 180°C) occurs at 554 m where measured temperatures indicate 50°C., prehnite (stable above 230°C) and epidote (stable above 250°C) located at depths of 904 m and 950 m respectively, occur at measured formation temperatures of approximately 240°C, this reflects the current conditions in the reservoir. At 2064 m, actinolite (stable above 280°C) is noted at current formation temperatures of 223°C which shows some cooling of the reservoir around the well at that depth.

From alteration mineral sequence of OW-914A, it indicates a prograde evolution from lower to higher temperature alteration minerals. Fine-grained clays appeared, succeeded by coarse-grained clays, and then epidote. From these analyses, it is inferred that the system has been in a state of equilibrium. The fluid inclusion analyses more or less lie within the alteration mineral temperature curve. This indicates that no significant temperature changes have occurred from the time the inclusions were trapped to the time alteration minerals started forming. Owing to the limited number of temperature recovery logs, it has been difficult to make a reliable estimate of the formation temperatures in well OW-914A. Therefore it is not possible to compare the thermal history in the alteration minerals to the present conditions.

In well OW-916, (Figure 10) the relationship between the fluid inclusion geothermometry, current measured temperature, alteration mineral temperature and the boiling point curve shows that the geothermal system has cooled to less than (~25°C). This is particularly so when comparing the estimated formation temperature with the first appearance of selected hydrothermal alteration minerals. For example, epidote was first observed where the measured formation temperature was below its temperature stability range. This indicates that it was formed under the past geothermal conditions that prevailed in this system. But fluid inclusion temperatures seem to reflect current conditions. The average homogenization temperature of 282°C is close to the measured formation temperature of 276°C, indicating quartz crystals recrystallized within this temperature range. This infers that the system is in a state of equilibrium.



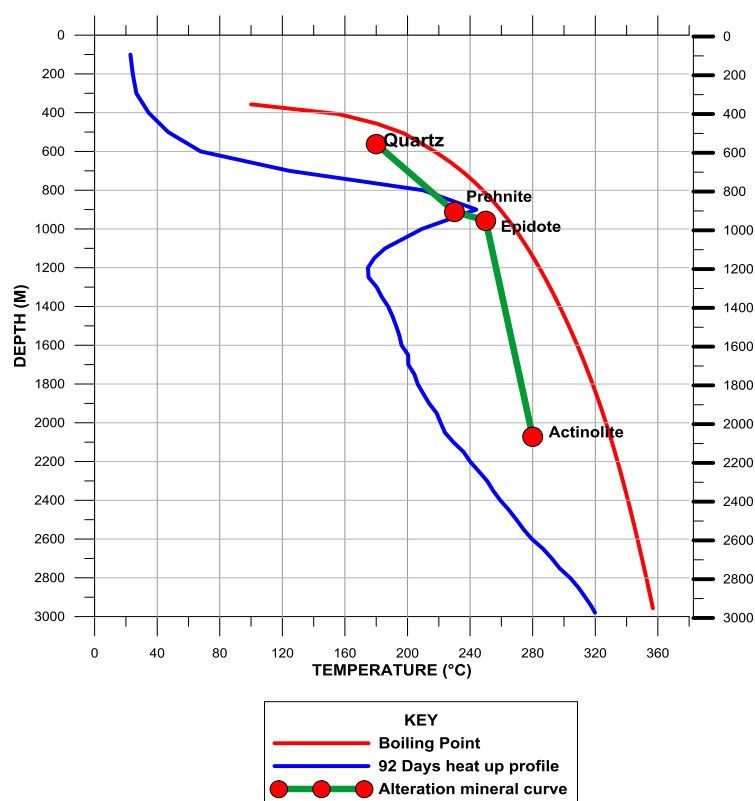


Figure 9: Comparison of alteration temperature with measured temperature and boiling point curve of well OW-919

