Presented at Short Course X on Exploration for Geothermal Resources,
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Nov. 9-Dec. 1, 2015.

Geothermal Development Company
Powering the Vision

UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

KenGen
Kenya Electricity Generating Co., Ltd.

STRATIGRAPHY, HYDROTHERMAL ALTERATION, FORMATION TEMPERATURE AND PETROLOGY OF THE DOMES AREA, GREATER OLKARIA VOLCANIC COMPLEX

Xavier Shioya Musonye
Kenya Electricity Generating Company – KenGen
P.O. Box 785
KENYA
xmusonye@kengen.co.ke

ABSTRACT

Wells OW-905A, OW-910 and OW-917 have been drilled in the Domes area of the Olkaria geothermal field. Well OW-905A has been drilled to the west while OW-910 in the central part of the Domes field inside the caldera. OW-917 has been drilled on the eastern margins of the ring structure. Two wells, OW-905A and OW-910 reveal seven stratigraphic units; basalt, trachybasalt, basaltic trachyandesite, trachyandesite, trachyte, rhyolite and tuff. Well OW-917 cuts across two stratigraphic units; rhyolite and trachyte. Syenitic, basaltic and micro-syenitic intrusives are also encountered in the three wells. The meausred formation temperature is consistent with the abundance and depth distribution of alteration mineral assemblages. Well OW-910 has high abundance of high temperature alteration minerals, OW-905A has moderate abundance while OW-917 has low abundance of these minerals. Temparature of 225°C is recorded at shallower depth (1200 m.a.s.l) in well OW-910. This is consistent with the the location of the upflow zone and the heat source in Domes area. In OW-905A, 225°C temperature is recorded at 600 m.a.s.l. This well is located in a recharge zone. Well OW-917 has 225°C temperature recorded at 200 m.a.s.l. This well is located in a down-flow zone. High permeability is observed in wells OW-905A and OW-910 while well OW-917 shows poor permeability. The basalt-trachyte suite in the Greater Olkaria Volcanic Complex (GOVC) have been generated through fractional crystallisation and magma mixing. Rhyolites were mainly generated through fractionation of trachytes and partial melting of syenites. The GOVC plumbing system is composed of independent discrete magma chambers and conduits. In these chambers, magma underwent modification before being erupted. The GOVC has had different episodes of eruptions.

1. INTRODUCTION

The Greater Olkaria Volcanic Complex (GOVC) is located 125 km northwest of Nairobi city. This is within the south central Kenyan Rift Valley, to the southwest of Lake Naivasha (Figure 1). The Olkaria geothermal field is located within the GOVC. The GOVC is bound by other late Quaternary volcanic centers. These other volcanic centers have distinct calderas unlike the GOVC. To the north, the GOVC is bound by Eburru, Longonot to the east and Suswa to the south. Previous scientific studies have shown mixed results on whether there existed a caldera in the GOVC or not. Clarke et al. (1990) and Simiyu et al. (1998), using geological mapping and seismic studies respectively, have proposed a caldera to have existed within the GOVC. They based their findings on a ring of rhyolitic domes found on the eastern and southern margins of GOVC and the seismic anomaly recorded along this ring. The ignimbritic eruptions which are normally associated with a collapsed caldera are absent within the GOVC (Omenda, 1993). Resistivity studies have also failed to show anomaly along the proposed collapsed caldera rim (Onacha, 1993). The GOVC is located in an area associated with high volcanism during rift development (Clarke et al, 1990). The estimated crustal thickness in this region is 35 km (Simiyu et al, 1995; Simiyu and Keller, 1997). Clarke et al. (1990) observed that the GOVC is a multi-cantered volcanic field with 80 different volcanic centres. The centres are mainly rhyolitic and occur as steep sided domes of thick lava flows with restricted lateral extent or pyroclastic covers.

The axial region of the Kenyan Rift Valley is similarly characterised by late Quaternary volcanic centres, which occur from north to south. They include from north to south: Emurruangogalak, Silali, Paka, Korosi, Menengai, Longonot, Eburru and Suswa (Figure 1). Geothermal exploration surveys indicate that these centres are characterised by shallow intrusions. These intrusions have resulted into high thermal gradient at these centres. Olkaria, Eburru and Menengai volcanic centres are in their geothermal production stage. The rest of the volcanic centres are in various stages of exploration (Omenda, 1997).

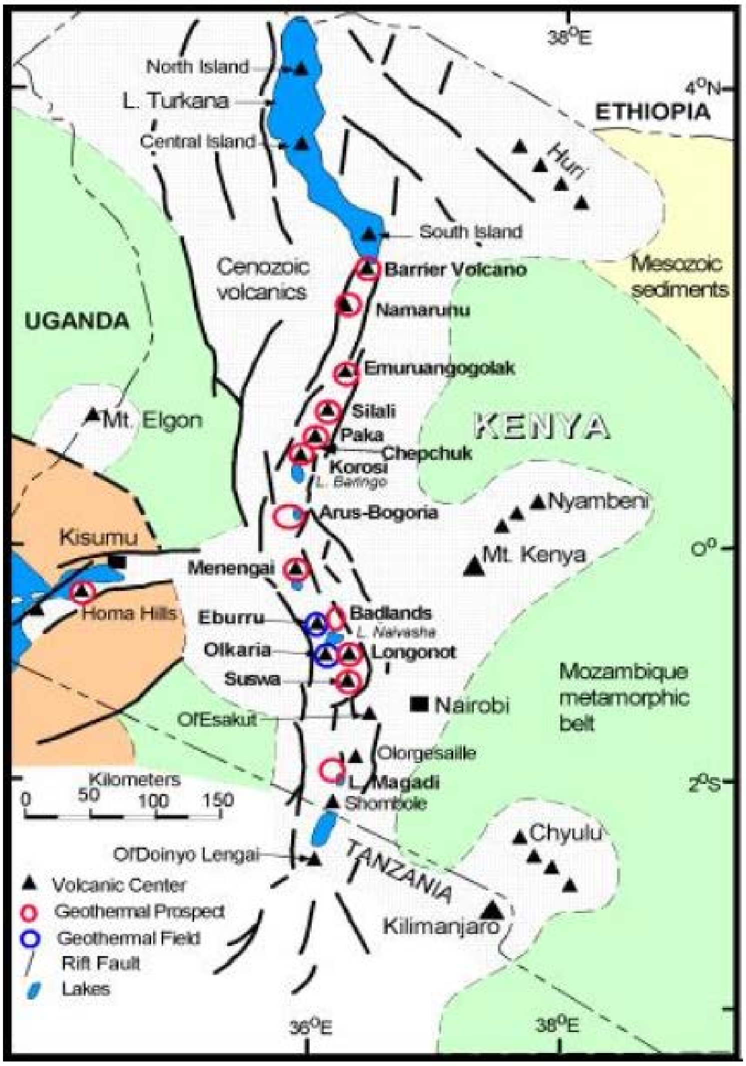

FIGURE 1: Location of Olkaria Volcanic Complex and other volcanic centres within the Kenyan

Olkaria geothermal field, a high temperature geothermal field, has an estimated resource area of 204 km^2. It is divided into seven fields for the purpose of management (Figure 2). These include the Olkaria East, Olkaria West, Olkaria Southeast, Olkaria Northeast, Olkaria West, Olkaria Central and the Domes fields. The Domes field is the focus of this study. Data from drilled wells in the Domes area reveal a variation in reservoir characteristic across the area. The reservoir enthalpy, formation temperature, fluid chemistry and alteration mineralogy vary across the field. Two step-out wells have been drilled to the east and eastern margins of the Domes are in order to assess the resource to the east of Domes field. These are wells OW-922 and OW-917 respectively (Figure 3). These wells will help in deciding whether to expand production drilling further east of Domes or confine in within the Domes area.

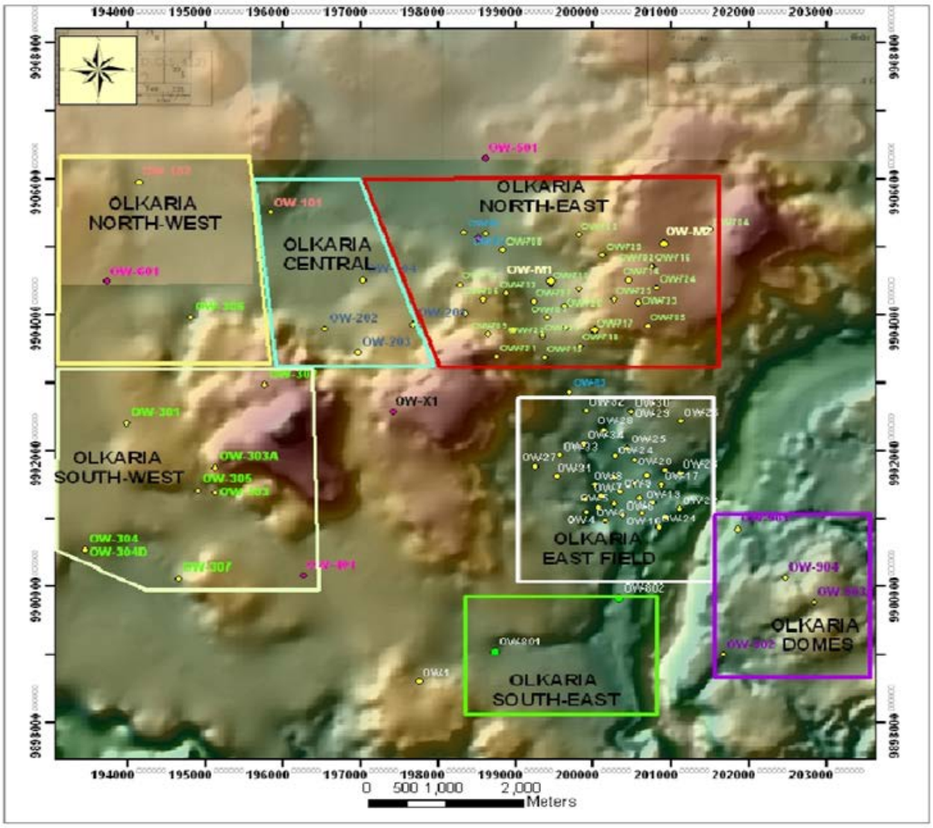

FIGURE 2*:* The seven sections (fields) of the Greater Olkaria geothermal area (from KenGen, 2012)

The aim of the borehole geology analysis is to delineate the variability in reservoir characteristic between the area east of Domes (outside the ring structure) and inside the Domes area (inside the ring structure) and to delineate buried faults through correlating stratigraphic units, along a NW-SE traverse (Figure 3). From the drill cutting analysis, the fluid-rock interaction at depth can be deduced. From these deductions, the reservoir characteristics along the traverse can be analysed, hence the decision to either expand to the east of Domes or not. For the petrochemical study, the aim is to find out the main magma differentiation process involved in generating sub-surface magmas within the GOVC; to find out if the sub-surface rocks show bi-modal or linear distribution on TAS diagram and to correlate the chemical composition of the surface and sub-surface rocks. Previous petrochemical studies carried out in this area were only on surface rocks (Macdonald et al., 1987; Heumann and Davies, 2002; Macdonald et al 2008 and Marshall et al., 2009).

