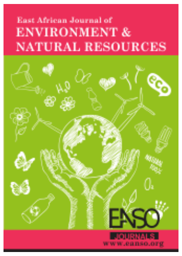

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Original Article

Characterizing Permeability from Geological and Geochemical Data in the Olkaria Domes Field in Kenya.

*Harriet Nkatha Achini[1]**, *Olubunmi C. Adeigbe[2]* & *Prof. Bernard Kipsang Rop, PhD[3]*

[1] Pan African University Life and Earth Sciences Institute.
[2] University of Ibadan, Ibadan, Nigeria
[3] Jomo Kenyatta University of Agriculture and Technology, Juja, Nairobi, Kenya
* Correspondence email: hachini93@gmail.com.

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ABSTRACT

Olkaria geothermal field is located in the Kenyan Rift Valley that is a part of the Great East Africa Rift System (EARS). The geothermal field continues to be associated with a high geothermal gradient that arises from shallow magmatic activities which are ongoing in the enormous igneous province. Exploration and drilling of wells that were undertaken in the past revealed the existence of exploitable geothermal steam. The Olkaria field is divided into seven sections namely; Olkaria East field, Olkaria North East field, Olkaria North West field, Olkaria South East field, Olkaria South West field, Olkaria Central field, and Olkaria Domes field. The productivity of the geothermal wells continues to be influenced by factors such as subsurface permeability. Permeability is one of the parameters used for the characterization of geothermal fields. Other parameters used for characterization are associated with geotechnical weak zones and include features such as; fractures, vein bodies, and deformational fault systems. The research work involved geoscientific characteristics of the Olkaria Domes field based on the geological and geochemical factors to characterize the permeability of the field. The research involved studying rock types in the area by analysing drill cuttings obtained from six drilled wells in the Olkaria Domes field. Three of the six drill wells were considered for correlative description for the purpose of this paper. Correlation of the main lithologies and zones for loss of circulation in the field was also undertaken as well as the creation of mineralogical maps to capture the distribution of the minerals that were derived from hydrothermal weathering processes. The depths and formation for major loss circulation zones in the reservoir section of the field were identified and included in the description. Analysis of soil gas survey using radon as a geochemical tool in the Domes field was also carried out successfully. The relatively high levels of the soil gas ratios that were analysed captured the ratio distribution of carbon dioxide to radon at various reservoir depths. The detection of the two gases at the surface showed the existence of permeable zones which facilitated the movement of the gases through the fault-controlled structural systems of the studied Olkaria Domes field.

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INTRODUCTION

Kenya is well endowed with high-temperature geothermal resources that are largely unexploited. Several geothermal fields are located within the Kenyan Rift Valley as a part of the East African Rift System (EARS). The ones that have been surveyed have already been developed and are in the production drilling stage and further exploration drilling is taking place as well. They include Olkaria, Eburru, and Menengai fields. Exploration drilling is ongoing in other fields especially in the Lake Baringo-Silali and Paka prospects. Kenya has made commendable strides also in the direct utilization of geothermal resources. The uses include heating and fumigation of greenhouses, drying of crop harvests, milk pasteurization, fish farming, and recreational purposes among others. Geothermal energy development in the country has not been exempted from challenges ranging from financial, technological, human capacity, environmental, and socioeconomic challenges including legislative and policy issues. The study to be undertaken intends to focus on the properties of the Olkaria Domes field. A typical powered generation plant located in the dome is as shown in (*Plate 1).*

Plate 1: Geothermal power generation

The Eastern Africa Rift Valley has several volcanic centres located in Kenya. These volcanic centres are associated with numerous geysers such as the ones in Olkaria present study area of Nakuru County; while others are to the northern rift in Lake Bogoria and Lake Baringo which are located in Baringo County (Rop et al., 2020; Rop and Namwiba, 2018).

The Olkaria geothermal field is located in Naivasha, Nakuru County (*Figures 2* and *3).* The harnessing of the geothermal resources is undertaken by a parastatal company known as Kenya Electricity Generating Company (KenGen). The company is the largest producer of electricity in the country having drilled over three hundred geothermal wells in the Olkaria field. It is important to study properties of the field such as permeability since permeability is a key property of reservoirs that contributes to the unrestricted flow of reservoir fluids.

Problem Statement

The Olkaria field has a lot of geothermal potentials that can be used for the generation of electricity. The study of the properties that influence fluid flow is, therefore, crucial for field development. If these properties are low in the already drilled wells that means the steam captured will not be adequate for the harnessing of the projected geothermal resource. This study will analyse and interrelate permeability to geothermal parameters.

Significance of Study

Kenya needs to secure a reliable, sustainable, and affordable green power supply to meet current and future energy demands. The consumption of electrical energy in the country on a daily basis continues to escalate. As of 2019, the demand was 1600 MW and was projected to grow to 2600-3600 MW by 2020. Indeed, the supply of electrical power has been heavily dependent on large hydropower generation systems in the past. That supply accounts for almost half of the country's current installed capacity. However, hydropower generation has become increasingly unreliable due to impacts caused by climatic change and generation from short-term fossil-fuelled sources which are of high cost, more so, during dry seasons water levels in reservoirs get considerably low and subsequently results in less hydro-electrical power generation. Clearing of land to set up dams for hydro generation is not very friendly to the environment as it leads to the generation of more greenhouse gases which impact negatively on the same environment. Similarly, dependence on fossil-fuelled electrical power generation has been found to be unfavourable and expensive other than being environmentally unfriendly.

Objectives of the Study

The main objective of the research was to characterize the permeability of Olkaria Domes Field by the use of geological and geochemical data. Specific objectives for the study were to;

- Identify the rock types in the study area, through the analysis of rock cuttings from selected wells of the study area.
- Carry out the lithological correlation of the field rock formation using data obtained from the core/ditch cuttings that were sampled from selected wells.
- Carry out gas survey analysis from the study area to get the CO2 and Radon gas concentrations in the field of study at the time of the survey.
- Create permeability-related facies' maps at different depths for the domes field which could be of interest for future infill drilling to enhance the field's productivity.

LITERATURE REVIEW

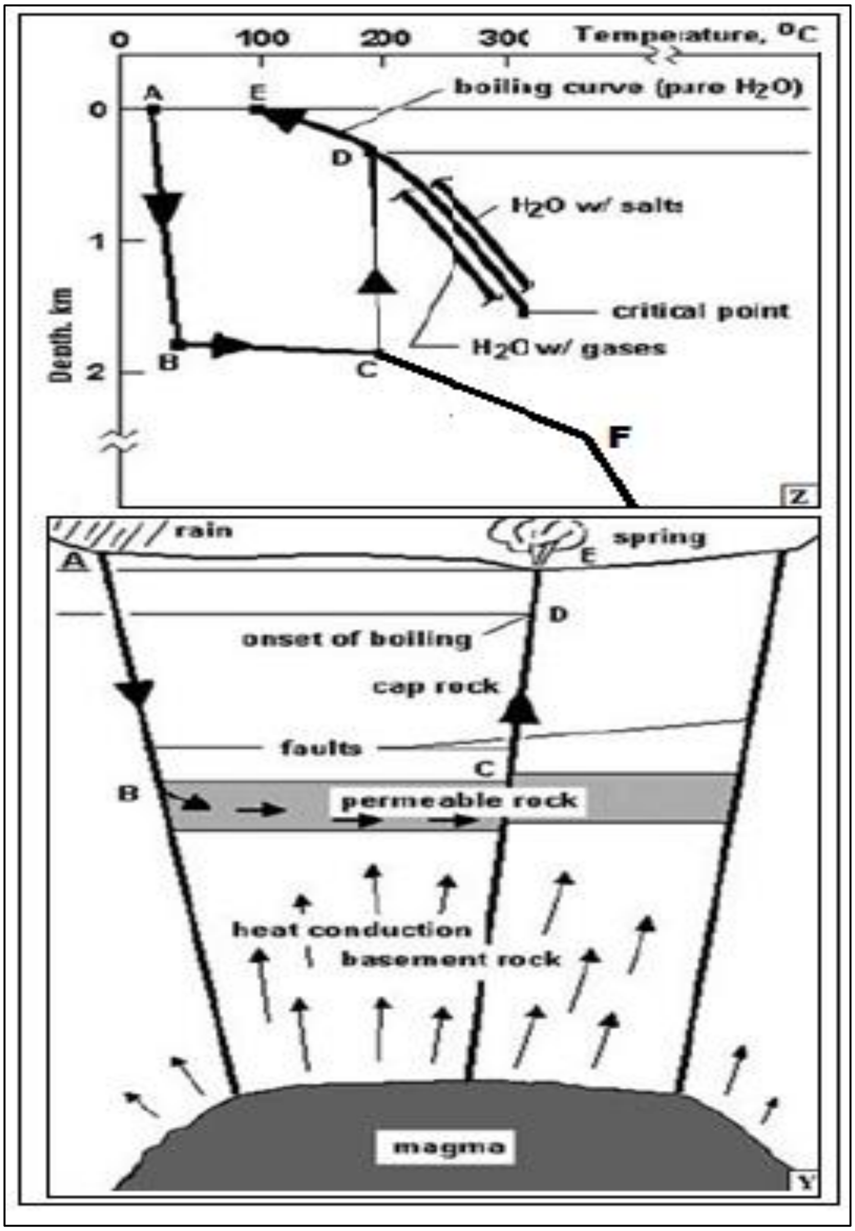
Geothermal Energy Resource

Geothermal energy is a term that is used to refer to thermal energy confined in the rocks and fluids filling fractures and pores in rocks at temperatures above a specified reference temperature within the earth's crust. Radioactivity contributes greatly to heat generation that heats water to form a geothermal resource deep inside the earth (Smith, 1983).

