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Geology and Structural Control of Geothermal System in Olkaria Northeast Field, Naivasha Kenya.

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ABSTRACT

The general subsurface strata of Olkaria Northeast field is divided into four main series as depicted from the analysis of cuttings from the drilled wells. Pyroclastics form the top most layer and it is believed to be from Olkaria, Longonot, and Suswa eruptive products. It overlies a series dominated by eruptives of rhyolitic composition underlain by a series of basaltic lavas intercalated with trachytes. The upper basalt units at Olkaria have been used as a marker horizon in the Greater Olkaria field. The bottom most series is dominated by trachytes and form the main reservoir rock. Intrusives are first encountered as dykes within the trachytic series. The trends in the occurrence of alteration minerals with reference to high temperature minerals indicate Olkaria fault and gorge farm fault had high paleo-temperatures. Delineation of the field by use of temperature models into upflow and downflow clearly indicates that cooler fluids are recharged into the system along the Gorge farm fault. Well OW-737 that has been drilled approximately 1 km to the east of the gorge farm fault also indicates cooling within the vicinity of the well. This cooling trend extends from the Gorge farm fault to well OW-737 indicating that the fault could be marking the boundary of the geothermal resource to the east of the Northeast production field. The veining observed from the analysis of cuttings from the wells comprising of hydrothermal minerals indicates fracturing and exemplify movement of hydrothermal fluids along these fractures. The permeability in the Northeast field structurally controlled. Major feed zones are mainly controlled by large fractures and the interconnection of smaller fractures within the rocks.

1. INTRODUCTION

1.1 General information

Olkaria Northeast is one of the sub-fields of the Greater Olkaria geothermal field (Figure 1). The Greater Olkaria Geothermal field is a high temperature field with temperatures of more than 200˚C. The field is subdivided in to seven subsectors fields namely; East, Northeast, Northwest, Central, Domes, Southwest and Southeast. Over 70 wells have been drilled in the Northeast field with varying degree of permeability and temperatures. The variation in the temperature characteristics of the wells is controlled by the NW-SE trending fault in the south west of the area, Gorge farm fault and Olkaria fault.

2. GEOLOGICAL SETTING

The Greater Olkaria volcanic complex, which is located in the African rift (Figure 2), is characterized by numerous volcanic centres of Quaternary age (Macdonald et al., 1987, Marshall et al. 2009). These volcanic centers appear as steep-sided domes formed by successions of lavas and/or pyroclastic rocks, or as thick lava flows of restricted lateral extent (Figure 3). Magmatic activities associated with this complex commenced during the late Pleistocene and continue to Recent times as indicated by the Ololbutot comendite lava, which has been dated at 180±50 yrs B.P (Clarke et al., 1990). Other Quaternary volcanic centres adjacent to Olkaria Volcanic complex include Longonot volcano to the east, Suswa caldera to the south, and the Eburru volcanic complex to the north. Whereas the other volcanoes are associated with calderas of varying sizes, Olkaria volcanic complex does not have a clear caldera subsidence structure. The presence of a ring of volcanic domes in the east south, and southwest (Figure 3) has been used to invoke the presence of a buried caldera (Naylor, 1972; Virkir, 1980; Clarke et al., 1990; Mungania, 1992). Seismic wave attenuation studies for the whole of the Olkaria area have also indicated an anomaly in an area coinciding with the proposed caldera (Simiyu et al., 1998). Other studies on Olkaria have not identified the existence of the caldera e.g., resistivity studies do not map a clear discontinuity at the margin of the proposed caldera (Onacha, 1993). Ignimbrite flows that could have been associated with the caldera collapse have not been positively identified in Olkaria (Omenda, 1998). Furthermore, petrochemistry of lavas within the Olkaria area shows that they were produced from discrete magma chambers (Omenda, 2000). Another explanation to the caldera hypothesis, which has been proposed, is that the ring structure was formed by magmatic stresses in the Olkaria "magma chamber" with the line of weakness being loci for volcanism (Omenda, 2000).The geological structures (Figure 3) within the Greater Olkaria volcanic complex include; the ring structure, rift fault systems, the Ol'Njorowa gorge, and dykes swarms. The faults are trending ENE-WSW, N-S, NNE-SSW, NW-SE and WNW-ESE. The NW-SE and WNW-ESE faults are thought to be the oldest fault system and they link the parallel rift basins to the main extensional zone (Wheeler and Karson, 1994). Gorge Farm fault is the most prominent of these faults. It bounds the geothermal fields in the north eastern part and extends to the Olkaria Domes area. The most recent structures are the N-S (Ololbuttot eruptive fissure) and the NNE-SSW faults.

