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STRATIGRAPHY HYDROTHERMAL ALTERATION AND PALEO-THERMAL HISTORY OF THE OLKARIA - DOMES GEOTHERMAL FIELD KENYA

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ABSTRACT

Paleo-thermal history, stratigraphy and alteration mineralogy within the Domes field has been of keen interest for the purpose of reservoir monitoring and field expansion. In this paper, we present results of analysis whose objective was to understand temperature changes in Domes area over time. In this study, four wells were analysed. The wells were selected from the eastern and southern sectors of the Domes field. They include OW-914A, OW-916, OW-911A and OW-912B. Rocks encountered in wells OW-914A, OW-916, OW-912B and OW-911A include pyroclastics, rhyolite, basalt, tuff and trachyte. The latter is the most dominant rock type. The wells cut across two intrusives: syenite intrusion and basaltic dyke. However, the depths of the first appearance of alteration minerals in the study wells vary from one well to another. For example, epidote, a high temperature Ca-silicate mineral, was first encountered at 556 m depth in OW-916, 670 m in OW-911A, 732 m in OW-914A and 950 m in OW-912B. Other hydrothermal minerals present include zeolites, quartz, albite, pyrite, Fe-Ti oxides (e.g. titano-magnetite and ilmenite), calcite, chalcedony, prehnite, wairakite, epidote, actinolite, chlorite, and garnet. The highest recorded formation temperature in the four wells is 280 °C, which correlates well with alteration mineral assemblages at various depths. Fluid inclusion in secondary quartz recorded minimum temperature of 160 °C and maximum of 300 °C at 765 m and 1600 m, respectively. These temperatures more or less lie within the same range as alteration mineral and formation temperatures. This is a clear indication that no significant temperature changes have occurred from the time the system was formed, through alteration period to the current time of the Domes field system.

1. INTRODUCTION

The Olkaria geothermal system is a result of the Greater Olkaria Volcanic Complex (GOVC). The latter is located within the southern central sector of the Kenya Rift Valley about 125 km northwest of Nairobi city (Figure 1). Other volcanic centres located within the axial rift system from north to south include: Barrier, Emuruangogolak, Silali, Paka, Korosi, Menengai, Olkaria, Longonot, Eburru and Suswa (Figure 1). Geothermal exploration survey carried out in the past (Omenda, 1998) indicates that these volcanic centres are characterised by shallow intrusions. These intrusions have resulted into high thermal gradient at these centers. Three volcanic centers, namely Olkaria, Eburru and Menengai are in their geothermal production stage.

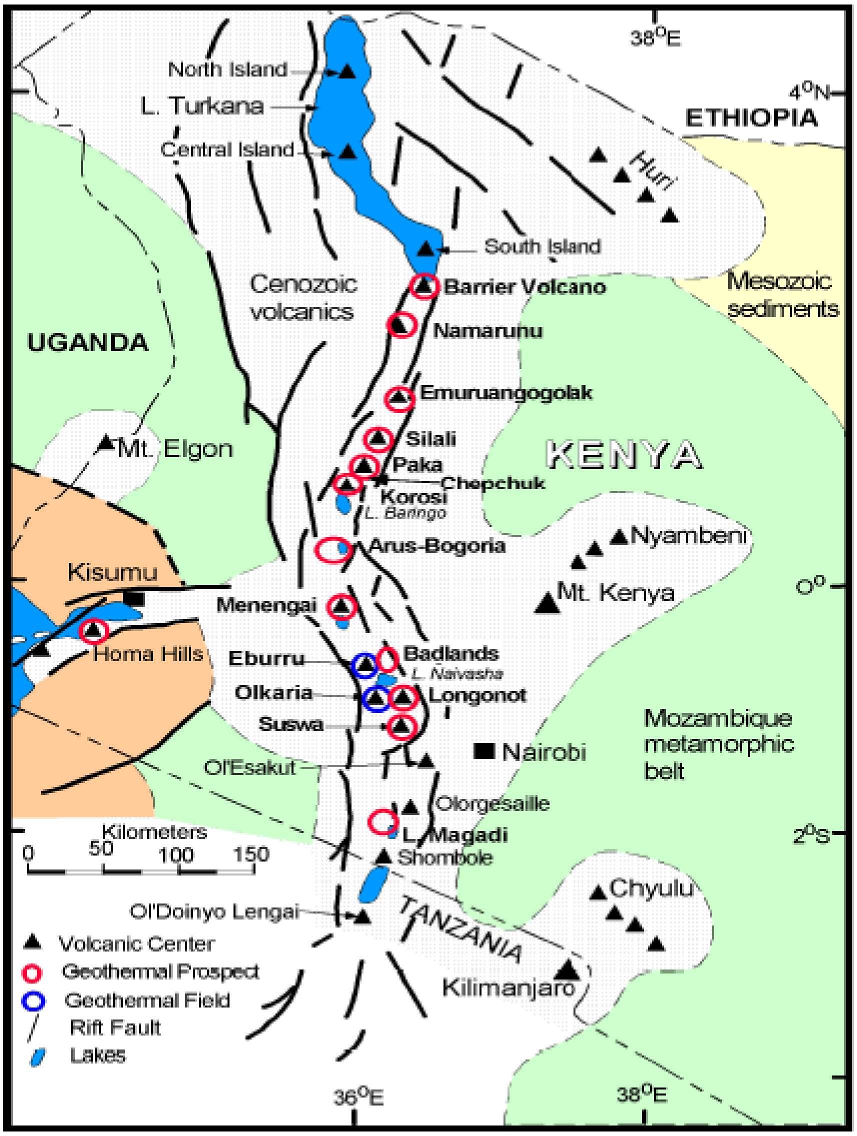

Figure 1: Simplified geological map of Kenya showing locations of geothermal field and prospects (from Simiyu, 2010).

