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Structural and Hydrogeological Characterization of the Olkaria Dome Geothermal Field, Lake Naivasha Basin

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Abstract

The Olkaria Dome Geothermal Field in the Lake Naivasha Basin is one of Kenya's principal geothermal resource areas, where fluid circulation and reservoir performance are strongly controlled by geological structures and hydrogeological conditions. This study integrates geological, structural, hydrogeological, mineralogical, and soil-gas data to characterize reservoir permeability and fluid flow pathways. Correlation of lithological units with drilling circulation-loss zones identifies highly fractured formations that enhance geothermal fluid movement. Mineralogical mapping delineates hydrothermal alteration associated with fluid–rock interaction, while soil-gas surveys using radon and carbon dioxide reveal fault-controlled permeable zones and subsurface connectivity within the geothermal system. The results demonstrate that structural controls significantly influence geothermal fluid circulation and reservoir behavior. These findings provide a basis for improved reservoir management, well targeting, and sustainable geothermal resource development in the Olkaria Dome Geothermal Field.

Keywords: Olkaria dome geothermal field, Lake Naivasha basin, geothermal exploration, structural geology, hydrogeology, reservoir permeability, soil-gas geochemistry

INTRODUCTION

The Olkaria geothermal field, situated within the Kenyan Rift Valley and part of the East African Rift System (EARS), remains largely underexploited, despite its significant geothermal potential. EARS offers a valuable opportunity to investigate plume-driven continental rifting. The eastern branch of the EARS extends over 2000 km from the Red Sea southward to Mozambique (Figures 1–3). This branch traverses two regions characterized by topographic uplift: the Ethiopian and Kenyan domes, both of which are considered surface expressions of mantle plumes [1–3].

Two models have been proposed for the evolution of the East African Rift System (Figure 1(a)–(c)). The first model posits that hotspots in the mantle caused significant crustal uplift during the early Miocene, leading to the formation of highlands and the development of cracks along weak fault lines (Klemens et al., 2010). Davis and Slack (2002) used S-wave delays and P-wave tomography to identify a mantle convection cell beneath the Kenyan and Ethiopian domes. They suggested that the East African rifts resulted from the separation of deeper mantle upwellings into three currents, which eroded the lithosphere's base, driving domal uplift and the brittle failure of the upper lithosphere, ultimately forming rift grabens [4–6].

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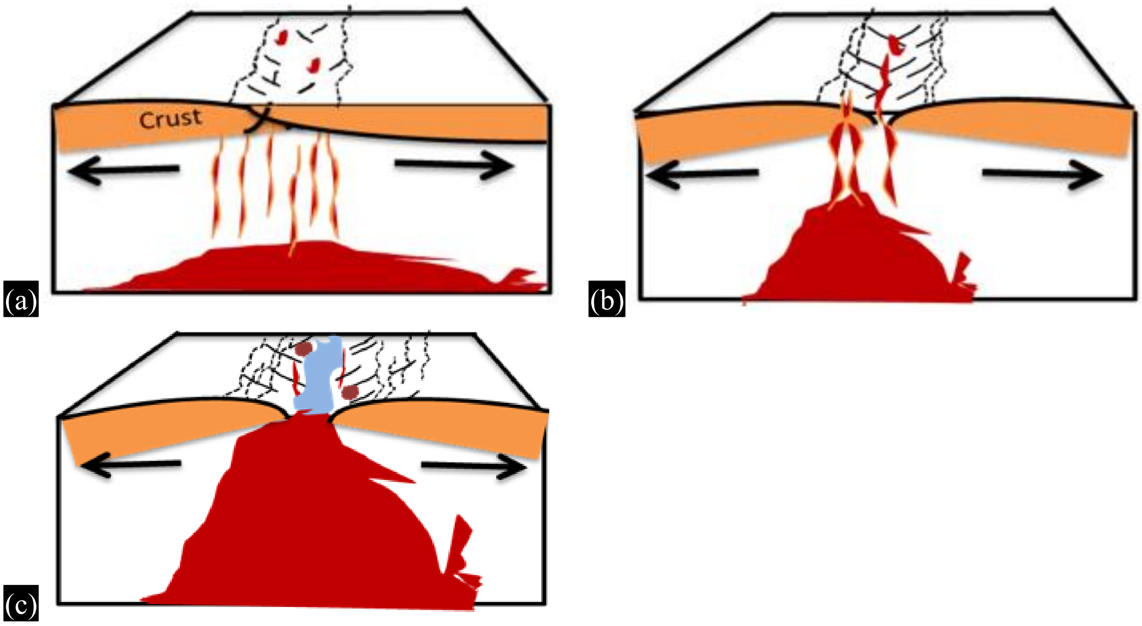

Figure 1. (a-c) The tectonic evolution of the East African Rift System (EARS). It illustrates the geological processes and structural changes that have occurred over time, highlighting the key phases of rifting and the development of associated geological features (Figure 1 (a)). Crustal thinning, combined with magma upwelling, causes tear on the continental crust (Figure 1(b)). Continued thinning causes further extension of the crust, with formation of graben and half-graben (Figure 1(c) Magmatic intrusion leads to formation of oceanic crust, with sediment accumulating progressively.

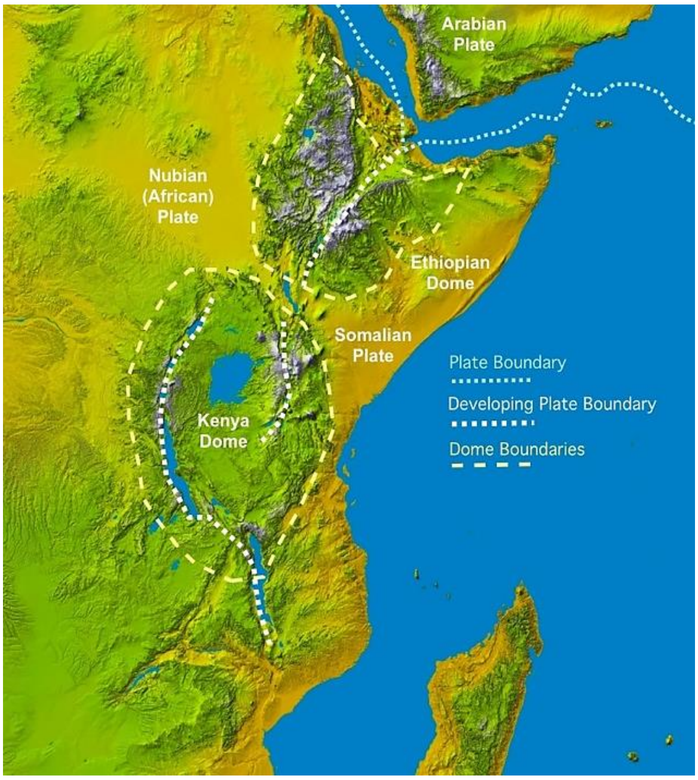

Figure 2. A color-rendered Digital Elevation Model showing tectonic plate boundaries, elevation highs representing thermal bulges, and the locations of large lakes in East Africa. The basemap is derived from a Space Shuttle radar topography image from NASA [4].

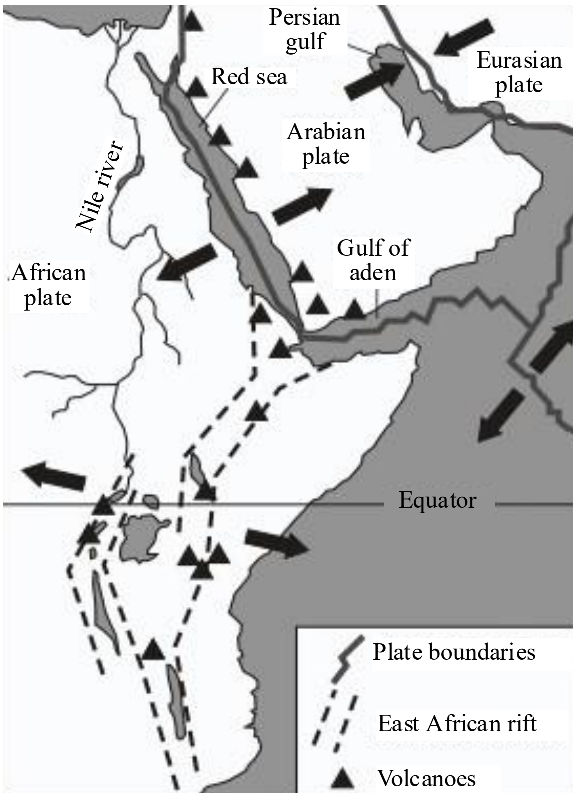

Figure 3. A schematic diagram of Rift Valley formation alongside the East African Rift System. It visually represents the geological processes and structures involved in the rifting, highlighting key features of the rift system.

