Presented at SDG Short Course II on Exploration and Development of Geothermal Resources,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Nov. 9-29, 2017.

BOREHOLE GEOLOGY WITH CASE EXAMPLES FROM KENYA

Irene Ronoh
Kenya Electricity Generating Company Ltd.
Olkaria
KENYA
ironoh@kengen.co.ke

ABSTRACT

Hydrothermal alteration minerals have been used successfully to determine the relative permeability, temperature, fluid composition, pressure changes and thermal history of a geothermal reservoir. The alterations noted in the reservoir rocks have been due to changes in the prevailing conditions leading to change from primary to secondary minerals deposited in veins, vugs and also within the rock matrix. In Olkaria Domes geothermal area, OW-921A, OW-916 and OW-922 have been discussed to show how alteration minerals have been used to determine the thermal history of the reservoir surrounding the wells. In the Olkaria East Field, OW-35, OW-37A and OW-39A give a good contrast on the characteristics of the wells in the upflow and downflow zones. In Menengai geothermal area, wells MW-04 and MW-06 are located in the upflow zone as depicted by the abundance of high temperature alteration minerals and good permeability from the fractured formation. On the other hand, MW-02 and MW-07 are sited in the downflow zones of the field as shown by the low permeability and low enthalpy hence used are reinjection wells.

1. INTRODUCTION

Wells OW-35, OW-37A and OW-39A in the Olkaria East geothermal area were drilled between March 2009 and December 2010 while wells OW-916, OW-921A and OW-922 were drilled between February 2010 and September 2014. Cutting samples from the wells were taken at every 2 m interval with a few metres experiencing partial-to- total loss of circulation returns. Aerated drilling technique was used during drilling to ensure better sample collection and to avoid clogging of the production zones. Geosweeps were carried out during the drilling operation where mixing of cuttings was suspected. No cores were collected in these wells and therefore all the descriptions and interpretations are based on cuttings samples. Exploration and appraisal wells MW-02, MW-04, MW-06 and MW-07 in Menengai geothermal field were drilled between 28th February 2011 and 1st June 2012. Rock cuttings in these wells were sampled at a 2 m interval for lithological analysis.

Three analytical methods were employed during sample analyses. These include; binocular microscope, petrographic microscope and X-Ray Diffractometer (XRD) analyses. Binocular microscope was used in the initial analysis of rock cuttings to identify colors of the cuttings, rock type(s), grain size, rock fabrics, alteration mineralogy and intensity, vein and vesicle infillings and lithological boundaries. Petrographic (thin sections) analyses, was done to confirm the rock types, alteration minerals and alteration mineral sequences while XRD clay analysis was specifically carried out to identify specific clay minerals present in the rock cuttings.

1.1 Alteration of primary minerals

The interaction of geothermal fluids with rocks leads to changes in the compositions of both fluids and the rocks. The mineralogy, color and texture of the rocks are then altered as a result of change in conditions e.g. heating or cooling. The primary minerals are replaced by the secondary minerals because there has been a change in the prevailing conditions subjected to the rock.

Factors affecting the type of alteration products apart from temperature include parameters such as tectonic setting, lithology, composition of the geothermal fluids and the duration subjected to the fluid-rock interaction. Permeability of the rocks controls the access of thermal fluids, which cause hydrothermal alteration of the rocks and precipitation of secondary minerals in open spaces. The chemical composition of the host rock determines the availability of components to form alteration minerals as well as possible fugitive components from the presumed magmatic heat source. However, Lagat (2004) states that temperature is the most significant factor in hydrothermal alteration because most of the chemical reactions require elevated temperatures and, also, most minerals are thermodynamically stable at high temperatures. Pressure does not affect hydrothermal alterations as the systems exploited are relatively shallow, i.e. 1 bar or less (Lagat, 2004).

Hydrothermal alteration minerals can be used in estimating fluid pH and other chemical parameters, to predict scaling and corrosion tendencies in fluids, measuring permeability and possible cold water influx and as a guide to the hydrology (Reyes, 1990).

The main primary minerals in both Olkaria and Menengai geothermal field include glass, olivine, feldspars, pyroxene and opaques in order of their susceptibility to alteration, glass being the most unstable. The alteration of volcanic glass and primary mineral assemblage is decribed in Table 1.

TABLE 1: Primary minerals and alteration products of Olkaria Domes volcanics. Modified from Browne (1984)

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

1.2 Distribution of hydrothermal minerals

The main hydrothermal minerals in Olkaria and Menengai geothermal fields include zeolites, fine to coarse grained clays, albite, actinolite, calcite, chlorite, chalcedony, epidote, prehnite, hematite, illite, adularia, secondary Fe-Ti oxides, pyrite, sphene, wollastonite and quartz. Mineral associations in vesicles are common and consist of two or more of the following minerals; illite, chlorite, quartz, calcite, epidote and pyrite with the paragenetic sequence varying with depth and temperature. Hydrothermal alteration is not a function of subsurface temperature only but the rock composition also influences the kinetics of the hydrothermal alteration minerals formation. The temperature stability ranges of the alteration minerals in most of the studied wells in the Olkaria and Menengai fields are summarized in Figure 1.

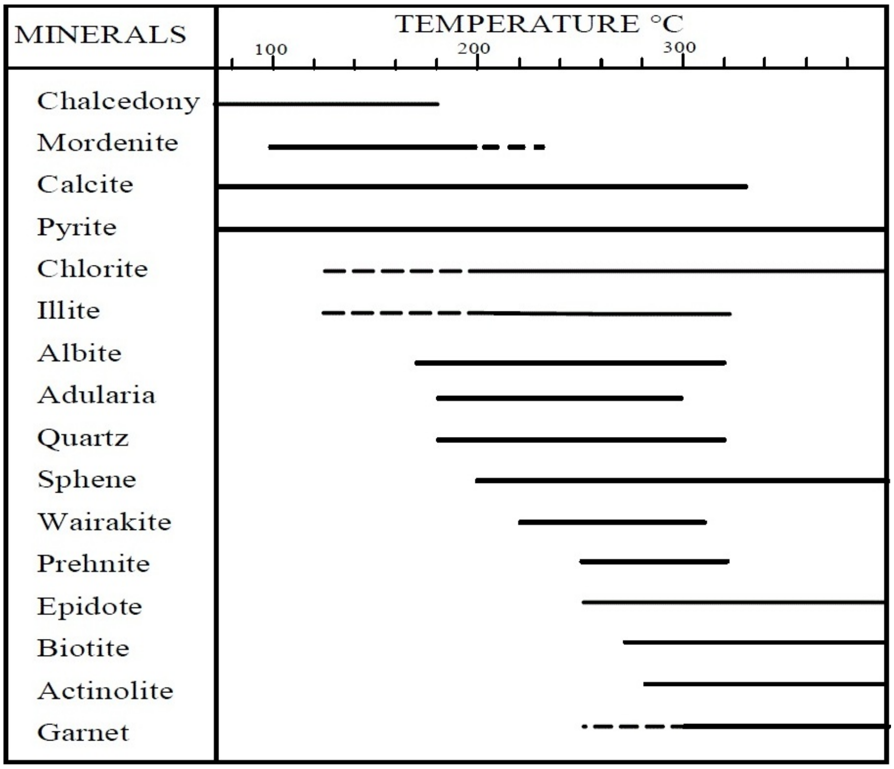

FIGURE 1: Temperature stability ranges of the alteration minerals in most of the studied wells in the Olkaria and Menengai geothermal fields

1.3 Olkaria Domes field

1.3.1 OW-921A

Well OW-921A was drilled between 27th August 2012 and 16th October 2012 to a depth of 2988 m with the production casing being set at 1097 m depth. Maximum formation temperatures of 319°C were measured at 2980 m depth with an injectivity index calculated after well testing is 357 lpm/bar. Rock types identified in the well include pyroclastics, rhyolites, tuffs, trachytes, basalts and intrusives (Figure 2). Dyke intrusions of syenitic compositions were encountered at depths of 2126-2130 m. Parameters controlling hydrothermal alteration in the well are temperature, rock type, fluid chemistry and permeability. First appearance of epidote occurs at depths of 1138 m. Permeability is deduced from loss of circulation zones, stratigraphic boundaries, heat-up temperature profiles and changes in intensity of alteration. The well has a major feed zones from 600-1100 m, 1700-1900 m, 2150-2400 m and 2900 m to the bottom of the well. The well intersects permeable fractures.

By comparing current formation temperature and alteration mineralogy, the indication is that the area around the well has experienced boiling between 600 and 1250 m and a state of thermal equilibrium is observed below 2000 m (Figure 3).