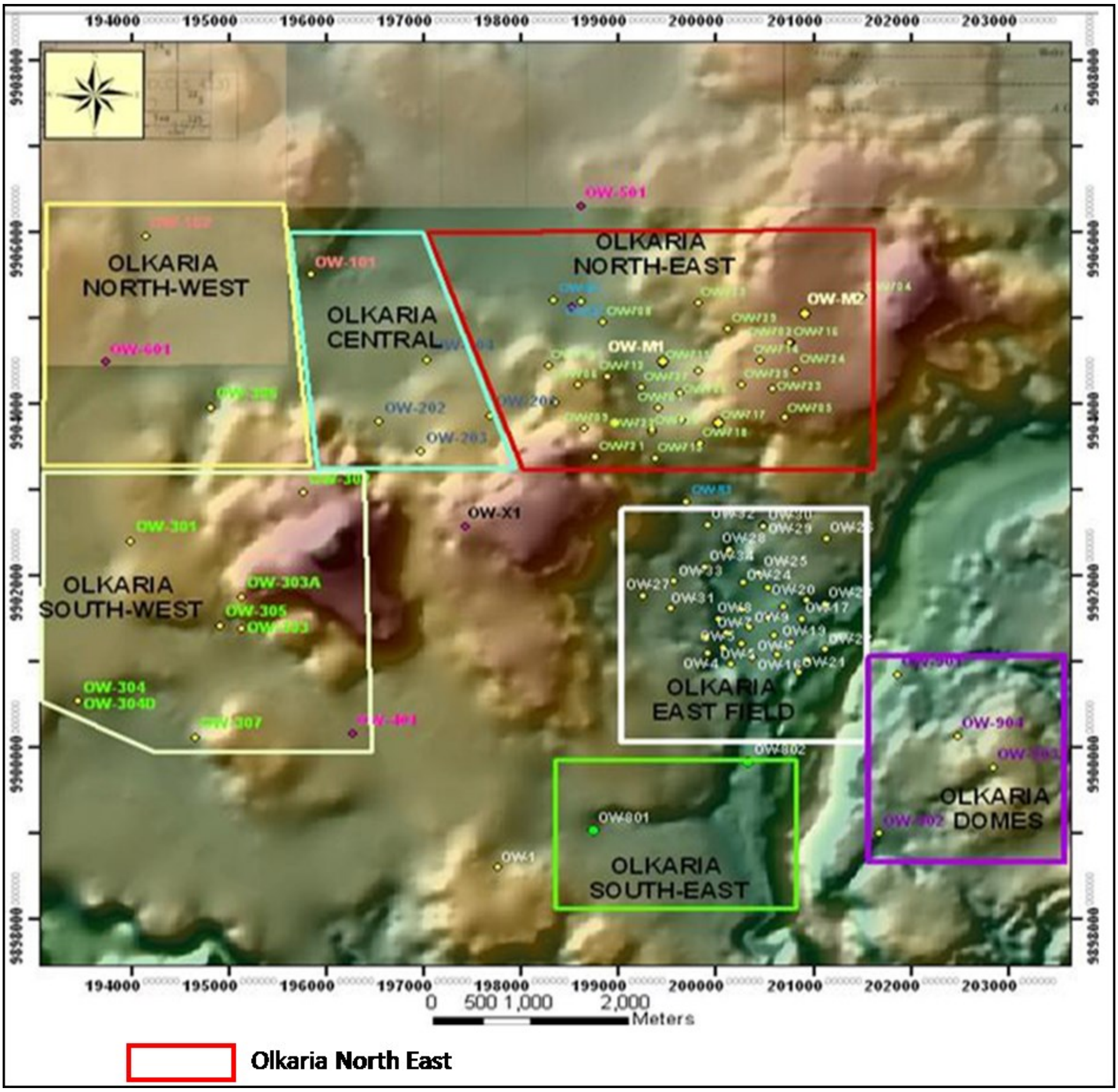

Figure 1: Sub-sectors of the Greater Olkaria Geothermal Field

3. GEOLOGY OF OLKARIA

3.1 Surface geology

The surface geology of Olkaria as described by Clarke et al. in 1990 indicate that the geology is comprised of pumice lapaili, ash deposits, pyroclastic deposits and commenditic lavas. The pyroclastic deposits and the ash, are mainly derived from the neighbouring Longonot volcano. The eruptions of rhyolite lavas and domes are strongly related to N-S tectonic structures, some of which cross the Olkaria ring structure (Figure 3). They, furthermore, appear to erupt along the ring structures as is particularly evident in the east and south. The Ring or caldera structures are clearly related to magmatic activity, as is evident by the close association of these with magma extrusion in the east and south. There is a common occurrence of geothermal manifestations along the permeable structures, a clear indication of the ascent of geothermal fluids, at least from the upper part of the system to surface. In the Northeast field the pyroclastic layer forms a very thin layer on the surface. In areas where the pyroclastic and ash deposits are absent the Olkaria rhyolite are exposed to the surface.

