Evaluation of Subsurface Structures Using Hydrothermal Alteration Mineralogy— A Case Study of Olkaria South East Field

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Keywords

Facies, tecto-stratigraphy, hydrothermal alteration, Logplot, Olkaria, permeability

ABSTRACT

South East Production area (SEP) is one of prime geothermal field under exploitation for electricity generation within the Great Olkaria Geothermal Area (GOGA). It is currently under exploitation for geothermal resource to supply steam for the proposed Olkaria VI power plant of 140MWe. The subsurface structural controls in this field are not well understood owing to limited characterization of the system in terms of stratigraphic settings and characteristic hydrothermal alteration mineralogy.

To deduce the subsurface structural controls, analysis for hydrothermal alteration characteristic and assemblages were carried out in three wells; OW-802, OW-803 and OW-804. The hydrothermal alteration in the area depict fairly similar characteristics though intensities differ from one well to another. This is evidenced by the bulk permeability and cumulative water-rock interaction processes, which are apparently controlled by either channelized or diffuse flow characteristics within the system. This paper, therefore presents pertinent information on the characteristic hydrothermal alteration patterns and mineral facies that have been used to define the major subsurface structural controls governing the fluid movement within the system.

1. Introduction

Olkaria South East geothermal field lies within the Greater Olkaria Geothermal Area (GOGA) and is located south of Lake Naivasha approximately 150 km from Nairobi. Exploration for geothermal resources in the area dates back to late 1950's where the first exploration well (X1) was drilled though not successful. Subsequent exploration activities led to deep drilling in 1973 and further feasibility studies which saw the development of Olkaria I power plant in 1980's with total generation of 45MWe. Currently, 583 MWe of geothermal energy is extracted from the Olkaria geothermal field; i.e. Olkaria I & IAU, II, III and IV, and from OrPower with plans geared to increase production to

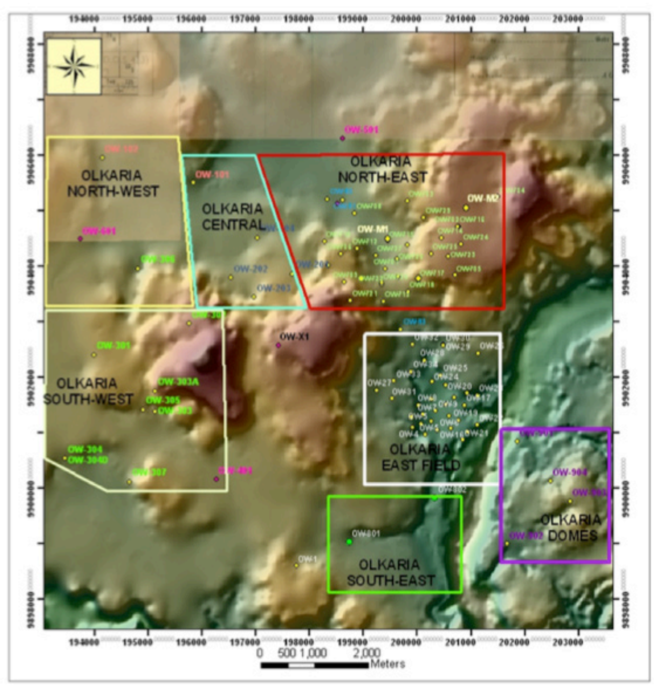

Figure 1. Location map of Olkaria Geothermal field sectors.

700MWe by the year 2016. Olkaria V and VI are still under way with later proposed to be developed within the SEPF. Over twenty (20) wells have been so far drilled in field, however for the purpose of this study, the focus will be on three wells; OW-802, OW-803 and OW-804 two of them located with the inferred up-flow zone. A location map of the field under study and relative location of the wells map are presented in figures 1 and 2.