1.3.2 OW-916

The relationship between depth and hydrothermal mineral formation indicates low-temperature minerals at shallow depths and high-temperature minerals at greater depths (Mwangi, 2012). There is a progressive increase with depth. Three alteration zones were identified: zeolite-illite zone, epidote-chlorite-illite zone and actinolite-epidote-chlorite-illite zone (Figure 4). Several feed zones were encountered and classified into major and minor feed zones, and they are associated with fractures, lithological contacts and circulation losses encountered during drilling. The larger feed zones are between 650 and 1300 m and they show little cooling when comparing the alteration and formation temperatures. Epidote and actinolite are observed at shallow depth in this well compared to the other wells in the Olkaria Domes field indicating that this area could be an up flow zone.

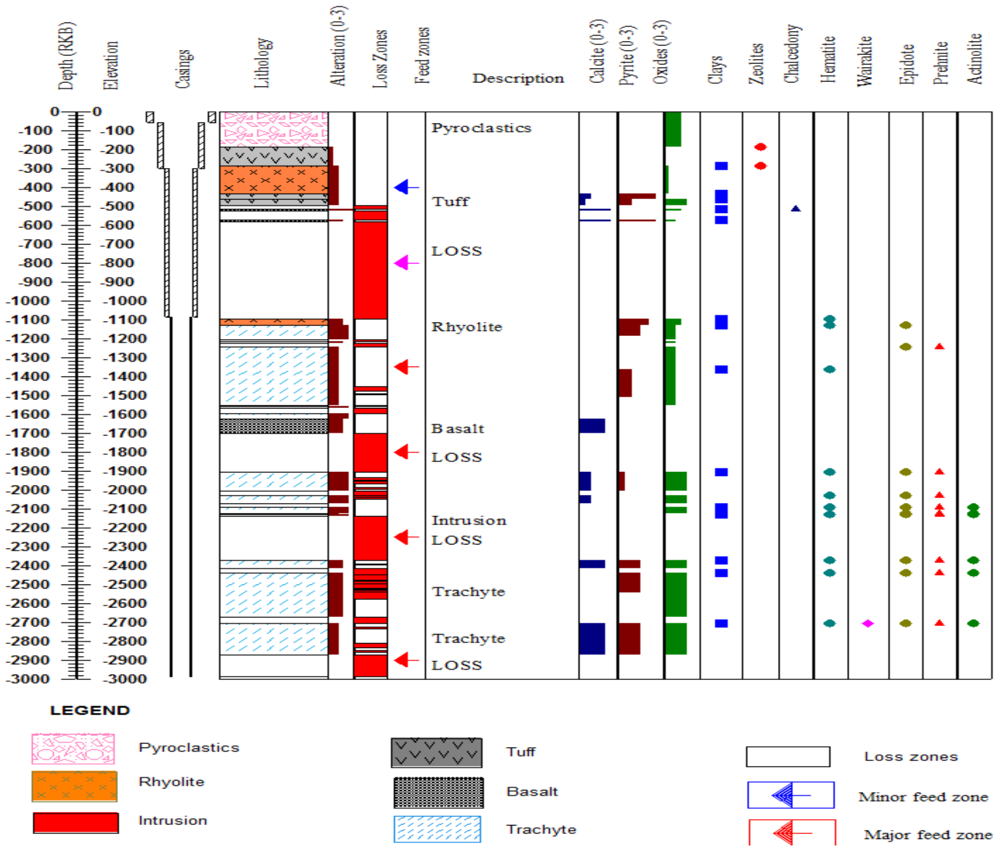

FIGURE 2: Alteration minerals distribution in well OW-921A

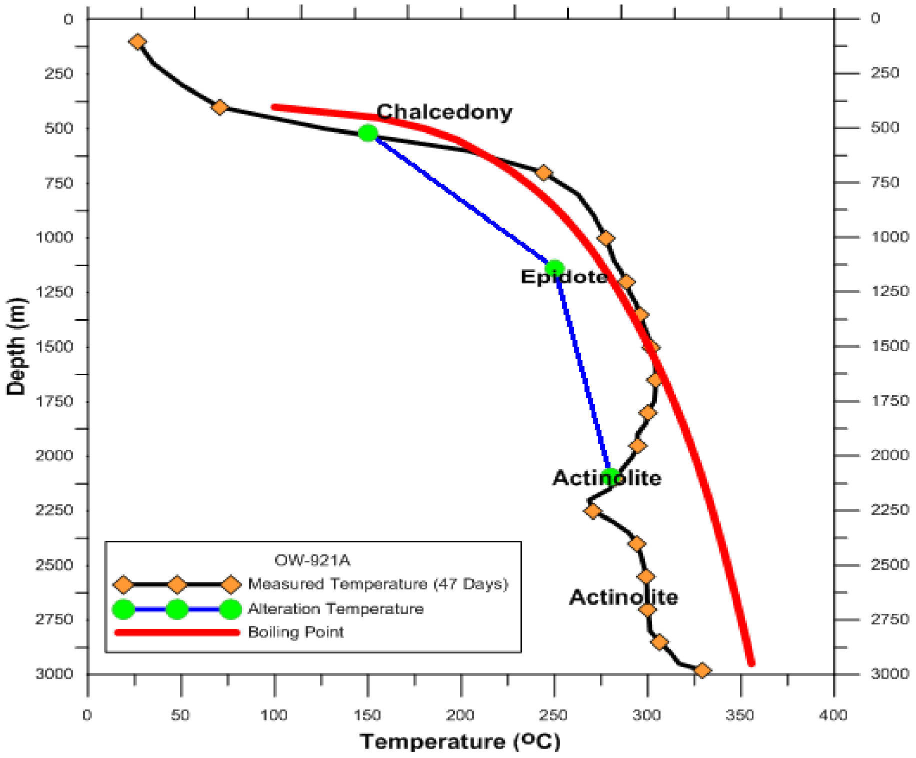

FIGURE 3: Comparison between measured, alteration minerals and boiling point temperature

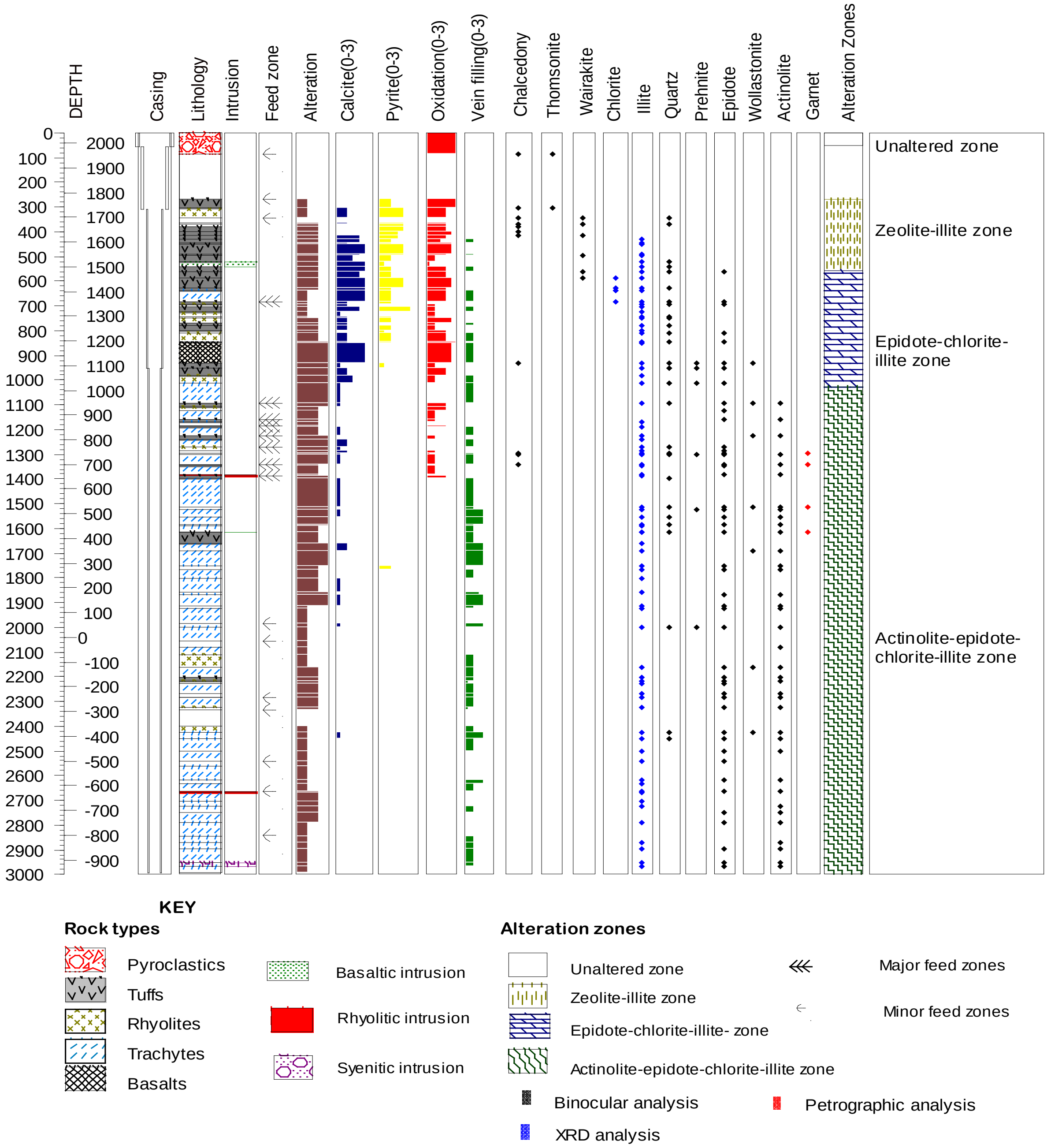

FIGURE 4: Hydrothermal alteration minerals in well OW 916 (Mwangi, 2012)