Hydrothermal System

A hydrothermal system refers to five essential features, which include natural hot water which is of economic significance that emanates from underground (Smith, 1983). The features are; large heat source, permeable reservoir, supply of ground water, an overlying layer of impervious rock that acts as caprock, and a reliable recharge mechanism. The features are as illustrated simultaneously in *Figure 1* [(Y) and (Z)]. Cold recharge water arrives as rain i.e., at point 'A' on the illustration from the atmosphere and percolating through faults and fractures deep into the formation where it comes in contact with heated rocks. The permeable layer offers a path of lower resistance (point B) and as the liquid heats up, it becomes less dense and tends to rise within the igneous rock formation.

Figure 1: Model representation of a hydrothermal system



Source: (Smith, 1983)

Enhanced Geothermal Systems

These are new types of geothermal power technologies that do not require natural convective hydrothermal resources. Until recently, geothermal power systems have only been exploited from resources where naturally occurring water and rock porosity are sufficient to carry heat to the surface. However, the vast majority of geothermal energy, within drilling reach, occurs in the dry and non-porous rock. The Enhanced Geothermal Systems (EGS) technology is also referred to as hot dry rock (HDR) technology. The technology involves a hydraulic stimulation process which leads to increased extraction of geothermal resources. All the utilized hot water, when cooled down, is injected back into the ground to get heated up again in a closed-loop. Such HDR and EGS systems are currently being developed and tested in France, Australia, Japan, Germany, the U.S., and

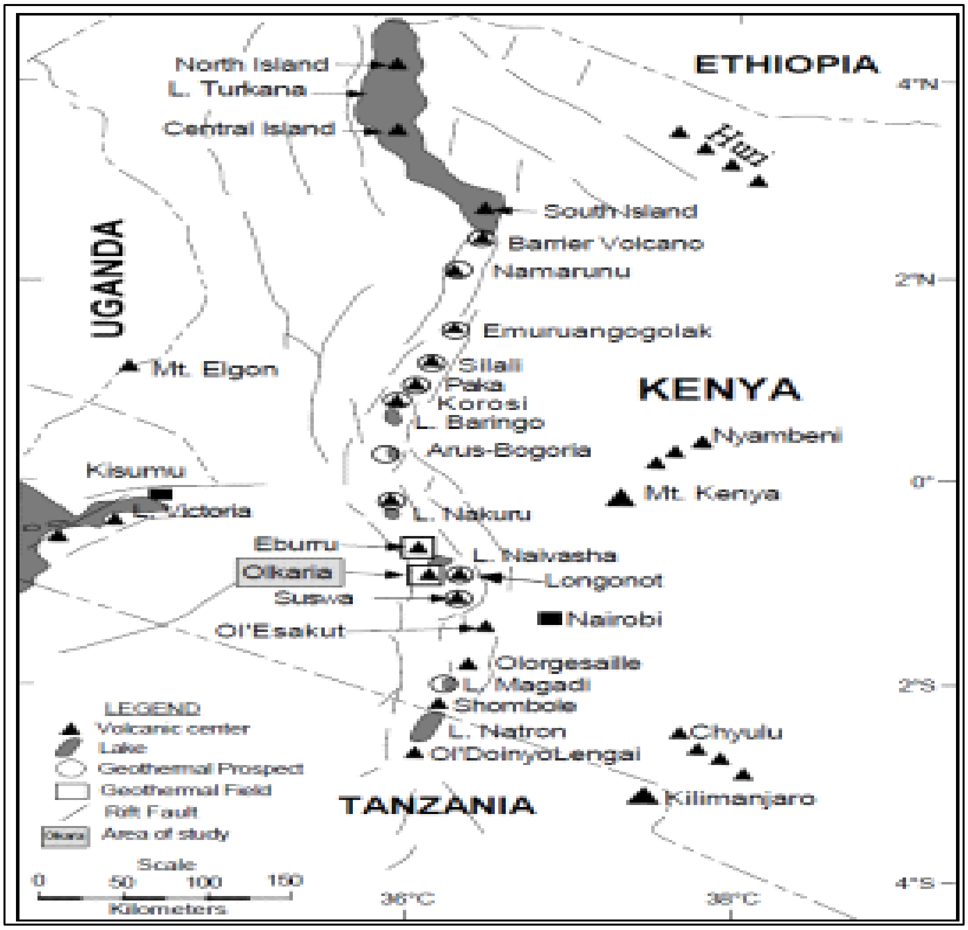
Switzerland. The largest EGS project in the world is a 25-megawatt demonstration plant currently being developed in the Cooper Basin, Australia. Further exploration showed that the Cooper Basin has the potential of generating 5,000–10,000 MW of EGS geothermal power.

Permeability

The ability of rocks to transmit fluids through the pore spaces is called permeability. The ability is denoted by the symbol k (Schön, 2015). The permeability is mostly dependent on the interconnectivity of pore spaces. Thus, permeability can be said to be interrelated to porosity, although they are not dependent on each other. Porosity is the fraction of total formation volume that is not occupied by solid rock. It is the spaces formation that can be filled with fluids. Pore spaces or fractures need to be interlinked and packed with water for fluid transmission to take place (Heap et al., 2018). The extent of pore interconnectivity is called effective porosity which has to be sufficient. Permeability in geothermal reservoirs is mostly structure controlled. It is influenced by the presence of fractures, faults fragments breccias, lithology contacts, and thermally induced joints (Lagat et al., 2005). Another parameter to note is intense loss zones alteration intensity, veining, and abundance of calcite and pyrite (Omwenga, 2015).

Geological Setting of the Study Area

Figure 2: Kenyan Rift Map showing the location of Olkaria geothermal field



The evolution of the East African rift system is structurally controlled with the rift faults exploiting the weak collisional zone at the contact between the Archean Tanzania craton and Proterozoic Orogenic belts (Lagat, 2004). Volcanism associated with rifting started during the Miocene. The magmatic activity was accompanied by domal uplift of about 300 m on the crest of which erupted phonolites

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(Baker and Wohlenberg, 1971). The total volume of eruptive rocks associated with rifting is estimated to be more than 220,000 km^3 (Baker, 1987).

The Pliocene volcanic were subsequently faulted and then followed by massive and extensive Miocene eruption of trachytic ignimbrites in the central area to form the Mau and Kinangop Tuffs. A second faulting episode, which followed the ignimbrite eruptions, resulted in the formation of the graben structure, as it is known today. In the developing graben, fissure eruptions of trachytes, basalts, basaltic trachy-andesites occurred.

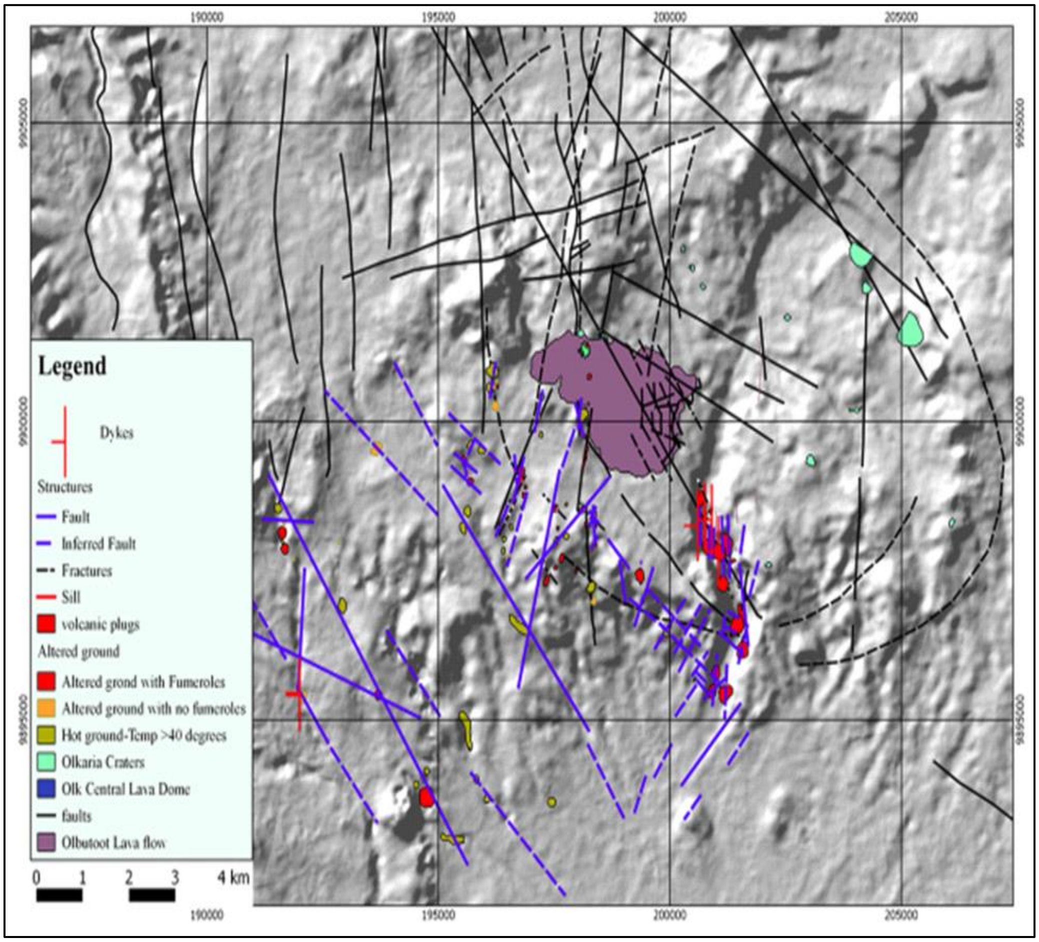
The most intense volcanic activity occurred within the central sector of the rift where the volcanic succession is thought to be of the order of 5 km thick (Keller and Simiyu, 1997; Baker et al., 1972).

