# SUCCESSFUL USE OF HYDROTHERMAL ALTERATION MINERALOGY IN APPRAISING A GEOTHERMAL RESERVOIR: CASE STUDY: OLKARIA DOMES GEOTHERMAL FIELD, KENYA

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## ABSTRACT

Three geothermal exploration wells OW-901, OW-902 and OW-903 were drilled in Olkaria Domes field to evaluate its geothermal potential. The three wells were drilled to a depth of 2200 m and all encountered a high temperature system and discharged on test. Completion tests and hydrothermal alteration mineralogy indicated a cold zone between 900-1150 m in all the three wells. Permeability of the wells was low compared to wells drilled in the neighbouring Olkaria East and Olkaria North East fields hence low productivity. The analyses of well completion tests and alteration mineralogy indicted that the resource was deeper compared to the other fields in Olkaria. Six appraisal wells OW-903A, OW-904A, OW-905A, OW-906A, OW-907A and OW-908 were recommended to delineate the geothermal reservoir and also site the best localities to drill production wells. Deep casing set at 1200 m recommended from the exploration wells studies for the appraisal wells was successfully, with the cold zone being isolated completely. Directional drilling was able to intersect the faults and fractures thus enhancing permeability and average production in the field increased from 2.5 MWe to 8 MWe per well, with the highest producer being over 14 MWe. Deep drilling to 3000 m was able to tap the deeper aquifers. Alteration mineralogy studies from the six appraisal wells were able to delineate the field and currently production drilling is underway to provide enough steam for a 140 MWe power plant. This paper therefore discusses the successful use of hydrothermal alteration mineralogy in to optimize the geothermal resource in Olkaria Domes field.

**Key Words:** Rift, Olkaria-Domes, Geothermal, Alteration

## INTRODUCTION

The Greater Olkaria geothermal area is situated south of Lake Naivasha on the floor of the southern segment of the Kenya rift (Figure 1). The Kenya rift is part of the East African rift system that runs from Afar triple junction at the Gulf of Eden in the north to Beira, Mozambique in the south. It is the segment of the eastern arm of the rift that extends from Lake Turkana to the North to Lake Natron, northern Tanzania to the south (Figure 1). The rift is part of a continental divergent zone where spreading occurs resulting to the thinning of the crust hence eruption of lavas and associated volcanic activities.

The Greater Olkaria geothermal area is within the Greater Olkaria volcanic complex. It is subdivided into seven fields for geothermal development purposes namely Olkaria East, Olkaria Northeast, Olkaria Central, Olkaria Northwest, Olkaria Southwest, Olkaria Southeast and Olkaria Domes (Figure 2). Olkaria East field (Olkaria I) has been producing power since 1981 when the first of the three 15 MWe units was commissioned. The current generating capacity of the field is 45 MWe. Olkaria Northeast field (Olkaria II) is generating 70 MWe and an additional 35 MWe is under construction and is expected to be commissioned in 2010. Olkaria Northwest field (Olkaria III) which is being developed by an Independent Power Producer (IPP) was commissioned in 2009 and is currently producing 55 MWe. The rest of the fields are at various exploration stages. This paper therefore discus the results obtained from the analysis of samples recovered from the exploratory, appraisal and production wells drilled in the Olkaria Domes field, which is the field earmarked for development as Olkaria IV with an expected 140 MWe.