The relationship between the four parameters shows that the geothermal system has cooled ~25°C, when comparing the estimated formation temperature with the first appearance of selected hydrothermal alteration minerals. For example, epidote is first observed where the measured formation temperature is below its temperature stability range, indicating that the reservoir had boiling conditions when the alteration minerals were formed. But from the comparison of fluid inclusion temperatures and formation temperatures, the geothermal conditions show slight cooling and the temperature has stabilized over time (Figure 5).

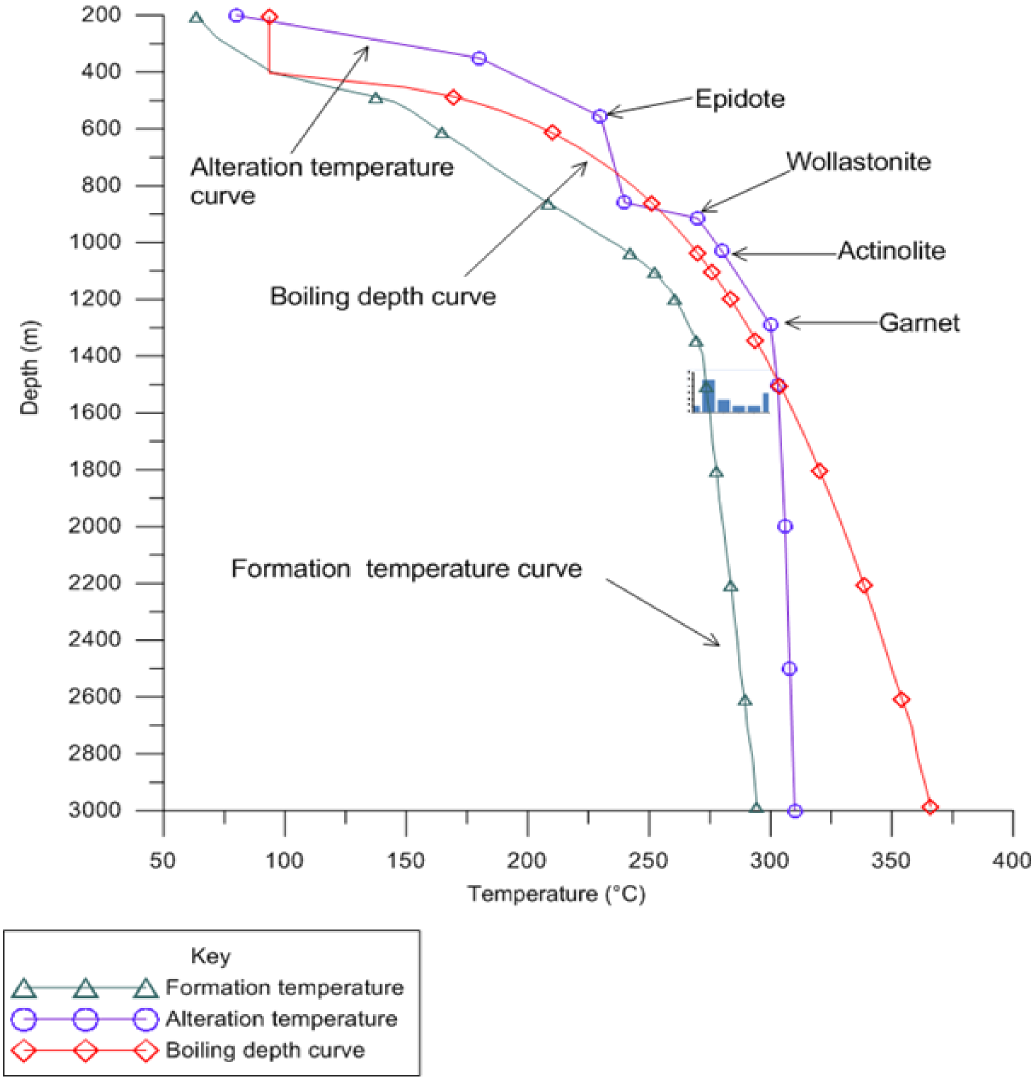

FIGURE 5: Comparison between formation, alteration minerals and boiling point temperature (Mwangi, 2012)

1.3.3 OW-922

The well recorded a low permeability with the lithologies intersected including pyroclastics, tuff, rhyolite, basalt, trachydacite, basaltic trachyandesite, trachyandesite and trachyte (Otieno, 2016). The well intersects no intrusions (Figure 6). Low to moderate intensity of alteration with most hydrothermal products in the well occurring both as replacement of primary components or glassy matrix and as open space filling in veins, fractures and vesicles. Cases of calcite overprinting epidote further points towards a cooling process. High temperature minerals appear intermittently. Five small feed zones have been deduced from the well and are associated with lithological contacts, alteration intensity and changes in temperatures.

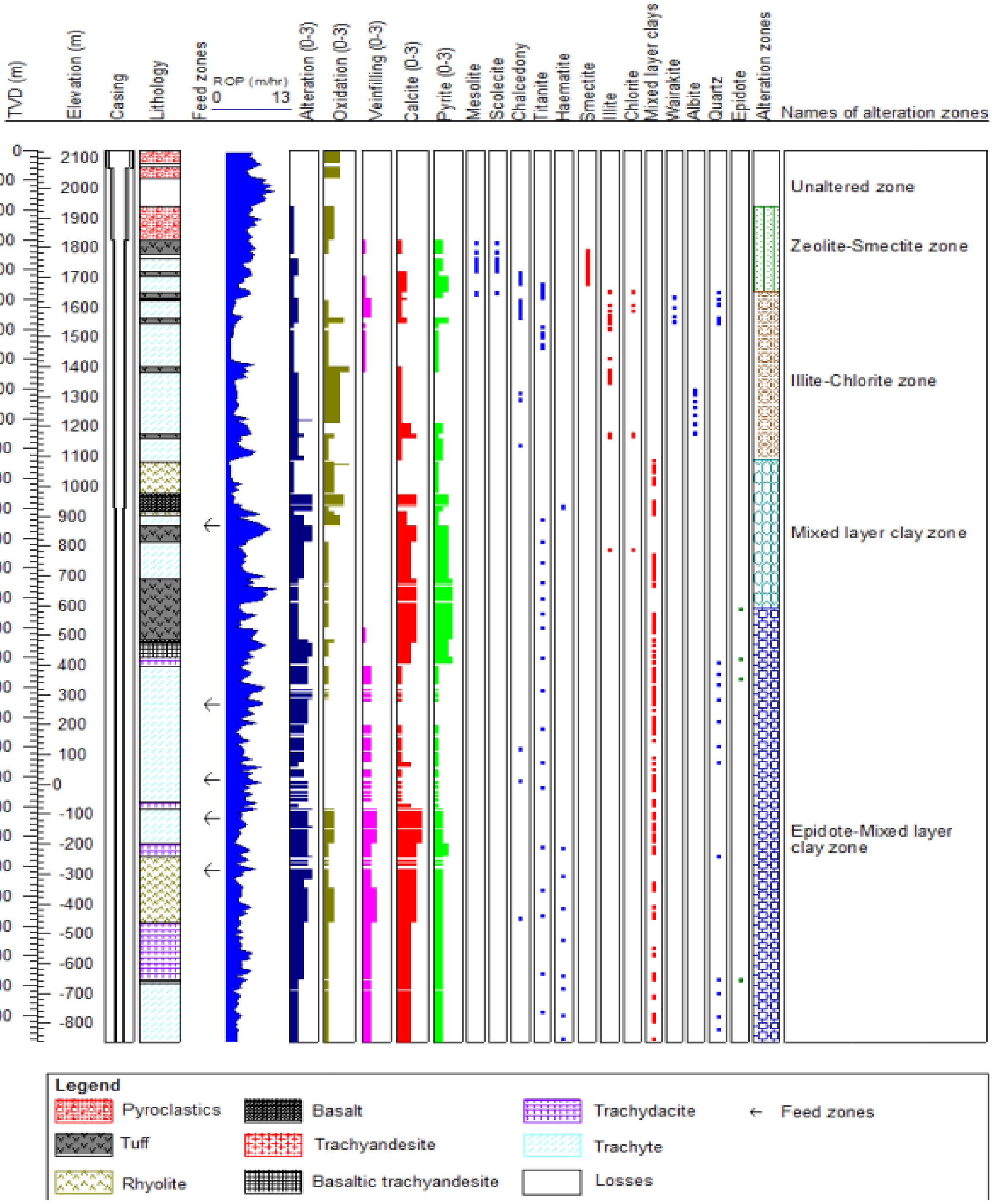

FIGURE 6: Hydrothermal alteration minerals in well OW 922 (Otieno, 2016)