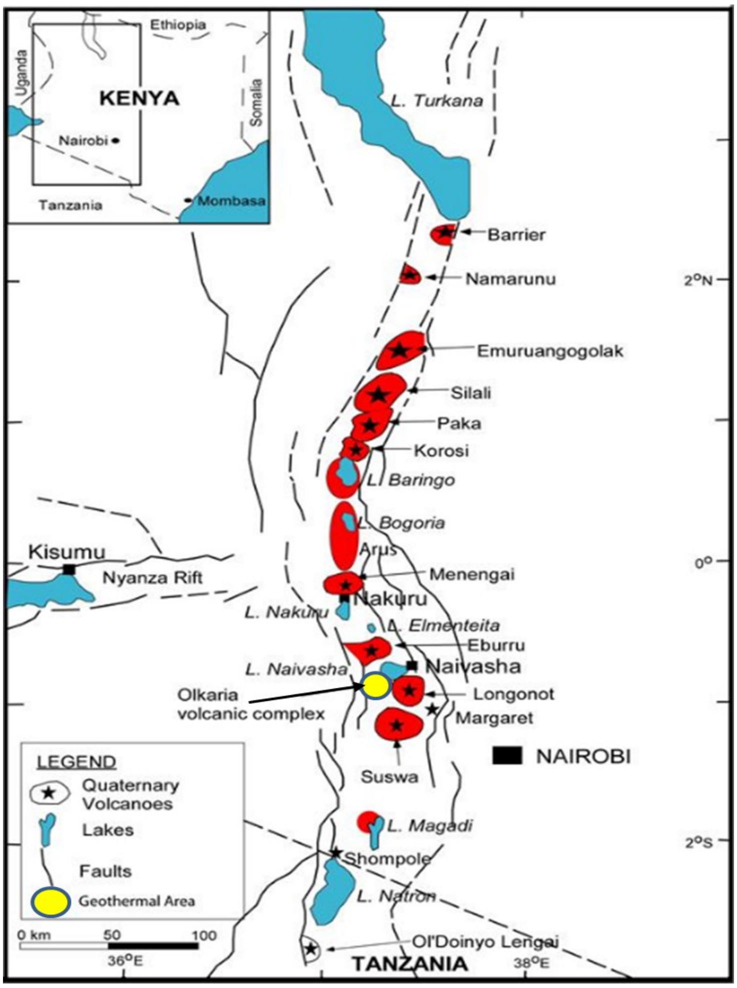

Figure 2: Map showing the location of Olkaria in the African rift

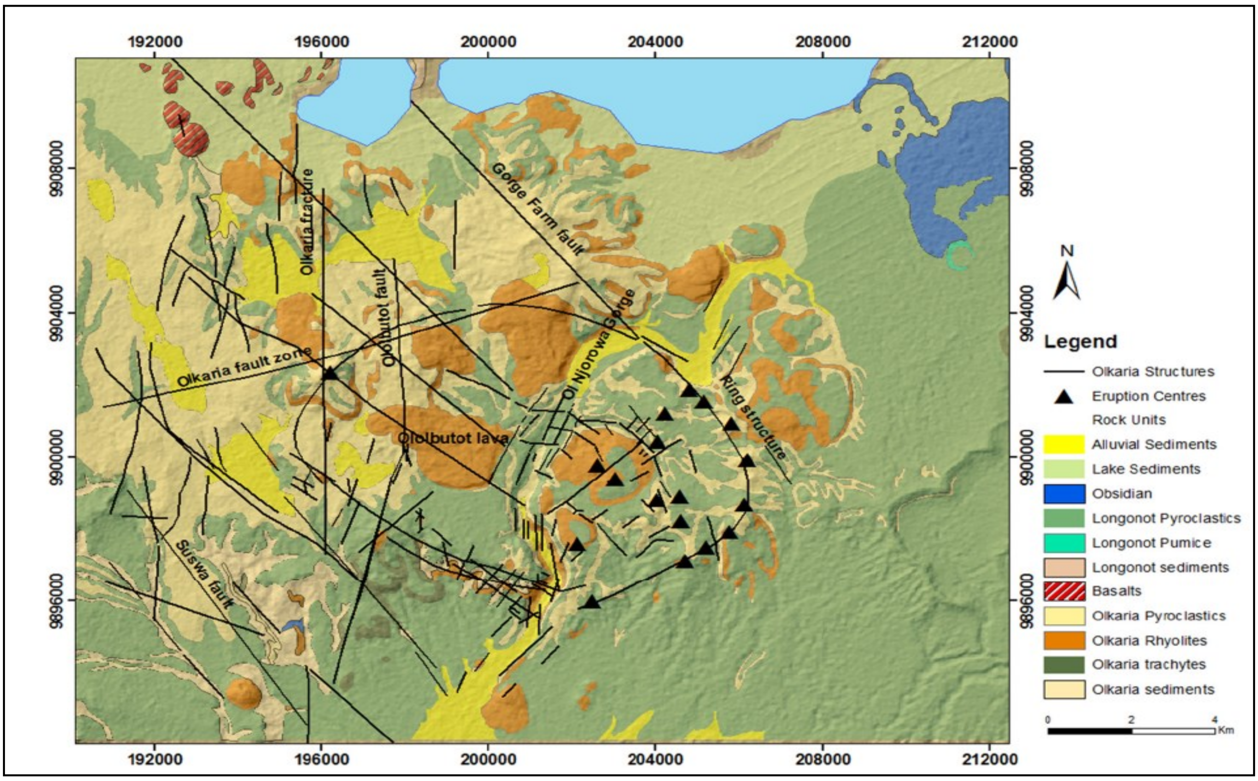

Figure 3: Structural and geological map of Olkaria (Munyiri 2016)

3.2 Subsurface geology and stratigraphy

More than 70 wells have been drilled in Northeast field to a depth range from 500 m to 3650 m measured depth. The results of the analysis of drill cuttings from the drilled wells identify five types of rocks namely; pyroclastics, rhyolites, basalts, tuffs, trachytes and intrusives. The intrusives encountered are: granite, basaltic and syenite. According to Omenda 2000 and Lagat 2004, the lithostratigraphy of Olkaria geothermal field is comprised of five main groups namely; Pre-Mau volcanics, Mau tuffs, Plateau trachytes, Olkaria Basalts and the Upper Olkaria Volcanics. Stratigraphic mapping in geothermal wells is carried out in order to advise on condition of rock formation during drilling, obtain information on the volcanic products and likely age of the volcanic finding. In this regard, general subsurface strata in the Northeast field is divided into four main series (Figure 4) as depicted from the analysis of rock cuttings from the wells, where the top most layer comprise of pyroclastics believed to be from the nearby longonot volcano. This pyroclastic layer is greyish in colour and forms a thin layer of ~0-10 m thick. The pyroclastic layer overlies the Upper Olkaria Volcanics, a zone dominated by eruptives of rhyolitic composition with minor inter-beds of trachytes and basalts. The Upper volcanics are underlain by Olkaria Basaltic series intercalated with trachytes, tuffs and rhyolites. The basaltic series is thicker in the Northeast production field than in the other sub-fields in the Olkaria geothermal system (Okoo, 2016). Reservoir modelling and hydrothermal alteration analysis has proved that the basaltic series form the cap rock of the North east field (Okoo 2016). Basaltic lava is less viscous hence flow freely. This property makes the lava suitable as marker horizon in the Olkaria strata. Marker horizons are important when finding, delineating and evaluating possible fault structures both surface and buried.