Numerous studies have been conducted in the region, leading to significant advancements in the direct utilization of geothermal resources. A variety of wells have been drilled and developed across the Olkaria, Eburru, and Menengai fields, facilitating applications such as greenhouse heating, fumigation, crop drying, milk pasteurization, fish farming, and recreational activities [7].

This study focuses on the geoscientific characteristics of the Olkaria Domes field, specifically examining geological and geochemical factors to assess the permeability of the area. This study involved a detailed analysis of rock types through the examination of drill cuttings obtained from various wells within the Olkaria Domes field, situated in the Lake Naivasha Basin, which is characterized by a complex hydrogeological system significantly influenced by volcanic activity and faulting [8].

Geothermal manifestations occur when magma, a natural material at high temperatures, heats groundwater that seeps down from the surface through pores and weak zones in the rock masses. This magma can form a magmatic chamber located at shallow depths beneath the ground surface, erupt at volcanic centers, or upwell to the surface through regional faults, particularly those associated with the evolution of rift valleys (Figure 1). These processes contribute to the development of geothermal features and energy resources [9].

Geothermal systems are classified into three main categories. The first category is *volcanic geothermal systems*, which have their heat source from hot intrusions or magma chambers located within the Earth's crust. The second category, *convective systems*, is characterized by deep water circulation in tectonically active areas, which typically exhibit a high geothermal gradient. Lastly, *sedimentary systems* consist of permeable layers found at depths of 2–5 km, often including geo-pressured systems that are frequently associated with oil resources. Each category represents distinct geological conditions and mechanisms for harnessing geothermal energy [10–14].

Understanding the hydrogeology of a basin is essential for the sustainable management of geothermal resources, which includes optimizing well placement, developing effective reinjection strategies, and mitigating potential environmental impacts. Sustainable practices are vital for ensuring the long-term viability of geothermal energy production [15].

Further research is necessary to develop sophisticated models that simulate fluid flow and heat transport within the Olkaria geothermal system, which is crucial for optimizing resource management. Enhanced modelling efforts can provide insights into the complex interactions within geothermal systems. Continuous monitoring of water levels, water quality, and fluid pressure in the basin is essential for tracking changes in the hydrogeological system and assessing the impacts of geothermal development. Regular data collection informs adaptive management strategies [16–18].

An integrated approach that combines geological, geophysical, geochemical, and hydrological data is essential for comprehensively understanding the Olkaria geothermal field and its surrounding environment. This holistic approach will facilitate more effective resource management and contribute to the sustainability of geothermal energy production, ultimately supporting the broader goal of harnessing renewable energy sources to meet the growing energy demands in Kenya and beyond while promoting environmental sustainability [19].

The implications of this study extend beyond the immediate context of the Olkaria geothermal field. As the demand for renewable energy sources continues to rise globally, the insights gained from this study can serve as a model for similar geothermal projects in other regions of the world. By demonstrating the importance of an integrated approach to resource management, this study underscores the necessity of collaboration among geoscientists, engineers, and policymakers to ensure that geothermal energy is developed responsibly and sustainably [20].

Moreover, the findings contribute to the formulation of best practices for geothermal resource exploitation, particularly in areas with complex hydrogeological systems. The emphasis on continuous monitoring and adaptive management will help mitigate the potential risks associated with geothermal development, such as land subsidence, water depletion, and environmental degradation [21].

In conclusion, the Olkaria geothermal field presents a significant opportunity for sustainable energy production, provided comprehensive research and management strategies are implemented. This study aims to enhance the understanding of the dynamics of geothermal systems, thereby facilitating informed decision-making and promoting the sustainable utilization of geothermal resources. By prioritizing sustainability and environmental stewardship, the Olkaria geothermal field can play a pivotal role in meeting Kenya's energy needs while contributing to global efforts to transition to renewable energy sources [22].

Geotectonic-Geothermal Evolution of the EARS

The East African Rift System (EARS) developed a series of asymmetric grabens and half-grabens from the Late Permian to the Tertiary period, driven by protracted continental rifting. These structures have undergone continuous subsidence, amplified by rapid sediment loading from adjacent highlands, with their orientations controlled by the dominant tectonic regimes [23].

The EARS hosts extensive geothermal manifestations, including high-temperature fumaroles, hot springs, and volcanic lakes, which result from shallow magma chambers and deep-circulating meteoric fluids along fault conduits (Figures 4 and 5).

Notably, Quaternary volcanism and elevated heat flow (>100 mW/m^2) in the Kenyan and Ethiopian rifts underscore the system's active magma-assisted extension. The spatial correlation between rift faults and geothermal fields (e.g., Olkaria) highlights the critical role of graben-bounding faults in localizing hydrothermal upflow, offering direct exploration targets for renewable energy exploitation.

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The Olkaria geothermal field (0°54′S, 36°17′E) is located within the Kenya Rift Valley (Figure 6), a segment of the East African Rift System (EARS), characterized by Cenozoic continental rifting, crustal extension, volcanism, and associated hydrothermal activity. Faults in geological formations have significant environmental effects, including increased hydraulic conductivity of rock masses, facilitating fluid flow. They create pathways for magma, leading to volcanic activity and dike formation. Movement along faults can concentrate minerals through hydrothermal fluid deposition.

Figure 4. Illustrates the Olkaria geothermal steam-head site, highlighting its geothermal features and steam emissions. This site is crucial for Kenya's geothermal energy production, showcasing both the natural geothermal activity and the infrastructure used to harness steam for electricity generation within the East African Rift System.

Geothermal Manifestations: Hot springs (A), Geysers (B), Fumaroles (C), Hot ground (D) and Sulphur deposition (E)

Figure 5. (a-e) Depicts various geothermal manifestation features in the Kenya Rift Valley, including hot springs, geysers, fumaroles, and steaming grounds. These features highlight the region's geothermal potential, linked to the tectonic activity of the East African Rift System. The plate emphasizes the significance of these manifestations for renewable energy development and their role in the local ecosystem.

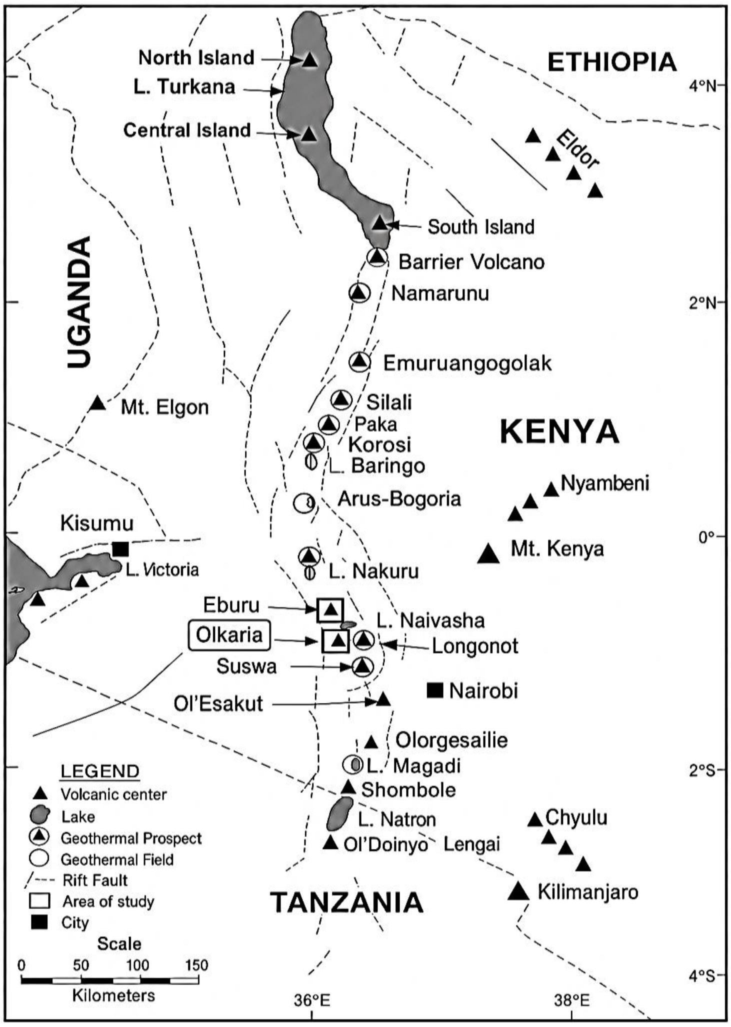

Figure 6. Is a map of the Kenyan Rift, showing the location of the Olkaria geothermal field and other volcanic centers, highlighting the region's geothermal resources and volcanic activity.

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Additionally, faults influence the stress distribution in the Earth's crust, potentially causing seismic activity and earthquakes. They can alter landscapes, affect stream bed flow and elevation, and cause lateral displacement of mineralized rock formations, impacting resource extraction. In geothermal systems, faults are essential for energy production, as they significantly influence various processes (Figure 7).