The well is largely liquid dominated with a significant cooling (up to over 110°C) in the geothermal system around the well (Otieno, 2016). The difference between measured formation temperature (127°C) and inferred hydrothermal alteration temperature (epidote 240°C) noted from the comparison from the current measured and alteration temperatures is shown in Figure 7.

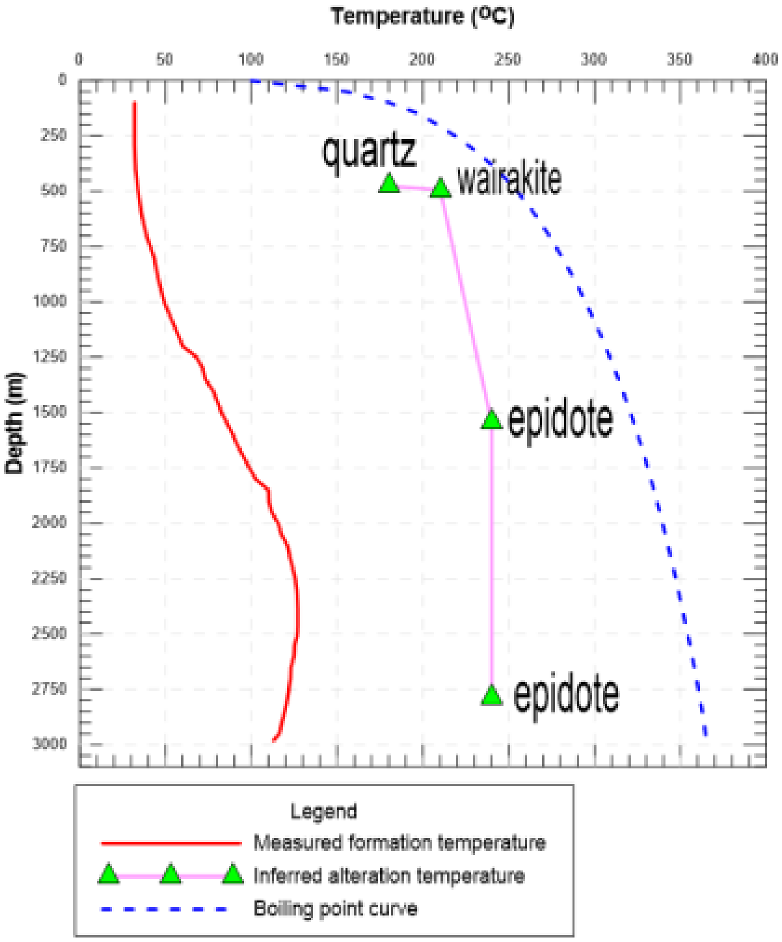

FIGURE 7: Comparison between formation, alteration minerals and boiling point temperature of well OW-922 (Otieno, 2016)

A cross section of the Olkaria Domes field indicates the well OW-916 is located at the zone of temperature up doming hence at the upflow zone of the field, while well OW-922 is drilled in a zone of low permeability and abundant calcite in the formation. The well is located in the downflow zone and probably at the boundary of the field as shown in Figure 8.

1.4 Olkaria East field

The lithology of the three wells (OW-35, OW-37A and OW-39A) in the Olkaria East field shows the same type of rocks as indicated by previous authors (Mwania, et al., 2013; Otieno, et al., 2013; Okoo, 2013). The top formation is composed of pyroclastic rock, which is very thin in Well OW-39A but thicker in Wells OW-37A and OW-35, indicating there could have been a flow forming thicker layers in the low lying areas of Wells OW-37A and OW-35. These pyroclasts overlie rhyolitic lavas in all the wells with subsequent layers of tuff, trachyte and basalt. Tuffs are common rocks in the three wells above 800 m, intercalating with basalt, rhyolite and trachyte; this could indicate that this area experienced phreatic episodes of eruptions in the past. The intrusions are only encountered in Wells OW-39A and OW-35. Basaltic and granitic intrusions occur only in Well OW- 39A, whereas rhyolitic and syenitic intrusions occur in both wells (OW-39A and OW-35). There are no intrusions encountered in Well OW-37A. The occurrence of the intrusions in specific wells may imply that these intrusions are dykes which act either as heat sources or barriers in the wells. By analysing the characteristics of these wells, a difference in alteration minerals noted with high temperature minerals (epidote and actinolite) occurring sporadically in well OW-39A.

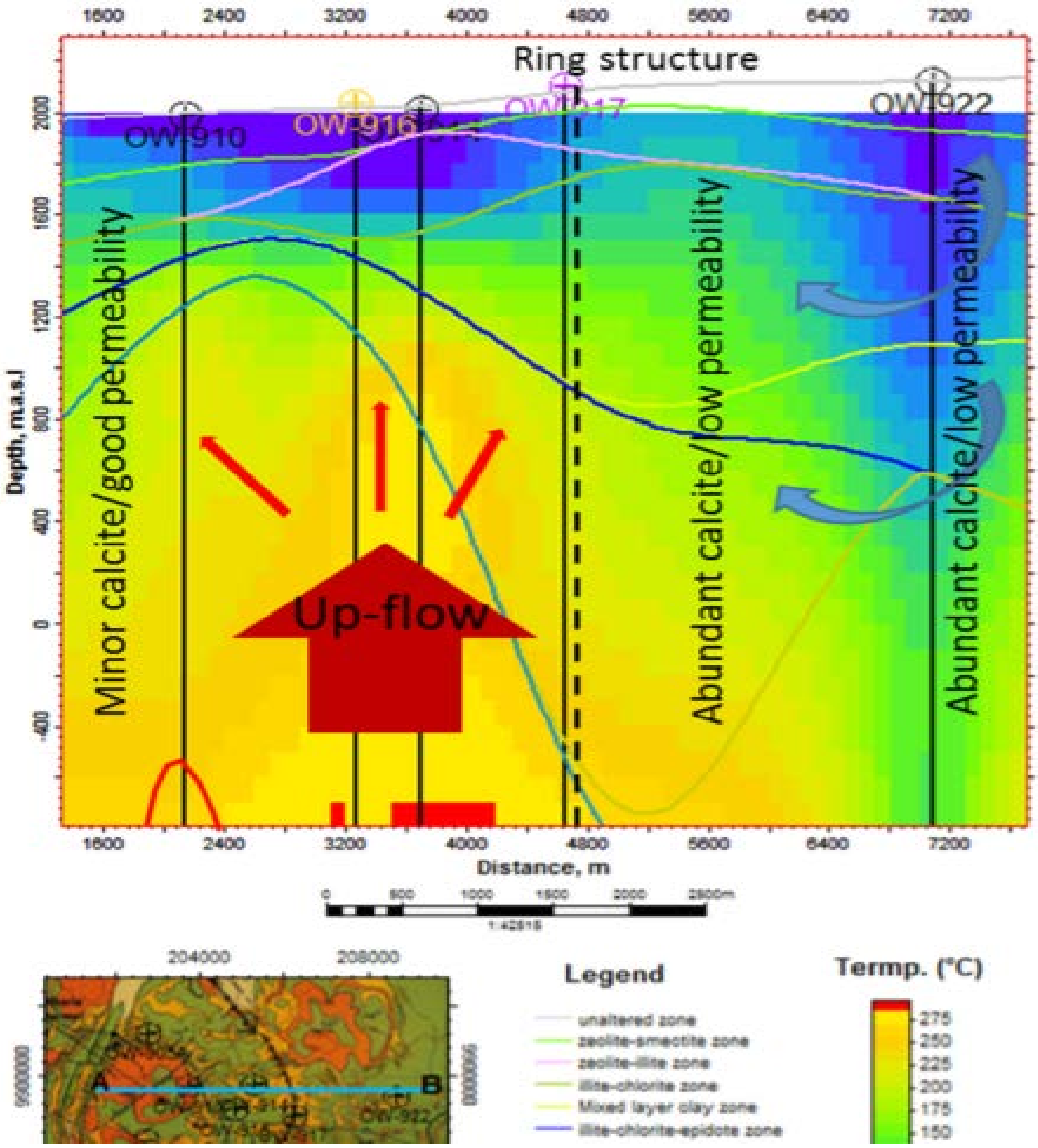

FIGURE 8: A cross section across the Olkaria Domes field (Otieno, 2016)

A geological cross-section extending from the southwest at OW-39A, through OW-37A and to OW-35 in the northwest (Figure 9) show an existence of a fault between well OW-39A and OW-37A.