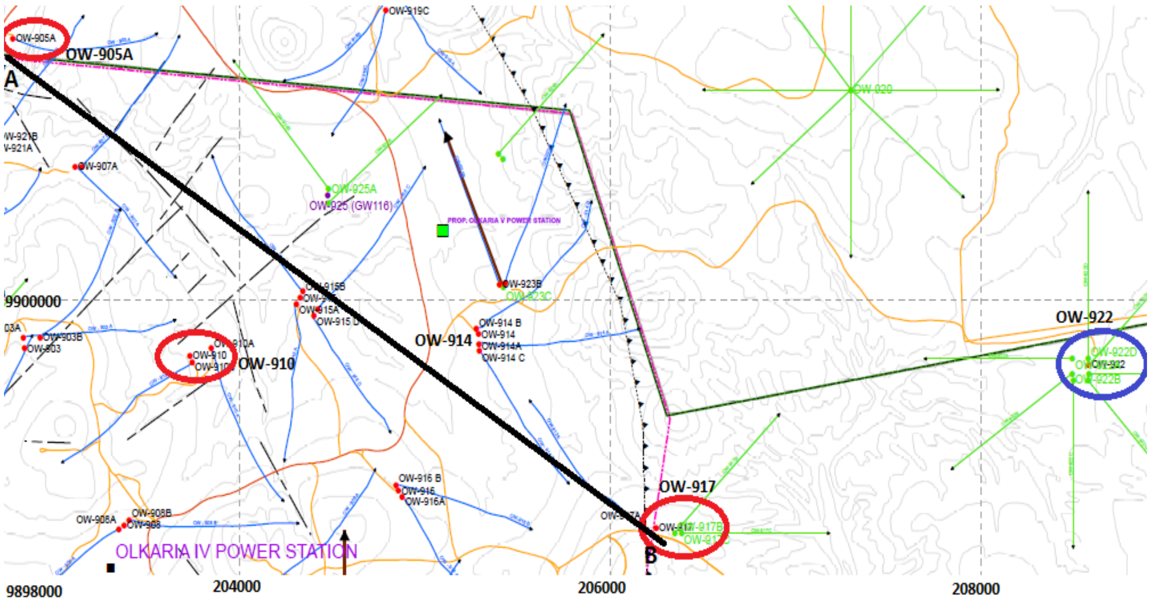

FIGURE 3: Map showing the location of study wells (circled in red) and one of the step-out wells OW-922 (circled blue) within the Domes area

1.2 Geothermal development

Geothermal exploration in Olkaria geothermal field began in 1960's. A summary of the Olkaria geothermal field development is presented in Table 1 below.

TABLE 1: Greater Olkaria Geothermal field development (Koech, 2014)

Year	Activity
1950s	Scientific investigations in Olkaria, Eburru and Lake Bogoria all within Great Rift Valley (Noble and Ojiambo, 1975)
1958	Two exploration wells X-1 and X-2 drilled in Olkaria. Encountered high temperature but unproductive (Noble and Ojiambo, 1975)
1970s	Extensive exploration project carried out with financial support of UNDP (Noble and Ojiambo, 1975)
1976	6 additional wells drilled and feasibility of field development confirmed
1981, 1982 and 1985	1st, 2nd and 3rd 15 MWe generating units commissioned in Olkaria East (Olkaria I). A plant with total 45 MWe capacity operated by KenGen (Bodvarsson et al., 1987)
1990s	Detailed Exploration and Later drilling of 3 exploration wells in Olkaria Domes (located in the southeast part of the Olkaria field)
2000	12 MWe unit commissioned in Olkaria west part of the field (Olkaria III) operated by Independent Power Producer (IPP) OrPower4 Inc.
2003, 2010	Olkaria II plant, located in Olkaria Northeast field, was commissioned with 2 units each 35 MWe, and later 3rd unit with 35 MWe, making a total of 105 MWe operated by KenGen
2009, 2011	Olkaria III production was increased first by 36 MWe and later by 62 MWe making the current total by OrPower4 Inc. to be about 110 MWe
2011-2014	• Well heads units introduced; 3 units with a combined capacity of more than 40 MWe (operated by KenGen) • Beginning of production in Olkaria Domes (units I and II) with combined capacity 140 MWe being commissioned (operated by KenGen) • Production in Olkaria East expanded with Olkaria I units IV and V, combined capacity 140 MWe, in commissioning stages (operated by KenGen)

2. GEOLOGY OF GOVC

2.1 Surface geology and evolution stages of GOVC

The GOVC is located in the south central Kenyan Rift Valley, where the orientation of the rift changes from N-S orientation in the north to a NNW-SSE in the south. Approximately 80, structurally controlled volcanic centers are formed within the GOVC. GOVC is estimated to have formed at 20 ka BP. It is a multi-centered complex dominated by peralkaline rhyolitic domes and comenditic lavas on the surface (Clarke et al., 1990). The surface geology is comprised of ash deposits, pumice lapilli, pyroclastics and comenditic lavas (Clarke et al., 1990). The pyroclastics cover most part of the Olkaria geothermal field. They are thicker in the Domes area. Clarke et al. (1990) stated that the pyroclastics in Olkaria are a mixture of pyroclastics from Olkaria, Longonot and Suswa volcanic complexes. The contribution of each of these volcanic centers to the Olkaria pyroclastics has not been quantified. The comendites are mostly exposed in Olkaria East field.

The evolution of GOVC has been divided into six stages (Clarke et al., 1990). The initiation of its evolution has been set at 22-20 ka BP. The first stage was characterised by the formation of Olkaria Trachyte Formation and the Maiella Pumice Formation (Mp) (Figure 4). The Trachyte Formation is exposed in gullies to the southwest of the complex while the Maiella pumice is found to the west. The Pumice Formation is believed to have erupted from vents within the complex. Stage 2 involved caldera collapse. This left a depression of 11 km by 7.5 km. Eruption of welded pyroclastic rocks of Ol Njorowa pantellerite Formation (O^1) accompanied caldera collapse. Post-caldera magmatism, which characterised stage 3, deposited the Lower Comendite Member of Olkaria Formation. Olkaria Formation, dated at >9150±110 BP, comprises of rhyolitic lavas (O^2) and pyroclastics (Op^2) (Figure 4). Deposition of a ring of rhyolitic domes (O^3) and eruption of thick surge deposits (Op^3) characterised stage 4. This was associated with deposition of the Middle Comendite Member which has been dated between 9150±110 and 3280±120 BP (Clarke et al., 1990).

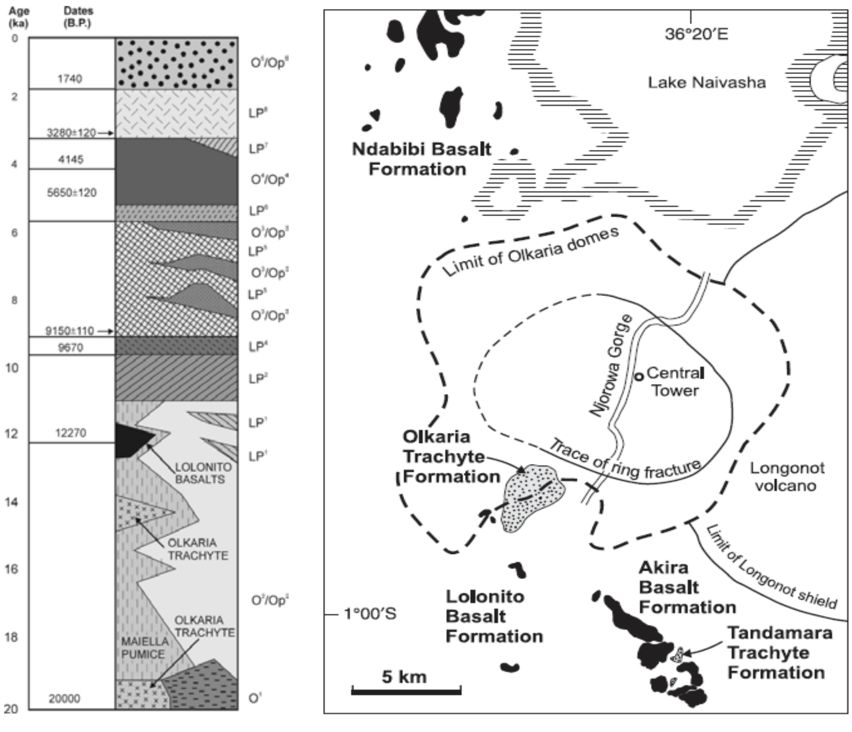

FIGURE 4*:* Stratigraphic column (from Marshall et al., 2009) for the GOVC and its surface formations (from Clarke et al., 1990) (together with the surrounding areas)

Stage 5 involved the resurgence of the caldera floor, accompanied by the formation of short and thick comenditic lava flows that constitute the Upper Comendite Member (O^4). Stage 6 involved the eruptions of thick flows of comendite lavas from a north-south fissure system (O^5). The youngest of the comendite flows (Ololbutot lava) has been ^{14}C dated 180±50 BP.

Akira Basalt Formation (Ba) occur to the south of the GOVC. It comprises of lavas, scoria and spatter cones. Lolonito Basalt Formation (Ba^1), which occurs to the SE, has been dated <0.45 Ma (Clarke et al., 1990). This is believed to represent the early phase of Akira Basalt Formation. The Tandamara Trachyte Formation (Tt) has the same general age as the Akira Basalt Formation (Clarke et al., 1990). Ndabibi Basalt Formation (Bn) occur to the north of the GOVC. The youngest units are largely contemporary with the post-caldera rhyolites dated <20 ka BP.

2.2 Sub-surface geology of the GOVC

The sub-surface geology of the GOVC has been divided into six units. This has been based on data from drilled geothermal wells. The first unit is the Upper Olkaria Volcanics (Omenda, 1997) (Figure 5). They occur from the surface to 500 m and comprises of comenditic lavas and their pyroclastic equivalent. Minor trachyte and basalt are also intercalated. Olkaria Basalt forms the second unit. The main rock is basalt. It occurs between 500 m to 1000 m depth. Trachyte, rhyolite and minor pyroclastics are also intercalated in this unit. It forms the Olkaria geothermal system cap rock (Ambusso and Ouma, 1991).

