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Deciphering Thermal Evolution History of the Olkaria Northeast Field Based on Correlation of Alteration Mineralogy and Down-Hole Temperature Isotherms

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ABSTRACT

Thermal evolution history of geothermal fields has been of keen interest for the purpose of drilling successful production wells and quantifying the potentiality of the field. This paper aims to combine the data from down-hole temperature gradients, alteration mineral assemblages and hydrothermal mineral zones from Olkaria Northeast field to unravel the historical evolution of the thermal system. A systematic study of hydrothermal mineral assemblages found in eight wells (with a total depth ranging between 3000-3500 m) of the Olkaria Northeast geothermal field exhibit a complex water-rock interaction processes. The region considered as the upflow zone is characterized by high formation temperatures (up to 320 ˚C) and the presence of greenschist facies alteration mineral assemblages (chlorite, epidote, prehnite, actinolite) as the major phases. On the other hand, the region considered as the zone of lateral out-flow, largely demarcated by wells drilled slightly off and further outside the Gorge Farm fault is characterized by relatively low formation temperatures (about 100-180 ˚C) and, still the existence of high temperature alteration minerals. In the perceived up-low zone, it is observed that the calculated formation temperatures corroborates with the alteration products which contradicts the observation in the perceived out-flow zone. We infer the temperature changes in the geothermal system to be indicative of different thermal regimes. The tectonic structure of the studied area is controlled predominantly by NW-SE (Gorge Farm fault) and ENE-WSW (Olkaria Fault zone) directional forces.

1. INTRODUCTION

Geothermal system offer unique opportunities for studying the nature of high temperature fluid-rock interaction processes (e.g. Franzson et al., 2010). Olkaria Olkaria Northeast geothermal sub-field is located within the Olkaria geothermal field. The latter is a high-enthalpy geothermal field (temperature > 200 ˚C at 1 km depth), associated with a region of Quaternary volcanism in the Kenya Rift System (KRS). Apart from the Olkaria Northeast field, other sub-fields in Olkaria geothermal field include, Olkaria East, Olkaria Central, Olkaria Domes, Olkaria Southeast, Olkaria Northwest and Olkaria Southwest. Exploration for geothermal resources in Olkaria began in the early 1950s, culminating in the drilling of exploration well X-1 with little success. Subsequent detailed exploration and review of pre-existing data resulted to drilling of deeper (~ 1200 m) wells with good indications. Exploration for the vast geothermal resources is mainly for electricity production at five conventional power plants and several wellhead generators. Presently, the geothermal field supports an aggregate installed generating capacity of ~ 677 MWe. Geothermal systems are complex and inherently dynamic systems that can evolve over short periods of time. Understanding of the temporal evolution pattern allows for reconstruction of the history of geothermal systems (e.g. Stimac et al., 2001), which in turn can be used to ascertain at what evolutionary stage a particular system is, hence determining the potentiality and type of a current geothermal play. Consequently, the knowledge of thermal evolution of a geothermal system offers useful approach that can assist in exploring and evaluating potential geothermal resources.

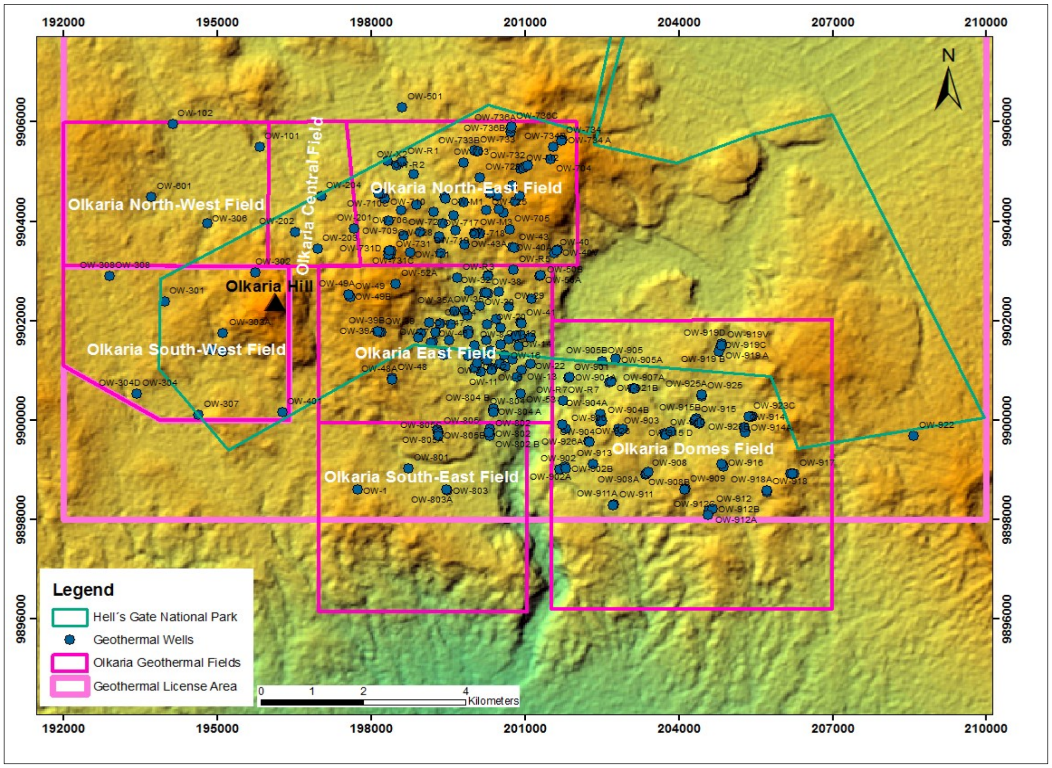

Figure 1: Olkaria geothermal field showing location of the various sub-fields (modified from Otieno and Kubai, 2013).