1.1. Objectives

Different geothermal fields reveal different paleo-thermal histories depending on the tectonic settings and history of the fields. Understanding the paleo-thermal trends of geothermal fields is important in power plant management and monitoring. This also helps in siting of step-out wells. The paper presents a review and comparison of stratigraphy and hydrothermal alteration mineralogy from the four wells highlighted earlier. Also, a comparison for the paleo-thermal trends recorded in the four wells is made. From the comparison, a conclusion is drawn about the stratigraphy, alteration mineralogy and paleo-thermal history of the Domes field.

1.2 Olkaria Geothermal Field

Olkaria geothermal field is a high temperature geothermal field with an estimated resource area of 204 km^2. The geothermal field is divided into seven sub-fields (or sectors) for the ease of geothermal development and management (Figure 2). These include the Olkaria east, Olkaria Northwest, Olkaria Southeast, Olkaria Northeast, Olkaria Southwest, Olkaria Central and Olkaria Domes fields. Briefly, the surface geology is mainly characterised by ash deposits, pumice lapilli, pyroclastics and comenditic lava (Clarke et al., 1990). Pyroclasts cover most parts of Olkaria geothermal area. In contrast, sub-surface data from the wells reveal five distinct rocks units. These include pyroclasts, tuff, basalt, rhyolite and trachyte. Basaltic dykes, syenitic, micro-granite and granitic intrusions also occur (e.g. Lagat, 2004).

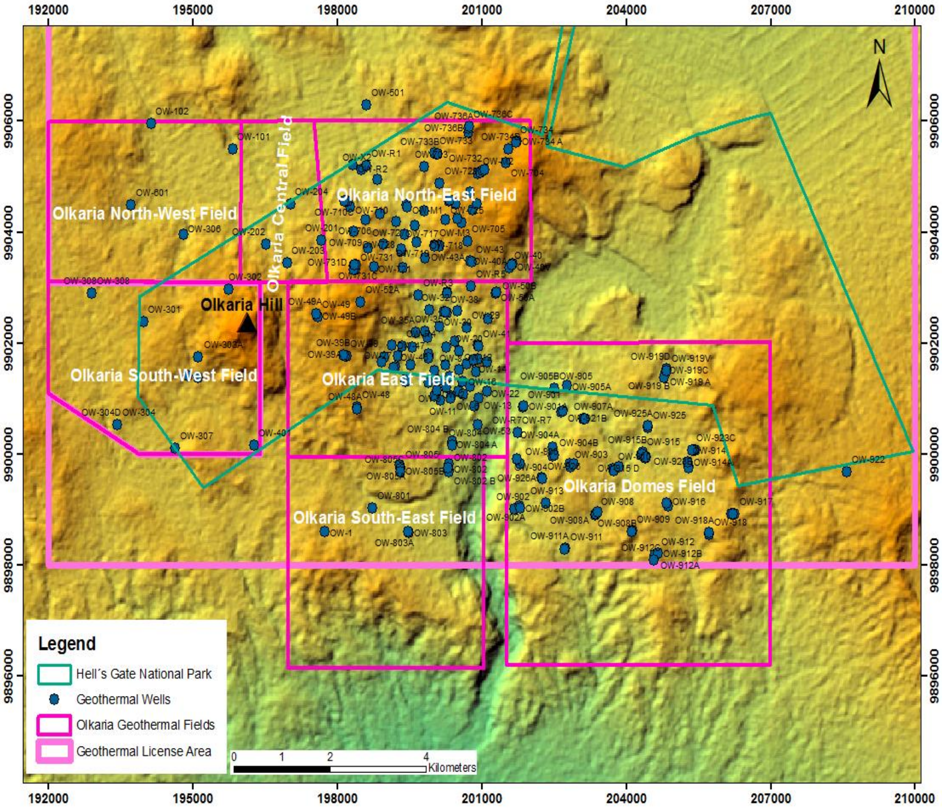

Figure 2: The seven divisions of Olkaria geothermal field.

Exploration for geothermal resources in Olkaria began in 1950s. The first unit of the first power plant was commissioned in 1981. It generates 15 MWe. Two more units were added in 1982 and 1985 with each generating 15 MWe. It has three units and generates a total of 45 MWe. This power plant taps steam from the Olkaria east field and generates a total of 45 MWe. Two additional units each generating 70 MWe were added in 2014. Olkaria Northeast generates 105 MWe, Olkaria Northwest produces 140 MW and Olkaria central 2 MWe.

The Olkaria Domes has a generation capacity of about 172.8 MWe. Out of these, 140 MWe is derived from a conventional power plant, whereas, about 32.8 MWe is from well-head generators. Details about the development of these fields can be found in a study by Musonye (2015). More than 100 geothermal wells have been drilled in the Domes area. Examples of these wells include OW-914A, OW-916, OW-912B and OW-911A. These wells have been chosen for this study and their location within the Domes field is shown in Figure 3. The wells were drilled to a total depth of about 3000 m. Sub-surface data from the wells provide useful insights into the hydrothermal alteration and paleo-thermal trends of the Domes field.