Understanding fault dynamics is crucial for simulating geothermal reservoir sections and predicting their behavior. Faults control fluid flow patterns, impacting the efficiency of heat extraction, whereas their hydraulic properties affect temperature and pressure distributions within these systems (Figures 7 and 8).

Faults often serve as conduits for geothermal fluids, contributing to the formation of geysers and hot springs. Knowledge of fault locations is important for selecting optimal drilling sites for geothermal exploration, and effective reservoir management depends on an understanding of fault interactions and their effects on reservoir dynamics. Consequently, fluid flow along fault zones is a key aspect of both geological processes and geothermal energy systems, facilitating the movement of fluids that transport heat and minerals and influencing seismic activity and geological stability.

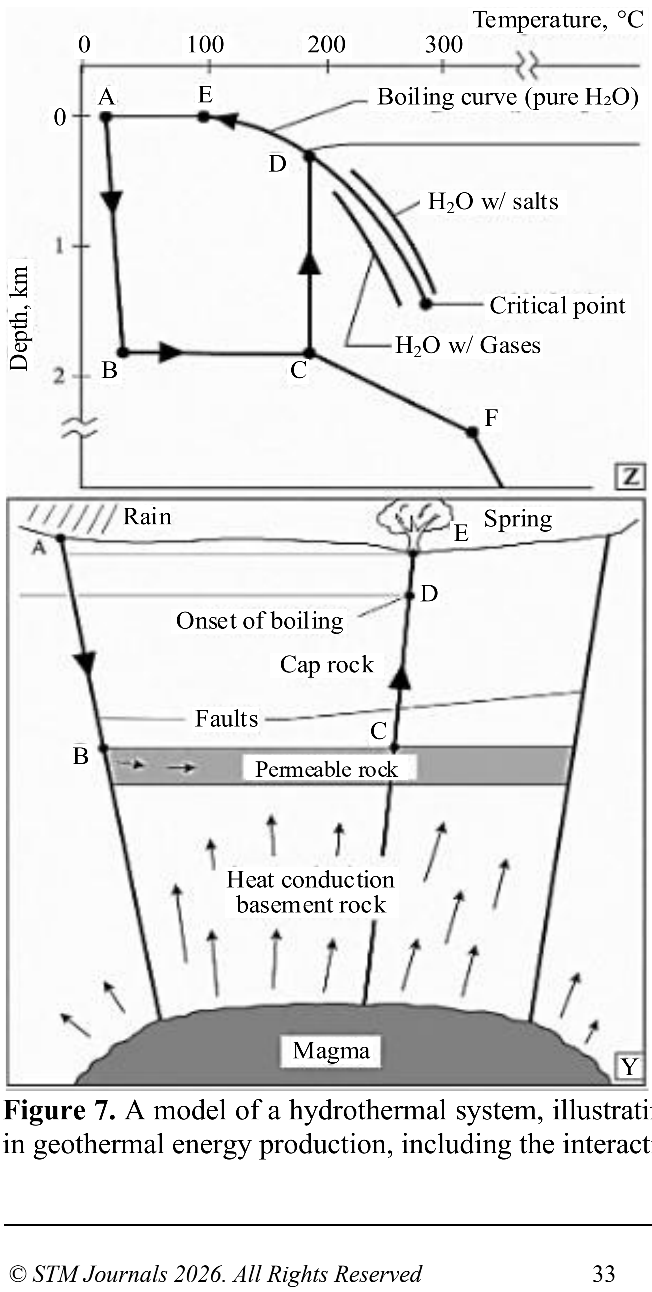

Figure 7. A model of a hydrothermal system, illustrating the key components and processes involved in geothermal energy production, including the interactions between water, heat sources, and geology.

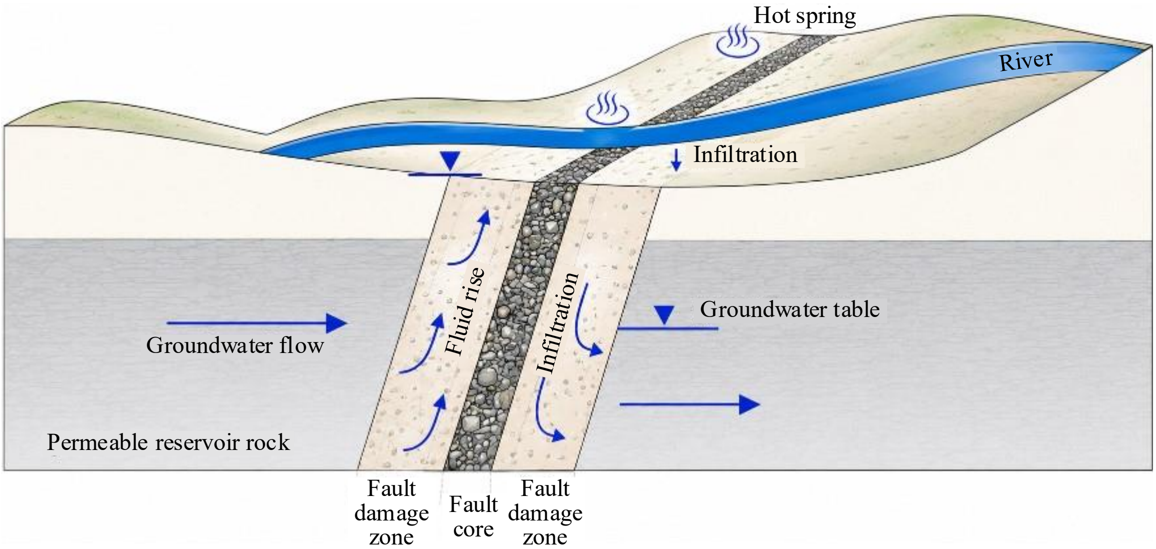

Figure 8. A schematic section of the Lahendong geothermal area in Indonesia, illustrating the geological layers, reservoir characteristics, and fluid flow pathways. It highlights the subsurface features essential for understanding the geothermal system's energy potential and the infrastructure necessary for geothermal energy extraction and utilization.

Thus, the Lake Naivasha Basin exemplifies a half-graben structure delineated by north-south-trending border faults, including the Solai and Kinangop faults. This basin is filled with an asymmetric depression containing Pleistocene to Holocene pyroclastics, trachytic lavas, and lacustrine sediments (Figure 8).

The Olkaria volcanic complex consists of late Pleistocene trachyte domes that intrude into earlier rift-filling ignimbrites. The lithological diversity, ranging from permeable tuffs to fractured trachyte flows, results in anisotropic permeability domains that govern fluid migration. Notably, the NNE-SSW-trending Gicheru fault system intersects the domes, localizing upflow zones for geothermal fluids.

Hydrogeological Characteristics and Fluid Dynamics

The hydrogeological framework of the Lake Naivasha Basin comprises a complex aquifer system that is crucial for the hydrology and geothermal dynamics of the region. This system can be broadly categorized into two components: shallower aquifers and deep geothermal reservoirs.

Shallower Aquifers (0–300 m Depth)

Shallower aquifers are primarily composed of unconsolidated pyroclastic materials, including pumice and tuffs, exhibiting significant porosity (15%–25%) that facilitates groundwater storage and movement. The hydraulic conductivity of these aquifers ranges from 0.1 to 0.5 m/s, indicating a moderate capacity for water transmission, particularly during recharge periods. Recharge is predominantly driven by orographic rainfall on the Mau Escarpment, where high precipitation rates result from the interaction between steep slopes and moisture-laden winds. This process replenishes shallow aquifers, which are critical for local water supply, supporting ecological systems and human activities, including agriculture and domestic use.

Deep Geothermal Reservoir (500–2,500 m)

Beneath the shallower aquifers lies a deep geothermal reservoir, extending from 500 to 2,500 m. This reservoir is primarily composed of fractured trachyte (Table 1), which exhibits a lower fracture porosity (typically less than 5%). However, hydrothermal alteration processes enhance matrix permeability, resulting in illite-smectite zonation that influences the thermal and chemical characteristics of geothermal fluids. Isotopic analyses of stable isotopes, such as oxygen (^{18}O) and hydrogen (^{2}H), reveal distinct mixing patterns between meteoric water and geothermal fluids, providing insights into the hydrological dynamics of the reservoir. Chloride-enthalpy modelling estimates reservoir temperatures in the central production zone to be between 240°C and 300°C, which are essential for efficient geothermal energy production. Tritium dating studies indicate that the residence times of deep geothermal fluids exceed 50 years, suggesting a stable geothermal system with significant thermal and chemical evolution during subsurface passage.

Understanding these residence times is crucial for assessing the sustainability of geothermal resource extraction and the potential impact of groundwater abstraction on hydrological systems.