A temperature isograd shows that high temperatures (250°C) is shallower in Wells OW-39A and OW-35 while deeper in Well OW-37A (Figure 10). The epidote zone is thinner in Well OW-39A and thicker in Well OW-35. Actinolite first appears in Well OW-39A at 1242 m a.s.l. Well OW-37A at 467 m a.s.l. and in Well OW-35 at 342 m a.s.l. The plots indicate that this zone is shallowest in Well OW-39A, indicating hotter shallow depth of alteration temperatures above 280°C, (Okoo, 2013). The correlation indicates elevation of the hydrothermal alteration in the area around Well OW-39A, implying the proximity of an upflow zone. Formation and alteration temperatures are within a similar range in Wells OW-37A and OW-35 but, in Well OW-39A, the formation and alteration temperatures are the reverse of each other, that is, the alteration temperature indicates the proximity of upflow while the current formation temperature indicates marked cooling of the same structure. This might indicate a flow reversal of a specific permeability structure from a geothermal outflow to an inflow of cooler fluid into the geothermal system.

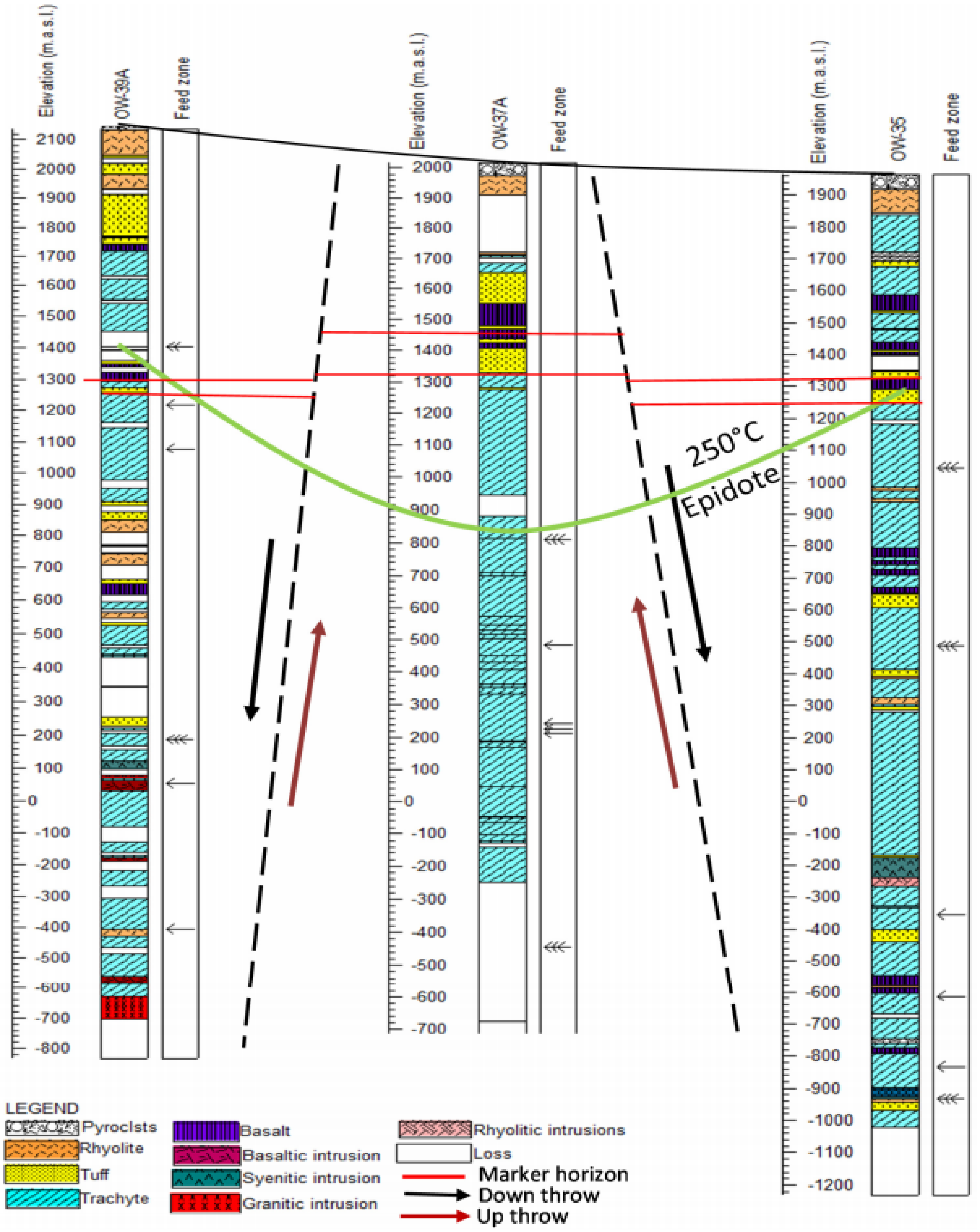

FIGURE 9: Stratigraphic correlation between Wells OW-39A, OW-37A and OW-35 (Okoo, 2013**)**

