

Stratigraphy, Thermal history and Structural control of Geothermal System in Olkaria Northeast Field, Naivasha Kenya.

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ABSTRACT

The general stratigraphy 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 clearly indicates Northeast field is generally in equilibrium with a few elevated peaks of heating in some areas. The temperature models also reveal that cooler fluids are recharged into the system along 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 drill cuttings from the wells comprising of hydrothermal minerals indicates fracturing and exemplify movement 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.

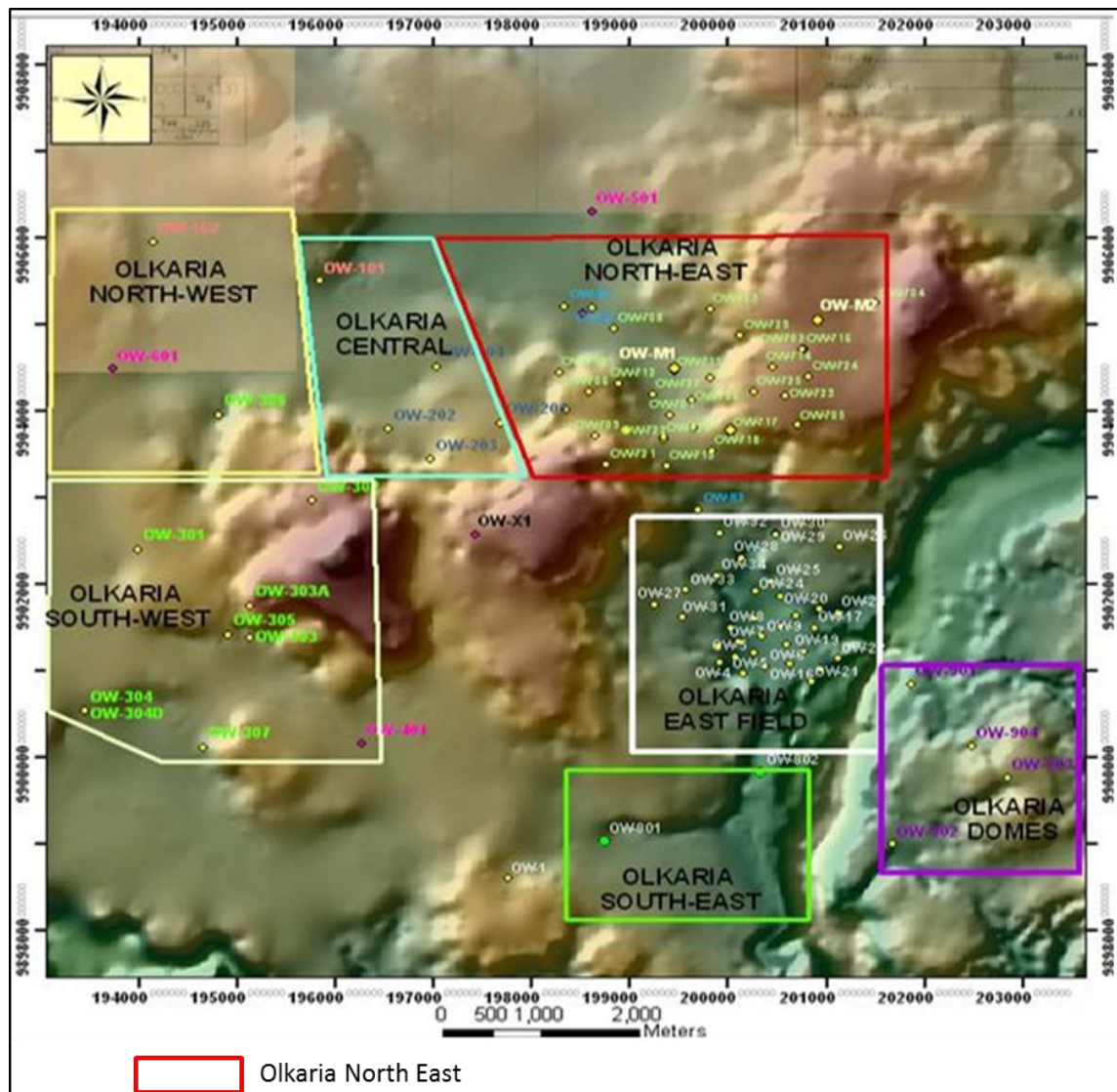


Figure 1: Sub-sectors of the Greater Olkaria Geothermal Field

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 Eburreu 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 (Ololbutot eruptive fissure) and the NNE-SSW faults.