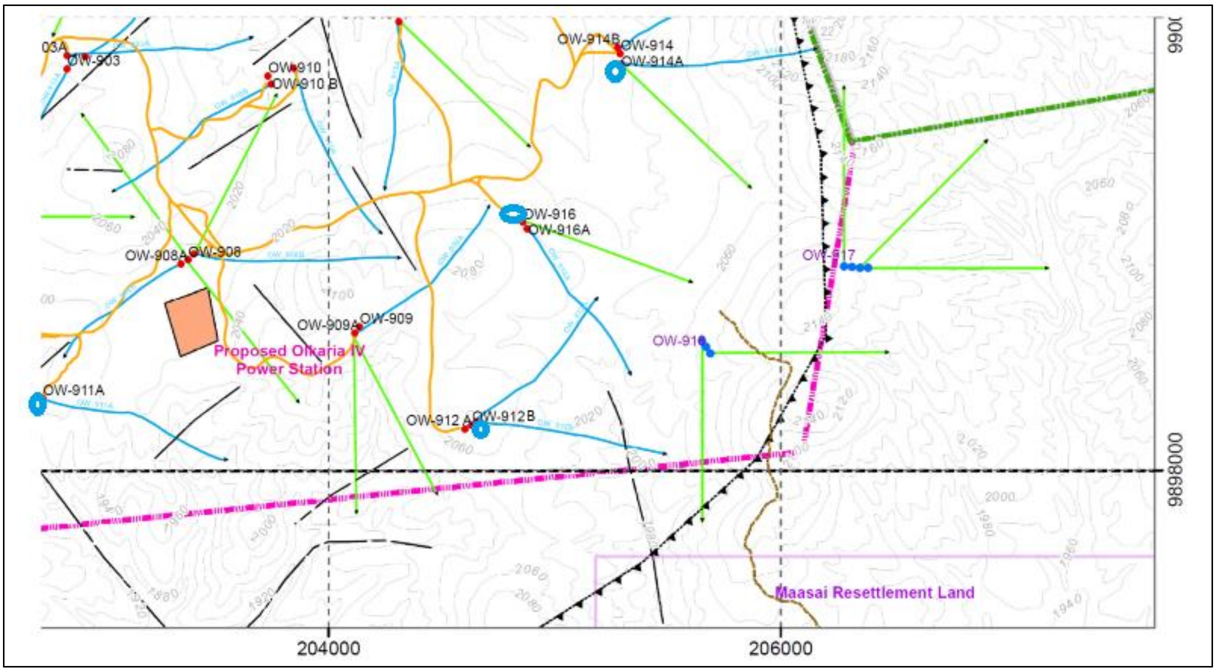

Figure 3: Figure showing the location of the study wells.

2. SAMPLING AND ANALYTICAL TECHNIQUES

Sampling was carried out at the rig during drilling. Drill cutting samples were collected at 2 m intervals. 1200-1400 samples were analysed from each well. The number of samples from each well depended on the depths at which losses were encountered. Depths at which loss of drill cuttings were encountered were also recorded. Descriptions of the stratigraphy and hydrothermal alteration mineralogy of approximately 4300 samples were based on binocular microscope, petrographic and X-ray diffraction analyses.

For binocular analysis, the samples were washed in clean water to remove impurities and dust in order to enhance visibility and reveal features such as finely disseminated sulphides, e.g. pyrite. The sample was mounted on the stage of a binocular microscope and its properties observed. For petrographic microscope analysis, samples were selected at 20 m interval. In other instances, the samples were also selected depending on the change of lithology as observed under binocular microscope. The samples were dried, mounted on a glass slide and grounded to 20 microns. These samples were mounted on a petrographic microscope stage and their properties observed.

From the three analyses, classification of lithological units was done. The classification of these lithological units was based on the colour, texture and mineralogy (e.g. presence of quartz as a primary mineral or its absence thereof, abundance of sanidine or plagioclase feldspars, mafic minerals and the presence of lithic groundmass).

X-ray Diffractometer analysis was done to find out the type of clays present in these wells. A teaspoon full of cuttings was taken from the selected cuttings samples and placed in water in a test tube. This was shaken for four hours by arranging the test tubes in a shaker to dissolve the clays out of the drill cuttings. Drops of water from each of the dissolved drill cutting were each placed on a slide, which had been washed by acetone to enhance cohesion and adhesion of the water and the slide, where they settled for twelve hours before being taken for analysis. The samples were analysed under heated, air-dried and glycolated conditions.

For the paleo-thermal studies, analysis of primary and secondary fluid inclusions was carried out using fluid inclusion geothermometry. Primary inclusions are formed during mineral crystallisation while secondary inclusions are formed during mineral re-crystallisation. In this study, focus was placed on homogenisation temperature of secondary fluid inclusions. Quartz mineral grains containing fluid inclusions were selected from the samples. The grains were mounted on a glass slide and polished. They were mounted on a fluid inclusion microscope stage and heated. The temperature at which the fluids trapped in the inclusions homogenised was recorded. Fluid inclusions preserve the thermal history of the system during its inception. Upon heating, the trapped fluid vaporises into one phase on attaining homogenisation temperature (T_h) which gives us the temperature conditions at the time the system was formed. The geo-fluids have paleo-microscopic records of composition, temperature and pressure conditions that existed at the time these fluids were trapped. Forty fluid inclusions selected at 836 m depth were heated in well OW-914A. In well OW-911A, fifteen fluid inclusions obtained at 1050 m depth heated while for well OW-916, thirteen fluid inclusions at 1600 m depth were analysed. Two sets of fluid inclusions were heated for well OW-912B. Twenty-one inclusions were selected at 756 m depth and ten inclusions at 1456 m depth.

To reconstruct the temperature history of the Domes area, a correlation was made between the fluid inclusion homogenisation temperature, alteration mineral temperature and formation temperatures of the study wells. However, OW-914A was not given enough time to heat up before being discharged. Therefore, no stable formation temperature was measured. In this case, fluid inclusion homogenisation temperature was compared only with alteration mineral temperature.