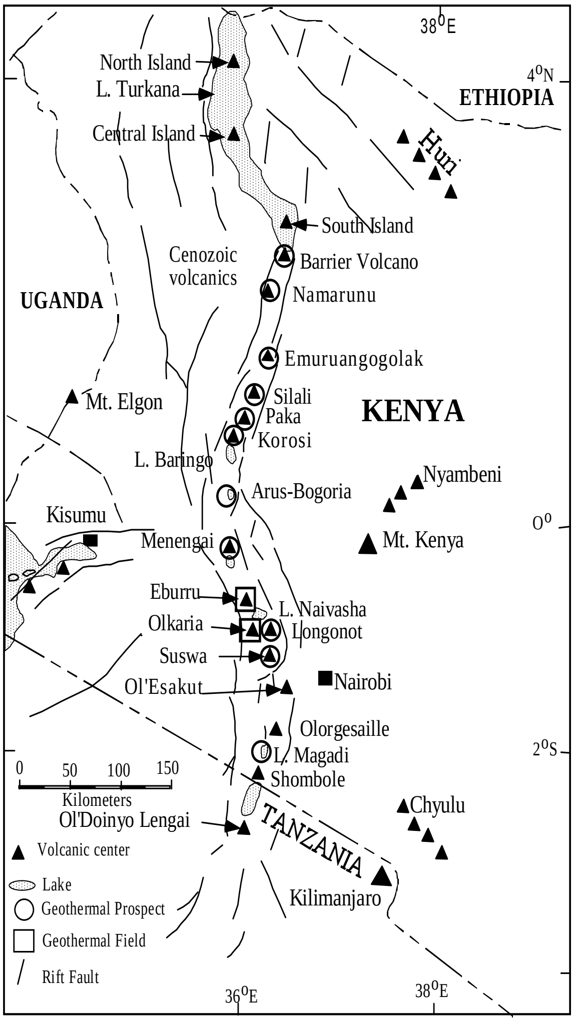


**Figure 1**: Map of the Kenya rift showing the location of Olkaria geothermal field.

**OBJECTIVES OF THE STUDY**

1. To identify the rocks and thereby understand the stratigraphy.
2. To identify the hydrothermal alteration minerals found in the field.
3. To determine the general location of the wells with respect to the upflow, outflow and the marginal zones of the system
4. Determine the appropriate casing depths in the field.

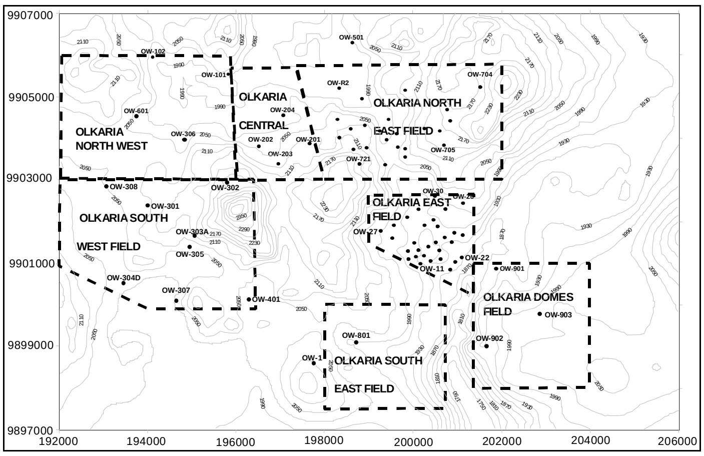


**Figure 2**: Map of the Greater Olkaria geothermal area showing the location of the fields.Geology

## GEOLOGY

### *Geology of Olkaria volcanic complex*

The Greater Olkaria volcanic complex is characterized by numerous volcanic centers of Quaternary age and is the only area within the Kenya rift with occurrences of comendite on the surface. Other Quaternary volcanic centers adjacent to Olkaria include Longonot volcano to the southeast, Suswa caldera to the south, and the Eburru volcanic complex to the north. Whereas the other volcanoes are associated with calderas of varying sizes, Olkaria volcanic complex does not have a clear caldera association. The presence of a ring of volcanic domes in the east and south, and southwest has been used to invoke the presence of a buried caldera (Clarke et al., 1990, Mungania, 1992).

Magmatic activity associated with Olkaria volcanic complex commenced during the late Pleistocene and continues to Recent as indicated by Ololbutot comendite, which has been dated at 180±50 yrs B.P using $^{14}C$ from carbonized wood obtained from a pumice flow associated with the lava (Clarke et al., 1990).

The litho-stratigraphy of the Olkaria geothermal area as revealed by data from geothermal wells and regional geology can be divided into six main groups; namely Proterozoic "basement" formations, Pre-Mau volcanics, Mau tuffs, plateau trachytes, Olkaria basalt and Upper Olkaria volcanics (Omenda, 2000).