Quaternary age volcanic centres characterize the geology of the Olkaria Volcanic Complex. There is comendite occurring on the surface of the complex (Lagat, 2004). It is bound by the Longonot volcanic centre to the Southeast, Eburru to the North, and Suswa volcanic complex to the South. The complex has a ring of dome structures as compared to the other volcanic complexes that are characterized by having calderas.

Structural Setting

Geological structures control the movement of fluids in a geothermal system. They either provide channels of enhanced permeability or barriers that restrict or divert flow. These include faults, fractures, and fissures *(Figure 3*).

Figure 3: Structural Map of Olkaria



Source: (Mwania, 2015)

The main structures include older fault system that trends NW-SE and NNE-SSW N-S, and ENE-WSW trending faults as the recent faults that form the Olkaria fracture, Ol'Njorowa gorge, and Ololbutot fault zone (Omenda, 1998) and the 'ring structure' (a series of Rhyolitic domes forming loci) notable in the dome's area (Lagat, 1995). The major faults are common in the East, Northeast, and West Olkaria fields. In the Olkaria Domes, they are scarce and this can be associated with pyroclastic material covering the surface. The Ol'Njorowa gorge was formed by faulting followed by Lake Naivasha's outflow due to its high stand (Clarke et al., 1990).

Stratigraphy of the Olkaria Field

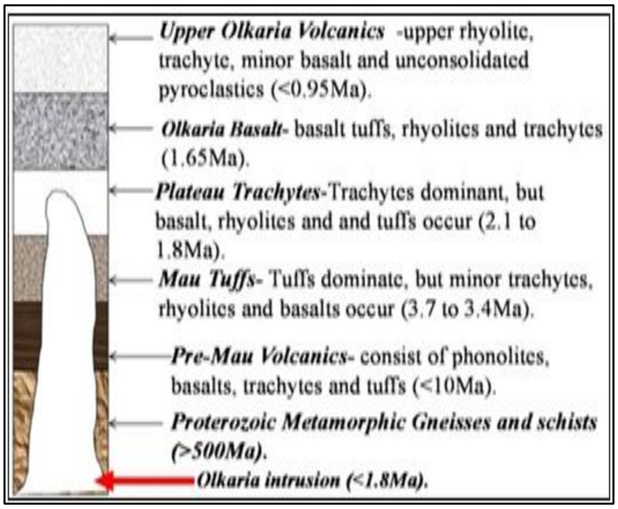
Table 1: Stratigraphy of Olkaria field

Formation Name	**Lithology**	**Thickness (m)**
Upper Olkaria Volcanics	Comendite lavas and their pyroclastic equivalent, ashes, minor basalts (Cleark et al., 1990, Omend, 1998a)	Surface to 500
Olkaria Basalts	Basalt flow, minor pyroclastics, and trachytes (Omenda, 1998a)	100-500 (Cap Rock)
Plateau trachytes	Trachytes with minor basalts, tuffs, and rhyolites (Omenda, 1994, 1998a)	1000-2600 (Reservoir)
Mau Tuffs	Consolidated ignimbrites (Omenda, 1994, 1998a)	>2600 (Reservoir)
Pre-Mau Formation	Trachytes, Basalts, Ignimbrites	Unknown (Reservoir)
Olkaria Intrusives	Occur as Batholiths or Granitic, Syenitic and basaltic in composition; as dykes and sills in basement rocks. Tuffs and trachyte units present	Varying
Proterozoic Basement Rocks	Gneisses, Schists, Marbles, Quartzites (Msley, 1993, Smith and Mosley, 1993, Simiyu et al., 1993)	5000-6000

Source: (Modified from Mwania, 2015)

The lithostratigraphy of the Olkaria field has been sub-divided into these groups by previous authors according to the lithology, tectono-stratigraphy, and age (Omenda, 1998). The formations from the youngest to the oldest include Upper Olkaria Volcanics, Olkaria Basalt, Plateau Trachyte, Mau Tuffs, Pre-Mau Formation, Olkaria Intrusion, and the Proterozoic Basement rocks. Studies from reflection seismic and geological correlations indicated the depth of the basement as around 5000-6000 m as well as intrusion into the basement as shown in *figure 4* (Baker and Wohlenberg, 1971).

Figure 4: Stratigraphy of Olkaria field



Source: (Baker and Wohlenberg, 1971)

Previous Works on Influence of Permeability

Various geoscientists undertook exploratory work on geothermal systems of the Great Rift Valley particularly on the Wide Nakuru Dome so as to capture geotechnical features that influence the movement of high enthalpy waters. For instance, Omwenga (2019), carried a study on the characterization of subsurface permeability of the Olkaria East Geothermal field where the permeability controls for the field are discussed. Parameters for permeability in a geothermal well are noted as loss zones, fracturing, veining, and micro faulting. Minerals noted to characterize permeabilities were pyrite and calcite abundance. The findings were loss zones being correlated across the main lithology units that form the reservoir, veins' filling which mostly showed that the veins were filled with secondary minerals. Fractures and faults were discussed also as structures influencing permeability. They create the avenues for a fluid mass movement in the field. Surface manifestations of gases were attributed to the presence of faults in the subsurface.

Mwania (2015) evaluated the subsurface structures with the use of hydrothermal alteration mineralogy in the Olkaria South East Field. From the study, the hydrothermal alteration facies were grouped into three: argillic alteration facies, phyllic alteration facies, and prophyllic alteration facies. The hydrothermal alteration was noted as an important parameter for giving subsurface information about a geothermal system. The different types of alterations depict different characteristics of the system. For instance, argillic facies were found to be associated with the low temperature at shallower depths, phyllic facies associated with increasing temperature, and reservoirs identified with them while the prophyllic facies were associated with high temperatures.

METHODS

Sampling and Analytical Methods

The rock cuttings from the wells were sampled from every 2 m interval but after 4 m intervals in cases where the samples were too little and unrepresentative. Analysis of the cuttings was first done on-site using a binocular microscope and specific samples which were typical of the rock units encountered in the well were selected for detailed laboratory analysis using a petrographic microscope.

Binocular Microscope Analysis

A small amount of cuttings was scooped from the sample bag and first washed with running water to remove impurities (drilling foam, dust, etc.). They were then wetted to enhance visibility and reduce reflection that could arise from surface reflection. The main features noted in the analysis were the rock colour, grain size, rock fabric, rock type, primary and secondary [alteration] mineralogy and intensities, both in the rock matrix and in fractures, vesicles/vugs, and veins.

Petrographic Microscope Analysis

Thin sections of selected representative samples were made and detailed analysis was done to confirm the rock type, its texture, alteration mineralogy, and in addition identification of mineralogical evolution/sequence in the well thereby attaining additional information other than the one obtained when using the binocular microscope.

X-ray Diffractometer Analysis

The method of X-ray diffraction analysis was used to identify clay minerals in the well. It first involved the separation of a clay-sized fraction (usually < 2 micron) from the sample. Once obtained the clay fraction was prepared by collecting it on a filter and transferring the layer of clay to a glass slide substrate. This so-called 'filter peel' method enhanced the preferred orientation of the platy clay particles, which helped to obtain a good diffraction signal from the diagnostic basal planes of the clay minerals. It was also the best way to make a homogenous sample for generating quantitative results. The oriented samples were run on the diffractometer (air-dried) and then run again using solvation with ethylene glycol and heating to controlled conditions. Peak positions, shapes, intensities, and changes in the specified treatments were diagnostic for the identification of different clay minerals.

