

Effects of Hydrothermal Alteration on Petrophysics and Geochemical Mobility of Reservoir Rocks In Olkaria Northeast Geothermal Field, Kenya

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ABSTRACT

Reservoir rock characterization for any geothermal field under both exploitation and exploration provide rationale for further utilization programs. The Olkaria reservoir rocks within the Northeast production field (NEPF) are largely typified by trachytes and rhyolitic intercalation. In attempt to characterise the reservoir geometry under the influence of hydrothermal alteration three wells; OW-706, OW-717 and OW-725 located in the NEPF are studied. The key petrophysical parameters studied include; porosity, relative permeability and lithological characteristics under influence of hydrothermal metamorphism. Effects of hydrothermal alteration on geochemical mobility were also evaluated selected elements mainly on bulk chemistry (K_2O , Al_2O_3 , CaO , FeO SiO_2 etc.) and trace elements (Nb, Y, Rb, Zr, Ba, etc) dispersion through empirical comparisons between the protolith samples and subsurface samples. The former are considered relatively fresh and perhaps least affected by hydrothermal alteration while the latter are assumed to have undergone some changes due to the effects of hydrothermal alteration. The findings of this research reveal that, the reservoir rocks (trachytes and rhyolites) lack primary porosity and permeability is mainly controlled by the secondary porosity. The broad mechanism controlling porosity and permeability distribution include; dissolution, deposition and replacement. These mechanisms has direct bearing on elemental transfers where K_2O and Al_2O_3 show significant depletion trends from protolith samples while CaO and FeO show enrichment of subsurface samples. On trace elements, there are no major shifts, however positive correlation of Nb, Y and Rb against Zr suggest possible enrichment. Based on the findings, the research concludes that, variability of petrophysical properties have direct bearing on mobility of chemical elements. In addition, the reservoir geometry from study wells is well enhanced along the NW-SE fault and less propagated to the eastern periphery of the field. The effect is largely attributed to major structural controls which augments the vertical permeability within the field sector. For optimal management of exploration programs, future production drilling should aim at targeting the NW-SE fault inferred to be the possible upwelling zone and where the reservoir geometry appear well developed. Correspondingly, re-injection wells should be sited to the eastern periphery of the field adjacent to the Gorge farm fault which seemingly channels cooler fluids and equally considered to be a possible recharge zone at shallow depth.

1. INTRODUCTION

The Greater Olkaria Volcanic Complex is located approximately located approximately 120 km northwest of Nairobi City and south of Lake Naivasha within the eastern branch of East African Rift System (EARS). The Kenya rift is the segment that extends from Lake Turkana to northern Tanzania and is characterised by several geothermal prospects and some young Quaternary volcanoes along its axis (Omenda, 2007). According to Omenda (2007), the estimated potential that can be generated from these geothermal systems in Kenya is over 7,000 MWe which is considered sufficient enough to cater for the energy demands in the country. Out of the seventeen (17) geothermal prospects occurring within the Kenya rift, only three have proven geothermal potential after successful drilling; Olkaria, Eburru and Menengai fields. The Greater Olkaria Volcanic Complex (GOVC) is bordered to the North by Eburru massif and to the East and South by Longonot and Suswa volcanoes respectively.

For ease of exploration and management of field, GOVC is divided into seven distinct field sectors; Olkaria Northwest, West, Central, Northeast, East, Southeast and Olkaria Domes field (Figure 1). These field sectors are under intense exploration and utilisation for geothermal sourced energy. However for the purpose of this research, focus is exerted on the Northeast field sector in attempt to unravel the reservoir geometry.

1.1 Overview of exploration history

Exploration for geothermal resources within the Greater Olkaria Volcanic Complex (GOVC) dates back to late 1950's when the first two exploration wells (X1 and X2) were drilled. Well OW-X1 was drilled to 502 m and OW-X2 to 942 m below ground level (m bgl) (Ofwona, 2002). Subsequent exploration activities continued which led to deep drilling in 1973 and feasibility studies that saw the development of Olkaria 1 power plant in 1981. Further drilling and exploration continued within the GOVC and to date over 600 MWe are currently generated from five power plants and well-head units (modular power plants). Four of these power plants (Olkaria I, Olkaria IAU, Olkaria II and Olkaria IV) and well head units are operated by KenGen while Olkaria III is operated by independent power company (OrPower4 Ltd). Other new power plants are still in pipeline, though construction for Olkaria V is due for commission soon (early 2017). To present, over 285 geothermal wells have been drilled within the GOVC, however, for the purpose of this study, three wells; OW-706, OW-717 and OW-725 located in Olkaria Northeast field will be considered in attempt to delineate the reservoir geometry (Figure-1).