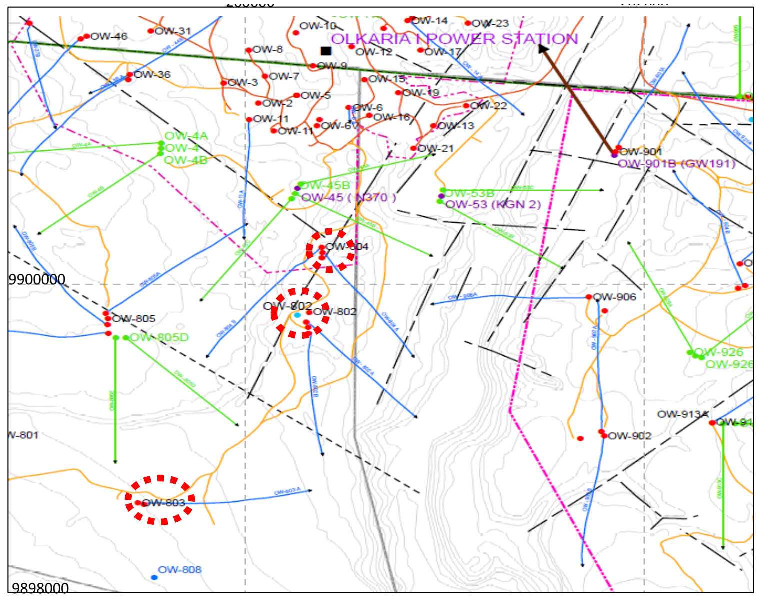

Figure 2. Relative location of the wells under study in Olkaria South East Field. The Red circles are the vertical wells of interest, Blue arrows show already drilled wells while Green arrows show wells planned for drilling.

1.1 Geological and Tectonic Setting

The Olkaria volcanic complex is characterized by numerous volcanic centres of Quaternary age and is the only area within the Kenya rift with occurrences of comendite on the surface (Lagat, 2004). The surface geology of the Olkaria Volcanic Complex is covered by ash falls from Mt. Longonot and Suswa and numerous comendite and pantellerite lavas. The adjacent Quaternary volcanoes to Olkaria volcanic complex which include Longonot, Suswa and Eburru are associated with calderas of the varying sizes. However, the Olkaria volcanic complex doesn't have a clear association of caldera. Naylor, 1972, Virkir, 1980, Clarke et al., 1990, Mungania, 1992, invoked the presence of buried caldera to be associated with a ring of volcanic domes in the east and south, and southwest. Further, Naylor (1972) while carrying out surface mapping of Olkaria area, identified remnants of an old caldera complex, subsequently cut by north-south normal rift faulting that provided the loci for later eruptions of rhyolitic and pumice domes now exposed in the Ol Njorowa Gorge. Several studies have been conducted in the area and have shown the existence of caldera. The presence of ignibritic flows identified in Olkaria are closely associated with caldera collapse (Omenda, 1998a). Omenda (2000), postulated that the ring structure was produced by magmatic stresses in the Olkaria "magma chamber" with the line of weakness being loci for volcanism. The volcanism in the Olkaria complex is associated with late Pleistocene and continues to Recent as indicated by Ololbutot comendite and pantellerites, which, have been dated at 180±50 yrs B.P (Clarke et al., 1990).

The subsurface geology of Olkaria volcanic complex is deduced from the regional geology and the data obtained from the drilled geothermal wells. These comprises pyroclastics and rhyolites of varying thickness dominating the upper subsurface geology to depth of about 1500 m a.s.l while basalts, tuffs, trachytes and intrusives (syenites and granites) are the dominant rock types at depth. Intrusives have been observed in some wells in Domes, North East, East and South East fields. In South East field, the intrusives are observed at fairly shallower depth of about 400 m a.s.l presumably forming the batholithic type of intrusion. A generalized stratigraphy of the Olkaria volcanic complex updated from the borehole geology of the recent drilled wells is provided in Table 1.

Table 1. Generalized stratigraphy of Olkaria Geothermal field (KenGen Internal Report, August, 2014).