The Plateau Trachytes form the bottom most series of the Olkaria Northeast stratigraphy with subordinate basalts, tuffs and acidic volcanics. Plateau trachytes form the reservoir rock and it is in this series where the intrusives were first encountered (Figure 4). Well OW-737 is located about 1 km east from the Gorge farm fault and slightly outside the perimeter of the Olkaria flank. The stratigraphy shown in this well indicate the Basaltic layer is thinner compared to the wells drilled in the proposed caldera.

3.3 Intrusions

Intrusions are key in a geothermal system as they can act as conductors of heat into the system and/or permeable zone at the contact with host rock. Intrusions in Olkaria Geothermal system are mainly seen in the lower part of stratigraphy and mainly as dykes and/or sheets of limited apparent thicknesses. Identification of intrusions within a reservoir is mainly by analysis of drilled cuttings on grounds of the contrast in alteration against the more altered wall rock, and in some cases by contact alteration along their margins. In the Northeast production field the intrusives (Figure 4) encountered in the stratigraphic analysis include granitic, syenitic and basaltic and were observed mainly as dykes. The granitic intrusion is common in the wells in the western area of the field while the syenites and basaltic ones were common in the eastern area. The analysis of the intrusions reveal the intensity of alteration ranges from less to highly altered, indicating younger and older intrusions were encountered respectively. The intrusives in the Northeast field first occur below approximately 1000 m a.s.l. (~1000 m depth) and are observed as dykes.