CONCLUSION

The hydrogeological characteristics and fluid dynamics of the Lake Naivasha Basin are defined by a dual aquifer system comprising shallower aquifers and a deep geothermal reservoir (Table 1).

Shallower aquifers, characterized by unconsolidated pyroclastics, are vital for local water supply and are recharged by orographic rainfall. In contrast, deep geothermal reservoirs, composed of fractured trachyte, are essential for geothermal energy production, and their thermal and chemical properties are influenced by hydrothermal alteration and fluid mixing processes. Continued research and monitoring of these hydrogeological dynamics are essential for sustainable resource management and optimization of geothermal energy extraction in the region.

Hydrothermal alteration is a critical parameter for understanding the subsurface characteristics of geothermal systems. It can be categorized into three alteration facies: argillic, phyllic, and propylitic. Each facies reflects distinct thermal conditions within the system: argillic facies indicate low temperatures at shallower depths, and phyllic facies are associated with increasing temperatures and the presence of reservoirs. In contrast, the propylitic facies correspond to high-temperature environments. The occurrence of phyllic and propylitic alteration facies often signifies the presence of reservoirs and permeable zones.

Summary of Hydrogeology and Hydrological Dynamics of Lake Naivasha and Olkaria Dome Fields

Lake Naivasha, located in the Kenyan Rift Valley, is a crucial freshwater lake within an active rift basin, characterized by complex geological interactions and bordered by significant fault lines. The groundwater system surrounding the lake is intricately linked to its water balance, influenced by recharge from adjacent highlands, evapotranspiration, and subterranean outflows, particularly from the Mau Escarpment.

As a significant groundwater reservoir with no surface outflow, Lake Naivasha relies on a delicate equilibrium between precipitation, evaporation, and groundwater interaction. However, long-term data indicate declining water levels due to climatic variability and increased groundwater extraction for irrigation purposes.

The Olkaria Dome Fields contribute to the hydrogeological framework through geothermal activity, with volcanic rocks facilitating fluid migration. Hydrogeochemical analyses show mixing between geothermal fluids and meteoric waters, characterized by alkaline-chloride chemistry.

However, geophysical investigations have mapped subsurface structures that control fluid flow and heat transfer, identifying critical fault zones and thermal anomalies for resource development. Sustainable management of this hydrological system requires integrated models that combine geological, geochemical, and hydrological data, along with continuous monitoring of water levels and quality, to mitigate adverse effects such as lake-level decline and resource depletion.

Table 1. Primary minerals and their alteration products, highlighting the mineralogical changes in geothermal systems (Lagat, 2004)

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

In conclusion, the hydrogeology of Lake Naivasha and the Olkaria Dome Fields represents a dynamic and interconnected system that necessitates coordinated scientific investigation and resource management to balance geothermal exploitation, agricultural needs, and ecological preservation.

Geological and Structural Framework

The Lake Naivasha Basin is a tectonically active half-graben, characterized by distinctive geological and structural features. Bounded to the west by the Mau Escarpment and to the east by the Kinangop Plateau, the basin has been shaped by Quaternary extensional tectonics, resulting in a series of normal faults that are critical to its architecture and hydrology.

The structural framework is dominated by north-south (N-S) trending faults, including the Gilgil and Olkaria Fault Zones, which compartmentalize the aquifer system and significantly influence groundwater flow and geothermal activity. The Olkaria Dome Fields, situated approximately 20 km southeast of Lake Naivasha, consist of Pleistocene trachytic-rhyolitic domes formed along fault systems, indicative of volcanic activity and essential to the region's geothermal potential.

Lithology

The lithological composition of the Lake Naivasha Basin varies significantly with depth, impacting both aquifer characteristics and the geothermal reservoir.

Shallow Aquifers (0–300 m): These are composed of unconsolidated pyroclastics, including pumice and tuffs, with porosity levels ranging from 15% to 25%. This high porosity facilitates groundwater storage and movement, allowing for rapid infiltration and recharge, which are crucial for local water supply and ecological sustainability.

Reservoir Rocks (>500 m): At greater depths, the lithology transitions to fractured trachyte lavas, which serve as the primary reservoir rocks for the geothermal system. These rocks exhibit secondary permeability enhanced by hydrothermal alteration processes, resulting in illite-smectite assemblages that contribute to the overall permeability and thermal conductivity (Karingithi, 2020). The fractures within these trachyte lavas provide pathways for geothermal fluids, enabling efficient heat transfer and energy extraction.

The geological and structural framework, along with lithological characteristics, plays a pivotal role in shaping the hydrology and geothermal potential of the region. A comprehensive understanding of these elements is essential for effective resource management and the sustainable development of geothermal energy.

PREVIOUS RESEARCH IN OLKARIA

The Lake Naivasha Basin and adjacent Olkaria Dome Fields have attracted considerable scientific interest owing to their geothermal potential within the tectonically active Kenya Rift Valley. Previous studies have extensively investigated the structural framework, hydrogeology, and geochemical processes governing these geothermal systems, yielding critical insights into exploration strategies and sustainable resource development. The field has been advanced by employing gravity surveys to assess geothermal resources in the Olkaria Dome area. Their geophysical approach mapped subsurface density variations, delineating major fault zones and volcanic structures that act as permeability pathways for the geothermal fluids. These structural insights are essential for targeting geothermal reservoirs and effectively managing exploration risk.

In a complementary study, Short-Wave Infrared Reflectance (SWIR) spectroscopy was used to characterize hydrothermal alteration minerals within the Olkaria geothermal field. This innovative method enabled high-resolution mineralogical mapping, revealing alteration zones indicative of temperature and fluid pathways at depth. Their findings enhanced the understanding of the evolution of geothermal systems by correlating mineralogical signatures with underlying structural controls.

The subdivision of the Olkaria geothermal field into seven distinct sections, including the Olkaria Domes field, has been instrumental in addressing reservoir heterogeneity and structural compartmentalization. This segmentation has improved reservoir characterization by highlighting the varying productivity levels across sectors, which are primarily influenced by fault-bounded blocks and fracture networks. This geological segmentation aligns with geophysical data identifying fault zones as fluid conduits.

Hydrogeological studies have emphasized the significance of tectonic faults and fracture permeability in governing groundwater and geothermal fluid flow. The hydrothermal system is sustained by recharge from the Mau Escarpment, with fluid migration facilitated by north-south to northeast-southwest-trending faults and intersecting fracture networks. Fluid geochemistry indicates a mixing of meteoric waters and deep geothermal fluids, characterized by distinctive alkali-chloride water types rich in sodium, potassium, and bicarbonate ions.

Additional geophysical investigations, including magnetotelluric, seismic, and gravity surveys, have complemented structural studies by mapping the extent and geometry of geothermal reservoirs, heat sources, and alteration zones. These multi-method surveys provide a three-dimensional understanding of permeability distribution, which is essential for optimal well placement and sustainable resource extraction in aquifers.

Collectively, these contributions underscore a multidisciplinary approach that integrates structural geology, geophysics, mineralogy, and hydrogeochemistry to characterize the Lake Naivasha Basin and Olkaria Dome Fields as prime geothermal exploration domains. The integration of these datasets has refined geothermal conceptual models, enhanced predictive capabilities for exploration, and informed best practices for resource management.

RESEARCH METHODS

Introduction

The Olkaria Domes geothermal field, located within the East African Rift System, is one of Kenya's most productive geothermal areas. A thorough understanding of the geological and structural characteristics of this field is essential for effective resource management and its development. This study employed a combination of field surveys, geological mapping, and geochemical analyses to characterize the subsurface features and assess the permeability distribution within the geothermal system.

Sampling and Analytical Methods

Rock cuttings from the wells were sampled at 2 m intervals, with 4 m intervals used when the samples were insufficient or unrepresentative. Initial analysis of the cuttings was conducted on-site using a binocular microscope, from which representative samples typical of the encountered rock units 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 washed with running water to remove impurities, such as drilling foam and dust. The samples were then wetted to enhance their visibility and minimize surface reflection. Key features noted during the analysis included rock color, grain size, rock fabric, rock type, and both primary and secondary alteration mineralogy and intensities, observed in the rock matrix, fractures, vesicles/vugs, and mineral veins.

Petrographic Microscope Analysis

Thin sections of selected representative samples were prepared for a detailed analysis. This analysis confirmed the rock type, texture, and alteration mineralogy, while also providing insights into the mineralogical evolution and sequence within the well, thereby supplementing the information obtained from the binocular microscope observations.