Formation Name	Lithology	Thickness (M)	Characteristic (Age)
Upper Olkaria Volcanics	Comendite lavas and their pyroclastic equivalents, ashes , minor basalts (Clarke et al.,1990, Omenda, 1998a)	Surface-500 m	Superficial (Quaternary)
Olkaria Basalt	Basalt flow, minor pyroclastics and trachytes (Omenda 1998a)	100-500	Cap-rock
Plateau Trachyte	Trachytes with minor basalts, tuffs and rhyolites (Omenda 1994,1998a)	1000-2600	Reservoir (Pleistocene)
Mau Tuffs	Consolidated ignimbrites (Omenda 1994,1998a)	>2600	Reservoir (Late Miocene)
Pre Mau Formation	Trachytes, basalts, ignimbrites	unknown	Reservoir
Olkaria Intrusion	Granites, Syenite and Basaltic in composition. They occur as dykes and sills cutting through the basement rocks, tuffs and the trachytic units. They also occur as batholiths	Varying	Intrusive (Late Pleistocene-Holocene)
Proterozoic Basement rocks	Gneisses, schists, marbles and quartzites (Mosley,1993, Smith and Mosley, 1993, Simiyu et al., 1993)	5000-6000	Basement (Proterozoic)

1.2 Tectonic Setting

Structures play a vital role as conduits for the movement of fluids. In particular, faults are considered to have two effects on fluid flow; they may facilitate flow by providing channels of high permeability, or they may prove to be barriers to flow by offsetting zones of relatively high permeability (Jean, 2005). Within the Rift Valley, the main direction of faulting is along the axis of the rift, and this has a significant effect on the flows across the rift. It is apparent from the high hydraulic gradients that are developed across the rift escarpments that the effects of the major fault act as zones of low permeability (Lagat, 2004).

The structural setting of the greater Olkaria volcanic complex area depict a NW-SE and NNW-SSE faults believed to be the oldest and are associated with the development of the rift. The young and most recent faults are the N-S and the NNE-SSW faults which are undoubtedly considered to have substantial effect on the geothermal fluid flow systems of the area (Omenda 1998). Recently, the KenGen geoscientific team carried out structural geological mapping of the South-West field of the Olkaria geothermal field and identified faults within the area with NW-SE (old faults) and NNE-SSW (young faults) trending faults (Kengen Internal report, August, 2014). The intersection of these faults provides good permeability for the fluid movement and likewise the possible areas of up-flow which should be targeted for exploitation. An updated structural map of the area is provided (figure 3).

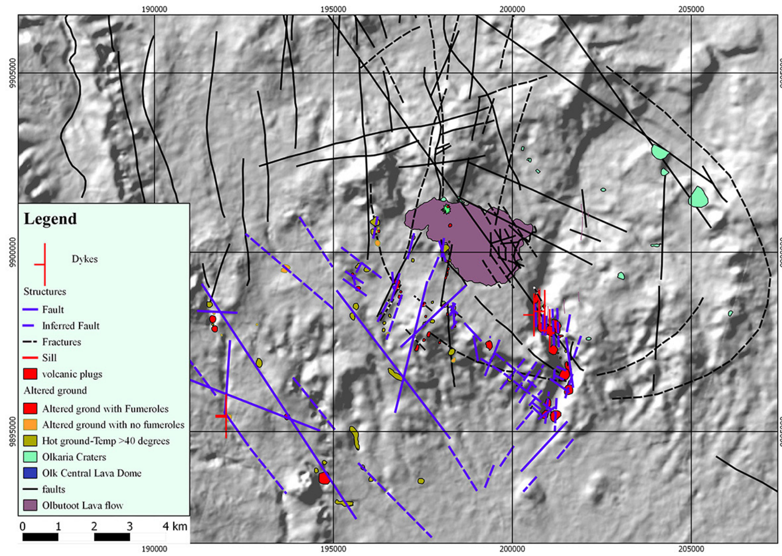

Figure 3. An updated structural map of Olkaria geothermal field. The blue lines show the newly identified structures from surface geological mapping (KenGen internal report, August, 2014) while the black lines show the structures which have been in existence (after Omenda, 1998).