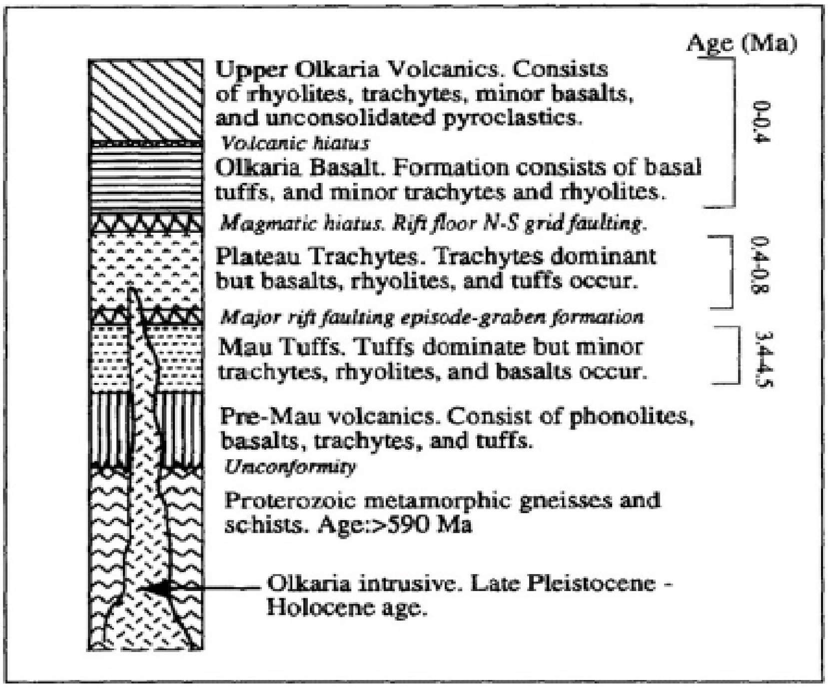

FIGURE 5*:* Rock units and stratigraphic correlation of drilled wells in Olkaria geothermal area (from Lagat, 2004)

The third unit is the Plateau Trachytes (Figure 5). The units mainly composed of trachyte and occur between 1000 m to 2600 m depth. It forms the reservoir rock for Olkaria East field. The fourth unit is the Mau Tuffs. They form the reservoir rocks of the Olkaria West field (Omenda, 1998). They are the oldest exposed rocks in the Olkaria area. The tuffs are mainly consolidated and have ignimbritic texture.

The other two stratigraphic units are neither exposed in Olkaria area nor encountered in geothermal drill holes within Olkaria. However, they are exposed on the southern flanks of the rift. The Pre-Mau Volcanics, which form the fifth unit, are composed of trachytes, basalts and ignimbrites. The Proterozoic Formation is the sixth unit. It forms the basement rock. It comprises amphibolite grade gneisses and schist with associated marble and quartzite of the Mozambican Group (Shackleton, 1986).

2.3 Petrochemistry of the surface rocks of GOVC

Macdonald et al. (2008) carried out geochemical analysis on surface rocks from GOVC and its surroundings. In their study, they collected samples from the Olkaria and Tandamara Trachyte Formations, the Lolonito, Akira and Ndabibi Basalt Formations, the Olkaria Comendite Formation and magmatic inclusions in the post-caldera comendites.

From this analysis, they divided the rocks into three groups (Figure 6). In the TAS classification scheme (Figure 6), Group 1 rock type range from basalt-hawaiite-mugearite-benmoreite-trachyte to rhyolite (Macdonald et al. 2008). Group 2 has a bulk composition ranging from hawaiite-benmoreite. Group 3 rocks mainly comprised of the magmatic inclusions and are silica-undersaturated. The basalt-benmoreite range showed constant trace element ratios (for example Zr/Nb, Zr/Y, Ce/Y, Ce/Zr, Rb/Zr and Th/U) while the trachytes showed variation. Macdonald et al. (2008), stated that the main magma differentiation process was fractionation. Minor magma modification processes like anatexis, magma mixing modified the fractionated magma. Magma modification mainly affected the intermediate and silicic magmas.

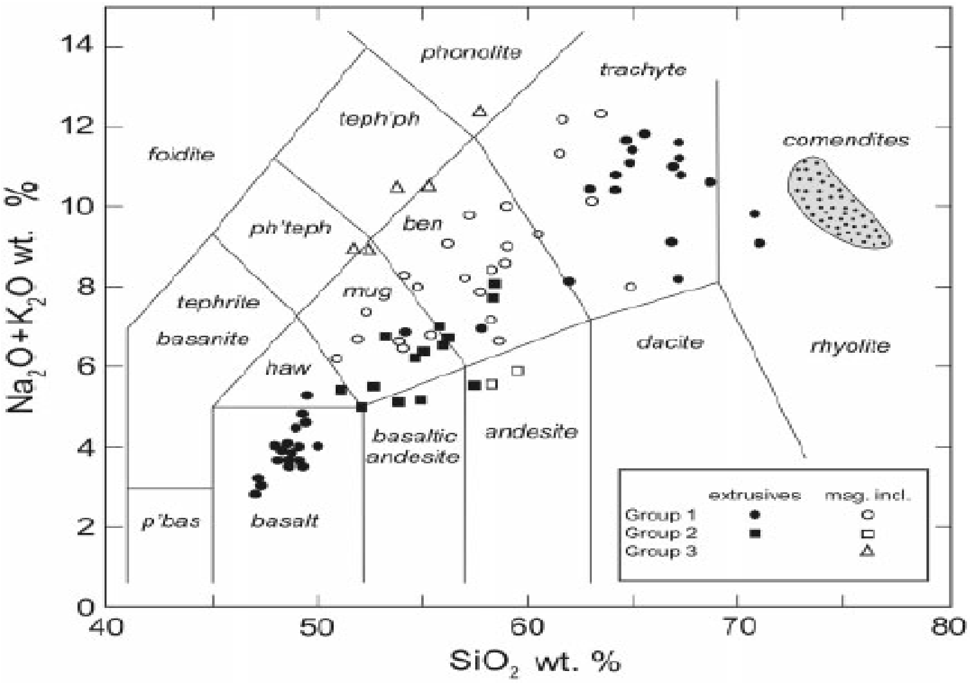

FIGURE 6: TAS classification scheme for GOVC surface rocks. Extrusives include high-level dykes and plugs, bombs and blocks in pyroclastic deposits (from Macdonald et al., 2008)

3. SAMPLING AND ANALYTICAL METHODS

Three wells were chosen for this study, OW-905A, OW-910 and OW-917. Sampling was done at the rig during drilling, with samples collected at 2 m interval from the surface to 3000 m depth per well. The main analytical methods used are:

1. Binocular microscope analysis;
2. Petrographic microscope analysis;
3. X-ray diffractometer analysis; and
4. Inductively coupled plasma-optical emission spectrometry (ICP-OES) analysis.

A detailed explanation of the binocular, petrographic and X-ray analyses procedures can be found in Musonye 2012 while the ICP-OES can be found in Mbia, (2014); Kwiecien (1990); Fang and Niu (2003).

4. RESULTS

4.1 Rockt types and stratigraphy

Seven rock types were identified in thus study. Five of these rocks were identifiable under binocular and petrographic microscope while two were only identifiable through the ICE-OES analysis. Well OW-905 A and OW-910 has all seven rock units while OW-917 has only 5 units. The rock types identified include pyroclasts, rhyolite, tuff, basalt, trachyte, basaltic trachy-andesite, trachy-andesite and trachy-basalt. The rock types observed include pyroclastics, rhyolite, tuff, basalt, trachyte, basaltic trachy-andesite, trachy-andesite and trachy-basalt (Figure 7). The pyroclastics and rhyolite mainly occur from 0-500 m. These units form the Upper Olkaria Volcanics. The rhyolite occurs in two different textures; spheluritic and granular. Minor trachyte and tuff intercalate this formation. Basalts occur between 500-1000 m. They mostly occur as thin lenses. They form the Olkaria basalt. Trachyte,

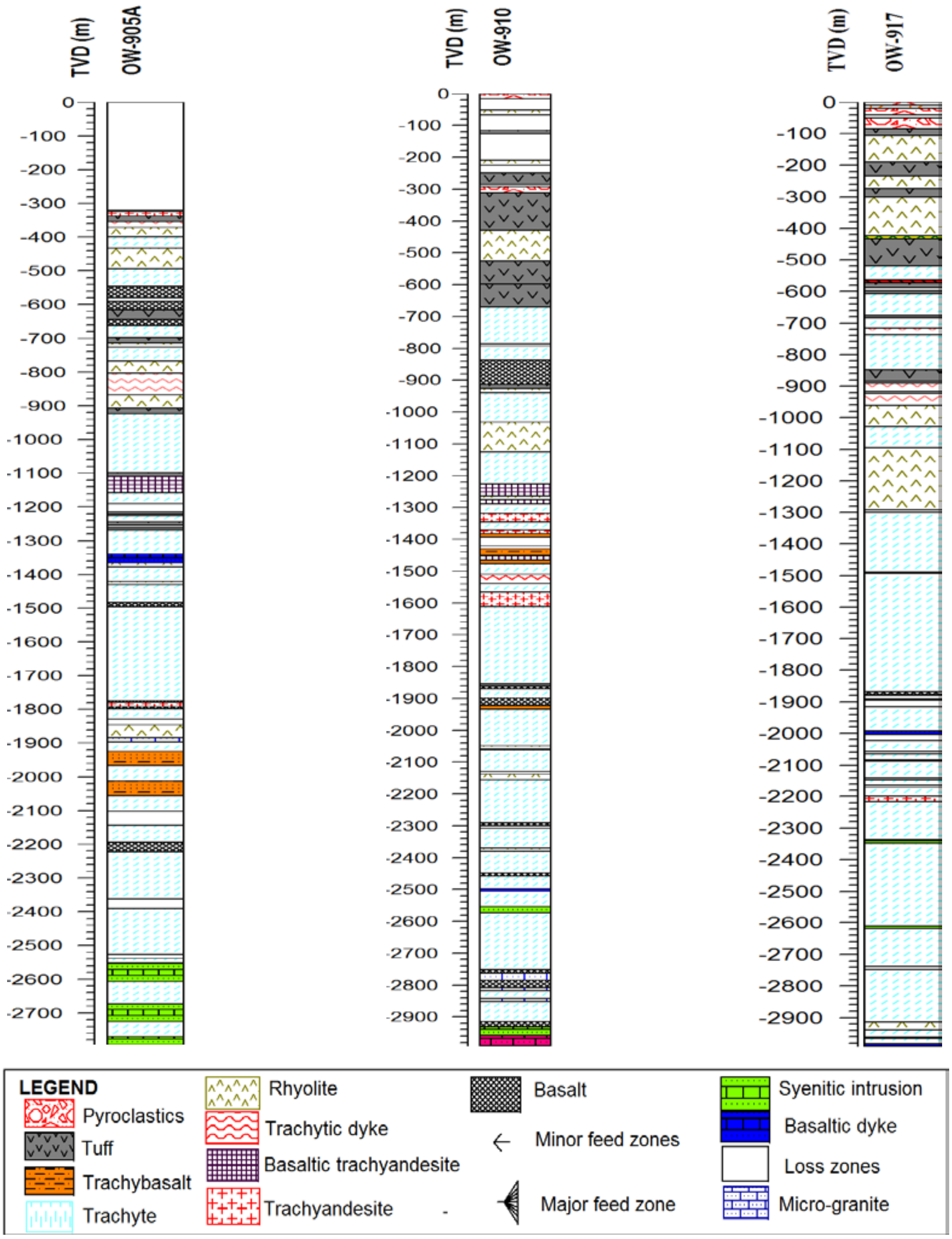

FIGURE 7: The rock units observed in the three wells under the four analytical techniques

rhyolite and tuff are also found within this depth range. The intermediate magmas, that is, trachybasalt, basaltic-trachyandesite and trachyandesite are found as thin units between 900 m to 1600 m depth. Trachyte is the dominant rock type from 100 m to 3000 m. It is intercalated by rhyolite, basalt, tuff and intermediate rocks. This forms the plateau trachytes. Micro-granite intrusives, syenitic intrusives and basaltic dykes were also noted. Basaltic dykes occur as from 1300 m while the syenitic, micro-granitic and micro-syenitic intrusives occur below 2000 m. They occur as thin lenses embedded concordantly between rock strata.