### *Structures in the Greater Olkaria volcanic complex*

Structures in the Greater Olkaria volcanic complex include; the ring structure, the Ol' Njorowa gorge, the ENE-WSW Olkaria fault and N-S, NNE-SSW, NW-SE and WNW-ESE trending faults (Figure 3). The faults are more prominent in the East, Northeast and West Olkaria fields but are scarce in the Olkaria Domes area, possibly due to the thick pyroclastics cover. The NW-SE and WNW-ESE faults are thought to be the oldest and are associated with the development of the rift. The most prominent of these faults is the Gorge Farm fault, which bounds the geothermal fields in the northeastern part and extends to the Olkaria Domes area. The most recent structures are the N-S and the NNE-SSW faults. Hydroclastic craters located on the northern edge of the Olkaria Domes area mark magmatic explosions, which occurred in submerged country (Mungania, 1992). These craters form a row along where the extrapolated caldera rim trace passes.

Dike swarms exposed in the Ol' Njorowa gorge trend in a NNE direction further attesting to the recent reactivation of faults with that trend. The development of the Ol' Njorowa gorge was initiated by faulting along the trend of the gorge but the feature as it is known today was mainly due to catastrophic outflow of Lake Naivasha during its high stands (Clarke et al., 1990). Volcanic plugs (necks) and felsic dikes occurring along the gorge further attests to the fault control in the development of this feature. Subsurface faults have been encountered in most Olkaria wells (KenGen, 2000). The wells encountered drilling problems when these faults were dissected due to cave-ins and loss of drilling fluids and cement. Materials recovered from these zones were mainly fault breccia.

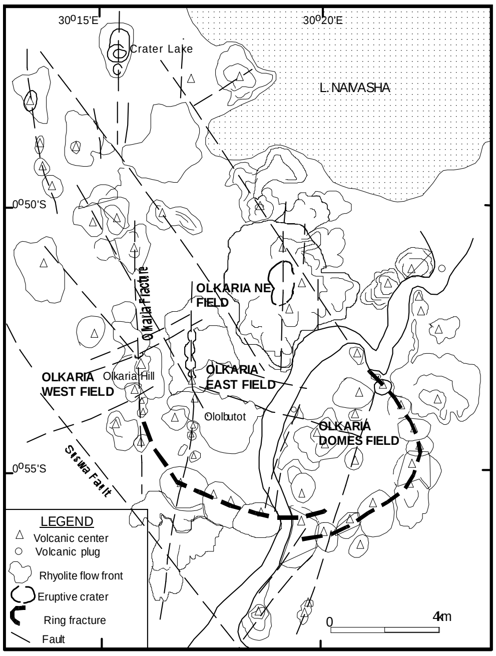


**Figure 3**: The volcano tectonic map of the greater Olkaria volcanic complex showing the structures in the area.

## SAMPLING AND ANALYTICAL METHODS

Cuttings samples from Olkaria Domes wells were taken at every 2 m interval. Very few and unrepresentative cores were cut in Olkaria Domes field and therefore nearly all the descriptions and interpretations are based on cuttings samples. Binocular analysis of the cuttings samples was done using the Wild Heerbrugg binocular microscope. A sample is scooped from the sample bag into a petri dish and washed with clean water to remove impurities and dust. Wetting the cuttings is necessary to enhance visibility of samples and obscure features such as finely disseminated sulphides e.g. pyrite.

Representative samples from all the lithologic units encountered in wells were selected and thin sections prepared for petrographic studies. The thin sections were analyzed using the Leitz Wetzler petrographic microscope.

The X-ray Diffractometer is used to identify individual minerals especially clays. Samples were selected from all the lithologic units and analysed for clays. The <2 microns fractions were prepared for X-ray diffraction by crushing the rock into fine powder and dissolving in a test tube half full of distilled water. The test tube is left in a rack so that the <2 microns phylosilicates are left in suspension. A few drops are placed in marked glass slides and left to dry so that the sample can be run using the XRD machine. A Shimandzu 6000 Diffractometer, with CuKα radiation (at 40 kV and 50 mA), automatic divergence slit, fine receiving slit, and graphite monochrometor was used for the analyses.