1.3 Hydrothermal Alteration Characteristics

Hydrothermal alteration is broadly used to refer to change in mineralogy of the host rock resulting from the interaction with circulating chemically rich hydrothermal fluids. It involves the replacement of primary minerals with alteration minerals stable at the conditions of alteration (Pat Shanks III W.C, 2012). The hydrothermal alteration zones thus provide important clues for pathways of fluid travel and geochemical evidence for physical-chemical conditions of alteration. Hydrothermal alteration in geothermal exploitation is a very important parameter that can deduce a lot of subsurface information in a geothermal system. From many geothermal systems, factors influencing the distribution and kind of hydrothermal mineral assemblage include; permeability, composition of the host rock and the circulating fluids, temperature, pressure and duration of hydrothermal alteration (Lagat, 2004). These factors are largely independent, but the effects of one or more of the factors can exert a dominant influence on the location and extent of hydrothermal alteration (Browne, 1978). The susceptibility of the main primary minerals to hydrothermal alteration depends largely on Bowen's Reaction Series in which the earlier formed minerals are the first to alter, whereas the later formed are the last to alter, with quartz mostly being unaffected.

2. Data Type and Methodology of the Study

Data used for this study is majorly based on three main sources namely; the borehole geology data gathered from the drill cuttings for the wells under the study and surface structural geological mapping reports carried out in the area. This data will be processed by use of MS Office Excel, Logplot and Petrel softwares for the presentation of the findings.

The borehole data in reference includes the subsurface rock types, structures and alteration characteristics. This is useful in determining the possible permeable zones based on the alteration characteristics as well as examining the temporal changes of reservoir conditions. The pattern of hydrothermal alteration mineral assemblages, intensities and sequences are similarly important tools for identification of the subsurface structural controls for the fluid movement.

The approach for the study will focused on the following aspects but not limited to;-

a. Analysis and interpretation of the borehole geology data from the three wells OW-802, OW-803 and OW-804 with the aid of binocular, petrographic and XRD methods to establish the type and nature of hydrothermal alteration characteristics

b. Use of LogPlot and Petrel softwares for modelling and presentations of the findings

c. Comparison of the alteration characteristics in the three wells to define the preferential fluid flow within the South east field.

3. Results and Interpretations

Alteration characteristics present an interesting domain in appraising active geothermal systems. They have been applied in many geothermal systems in the world as tool to define the reservoir characteristics and also to interpret the type of structural-stratigraphic controls for fluid movement. In this study, the emphasis has been on the type of alteration and characteristic alteration zones, distribution and intensity. To evaluate the subsurface setting, hydrothermal alteration characteristics and assemblages have been used to define the fault geometry controlling fluid movement. Figures 4 to 6, are the summary charts for alteration characteristics and mineral zonations for three wells within SEP.

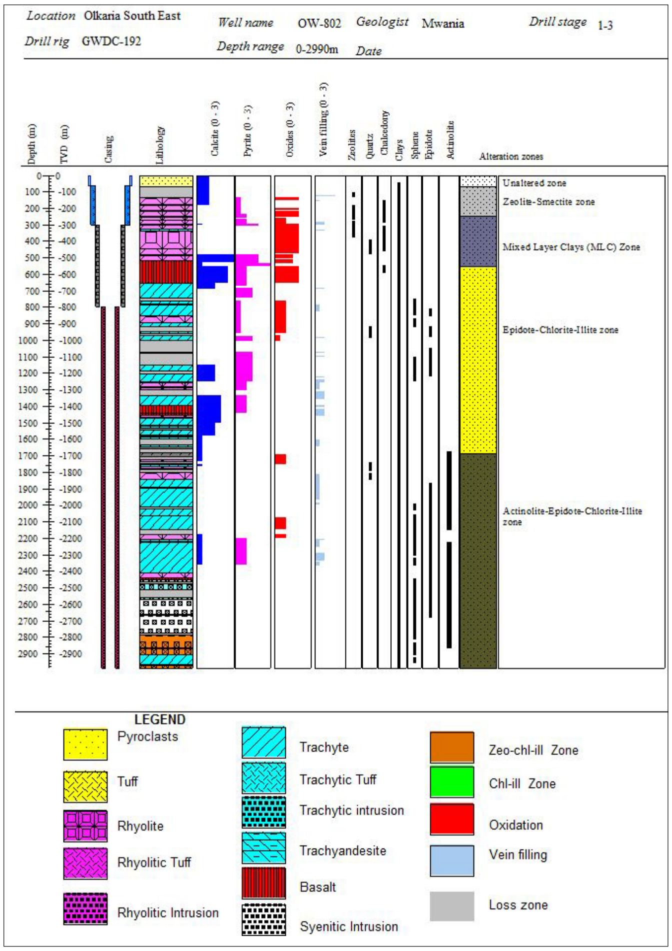

Figure 4. Hydrothermal alteration characteristics and mineral assemblage in well OW-802.