Use of Software

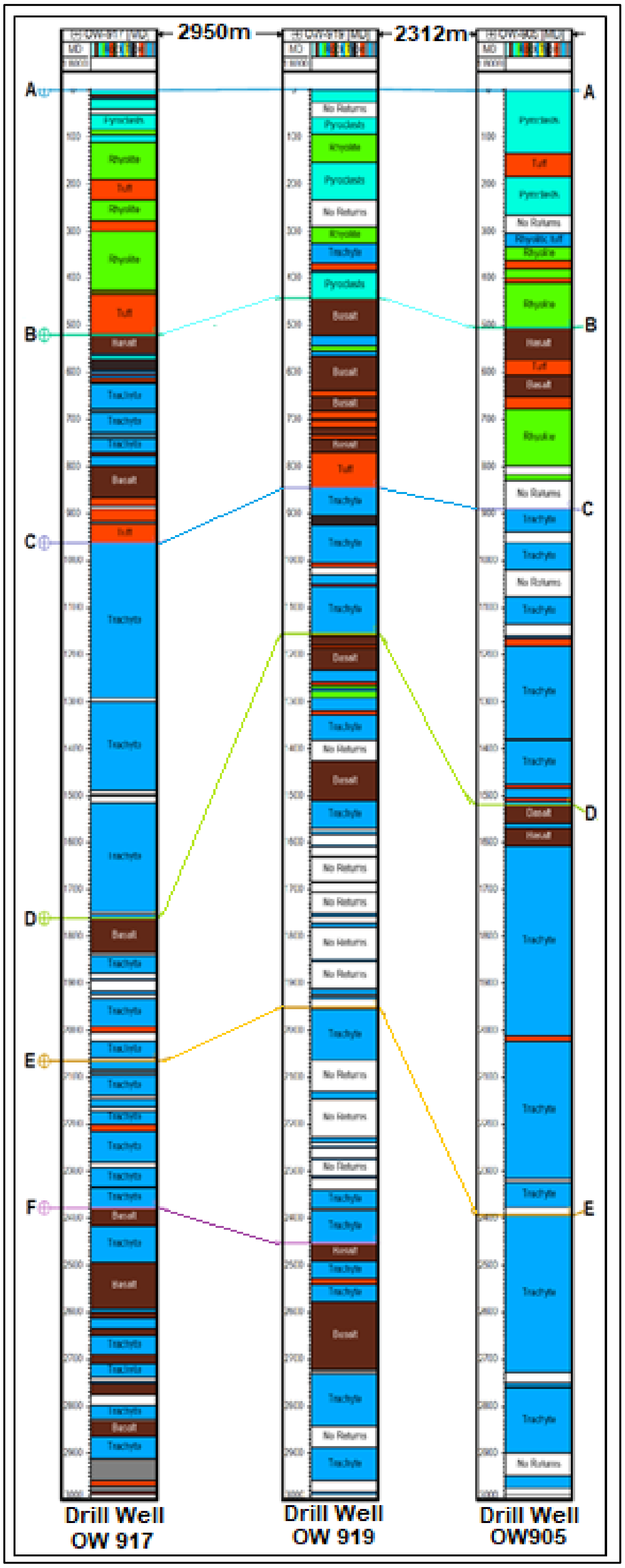
The software used for this work were; Petrel 2015 to create the lithological correlation and mineralogical map distributions, ArcGIS to develop the Radon and CO2 concentration maps, and Excel to arrange and process the data sets.

RESULTS AND DISCUSSION

The Lithology of the Wells

Six drill wells of Olkaria field for the study were studied. However, three drill wells have been considered for this paper to illustrate the descriptive concept for the analysis done. *Figure 5* shows the correlation of the three drill wells which were designated as; Drill Well OW 917, Drill Well OW 919, Drill Well OW 905

Figure 5: Stratigraphic well correlations of volcanic rocks in study area



Well Correlations and Lithostratigraphy of Olkaria Field

The lithostratigraphy of Olkaria Field was discussed in section 2.2.2 above. The drill wells studied had been drilled in the Olkaria Domes Field to depths of about 3000 m, with varying separation distances. The separation distance for the three wells considered in this paper was 2950 m and 2312 m and are as shown in *Figure 5*. Rock cuttings analysis from these wells right from the surface were sampled, studied and correlation done accordingly, capturing various mineral assemblages. The correlation was performed in order to understand the characterization of subsurface permeability controls within sections of the wells.

Correlation between A-B points

From *Figure 5*, the section depths between 0 to 530 m, 0 to 440 m, and 0 to 510 m for the three drill wells showed an abundance of pyroclasts, rhyolite, and trachyte. Some sections showed 'no returns' due to loose unconsolidated soils within the volcanic rocks. Loss zones could also be due to the presence of large fractures in the formation. These sections of the drill wells have been represented by points marked A and B as were correlated horizontally across the 6 wells that were studied. The depth ranged, the first three wells, from 0 to 500 m with Drill Well Ow 917 (530 m), Drill Well OW 919 (440 m), and Drill Well OW 905 (500 m). However, pyroclasts were encountered in the upper 100 m depth. Only sections from well OW 905, which showed tuff intrusions (130-180 m), were repeated in the other wells that ranged from 200 m up to 300 m depths. It is interesting to note that pyroclasts encountered in the middle (150 – 230 m) and the lower (390 – 440 m) strata of Drill Well OW 919 well were underlain by rhyolite and trachyte with minor tuff intrusion respectively. Similarly, pyroclasts (180 – 270 m) were encountered immediately below the tuff (130 – 180 m) layer. This pure tuff was underlain by rhyolitic tuff and rhyolite with intercalations of tuff and rhyolite seen up to 400 m depth.

Thus, the above sections' description between points marked A and B shown in *Figure 5* revealed a characteristic of a section which represents Upper Olkaria Volcanics (< 0.95 Ma); comprising mainly trachyte, minor basalts, pyroclasts, and unconsolidated soils.

Correlation between B and C points

These sections indicate various depths for the wells ranging between 500 m to about 1000 m. The wells are mainly characterized by 200 m thick Olkaria basalts (100 – 300 m) and Plateau trachytes (20 – 200 m) with thick tuff layers observed at the base of the basalt for the two wells Drill Well OW 917 having 70 m (870 – 950 m) and Drill Well OW 919 about 80 m thick (770 – 840 m). The thick section of Drill Well OW 917 (620 – 800 m) indicated trachytes which were overlain as well as underlain by similarly thick 120 m (500 – 620 m) of basalts on the top part and 60 m (800 – 860 m) below, followed by another thick tuff (110 m) at 860-970 m. There was a divergence in Drill Well OW 919 which comprised mainly of thick basalts that were interstratified by thin trachyte, rhyolite, and tuff (5 – 10 m).

From Drill Well OW 905, the top section showed repeated sequences of basalts with tuff deposition and 680 – 803 m thick rhyolite toward its base. Thus, the entire B-C correlation section indicated a decrease in the thickness of Olkaria basalts as well as a decrease in the thickness of Rhyolites. Therefore, the correlated section B-C was treated as a geological section that represents Olkaria basalt (1.65 Ma) with intercalations of tuff, rhyolite, and trachyte.

Well Correlations between Points C and D

From this section, wells OW 917, OW 919, and OW 905 had depth intervals of 960 m, 850 m, and 890 m respectively. The wells had all encountered thick trachyte (950 – 1770 m), (850 – 1160 m), and (890 – 1520 m), thicknesses being 820 m, 310 m, and 630 m, respectively. Thus, this correlation section between C and D was considered to have represented Plateau trachyte with few intercalations of basalts, rhyolites, and tuffs belonging to 2.1 to 1.8 Ma in age.

Well, Correlations between Points D, E, and F.

The lithostratigraphy between points D, E, and F for the wells indicated more or less similar characteristics in their respective intervals. For instance, Drill Well OW 917 intervals (1760 – 2070 m), Drill Well OW 919 interval (1160 – 1950 m), and Drill Well OW 905 intervals (890 – 1520 m) comprised of thick basalts and trachytes (70 – 100 m). Drill Well OW 905 had thin trachyte intervals intermittently between depths 1610 m to 2380 m.

This correlation section between D and E could be considered as a formation that was representative of basalts, rhyolites, and trachytes of Mau Volcanics. Similarly, mineral assemblages were observed in section E-F with the exception of the clear presence of minor phonolitic tuffs thereby indicating a representation of Pre-Mau Volcanic eruptions of geologic age less than 10 Ma.

Summary of Lithostratigraphic Wells Correlation

It is of great importance to note that there were considerable lithological similarities, at different locations, for all the studied drill wells arising from the correlation analysis that was done. The drill wells Drill Well OW 917, Drill Well OW 919, and Drill Well OW 905 were drilled in an uplifted horst-like structure of the Olkaria field with thin lithologies. An increase in lithostratigraphic thicknesses in the cross-section of the Olkaria Volcanic rocks was noted to have occurred from east to west of the studied area.