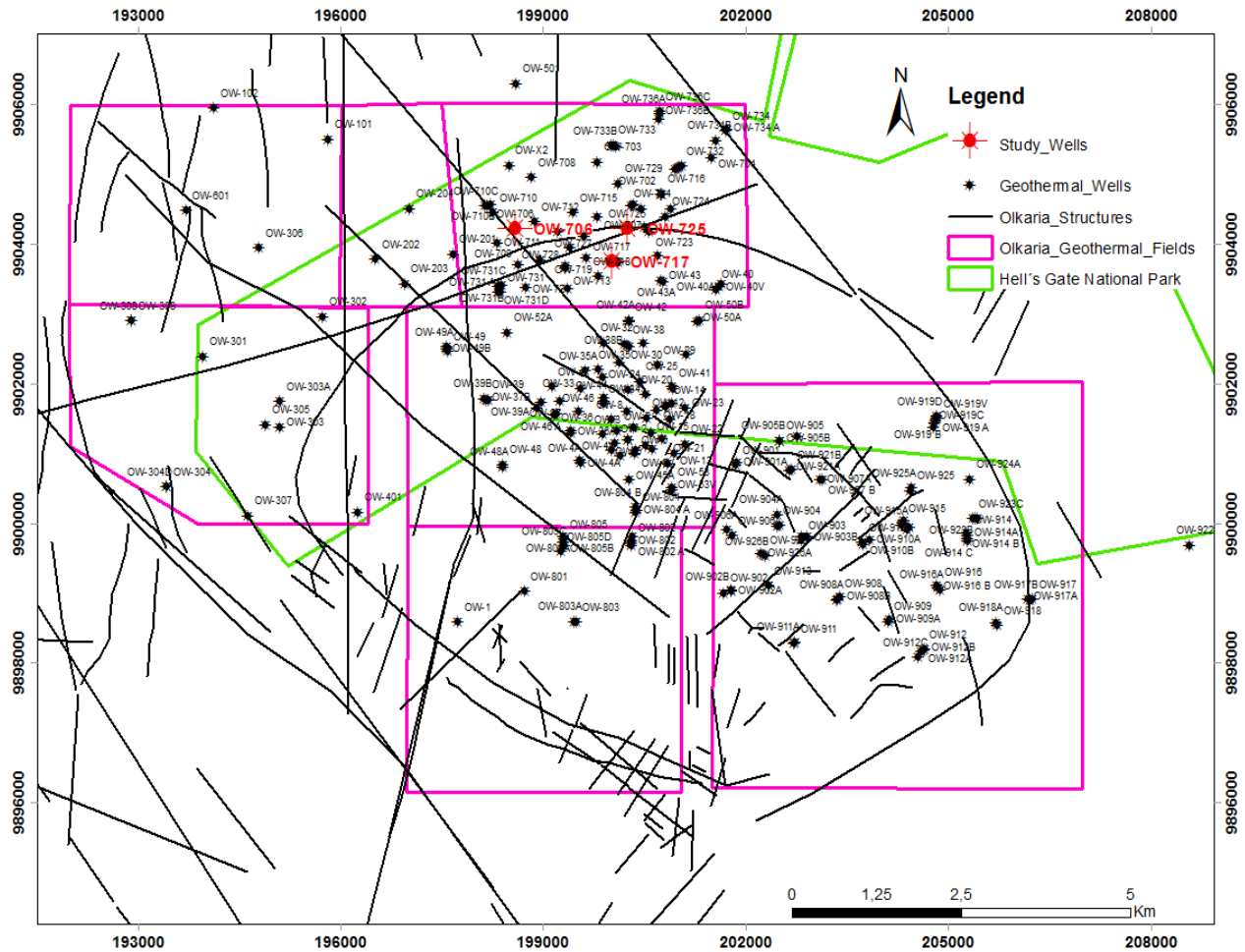


Figure 1: The Olkaria geothermal resource map showing geothermal sectors and the three study wells; OW-706, OW-717 and OW-725 located in Northeast field

1.2 Background of research and objectives

Development of geothermal resource for electricity generation require estimate of resource and its uncertainty. Of the paramount important parameters that have to be determined in order to ascertain the viability of any geothermal resource include; permeability, heat, recharge and characteristic cap-rock, hydrothermal alteration and metamorphism, and clues on chemical mobility during fluid-flux mechanisms.

In spite of Olkaria geothermal field being subject to extensive exploration and exploitation activities over time, previous studies have been geared towards unfolding the geology and stratigraphy of the area, structural setting, reservoir rock types and hydrothermal alteration characteristics. This has feasibly created paucity of information regarding reservoir rock characterisation in terms of petrophysical properties and geochemical mobility relative to hydrothermal alteration patterns, yet is a requisite aspect when evaluating changes in the reservoir morphology. To expend this proposition adequately, it is necessary to delineate the reservoir geometry from wells with similar petrogenetic provenance and thereby establish a rationale for further exploration programs to the peripheral areas.

1.2.1 Objective of the study

The aim of this research is to evaluate the effects of hydrothermal alteration on petrophysics and geochemical mobility of reservoir rocks mainly trachytes and rhyolitic intercalations, and develop reservoir facies model for Olkaria Northeast field. To achieve this, three wells; OW-706, OW-717 and OW-725, with similar petrogenetic provenance were studied

2.1 Subsurface stratigraphy of Olkaria Northwest and Northeast fields

The subsurface lithology for both two fields present a spectacular geology and distinctive structural framework necessitating fluid movement within the geothermal system. In these particular fields, the lithostratigraphy is well described by Omenda (1998) who gave a detailed account of the stratigraphy and the reservoir rock characteristics. From the analysis of drill cuttings, Omenda (1998) pointed that, the east and west sectors have distinct lithostratigraphy with a major structural divide cutting approximately through the Olkaria Hill. This structure is thought to be a major high-angle normal rift fault downthrown to the east. Subsequent volcanism occurred on the graben side of the fault (Omenda, 1998). The west sector is characterized by the abundance of Mau tufts while Plateau trachytes and the Olkaria basalt are unique to the east sector (Omenda, 1998). The occurrence of Plateau trachytes in large volumes and occasional rhyolites in Northeast sector below the cap rock confirm them to be the main reservoir rock.

3. METHODOLOGY OF STUDY

Several analytical techniques were used for determining petrophysical properties and evaluation of chemical mobility within the reservoir rocks.

3.1. Petrophysical properties

For petrophysical properties key parameters evaluated during the study included; porosity, permeability and lithological variance. For detailed evaluation of the lithological character, porosity and permeability in relation to variability of hydrothermal alteration patterns, the optical method was employed. However, for porosity measurements, Gravimetric techniques were employed since they are more reliable than optical methods. Using the gravimetric techniques, the porosity measurements were derived from the difference between the saturated sample and dry sample gives the mass of water in pore spaces ($M_{wtr} = M_{sat} - M_{dry}$) and the pore volume (V_p) was then calculated from the density of water ($V_p = M_{wtr}/\rho_{wtr}$). The bulk volume of the sample is calculated from the sample when put in a beaker and the displaced volume of water is weighed, and the volume calculated from the known density of water. The fractional porosity was then determined from the calculated ratio of pore and bulk volume measurements as shown in equation 1 below;-

$$Porosity = \frac{pore}{bulk} volume \times 100 \quad (1)$$

Permeability on the hand was determined through visual observation under optical microscopy and also inferred from indirectly from the temperature distribution within the reservoir. There were no direct measurements on permeability, however, the results were equally compared with the known permeability values of the major structural controls within the field sector.