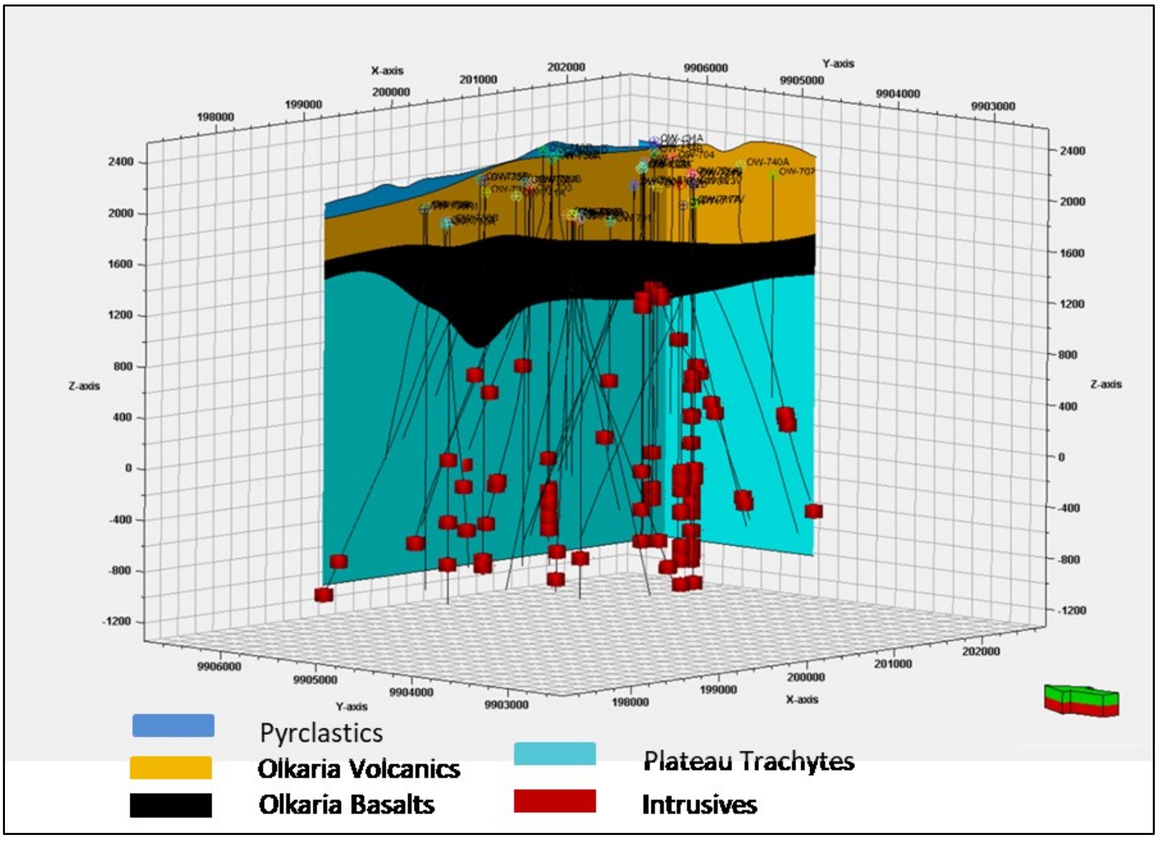

Figure 4: General stratigraphy of Olkaria Northeast wells

4. FAULTS AND FRACTURES

Fault system provides a unique geologic setting to evaluate the influence of structural controls on a geothermal system. These faults in a geothermal system can act as (1) Fluid flow conductors (2) fluid flow barriers (3) both conductors and barriers. These characteristics depend on fault filling material i.e. brecia or clays, age of the faults, fault termination patterns, intersection between these faults and accommodation zone of the faults. Permeability of the Olkaria system is mainly controlled by major faults predominantly NW-SE, NE-SW and N-S trending faults as well as the proposed ring structure (inner and outer ring) and intersections of such structures. Both the inner and the outer ring structures connect to the Gorge Farm fault, located northeast of the main production area and possibly extending north to Lake Naivasha. In the northeast production field, Gorge farm fault to the east, Olkaria fault to the south and another major NW-SE trending fault located in the west (Figure 4) are the major faults that influence the geothermal system. Ololbutot fault bounds the Northeast field to the west. Due to extensive drilling in the Northeast, the formation and alteration temperature are well known. The formation temperature is characterized by sharp boundaries as seen in the temperature model (Figure 5) of the drilled wells. The model reveals that cooler fluids flow into the system through Gorge farm fault (Figure 5), Wells located along the gorge farm have recorded low formation temperatures due to the flow of the cold water within their vicinity. Cold water is also believed to flow into the Olkaria system through the N-S fault system along the Ololbutot fault, which is also associated with plentiful geothermal surface manifestations. The flow of cold water along these two faults is supported by high levels of oxidation observed in the formation at depths between 0 and 1000 m below the surface. Along the Olkaria fault, the temperature model (Figure 6) shows that hotter fluids flow along the fault and within it's the proximity. A few isolated cases of cooler fluid incursion are noted especially to the east at its intersection with gorge farm fault. Stratigraphic mapping was used in delineating and evaluating possible fault structures both surface and buried. Basalt was used as the marker horizon, hence the inter-well stratigraphic correlation done identified new faults both surface and buried (Figure 5) in the Olkaria Northeast field. The exact location of the faults is not conclusive until ground truthing is done through detailed structural mapping and by geophysical investigation of the field.

Fractures occur in different sizes in a geothermal system. The size is characterized by apertures, length and permeability. Fracture permeability is related to fracture aperture which is usually proportional to fracture length (Mineyuki 2000). Fractures play two main roles in a geothermal system. 1) Contribution to the onset of natural convection and 2) Act as a fluid flow path to connect wells to the reservoir where fluids flow in and out of the wells. Therefore, fractures are important in a geothermal system in the reservoir as they can enable well production. Fractures which contribute to well production are limited to those of high permeability. These fractures have a wider range of sizes and cause large amounts of loss of circulation that is, total loss of circulation or similar magnitude. These fractures were identified from total circulation losses recorded during drilling and from the observations made from the analysis of drill cuttings. In the zone where wells OW-710C, OW-710A, OW-739 and OW-501 were drilled, no major total loss of circulation was observed during drilling indicating this zone lacks fractures that enable well production hence low permeability.

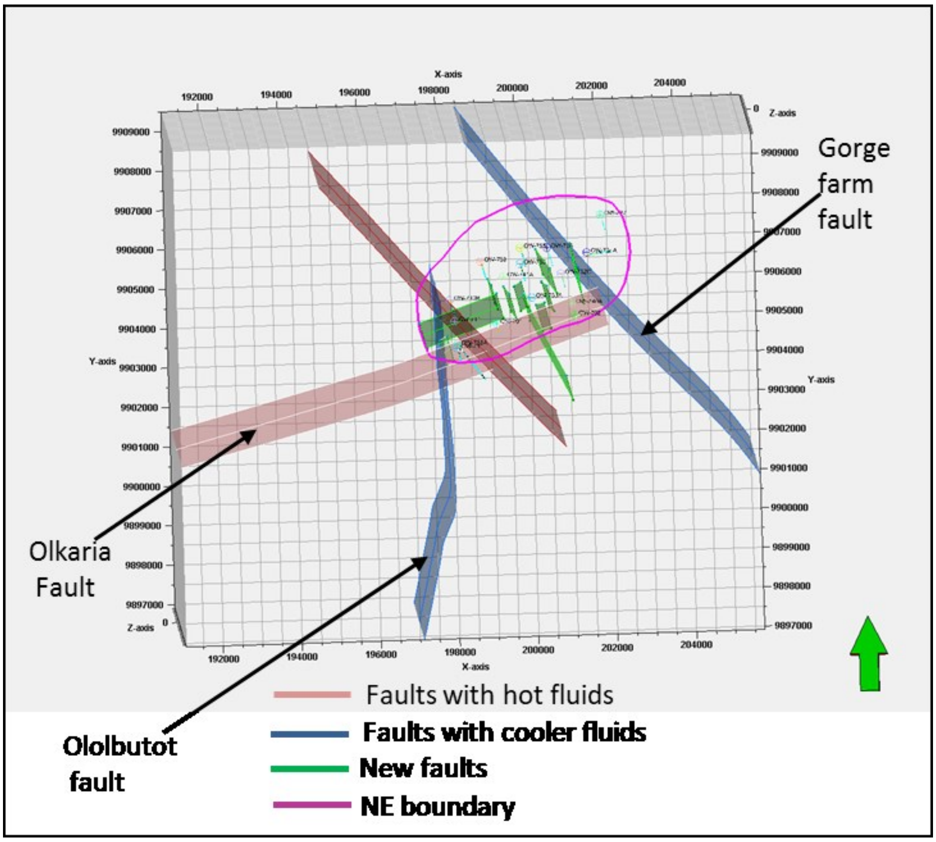

Figure 5: Major faults assumed to be controlling the Olkaria geothermal system and the newly identified faults