## RESULTS

### *Lithology*

The drilled lithological column in Olkaria Domes field is composed of unconsolidated pyroclastics that are dominant in the shallow levels overlying a volcanic sequence whose lithological composition is dominated by comenditic rhyolite, trachyte, basalt, tuff and some granitic and syenitic dykes. Below is a brief description of the lithology, The drilled lithological column in Olkaria domes is composed of unconsolidated pyroclastics that are dominant in the shallow levels overlying a volcanic sequence whose lithological composition is dominated by comenditic, rhyolite, trachyte, intrusives and basalt (Lagat 2007, Lagat 2008, Lagat 2009). Petrochemical analysis indicates that most rocks from Olkaria domes plot in the region of rhyolite, trachyte and basalt. A summary descriptions of the lithologic units encountered in the Olkaria domes are as follows.

#### Pyroclastics

The pyroclastics are yellowish to brown and form the upper pats of Domes field. The rock unit is unindurated and consists of lithic fragments of rhyolite, trachyte and ash. The formation is mostly unconsolidated matrix dominated by ash size particles, crystals of glass, quartz, feldspars, amphiboles, obsidian and pumice.

#### Tuffs

The tuffs are brownish grey, grey to white in colour and occur in two types; the glassy and the fragmental tuff. The glassy (vitric) tuff is wholly glassy whereas the fragmental tuff is made up of lithics of lava fragments as well as subhedral to anhedral crystal lithics of quartz and feldspars.

#### Rhyolites

Rhyolites are of two types; (i) the granular non-porphyritic to quartz and sanidine porphyritic with abundant riebeckite and occasional hornblende and (ii) the spherulitic rhyolites with bands of volcanic glass enriched with quartz and feldspar crystals. The first type is light grey to brownish grey in colour, mainly comenditic and occurs at shallow depths and the second type occurs at depth.

#### Trachytes

Trachyte occurs alternating with tuff, basalt and rhyolite and is the dominant rock type, with minor tuff intercalation at greater depths. The rock is grey to brownish grey, fine grained and is composed of phenocrysts of sanidine, arfvedsonite-riebeckite, and aegirine. The matrix consists of flow oriented feldspar microlites in a fine grained to glassy groundmass. Sanidine crystals are the most common phenocryst and occur in crystals measuring up to 5 mm.

#### Basalts

Basalt is light greenish grey to black, with holocrystalline groundmass composed of plagioclase laths and anhedral clinopyroxene and magnetite. It is porphyritic with plagioclase phenocrysts, some of which are zoned, clinopyroxene and glomeroporphyritic clots of pyroxene. Olivine occurs in unaltered basalts, but at depth the mineral has undergone metasomatism and its presence is revealed by the crystal outline of the alteration products.

### *Hydrothermal alteration*

In the Olkaria Domes geothermal field, hydrothermal alteration minerals appear both as replacement of the primary minerals, as well as fillings in vesicles, vugs and fractures. 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 (Browne and Ellis, 1970). 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. 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. Temperature is the most significant factor in hydrothermal alteration because most of the chemical reactions require elevated temperatures and also minerals are thermodynamically stable at high temperatures. Pressures at the depths penetrated by Olkaria Domes drill holes, like in other geothermal fields elsewhere in the world are not sufficient to greatly affect hydrothermal alteration minerals transformation (Browne and Ellis, 1970).

Although hydrothermal alteration has changed the primary minerals in different ways and magnitude, often the original textures and minerals are still recognizable. The main hydrothermal minerals in Olkaria Domes field are albite, amphibole (actinolite), biotite, calcite, chlorite, chalcedony, epidote, fluorite, garnet, illite, K-feldspar (adularia), mordenite, secondary Fe-Ti oxides, sulfides (pyrite), titanite (sphene) and quartz. In addition, minor amounts of wairakite and prehnite are present. Mineral associations in vesicles are common and consist of two or more of the following minerals; chlorite, quartz, calcite, epidote and pyrite with the paragenetic sequence varying with depth and from one well to another. Table 1 below shows the primary minerals observed in Olkaria Domes geothermal field and their alteration products.