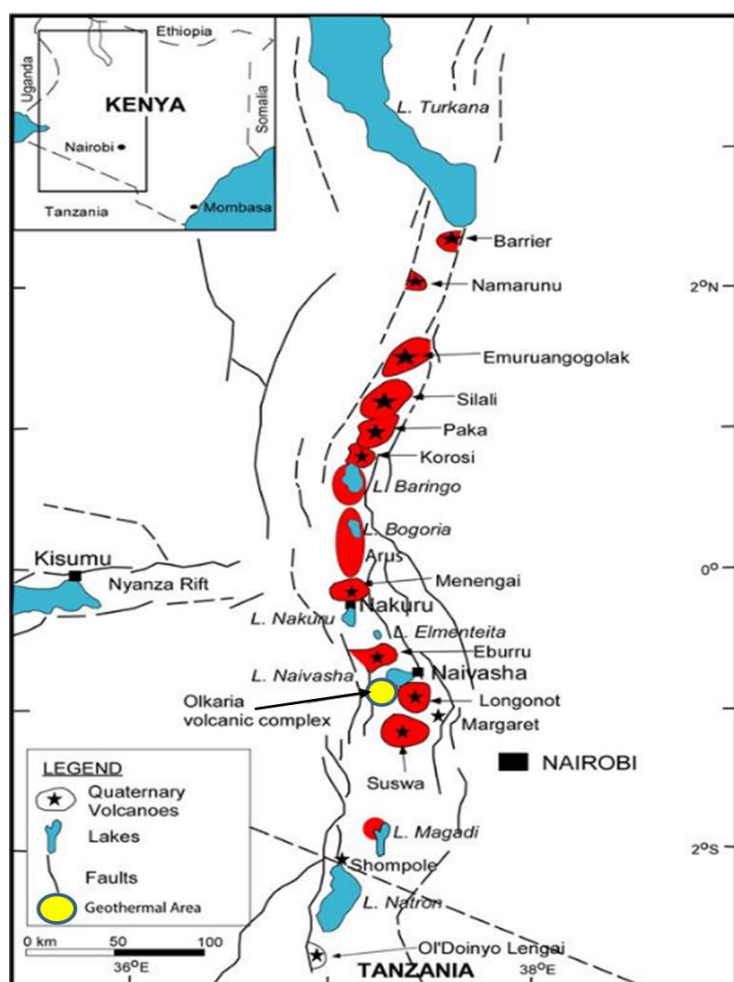


Figure 2: Map showing the location of Olkaria in the African rift

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 bottom of 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.