In this paper, we attempt to reconstruct the temporal thermal evolution of the Olkaria Northeast geothermal field based exclusively on a comparison of the calculated formation temperature and the observed index alteration minerals. It is worth noting that fluid inclusion measurements were however, not conducted on samples from the study wells due to certain limitations with the inclusion measurements. Generally, alteration temperature is used to present temperature in a geothermal system, and in many cases is assumed to represent the maximum long-term temperature state. Contrastingly, calculated formation temperature represents the current state of the system (Franzson, 2010). Specific alteration minerals become stable at specific temperatures and fluid compositions, thus by mapping mineral and mineral sequences it is possible to make a plausible and realistic outline of the thermal condition and evolution of the geothermal system (Mortensen et al., 2014).

2. SUMMARY OF THE STUDY WELLS

This study largely focuses on eight production wells namely; OW-732, OW-733, OW-735, OW-734, OW-734A, OW-736, OW-736A and OW-737 drilled between January, 2011 and December, 2016 to a bottom hole depth of between 3000 m and 3490 m RKB. Wells OW-732, OW-733, OW-734 and OW-737 are vertical, whereas, the rest are directional. Other than well OW-737, which is a step-out well drilled approximately 1.5 km from the Gorge farm fault and, OW-734 and OW-734A drilled slightly off the same fault, the remaining wells have been drilled within the proposed Olkaria caldera structure. The purpose of drilling well OW-737 was to ascertain whether the resource extends outside the proposed caldera structure.

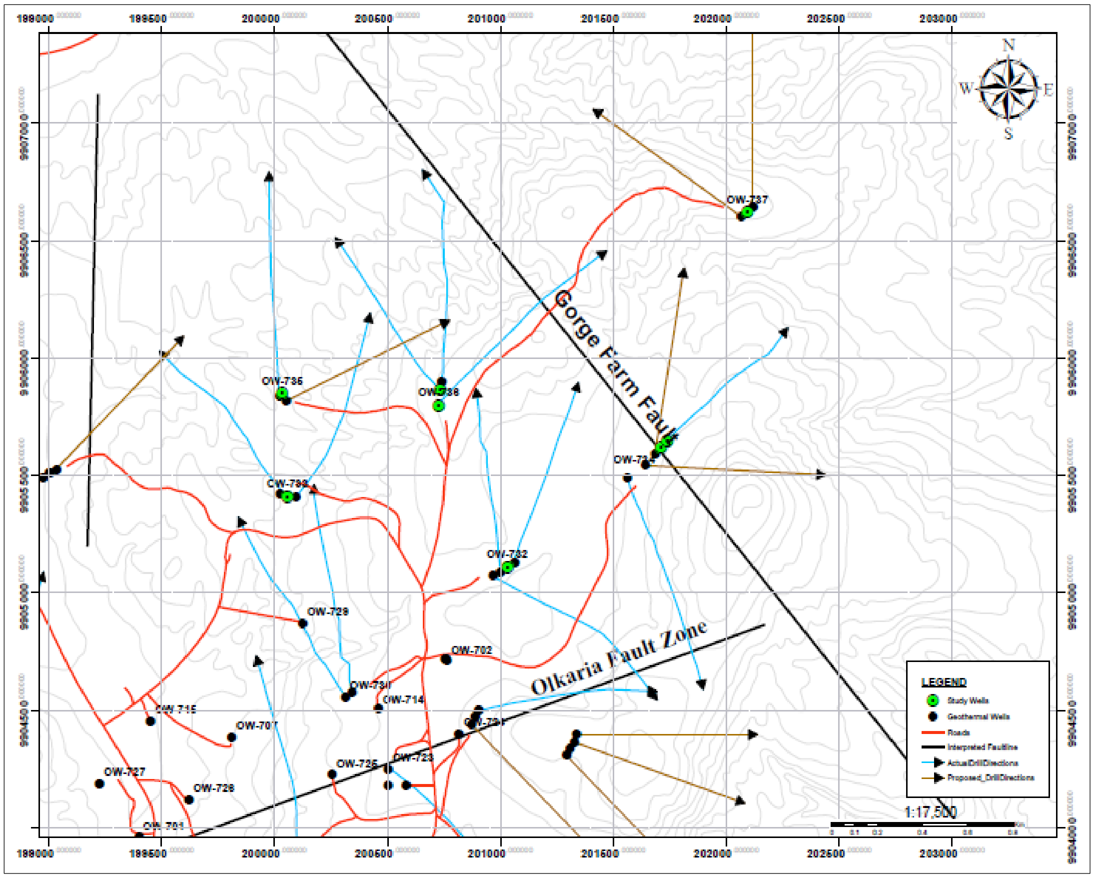

Figure 2: A simplified base map showing a section of the Northeast field with the location of the study wells. Also shown are other wells already drilled and planned to be drilled in the study area.

3. GEOLOGICAL FRAMEWORK

The geothermal system at Olkaria is hosted by a proposed volcanic caldera complex, measuring 11×7.5 km across. To date, in spite of the various scientific studies conducted considerable uncertainty still exist regarding the existence of the caldera structure with little success. The curved lineament of coalesced rhyolitic domes adjudged to mark the outline of the caldera structure demarcate only 30% of a caldera rim. Knowledge of the geology of Olkaria Volcanic Complex (OVC) is derived from the detailed pioneering of a plethora of scholars including Clarke at al., (1990), Marshall et al., (2009) and Omenda, (1998), just to mention a few. The geology of OVC can be distinctly divided into two groups: surface and sub-surface geology. The surface geology is dominated by comenditic lavas, pumice fall and pyroclastics. A large fraction of the pyroclastic deposits and pumice fall is hypothesized to have originated from Longonot and Suswa volcanoes, lying immediately 20 km east and 40 km south of OVC, respectively (Omenda, 1998).