X-ray Diffractometer Analysis

X-ray diffraction analysis was employed to identify the clay minerals within the well. This process began with the separation of a clay-sized fraction (typically < 2 microns) from the sample. The clay fraction was collected on a filter and transferred to a glass slide substrate using the 'filter peel' method, which enhanced the preferred orientation of platy clay particles, yielding a strong diffraction signal from the diagnostic basal planes of the clay minerals. This method also ensured a homogeneous sample for quantitative analysis. The oriented samples were analyzed on the diffractometer in their air-dried state, followed by treatments such as solvation with ethylene glycol and heating at specified temperatures for designated durations. The resulting peak positions, shapes, intensities, and changes due to these treatments were critical for identifying various clay minerals.

Lithological Analysis

Detailed field mapping was conducted to document the distribution of volcanic units, including trachytic lavas, pyroclastics, and ignimbrites, as well as structural features such as faults, fractures, and hydrothermal alteration zones. This analysis provides a foundational understanding of the geological framework of the Olkaria Domes field.

Stratigraphic Correlation

The measured sections were logged to establish the vertical and lateral relationships between the rock units, facilitating the identification of potential reservoir horizons. This stratigraphic correlation is essential for understanding the geological history and fluid flow pathways of the geothermal system.

Structural and Geological Setting of the Olkaria Domes Field

The Olkaria Domes Field is characterized by several key geological and structural features:

i. *Structural framework:* The field is defined by north-south-trending normal faults with vertical displacements ranging from 100 to 500 m. These faults serve as conduits for fluid upflow, facilitating the movement of geothermal fluids in the system.
ii. *Lithological characteristics:* The predominant lithology consists of porphyritic trachyte lava intercalated with pyroclastic deposits. These materials exhibit variations in primary porosity, ranging from 5% to 25%, which influences the capacity of the reservoir to store and transmit fluids.
iii. *Hydrothermal alteration zonation:* A distinct vertical alteration profile was observed, transitioning from smectite-dominated zones at lower temperatures to epidote-actinolite zones at higher temperatures. This alteration reflects the temperature gradients and fluid-rock interactions occurring within the geothermal system.

Geological structures play a crucial role in governing fluid movement in geothermal systems. They can create channels with enhanced permeability or act as barriers that restrict or redirect flow. Key structures include faults, fractures, and fissures, which significantly influence the dynamics of fluid movement and the overall efficiency of geothermal reservoirs (Figure 9).

This comprehensive approach integrates geological, geochemical, and remote sensing data to effectively characterize the Olkaria Domes Field, facilitating informed decision-making for geothermal resource management.

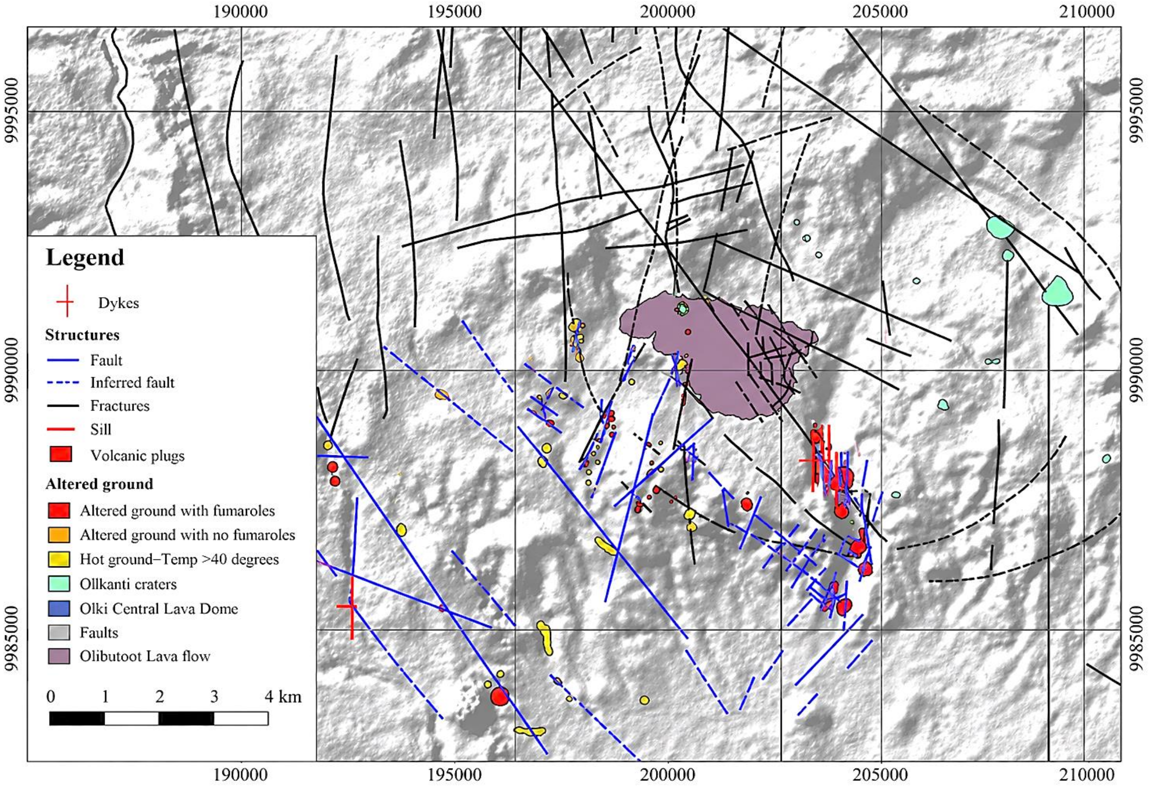

Figure 9. Structural map of Olkaria (Mwania, 2015.

INTERPRETATIONS, RESULTS AND DISCUSSIONS

A comprehensive lithological correlation and petrographic analysis were undertaken, encompassing six drill wells: OW-905, OW-912B, OW-916, OW-917, OW-918, and OW-919, which were subjected to detailed geological characterization.

Concurrently, geochemical data were acquired through soil gas surveys conducted across the Olkaria Domes field, specifically targeting CO_2 and radon concentrations, which are critical geochemical indicators for delineating permeable zones and elevated temperature regimes within geothermal systems.

The petrographic examination of drill cuttings focused on several key diagnostic parameters: lithochromatic characteristics, granulometric properties, textural relationships, lithological classification, and both primary and secondary (hydrothermal alteration) mineralogical assemblages, including their respective intensities. Mineralogical identification was enhanced through X-ray diffractometry (XRD) analysis, which proved instrumental in characterizing clay mineral assemblages within the drill wells. The analytical protocol involved the preparation of oriented clay specimens, which were subsequently analyzed under air-dried conditions, followed by ethylene glycol solvation treatment and controlled thermal analysis at predetermined temperatures.

Thus, this study focuses on a detailed analysis of three representative drill wells—OW-917, OW-919, and OW-905—from a comprehensive study encompassing a total of six wells in the Olkaria geothermal field. The primary aim of this analysis was to elucidate the fundamental descriptive methodologies employed in the examination of these wells. By doing so, this study seeks to demonstrate the analytical framework that underpins the entire investigation.

This targeted approach not only enhances our understanding of the geological characteristics inherent to the Olkaria geothermal field but also highlights the analytical techniques crucial for interpreting the data collected from these wells. Through a thorough examination of the selected wells, we aim to provide insights into the geothermal potential of the region and the methodologies that can be applied to similar geological studies. Ultimately, this study contributes to the broader field of geothermal research by offering a detailed case study that can inspire and trigger future investigations and applications.

By providing a comprehensive analysis of the selected drill wells, this study not only enhances our understanding of the Olkaria geothermal field but also serves as a valuable reference for researchers and practitioners seeking to explore similar geothermal systems in the future. The insights gained from this study may pave the way for innovative approaches and methodologies in the field, fostering further exploration and development of geothermal resources.

Figure 7 illustrates the lithological variations across the different drill wells, delineating the depth intervals of key rock types, including pyroclasts, rhyolite, tuff, basalt, and trachyte. Furthermore, the figure highlights the zones of lost circulation, which offer valuable insights into the geological structure and composition of the volcanic formations in the region. These correlations enhance our understanding of the geological framework and compositional characteristics of the volcanic formations within the Olkaria field.

In the following paragraphs, we provide a succinct summary of the six drilled wells included in our study of the Olkaria geothermal field. This summary encompasses essential information regarding each well, including descriptions of the rock types, depths, and geological formations encountered during drilling. Furthermore, we present the specific characteristics and data collected from each well, which are vital for characterizing the geothermal sequence in the region. Through a detailed examination of these wells, we aim to elucidate the subsurface conditions and overall geothermal system, thereby establishing a foundation for future analysis and exploration Figure 10.