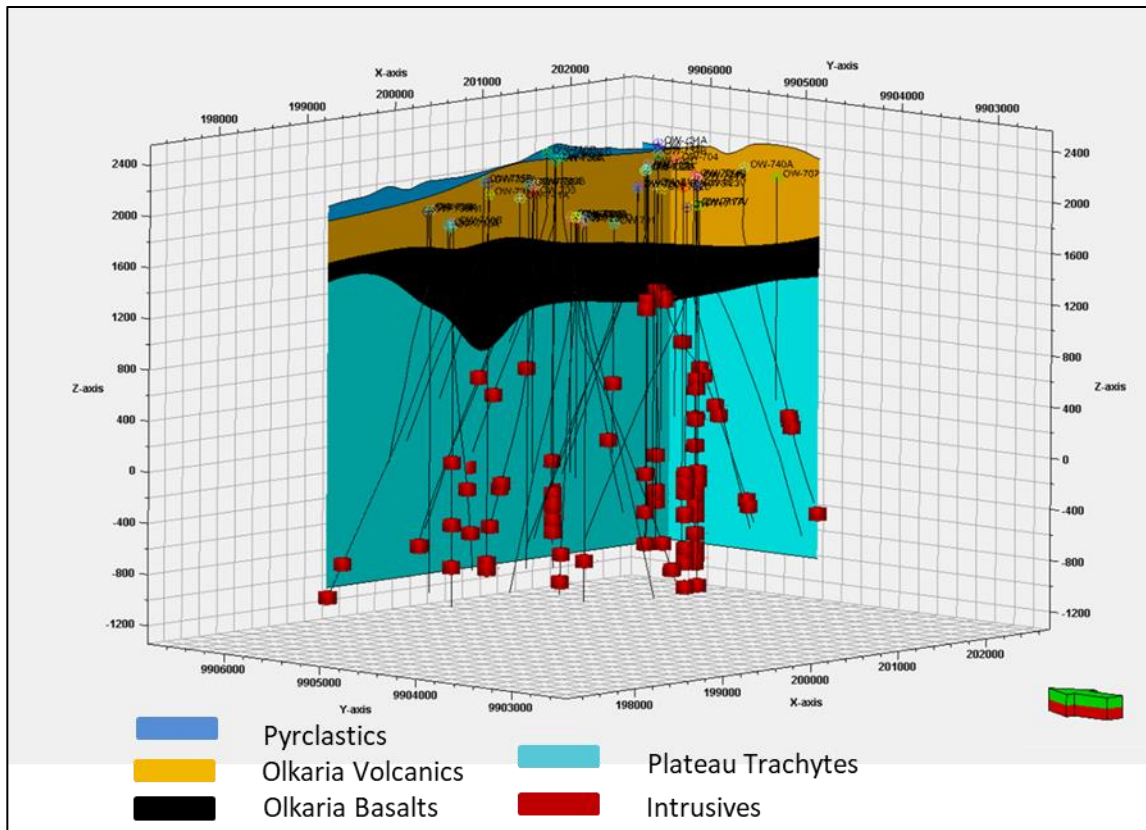


Figure 4: General stratigraphy of Olkaria Northeast wells

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 conduits where geothermal waters feed the geothermal system (2) fluid flow barriers (3) both conduits and barriers (Faulds, et. al. 2010). These characteristics depend on: fault filling material i.e breccia or clays, age of the faults, fault termination patterns, intersection between these faults and accommodation zone of the faults (Anderson and Faulds 2013; Faulds and Varga 1998). Faults zones are usually irregular, branched and curved (Faulds, et. al. 2012). 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 5) are the major faults that influence the geothermal system. Ololbutot fault bounds the Northeast field to the west. Due to extensive drilling in Northeast, the formation and alteration temperature are well known. The formation temperature is characterized by sharp boundaries (Okoo, 2018) as seen in the temperature model (Figure 6) of the drilled wells. The model reveal that cooler fluids flow into the system through Gorge farm fault (Figure 6), Wells located along the gorge farm fault have recorded low bottom hole formation temperatures (150°C) due to the flow of the cooler fluids within their vicinity. Cooler fluids are 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 cooler fluids along these two faults is supported by high levels of oxidation observed in the formation at depths between 0 and 800 m below the surface. Along the Olkaria fault, the temperature model (Figure 7) shows that hotter fluids flow along the fault and within its proximity. A few isolated cases of cooler fluid incursion are also 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. 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 may develop due to rock deformation during tectonic activity or around intrusive bodies which develop during the intrusion of igneous rocks. 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 (Grant, et. al. 1982; Mineyuki, 2000). Fractures play two main roles in a geothermal system. 1) Contribution to the onset of natural convection and 2) Act as 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 hence fracture zones are the best targets for geothermal exploitation for production. In Olkaria, 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. In the Northeast field, these fractures were identified from total circulation losses recorded during drilling and from the observations made from the analysis of drill cuttings. The analysis of these drill cuttings indicate that permeable zones within the Olkaria reservoir comprise of fractures and open cracks. In the zone where wells OW-710C, OW-710A and OW-739 were drilled, no major total loss of circulation was observed during drilling indicating this zone lacks fractures that enable well production hence low permeability.