4.2 Hydrothermal alteration

Hydrothermal alteration is the change in chemical or physical composition of a rock or minerals contained in a rock as a result of interaction with fluids called hydrothermal fluids (Browne, 1978). The original minerals contained a rock before hydrothermal alteration are called primary minerals while the new minerals formed are called secondary minerals. Factors affecting hydrothermal alteration include; temperature, permeability, pressure, fluid composition, duration of hydrothermal activity and the mineral composition of the primary rock (Browne, 1978). From studies conducted in various geothermal fields, it has been possible to correlate alteration temperatures with alteration minerals (Kristmannsdóttir, 1979). This has been achieved in systems which have remained in a steady state of thermal equilibrium over a period of time. From these studies, it has been concluded that alteration minerals are deposited at specific temperature conditions. Figure 8 shows various depositional temperature for different alteration minerals. A summary of the alteration minerals found in the three wells is shown in Figures 8, 9 and 10.

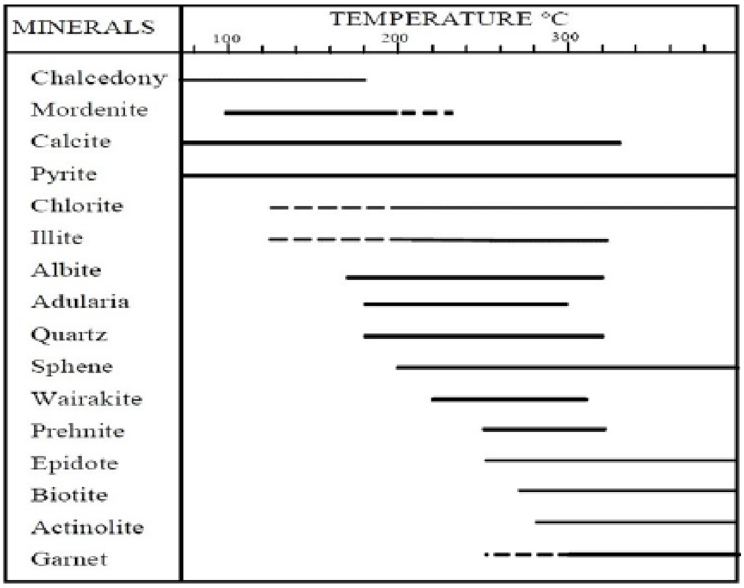

FIGURE 8: Various depositional temperature for different alteration minerals (From Lagat, 2004)

4.3 Alteration mineral zonation and temperature distribution across the Domes field

Alteration minerals form at specific temperature conditions that characterised the reservoir during their formation. Using alteration minerals observed in wells, isograds can be drawn to show temperature variation across the field at the time of alteration. The minerals whose alteration temperature is used are called index minerals. In this study, quartz, epidote, actinolite and garnet were used as index minerals. Well OW-914, which had been analysed earlier was also incorporated in the comparison. Plot of alteration mineral temperature and the formation temperature can give information about the thermal history of a geothermal field. This comparison might not give us 100% paleo-thermal information since some of the wells were not given enough time to heat up before this temperature measurements being taken, for example OW-914. However, the comparison gives a picture of thermal evolution over time.