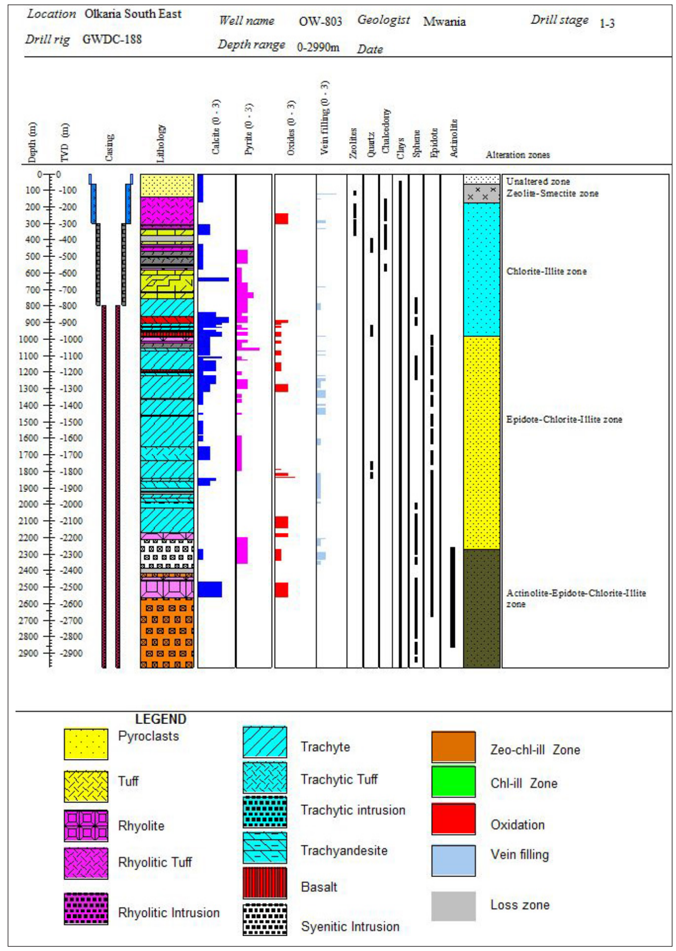

Figure 5. Hydrothermal alteration characteristics and mineral assemblage in well OW-803.

3.1 Hydrothermal Alteration Characteristics

Hydrothermal alteration characteristics and mineral assemblage in the SEP is largely controlled by the temperature, permeability, composition of fluid and duration of water rock interaction process. In conformity with Lagat's observations in 2004, permeability and temperature seems to play a dominant role in controlling the nature and characteristics of hydrothermal alteration and assemblage. Notably, the duration of water rock interaction is quite favorably noted to designate the rate of alteration intensity as well as the characteristic mineralogical assemblages. In these regards, the zones with large amount of pervasive hydrothermal fluid flow due to enhanced permeability exhibit diffuse flow characteristic vis-à-vis the channelized flow type hence the difference in type of hydrothermal alteration intensity. The characteristic hydrothermal mineral alteration can be used to deduce the nature of the reservoir and perhaps the temporal changes based on differing mineral assemblages, and compositions particularly through tracking changes in temperatures and permeability over time.

The alteration patterns in these three wells dispay fairly similar hydrothermal alteration charcateristics with slight deviation in some exceptional cases. Based on hydrothermal mineral assemblage and alteration charcateristics, three distinct alteration facies can be recogized; argillic, phyllic and propyllic facies.