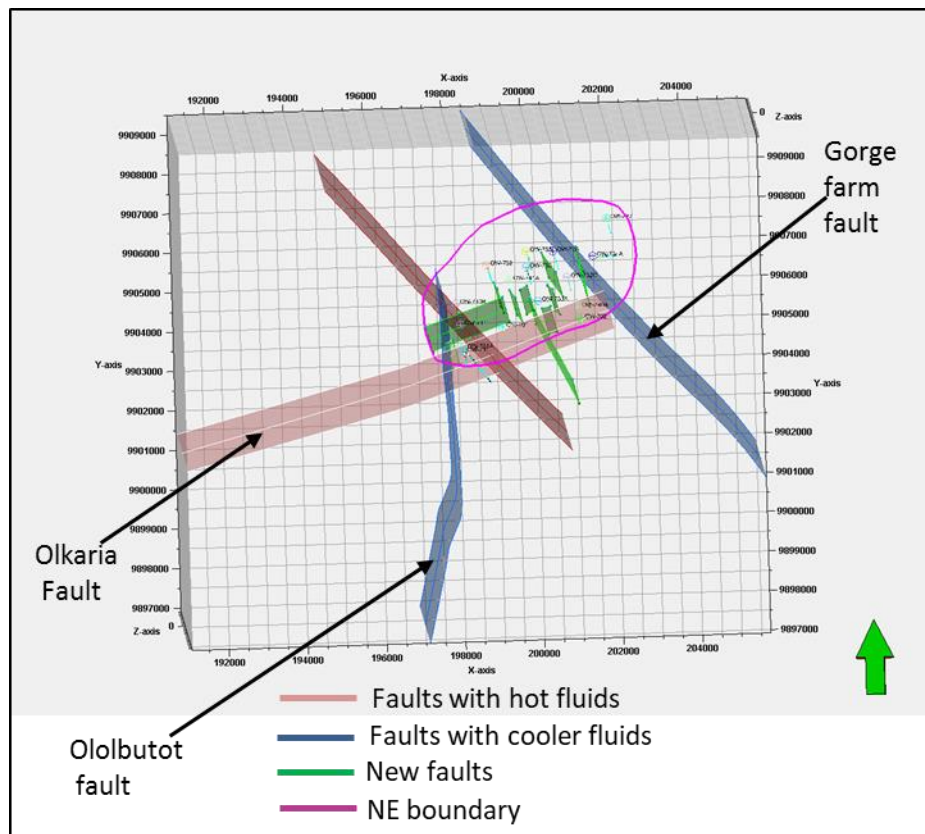


Figure 5: Major faults assumed to be controlling the Olkaria geothermal system and the newly identified faults

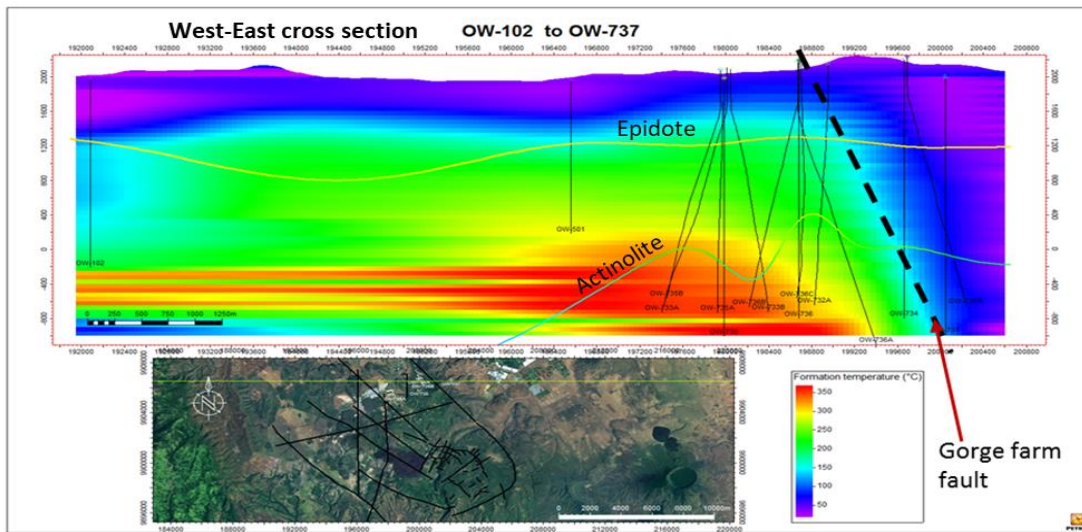


Figure 6: Temperature model showing Gorge Farm fault and alteration mineralogy(Okoo 2018)