On the other hand, sub-surface geology has been deduced through drill cuttings analysis from the numerous wells (> 200) used for geothermal production, injection and monitoring drilled in OVC. The lithostratigraphic units of the OVC as revealed by data from the geothermal wells comprise pyroclastics and comenditic rhyolites (dated at < 0.95 Ma) interspersed with thin horizons of tuff at the upper depths and extending to about 1500 m a.s.l. In the deeper portions of the wells, basalts, trachytes (dated at between 1.65-1.8 Ma) and intrusives (micro-granite and syenite) (dated at < 1.8 Ma) are predominant. Basalt forms the cap rock, whereas, trachyte is the reservoir rock (Musonye, 2015). In the Olkaria Northeast field interbeds of tuffs and rhyolite are prevalent as intercalations within the basalt and trachytes. Unlike the Olkaria Domes and Olkaria Southeast fields where intrusives are intersected at fairly shallow depths (i.e. at 500 m a.s.l), the scenario in Olkaria Northeast field is a bit different in that most of the intrusive rocks (mostly syenite) are encountered at much deeper depths (i.e. at 100 m a.s.l). A summarized sub-surface stratigraphy of the Olkaria geothermal field is presented in the Figure below.

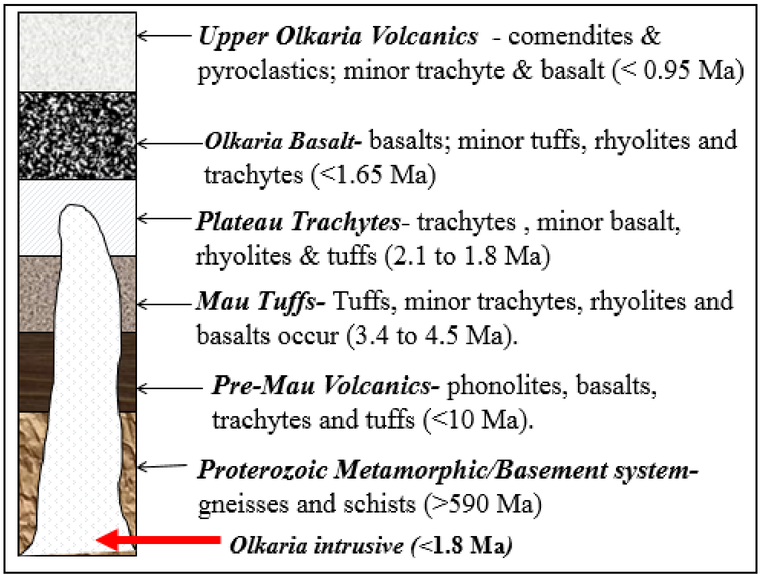

Figure 3: A summarised lithostratigraphic units of the Olkaria geothermal field (modified from Omenda, 1998).

4. HYDROTHERMAL ALTERATION CHARACTERISTICS

Hydrothermal alteration minerals are a result of interactions between thermal fluids and host rocks (protolith) or due to processes affecting the circulating hydrothermal fluids. Mielke et al., (2015) pointed out that formation of hydrothermal alteration minerals is dependent on temperature, permeability, pressure, duration of activity, initial composition of the rock system and initial composition of the circulating fluids. The latter is significant in determining which mineral assemblages to dissolve, deposit or be replaced. Consequently, by studying and comparing a particular set of hydrothermal mineral assemblages (index minerals) with calculated formation temperatures, one is able to make inference on whether the geothermal system was hotter than the currently measured system, has maintained a steady state of thermal equilibrium or is heating up.

5. MATERIALS AND METHODS

Samples studied are drill chips/cuttings from six wells. Cuttings were collected at 2 m intervals for the entire depth of the well for lithologic logging. However, in cases where partial circulation returns were encountered, cuttings were collected at 4 m interval. The mineralogical composition of about six wells was determined by binocular, petrographic and XRD analyses at the KenGen, Olkaria geology laboratory. Studies of drill chips provided important information on the stratigraphy and the nature of alteration minerals in the studied wells.

The depths of occurence of index minerals, namely quartz, epidote and actinolite in this case were clearly marked and plotted as isograds along the study wells. Clay minerals were identified from three diffractograms (air-dried, ethyleneglycolated and heat treatment) of the clays size fractions (< 2µm) extracted based on the standard sedimentation technique in deionized water.

On the other hand, downhole temperatures were obtained from temperature recovery profiles with depth logged between xx days of recovery and, later converted to calculated formation temperature using the Horner plot. During step pumping, the first pumping rate was set at 1000 l/min then subsequently increased to 1300 l/min, 1600 l/min and finally 1900 l/min. This is the pumping rate which has been adopted during step pumping of the Olkaria wells.

During all pumping rates, temperature measurements were carried out at 100 m interval from the surface to the production casing depth, which is quite variable from one well to another. Afterwards, the interval was reduced to 50 m to the well bottom. These intervals are constant for all wells. The data acquired was processed using MS office excel and then imported to the three-dimensional visualization software (petrel) in the form of notepad files.