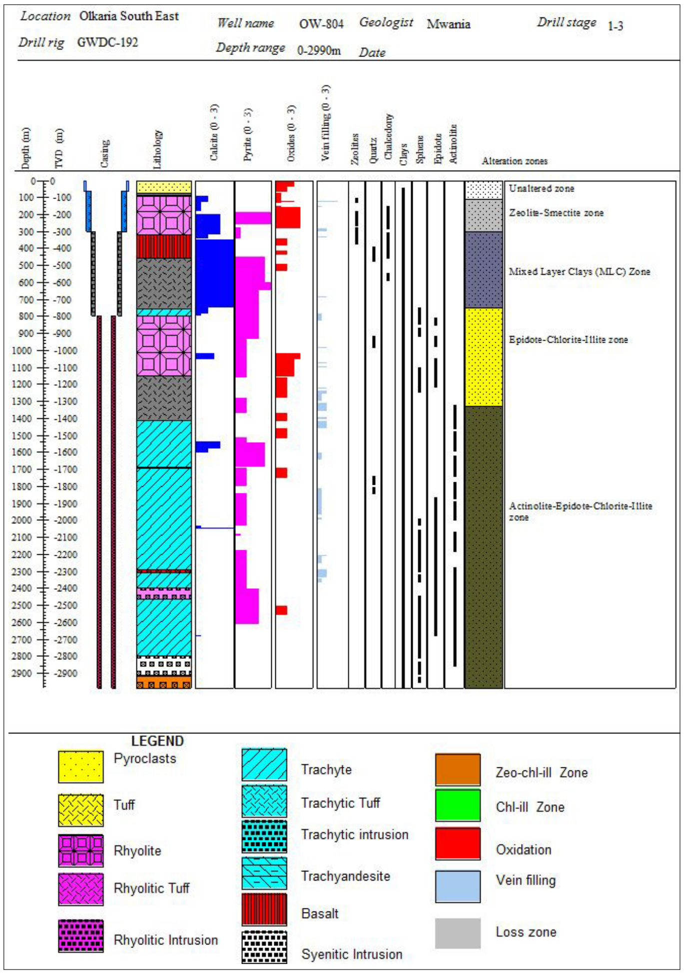

Figure 6. Hydrothermal alteration characteristics and mineral assemblage in well OW-804.

In the near sub-surface environment to depth <500m bgl, argillic alteration facies predominate and are characterized by low temperature hydrothermal minerals mainly zeolites, smectites, amorphous silica and other low temperature clays. This occurs at presumed temperatures of less than 180°C. With temperature increment, the argillic alteration facies progrades to phyllic alteration facies which is distiguished by the occurrence of chlorite, quartz, illite, intermittent epidote in the temperature regimes of 200-260°C. This is observed to occur within a depth range of 600-1500m bgl. The most and very unique mineral within this facie is the epidote which has been widely used as the geothermometer in the Great Olkaria Geothermal field to define the entrance into the reservoir.

At depth between 1500-3000m bgl, high temperature prophyllic alteration facie is observed characterized by high temperature geothermometers mainly the assemblages of epidote, chlorite, albite, illite, prehnite, actinolite and wollastonite. In these facies, actinolite and wollastonite are the characteristic geothermometers defining this facies though epidote is ubiquitous and well developed.

Below is a brief description of the alteration charcteristics each of these wells;

3.1.1 Wells OW-802, OW-804 and OW-803

The hydrothermal mineral assemblages in these two wells is fairly similar and often display good water-rock interaction process. This is evidenced by pervasive high alterattion intensity coupled with oxidation and pyritization alongside with strong epidotization at the inferred feedzones (table 2 below). Generally in these two wells, the upper parts of the well bore at depth less than 600m bgl, argillic alteration type is prevalent and often characterized by zeolites, calcite and smectites whose temperatures are presumed to be less than 180°C. The entrance into the reservoir is defined by the first appearance of the epidote at fairly shallower depths of 652m bgl and 700m bgl in well OW-802 and OW-804 respectively. The mechanisms of heat transfer within the permeable zones is principally by convection though at the bottom of these two wells the converse is true where permeability restricted due to the presence of intrusion at depth (below 2800m bgl) hence conduction is the prevailing mechanism of the heat transfer. The phyllic and prophyllic alteration characteristics are also closely associated with permeable zones where large volume of hot hydrothermal fluids are present. The possible aquifers in these wells occur within highly altered tuffs, basalts, trachytes and at the contacts between the lava flows.

In well OW-803, the alteration characteristic display a fairly different situation where the ubiquitous calcite deposition is very evident and veins filling the permeable structures are distinct. Though the entrance of the reservoir is defined by the first appearance of the epidote at 982m bgl, permeability is generally restricted in this well possibly due to precipitation of secondary minerals perceived to have sealed the previous permeable zones. The precipitation of secondary minerals especially the calcite is closely associated with possible incursion of cold groundwater. Granitic and syenitic intrusions in this well (OW-803) are fairly shallowest at around 2300m hence the permeability below this depth is hindered due to the massive nature of the formation.