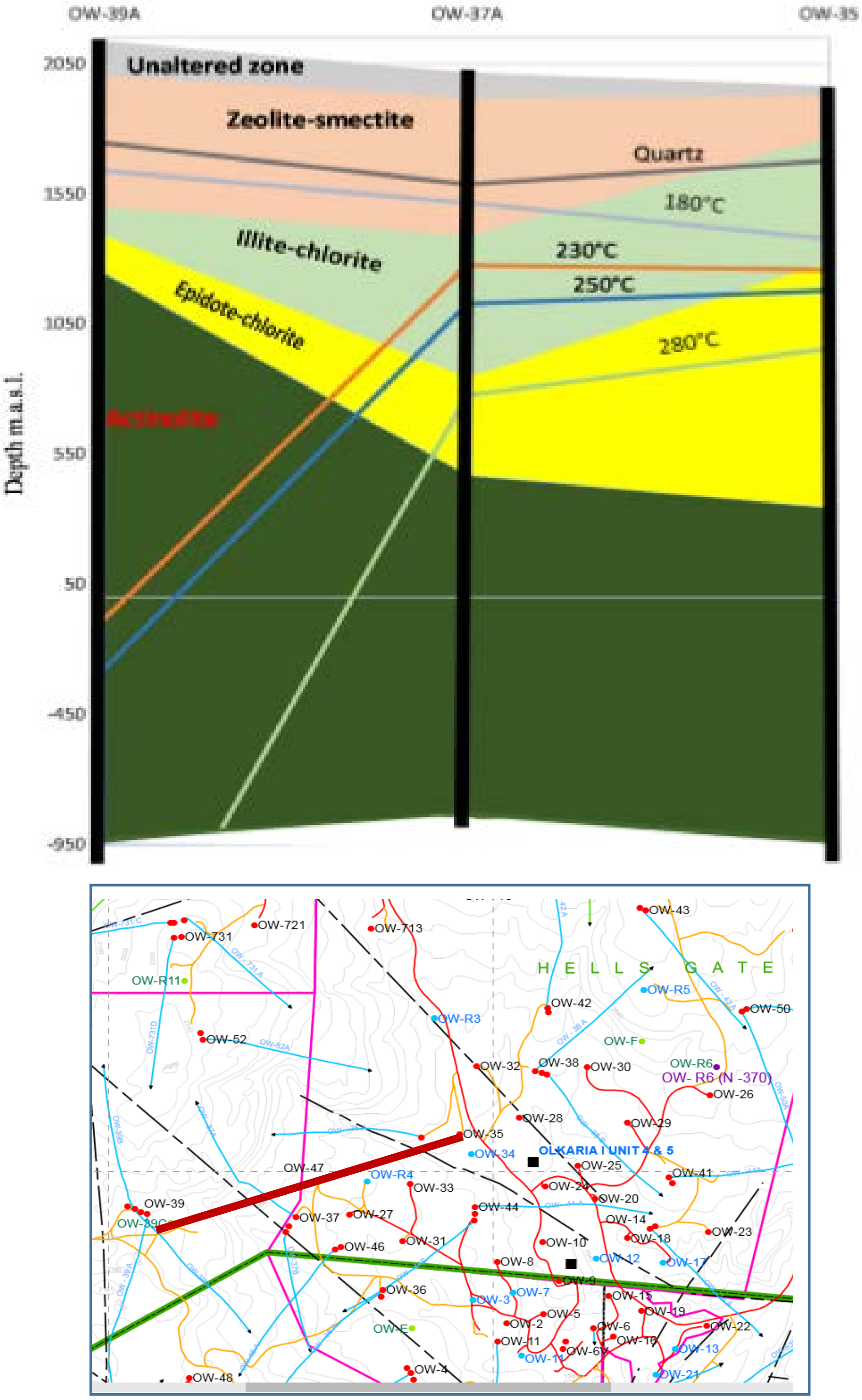

FIGURE 10: A cross section across the Olkaria East field (Okoo, 2013)

1.5 Menengai geothermal field

Drilling in the Menengai geothermal area (Figure 11) began in 2011 with the initial wells being drilled vertically. Analysis of wells MW-02, MW-04, MW-06 and MW0-07 indicated that the dominant stratigraphy composed of mainly volcanics and intrusives (Mbia, 2014) (Figures 12-14). Trachyte constitute 90% of the rocks. Hydrothermal alteration mineralogy shows that wells located at the centre of the volcano had a fresh chilled glassy intrusion at bottom of the well indicating the presence of a magma chamber.

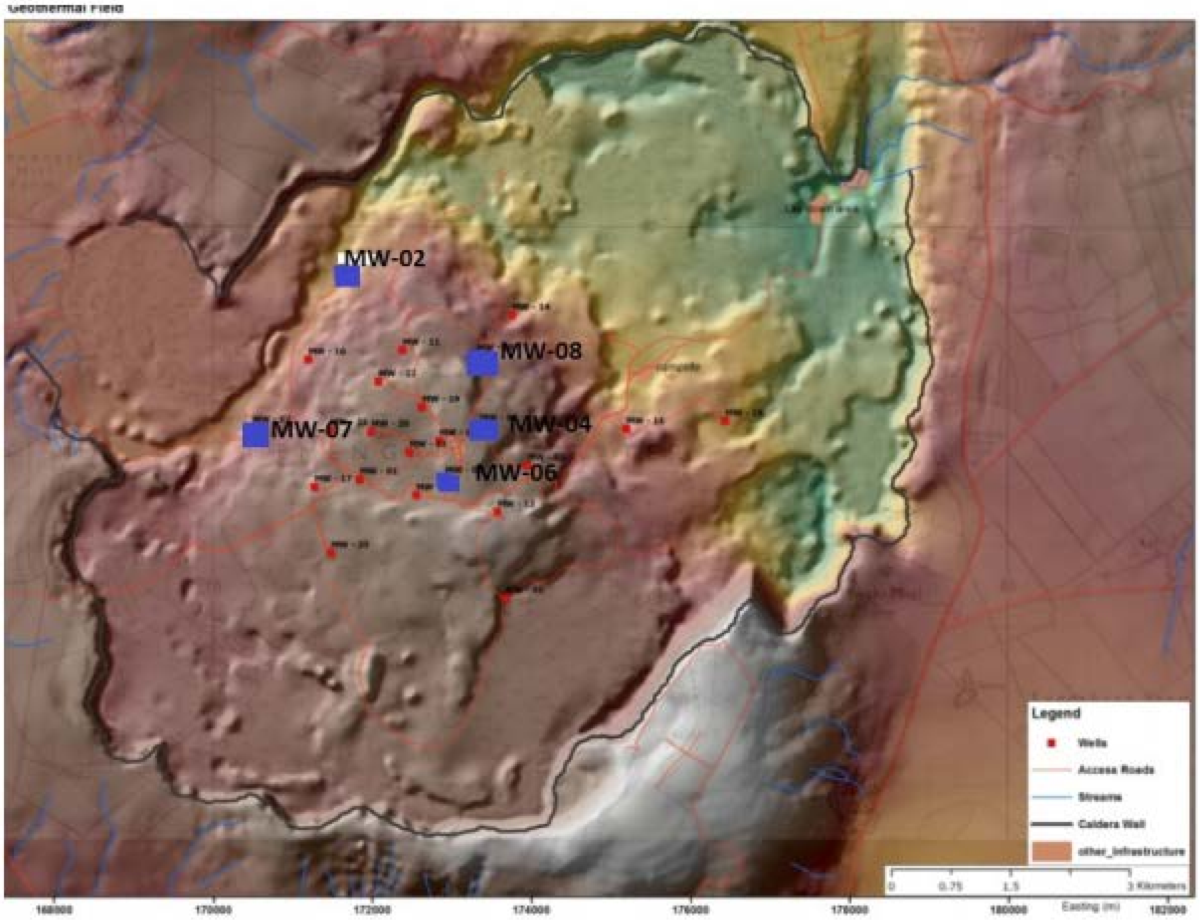

FIGURE 11: A map of the Menengai geothermal prospect. Modified from Mbia (2014)

Well MW-06 indicated temperatures above 270°C as shown by the occurrence of actinolite and wollastonite. However measured temperatures in other wells in the central part of the volcano such as MW-06 recorded temperatures over 350°C, while well MW-04 recording temperature of 398°C at the bottom of the well.

Peripheral wells like MW-02 and MW-07 has sporadic occurrence of epidote indicating lower temperatures in the wells. Fewer feed zones are noted which are associated with lithological contacts, changes in rate of penetration and varying intensity of alteration. Minerals like actinolite, wollastonite, and adularia were conspicuous missing suggesting less or little water-rock interaction in these well.

Calcite occurrence in these wells differ depending on the location of the well. Well MW-02 shows abundant calcite appearance from top to the bottom of the well. The calcite overprinting has resulted largely in the reduced permeability of the well.