The correlation and descriptions done were characterized according to lithological volcanic facies in the five respective horizontal categories which similarly matched those formations. The well sections (A to F) had been characterized as being representatives of the Upper Volcanics, Olkaria basalts, Plateau Trachytes, Mau Tuff, and Pre-Mau Volcanics (Baker and Wohlenberg, 1971).

However, the metamorphosed basement rocks were not encountered in well studied. The metamorphic probably occur at depths beyond 3000 m, hence confirming that the basement is deeper due to major structural down faulted features associated with the Olkaria Field (Smith, 1983; Lagat et al., 2005).

Minerals Maps

Hydrothermal alteration has been noted as an important parameter for giving subsurface information about a geothermal system (Mwania, 2015). Hydrothermal alteration facies for the area studied were grouped into three facies i.e., argillic, phyllic, and prophyllic alteration facies. Argillic facies are associated with low temperatures at shallower depths, phyllic facies are associated with increasing temperature while prophyllic facies were associated with high temperatures. Where phyllic and prophyllic alteration facies were found is where the reservoirs and permeable zones began to be encountered as affirmed by (Mwania, 2015; Lagat et al., 2005).

From the analysis of drill cuttings, the hydrothermal minerals were encountered in all the drill wells. Minerals that comprised the argillaceous facies were zeolites, amorphous silica, smectite, and other low-temperature clays. Phyllic facies are comprised of illite, quartz, chlorite, and intermittent epidote, while prophyllic facies were comprised of illite, albite, epidotes, prehnite, actinolite, chlorite, and wollastonite. The sequences of the minerals differed from well to well and according to the depths. The depth range to the occurrence of the facies was found to be; less than 500 m for argillic, 600-1500 m for phyllic, and 1500-3000 m for prophyllic. Mineral maps that were prepared showed the distribution of the minerals in the Olkaria domes field from the geological data of the wells studied.

Prominent argillitic minerals were encountered in the area of study. Thus, minerals captured were mainly secondary minerals that were a result of alteration from their primary mineral phases (*Table 2*).

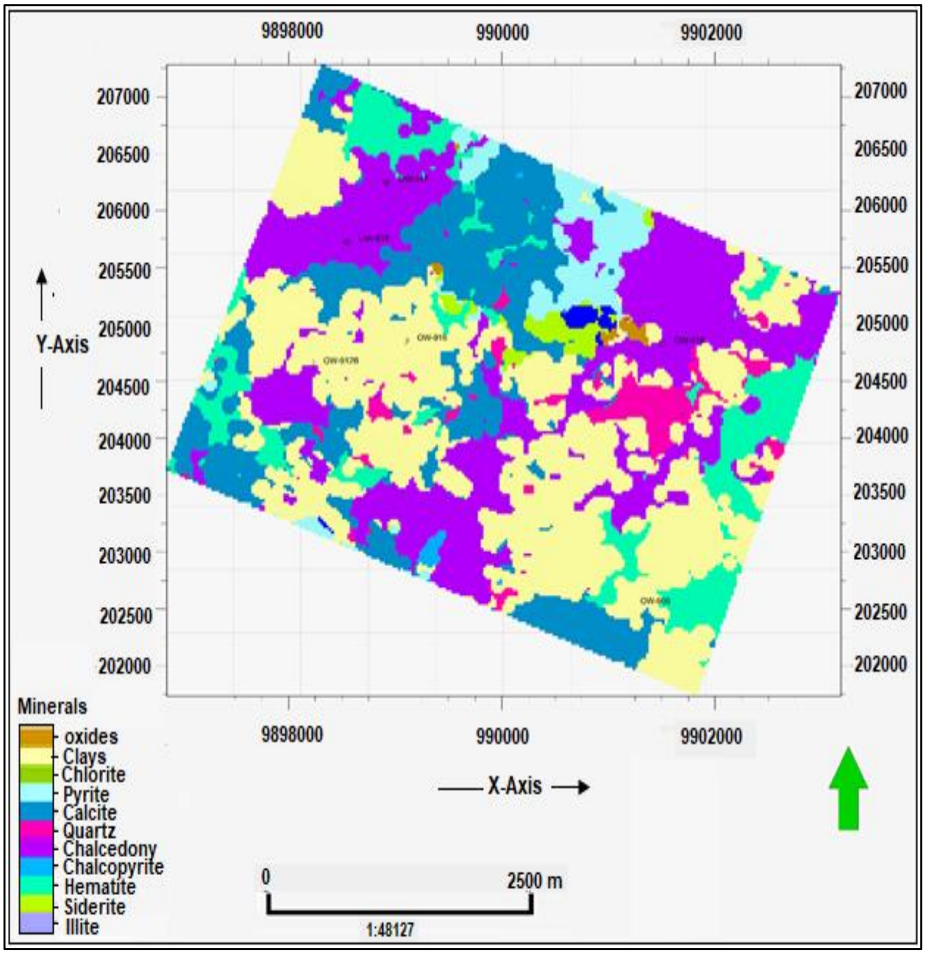
Table 2: Primary minerals and their alteration products

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

Source: (Lagat et al., 2005)

Mineral Map for Zone A

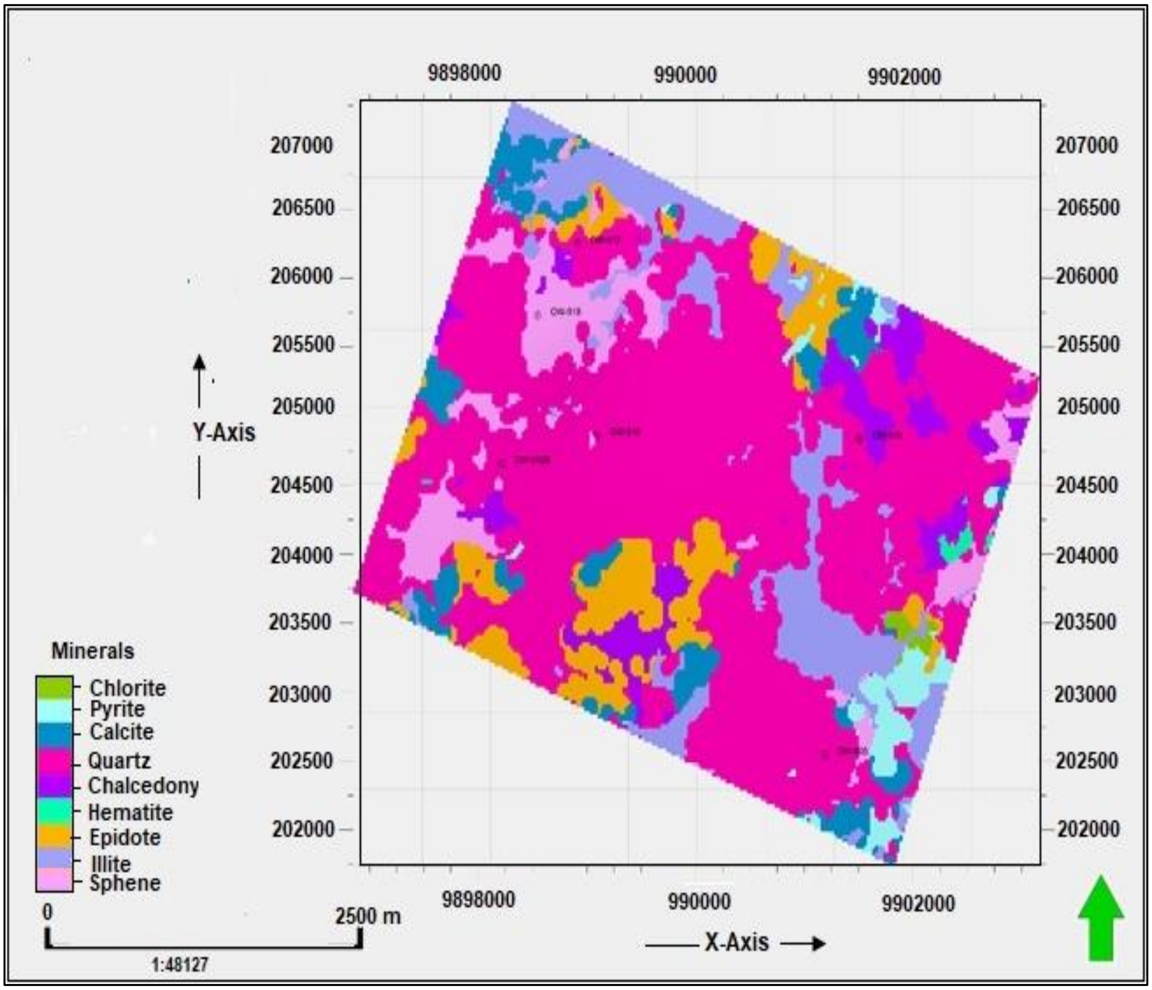
Figure 6: Mineral map for zone A



This zone was located at the shallower depths of the wells and low temperatures, the encountered minerals were oxides, clays, chlorite, pyrite, calcite, quartz, chalcedony, chalcopyrite, hematite, siderite, and illite. This mineral assemblage belonged to argillic facies that are associated with low temperatures and shallow depths. The depth of this zone is from 0 to 500 m or slightly more in the six wells.