6. RESULTS

6.1. Hydrothermal alteration in the Northeast field

Hydrothermal alteration in the study wells is essentially a product of two components: (a) replacement of primary components in the rocks by alteration minerals, and (b) precipitation of alteration minerals into open spaces (veins, fractures and vesicles) in the rock. The influence of the two structural systems (Figure 2) play a pivotal role in influencing the interplay between the hot circulating hydrothermal fluids and the host rocks. Most importantly the alteration patterns in the study wells display fairly similar characteristics, both in the region perceived to be the up-flow zone (around wells OW-732, OW-733, OW-735, OW-736A and OW-736) and the area perceived to be the possible out-flow of the system (around wells OW-734, OW-734A and OW-737). The top most zones of the wells (0-150 m b.g.l) contains relatively fresh rocks, including a sequence that do not show any indication of geothermal interaction and at the most show moderate oxidation due to groundwater enrichment.

The subsequent zone (150-500 m b.g.l) is dominated by relatively low-temperature alteration mineral assemblages signifying that inferred alteration temperatures are < 200 °C. Some of the key hydrothermal alteration minerals observed are low temperature zeolites (scolecite, mesolite and analcime), chalcedony and smectite. Petrographic analysis of the rock samples between this interval indicate that the primary mineral phases replaced are mostly volcanic glass and olivine. A prograde mineralogical change, marked by transition from secondary quartz, wairakite, illite, chlorite, wollastonite, prehnite, epidote and actinolite is eminent below 500 m b.g.l to almost the wells' bottom. The depth of occurence of the index minerals is almost fairly uniform for the two cadres of wells. However, the minerals are observed at slighlty shallower depths in the up-flow area relative to the proposed out-flow zone. Another important point to note is that occurence of calcite below 1600 m b.g.l in the wells drilled in the up-flow zone is spasmodic and in some cases diminishes significantly, whereas, the abundance is pronounced and continuous to the well bottom in the outer wells. In addition, the occurence of hematite correlates to that of calcite in the same wells. Figures 4 and 5 below, summarizes the lithology, alteration characteristics and alteration mineral zones from two selected wells in the Northeast production field.

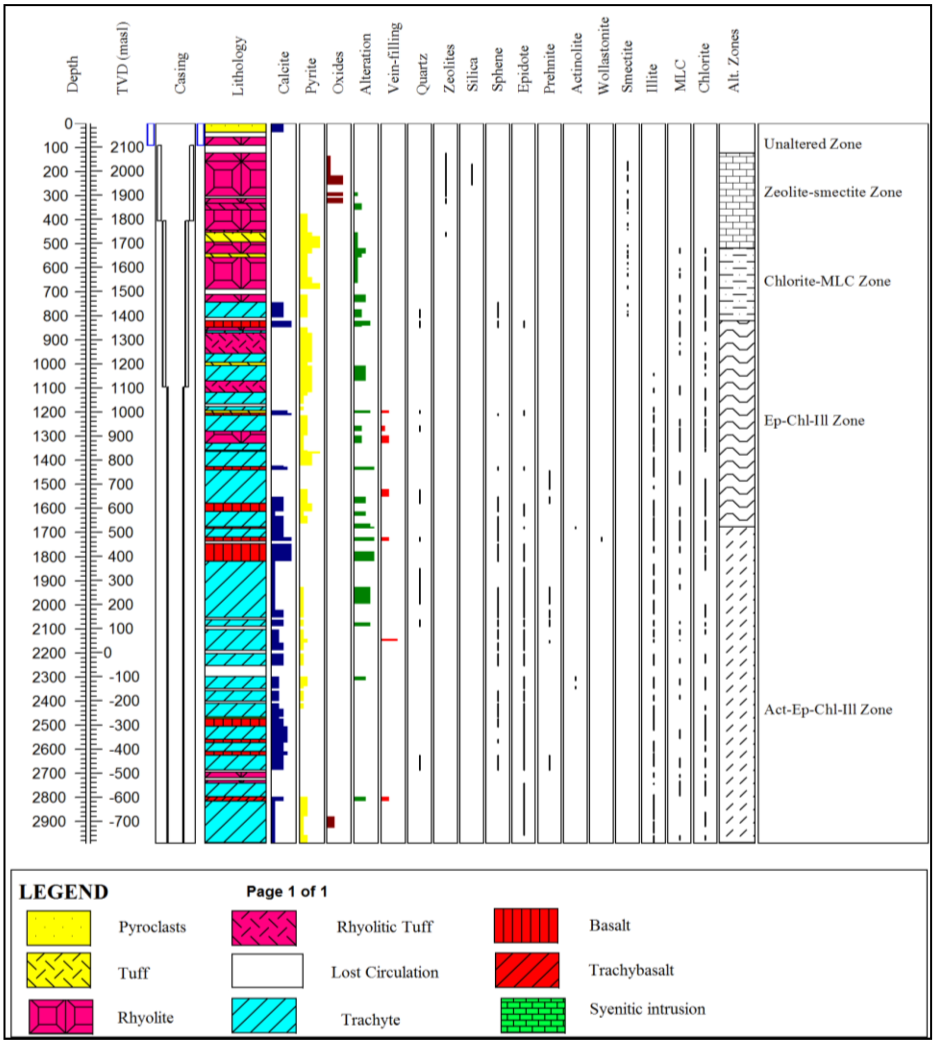

Figure 4: Hydrothermal alteration characteristics, mineral assemblages and alteration mineral zones in well OW-734A.