3.2. Geochemical mobility

Samples for geochemical analysis were subjected to X-Ray Fluorescence (XRF) techniques to evaluate the constituent elements (major and trace elements) of the reservoir rocks (trachytes and rhyolites). X-ray fluorescence (XRF) analysis is one of the most common non-destructive methods for qualitative as well as quantitative determination of elemental composition of materials and it is suitable for solids, liquids as well as powders (Torres-Alvarado, Pandarinath, Verma, and Dulski, 2007; Verma, Torres-Alvarado, Satir, and Dobson, 2005)

Rock samples from drill cuttings were analysed for bulk chemistry mainly for SiO_2 , K_2O , Al_2O_3 , CaO , Mn and FeO , and several trace elements; Zr , Y , Rb , Sr , Nb , and Ba to allow direct empirical comparison between the protolith rocks and altered rocks which constitute the bulk reservoir. The surface samples (trachytes and rhyolites) used for this study were adopted from Macdonald et al., (2008) and Marshall et al., (2009) which are assumed to offer representation of fresh or less altered samples. Although, the surface are not purely fresh, the assumption made is that, the surface samples are least affected by hydrothermal alteration and relatively remain stable. Immobile elements (SiO_2 and Zr) are considered as the independent variables for this study. An important indication of the immobile elements is that their ratios will remain relatively constant during dilution and depletion of other chemical components (Barret and MacLean, 1994).

4. RESULTS

4.1 Petrophysical properties

4.2.1 Porosity

Porosity distribution within the reservoir is determined by two-fold approach; (i) through the optical techniques by use of microscopes and (ii) experimental through gravimetric measurements.

i) Optical Method

In determination of porosity through the optical method, consideration is taken on the account of alteration intensity and permeability type. This technique is based on the visual point counting to characterise the surface morphology of the particular rock specimen. The analysed data was then tabulated and plotted on a graph with depth and with respect to alteration intensity to decipher the spatial distribution within the reservoir and also to predict the influence of progressive hydrothermal metamorphism (Figures 3, 4, 5).

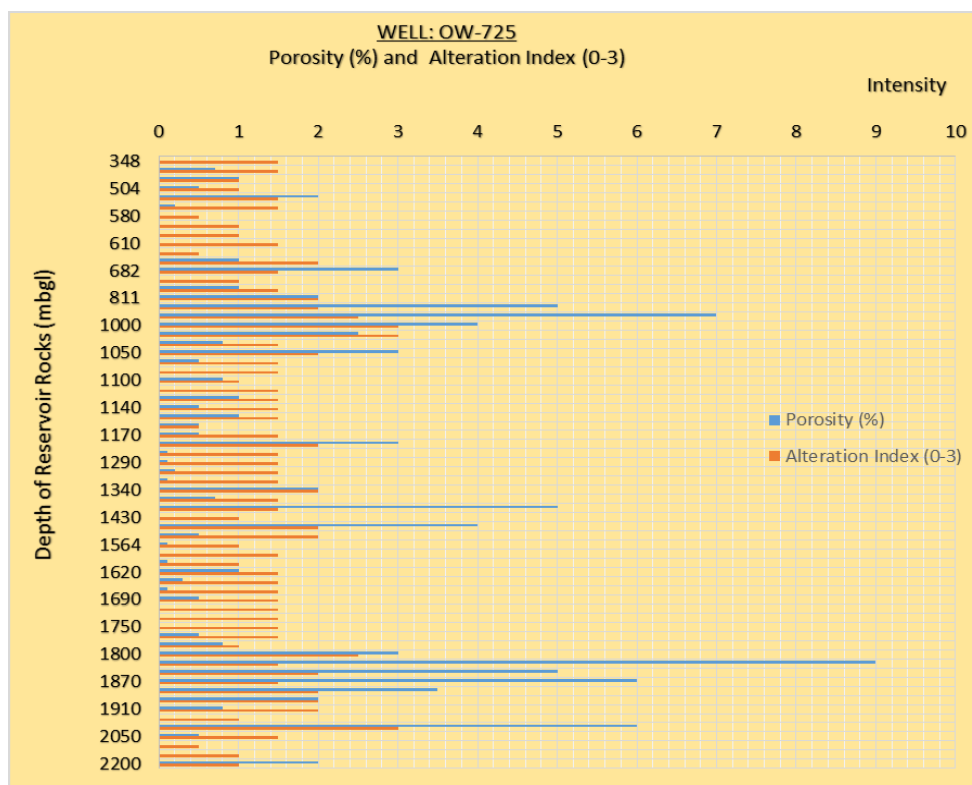


Figure 3: Visual porosity (blue colour) and alteration intensity (orange colour) distribution with depth in well OW-725, Olkaria Northeast field

Observations from well OW-725

Well OW-725 (Figure 3, above) display three major petrophysical facies. Firstly, the two distinct facies at 650 – 1060 m bgl and 1770-1890 m bgl. These zones are characterised by moderate to high alteration intensity and high porosity. The average visual porosities for these two zones are estimated at 2.48 % and 3.73 %, respectively, and therefore considered as major feed zones in this well. The second facie is at the zone between 1080-1680 m bgl largely predominated by replacement and surface deposition which ultimately changes the mineral fabric. The average visual porosity distribution within this zone is estimated at 0.83 % and constitute intermittent minor feed zone. This zone is typified by moderate alteration intensity and poor porosity, an observation clearly evident from the photomicrographs (Figure 4).

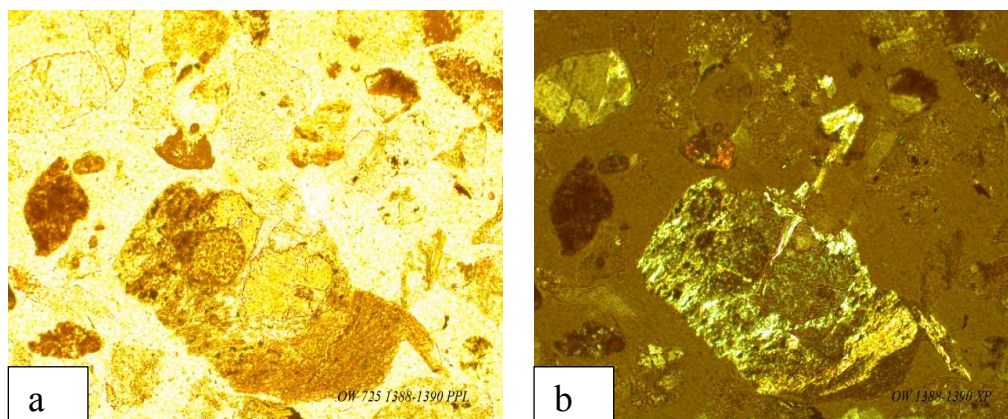


Figure 4: Photomicrographs of well OW-725 both under PPL (plane polar) (a) and XPL (crossed polar) (b) at depth of 1388-1390 m bgl, showing incipient stages of primary mineral (sanidine) dissolution and etch-pitting