Drill Well OW 905

The well features pyroclasts at depths of 0–266 m, intercalated with tuff from 134–184 m. The pyroclasts are a yellow-brown mixture of pumice, obsidian, and tuff, while the tuff is a greenish, fine-grained lava with silica-filled cavities. Rhyolite, tuff, and basalt dominate the next sections, with rhyolite appearing at various depths (304–362, 380–400, 410–506, and 678–830 m) and tuff at 362–380, 400–410, 574–606, and 652–678 m. Basalt is present at 506–574 and 606–652 m. The well also contains trachyte from 962 to 2974 m, with minor tuff and basalt occurrences. The loss of circulation was observed at multiple depths.

Drill Well OW 912B

The top section (0–12 m) consists of greyish unconsolidated pyroclastics, followed by a loss of returns from 12 to 48 m. Rhyolite dominates from 48 to 302 m, with loss of returns at specific intervals. A thick layer of trachyte extended from 302 to 1538 m, interspersed with rhyolitic sections. The well continued with rhyolite from 1538 to 2804 m, with further loss of returns at various depths. The trachyte at the bottom shows signs of intrusions.

Drill Well OW 916

The well begins with pyroclasts from 0–54 m, followed by intercalations of rhyolite, tuff, basalt, and trachyte at greater depths. Rhyolite was found at several depths, whereas tuff appeared as a brownish, fine-grained rock. Basalt is present at various depths, and the well features alternating layers of trachyte and rhyolite from 1172 to 2994 m. Loss of circulation occurs at multiple intervals.

Drill Well OW 917

The top section (0–110 m) consists of unconsolidated pyroclastic flow, with loss of circulation noted at 40–50 m. Rhyolite dominates from 110 to 560 m, with intercalations of tuff, breccia, and basalt. A thick layer of trachyte extends from 560 to 2912 m, with various intercalations and loss of circulation at several depths. Trachyte and basalt intrusions were also noted.

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Olkaria field.

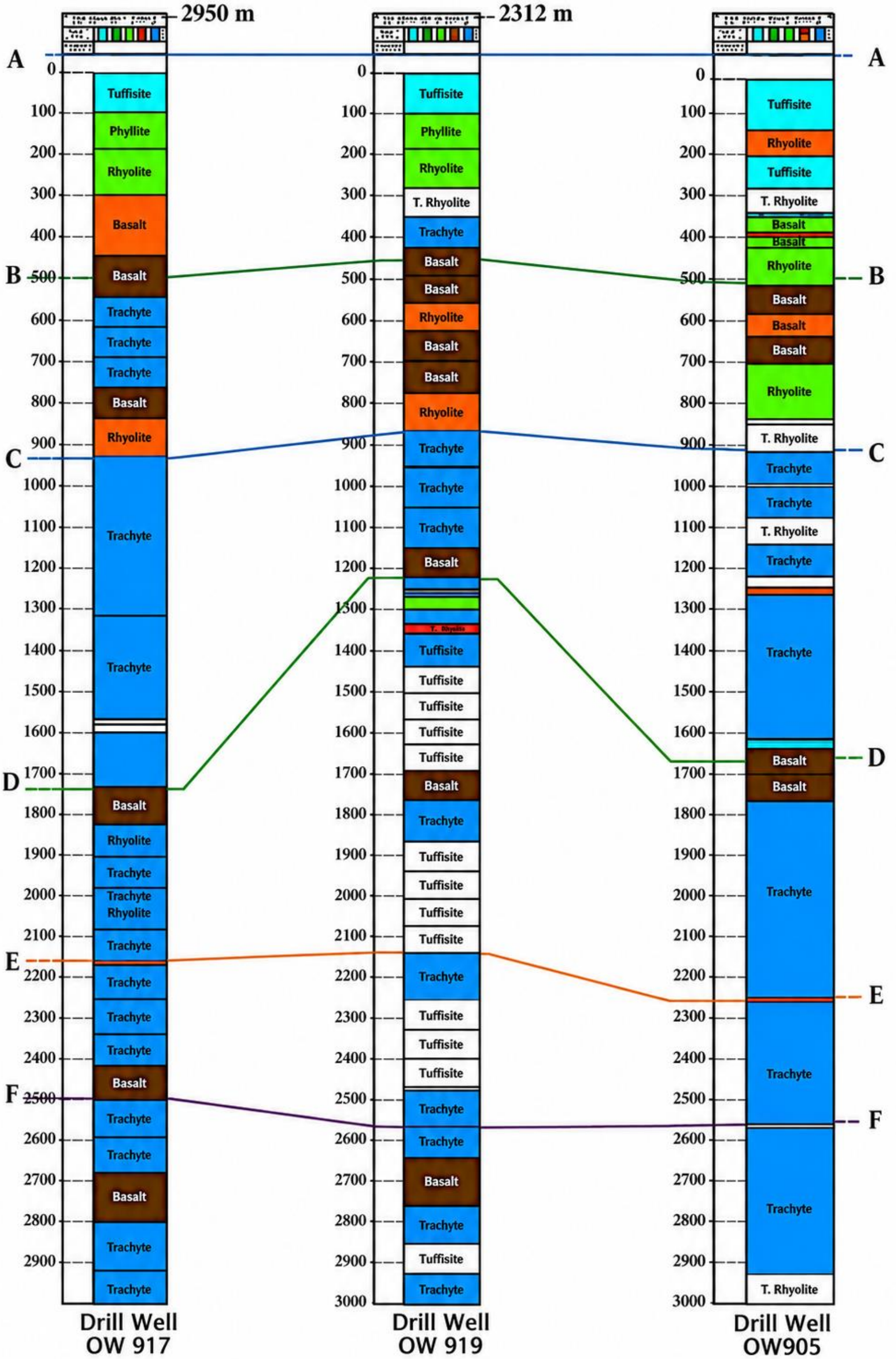

Figure 10. Stratigraphic well correlations of volcanic rocks in the study area.

Drill Well OW 918

The top section (0–98 m) features mixed pyroclasts, followed by rhyolite from 98 to 384 m. The well is predominantly trachyte from 384–2990 m, interstratified with rhyolites and tuffs. The loss of circulation occurs at multiple depths throughout the well.

Drill Well OW 919

The top section consists of fine-grained pyroclasts, with a basalt layer from 290 to 770 m intercalated with rhyolite, tuff, and trachyte. The well features various lithologies, including trachyte and tuff, with a loss of circulation at multiple depths. Basalt, rhyolite, and syenite intrusions were also encountered.

This summary provides a concise overview of the lithological characteristics and circulation losses observed in the drill wells in the Olkaria field.

SUMMARY OF MINERAL MAPS AND RADON CONCENTRATION IN THE OLKARIA GEOTHERMAL SYSTEM

Zone A, located at shallower depths (0–500 m) and lower temperatures, is characterized by an assemblage of minerals, including oxides, clays, chlorite, pyrite, calcite, quartz, chalcedony (Tables 11 and 12), chalcopyrite, hematite, siderite, and illite. This mineral composition is indicative of argillic facies associated with low-temperature conditions.

In Zone B, which spans depths of 600 to 1000 m, the alteration minerals identified include chlorite, pyrite, calcite, quartz, chalcedony, hematite, epidote, illite, and sphene. This zone is characterized by phyllic facies, typically found in permeable zones with temperatures of approximately 260°C. The presence of intermittent epidote suggests the onset of high-temperature zones, marking the beginning of the reservoir conditions Figures 11-17.