Mineral Map for Zone B

Figure 7: Mineral map for zone B



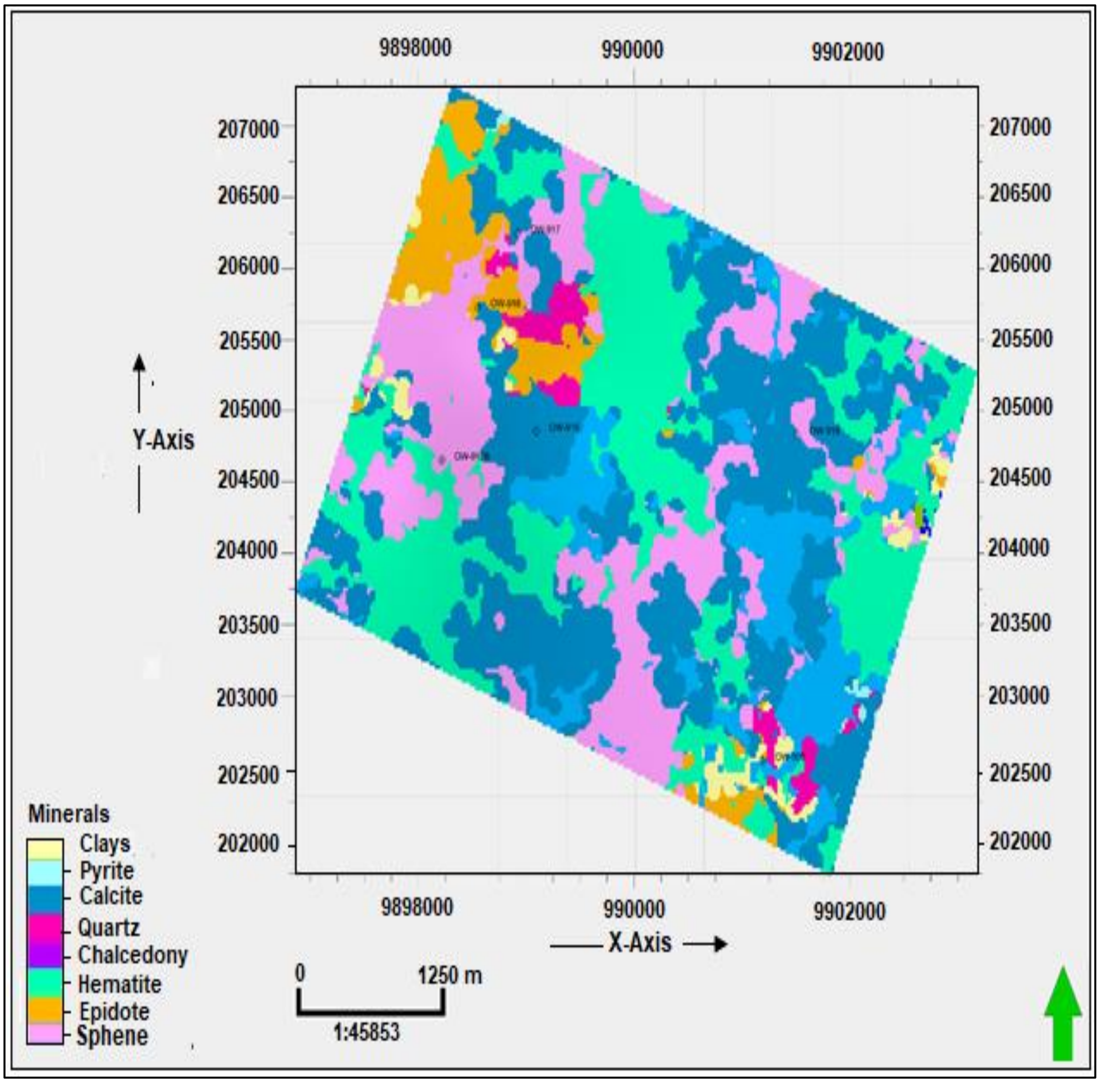
In this zone, the minerals of alteration were chlorite, pyrite, calcite, quartz, chalcedony, hematite, epidote, illite, and sphene. The depth for the zone ranged from 600 m to about 1000 m, as shown in the stratigraphic correlation illustration. The secondary minerals encountered here were an association of phyllic facies. The facies are characteristic of permeable zones of temperatures around 260 ^{0}C (Mwania, 2015). The zone and section for the wells were considered to be the beginning of reservoir zones since the production casing in geothermal fields can be set from about 750 m. Normally, the occurrence of intermittent epidote is associated with the beginning of high-temperature zones as was for the phyllic facies zone.

Mineral Map for Zone C

The hydrothermal alteration minerals in this zone are clays, pyrite, calcite, quartz, chalcedony, hematite, epidote, and sphene. These minerals also constitute the phyllic alteration facies, which are characteristic of high temperatures and permeable zones of a geothermal system. The depths for this zone in the wells ranged from 800 m, 900 m, and 1000 m.

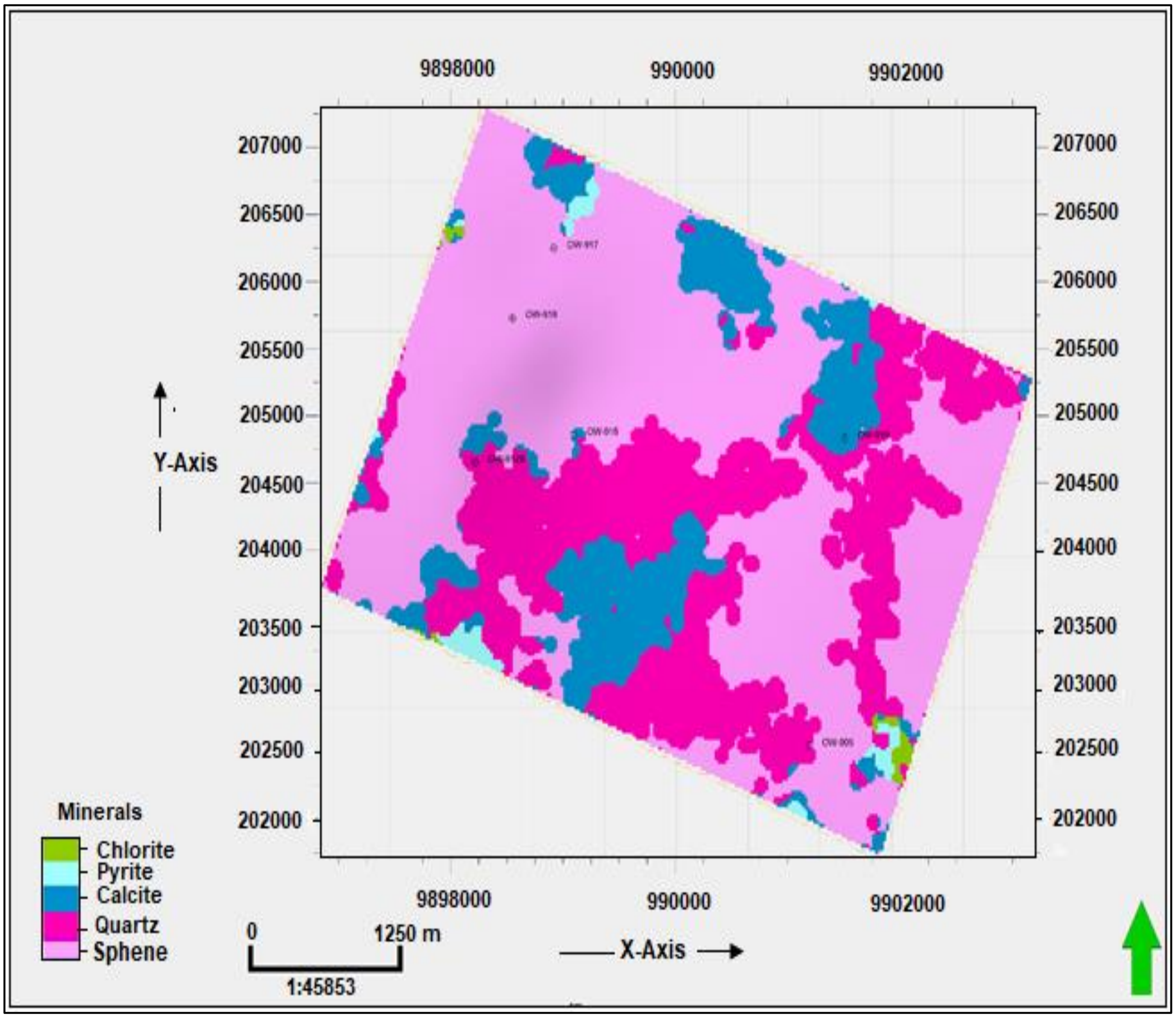
The lithology encountered in zone C, which was mainly trachyte, was a part of the reservoir rock formation of the Olkaria geothermal system.