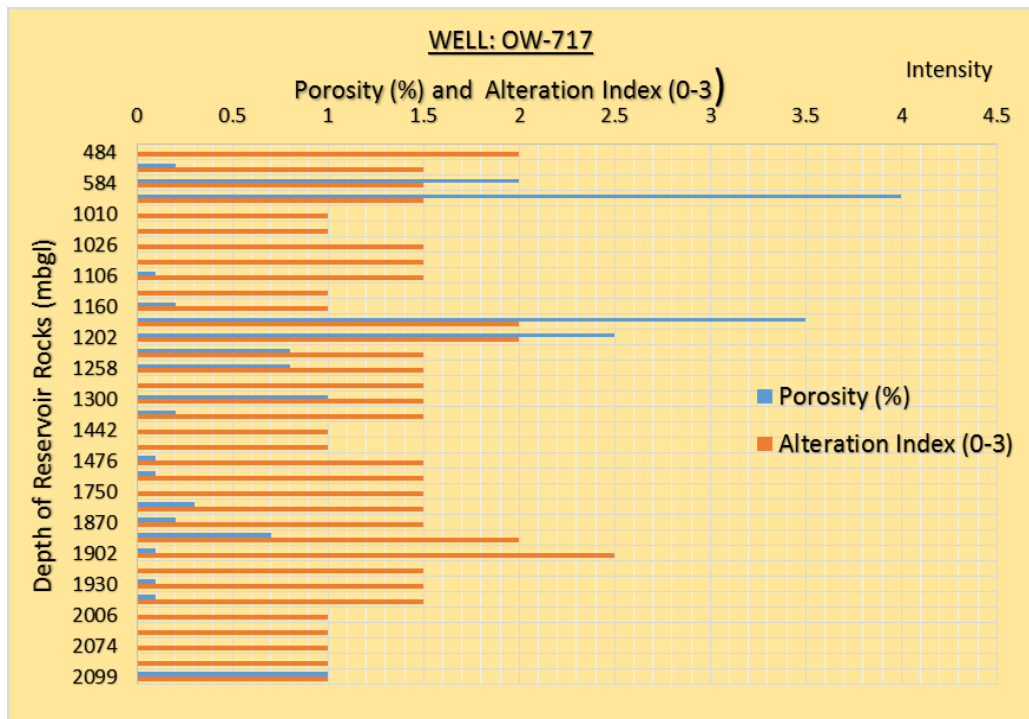


Figure 5: Porosity (blue colour) and alteration intensity (orange colour) distribution with depth in well OW-717, Olkaria Northeast field.

Observations from well OW-717

Well OW-717 display two distinct petrophysical facies; the first section from 1160 to 1250 m bgl characterised by dissolution and sparse deposition on the surface. The second section falls between 1250 -2000 m bgl and appears fairly tight with very poor porosity. The moderate alteration intensity is largely predominated by deposition on the surface. Average porosities within these sections are estimated at 1.56 % and 0.15%, respectively. Photomicrographs (Figure 6) for selected depths attest to this phenomenon of poor porosity within the reservoir rock.

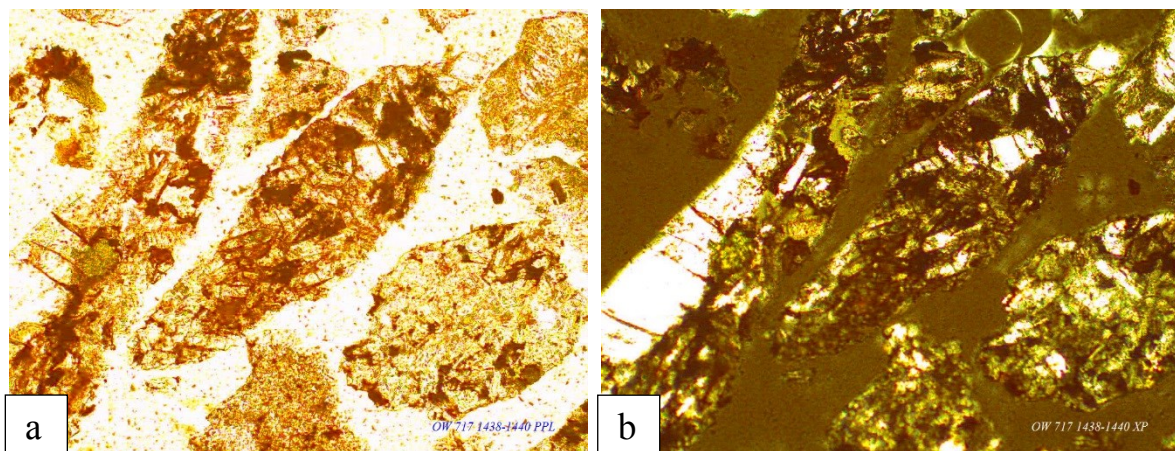


Figure 6: Photomicrographs of well OW-717 both under PPL (plane polar) (a) and XPL (crossed polar) (b) at depth of 1438-1440 m bgl, showing little alteration intensity as well as poor porosity within the rock matrix.