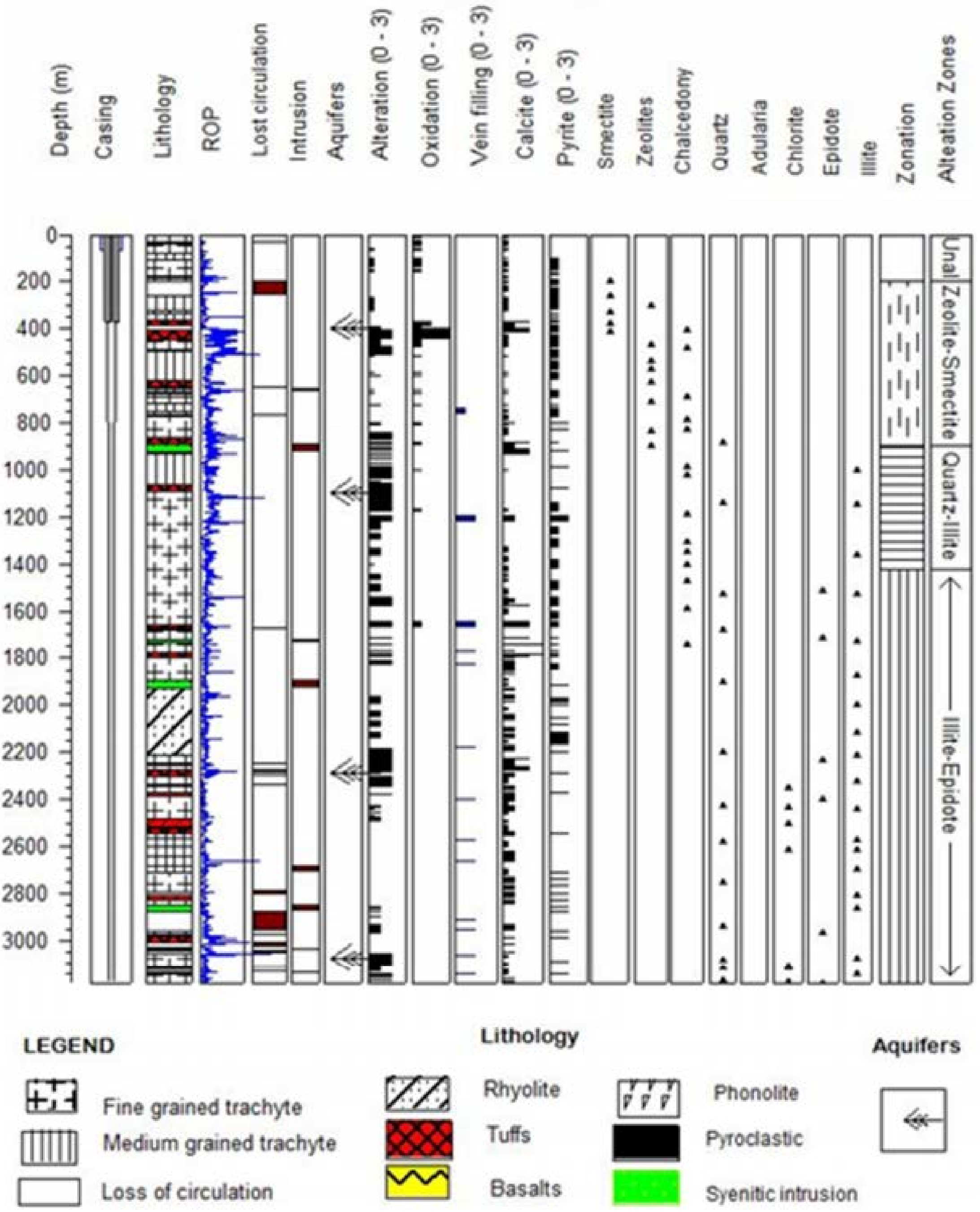

FIGURE 12: Lithostratigraphy, alteration zones and distribution of secondary minerals with depth in well MW-02. Feed points are inferred from loss of circulation, penetration rates and temperature logs (Mbia, 2014)

Hydrothermal mineral zonation in well MW-06 indicates a progressive increase in temperature from zeolites to quartz to wollastonite. Feed zones in this well are associated with increased rate of penetration,changes in alteration intensity and lithological contacts. The occurrence of Wollastonite from 1800 m indicates that there is a low possibility of scaling in the well.

Well MW-07 has high occurrence of calcite and pyrite in the rock matrix. The well show low to medium intensity of alteration with most of the minerals indicating a dominant low temperature and permeability. Blind drilling was experienced during drilling from 1800 m to the bottom of the well.

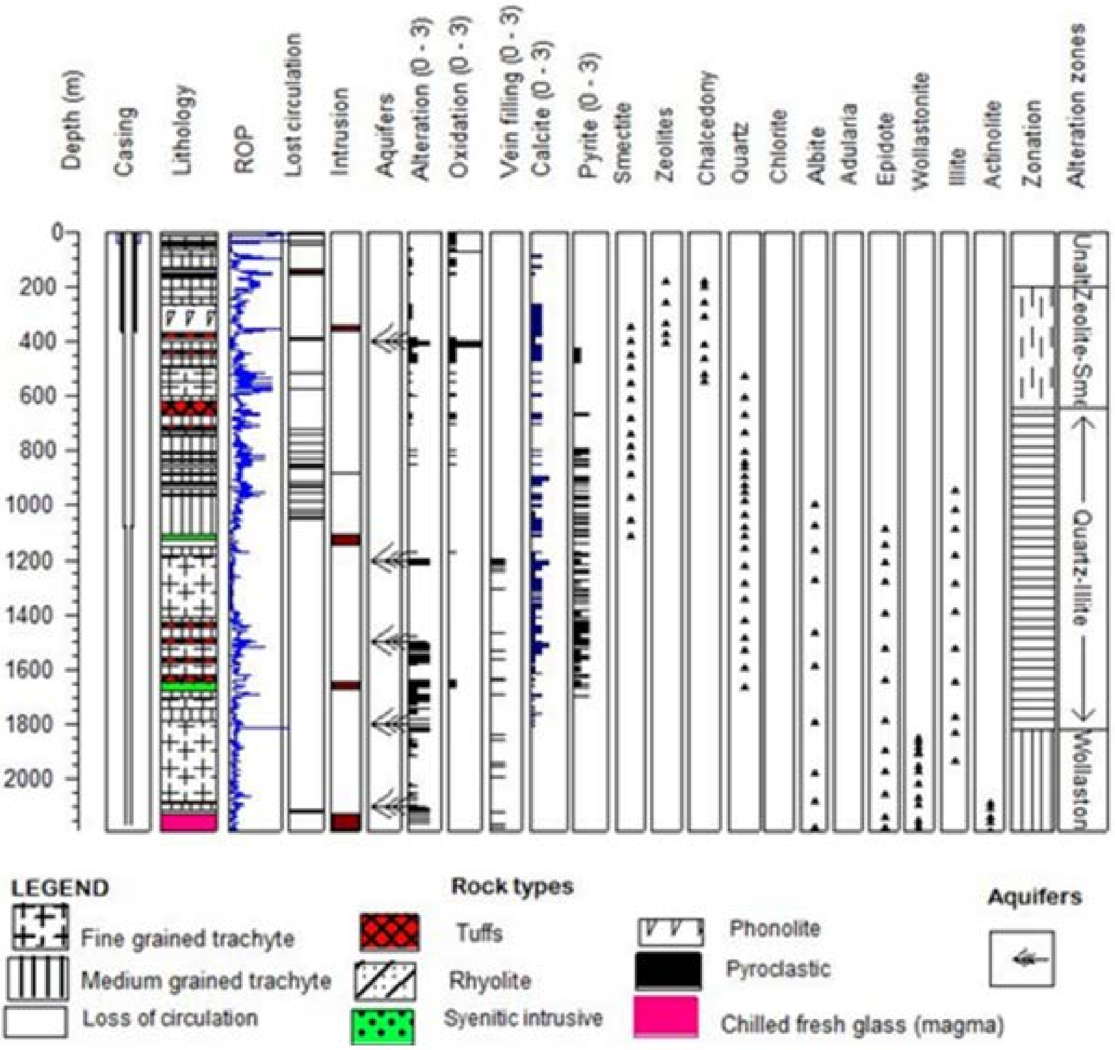

FIGURE 13: Lithostratigraphy, alteration zones and distribution of secondary minerals with depth in well MW-06. Feed points are inferred from loss of circulation, penetration rates and temperature logs (Mbia, 2014)

By comparing the hydrothermal alteration mineralogy and temperature logs of wells MW-04 and MW-06, it shows that well MW-06 has higher current measured temperatures than the alteration mineralogy temperatures indicating therefore that the system may be heating up (Figure 15). However, well MW-04, recorded current measured temperatures in equilibrium with the alteration mineral temperatures depicting that the reservoir around the well has been thermally stable.

2. DISCUSSION

Factors that influence the distribution and kind of mineral assemblages present in hydrothermal systems include permeability, rock and water composition, temperature, pressure and duration of hydrothermal alteration. These factors are largely independent, but the effects of one or more of the factors can exert a dominant influence in the location and extent of hydrothermal alteration. Permeability of the rocks controls the access of thermal fluids, which cause hydrothermal alteration of the rocks and precipitation of secondary minerals in open spaces.