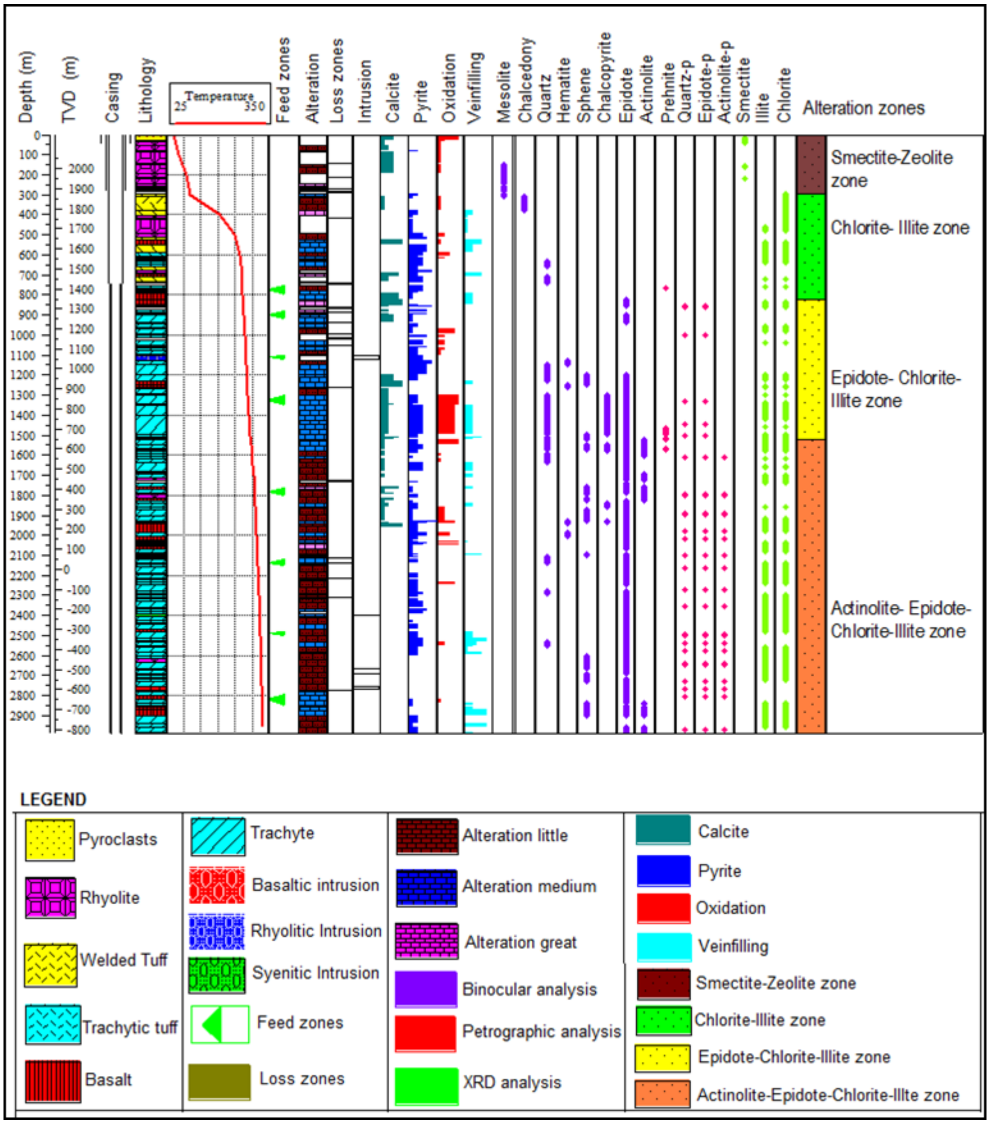

Figure 5: Hydrothermal alteration characteristics, mineral assemblages and alteration mineral zones in well OW-732.

6.2. Comparison of formation and alteration temperature

Studies of temperature dependent alteration minerals, temperature logging (direct down-hole measurements) and fluid inclusion homogenization temperatures (Th) have successfully been applied to assess the physico-chemical conditions and temporal evolution of geothermal reservoirs in active geothermal fields (e.g. Marks et al., 2010). A hydrothermal alteration sequence provides significant insights into the history of a geothermal system. There is always some uncertainty whether the observed alteration mineral assemblages reflect the present formation temperatures or are related to some past thermal events.

Like in many geothermal systems, hydrothermal alteration minerals in the Olkaria Northeast field have successfully served as important indicators of sub-surface thermal changes (e.g. Lagat, 2004). As mentioned earlier, alteration temperature is used to present temperature in a geothermal system, and is thus assumed to represent the maximum long-term temperature state. In contrast, measured formation temperature represents the current state of the system. Formation and alteration curves from two selected wells (OW-732 and OW-737) have been plotted to establish the behavior of the geothermal system, i.e. whether the system has maintained a steady state of thermal equilibrium, heating up or depicts some conditions of cooling down over a period of time. Once again, it is important to note that homogenization temperatures of inclusions entrapped during crystallization or recrystallization of minerals and which represent initial conditions during boiling in a geothermal system were not measured as part of this study. Formation temperatures were calculated using Horner plot based on the temperature recovery profiles. On the other hand, the alteration temperature curve is based on the first appearance of index alteration minerals, in this case secondary quartz, epidote and actinolite observed using binocular and petrographic analysis; these minerals were used as geothermometers. The first appearence of the index minerals indicate temperatures equal to or in excess of 180 °C, 240 °C and 270 °C, respectively (e.g. Reyes, 2000).