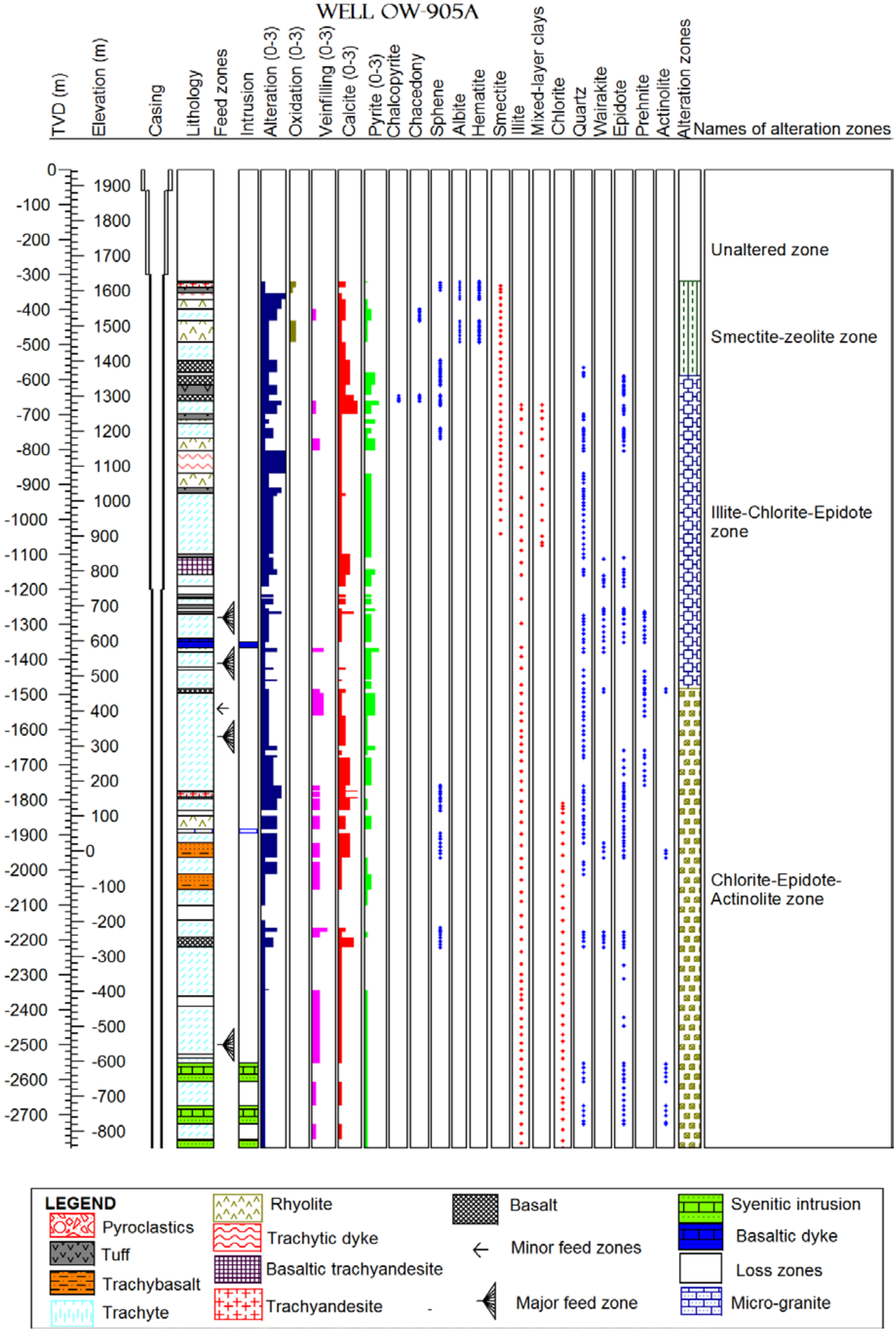

FIGURE 9*:* Lithology, alteration minerals and alteration zones of OW-905A

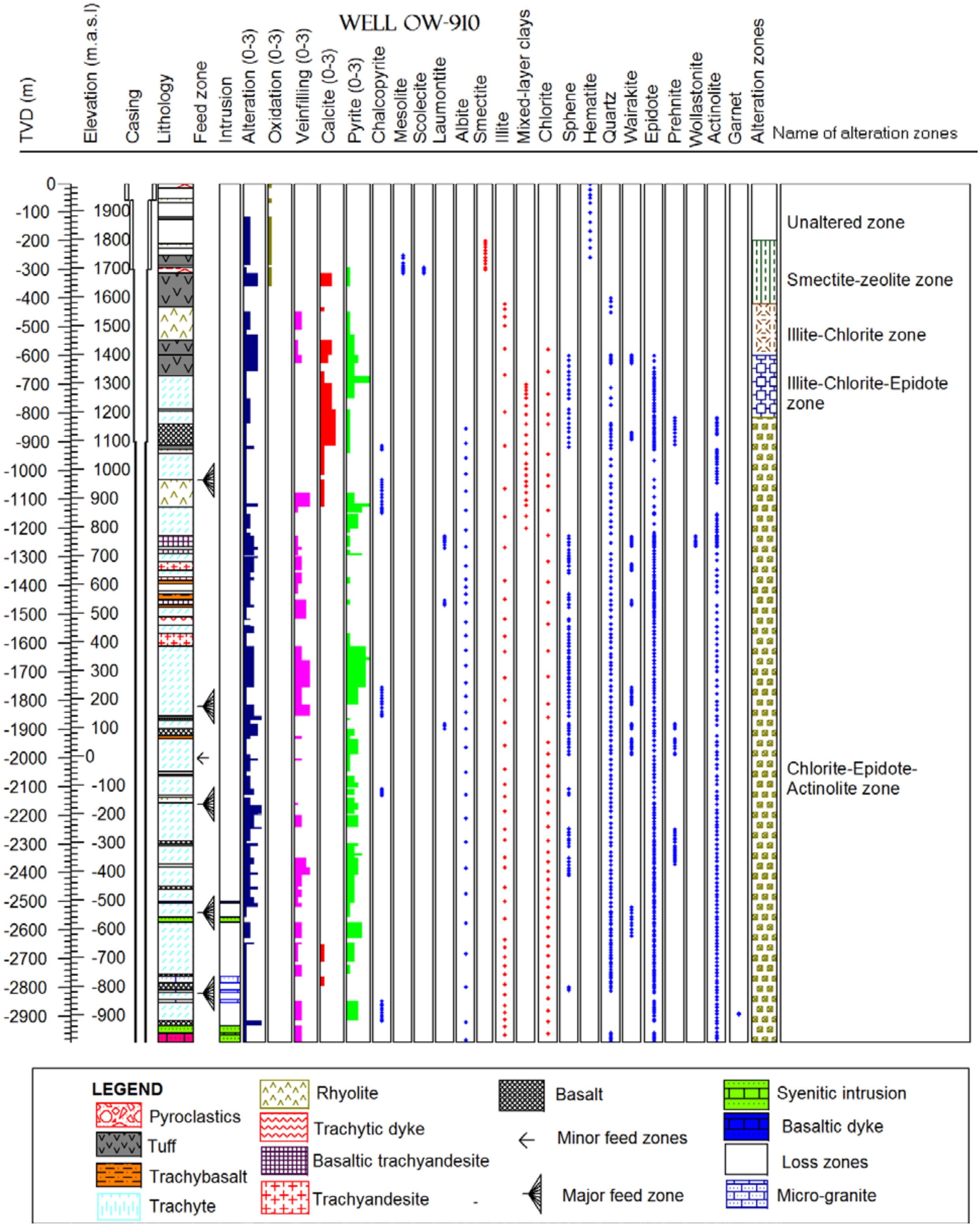

FIGURE 10*:* Lithology, alteration minerals and alteration zones of OW-910

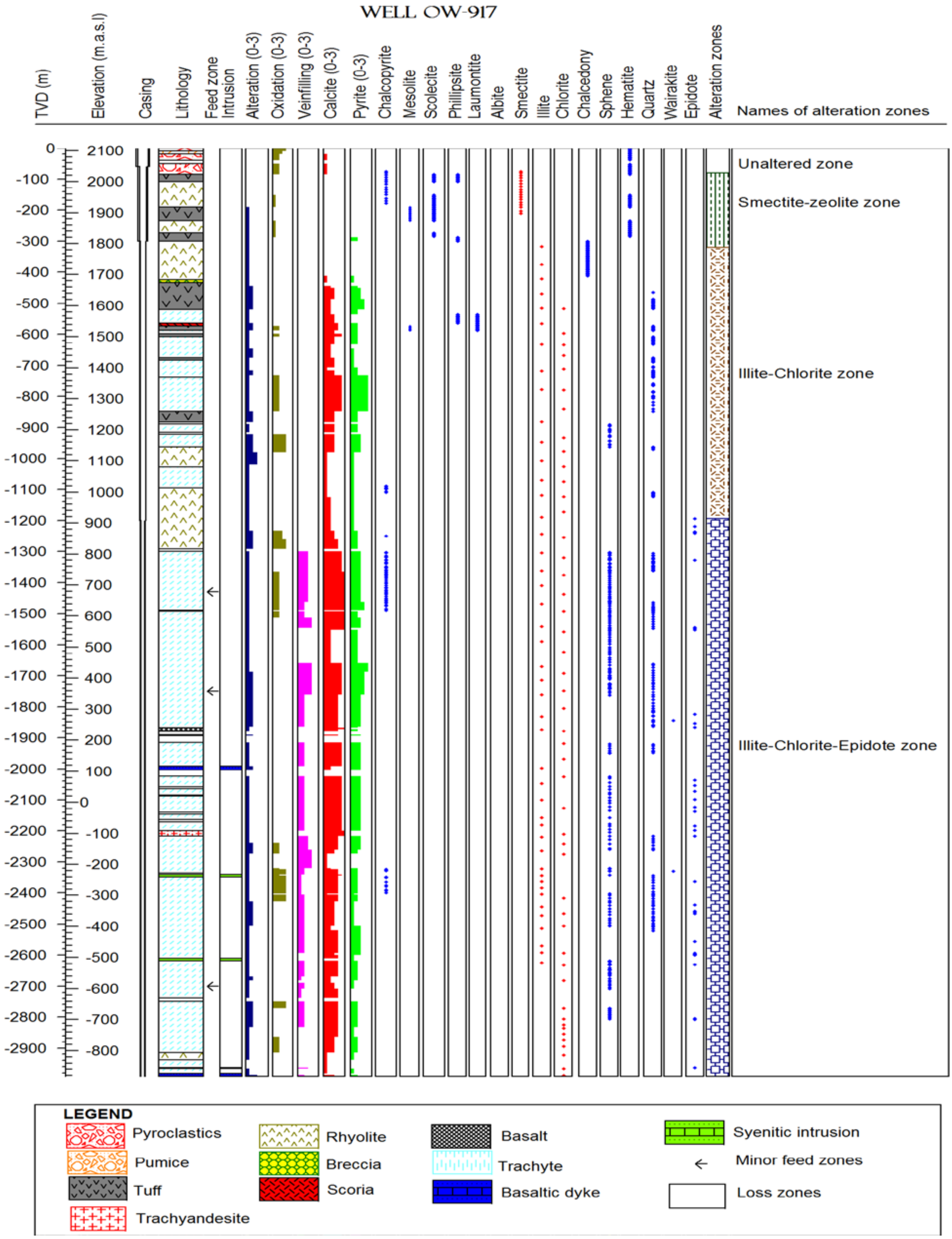

FIGURE 11: Lithology, alteration minerals and alteration zones of OW-917

From Figure 12, wells OW-905A and OW-917 exhibit temperatures below 150°C in larger part of their upper sections (the upper 615 m and 700 m respectively). The other two wells, OW-910 and OW-914, which are drilled in the central part of the Domes field, have only the upper 470 m and 500 m with temperatures below 150°C. Well OW-905A generally has lower formation temperatures with most of it ranging between 225°C to 250°C. The highest temperature was recorded at the deepest part of the well, that is, between 275°C to 300°C, below 2600 m. The highest temperature recorded is 250°C and is below 2000 m. Wells OW-910 and OW-914 have higher temperatures at shallow depth. Formation temperature of 250°C is recorded at about 800 m depth. From 800 m to the bottom of the wells, the temperature range is between 250°C and 350°C.

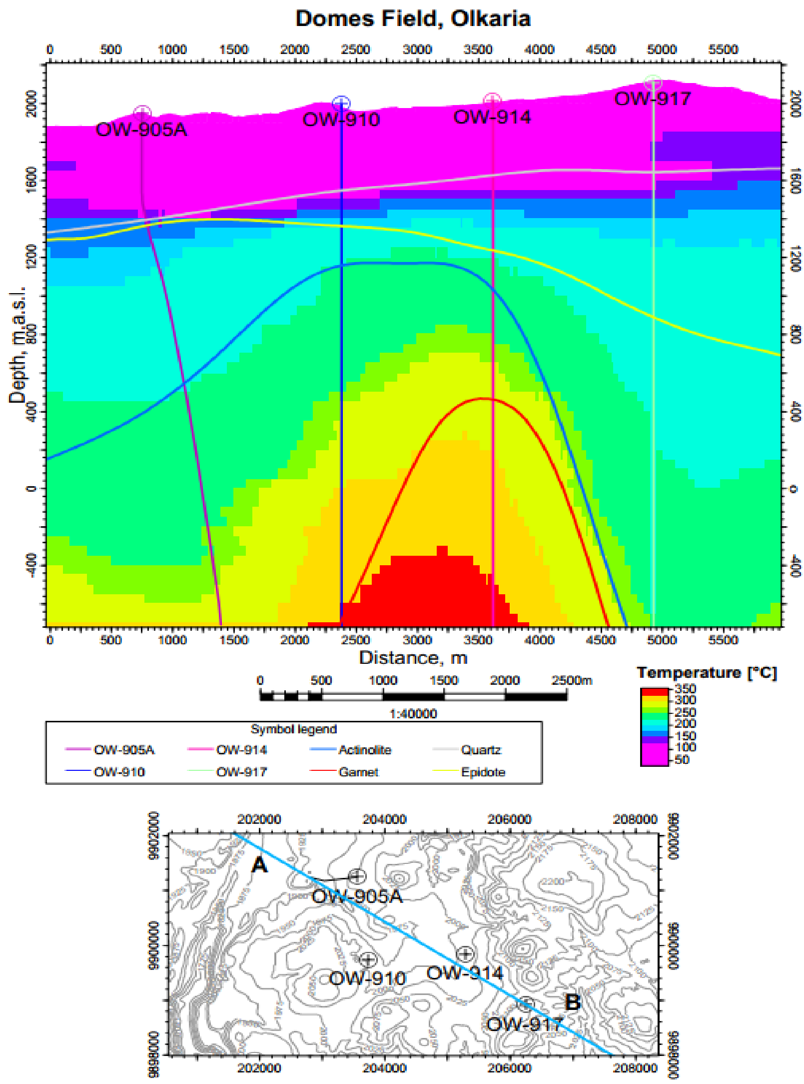

FIGURE 12**:** Formation temperatures and alteration mineral isograds cross section across AB

The comparison between the mineral isograds and formation temperature shows that some of the mineral isograds indicate higher temperatures at shallow depth contrary to the formation temperatures. Epidote plots at depth with lower formation temperatures that its alteration temperature. In well OW-905A, the epidote isograd plots at depth which has recorded a formation temperature of between 150°C to 180°C, while the depositional temperature for epidote is 240°C. For wells OW-917, OW-910 and OW-914, epidote isograd plots at depth with formation temperature range of between 220°C to 220°C. The actinolite isograd in well OW-905A plots at a depth with formation temperature of between 180°C to 220°C. In wells OW-910 and OW-914, the actinolite isograd plots at a depth with temperature range of between 220°C to 250°C. This isograd is absent in well OW-917. The depositional temperature for actinolite is estimated at 280°C. The garnet isograd, which represents depositional temperature of 300°C, plots at 275°C and 325°C formation temperature in OW-914 and OW-910 respectively. In well OW-914, it is found at 1794 while in OW-910 at 2884 m.

4.4 Petrochemical classification

One of the most common used method in geochemical classification of rocks is the Total Alkali (Na_2O+K_2O) versus Silica (TAS) classification scheme. This method was after Le Maitre et al. (2002). This method classifies rocks into either basaltic, intermediate or silicic magmas. It further classifies rock into alkali and sub-alkali.