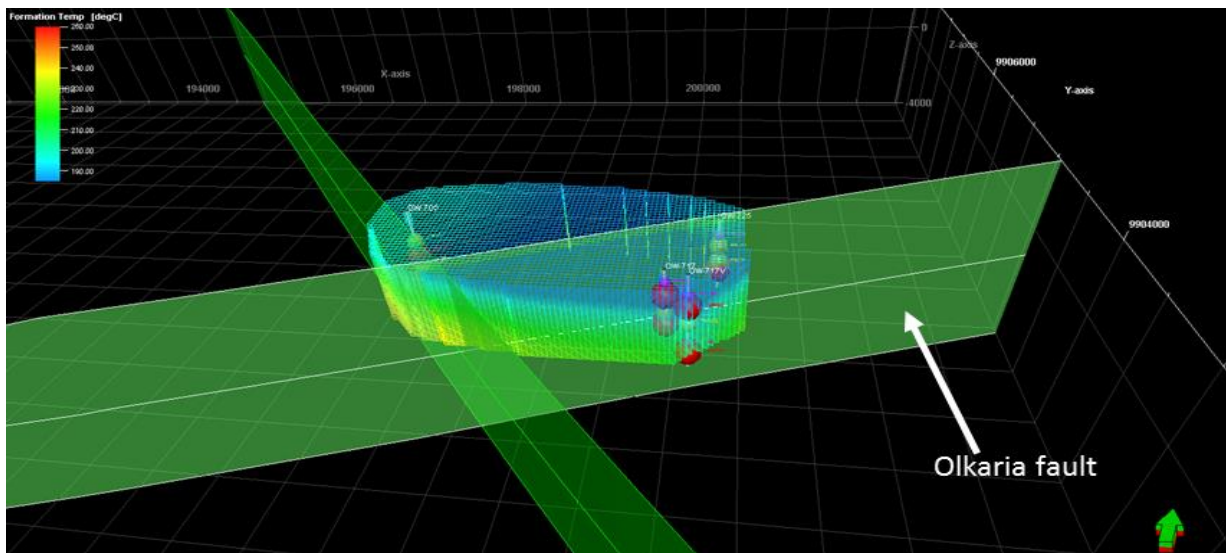


Figure 7: Temperature model showing Olkaria fault (Saitet 2018)

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 fluid column in the wellbore at a time. Geologically, examination of the drill cuttings will provide information such, abundance of permeability indicator minerals such as 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 rate 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 range between 50 m to hundreds of metres 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. Circulation of geothermal fluids along dykes, fault zones and through crustal layers result in the precipitation of secondary minerals in cavities, pores and fractures forming amygdaloids and veins respectively. Formation of amygdaloids in vesicles and vugs in the reservoir rock of a geothermal system gradually reduces the permeability, hence diminishes the storage capacity of the reservoir. Occurrence of veins reveal a large network that transport geothermal fluids from the heat sources towards the surface. Alteration mineralogy can also reduce permeability when the fractures 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 and fractures surfaces either completely or partially infilling the fractures. Secondary quartz only forms by precipitation process from geothermal fluids. Its' observation in drill cuttings is an indication there is circulation of silica rich hydrothermal fluids within the rocks. Quartz was a common mineral forming as vein filling in the Northeast. Other mineral observed forming vein filling were epidote, calcite, clays, and zeolites. The zone within the vicinity of wells OW-710C, OW-710A OW-39 and OW-739A, minimal fracturing is observed and for cases where there was fracturing, mineral veins formed completely sealed the fractures. Occurrence of alteration minerals along the gorge farm fault is very good and high temperature minerals are observed at shallow depths of 850 m measured depth (Figure 5) but there is no mineralogical evidence of cooling along this fault

7. THERMAL HISTORY

Alteration temperature is assumed to represent the maximum long-term temperature state, while the measured formation temperature represents the present state of a geothermal system. A comparison of the formation and alteration temperatures may therefore give indications of the thermal changes that have taken place "recently" in a geothermal system. Epidote was chosen as the reference temperature dependent mineral for this case. The first depth of occurrence of epidote in the Northeast field is approximately 1400 m.a.s.l down to 1200 m.a.s.l. The depth to the first occurrence of epidote indicating alteration temperatures of 250°C and the actual measured formation temperatures at these depths were noted hence the difference between the formation and alteration temperatures plotted figure 8. The figure delineates the field in to heating, equilibrium and cooling zones marked by red, yellow and blue colours respectively as the current state of the field.