**Table 1:** Primary minerals, order of replacement and alteration products of Olkaria Domes volcanics (modified from Browne, 1984a)

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

### *Distribution of hydrothermal alteration minerals*

The distribution of hydrothermal alteration minerals in Olkaria Domes show that at shallow depths, low temperature phases occur with mainly silica, smectite, calcite, zeolites, phyllosilicates, oxides and sulphides being the alteration minerals present. In the deeper parts of the wells, however, hydrothermal alteration to ranged from high to extensive. Hydrothermal zeolites, calcite, epidote, phyllosilicates, silica, sulphides, epidote, albite, adularia, biotite, garnet, fluorite, prehnite, oxides and titanite are the alteration minerals observed. The hydrothermal alteration mineralogy patterns show prograde alteration with increase in temperature and depth with the low temperature phases disappearing as the high temperature phases appear.

### *Case study wells*

#### Well OW-905A

Well OW-905A was drilled as an appraisal well in Olkaria Domes field. The rock types encountered consist of rhyolite, tuffs, trachyte, basalt and syenitic intrusives at depth. The rocks at shallow depths exhibit little or no hydrothermal alteration at all with mainly smectite silica, calcite, clays, oxides and pyrite being the alteration minerals present. Smectite a low temperature clay occurs from the surface to 1494 m depth, indicating temperatures of <200ºC above that depth. First occurrence of crystalline epidote was encountered at 1362 m indicating expected formation temperatures below this depth is >250ºC Unlike the nearby wells OW-904A and OW-903A where biotite and actinolite were encountered at depth, it was conspicuously absent in this well indicating probable formation temperatures of <300°C. Deeper casing therefore managed to isolate the low temperature zones, however when the well was discharge tested, it produced low pressure steam. Hydrothermal alteration mineralogy indicates that the well is at the resource boundary. This well is drilled N90°E and the next well to be drilled in the sector, OW-907A had to be drilled at N150°E and is a good producer (7 MWe).

Hydrothermal alteration mineralogy was therefore successfully used to set the production casing in this well and determine the boundary conditions.

Well OW-910A

Well OW-910A was drilled as a production well in Olkaria Domes field. The rocks at shallow depths exhibit little or no hydrothermal alteration at all with mainly smectite silica, calcite, clays, oxides and pyrite being the alteration minerals present. Smectite occurs from the surface to 680 m depth, indicating temperatures of <200ºC above that depth. Appearance of chlorite and illite below 680 indicate temperatures of over 220ºC. First occurrence of crystalline epidote was encountered at 820 m indicating expected formation temperatures >250ºC below this depth. In this well, the casing initially was to be set at 1200 m, but after careful study of hydrothermal mineralogy patterns, the well was cased at 850 m depth. The well is a good produces with an output of 12 MWe. Hydrothermal alteration was therefore successfully used to set the production casing in this well.

## DISCUSSIONS

In any geothermal system, there is always some uncertainty whether observed minerals distribution reflect current formation temperatures or are related to some previous thermal events or regimes. In the Greater Olkaria geothermal area as in other geothermal fields throughout the world, hydrothermal alteration minerals are important indicators of subsurface thermal changes. Index minerals used to construct determine parameters in Olkaria domes include smectite, chlorite and crystalline epidote with stability temperatures of <200ºC, <220ºC and >250ºC respectively. Hydrothermal alteration mineralogy can be a cheaper way of determining the subsurface conditions of a geothermal well during drilling where decisions have to be made real time.

## CONCLUSIONS

1. The Lithology of Olkaria Domes is made up of pyroclastics, tuff. Rhyolite, trachyte, and Basalts.
2. Stable formation temperatures of epidote, smectite and chlorite are <200ºC, >220ºC and >250ºC respectively.
3. Hydrothermal alteration has been used successfully to set production casing and also delineate the Olkaria Domes field.

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