From the TAS classification scheme (Figure 13), the Olkaria sub-surface rocks show a more or less linear distribution. The chemical composition generally ranges from basaltic through intermediate to silicic magmas. However, there is a noticeable gap between trachy-andesite and trachyte. This gap may be explained by different magma generating processes of different magma sources. Well OW-917 has its samples plotting in trachyte and rhyolite fields, except two of its samples that plot in trachyandesite and dacite. The sample that plotted in dacite was a highly altered trachyte, with all the sanidine having been replaced with clays. Trachyte is mainly composed of sanidine feldspars. Sanidine has Na as one of constituent elements. The alteration resulted into depletion of Na, which is a mobile element. Samples from well OW-905A and OW-910 plotted in basalt-rhyolite range. However, a bulk of these samples plotted in trachyte and rhyolite fields. This relates well with the geology of the GOVC as well its stratigraphy. GOVC is a silicic volcano while its stratigraphy is mainly composed of trachyte and rhyolite. Two samples from OW-905A and OW-910 plotted in phonotephrite field. One sample in OW-905A plotted in the tephrite basanite field. These samples were highly porphyritic with plagioclase phenocrysts.

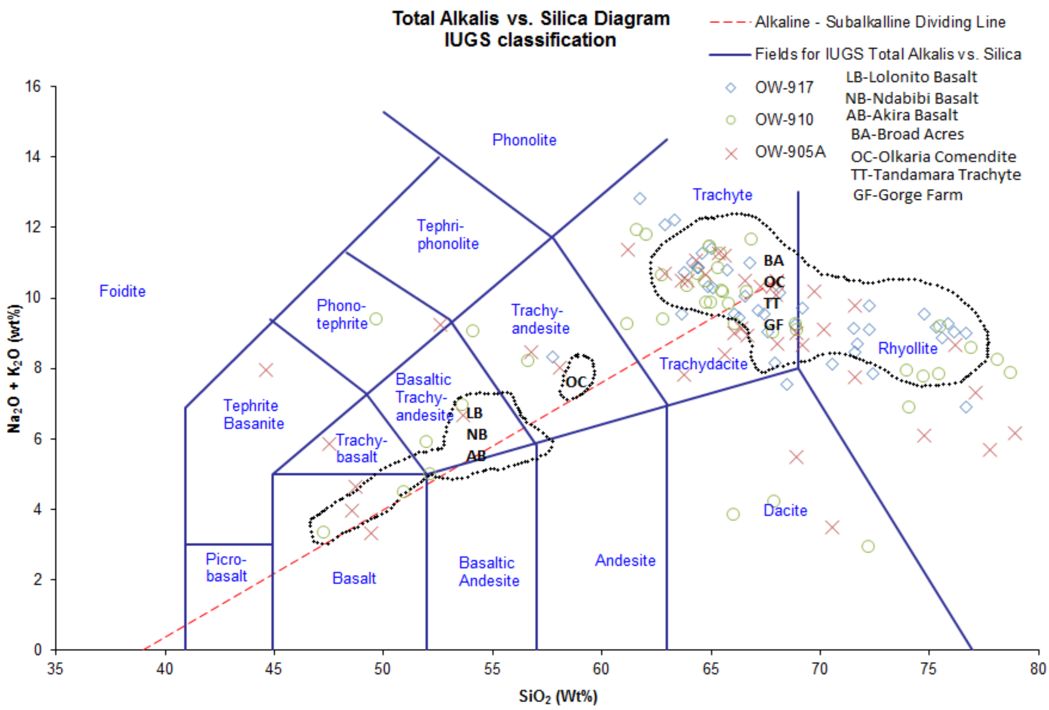

FIGURE 13: TAS classification scheme plot showing the compositional range for the Olkaria sub-surface rocks with the superimposed surface samples data (fields delineated with dotted lines)

The analysed surface rocks (data from Macdonald et al., 2008 and Marshall et al., 2009) exhibit similar compositional range as the sub-surface rocks. The Lolonito, Akira and Ndabibi basalts, which are found to the south and north of the proposed collapsed caldera, plot in the same field as the Olkaria sub-surface basalts. The Olkaria Comendites (OC), Tandamara Trachyte (TT), Gorge Farm (GF) rhyolites and Broad Acres (BA) rhyolites, which lie to the east but adjacent to the proposed collapsed caldera, plot with the sub-surface trachytes, rhyolites and trachyandesites. A few of the sub-surface samples plot in the dacite field most likely due to Na loss caused by hydrothermal alteration.

4.5 Geochemical evolution and magma differentiation process of the GOVC

Analysis of surface rocks from GOVC has been done by Macdonald et al. (2008) and Marshall et al. (2009). In their studies, they analysed silicic rocks from the complex and mafic rock samples from the periphery of the complex. In this study, we are looking at the sub-surface rocks. This will enable us to have a full picture of the range in composition of erupted rocks. The analysed samples were drill cuttings sampled from the surface down to a depth of 2900 m. This gives us an opportunity to identify the similarities between magmas buried beneath the collapsed caldera and the silicic surface rocks of the GOVC and the mafic emplacements on its periphery. 120 samples from three wells; OW-905A, OW-910 and OW-917, located in the Domes area of Olkaria geothermal area, were used in this study.

To establish magma differentiation processes and the evolution trends, all the major oxides were plotted against SiO_2 while the trace elements were plotted against Zr. SiO_2 was chosen as an index of differentiation because it shows a remarkably wide range of variation from 44% to 80.4%. It is also immobile, hence less affected by hydrothermal alteration. Zr has a wide range of values and is highly incompatible. It is therefore immobile and resistant to hydrothermal alteration (Franzson et al., 2008). Overall, with increasing SiO_2, there is a decrease in Al_2O_3, CaO, TiO_2, MnO, MgO, P_2O_5 and FeO contents (Figure 14). Na_2O and K_2O generally increase up to approximately 62% SiO_2 and then start to decrease. From Figure 15, a change in mineral phases that crystallises from the magma at 62% SiO_2 can be seen. The major elements versus SiO_2 trends are coherent with crystal fractionation process. Well OW-917 is mainly composed of highly evolved rocks. The SiO_2 content ranges between 62% and 81%. Wells OW-905A and OW-910 show a wide range of evolution with SiO_2 content ranging between 44% and 80%.

For the trace elements, Ba, Sr, Co, Ni, V and Cr generally decrease with increasing Zr (Figure 15). These elements are compatible and reduce in concentration as they are removed from the melt with increased crystal fractionation. La and Y shows a positive correlation with Zr. There is a kink on the Y versus Zr plot at 1700 ppm Zr (Figure 16). There are also two lines of descend on the La versus Zr plot (Figure 16). This may indicate other source components that were involved in the petrogenesis of these rocks. The positive correlation of the trend for the majority of the samples in the La versus Zr plot is consistent with the explanation that, fractional crystallisation is the main magma differentiation process generating these rocks.

5. DISCUSSION

The Olkaria Volcanic Complex is mainly dominated by Comenditic rhyolite and pyroclastics on the surface. These surface rocks are Pliocene to Holocene in age (Clarke et al., 1990). The ICPE-OES analysis of drill cuttings reveal that the Olkaria geothermal area stratigraphy is composed of basalts, trachy-basalt, basaltic trachyandesite, trachyandesite, trachyte, rhyolite and tuffs. Syenitic intrusions, trachytic dykes, basaltic dykes and micro-granite intrusives are also found. Wells OW-905A and OW-910 cut through all these types of rocks, while OW-917 only cuts through trachyte and rhyolite rock units. The variation of the rocks in the basalt-rhyolite range in wells OW-910 and OW-905A shows that the development of GOVC was characterised by episodic magmatic events. The occurrence of basaltic-intermediate magmas in wells OW-905A and OW-910, contrary to OW-917, indicates the probability of a buried major structural divide between OW-910 and OW-917. The proposed caldera (Clarke et al., 1990) might have inhibited the flow of mafic lavas outside the caldera. The absence of basaltic-intermediate rocks in well OW-917 may also be attributed to the smaller volumes of these magmas intruded beneath the complex. The smaller volumes could not flow all the way to the proposed caldera rim, where well OW-917 has been drilled. The appearance of pyroclastics and rhyolite within the upper 500 m and trachyte below 1000 m is linked to extensive differentiation that occurred beneath the GOVC (Omenda, 2000). Intrusives are formed as a result of fresh magma pulses from the magma chamber being injected into the overlying formations. The volumes of these pulses are too small; hence the magmas solidify between rock strata at depth. They cool fast due to the low temperatures from the surrounding formation. These intrusives may be associated with the magma chamber that has been indicated at 7-10 km depth (Omenda, 2000; Simiyu and Keller, 1997).