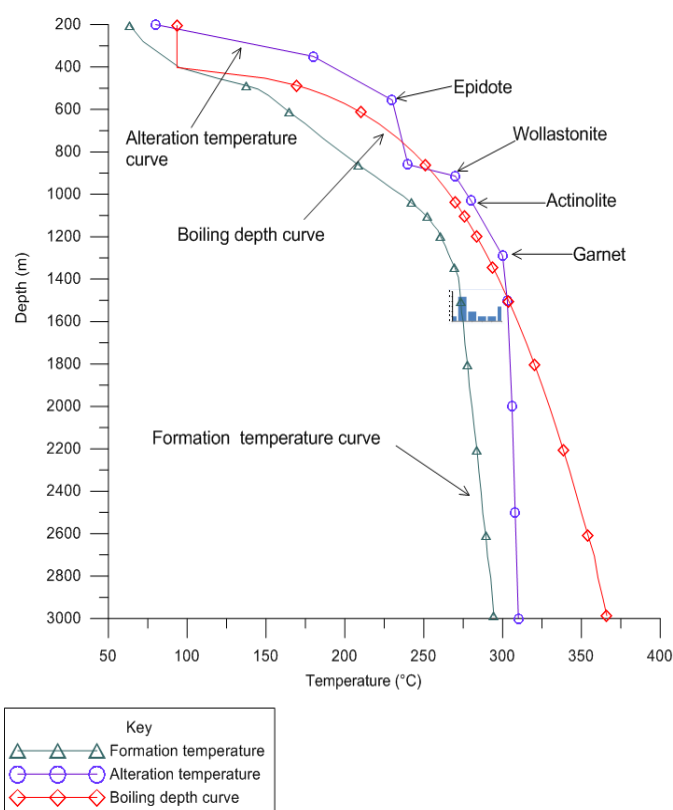
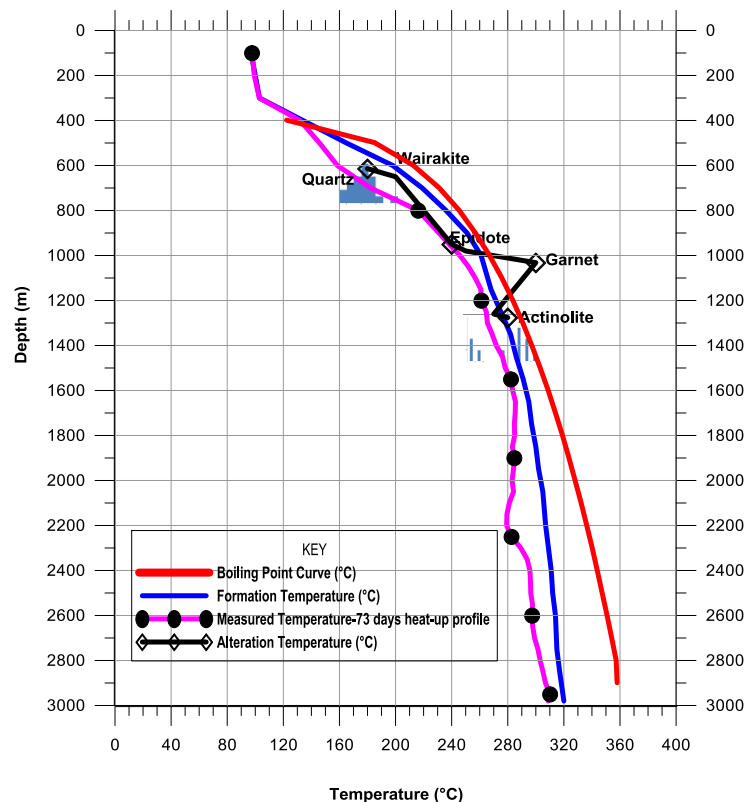


Figure 10; Comparison of alteration temperature with measured temperature, formation temperature, boiling point curve and results of fluid inclusion analysis of well OW-916

In well OW-912B, the comparison between the alteration, measured and formation temperatures shows that the reservoir temperatures are near equilibrium (Figure 11). The occurrence of quartz (stable above 180°C) and presence of fluid inclusions from quartz veins (with homogenization temperatures averaging 176°C) at current formation temperatures of 200°C, reflect no major

changes in reservoir temperatures over time. Epidote (stable above 240°C) occurs at measured formation temperature of >240°C, reflecting the current conditions in the reservoir. Boiling conditions are encountered between 1000 m to 1180 m (Figure 11) associated with high permeability. Elevated temperatures at this depth resulted to formation of garnet. This implies that the prevailing temperatures are in excess of 300°C (Browne, 1993). The high permeability zone is characterized by a rhyolitic intrusion and is related to the contacts of the intrusive.