3. RESULTS

3.1 STRATIGRAPHY

From the results of the binocular and petrographic analyses, it was found that the wells cut through five rock units. These include pyroclastics, rhyolite, tuff, basalt and trachyte. Figure 4 summarises the rock units encountered or intersected in these four wells.

Pyroclastics: Pyroclastics form the top most part of the stratigraphy. The unit varies in thickness between 70 and 100 m. It is brown to yellow, unconsolidated mixture of volcanic glass, scoria, pumice, tuff, rhyolitic and trachytic fragments. Volcanic glass, which is highly susceptible to alteration is noted altering to palagonite. It is also oxidised as a result of interaction with descending oxygen-rich groundwater, forming limonite. Pyroclastics are thicker in Domes field compared to the other Olkaria geothermal fields (Lagat, 2004). The pyroclastics are believed to have come from three sources; Olkaria, Longonot and Suswa volcanic centers (Clarke et al., 1990). The Longonot and Suswa volcanic centers are believed to have erupted in more or less the same period as Olkaria.

Rhyolite: The main rhyolitic units occur between 100 and 500 m depth. Below 500 m, the unit mostly occurs as thin intercalation in other rock units. There are two different types of rhyolite observed in these wells. One is the spherulitic rhyolite and the other granular rhyolite. Spherulitic rhyolite is glassy to light grey, fine grained, moderately to highly porphyritic. Quartz and sanidine phenocrysts dominate the finely grained quartz rich groundmass. Micro-phenocrysts of aegirine, augite and riebeckite are also observed. Its distinguishing feature is the spherulitic texture which is characterised by bands of sanidine, quartz and pyroxene (aegirine-augite) radiating from a central point. This is also called the comenditic rhyolite (Lagat, 2004).

Granular rhyolite is pink to brownish in colour. It is aphyric to moderately porphyritic. Finely grained quartz and sanidine forms the groundmass. In moderately porphyritic samples, minute pyroxene, riebeckite and magnetite form the phenocrysts. The rhyolite and pyroclasts form the Upper Olkaria Volcanic sequence of the GOVC stratigraphic classification scheme by Omenda (1997).

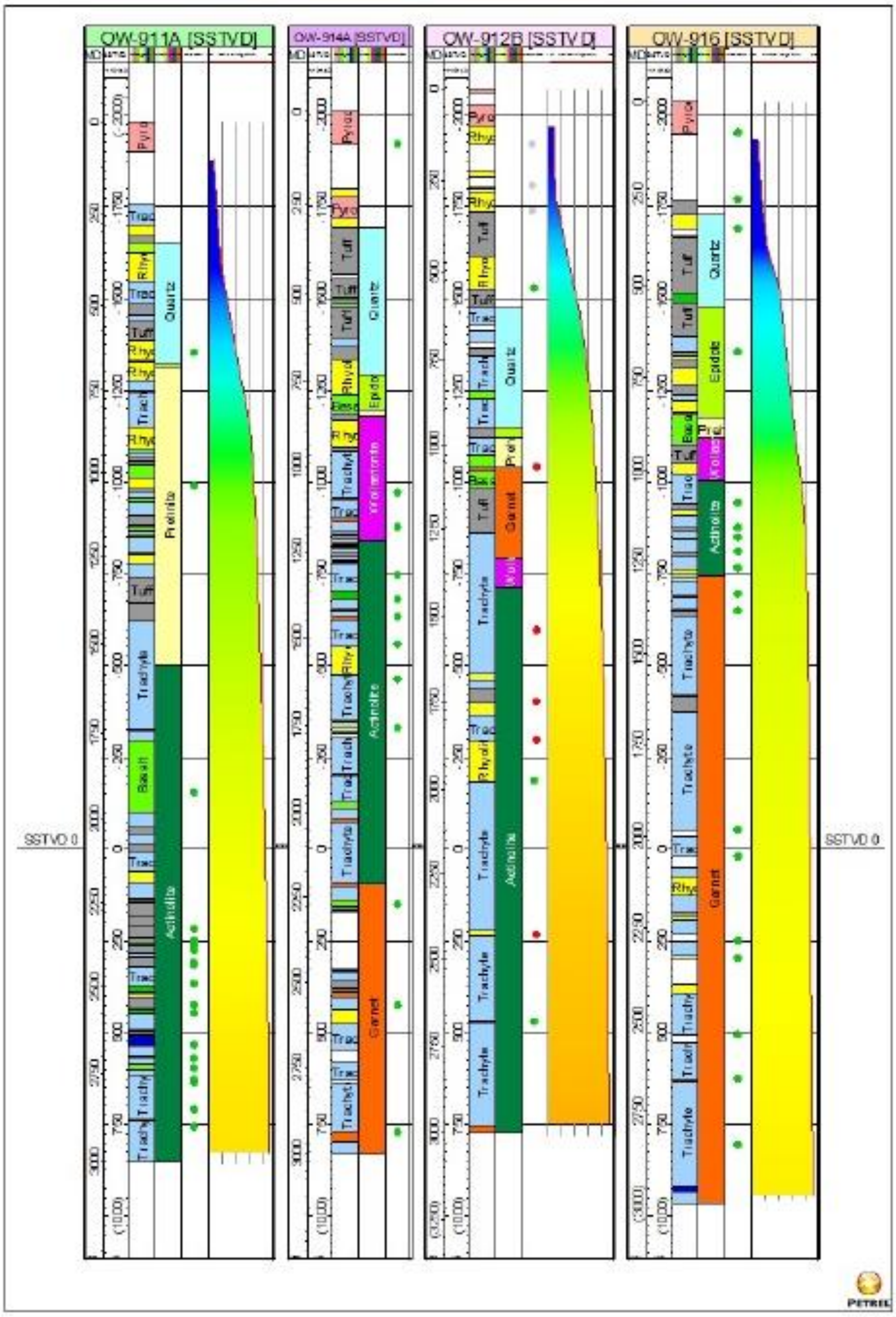

Figure 4: Stratigraphic columns and alteration minerals as observed in the four wells.