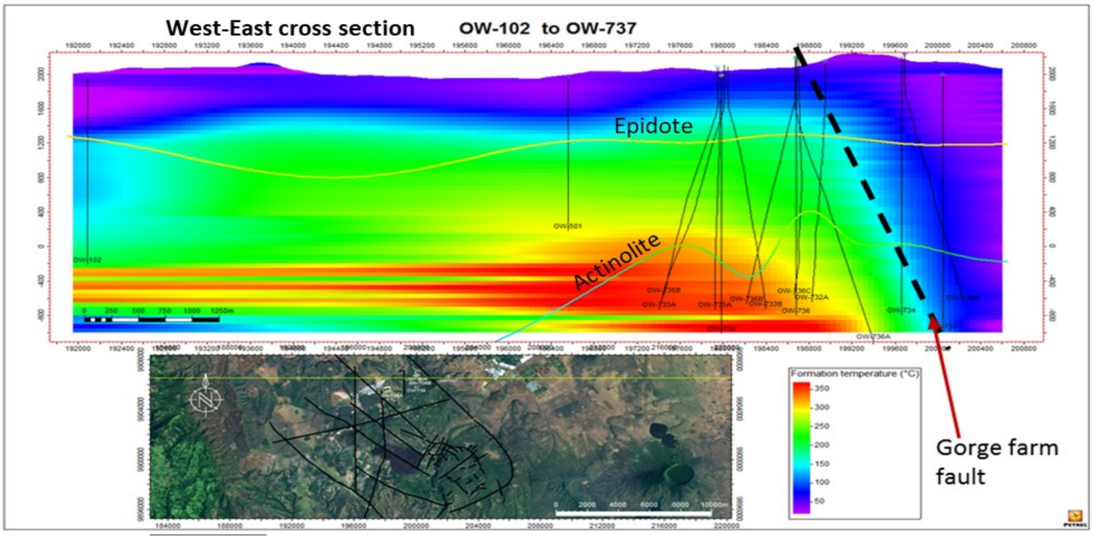

Figure 6: Temparature model showing Gorge Farm fault and alteration mineralogy(Okoo 2018)

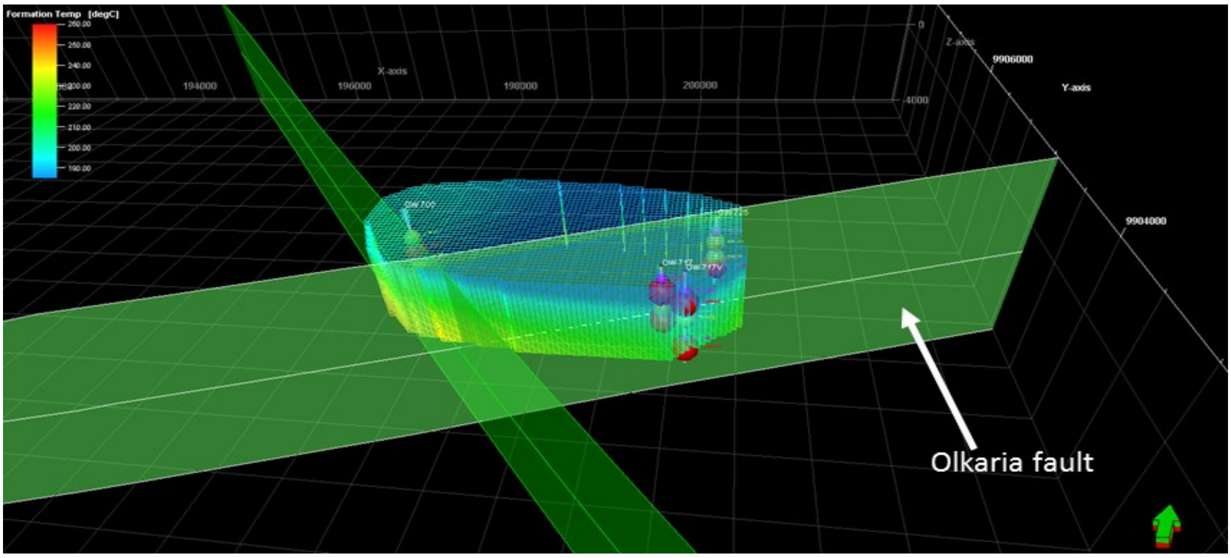

Figure 7: Temparature model showing Olkaria fault (Saitet 2018)

5. FEED ZONES

Feed zones are the sources of geothermal fluid entry into a geothermal well. They are identified and characterized in a well from geological analysis of drill cuttings, drilling data and during the well completion test. Feed zones connect a well to the reservoir and are an indication of permeable zones, but it should be noted that not all permeable zones will show as feed zones during a Pressure-Temperature-spinner run (Glynn-Morris et. al 2011). Feed zones require interconnected permeability and pressure difference with respect to the fluid column in the wellbore at the time. Geologically, examination of the drill cuttings will provide information such as, abundance of permeability indicator minerals like platy calcite and pyrite, increased intensity of alteration, presence of vein filling, indications of fracturing and zones of total loss of returns. Drilling data includes zones of increased rates of penetration and loss of circulation of returns. In the Northeast field, the feed zones occur from approximately 1500 m.a.s.l.(600 m measured depth) and at varying depth range to the bottom of the well. They are classified into major, intermediate and minor feed zones. The major feed zones are mainly controlled by large fractures as indicated by total loss of circulation at depths ranging from 50 m to hundreds of meters thick. Fracture permeability within the trachytic and rhyolitic lavas, and primary porosity in the tuffs and basaltic rocks also influence the major feed zones. Intrusives least control the major feed zones. For the intermediate and minor feed zones the major controlling factor is fracture permeability and primary porosity.

6. HYDROTHERMAL ALTERATION MINERALOGY

The study of hydrothermal alteration mineralogy from drill cuttings during drilling process is key and very important when determining the entrance into the reservoir and the depth of the production casing, interpreting the quantity and type of fluid flowing through the rocks and also in the interpretation of resistivity and magnetic anomaly. Alteration minerals can be formed by precipitation from a saturated hydrothermal fluid into vugs, vesicles and fractures, or by replacement reaction between the hydrothermal fluid and the host rock. Alteration mineralogy can reduce permeability when the fractures, vugs and vesicles are completely in-filled with hydrothermal minerals. For purposes of this study, it was therefore important to recognize the occurrence of minerals in the fractures hence formation of veins. Observations of veining in drill cuttings is an indication of fracturing. Veinlets and veins of varying widths were observed at different depths in some wells to the bottom. Generally, deposition of alteration minerals was common on fractures surfaces. The fractures were either completely or partially filled with alteration minerals. Observation of secondary quartz in drill cuttings is an indicator there is circulation of silica rich hydrothermal fluid within the rocks. The quartz was a common mineral forming as vein filling in the Northeast. Other minerals observed forming vein filling were epidote, calcite, clays, and zeolites. In the zone where wells OW-710C, OW-710A, OW-739 and OW-501 show minimal fracturing, the mineral veins formed completely sealed the fractures. Occurrence of alteration minerals along the gorge farm fault is very good. High temperature minerals of alteration temperatures above are observed at shallow depths of 850 m measured depth (Figure 5) but there is no mineralogical evidence of cooling along this fault.