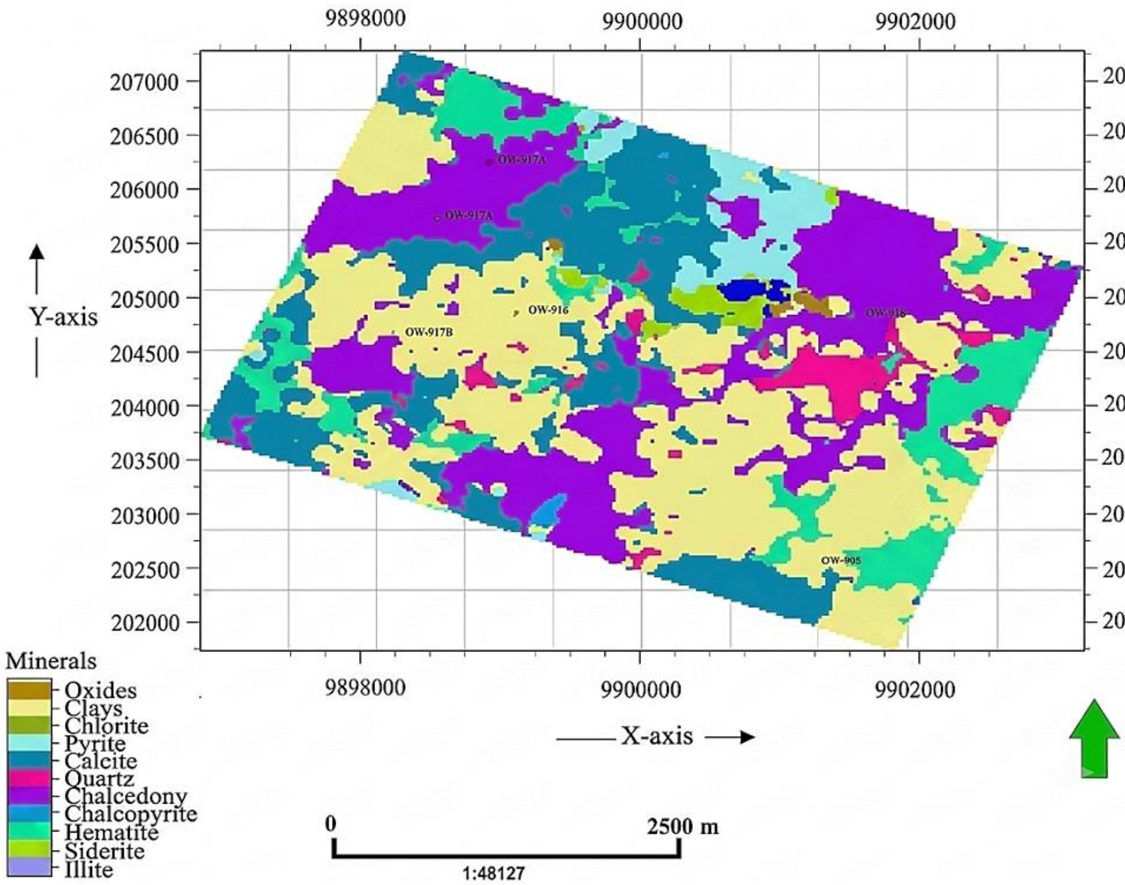

Figure 11. Mineral map for zone A.

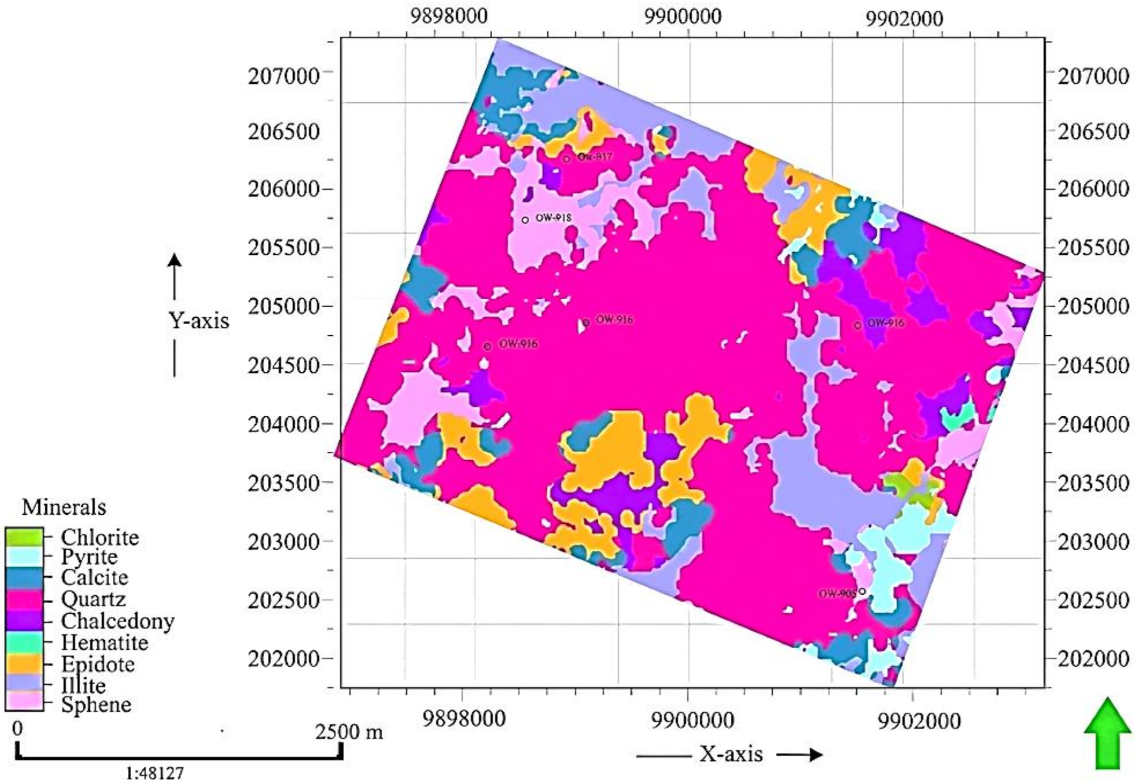

Figure 12. Mineral map for zone B.

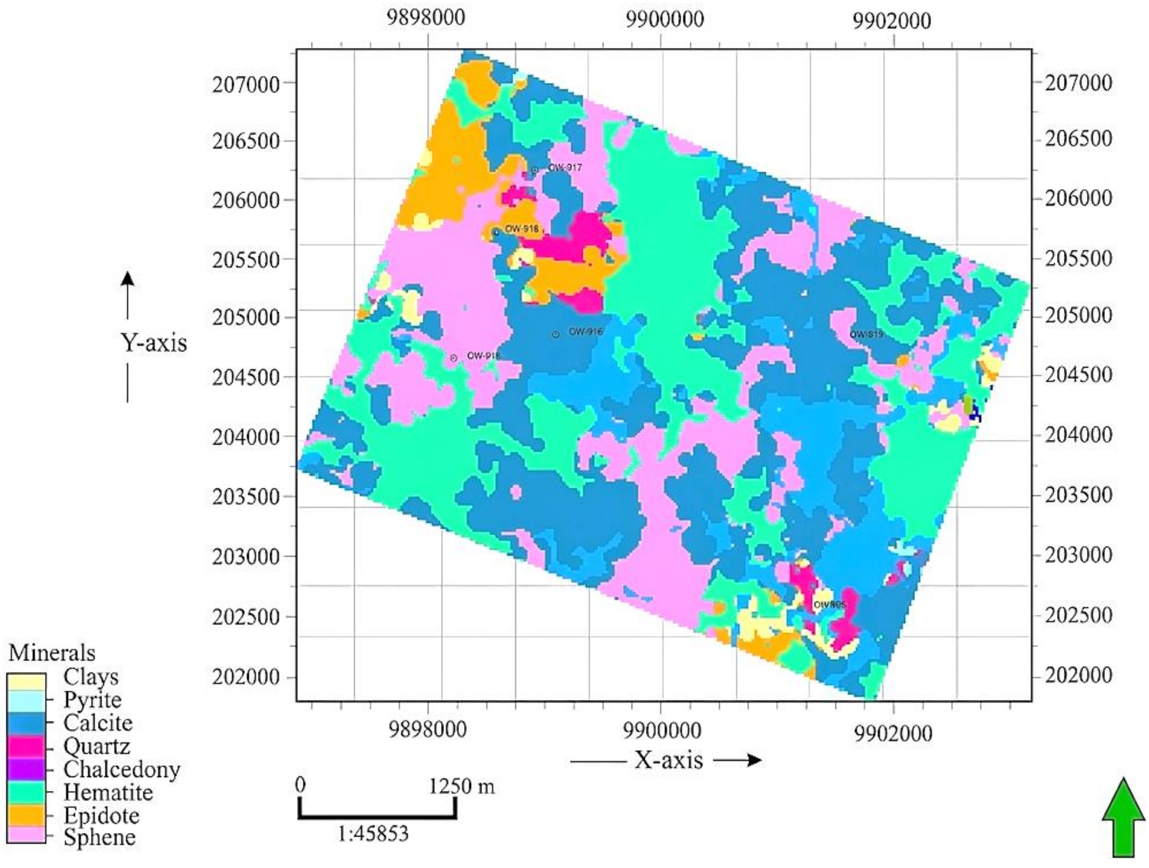

Figure 13. Mineral Map for Zone C.

