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Evaluation of Reservoir Sub Surface Structures from Temperature Heat Up and Alteration Minerals in Olkaria Domes Geothermal Field, Kenya

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Abstract
The Olkaria Domes Geothermal field is situated in the south of Lake Naivasha, in southern sector of the Kenya Rift system, approximately 127 km northwest of Nairobi in Kenya. Geothermal reservoir evaluation involves various kinds of tests, data interpretation and modelling. In this paper, heat-up temperature profiles tests during well recovery for fourteen wells and the first occurrence of high temperature alteration minerals such as Illites and Quartz data from five wells were analysed for the purpose of obtaining temperature distribution, permeability structures, feed zone locations as well as the up-flow and down-flow zones. From the temperature distribution results, two main heat sources were inferred; one to the Northwest and the second to the Eastern side of the field. The two heat sources are separated by a SW-NE oriented fault that is believed to control the fluid flow. The natural recharge to the reservoir comes from the SW direction. The reservoir had two major feed zones at depths of (900-1300) masl and (250-0) masl. The Illites and Quartz contour distribution indicate the minerals first appear shallower on the Eastern region as compared to the Western region of the field hence elevated temperatures to the eastern side. This indicates that the heat source on the Eastern side is closer to the surface compared to the west side and therefore SW-NE oriented fault could be as a result of differential upward movement of the two magma chambers with more upthrow to the east as compared to the west. It is recommended that more production wells be drilled in the eastern region of the geothermal field.

Key Words: Geothermal Reservoir, Temperature, Well Testing, Alteration Minerals

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I. Introduction

The greater Olkaria geothermal area is situated in the southern part of the Kenyan rift, nearly 127 Km from Nairobi (0° 53'S; 36° 18'E) as shown in Figure 1. The Kenyan rift forms part of the structure of the East African rift that extends to Mozambique region in the south from Ethiopia (Kandie *et al.*, 2016). It forms a section of the eastern arm that extends to Lake Natron from Lake Turkana, (Omenda *et al.*, 2016).

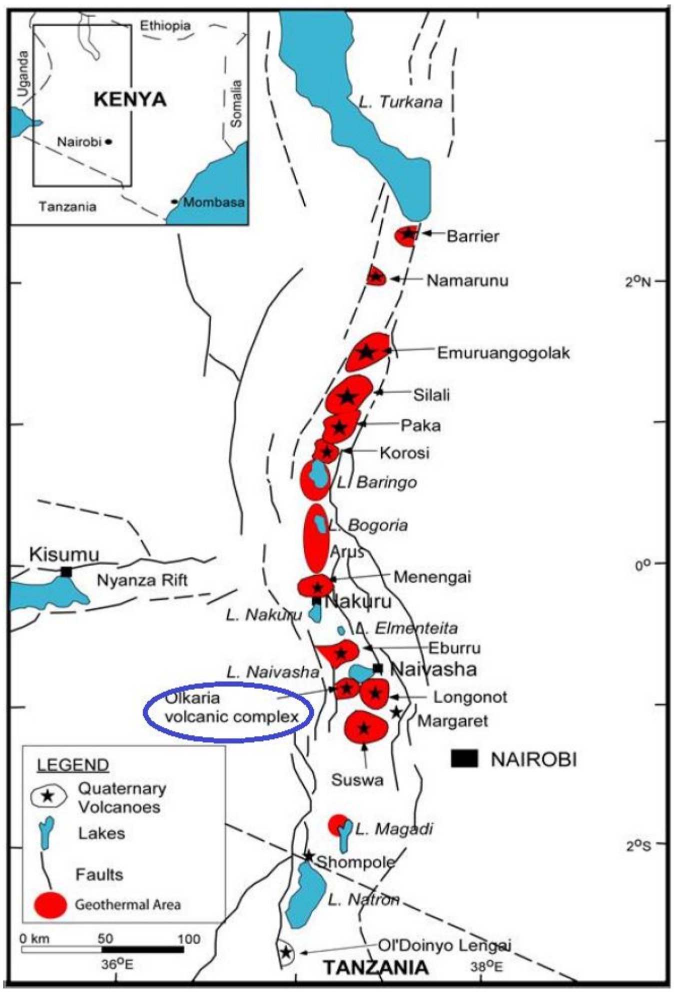


Figure 1: Location of Olkaria Field in the Kenyan Rift Valley (Wanjohi, 2014)