7. DISCUSSIONS AND CONCLUSION

DISCUSSION

The general subsurface strata of Northeast subfield in the Olkaria geothermal system is divided into four main series as revealed from the analysis of cuttings from the drilled wells. The top most layer is comprised of pyroclastics believed to be from the nearby longonot volcano. This pyroclastic layer is greyish in colour and is very thin compared to other subfields in the olkaria geothermal system.

The pyroclastic layer overlies a series dominated by eruptives of rhyolitic composition underlain by a series of basaltic lavas intercalated with trachytes. Basaltic layer has been used as a marker horizon since it is less viscous and flows freely. It is thicker here as compared to other subfields The basaltic series is observed to be thinner at well OW-737, a well located approximately1 km from the gorge farm fault and the proposed caldera rim. Plateau trachytes form the bottom most layer. This series is dominated by trachyte lava with minor intercalations of basalts, rhyolite and tuffs. This series forms the reservoir rock. Occurrence of intrusives are first observed in the trachyte series.

Faults in a geothermal system can act as (1) Fluid flow conductors (2) fluid flow barriers (3) both conductors and barriers. These characteristics depend on fault filling material i.e. brecia or clays, age of the faults and intersection between these faults. Gorge farm fault is a conduit for cooler fluid. This is depicted from the temperature models. The flow of cooler fluids along this fault is recent as the alteration mineralogy reveals existence of high paleo-temperatures. Olkaria fault, is a conduit of hotter fluids except for the isolated case to the east at its intersection with the Gorge farm fault. At this point this is the effect of cooler fluids flowing along the Gorge farm fault. Also, this cooling trend extends from the Gorge farm fault to well OW-737 indicating that the fault could be marking the boundary of the geothermal resource to the east of the Northeast production field.

Stratigraphic mapping was used in delineating and evaluating possible fault structures both surface and buried. Basalt was used as the marker horizon, hence the inter-well stratigraphic correlation carried out identified new faults both surface and buried in the Olkaria Northeast field. The identification of these new faults in the Northeast field reveal that the area is fractured and possibly permeable.

Fractures occur in different sizes in a geothermal system and are important in a geothermal system in the reservoir as they can enable well production. Fractures which contribute to well production are limited to those of high permeability. The Northeast field is highly permeable as characterized by high fracturing, veining, intensity of alteration and circulation losses. The fractures in the Northeast field have a wider range of sizes as depicted from large amounts of loss of circulation that is, total loss of circulation or similar magnitude and formation of veinlets. The zone where wells OW-710C, OW-710A, OW-739 wells and OW-501 show minimal fracturing where the veins formed were completely sealed. No major total loss of circulation was observed indicating this zone where these wells were drilled lacks sufficient fracturing and, therefore, low permeability.

Intrusions are key in a geothermal system as they can act as conductors of heat into the system and/or permeable zone at the contact with host rock. In the North East production field the intrusives encountered in the stratigraphic analysis include granite, syenite and basalts and were observed mainly as dykes. The granitic intrusion is common in the wells in the western area of the field while the syenites and basaltic ones were common in the eastern area. The analysis of the intrusions reveal the intensity of alteration ranges from less to highly altered, indicating younger and older intrusions were encountered respectively. The intrusives have their roots to the heat source hence can serve as a local heat source into the system. In relation to this it is expected that all the wells that encountered intrusion to be hot. But the reverse is true for wells along the Gorge farm fault. Some of these wells have recorded measured bottom hole temperatures as low as 150ºC or less despite encountering young intrusives. This is possibly due to the effect of the cooler fluids flowing along the fault hence reduced formation temperatures. Intrusives in the Northeast field first occur below approximately 1000 m a.s.l. (~1000 m depth) and are observed as dykes.

Feed zones are the sources of geothermal fluid entry into a geothermal well. They are identified and characterized in a well from geological analysis of drill cuttings, drilling data and during the well completion test. Feed zones connect a well to the reservoir and are an indication of permeable zones. Feed zones require interconnected permeability and pressure difference with respect to fluid column in the wellbore at a time. The feed zones in the Northeast field are classified into major, intermediate and minor feed zones. The major feed zones are mainly controlled by large fractures as indicated by total loss of circulation at depths range between 50 m to hundreds of meters thick. Fracture permeability within the trachytic and rhyolitic lavas and primary porosity in the tuffs and basaltic rocks also influence the major feed zones. Intrusives (contact permeability) least control the major feed zones. For the intermediate and minor feed zones the major controlling factors are intensity of alteration, fracture permeability, contact permeability and primary porosity.

Hydrothermal alteration minerals were observed in veins, vugs and vesicles. Alteration minerals were formed by precipitation from a saturated hydrothermal fluid into vugs, vesicles and fractures, or by replacement reaction between the hydrothermal fluid and the host rock. Observations of veining in drill cuttings is an indication of fracturing. Veinlets and veins of varying widths were observed at different depths in some wells, to the bottom. Generally, deposition of alteration minerals was common on fractures surfaces. The fractures are either completely or partially filled with alteration minerals. Secondary quartz is mainly formed by precipitation process hence its observation as a vein filling is an indicator of circulation of silica rich hydrothermal fluid within the rocks. The quartz was a common mineral forming as vein filling in the Northeast. Other minerals observed forming vein fillings were epidote, calcite, clays, and zeolites. Occurrence of alteration minerals along the gorge farm fault is very good. High temperature minerals are observed at shallow depths of 850 m (approximately 1250 m a.s.l). No evidence of low temperature minerals overprinting high temperature minerals was observed along the gorge farm fault, indicating the flow of cooler fluids is a recent activity.