Tuff: Tuff was found to mainly occur between 0-600 m. It was also observed extending to 2600 m depth but as intercalation between other rock units. Tuff was observed in two distinct textures; lithic tuff and vitric tuff. Tuff occurred as thin layers ranging from as low as 5 to 30 m. The lithic tuff is grey to brown in colour with ash-like groundmass in which are embedded sub-hedral to euhedral quartz, sanidine, aegirine-augite, amphibole and volcanic glass crystals fragments. Basaltic, rhyolitic and trachytic rock fragments were also observed in the groundmass. It is vesicular with the vesicles being filled with alteration minerals, for example zeolite, mesolite, prehnite, quartz and epidote.

The vitric tuff was observed to be white, non-crystalline and highly vesicular. Quartz phenocrysts are embedded in the groundmass. When observed under petrographic microscope, the groundmass appeared glassy. The tuff ash in Olkaria is also believed to have come from the three volcanic centers; Olkaria, Longonot and Suswa (Opondo, 2007). Some of the tuff layers (those found at greater depth) form part of the Mau Tuffs stratigraphic unit of the GOVC stratigraphic column.

Basalt: Basaltic units were detected at between 500-1000 m depth. They form part of the Olkaria Basalt unit of the GOVC stratigraphic column. Below 100 m, they occur as intercalations between trachytic rock units. Basalts range in colour from grey, dark grey to green grey, fine to medium grained, moderately to highly porphyritic with phenocrysts of clinopyroxenes and plagioclase. The groundmass is rich in plagioclase feldspars and clinopyroxenes which interlock in a randomized manner. The olivine mineral is highly susceptible to alteration and cannot be observed due hydrothermal conditions under which the rock has been subjected to. However, the shape of olivine is noted to have been retained by the clays and/or calcite which commonly replace the mineral. In Olkaria East and NE fields, the basalt forms an important marker bed at about 500 m depth which was used in many cases to determine production casing shoe.

Trachyte: The analysis showed that Trachyte was the dominant rock unit in the Domes area stratigraphic column. In these four wells, it occurs from 600 m depth to the bottom of the wells. The trachyte varies in texture with some units showing flow texture. It varies from light grey, grey to whitish in colour. In other instances, the trachyte shows greenish colour as a result of chloritization. The groundmass is characterised by abundant sanidine, pyroxenes, rare microcline, albite and quartz. The texture varies from aphyric to phyric. For the phyric varieties, sanidine and pyroxene phenocrysts are observed. The various trachytic textures represent different eruption episodes that characterised GOVC formation. Some of the trachyte units belong to the Plateau Trachyte formation of the GOVC stratigraphic column while other trachyte units might be younger than the Plateau Trachyte group

3.2. OCCURRENCE AND DISTRIBUTION OF COMMON HYDROTHERMAL MINERALS

Hydrothermal alteration minerals occur either as deposition or replacement minerals. As depositional minerals, they occur filling in vugs, vesicles and fractures. For replacement minerals, they replace primary rock forming minerals, for example sanidine, pyroxene, plagioclase, volcanic glass and amphiboles. From the study of fluid-rock interaction dynamics, it has been ascertained that certain alteration minerals are deposited at specific temperatures. For example, Quartz is deposited at a minimum temperature of 180 °C, epidote at 240 °C, actinolite at 280 °C and garnet at 300 °C (Browne, 1978). Studies conducted in various geothermal fields around the world has made it possible to correlate formation temperature with alteration minerals. In a geothermal system that has retained a steady state of thermal equilibrium, alteration mineral temperature is more or less similar to formation temperature at a given depth.

Hydrothermal alteration minerals observed in the study wells include; zeolites (mesolite, scolecite, thomsonite, heulandite, analcime and wairakite), calcite, pyrite, chalcedony, opal, quartz, epidote, prehnite, wollastonite, actinolite, sphene, haematite and clays (chlorite, illite, mixed layer clays and smectite). The abundance of alteration minerals in the study wells varies from one well to the other. A few of the alteration minerals, for example garnet and fluorite are only found in two of the four wells.

Low temperature zeolites are found at shallow depth. These include mesolite, scolecite, heulandite, thomsonite and analcime. They are found between 200-240 m in OW-914A, 366-464 m in OW-12B, 222-468 m in OW-911A and 50-100 m in OW-916. The stability temperature of these minerals range between 60 °C -100 °C. The occurrence of these minerals at shallow depth indicate relatively lower temperatures at these depths.

Fe-Ti oxides are also observed in these wells. They include sphene, rutile and hematite. Hematite is an indication of cooler oxygen-rich water influx into the formation. It was only observed in OW-911A where it occurred between 282-1246 m. Sphene may indicate high or low temperature influx of fluids. This is deduced from the other type of alteration minerals present.