A geothermal energy business from exploration to exploitation is divided into four major series that include surface exploration, well drilling, reservoir analysis and operation stage that entails harvest of heat from the earth's subsurface (Parada, 2016). Dependable knowledge for the reservoir under study is paramount in determination on the best and economical exploitation method. Reservoir properties such as temperature distribution, permeability structures, feed zone locations as well as the up-flow and down-flow zones must be known in order to reach this decision (Sutopo and Pratama, 2016). This is achieved by well testing in combining with other disciplines such as geology, geochemistry and geophysics through development of a comprehensive conceptual model (Guðmundsson, et, al 2020).

Geothermal reservoir performance predictions in most cases depend on knowledge of the reservoir natural conditions established from temperature measurements that form part of the most crucial parameters required for geothermal resources assessment since temperature controls the movement and distribution of the reservoir fluids (Jansen and Miller, 2017). Other than its value, temperature distribution over the resource area is important. Location that are directly above or close to the main heat source or the magma chamber should beat the highest temperature. In these locations, temperature should increase with depth. High values are observed closer to the up flow zone while zones further away will be expected to have lower temperatures. Thus temperature variation may indicate proximity to the up flow zones and fluid movement from fluid up flow zones laterally outwards. Zones with consistent high temperature and increasing consistently with depth will define the probable or even possible reservoir.

Temperature contours drawn at selected elevations can be used to infer directions of fluid movement. Since temperature can be inverted by cold water inflow, temperature decline could be due to cold water inflow. Also temperature variations can define reservoir limits or boundaries. These zones may have low temperature (cold) or may show temperature decline from central locations. It is also possible to have situations where higher temperature caused by adverting hot fluid that is lying above a cold zone below within a well, referred to as inversion/ temperature reversal which can be shown by decreasing temperature with depth after an initial increase as shown in Figure 2. This inverted temperature profile is most likely to be an out flow zone.

Temperature recovery in a well after cold water injection or after drilling may also offer valuable data on intervals with permeability or feed zones. Such zones will generally accept water during injection or drilling and will start of cooler than less permeable zones where injection or drilling fluid will be passing largely on the surface and therefore will be less affected (Riley, 2018).

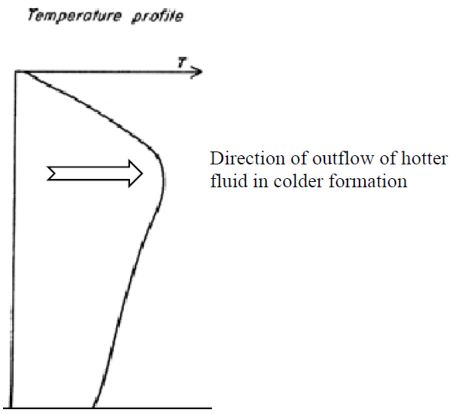


Figure 2: Direction of Fluid Movement (Menzies, 2013)

Rock alteration entails transformation of the mineralogy of rocks as a result of the changes to the existing conditions such as temperature, chemical composition, tectonic setting and the interaction period that the rock is subjected to. Temperature is the major determinant in the hydrothermal alteration as most of the chemical reactions do occur at elevated temperatures (Lagat, 2004). Also at elevated temperatures, minerals have been found to become thermodynamically stable. This is illustrated in Figure 3 below.

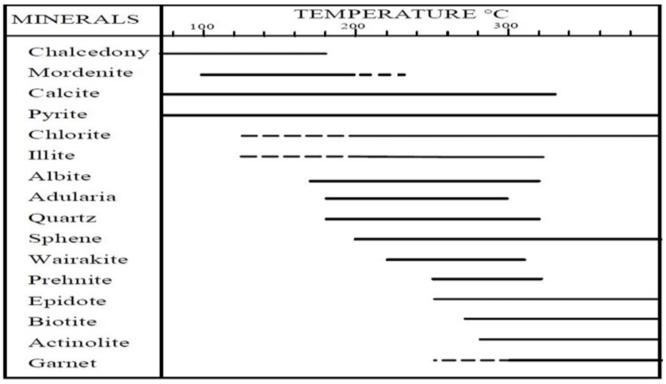
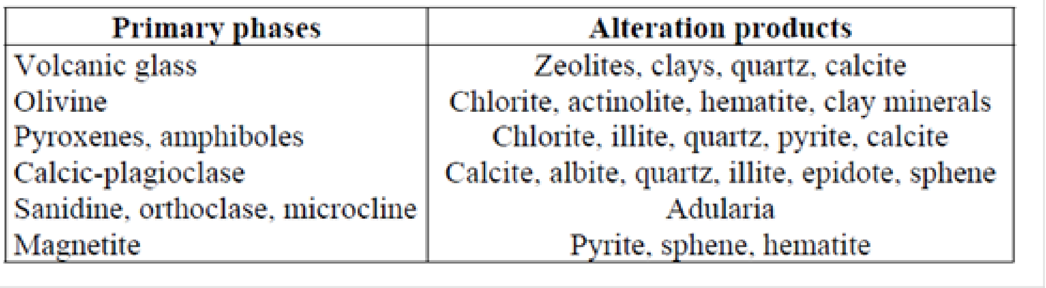