A summary of the discerned possible feedzones interpreted from lithological units and alteration patterns are presented in table 2.

Table 2. Summary of possible feedzones in wells OW-802, OW-804 and OW-803.

Well No.	Possible aquifers (m bgl)	Remarks on Feedzones
OW-802	850-1100	Major
	1200-1400	Major
	1500-1800	Moderate
	2150-2250	Minor
OW-804	1200-1400	Major
	1900-2000	Moderate
	2200	Minor
	2750	Minor
OW-803	1000-1100	Major
	1250-1300	Moderate
	1900	Minor
	2500	Minor

3.2 Hydrothermal Mineral Assemblages and Tectno-Stratigraphic Framework

The tectno-stratigraphic framework of a geothermal system has significant influence on the characterstic mineral assemblage. Zones with high flux of hydrothermal fluids especially on extensional terraines present favorable structural settings for geothermal activity. These are the environments majorly with intense hydrothermal alteration and particluar mineral assemblages. Spatial distribution of the specific geothermometers may therefore reflect structural relationship that are indicative of the preferential conduits for the hydrothermal fluids. For the purpose of this study, epidote which is a geothermometer indicative reservoir temperature >230^{0}C is used to deduce the tectno-stratigraphic framework of the area. Figures 7 and 8 present the epidote iso-surface map and 3D model showing the upflow zones.

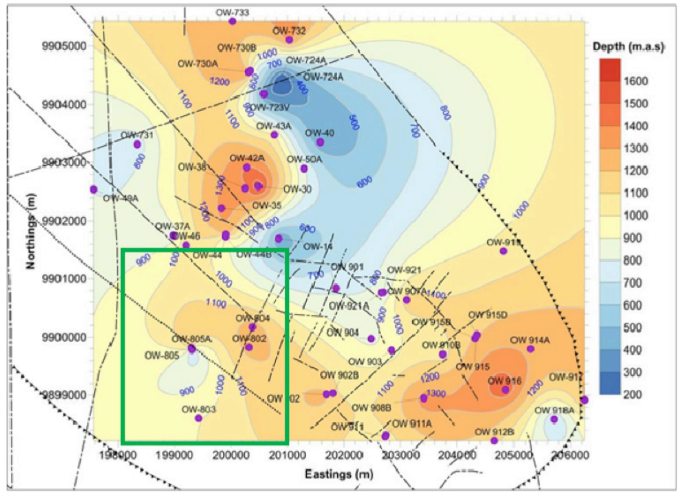

Figure 7. The Epidote first appearance surface map for for the greater Olkaria geothermal field with particular emphasis on the South-East field (with green rectangle). The mineralogical assemblage show NW-SE general trend mostly associated with bulk permeability of regional faults.

4. Discussions and Conclusions

Litho-stratigraphic analysis in the four wells within the SEPF present important information on the geochronology of the area. The sequence of relative time for lava placements events show the possible structural-stratigraphic controls and displacements that are believed to be responsible for the fluid movement. Major structural-stratigraphic controls have close association with the mapped surface structures whose general trend is NW-SE and NNE-SSW direction. Hot hydrothermal fluids are possibly controlled by the old NW-SE trending faults while permeability is enhanced by the intersection of young NNE-SSW trending faults. The presence of brecciated zone at OW-804 indicate a highly faulted zone that is associated with young tectonics which control pervasive flux of hydrothermal fluids. In well OW-803, permeability is restricted possibly due to NW-SE trending fault which could be barrier for the fluid flow.