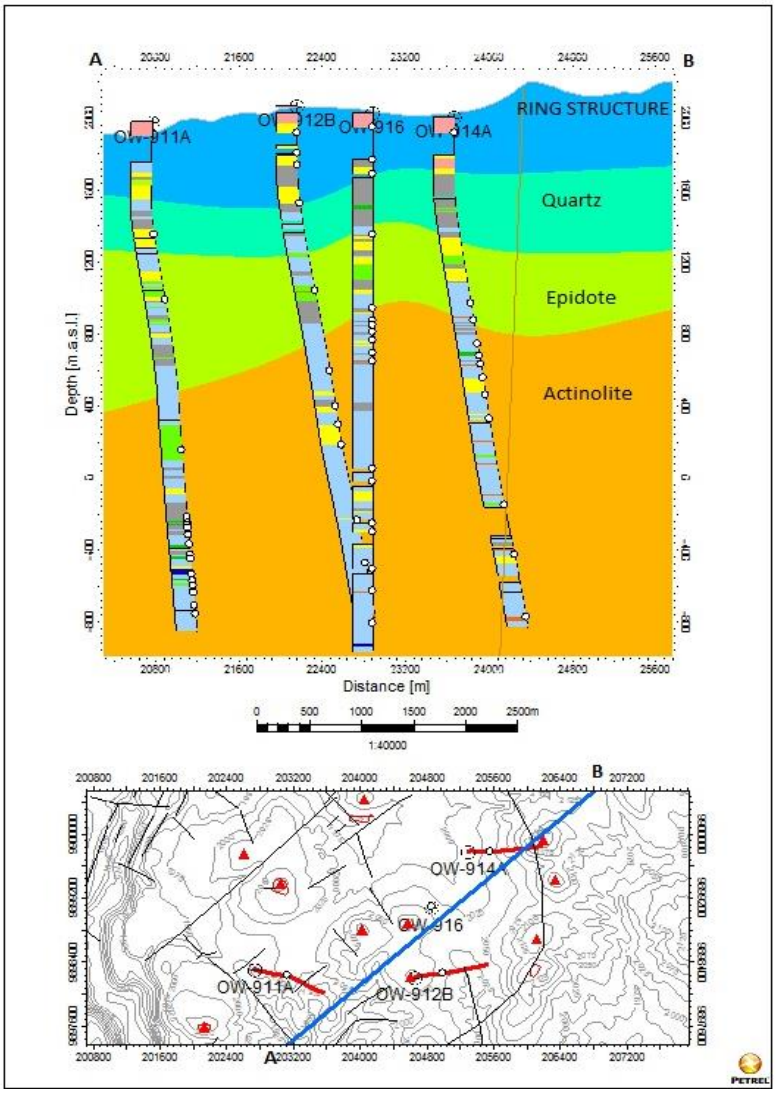

Figure 5: A cross section showing the occurrence of quartz, epidote and actinolite across the three wells.

The distribution of calcite and pyrite varies from well to well. In well OW-914A, calcite is observed from 350 m down to the bottom of the well. However, its abundance diminishes with increase in depth. In OW-916, calcite occurs between 266-1900 m while in OW-911A and OW-912B it occurs between 222-1200 m and 544-1544 m respectively. Calcite is an alteration mineral which indicates permeability. Calcite has stable deposition temperatures ranging between 50 °C to 280 °C. Platy calcite s associated with boiling conditions and it indicates temperature of above 270 °C. Pyrite on the other hand occurs from 404 m in OW-914A down to the bottom of the well. In wells OW-916, it occurs from 266-850 m with its intensity decreasing below 850 m. In OW-912B, it occurs between

102-2682 m while in OW-911A occurs from 222-1200 m. Pyrite is a good indicator of permeability and together with formation temperature curves, can be used to delineate feed zones.

Amorphous silica, which include opal and chalcedony is found at shallow depth except in well OW-912B. Amorphous silica is associated with low temperature. Opal is stable below 100 °C while chalcedony is stable between 100-180 °C. In OW-914A, they are found between 102-450 m, 266-408 m in OW-916, 342-526 m in OW-911A and 112-1090 in OW-912B. These zones associated with the low temperature minerals were cased off.

Secondary quartz and wairakite are stable at temperatures of 180 °C to 300 °C. Quartz occurs across all the wells. Its first appearance was noted at 318 m in OW-914A, 340 in OW-911A, 300 in OW-916 and 650 m in OW-912B. They occur down to the bottom of the wells. In some instances, quartz is observed deposited in association with other higher temperature minerals. For instance, in OW-914A, quartz is observed deposited in association with wairakite, epidote and wollastonite in that successive sequence. This is an indication that the system has been heating up or was at one time heating up.

Three types of clays were noted in these wells. They include illite, chlorite and mixed layer clays. Illite is found from 278 m in OW-914A, 418 m in OW-916, 600 m in OW-600 and at 377 m in OW-912B. Chlorite was first noted at 480 m in OW-914A, 578 in OW-916, 598 in OW-911A and 548 m in OW-912B. Mixed layer clays were observed between 700-1200 in well OW-916, 962-2178 in OW-912B and 1318-2900 m in OW-911A. These clays are formed at 200 °C.

High temperature alteration minerals observed in the three wells include prehnite, epidote, actinolite, wollastonite and garnet. These minerals were observed in high abundance in wells OW-916 and OW-914A compared to wells OW-912B and OW-911A. Prehnite and epidote are stable at 240 °C, actinolite and wollastonite at 270 °C and 280 °C respectively. Garnet is stable at 300 °C. The first appearance of these minerals in well OW-912B is at a relatively deeper depth as compared to the other three wells. Epidote is first observed at 732 m in OW-914A, 556 m in OW-916, 670 m in OW-911A and 950 m in OW-912B. Wollastonite is first observed at 856 km in OW-914A, 914 m in OW-916, 1100 m in OW-911A and 1276 m in OW-912B. Garnet was noted at 2206-2208 m in OW-914A. The occurrence of the high temperature minerals at relatively shallow depth in wells OW-914A and OW-916 indicate high temperature regimes at shallow levels in these two wells (Figure 5). However, it is imperative to note that the mineral occurrence on the NE part of the cross section (beyond well OW-914A) in Figure 5 is an extrapolation and not a true representative of the real data. The data beyond OW-914A was not included in this plot. In some instances, these minerals are observed occurring in a paragenetic sequence. For example, epidote is observed deposited followed by actinolite then wollastonite in that successive order. This indicates lower to higher temperature thermal evolution.