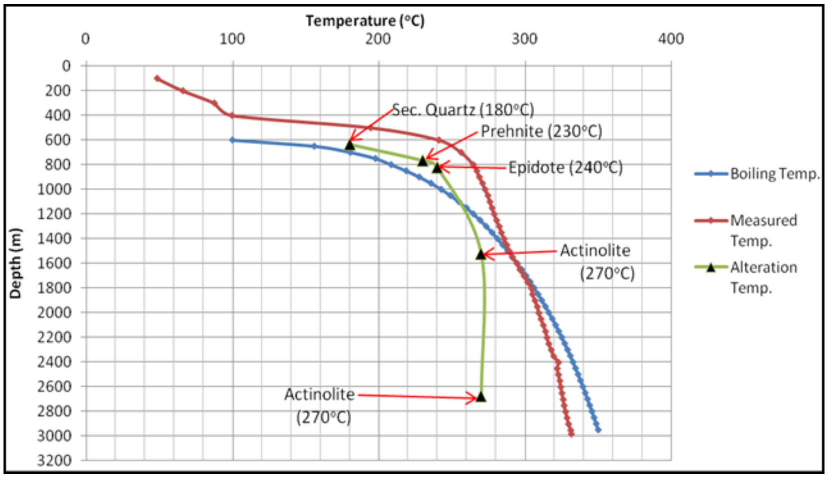

Figure 6: Comparison of formation and alteration temperature in well OW-732.

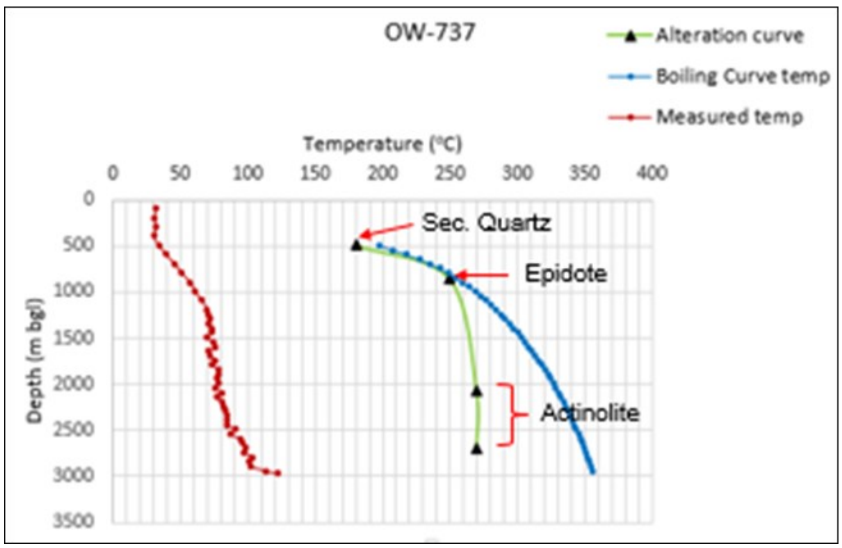

Figure 7: Comparison of formation and alteration temperature in well OW-737.

6.3. Temperature distribution across the field

A plot has been drawn of calculated formation temperature distribution cutting across the different study wells. The data has been plotted alongside hydrothermal isograds of index minerals extensively discussed above. The alteration mineral temperature isograds are not exactly parallel to the formation temperature trends. This is attributed to the fact that hydrothermal alteration, as earlier discussed is not solely a function of the formation temperature, but also initial composition of the host rocks and thermal fluids, duration of activity, permeability just a few to mention. To display the temperature distribution across the study field, N-S and E-W temperature cross-sections profiles (Figures 8 and 9) have been made and bisect the eight study wells.

However, it is prudent to note that it has not been possible to carry out temperature recovery measurements in well OW-737. This is a recently drilled well and is currently capped and undergoing recovery to stabilize with the system around the well's vicinity. Consequently, the temperature section covering well OW-737 is ideally an extrapolation of the sub-surface temperature conditions based on the three-dimensional visualization program (Petrel). From Figures 8 and 9, it is evident that wells drilled to the west of the NW-SE trending Gorge Farm fault (i.e. wells OW-733, OW-735, OW-732, OW-736 and OW-736A) and within the perceived up-flow zones intercept relatively high temperatures (200-320 ^{o}C) at shallow depths which corroborates with the alteration mineral isograds. Contrastingly, wells drilled to the east (OW-734, OW-734A and OW-737), i.e. slightly off and further away from the Gorge Farm fault are marked by relatively low temperature distribution (100-180 ^{o}C). The alteration mineral isograds in this region shows insignificant departure in terms of the depth of first appearence of the index alteration minerals.