Figure 8: Mineral Map for zone C



Mineral Map for Zone D

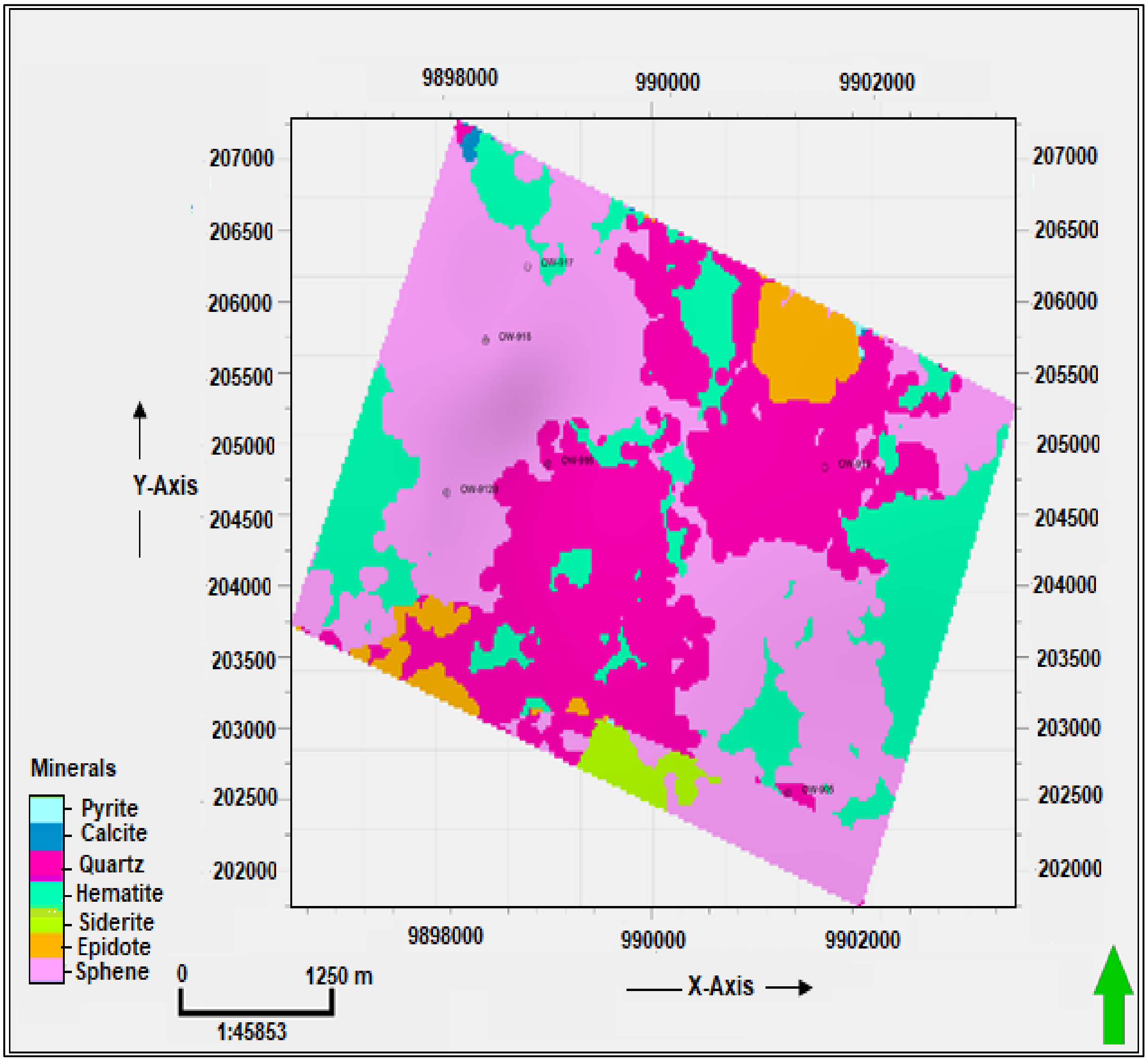
Figure 9: Mineral Map for zone D



The minerals encountered for this zone were chlorite, pyrite, calcite, quartz, and sphene.

Mineral Map for Zone E

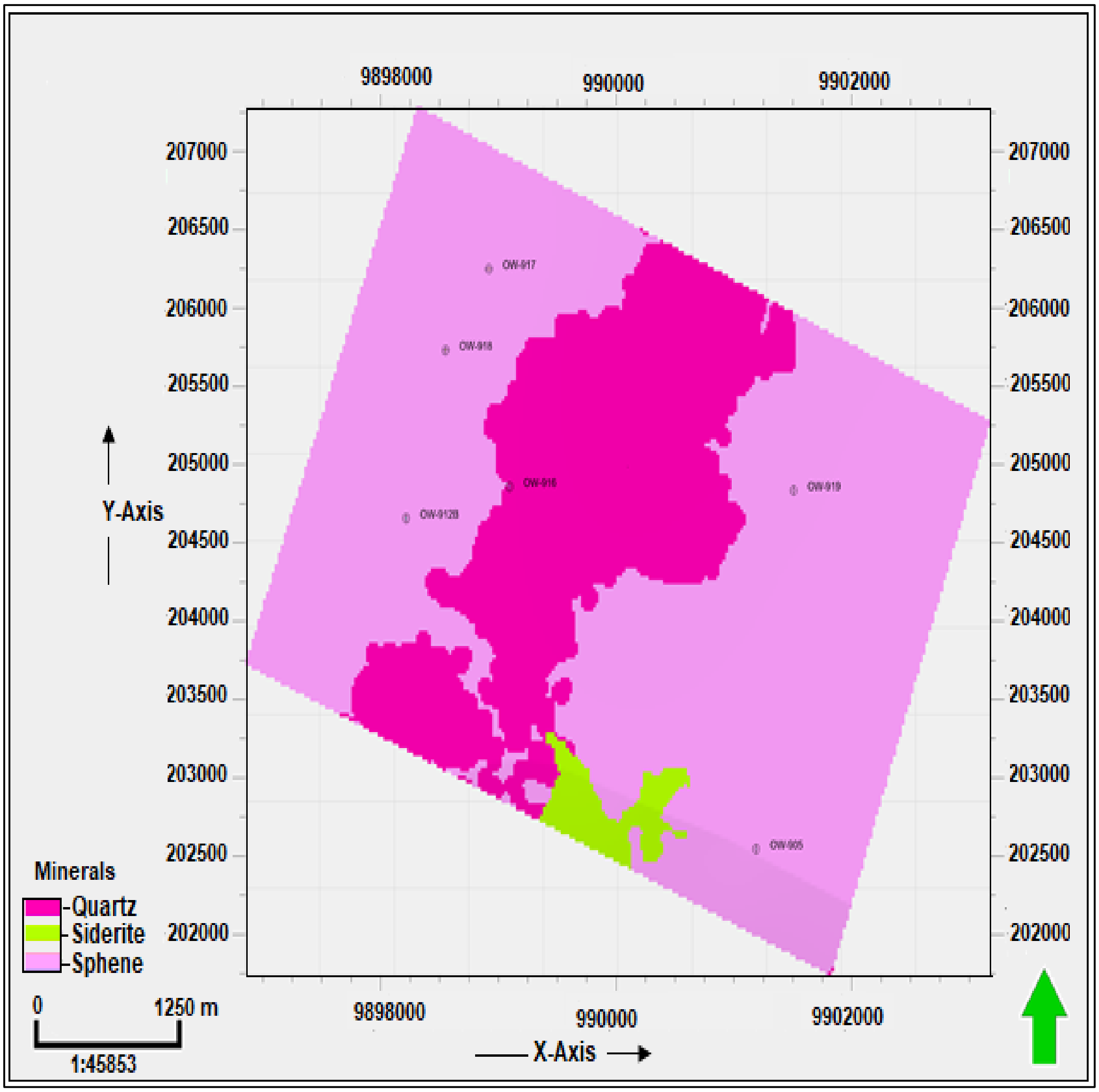
Figure 10:: Mineral Map for zone E



The minerals for this zone were pyrite, calcite, quartz, hematite, siderite, epidote, and sphene.