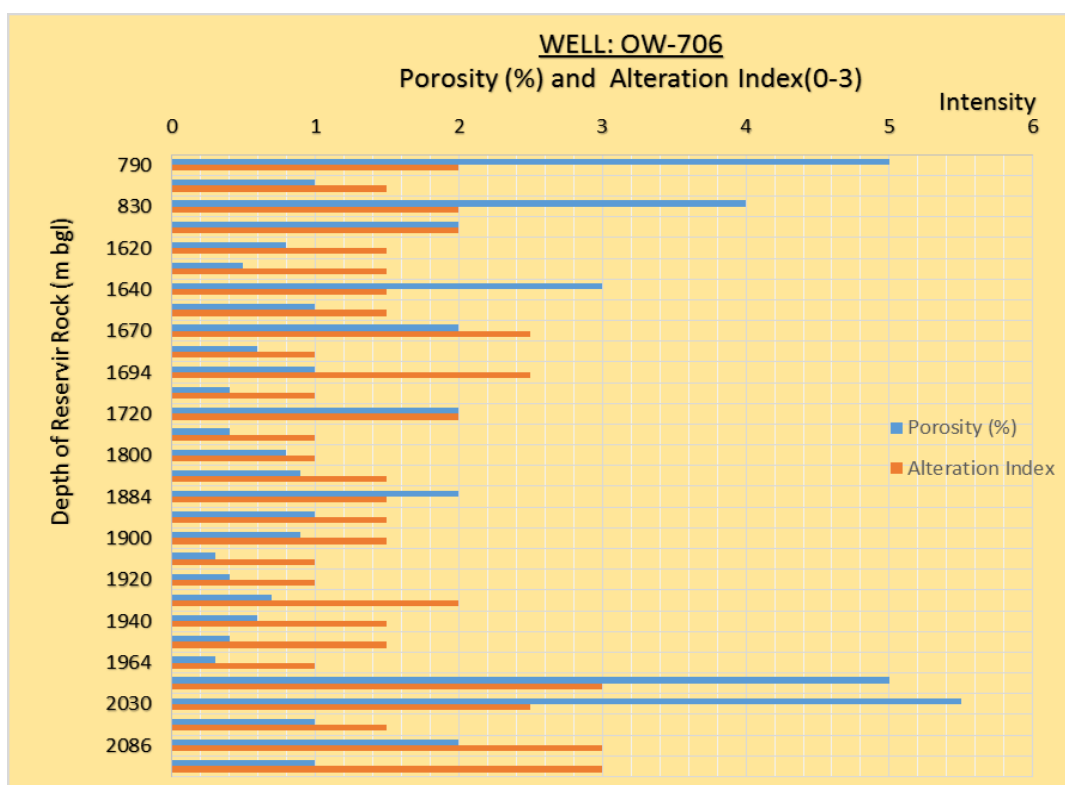


Figure 7: Porosity (blue colour) and alteration intensity (orange colour) distribution with depth in well OW-706, Olkaria Northeast field.

Observations from well OW-706

Dissolution of the primary minerals appear to be the predominant mechanism through which pores have developed and evolved. Although porosities are uniformly distributed within the well-bore, they are averaged at 3% and 0.95% for both major and minor feed zones, respectively

ii) Porosity results from Gravimetric (Archimedes) method

For the three wells; OW-706, OW-717 and OW-725, porosity distribution was analysed majorly on trachytes and rhyolitic rocks which occurs in large volumes and form the greater part of the reservoir. The limitation for this method was that, few recovered core samples which were available for analysis. Nevertheless, notable inferences have been drawn from analysed rock specimen (tables 1, 2, 3).

Table 1: Micro-porosity distribution and alteration index in well OW-706

Well-OW-706								
Depth (m)	Dry mass (gm)	Wet mass (gm)	Pore volume(m ³)	Bulk volume(m ³)	Fractional porosity	% porosity	Alteration Index	Alteration (%)
997-998	71.004	72.419	1.415	29.759	0.04754864	4.75	1.5	50
1602-1604	59.666	63.171	3.505	26.289	0.13332573	13.33	1	33
1821-1823	46.041	47.348	1.307	18.49	0.07068686	7.07	1	33
2093-2094	49.521	52.463	2.942	22.909	0.12842114	12.84	3	100
2094-2095	45.523	49.47	3.947	22.269	0.17724191	17.72	3	100
2095-2095.8	47.564	49.588	2.024	22.329	0.09064445	9.06	3	100
2095.8-2096	53.338	55.588	2.25	22.279	0.10099197	10.10	2	67
2096-2096.5	32.611	34.862	2.251	14.72	0.1529212	15.29	1.5	50
2096.5-2097	54.597	57.531	2.934	24.889	0.1178834	11.79	1	33
2097-2098	60.229	64.129	3.9	27.739	0.14059627	14.06	1.5	50
Density of water is 1 g/cm³ Average porosity 11.60%								

Table 2: Micro-porosity distribution and alteration index in well OW-717

Well-OW-717								
Depth (m)	Dry mass (gm)	Wet Mass (gm)	Pore volume(m ³)	Bulk volume(m ³)	Fractional porosity	% porosity	Alteration Index	Alteration (%)
884-886	59.973	61.723	1.75	26.269	0.06661845	6.66	0.5	17
886-888	56.440	58.711	2.271	25.869	0.08778847	8.78	1	33
2096-2099	46.116	48.4685	2.3525	19.8958	0.11824104	11.82	1	33
Density of water is 1 g/cm ³ , Average porosity 9.09%								

Table 3: Micro-porosity distribution and alteration index in well OW-725

Well-OW-725								
Depth (m)	Dry mass (gm)	Wet Mass (gm)	Pore volume(m ³)	Bulk volume(m ³)	Fractional porosity	% porosity	Alteration Index	Alteration (%)
808-809	44.181	45.728	1.547	19.329	0.08003518	8.00	1.5	50
809.5-810.5	49.407	51.940	2.533	22.419	0.11298452	11.30	2	67
811.5-813.5	59.289	62.332	3.043	26.879	0.11321106	11.32	2.5	83
2198-2199	66.543	68.779	2.236	28.569	0.07826665	7.83	2	67
2196-2197	53.329	55.809	2.48	22.489	0.11027613	11.03	1.5	50
2197-2198	56.474	58.642	2.168	23.809	0.091058	9.11	1	33
2199.5-2200.5	55.033	56.765	1.732	23.649	0.07323777	7.32	1.5	50
Density of water is 1 g/cm ³ , Average porosity 9.42%								

Remarkable porosity results via this method present relatively higher values compared to optical method. This is possibly attributed to micro-porosity of the inter-crystal matrix (Tables 1, 2, 3). The calculated average porosity values for these wells depict slight variability from 11.6% in well OW-706 to 9.9% in well OW-717, and in well OW-725 with median value of 9.42%.