Figure 3: Hydrothermal alteration minerals and their temperature stability range (Lagat, 2004)

In area with favorable conditions for hydrothermal alterations such as high temperature, high permeability to allow rock and fluid interactions as the fluids carry metals in solution, either from a nearby igneous source or from leaching out of some nearby rocks causing hydrothermal alteration of rocks by passing hot water fluids through the rocks and changing their composition by adding or removing or redistributing components, the primary minerals become unstable and forced to undergo chemical reactions with the hydrothermal fluids altering them to secondary minerals that become stable under the newly created natural conditions (Reyes, 1990). Secondary minerals are then formed by replacement of the primary minerals as shown in Table 1.



Primary phases	Alteration products
Volcanic glass	Zeolites, clays, quartz, calcite
Olivine	Chlorite, actinolite, hematite, clay minerals
Pyroxenes, amphiboles	Chlorite, illite, quartz, pyrite, calcite
Calcic-plagioclase	Calcite, albite, quartz, illite, epidote, sphene
Sanidine, orthoclase, microcline	Adularia
Magnetite	Pyrite, sphene, hematite

Table 1: Primary Minerals and Alteration Products (Ronoh, 2012)

The index minerals used to construct an isograd across the wells include quartz and Illite with minimum stable temperatures of 180 and 200°C respectively and therefore their presence indicate high temperatures within the field.

II. Material and Methods

The Kenya Electricity Generating Company has so far successfully drilled more than thirty deep wells in Olkaria domes field for the purpose of energy exploitation. For temperature heat up tests, fourteen wells were randomly selected with the aim of getting a good representation of the entire field. These wells included: OW901, OW902B, OW903, OW905A, OW908, OW910, OW911A, OW912, OW914B, OW915, OW917, OW918, OW919 and OW921. Well distribution is shown in Figure 4 below.

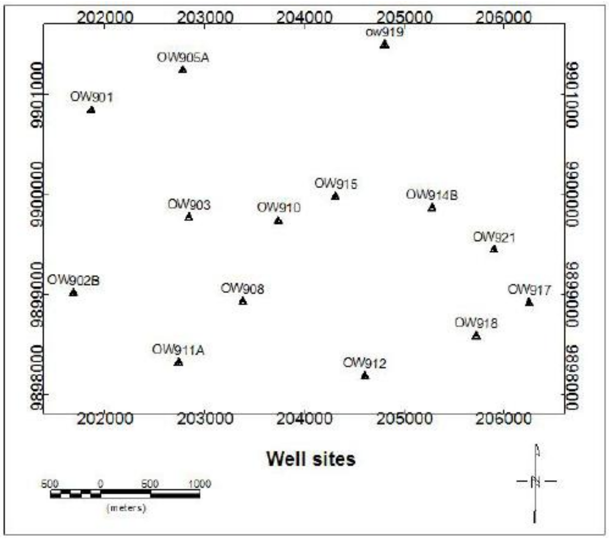


Figure 4: Well Distribution

The heat-up temperature profiles data used for this study was collected by the Kenya Electricity Generating Company during well completion tests for each well at different times. Before any test was conducted, a dummy run was conducted to determine the maximum clear depth of the wells and to ensure that the well was clear of any obstruction before running the down hole pressure and temperature logging tools. Cold fluids were pumped into the well at a rate of 1600lpm for a total period of 8 hrs.

The well was then shut to allow the well to recover. A temperature profile run was conducted periodically during well recovery.