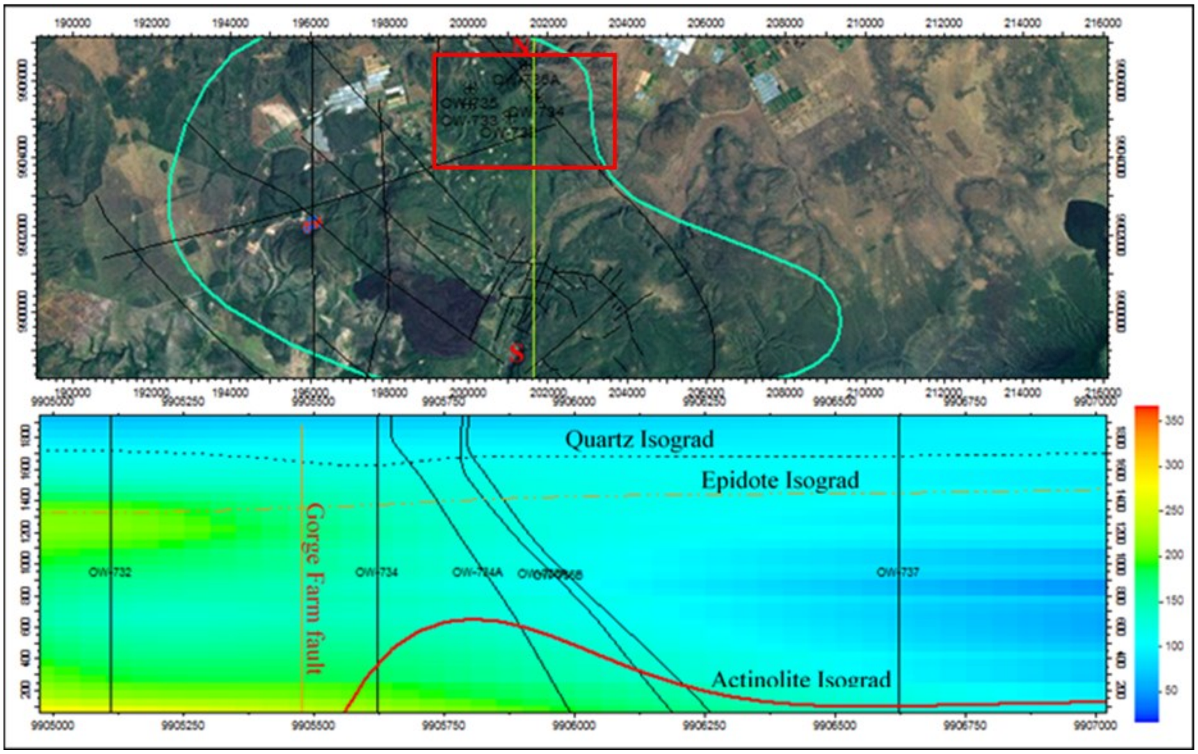

Figure 8: N-S profile showing formation temperature distribution and alteration mineral isograds across Olkaria Northeast field.

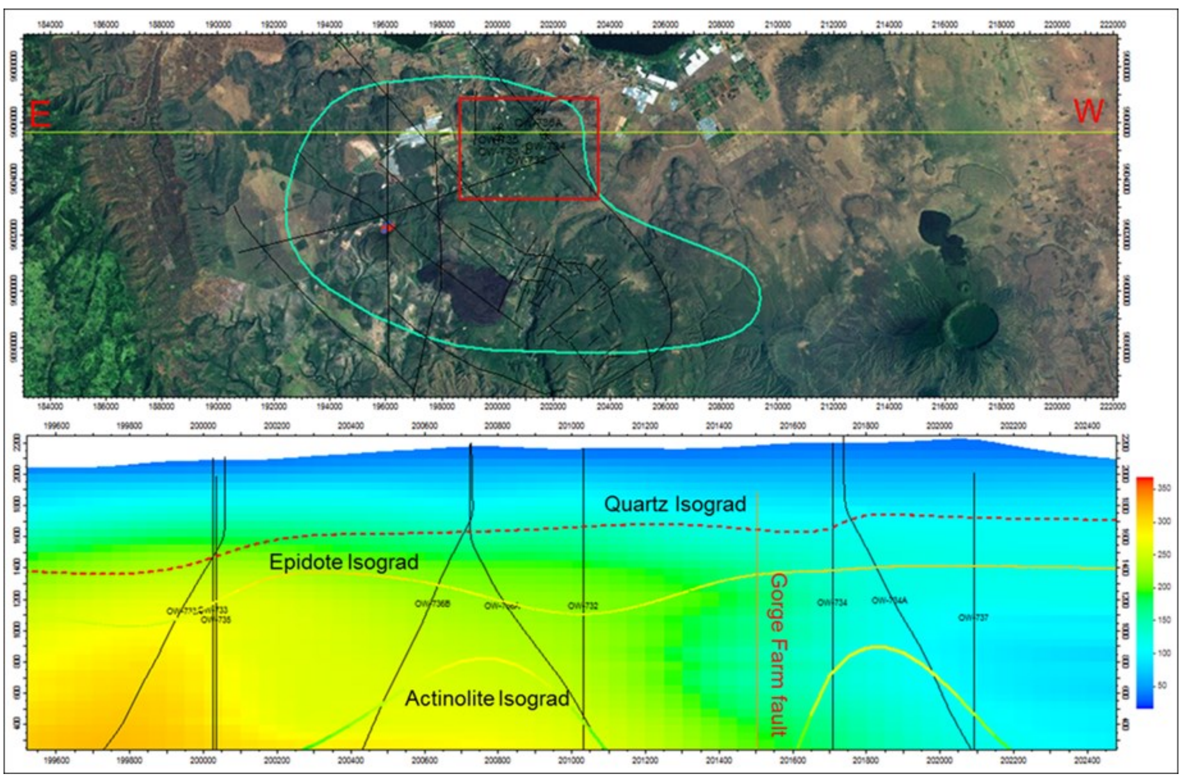

Figure 9: E-W profile showing formation temperature distribution and alteration mineral isograds across Olkaria Northeast field.

7. DISCUSSION AND CONCLUSIONS

Hydrothermal alteration in the Olkaria Northeast field depict fairly similar characteristics even though there is eminent variability on intensities of alteration from one well to another. Studies of hydrothermal alteration in the Olkaria Northeast field have been able to link different minerals to particular temperatures. Temperatures affect the crystal lattice of minerals, hence determining the stability of certain minerals at certain temperatures. The prograde mineralogical change observed in wells drilled within the perceived up-flow zone correlates positively with the mineralogic alteration patterns observed in other potential up-flow zones within the larger Olkaria geothermal field, for instance the Olkaria Domes and Olkaria East production fields. Just like in other high-temperature geothermal fields across the world, the first appearance of epidote in the Olkaria Northeast field is equally significant in that it has been applied to map the localized up-flow zones and also to explicitly unravel the tectono-stratigraphic framework.