4.2.2 Lithology, hydrothermal alteration and permeability distribution

i) Hydrothermal alteration facies

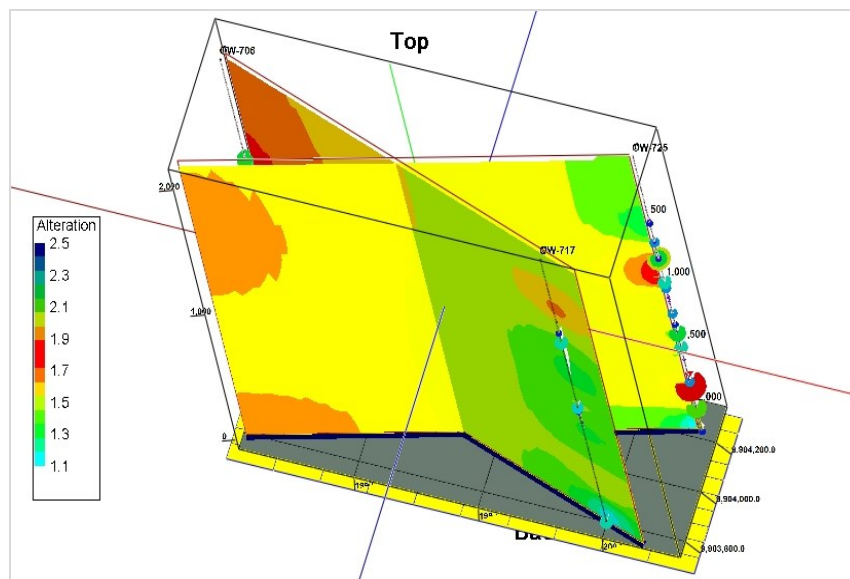


Figure 8: Fence model for hydrothermal alteration distribution in wells OW-706, OW-717 and OW-725 within the reservoir rocks (trachytes and rhyolites) in Olkaria Northeast field.

From the fence model moderate to high alteration is eminent in well OW-706 and clearly defined by two distinct alteration facies. These are zones characterised phyllic and prophylic alteration mainly typified by chloritisation and epidotisation processes. Alteration facies in wells; OW-717 and OW-725 are widely controlled by argillic-phyllic facies of low to moderately alteration intensity. Intercalated zones of low alteration zones are also prevalent and quite often associated low alteration minerals precipitating within the permeable zones and eventually comprising the reservoir permeability.

ii) Reservoir permeability model

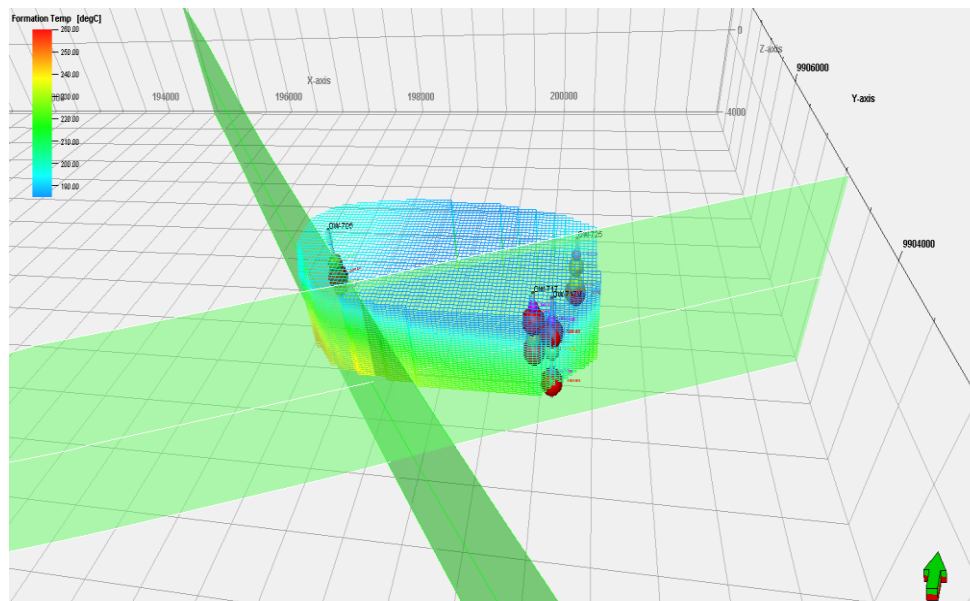


Figure 9: Permeability controls defined by NW-SE and ENE-WSW structures and feed-zones in the study wells (OW-706, OW-717 and OW-725), in Olkaria Northeast field.

Permeability within the reservoir was determined indirectly by invoking the temperature distribution and the character of the feed-zones from the study wells. The model indicate enhanced temperature distribution at fairly shallow depth along NW-SE trending fault, while on the other hand, high temperatures are observed to predominate at depth.

iii) Petrophysical model and predicted reservoir geometry

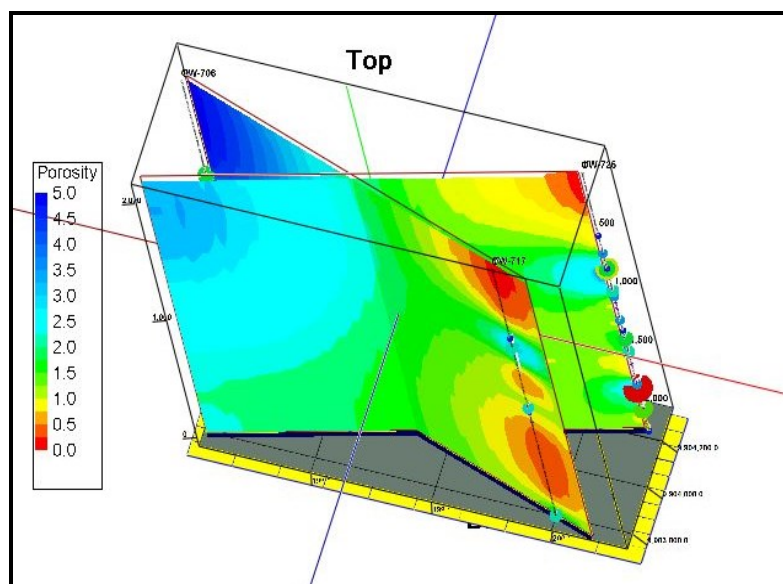


Figure 10: Petrophysical model for wells OW-706, OW-717 and OW-725 in Olkaria Northeast field.

The petrophysical facies model indicate high porosities in well OW-706 at the upper column of the well, while wells OW-717 and OW-725 manifest moderate to low porosity distribution. In particular, well OW-717 is typified by two distinct zones of low porosities which

are possibly tied to effects of hydrothermal alteration while OW-725 has moderate porosity. Generally, the zones with high porosity are also complimented by pervasive fluid-interaction leading to pore-evolution and subsequent permeability enhancement. The model is facies dependent and majorly controlled the characteristic nature of the interacting fluid. The influence of NW-SE and ENE-WSW (Olkaria fault) faults as preferential flow paths for hydrothermal fluids have also been factored in the model.