For alteration mineralogy analysis, six wells that included OW901, OW902, OW905A, OW910, OW914B and OW917 were selected with the main material being the geological logging data obtained from rock cuttings. Depth of the first appearance of Illites and Quartz for each well was used with the surface elevation depth to find the depth above sea level of alteration. This depth and coordinates of the well where used to generate contour maps

III. Results and Discussion

Permeability zones were identified on the basis of temperature recovery profiles. Two major permeable structures were identified. The first zone was in the range of 900-1300 m.a.s.l and the second permeable structure was at a depth of 250-0m.a.s.l in most of the wells as shown in Figures 5, 6 and 7. This suggests that permeability in the Domes is dominated by the same three horizontal structures.

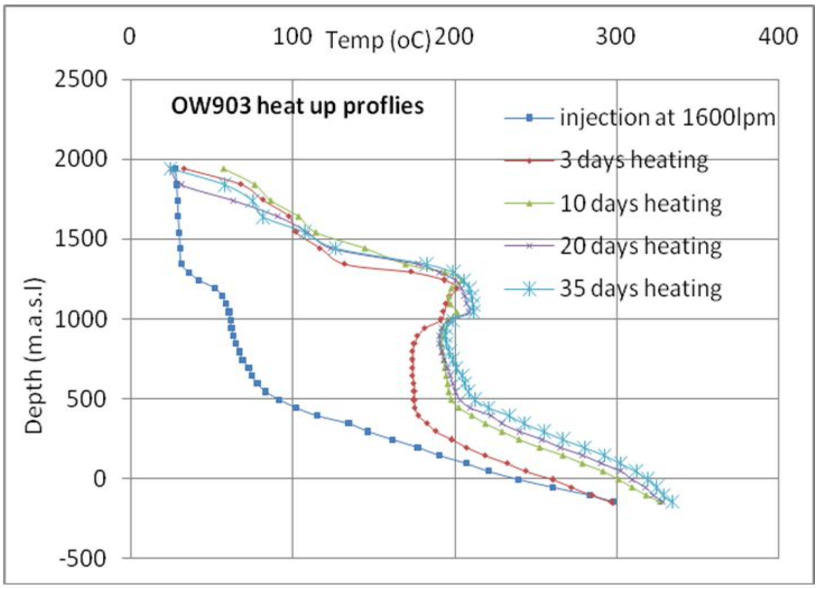


Figure 5: OW903 Pressure and Temperature Profiles

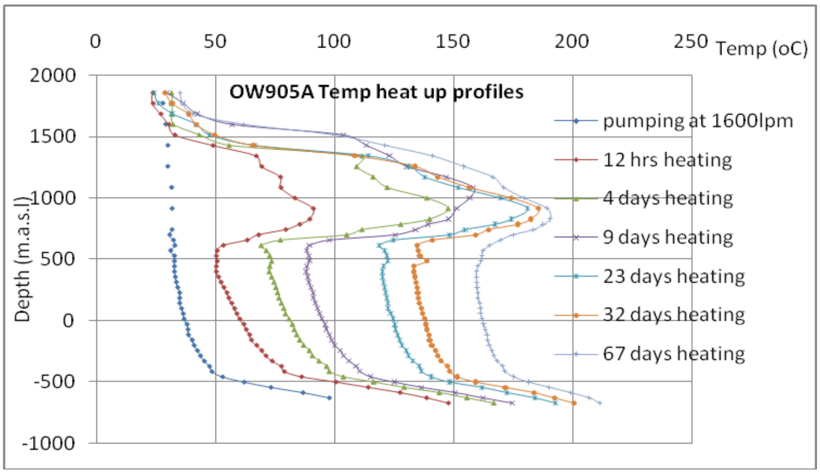


Figure 6: OW905A Pressure and Temperature Profiles