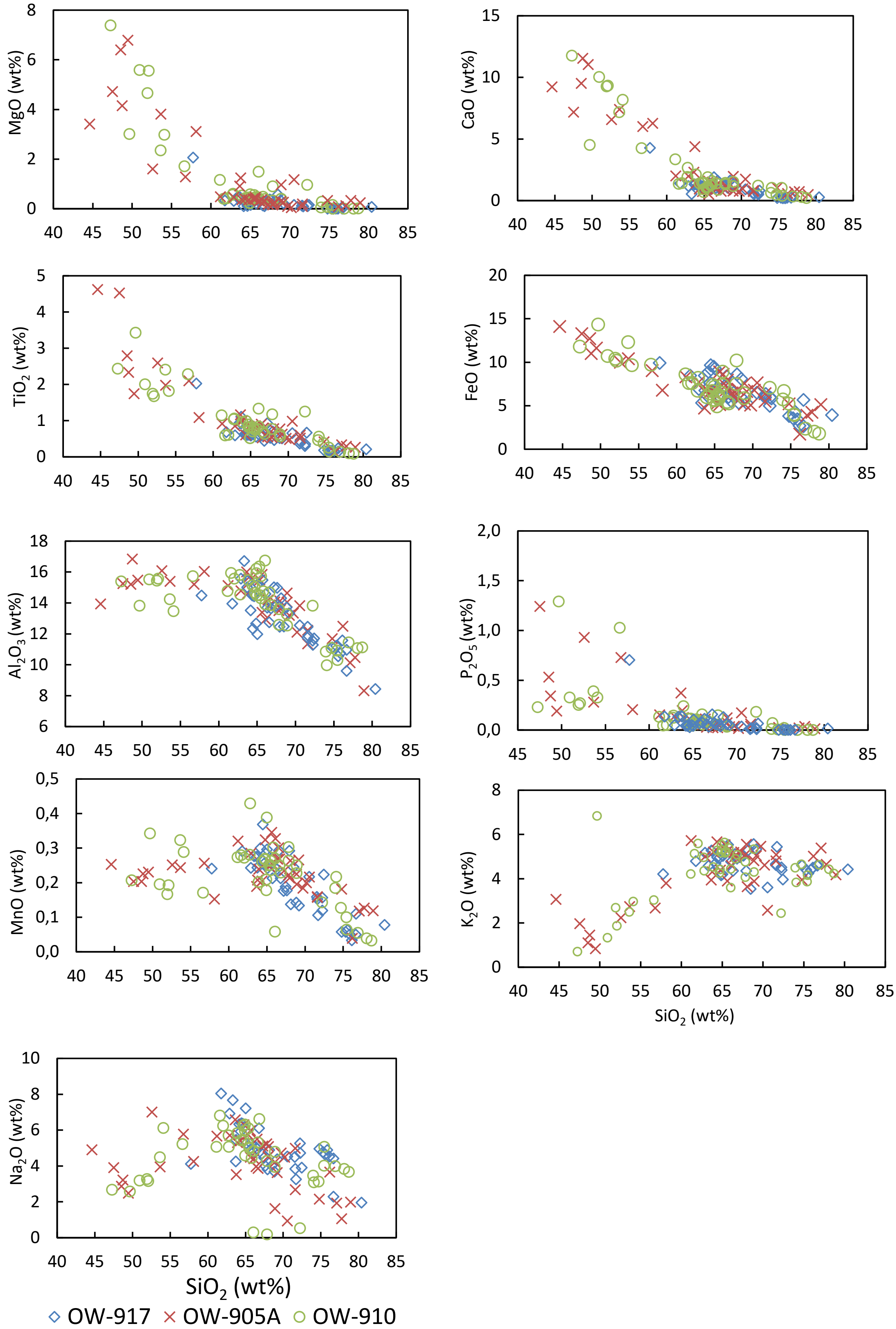

FIGURE 14: Whole-rock major element abundances as a function of SiO_2

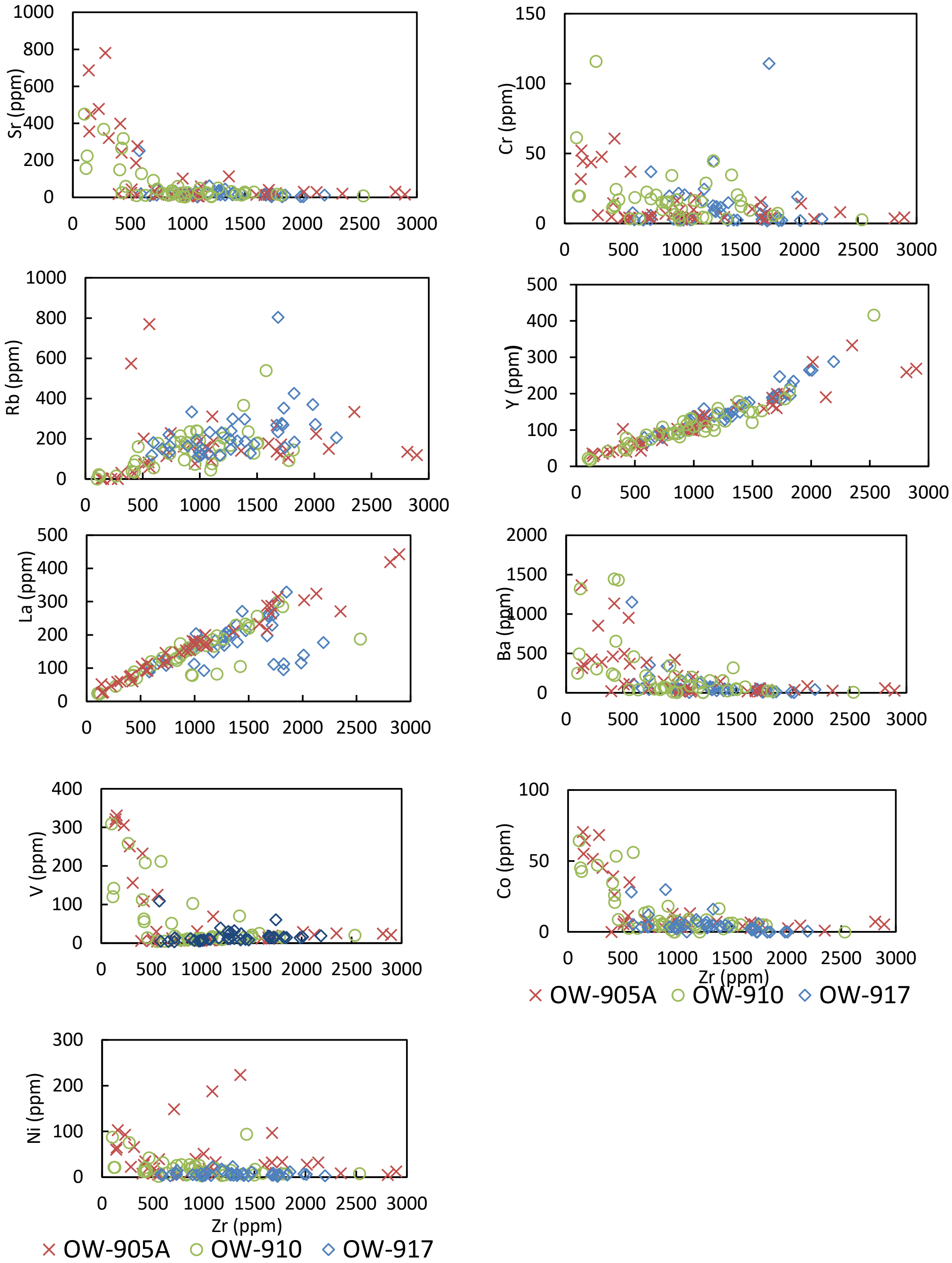

FIGURE 15: Whole-rock trace element abundances as a function of Zr

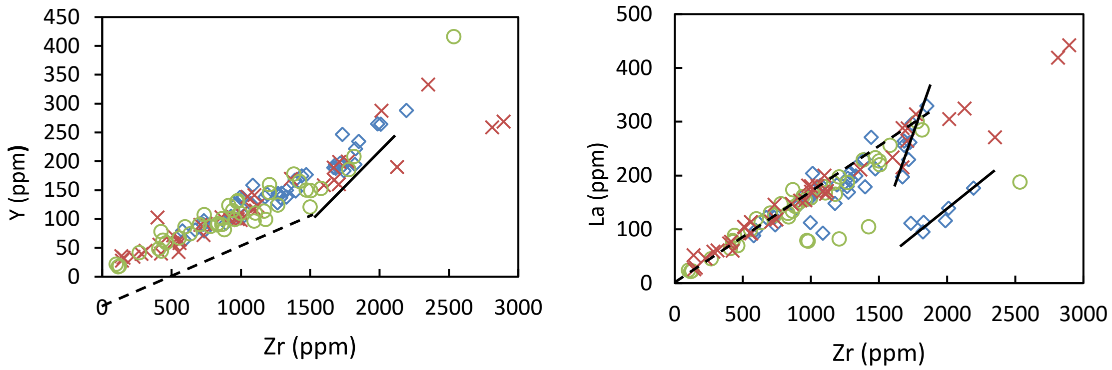

FIGURE 16: Y versus Zr and La versus Zr plot showing fractional crystallisation (dotted line) and other magma modification processes (continuous line), probably crustal anatexis or magma mixing

A variation in the occurrence of alteration minerals across the traverse in the study is attributed to the variation in reservoir conditions. Well OW-917 has high abundance of calcite compared to OW-905A and OW-910. Most of this calcite fills vugs, fractures, pore spaces and vesicles in the rock matrix. This has affected the permeability in OW-917. Permeability is a key factor in deposition of alteration minerals since it allows for water-rock interaction. This explains why there is scarcity of high temperature alteration minerals in OW-917. There is also high abundance of pyrite in well OW-917. The occurrence calcite and pyrite, combined with the scarcity of high temperature minerals indicates that the pyrite and calcite were deposited at lower temperature. Calcite and pyrite deposit over a wide range of temperature, from as low as 100°C to 280°C. Well OW-917 is located in the down-flow zone (Lagat, 2004). Convective mixing, a process associated with the cooler peripheral parts of a geothermal system (Simmons and Christenson, 1993), might have resulted in the deposition of abundant calcite in this region. Well OW-910 is located in a zone of high temperature. The abundance of high temperature alteration minerals (for example garnet, actinolite, epidote, prehnite, wairakite and quartz) coupled with high intensity of alteration and abundant pyrite shows there is high permeability as well as high temperatures in this region. This shows that the zone is associated with the heat source. Calcite is scarce and is only observed down to 100 m only. The moderate abundance of high-temperature minerals in OW-905A indicates lower temperatures in this region compared to the region at well OW-910. However, the high abundance of pyrite, moderate to high alteration intensity and low to moderate abundance of calcite indicate that permeability is good in this region. Well OW-905A is located in the recharge zone.

The variation in formation temperature along NW-SE traverse reveals that there is high temperature at shallow depth near the OW-910, followed by OW-905A, while the OW-917 area has low temperatures (below 230°C) from the surface to 3000 m depth. Well OW-910, together with other wells in this region are high power producing wells. This shows that the heat source is located in this region (Figure 17). The recharge in OW-905A as well as the greater depth at which high formation temperatures are measured, relate to its distance from the heat source. Moreover, the location of this well close to Ol Njorowa gorge, which is a conduit for that feeds cold water in this part of the Domes field, accounts for these observations. Well OW-917 is located at a distance from the heat source. This well is also located in the down-flow zone and next to the ring structure. These factors explain the low temperatures observed to greater depth in this well. The ring structure may be serving as a conduit flow of cold water. From the formation temperature-alteration mineral isograd relation, indicates that there have been two thermal regimes in Olkaria geothermal field. For instance, the epidote and actinolite isograds in wells OW-905A and OW-917 are present where formation temperatures are lower the epidote’ s depositional temperatures. This indicates that higher temperature existed at shallower depth in the past as compared to today. The garnet isograd in OW-914 and OW-910 occurs at a depth with formation temperatures of above 300°C. This indicates heating up in this zone.

Tectonic activities and magmatic intrusions associated with the recent eruption could be the source of this heat.