4.2 Effects of hydrothermal alteration on geochemical mobility

During hydrothermal alteration process, relative element transfers occur due to dissolution and precipitation mechanisms taking place within the reservoir. Alteration may thus to greater extent influence the physical morphology of the rock matrix which widely affects the inherent porosity of the reservoir rock. The analysed data was the plotted on Harker diagrams for selected major and trace elements to evaluate the characteristic chemical mobility as a result of hydrothermal alteration. From the bulk chemistry, the major constituents elements; K_2O , Al_2O_3 , CaO and Fe_2O_3 , are selected for empirical comparisons and plotted against SiO_2 as the independent variable (Figure 11)

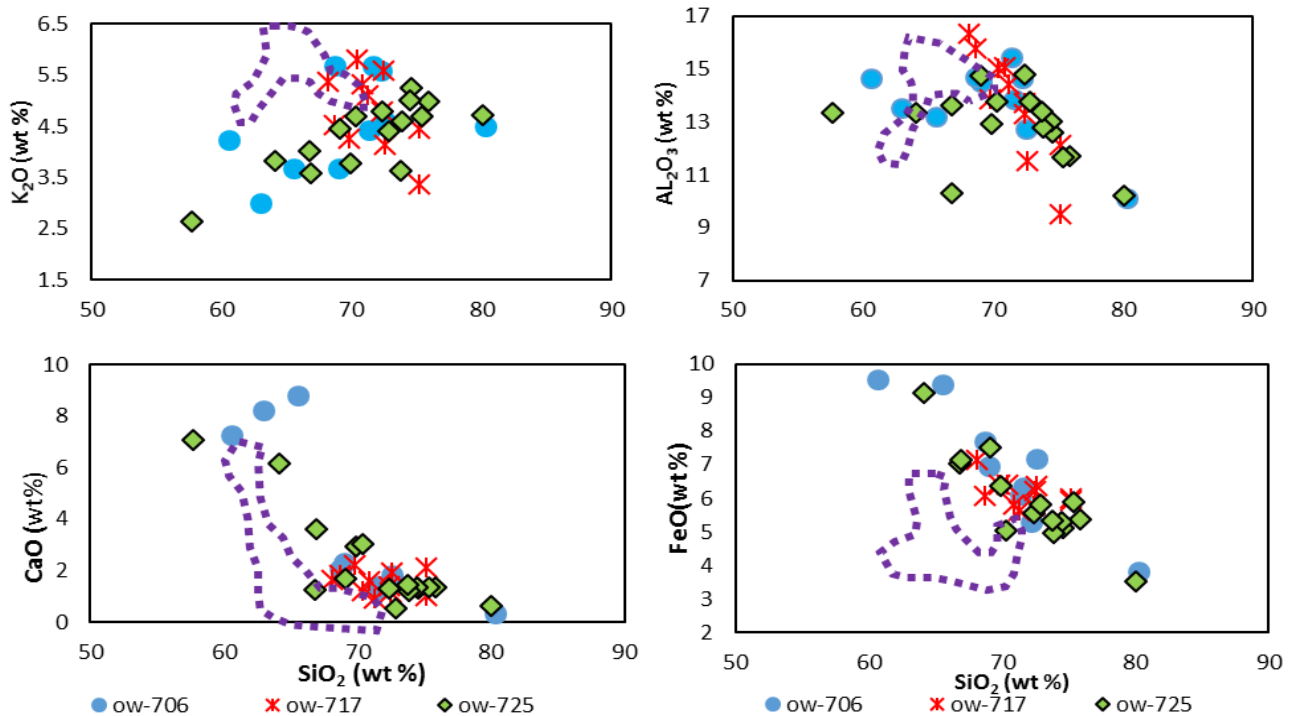


Figure 11: Selected major elements variability with respect to hydrothermal alteration as a function of SiO_2 for both protolith (surface samples are outlined by the broken line) and subsurface samples (shown by blue, green and red symbols for different wells)

Generally, K_2O and Al_2O_3 are major constituents of K-feldspars and widely affected during hydrothermal alteration. These elements undergo dissolution more easily eventually leaching them as the primary constituent elements of the rock. CaO and FeO show marginal enrichment possibly attributed to interacting thermal fluids rich in carbon dioxide and hydrated fluids.

Similarly, for the purpose of this study, some selected trace elements; Ba, Rb, Y, Nb and Zr were also were also analysed trough empirical comparisons. The elements were plotted on Harker diagrams with Zr as the independent variable because is least affected by hydrothermal alteration (Figure 12)