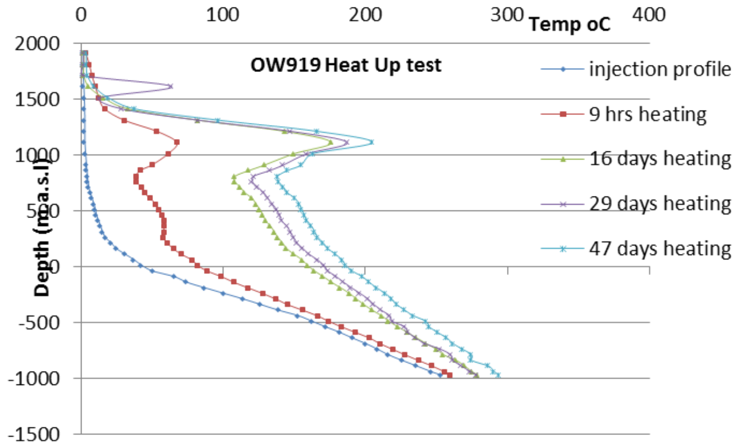
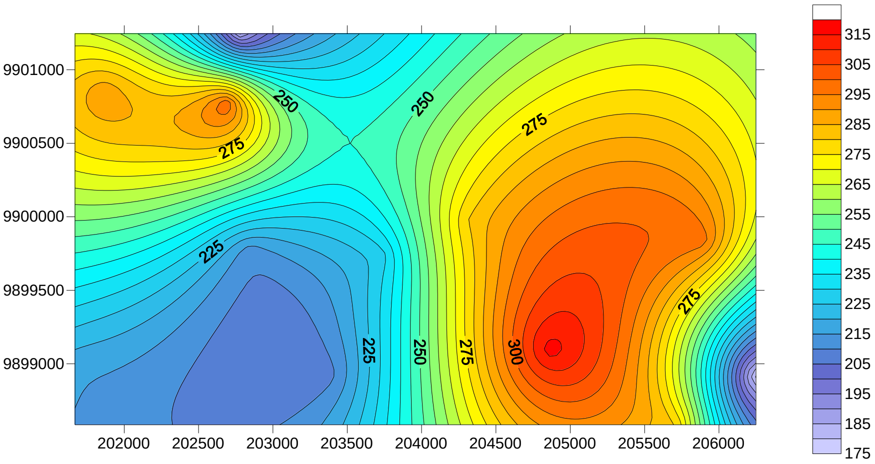


Figure 7: OW919 Pressure and Temperature Profiles from the Heat up Test

The recharge zones were identified from the lateral temperature contours at depths of 500 masl, and -200 masl as shown in Figures 8 and 9. From the two Figures, two major heat sources were inferred. The first heat source is located on the NorthWest side of the field while the second heat source is on the Eastern side of the study area.



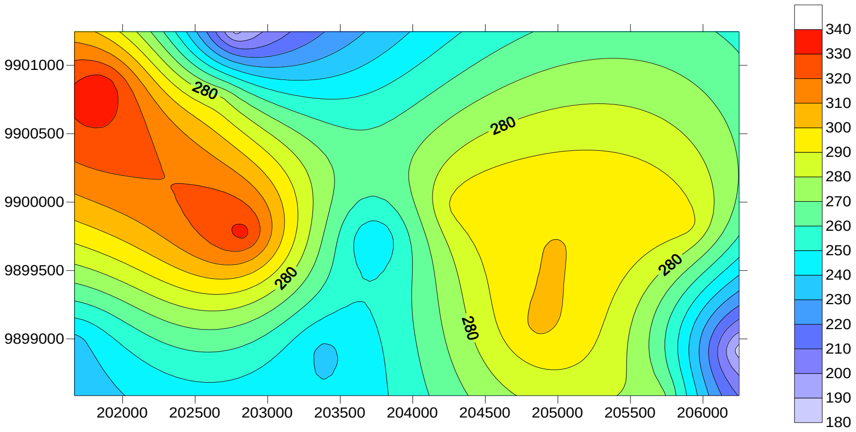


Figure 9: Lateral Temperature Contours at -200 masl

The two regions are characterized by high temperature isotherms. These regions exhibit temperatures more than 315^{0}C indicating magma chambers beneath the areas. These heat structures could be associated with magmatic intrusions.

The two heat sources are separated by a low temperature region that runs in the NE/SE direction that coincides with the geological fault structure as shown in geological map of Figure 10.