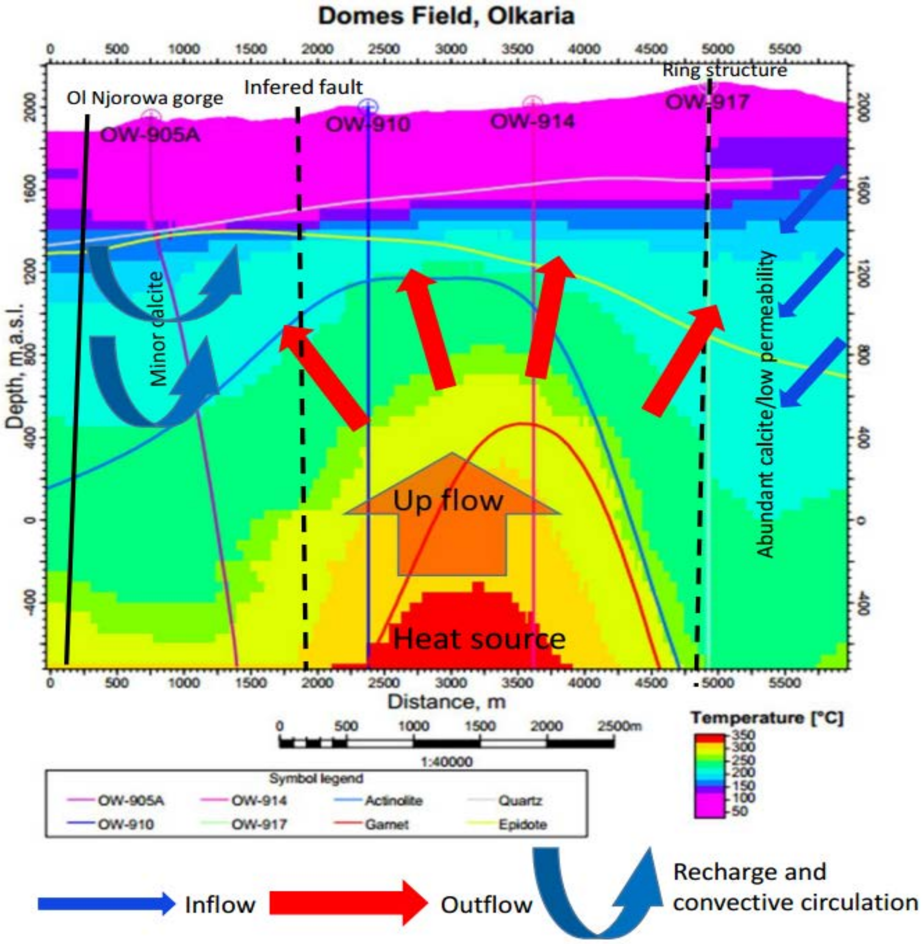

FIGURE 17: Conceptual model of the Domes area based on the research findings of this study

As speculated by Macdonald et al. (2008) and Marshall et al. (2009) in their surface studies, there is a full range of magmatic composition beneath the GOVC. The major and trace element plots indicate crystal fractionation as the main magma differentiation process. Mg, Al and Fe go into olivine, clinopyroxene and plagioclase in early phase of fractionation. FeTi-oxides go into ilmenite and magnetite. P goes into apatite. This explains why these oxides decrease with increasing SiO_2. Na and K behaves incompatibly in the early stages of fractionation (Wilson, 1989). As fractionation continues, Na and K goes into plagioclase and alkali feldspars. The high SiO_2 content associated with OW-917 can be attributed to the silicic magmas associated with the formation of a ring of Domes to the east and south of the complex. This well has been drilled on top of the ring structure. From the trace element plots, the correlation of the trace elements against Zr, is typical of crystal fractionation process. Ba, Sr, Co, Ni, V and Cr generally decrease with increasing Zr. Ba and Sr are taken by alkali feldspars and plagioclase during early phase of fractionation. Ni and Cr goes into olivine, orthopyroxene and clinopyroxene in the initial stages of fractionation. Co goes into FeTi-oxides while V goes into orthopyroxene. Rb, like K and Na remains incompatible in the initial stages of crystal fractionation and is later incorporated in alkali feldspars as fractionation gets in later stages. There is a positive correlation between the incompatible trace elements (La and Y versus Zr plot) with the best line of fit passing through the origin. However, a kink is observed in this at around 1700 ppm Zr. This can be attributed to other source components that were involved in evolution of the GOVC magmas. Marshal et al. (2009) indicated that crustal anatexis was involved in generation of rhyolites. He further pointed out that magma mixing was involved in generating the intermediate and trachyte magmas.

Elements like Na_2O, Ba and Rb are easily leached from the original rock. This explains the considerable scattering observed in their plots.

6. CONCLUSION

The Olkaria geothermal field stratigraphy is composed of basalt through intermediate to silicic rocks. The dominant rock type is trachyte.

There is a variation in alteration mineral occurrence across the Domes field. This is attributed to the temperature and permeability variation across the field.

The temperature variation across the field can be related to the distance from the heat source. Wells located close to the heat source, for example OW-910, have higher temperatures at shallow depth while those located far away from the heat source, e.g. OW-917 and OW-905A have higher temperatures at greater depth.

Two thermal regimes have existed in Olkaria geothermal system, as indicated by alteration minerals and formation temperatures. The earlier regime had high temperatures at shallow depth and existed during deposition of the alteration minerals while the current regime has high temperatures at greater depth compared to the early regime.

The main magma differentiation process was crystal fractionation. Other magma modification processes like magma mixing and crustal anatexis were also involved. The magma differentiation processes involved in generation of the surface rocks were the same as those involved in generation of the sub-surface rocks.

REFERENCES

Ambusso, W.J., and Ouma, P.A., 1991: Thermodynamic and permeability structure of Olkaria Northeast field: Olkaria fault, *Geothermal Resource Council Transactions, 15*, 237-242.

Browne, P.R.L., 1978: Hydrothermal alteration in active geothermal fields. *Annual Review Earth and Planetary Sciences, 6*, 229–250.

Clarke, M. C. G., Woodhall, D. G., Allen, D., Darling, G., 1990: Geological, Volcanological and hydrogeological controls of the occurrence of geothermal activity in the area surrounding Lake Naivasha. *Min. of Energy, Nairobi, report* 150, 138 pp.

Fang, N., Niu, Y., 2003: Late Paleozoic ultramafic lavas in Yunnan, SW China, and their geodynamic significance, *Journal of Petrology 44*, 141-158.

Franzson, H., Zierenberg, R. and Schiffman, P., 2008: Chemical transport in geothermal systems in Iceland, Evidence from hydrothermal alteration, *Journal of Volcanology and Geothermal Research, 173*, (3–4), 217-229.

Heumann, A., Davies, G.R., 2002: U-Th disequilibrium and Rb-Sr age constraints on the magmatic evolution of peralkaline rhyolites from Kenya, *Journal of Petrology 43, 557-577.*

KenGen, 2012: *Stratigraphy and hydrothermal alteration mineralogy of well OW-910 and OW-917*. KenGen internal report (unpublished).

Koech, V.K., 2014: *Numerical geothermal reservoir modelling and infield reinjection design, constrained by tracer test data: Case study for the Olkaria geothermal field in Kenya*. University of Iceland, MSc thesis, UNU-GTP, report 5, 69 pp.

Kristmannsdóttir, H., 1979: Alteration of Basaltic Rocks by Hydrothermal-Activity at 100-300° C, *Developments in sedimentology* 27. 359-367.

Kwiecien, W., 1990: *Silicate rock analysis by AAS. School of Geology*. Queensland University of Technology, Brisbane.

Lagat, J.K., 2004: *Geology, hydrothermal alteration and fluid inclusion studies of the Olkaria Domes geothermal field, Kenya*. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 2, 71 pp.

Le Maitre, Roger Walter, Albert Streckeisen, B. Zanettin, M. J. Le Bas, B. Bonin, and P. Bateman, eds, 2002: *Igneous rocks: a classification and glossary of terms: recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks*. Cambridge University Press, 2002.

MacDonald, R., Davies, G.R., Bliss, C.M., Leat, P.T., Bailey, D.K., and Smith, R.L., 1987: Geochemistry of high silica peralkaline rhyolites, Naivasha, Kenya rift valley. *J. Petrology, 28*, 979-1008.

MacDonald, R., Black, H.E., Fitton, J.G., Marshall, A.S., Nejbert, K., Rodgers, N.W., and Tindle, A.G., 2008: The roles of fractional crystallization, magma mixing, crystal mush remobilization and volatile-melt interactions in the genesis of a young basalt-peralkaline rhyolite suite, the Greater Olkaria volcanic complex, Kenya Rift Valley. *J. Volcanology, 49-8*, 1515-1547.

Mariita, N.O., 2009: Exploration history of Olkaria geothermal field by use of geophysics. *Paper presented at "Short Course IV on Exploration for Geothermal Resources", organized by UNU-GTP, KenGen and GDC, Lake Naivasha, Kenya*, 13 pp.

Marshall, A.S., MacDonald, R., Rogers, N.W., Fitton, J.G., Tindle, A.G., Nejbert, K., and Hinton, R.W., 2009: Fractionation of peralkaline silicic magmas: the Greater Olkaria volcanic complex, Kenya Rift Valley. *J. Petrology, 50*, 323-359.

Mbia, P.K., 2014: Sub-surface geology, petrology and hydrothermal alteration of Menengai geothermal field, Kenya. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 1, 87 pp.

Onacha, S.A., 1993: *Resistivity studies of the Olkaria-Domes geothermal project*. KenGen, internal report.

Omenda, P.A., 1993: *Geological investigation of Suswa geothermal prospect, Kenya*. KPC Internal report, 35 pp.

Omenda, P. A., 1997: The Geochemical Evolution of Quaternary Volcanism in the South-Central Portion of the Kenya Rift. PhD dissertation, Univ. Texas – El Paso, 218 pp.

Omenda, P.A., 1998: The geology of well OW-901. KenGen, internal report. Ambusso, W.J., and Ouma, P.A., 1991: Thermodynamic and permeability structure of Olkaria Northeast field: Olkaria fault. *Geothermal Resource Council Transactions, 15*, 237-242.

Omenda, P.A., 2000: Anatectic origin of comendite in Olkaria geothermal field, Kenya Rift; Geothermal evidence of syenitic protholith. *African J. Science & Technology, Science & Engineering Series, 1*, 39-47.

Shackleton, R.M., 1986: Precambrian collision tectonics in Africa. In: Coward, M.P., and Ries, A.C. (eds.), Collision tectonics. *Geol. Soc. Spec. Publ., 19*, 329-349.

Simiyu, S.M., Omenda, P.A., Keller, G.R and Antony, E.Y., 1995: Geophysical and geological evidence of the occurrence of shallow intrusion in the Naivasha sub-basin of the Kenya rift. *AGU Fall 1995 meeting, Abst. F657*, V21A-12.

Simiyu, S.M., and Keller, G.R., 1997: An integrated analysis of lithospheric structure across the East African plateau based on gravity anomalies and recent seismic studies, *Tectonophysics 278*, (1–4), 291–313.

Simiyu, S.M., Oduong, E.O., and Mboya, T.K., 1998: *Shear wave attenuation beneath the Olkaria volcanic field*. KenGen, internal report.

Simmons, S.F. and Christens, B.W., 1993: Towards a united Theory on Calcite Formation in Boiling Geothermal Systems. 15th Proc. *New Zealand Geothermal Workshop*, 145-148.

Wilson, B. Marjorie, 1989: *Igneous petrogenesis, a global tectonic approach*. Springer Science & Business Media, 1989.