High temperature hydrothermal alteration minerals e.g. actinolite and wollastonite encountered are within their temperature stability ranges and seem to be at equilibrium with the present geothermal system below 1200 m. The temperature determinations are mostly derived from the comparison of formation temperatures and the respective alteration mineral occurrences. As geothermal systems are very dynamic in nature, it must be expected that formation temperatures would fluctuate to some extent, making the comparison more difficult and error margin higher. The introduction of fluid inclusion studies is therefore a very important addition to these alteration temperature determinations as they measure the actual temperatures at those locations.

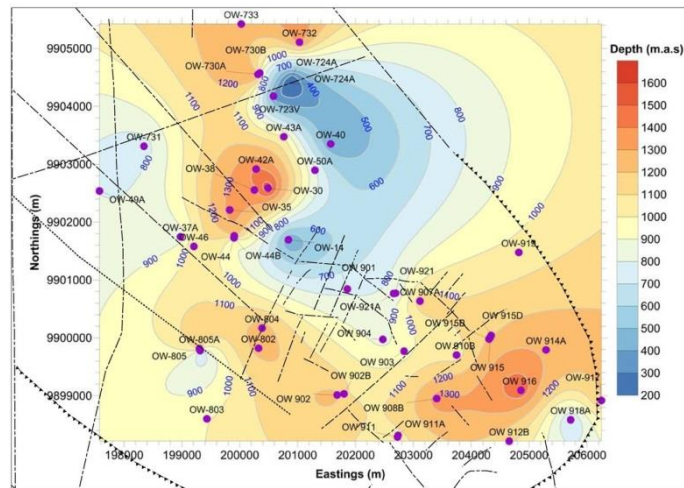


**Figure 11; Comparison of alteration temperature with measured temperature, formation temperature, boiling point curve and results of fluid inclusion analysis of well OW-912B**

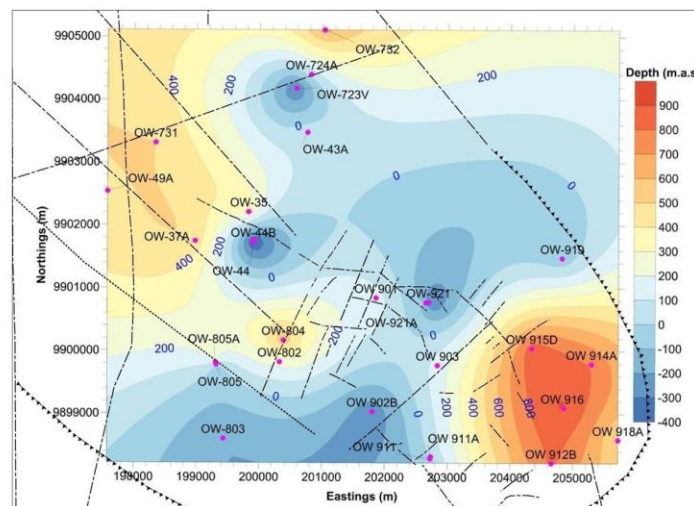
## 5. GEOLOGICAL CROSS-SECTION ACROSS THE OLKARIA DOMES WELLS

Hydrothermal alteration minerals can be used to observe the changes in the reservoir. Temperature dependent minerals are significant when determining the entrance to the reservoir and the production casing depths. The alteration intensity shows a quantity of fluid flow through the rock, therefore it is an indication of porosity/permeability. Isograds give a general picture of the temperature distribution in a geothermal system as they delineate the first appearance of an index mineral. However, a definite isograd (e.g. the epidote isograd) does not necessarily represent a definite temperature. The distribution of hydrothermal minerals isograds may not be distinctly parallel to the isothermal contours indicating that some thermal changes could have taken place in a geothermal reservoir over time. An attempt was made to compare first appearance of alteration minerals in four wells OW-919, OW-914A, OW-916 and OW-912B in Olkaria Domes field in order to appraise the field and determine the extent of the reservoir eastwards. Index minerals used to construct an isograd across the wells include chlorite, epidote and actinolite, with minimum stable temperatures of 200, 240 and 280°C respectively, (Figure 14).

The isotherms (Figure 13 and 14) clearly indicate that some of the wells are located at the up-flow zone while some show outflow characteristics. The updoming of alteration temperatures around OW-916 could infer an upflow zone in the reservoir around the well. From the first occurrence of the alteration minerals it is evident that they occur shallower around well OW-916 and gets deeper away from the well. Well OW-919 shows a deeper high temperature zone characterized by the existence of high temperature mineral assemblages.