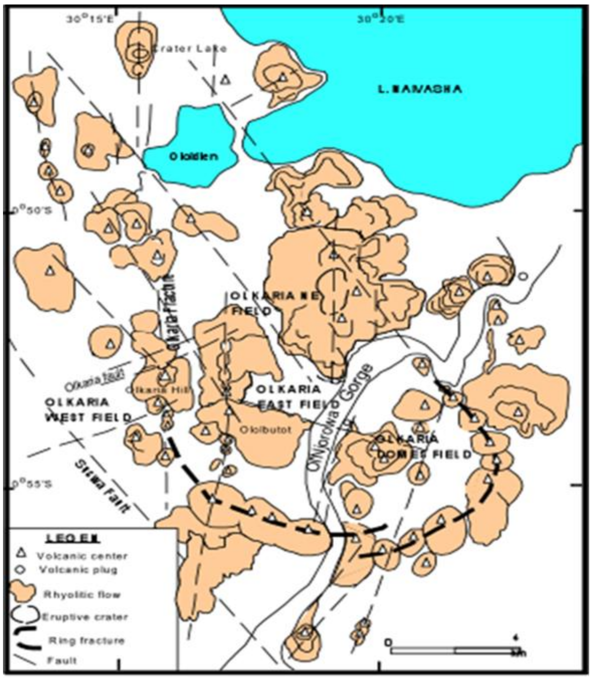


Figure 10: Geological Map of Olkara Field (Mariita, 2009)

Due to the low temperature nature of this fault structure, the fault is believed to control the fluid flow into the reservoir and therefore considered as the recharge to the reservoir. Three main recharge zones are observed. These are from the SW, NNW and the SE sides. These sides are colder as compared to the other regions of the reservoir. This indicate that the cold fluid flow into the reservoir from these directions.

The vertical temperature contour model from west to east direction shows two downflow zones (Figure 11). The first is located at the 202750 easting which is along the fault line while the second one is located at easting 205600 that corresponds to the SE recharge on the horizontal isotherm maps. An up dome of temperature contours on the western side of the study area indicates an up flow zone. Also this is the hottest region within the entire field. Two other up flow zones are found between eastings 20300 to 205500 and at 206000 Easting. The map also indicates lateral recharge zone at a depth between 1500 masl and 1000 masl but extending deep into the subsurface at the fault line up to 500m below sea level.

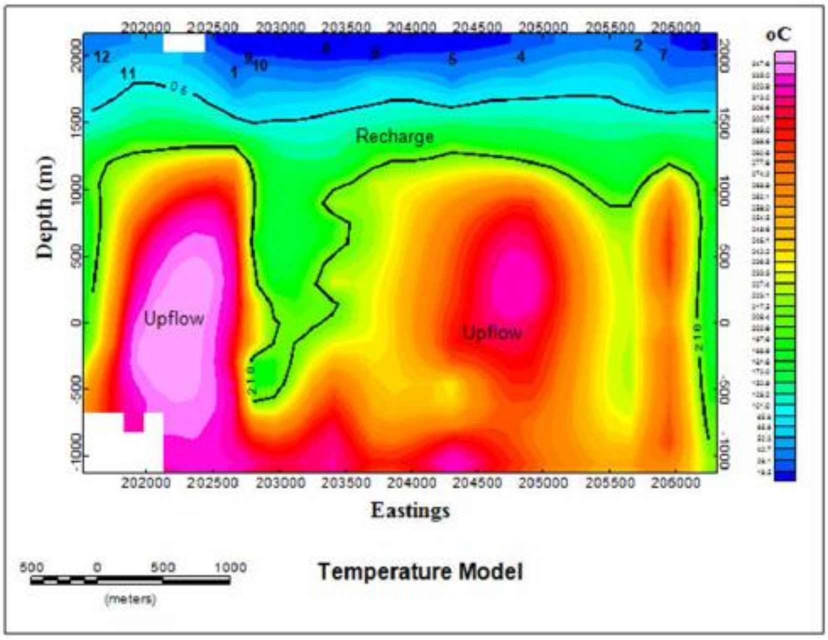


Figure 11: West-East temperature cross section

3.1 Mineral Alteration Distribution

Distribution of Quartz in Figure 12 that was generated from geological well logging data shows that in the Eastern region. Quartz was encountered at shallower depths of about 1600 masl compared to the western side where the first appearance of Quartz was as low as 1300masl.