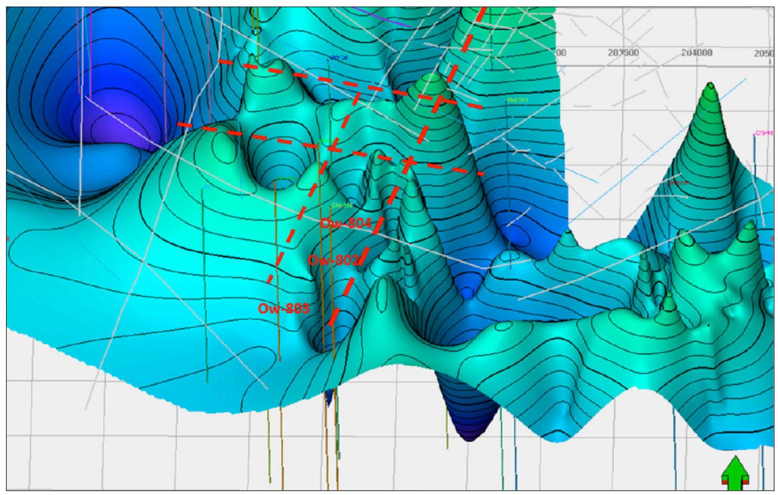

Figure 8. 3D model for the up-flow zones shown by the updoming regions within the South-East, East and partly North-East and Domes field.The red dashed lines represent the inferred subsurafce structures that have been deduced from the charcteristic assembly of Epidote as geothermometer.

Hydrothermal alteration in the area has also been studied and depict fairly similar characteristics though intensities of alteration differ from one well to another. The bulk permeability and cumulative water-rock interaction processes are controlled by either channelized or diffuse flow characteristics in the system. The latter accounts for complete replacement of the primary minerals whilst the former defines the partial replacement of the primary minerals and more often restricted within the walls of faulted zone. Ultimately, these interaction processes defines the characteristic mineral assemblages as well as the alteration intensities. Four alteration zones have also been defined which can be broadly grouped into three alteration facies mainly argillic, phyllic and prophyllic. The argillic alteration facies is defined by the zeolite-smectite zone and partly the mixed-clay layers whose alteration temperatures are inferred to be <180^{o}C. The phyllic and prophyllic facies are defined by the appearances of epidote-chlorite-illite series and actinolite-epidote-chlorite-illites series respectively. The presumed reservoir temperature regimes within these facies are greater than 240^{o}C.

The first appearance of the epidote is very significant in this study. First, it has been used to map the localized up-flow zones within the system and also elucidate the tectno-stratigraphic framework. Epidote observed at shallower depth in wells OW-802 and OW-804 indicating the localized up-flow zone within the SEPF. The envisaged outflow zone is at well OW-803 where epidote appears fairly deep and also the ubiquitous deposition of the calcite is indicative of the possible cold water incursion. The fault geometry appear to be consistent with the NNW-SSE general direction of rift system and partly characterized by young tectonics with NNE-SSW trending faults. The envisaged young faults have been inferred from presence of brecciated zones in well OW-804 which resulted from the shearing effect partly parallel to the direction of minimum principal stress. The development of breccia zones is critical in the opening up of intersecting fractures/cracks networks and subsequent increases in permeability rendering pervasive water rock interaction processes hence hydrothermal alteration. It is therefore likely that the young faults trending in NNE-SSW faults are responsible for the possible upwelling of the hot hydrothermal fluids in wells OW-802 and OW-804. On the basis of the characteristic mineralogical assemblages, new subsurface and apparently obscure structures on surface have been mapped with the general trend direction in WNW-ESE and NNE-SSW. These are the faults that have been inferred as the possible conduits for hot hydrothermal fluids within the system and thus control the possible occurrences of the localized up-flow zones within the SEPF and East fields.

5. Recommendations

Based on the inferences gathered on this study, the following recommendations are made;-

i) Future drilling targets in this area should aim the intersection of the NW-SE or WNW-ESE and NE-SW or NNE-SSW trending faults. This is envisaged to the south-west margin of the sector where there is evidence of the extensive fracturing

   There is also need for more infill wells close to the up-flow zone at wells OW-802 and OW-804 and possibly target the intersection of the faults.

ii) Further study is required to appraise the mechanisms of the fluid flow mechanisms, chemistry and water-rock interaction processes that necessitated the reversals of thermodynamic conditions in well OW-803 besides the presence of heat source in the vicinity.

iii) Drilling within this sector should be limited to depth at which the massive granitic intrusion is encountered. Below the intrusion, there is no permeability hence limited water-rock interaction process.

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