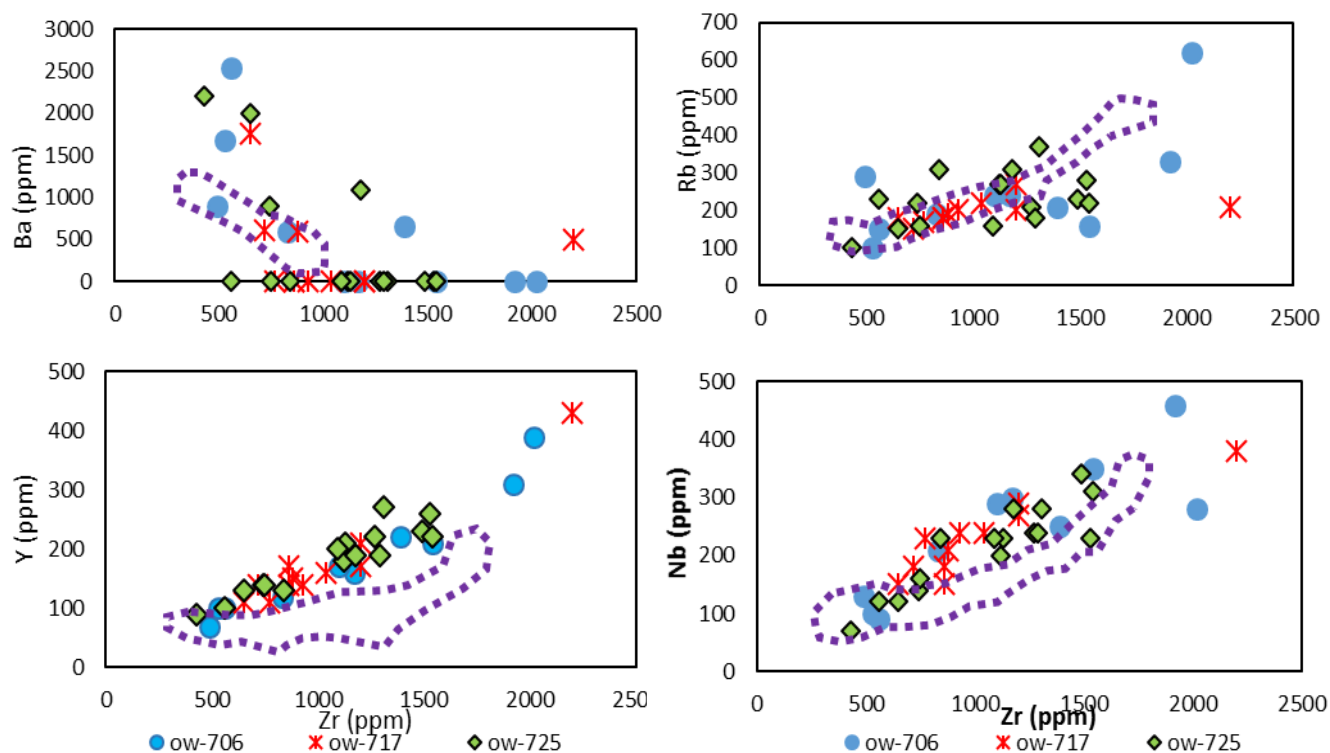


Figure 12: Selected trace elements concentrations as a function of Zr for both protolith (surface samples outlined by purple broken line) and sub-surface samples (shown by blue, green and red symbols for different wells)

The elements show marginal changes suggesting that they are slightly affected by hydrothermal alteration. The plots for Nb, Y and Rb against Zr show positive correlation signifying possible enrichment. However, the plot for Ba vs Zr show scattering effect due to its characteristic mobility nature in crustal rocks.

5.0 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussions and conclusions

The reservoir rocks studied for three wells; OW-706, OW-717 and OW-725 display variability of mechanical behavior, including physical and chemical changes during hydrothermal alteration. This is attributable to water-rock interaction processes often with fluids rich in some chemicals constituents, and as result, affecting the rock fabric, texture and pore shape as well as pore evolution. Porosity development has close relation to permeability and their variability within the reservoir rock have to a greater extend influenced by hydrothermal metamorphism. From both optical and gravimetric techniques employed to estimate porosity distribution, the results present good correlation and provide powerful insights into the evolution history and principal mechanism for fluid type and flux within the reservoir.

Macro porosity analysis indicate spectacular facies morphology of the rock specimens, where three broad alteration mechanism controlling porosity distribution are recognised. These are alteration by dissolution, deposition and replacement as the major processes controlling secondary porosity generation and etch-pitting of the mineral fabric. The integrated results for different facies zones predicate variability of reservoir geometry with differential hydrothermal metamorphism. This is clearly discerned in well OW-706, where three major lithological aquifer facies are recognised at variable depths; 790-1670m, 1820 -1900m and 1970-2086m bgl. On the other hand, wells OW-717 and OW-725 display selective precipitation of minerals which produce concentrated deposits of elements normally dispersed from crustal-rocks. The latter mechanisms of hydrothermal alteration restrict pervasive fluid flux wield negative consequence on permeability advancement within the reservoir. The overall effects being constricted fluid flow as evidenced by minor aquifer zones discerned at 1160-1250m bgl in well OW-717, and at 700-1050m and 1800-1900m bgl in well OW-725.

Remarkable porosity results via gravimetric method present relatively higher values compared to optical method. This is largely attributed to micro-porosity of the intestinal-crystal matrix. Generally, the judicious combination of the petrophysical parameters provide considerable information on the reservoir pore-geometry and also have a direct relationship on the pore-network evolution. This is quite conformable with the major structural lineaments, where the vertical permeability is notably high along NW-SE trending fault than ENE-WSW (Olkaria fault). Albeit small margin, the measured permeability agrees quite well with the results of petrophysical properties.

The results indicate that K_2O and Al_2O_3 from hydrothermally altered samples show significant depletion trends from protolith samples (relatively less altered samples from Macdonald et al., 2008; Marshall et al., 2009) suggesting possible hot hydrothermal fluids interacting with the host reservoir. Notably, K_2O and Al_2O_3 are major constituents of alkali feldspars and appear to undergo depletion resulting from dissolution effects during hydrothermal alteration. CaO and FeO show enrichment of mineral constituents apparently attributed to the precipitation of secondary minerals from the hydrothermal fluids. The quantification of the hydrothermal effects on reservoir rock is based on direct approaches which yield substantive inferences similarly adopted by other authors (Musonye, 2015; Victor Omondi Otieno, 2016; Pandarinath et al., 2008; Verma et al., 2005).

For selected trace elements, plots for Nb, Y and Rb against Zr show positive correlation suggesting possible enrichment during hydrothermal alteration. Ba vs Zr plots indicate scattering effects. This is chiefly due to characteristic mobility nature of the Ba solubility within the crustal rocks. In general, the hydrothermal alteration largely influences the bulk chemistry of a rock and to some extent on trace elements dispersion.

5.2 Recommendations

- ❑ Reservoir geometry propagation is controlled by fracture-fault permeability of NW-SE striking fault (adjacent to well OW-706). Therefore, future productive and Make-up wells should target this zone where the pore-network is well developed. Re-injection wells should be planned close to the periphery of the field on the eastern side adjacent to Gorge farm fault.
- ❑ The techniques employed in determination of petrophysical properties are not explicit and therefore further studies should consider other modern techniques such as computerized X-Ray tomography and mercury porosimeter among others
- ❑ Future drilling should aim at recovering core samples at reservoir depth for direct permeability measurements
- ❑ Similarly, on quantification of effects of hydrothermal metamorphism on bulk chemistry, other methods should also be considered as loss of ignition, mass balance calculations and statistical approaches (e.g. students T-tests)
- ❑ Further works should be expended to entire geothermal field especially at peripherals of highly explored zones in order to improve the confidence of well siting programs

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