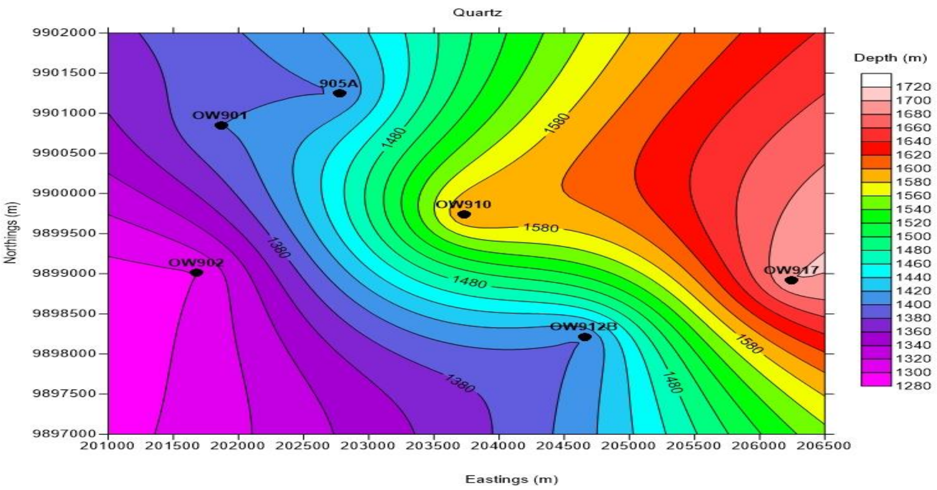


Figure 12: First appearance of Quartz in wells

Illites appeared shallower on the south eastern side with the shallowest being at the depth of 1750masl while the deepest was in the northwest side at 1150masl (Figure 13).

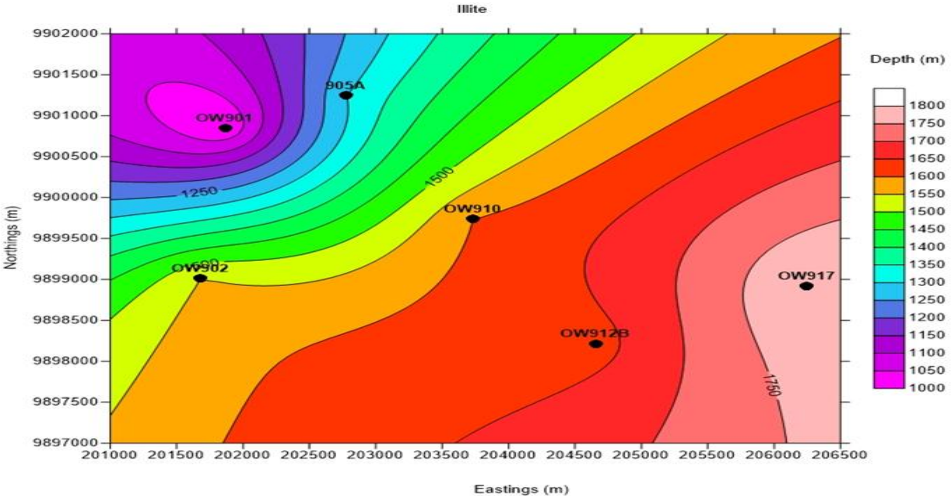


Figure 13: First appearance of Quartz in wells

The Illites and Quartz contour distribution indicate the minerals first appear shallower on the Eastern region as compared to the Western region of the field hence high-temperature zone characterized by the existence of high-temperature mineral assemblages in the eastern region. This distribution trend correspond well with the SW/NE structures and that the two heat sources separated by the SW/NE fault are at different depths and the heat source on the Eastern side is closer to the surface compared to the west side. Therefore SW/NE oriented fault could be as a result of more upthrow to the east as compared to the west leading to a normal fault.

IV. Conclusions and Recommendations

Olkaria Domes geothermal field can be classified as a high-temperature field since high tenperatures up to 315^{o}C were encountered. Two main heat sources were inferred; one to the Northwest and the second to the Eastern side of the field. The two heat sources are separated by a NE-SW trending fault that is believed to control the fluid flow with natural recharge to the reservoir coming from the SW direction. Eastern side heat source is closer to the surface. The reservoir had two major feed zones at depths of (900-1300) masl and (250-0) masl. Ilites and Quartz were encountered at shallower depths of in the eastern side as opposite to the western side. This is interpreted to mean that the Eastern side heat source is closer to the surface. It is recommended that more production wells can drilled in the east of the geothermal field with elevated heat source and convection mode of heat transfer dominates. Reinjection wells can be drilled along the NW-SWE trending fault to complement the natural recharge.

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