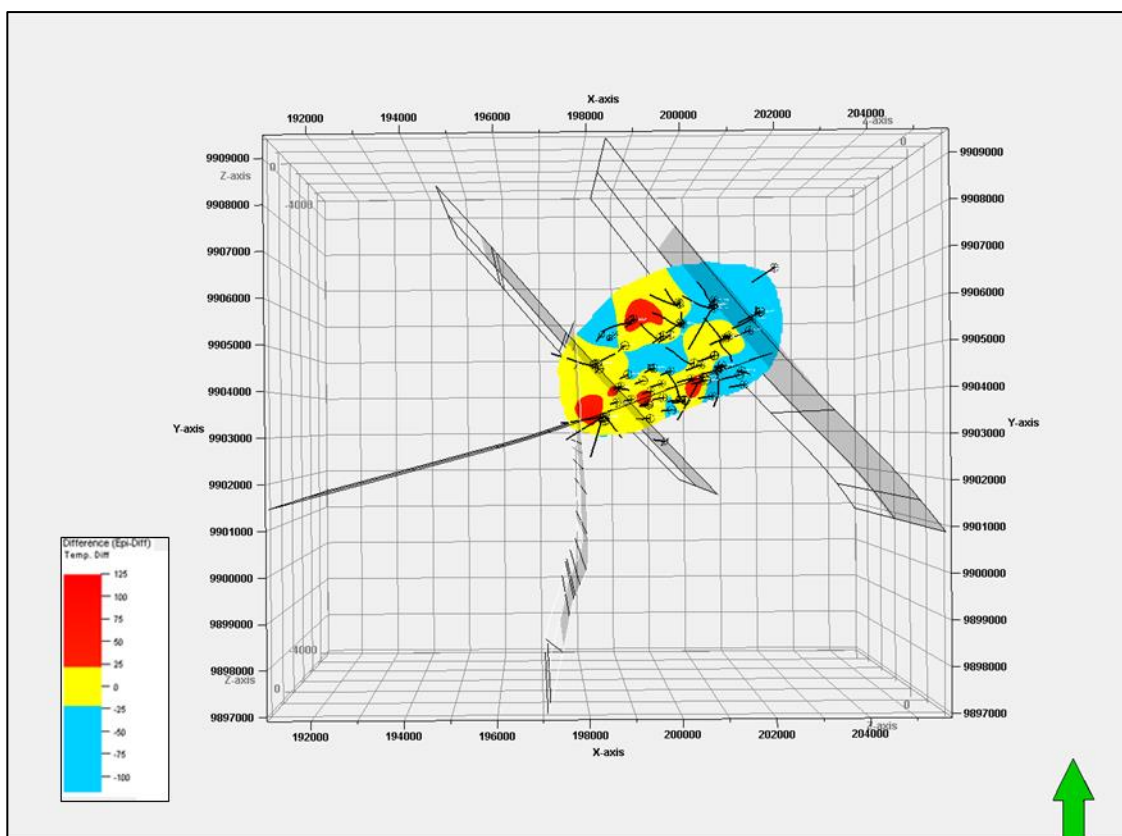


Figure 8: Showing thermal history of Olkaria Northeast field. Red-heating, Yellow-equilibrium and blue-cooling

8. DISCUSSIONS AND CONCLUSION

DISCUSSION

The general subsurface strata of Northeast subfield in Olkaria geothermal system is divided into four main series as revealed from the analysis of cuttings from the drilled wells. The top most layer comprise of pyroclastics believed to be from the nearby longonot volcano. This pyroclastic layer is greyish in colour and 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. The basaltic series is thicker here as compared to other subfields but thinner at well OW-737, a well located approximately 1 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 intrusive are first observed in the trachyte series.