3.3. PALEO-THERMAL RECONSTRUCTION

In well OW-916, the inclusions registered homogenisation temperature range between 275 °C and 305 °C, with an average of 282 °C. Figure 6 shows the homogenisation temperature recorded in the thirteen fluid inclusions. The estimated formation temperature at this depth is 276 °C. Comparison between fluid inclusion temperature and alteration mineral temperature curve showed that the Domes field has maintained a steady state of thermal equilibrium since its formation. The fluid inclusion temperature plot lies in the same path as the formation temperature curve. However, it is critical to note that the well was not given enough time to heat up before being discharged. The well was only given 9 days after the drilling was completed. Hence, the formation temperature is not a true reflection of the maximum temperature attained by the well. Comparison between homogenisation, formation and alteration mineral temperature showed a steady thermal state. The temperature difference between these curves is less than 20 °C. From the boiling point and alteration mineral temperature curves, it shows that the system was once above boiling conditions as indicated in Figure 6 between the 200-1500 m depth range.

The inclusions in well OW-914A recorded homogenisation temperature range between 250 °C and 290 °C, with a majority ranging between 250 °C and 255 °C as shown in Figure 7. The homogenisation temperature plot lies in a more or less same path as the alteration mineral curve. Comparison between homogenisation, alteration mineral temperatures and boiling point curve show that the system has been in a state of equilibrium. There is insignificant temperature difference between homogenisation temperature, alteration mineral temperature and boiling point curve. Owing to lack of temperature recovery logs, it has been difficult to make a reliable estimate of the formation temperature in well OW-914A; therefore, it is not possible to compare the thermal history in the fluid inclusion, alteration minerals and boiling conditions with the present conditions.

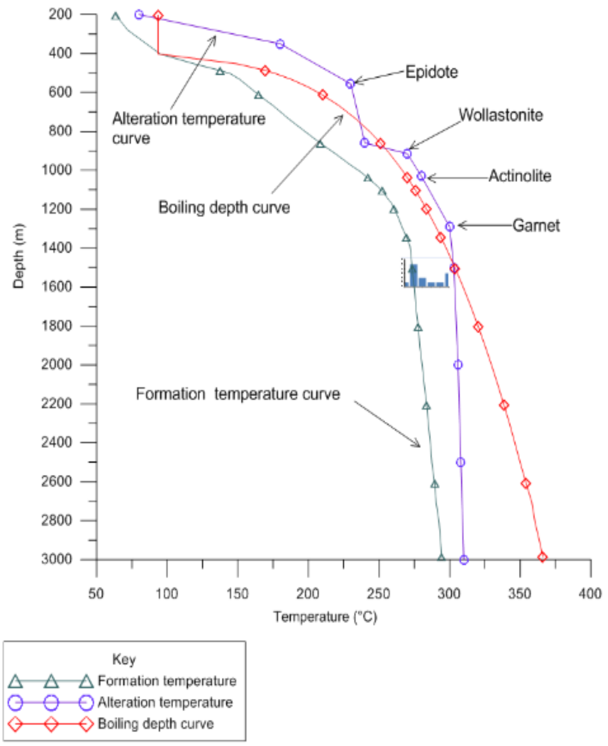

Figure 6: Alteration mineral temperature curve, formation temperatures, boiling point curve plotted alongside fluid inclusion temperatures for well OW-916. (The histogram represents fluid inclusion temp plots).

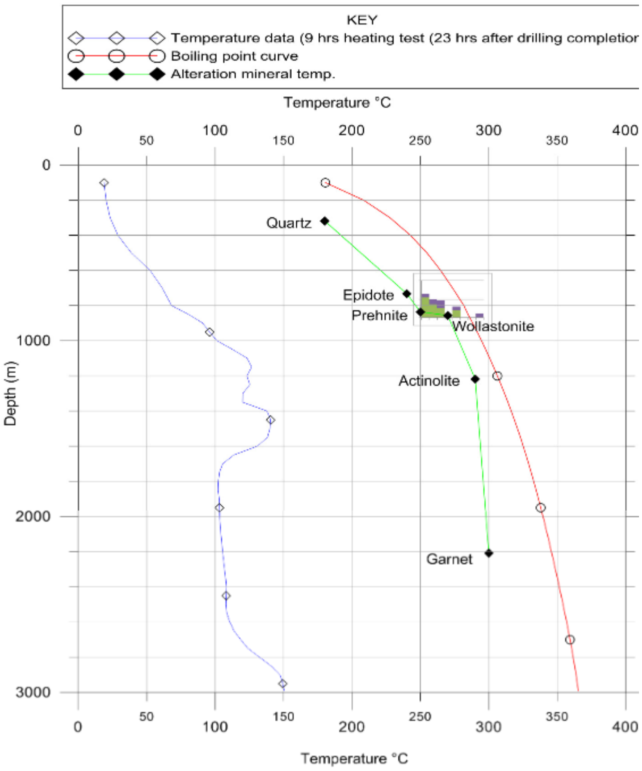

Figure 7: Alteration mineral temperature curve, formation temperatures, boiling point curve plotted alongside fluid inclusion temperatures for well OW-914a. (The histogram represents fluid inclusion temp plots).