Mineral Map for Zone F

Figure 11: Mineral Map for zone F

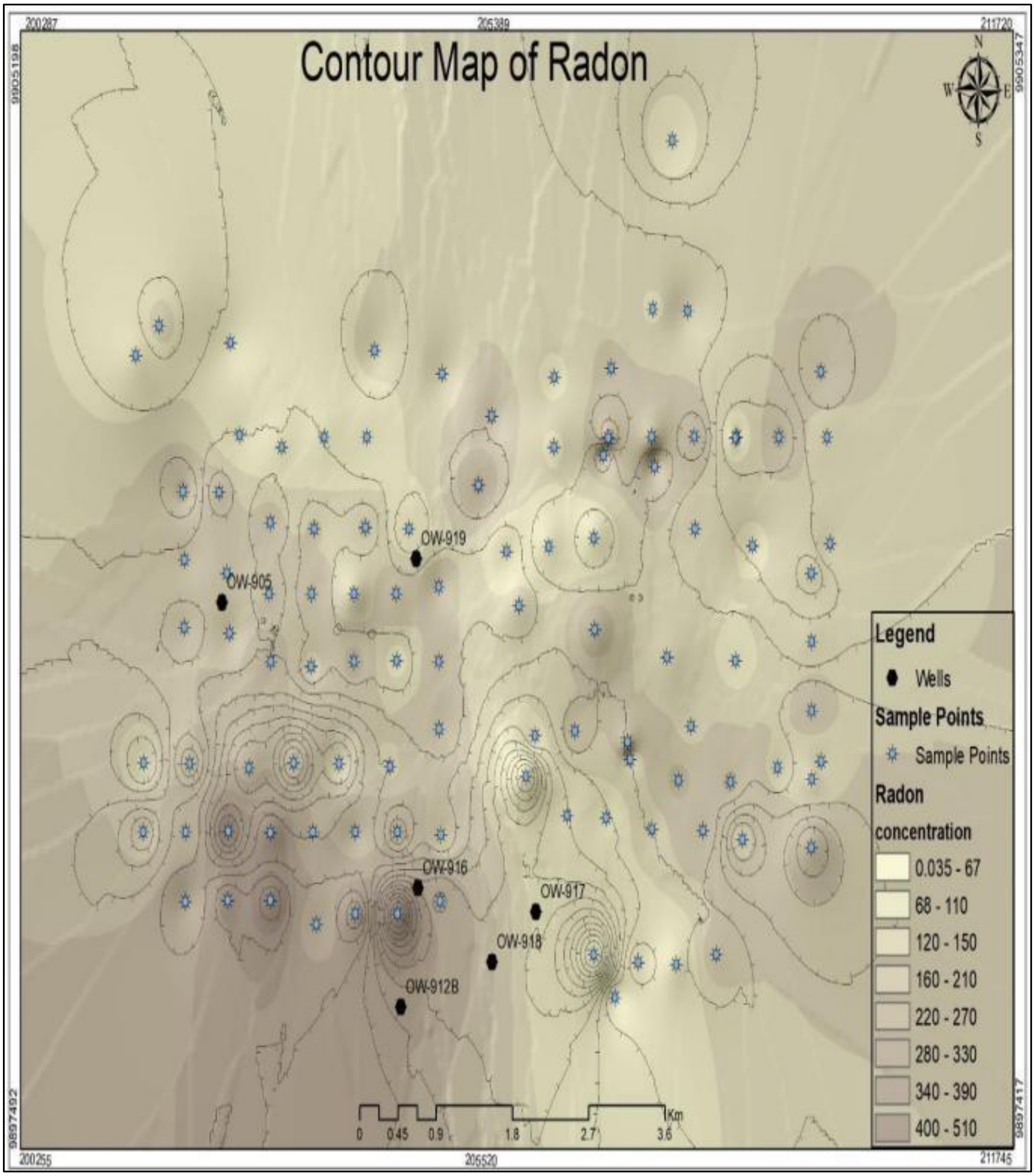


The minerals in this zone F were quartz, siderite, and sphene. It was concluded for the last three zones i.e., Zone D, E, and F, that the zones belonged to the prophyllic alteration facies. Normally, the prophyllic facies is associated with deeper depths and high temperatures in a geothermal system. The lithologies encountered in the deeper zones, being also permeable in the fractures section, were mainly basalts, trachyte, and rhyolites and were all part of the reservoirs in the Olkaria geothermal system.

Radon Concentration for the Domes field

The results from the Radon measurements in the Domes field were derived from 104 collection points. The highest concentration for Radon counts was 507 while the lowest concentration was 10 counts.

Figure 12: Map of Radon Concentration in Domes Field



The map for Radon concentration for high anomalies is as shown in figure 12 . The trends for the anomalies were west-southwest where Drill OW 905 and Drill OW 917 were located. It continued towards the East-south-east direction. These values of high radon indicate large permeability levels as it showed that the radon was readily migrating and reaching the surface through a highly permeable zone of high subsurface temperatures which is crucial for siting and drilling of additional wells in the Olkaria field.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Olkaria domes field is a high-temperature geothermal system. It has great potential for geothermal generation comprising a series of interconnected structural fractures and faults that enable hydrothermal fluids/gases to percolate. The regional E-W extensional forces caused the faults/fissures to develop, generally trending in NW-SE, N-S, and NE-SW directions. Magmatic intrusions that developed in the dome enhanced the generation of gases derived from the crater activities degassing carbon dioxide, radon, and even helium which then reached the ground surface through the fractures, cracks, and faults. The structures and faults either provide channels of enhanced permeability or divert flow direction. Some of the main features noted in binocular microscope analysis were; rock colour, grain size, rock fabric, rock type, primary and secondary mineralogy due to alteration and its intensities. Infilling of vesicles and vugs by secondary alteration minerals was an indication of permeability and porosity in the geothermal system of the dome.

The main features noted in the rock cuttings analysis were; rock colour, grain size, rock fabric, rock type, primary and secondary [alteration] mineralogy, and its intensities. X-ray diffractometer analysis done helped in the identification of clay minerals in the drill wells *(Figure 5)*. The platy-oriented samples were run on the diffractometer (air-dried) and treated by solvation with ethylene glycol, before heating to specified temperatures.

Identification of geological facies and radon gas concentration were also undertaken to show the areas of high temperatures and permeable zones.

Influence of Pyrite/Calcite on Subsurface Permeability in Olkaria Domes Field

Several authors (Mwania, 2015; Omwenga, 2019), had argued on alteration and geochemistry of Tertiary Volcanic Rocks such as those which were encountered in the Olkaria Domes Field of the area studied. Most of the bleaching processes in volcanic rocks were observed to occur relatively near-surface features as alteration of pyrite-bearing caused by the action of sulfuric acid (Whitebread, 1976).

Zones B, C, D, E, and F are the zones of interest since they had minerals that belong to both the phyllic and prophyllic alteration facies that are associated with reservoirs that have high temperatures and permeable zones in a geothermal system. Pyrite and calcite are concentrated in the South East (zone B and C and D), in the North West (zone B, C, D, and E), in the South West (zone B, C, and D). Mineralogy of lithologies was observed in six wells, although three wells were captured for this paper i.e., Drill Well OW 917, Drill Well OW 919, and Drill Well OW 905. Pyrite dissemination, calcite precipitation, and zeolite alterations were encountered for the characterization of permeability of the drilled wells. The occurrence of the secondary hydrothermal alteration minerals and their infilling of the vesicles and veins showed that the permeability of the Domes field was lithologically controlled, with pore spaces that were formed in the rocks from the magmatic cooling process.

As earlier noted, a hydrothermal alteration was contributed by pressure, temperature, nature of host rock or wall rock composition, fluid composition, and chemical potential of the fluid components such as H^+, CO_2, O_2, K^+, and SO_2 as well as fluid/rock ratio.

Radon Gas Survey and Subsurface Permeability of Olkaria Domes Field

The contour map for Radon concentration was plotted and it showed the areas with high anomalies. Trends for the anomalies were noted for the drill wells studied from West-southwest to the East-southeast direction. These values of high radon indicated large permeability levels as it showed that the radon was readily migrating and reaching the surface before reaching its decay endpoint. These anomalous zones are not only associated with highly permeable zones but also high subsurface temperatures which is crucial for siting and drilling of additional wells in the field. Subsequently, from mineral maps, the areas that showed high concentrations of radon gas were several with most of them forming lines with each other. The alignment of the high anomaly zones characterized the appearance of faults and or fractures (Haerudin et al., 2013). From the observations made it was concluded that some of the permeable zones in the domes field were structurally controlled by fractures, cracks, and faults in the field.

CONCLUSIONS

The lithology encountered in the study area is mainly pyroclastics, rhyolites, tuffs, basalts, and trachytes, and minor intrusions. Hydrothermal alteration facies were grouped into three. Argillic facies, phyllic facies, and prophyllic facies.

The secondary mineral maps created showed that pyrite and calcite are concentrated in the South East (zone B and C and D), in the North West (zone B, C, D, and E), in the South West (zone B, C, and D).

The occurrence of these secondary hydrothermal alteration minerals and their infilling of the vesicles and veins showed that the permeability of the Domes field is lithologically controlled, with pore spaces that were formed in the rocks from the cooling magma. The contour map for Radon concentration was plotted and it showed the areas with high anomalies. The alignment of the high anomaly zones was characterizing the appearance of faults and or fractures confirmed that some of the permeability in the domes field was structurally controlled by fractures, cracks, and faults in the field.

Recommendations

It was beyond the scope of this work to address other techniques that consider water, gas, and stable isotope composition (both in liquid and gas phases) of geothermal fluids in the Domes field. Apart from faulting and fracturing of volcanic rocks which enhance permeability as well as the porosity, other relevant processes like modification of isotopic composition after infiltration of subsurface water interfaces in terms of water-rock exchanges, formation of secondary minerals as well as exchange with the gaseous phases (CO_2 and H_2S) were not exhaustively undertaken and are hereby recommended although having been limitations to the present study efforts.

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