Apart from similar high temperature alteration minerals (e.g. epidote and actinolite) being observed in wells drilled slightly-off and further away from the Gorge Farm fault, and given that there is limited variation in the depths of first appearance, the ubiquitous and prevalence of calcite and hematite in these wells cannot be underestimated. The pronounced occurrence of calcite and hematite vis-à-vis the perceived up-flow zone wells is a clear attestation that the minerals were deposited at relatively low temperatures. In this respect, the occurence of calcite in these wells is strongly related to heating of cooler peripheral fluids entering the geothermal system by the hot host rocks, thus facilitating carbonate precipitation. This is contrary to calcite formation through hydrolysis and boiling of geothermal fluids. This observation is in accord with the interpretation put forth by Musonye (2015) to explain intense calcite deposition in well OW-917, located along the rim of the proposed ring structure. However, fluid inclusion studies would potentially provide detailed insights on the homogenization temperatures of the trapped inclusions. Occurence of hematite, a low-temperature Fe-oxide is commonly associated with the incursion of cold groundwater and other oxidizing conditions in a geothermal system (Brown, 1978). The mineralogical temperatures indicated by presence of high temperature alteration minerals (e.g. epidote and actinolite) in wells drilled in the potential out-flow zone suggest past inflow here of hotter fluids. Consequently, the minerals' occurence can be termed relict. A widely proposed hypothesis (e.g. Omenda, 1998) postulates that the Gorge Farm fault marks the boundary of the Olkaria Northeast production field to the north and is a channel of cold meteoric water along the fault trace.

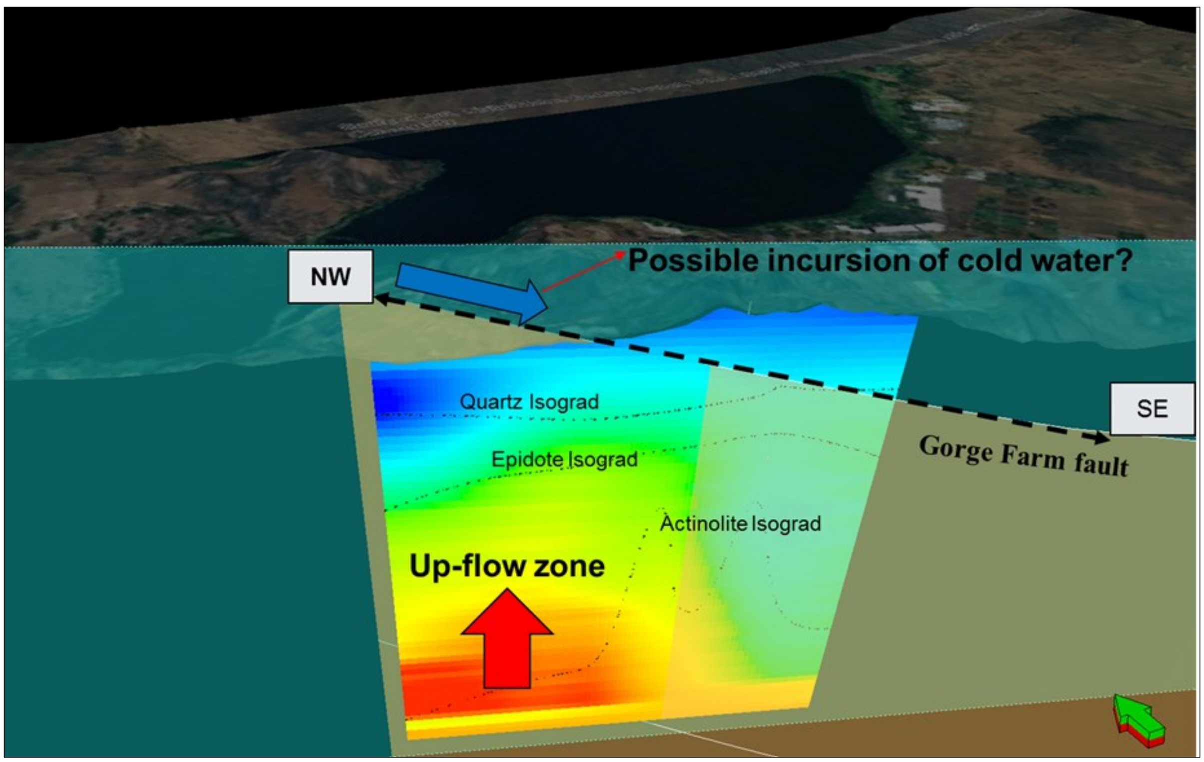

Figure 10: A 2-dimensional sketch of a possible conceptual model across the Olkaria Northeast field. The red arrow denotes the perceived up-flow zone, whereas, the blue arrow indicates possible incursion of colder meteoric water along the Gorge Farm fault. The green arrow is directed north.

From the comparison of formation and alteration temperature and temperature distribution across the field, two different hydrothermal systems are evident in the Olkaria Northeast field. The currently active thermal regime associated with wells drilled within the up-flow zone and the older hydrothermal activity. The latter is characterised by deduced cooling, interpreted as resulting from influx/incursion of cooler meteoric water along the Gorge Farm fault. The temperature logs for wells OW-734 and OW-734A supports that the recovery process was of conductive nature from about 1200 m down to the well bottom. This is characteristic of most wells drilled on the peripheral margins of most geothermal systems (e.g. Mortensen et al., 2014). Significant fluid convection is however, observed in the relatively good producer wells.

8. RECOMMENDATIONS

- Fluid inclusion studies need to be carried out and integrated with the inferred alteration and calculated formation temperatures. The findings would serve as a better means of reconstructing the past history of the geothermal system in the Olkaria Northeast field.

- Detailed studies on the fluid chemistry, particularly stable isotopes and tracer tests are strongly advocated for to provide constraints on the origin of the fluids, the potential hydraulic gradient and depth of circulation of the fluids.

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