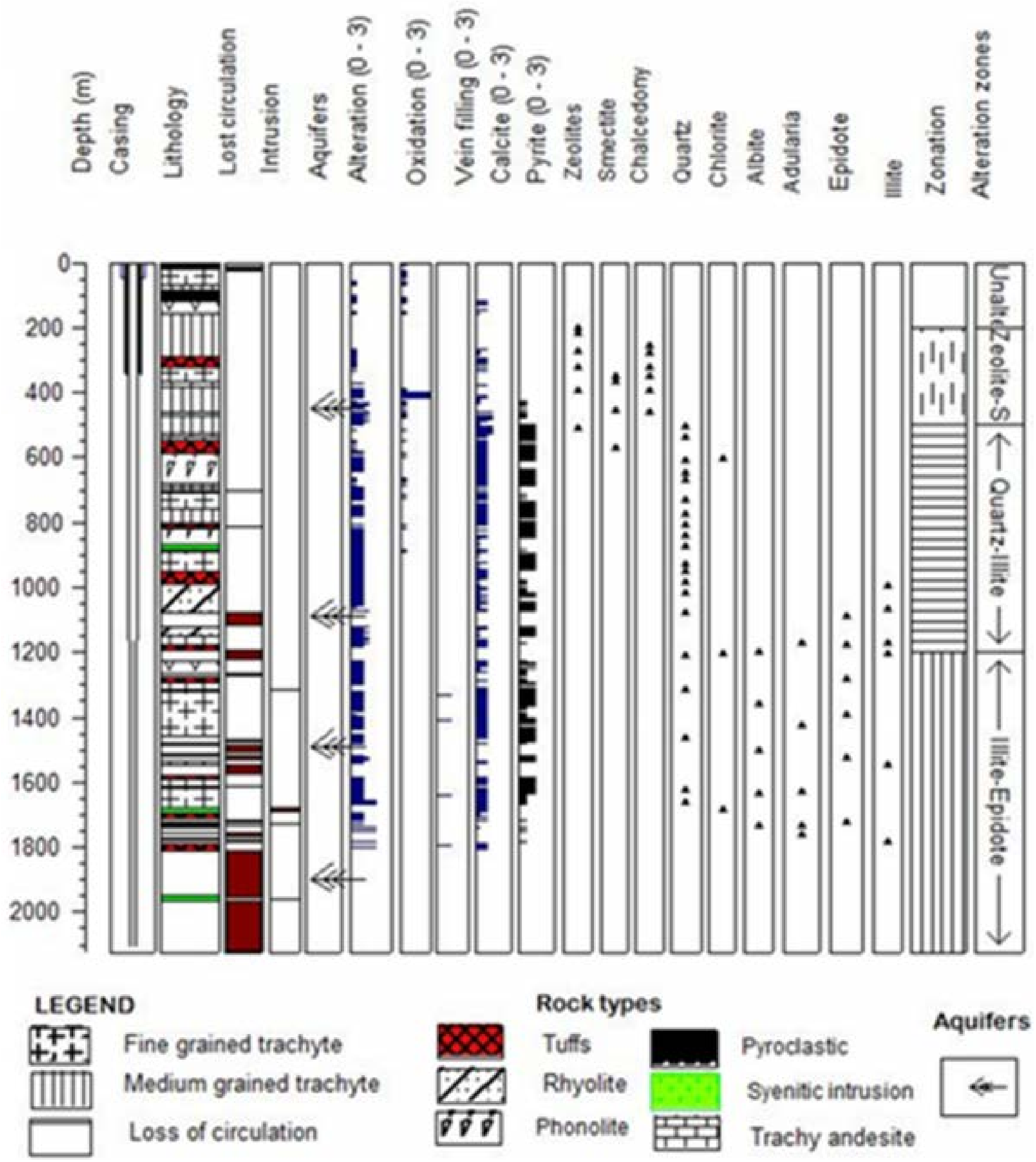

FIGURE 14: Lithostratigraphy, alteration zones and distribution of secondary minerals with depth in well MW-07. Feed points are inferred from loss of circulation, penetration rates and temperature logs (Mbia, 2014)

Alteration minerals have been used to identify zones of high temperature and permeability in Olkaria and Menengai geothermal fields hence mapping of the upflow and downflow zones for easy development. Other uses of minerals have been identification of boiling zones (presence of platy calcite and quartz), pressure changes in the reservoir (by mapping oxidation tendencies) and scaling possibilities in the well (hydrothermal calcite, wollastonite).

A correlation between measured, hydrothermal alteration and fluid inclusion temperatures indicates how a particular geothermal system has evolved with time. Common hydrothermal alteration minerals are used as geothermometers in Olkaria and Menengai geothermal fields and their stability temperature ranges have been estimated from measured formation temperatures. This has shown whether the system is heating up or cooling down over a long period of time.

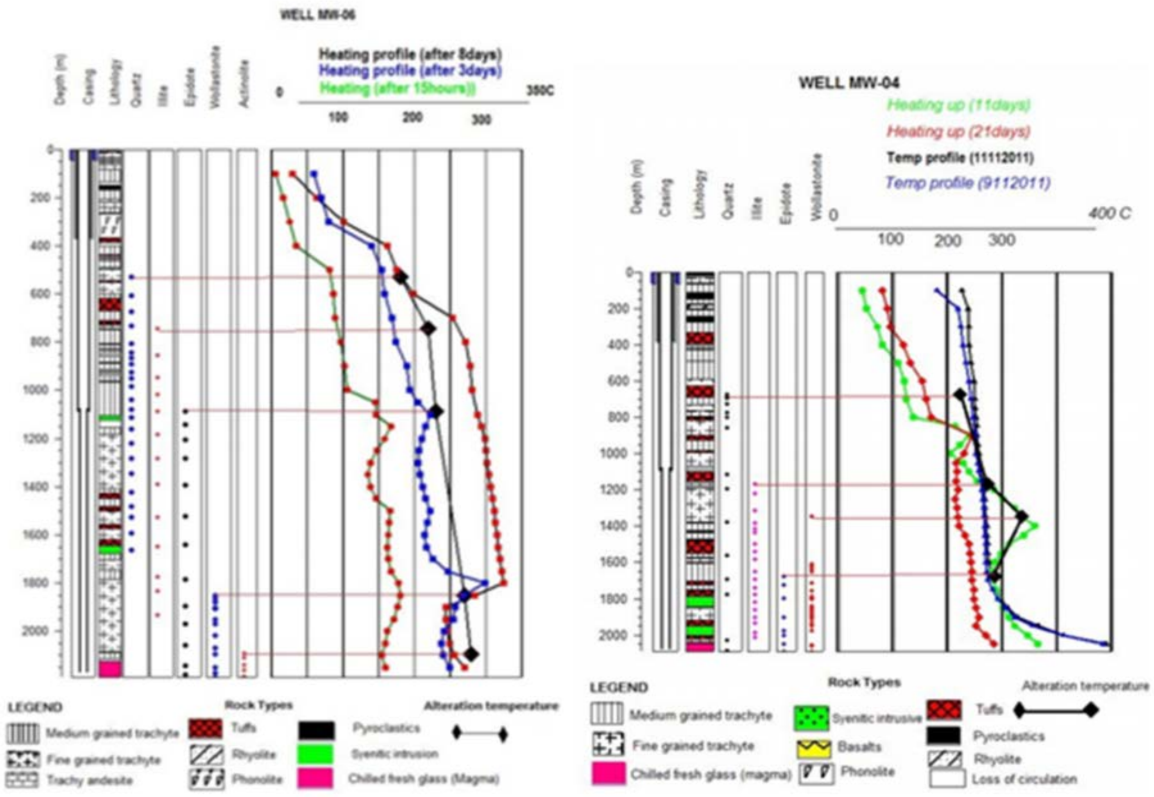

FIGURE 15: Lithostratigraphy, selected alteration minerals, temperature logs in correlation with the status of geothermal system in wells MW-04 and MW-06 (Mbia, 2014)

REFERENCES

Browne, P.R.L., 1984: Subsurface stratigraphy and hydrothermal alteration of the eastern section of the Olkaria geothermal field, Kenya. *Proceedings of the 6th New Zealand Geothermal Workshop*, Auckland, New Zealand, 33-41.

Lagat, J.L., 2004: *Geology, hydrothermal alteration and fluid inclusion studies of Olkaria domes geothermal field, Kenya*. University of Iceland, Reykjavík, Iceland, MSc thesis / United Nations University Geothermal Training Programme, Reykjavík, Iceland, report 2, 71 pp.

Mbia, P.K., 2014: *Sub-surface geology, petrology and hydrothermal alteration of Menengai geothermal field, Kenya*. University of Iceland, Reykjavík, Iceland, MSc thesis / United Nations University Geothermal Training Programme, Reykjavík, Iceland, report 1, 87 pp.

Mwangi, D.W., 2012: Borehole geology and hydrothermal mineralization of well OW-916, Domes geothermal field. Report 24 in: *Geothermal training in Iceland 2012*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 541-571.

Mwania, M., Munyiri, S., and Okech, E., 2013: Borehole geology and hydrothermal mineralisation of well OW-35, Olkaria East geothermal field, Central Kenya Rift Valley. Report 1 in: *Geothermal training in Kenya*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 1-56.

Okoo, J.A., 2013: Borehole geology and hydrothermal alteration mineralogy of well OW-39A, Olkaria geothermal project, Naivasha, Kenya. Report 24 in: *Geothermal training in Iceland 2013*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 547-576.

Otieno, V.O., 2016: Borehole geology and sub-surface Petrochemistry of the Domes Area, Olkaria Geothermal Field, Kenya, in relation to well OW-922. University of Iceland, Reykjavík, Iceland, MSc thesis / United Nations University Geothermal Training Programme, Reykjavík, Iceland, report 2, 84 pp.

Otieno, V. and Kubai, R., 2013: Borehole geology and hydrothermal mineralisation of well OW-37A, Olkaria East geothermal field, Kenya. Report 2 in: *Geothermal training in Kenya*. United Nations University Geothermal Training Programme, Reykjavík, Iceland, 57-105.

Reyes, A.G., 1990: Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment. *J. Volc. & Geothermal Res., 43*, 279-309.