CONCLUSION

From the interpretation and discussion the following conclusions are made:

1. The stratigraphy of North East filed comprise of four main series namely, Pyroclastics, Olkaria volcanics, Basaltic series and Plateau Trachytes.

2. Permeability of the Northeast field is mainly controlled by predominantly NW-SE and NE-SW trending faults as well as a good fracturing network within the system. Colder water flows into the system through the N-S fault system along the Ololbutot fault. Gorge farm fault is also a conduit of cooler fluids while Olkaria fault is a conduit of hot fluids.

3. Wells, OW-710A, OW-710B, OW-710C, OW-739, OW-739A, and OW-501 were drilled in a less permeable zone. This zone does not have large fractures, and the small fractures are not well interconnected.

4. The paleo-temperatures along Gorge farm fault is very good, but there is no mineralogical evidence of cooling along the gorge farm, this implies two geothermal histories are depicted. The first initial heating regime and a later cooling regime.

5. Gorge farm fault could be a possible boundary of the geothermal resource to the east of Northeast field.

6. Major feed zones are mainly controlled by large fractures depicted by total loss circulation, and to some extent interconnected fractures within the rock formation.

7. The veining observed from the analysis of cuttings from the wells comprising of hydrothermal minerals indicates fracturing and exemplifies movement of hydrothermal fluids along these fractures.

REFERENCES

Clarke, M.C.G., Woodhall, D.G., Allen, D., and Darling G., 1990: Geological, volcanological and hydrogeological controls on the occurrence of geothermal activity in the area surrounding Lake Naivasha, Kenya, with coloured 1:100 000 geological maps. Ministry of Energy, Nairobi, 138 pp.

Saitet, D., 2018: *Discussions on temperature models of Greater Olkaria*. Kengen Internal Scientific discussions.

Lagat, J.K., 2004: *Geology, hydrothermal alteration and fluid inclusion studies of Olkaria domes geothermal field, Kenya.* University of Iceland, MSc thesis, UNU-GTP, Iceland, report 2, 71 pp.

MacDonald, R., Davies, G.R., Bliss, C.M., Leat, P.T., Bailey, D.K., and Smith, R.L., 1987: Geochemistry of high silica peralkaline rhyolites, Naivasha, Kenya rift valley. *J. Petrology, 28*, 979-1008.

Marshall, A. S. l., Macdonald R., Rogers N. W., Fitton. J. G., Tindle, A. G. N., Nejbert, K., and Khinton, R. W., 2009: Fractionation of peralkaline silicic magmas: The Greater Olkaria volcanic complex, Kenya Rift valley.*J. Petrol., 50,*323-359.

Mineyuki H., 2000: Two different roles of fractures of Fractures in geothermal development. *Proceedings of World Geothermal Congress. Kyushu-Tohoku, Japan, May 28-June 10th 2000*

Mungania, J., 1992: *Preliminary field report on geology of Olkaria volcanic complex with emphasis on Domes area field investigations*. Kenya Power Company, internal report.

Munyiri, S.K., 2016: *Structural Mapping of Olkaria Domes Geothermal Field Using Geochemical Soil Gas Surveys, Remote Sensing and GIS.* University of Iceland MSc thesis, UNU-GTP, Iceland, report 5, 100 pp.

Naylor, W.I. 1972: *The geology of Eburru and Olkaria geothermal prospects*. UNDP project report, KPC, 58 pp.

Omenda, P.A., 1998: The geology and structural controls of the Olkaria geothermal system, Kenya. *Geothermics, 27-1,* 55-74.

Omenda, P.A., 2000: Anatectic origin for comendite in Olkaria geothermal field, Kenya Rift; Geochemical evidence for syenitic protholith. *African J. Science and Technology. Science and Engineering Series, 1*, 39-47.

Onacha, S.A., 1993: Resistivity studies of the Olkaria-Domes geothermal project. Kenya Power Company, internal report.

Okoo, J.A., 2016: *Updated geological conceptual model of Greater Olkaria Geothermal system, Olkaria geothermal project, Naivasha, Kenya*. Kengen Internal report..

Okoo,J.A., 2018:, *Discussions on updated geological conceptual model on greater Olkaria Geothermal Area*.. Kengen Internal Scientific discussion.

Simiyu, S.M., Oduong, E.O., and Mboya, T.K., 1998: *Shear wave attenuation beneath the Olkaria volcanic field.* KenGen, Kenya, internal report, 29 pp.

Glynn-Morris, T., Katie, M., and Kerin, B., 2011: Characterizing feed zones in geothermal fields: Learning from completion testing, Image logs and cores. New Zealand geothermal 2011 *proceedings.21-23 November 2011. Aukland New Zealand*

Wheeler, W.H., and Karson, J.A., 1994: Extension and subsidence adjacent to a ''weak'' continental transform: an example of the Rukwa Rift, East Africa. *Geology, 22,* 625-628.

Virkir Consulting Group, 1980: *Geothermal development at Olkaria*. Report prepared for Kenya Power Company.

West-JEC, 2009: The Olkaria Optimization Study (Phase II) – Final reservoir analysis report. West Japan Engineering Consultants, Inc., 301 pp.

Wheeler, W.H., and Karson, J.A., 1994: Extension and subsidence adjacent to a ''weak'' continental transform: an example of the Rukwa Rift, East Africa. *Geology, 22,* 625-628.