Faults in a geothermal system can determine the success or failure of a geothermal system and can act as (1) Fluid flow conduits (2) fluid flow barriers (3) both conduits and barriers. These characteristics depend on fault filling material that is breccia or clays dominated, 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 a recent event since there is no mineralogical evidence of cooling observed from the analysis of drill cuttings from the wells. Olkaria fault, is a conduit of hotter fluids except for an isolated case to the east at its intersection with the Gorge farm fault. This is due to the effect of cooler fluids flowing along the Gorge farm fault to the Olkaria fault at this intersection. This cooling trend extends from the Gorge farm fault to well OW-737 which is located approximately 1 km from the fault indicating that the gorge farm 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. This Inter-well correlation has revealed there is a probable major fault within the vicinity of OW-736 wells intercepting the gorge farm fault and trends in a NE-SW direction through the central region. This inferred new fault could possibly be a channel of cooler fluids from gorge farm fault, hence causing the cooling observed extending to the central region of the 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 the reservoir as they can enable well production. Fractures which contribute to well production are limited to those of high permeability. Northeast field is highly permeable as characterized by high fracturing, veining, and high 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 and OW-739 are located 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 hence low permeability.

Intrusions are internal structures in a geothermal system and are important in 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 basaltic and were observed mainly as dykes. The granitic intrusion is common at the bottom of 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 that 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 implying the younger intrusives could probably be source of heat. 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, where some of these wells have recorded measured bottom hole temperatures as low as 150°C or less despite encountering young intrusive. This is possibly due to the effect of the cooler fluids flowing along the fault hence reduced formation temperatures. Intrusives in the Northeast field were 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 on 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 fluids 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 were either completely or partially infilled 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 fluids 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 shows high grade alteration and there is no mineralogical evidence observed implying cooling along the fault. This means the flow of cooler fluids along the gorge farm fault is a recent activity.

Delineation of the field by use of temperature models clearly indicates Northeast field is generally in equilibrium with a few elevated peaks of heating in some areas. The difference between the formation temperature and alteration temperature models also reveal that cooler fluids are recharged into the system along 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. The system within the proximity of the Olkaria fault zone is generally either in equilibrium or heating up except towards the east at the intersection with gorge farm fault where the cooling

effect is due to recharge from gorge farm fault. Upflow zones along the Olkaria fault zone are; OW-731 wells, OW-723 wells and vicinity of well OW-701. Other elevated peaks indicating upflow zones are observed at well OW-733A and OW-741A to the north of the field and also well OW-742. Cooling is observed in the northwest area and this could probably be attributed to the re-injection in some of the wells in that proximity.

CONCLUSION

From the interpretation and discussion the following conclusions are made:

1. The stratigraphy of North East field 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 N-S, NW-SE and NE-SW trending faults as well as good fracturing network within the system.
3. Gorge farm fault is a conduit of cooler fluids while Olkaria fault is a conduit of hot fluids.
4. Wells, OW-710A, OW-710B, OW-710C, and OW-739A, were drilled in a less permeable zone. This zone does not have large fractures, and the small fractures are sealed by mineral deposition and not well interconnected.
5. The paleo-temperatures along Gorge farm fault extending to well OW-737 reveal high alteration grade, but there is no mineralogical evidence of cooling along the gorge farm, this implies that two geothermal histories are depicted. The first initial heating regime and a later cooling geothermal regime.
6. Gorge farm fault could be a possible boundary of the geothermal resource to the east of Northeast field.
7. Major feed zones are mainly controlled by large fractures depicted by total loss circulation, and to some extent interconnected fracture within rock formation
8. The veining observed from the analysis of cuttings from the wells comprising of hydrothermal minerals indicates fracturing and exemplify movement hydrothermal fluids along these fractures.
9. Comparison between formation and alteration model reveal that the field is generally in a thermal equilibrium state with a few areas of heating and an exception of cooling to the east of the field Central and northwest areas
10. There is a possible buried /or inferred fault oriented NE-SW intercepting Gorge farm fault flowing in cooler fluids the central region of the field

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