They recorded homogenisation temperature in OW-911A range between 195 °C and 286 °C with majority of the inclusions recording between 215 °C to 220 °C. The homogenisation temperature lies in the same path as the formation temperature curve (Figure 8). The homogenisation temperature alteration mineral and formation temperatures exhibit a small temperature difference of less than 25 °C. This indicates a steady state of thermal equilibrium has been maintained over time. The difference between the formation temperature and the alteration mineral temperature can be attributed to the less time given to the well to heat up before being discharged. The temperatures recorded in this well are relatively lower compared to those recorded in wells OW-916 and OW-914A. This relates well to its distant location from the heat source, located around wells OW-916 and OW-914A in the Domes area (Musonye, 2015).

For well OW-912B, two sets of fluid inclusions were heated. The inclusions at 756 m depth recorded minimum homogenisation temperature of 160 °C and a maximum homogenisation temperature of 200 °C, with majority recording temperature range between 175-180 °C. The average homogenisation temperature is 176 °C. This is 20 °C less than the formation temperature at this depth. For the inclusions at 1456 m depth, two sets of temperatures range were recorded. The first set range between 250 °C and 260 °C. The temperature difference between the temperature recorded in this set and the formation temperature was 10-20 °C. The second set of temperature range between 270 °C and 300 °C. This set is 30 °C above the formation temperature.

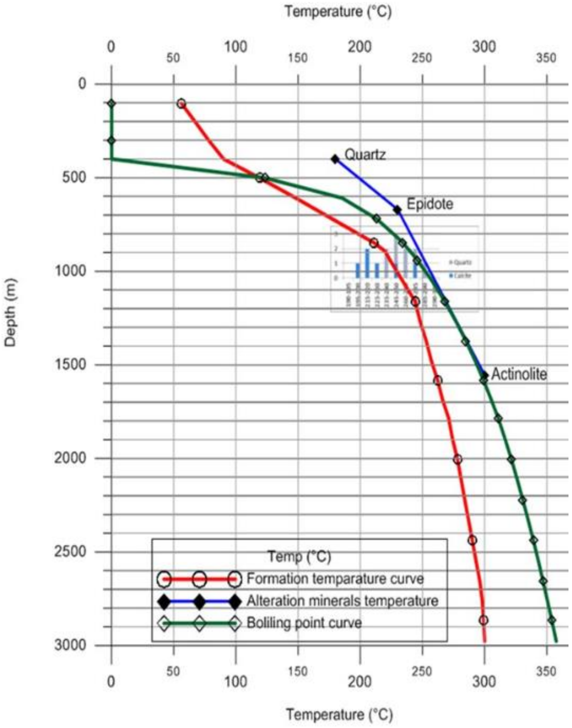

Figure 8: Alteration mineral temperature curve, formation temperatures, boiling point curve plotted alongside fluid inclusion temperatures for well OW-916. (The histogram represents fluid inclusion temp plots).

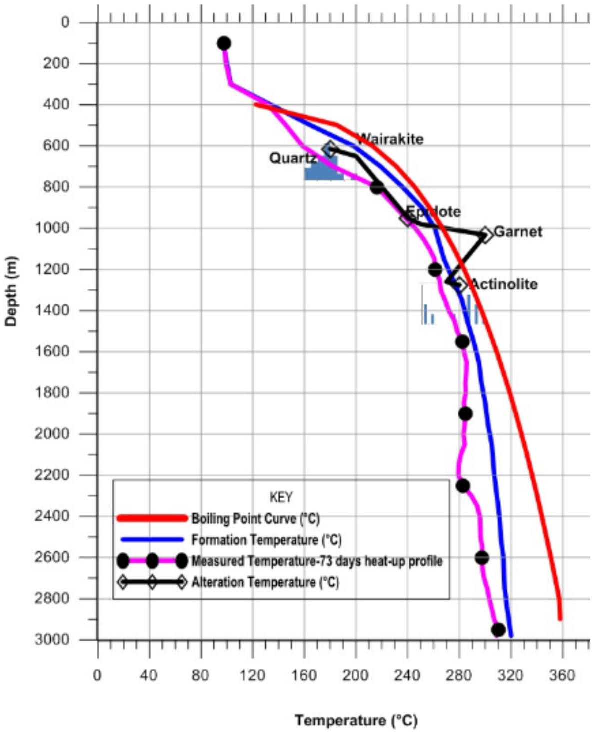

Figure 9: Alteration mineral temperature curve, formation temperatures, boiling point curve plotted alongside fluid inclusion temperatures for well OW-916. (The histogram represents fluid inclusion temp plots).

Homogenisation temperature diagram plots in the same path as formation temperature curve (Figure 9). The alteration mineral temperature curve also plots in more or less the same path as the formation temperature. This indicates that the temperature at the time at which the fluids were trapped and alteration took place is more or less in equilibrium with the current formation temperature. However, at 1010 m depth, the alteration mineral curve shoots beyond the boiling point curve. This can be attributed to contact metamorphism associated with diking.

4. CONCLUSIONS

This research studied the stratigraphy, alteration mineral abundances and paleo-thermal history of the Domes field. From the studies, it has been shown that the stratigraphy comprises of five lithological units; pyroclastics, rhyolite, tuff, basalt and trachyte.

Alteration minerals shows that higher alteration temperature are noted at shallower depth at the region of wells OW-916 and OW-914A. Well OW-912B recorded the greatest depth at which high temperature alteration mineral, for example epidote were recorded. This indicates that the area around wells OW-916 and OW-914A has the heat closer to the surface. Hence, this zone is closer to the heat source of the Domes field.

Fluid inclusion geothermometry together with alteration and formation temperature comparisons shows that the system has maintained a steady state of thermal equilibrium over time. However, more wells need to be analysed in order to get a detailed picture of the temperature variation in the whole of the Domes field. This will help in precise siting of step-out and makeup wells. This will go a long way in improving on monitoring and sustainability of power production from the Domes field.

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