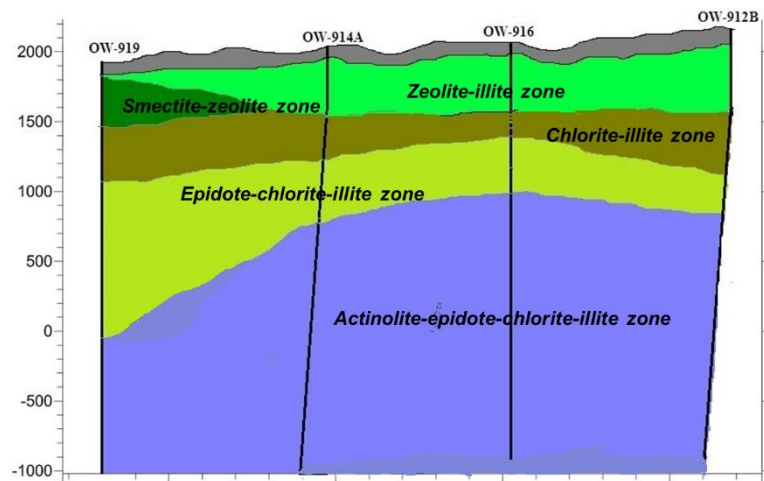
**Figure 12: First appearance of epidote in Olkaria geothermal wells with wells OW-919, OW-914A, OW-916 and OW-912B highlighted in red on the east of the map.**



**Figure13: First appearance of actinolite in Olkaria geothermal wells with wells OW-919, OW-914A, OW-916 and OW-912B highlighted in red on the east of the map.**

The boundary between one zone and another was defined by the first appearance of the successive dominant alteration mineral. The top 136m is the unaltered zone which uniformly appears across all the wells, (Figure 14). This zone is characterized by oxidation of the rock formation with deposition of siderite and limonite evident. Smectite-zeolite zone is present in well OW-919 while replaced by the Zeolite-illite zone in wells OW-914A, OW-916 and OW-912B. Chlorite-illite zone is marked by the dominance of the clay minerals hence act as the entrance into the reservoir. First occurrence of epidote characterizes the Epidote-chlorite-illite zone which indicates that well OW-916 shows an updoming in reservoir temperatures in the well. Well OW-919 shows the occurrence of high alteration minerals at relatively deep levels than the other analyzed wells. The Actinolite-epidote-chlorite-illite zone occurs deeper at 2064m in well OW-919 in association with quartz and prehnite, (Figure 4).

OW-914A has a shallow chlorite and epidote occurrence but at depth, actinolite appears deeper as it gets away from the upflow zone. From figure 14, it is clear that epidote is relatively shallow at well OW-919 but actinolite appears much deeper. This shows epidote temperatures prevailing much deeper before actinolite forms. OW-912B has epidote appearing deepest but approaches actinolite temperature before OW-919. This could mean that lower temperatures (a cold zone above 400 m) dominated the shallow depths but the well is hotter at bottom since it is closer to the up-flow zone. OW-912B is drilled in the direction of the up-flow zone.



**Figure 14: A cross-section of wells OW-919, OW-914A, OW-916 and OW-912B (Drawn not to horizontal scale)**

## CONCLUSION

Major rock types encountered in the Olkaria Domes geothermal wells include pyroclastics, rhyolites, tuffs, basalts and trachytes. Minor basaltic, rhyolitic and microsyenite intrusive occur in the subsurface. These rocks were recorded in wells OW-919, OW-914A, OW-916 and OW-912B with thin basaltic and rhyolitic dykes drilled through below 1000 m.

Temperatures encountered in the east of Olkaria Domes geothermal field exceed 250°C indicating high temperature reservoir. High temperature minerals are encountered shallower at wells OW-914A and OW-916 are found deeper or absent in the well and OW-919. OW-912B is drilled in the direction of high temperatures.

A comparison between current measured formation, alteration mineralogy and fluid inclusion measurements indicate that the area around wells OW-916, OW-914A and OW-912B are in a state of equilibrium. However temperature inversion is noted below 1000 m well OW-919 and denotes cooling by cold fluid incursion.

From shallower occurrences of high temperature minerals in OW-914A and OW-916, there is a strong indication that the wells are situated at the upflow zones of the field. Well OW-912B is drilled towards the upflow zone while well OW-919 is seen to be at the outflow zone of the geothermal system.

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