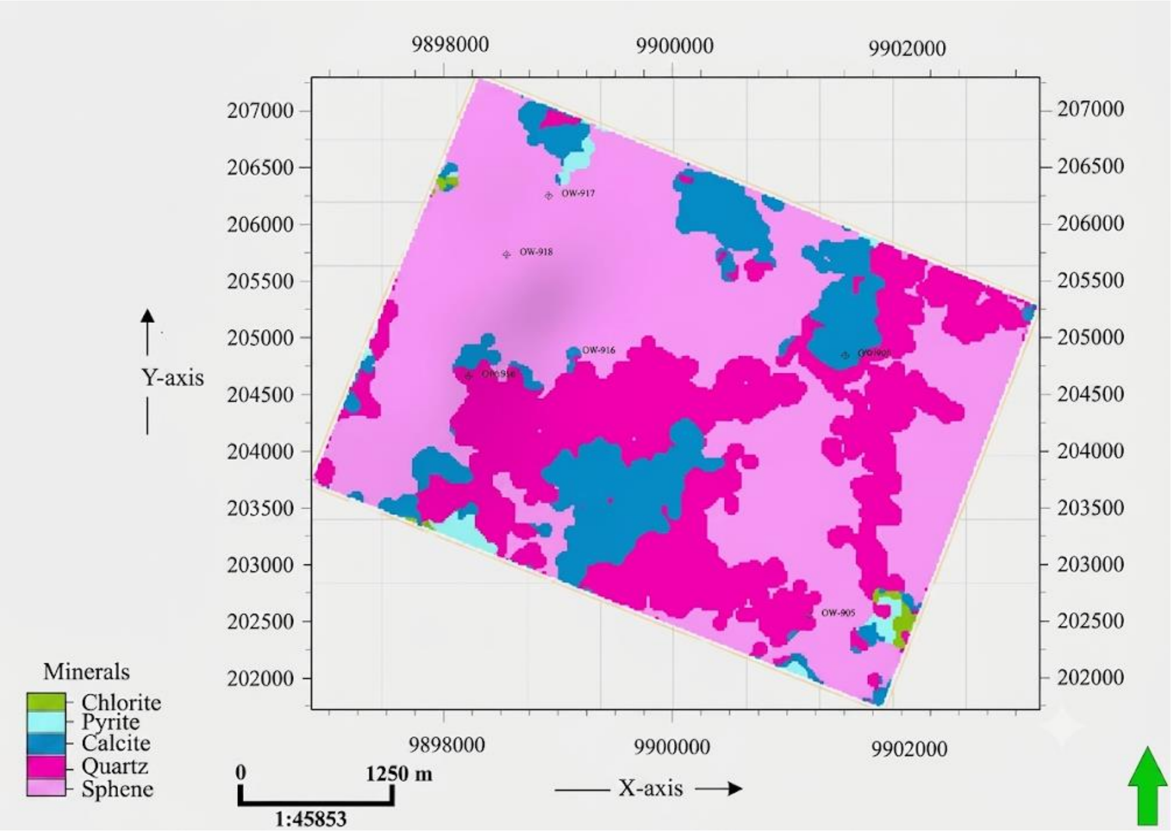

Figure 14. Mineral map for Zone D.

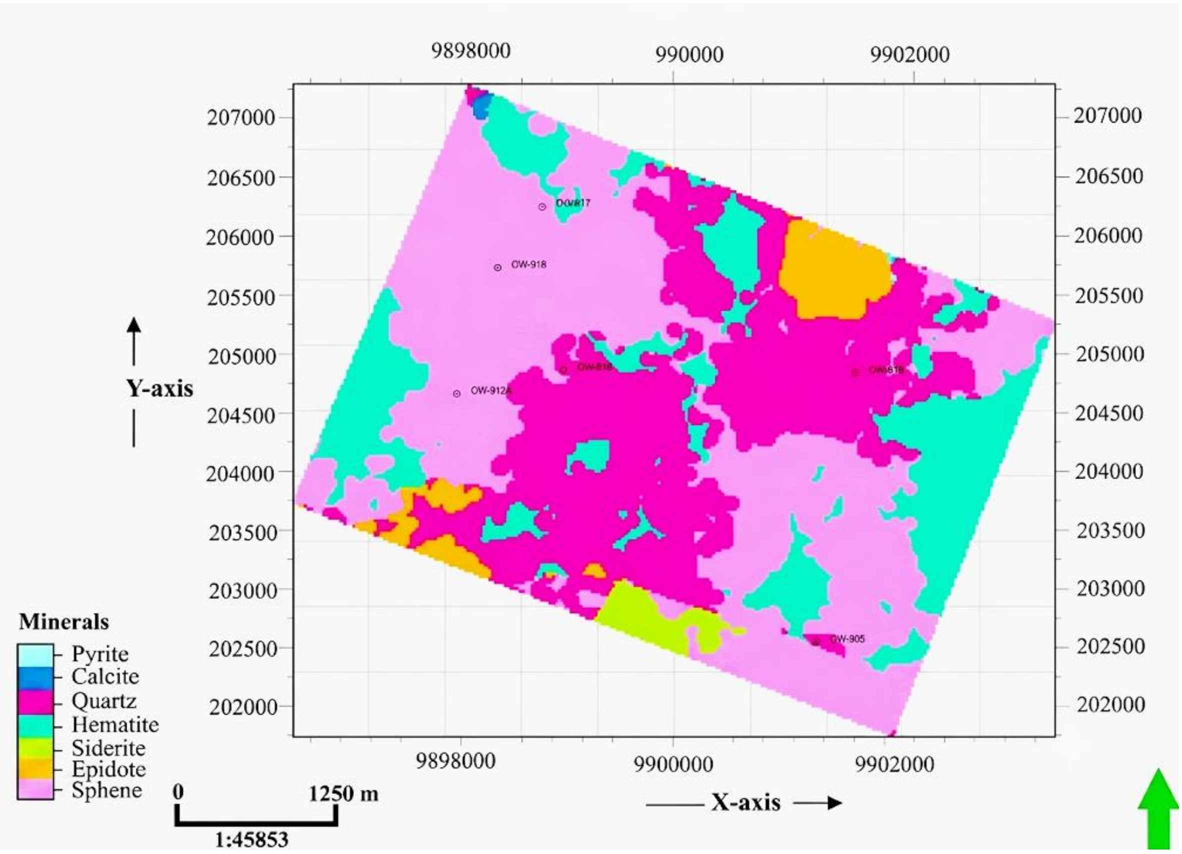

Figure 15. Mineral map for Zone E.

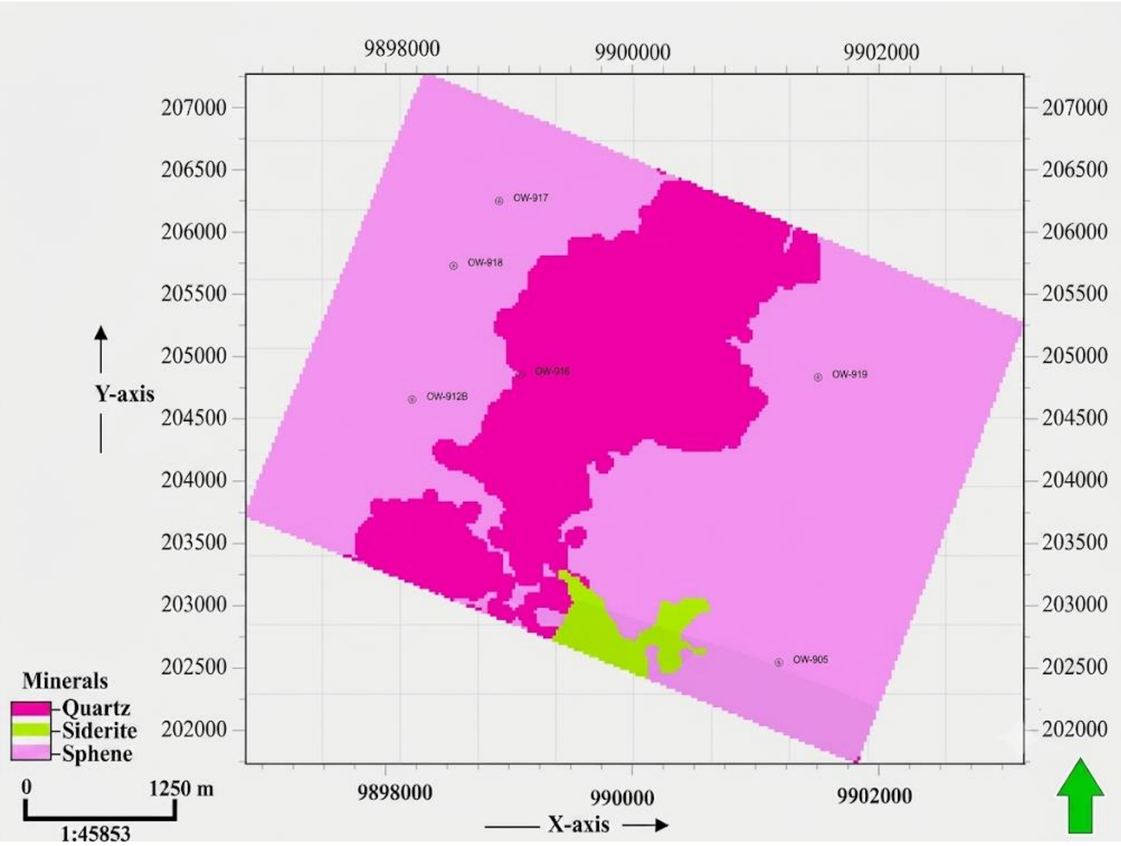

Figure 16. Mineral Map for zone F.

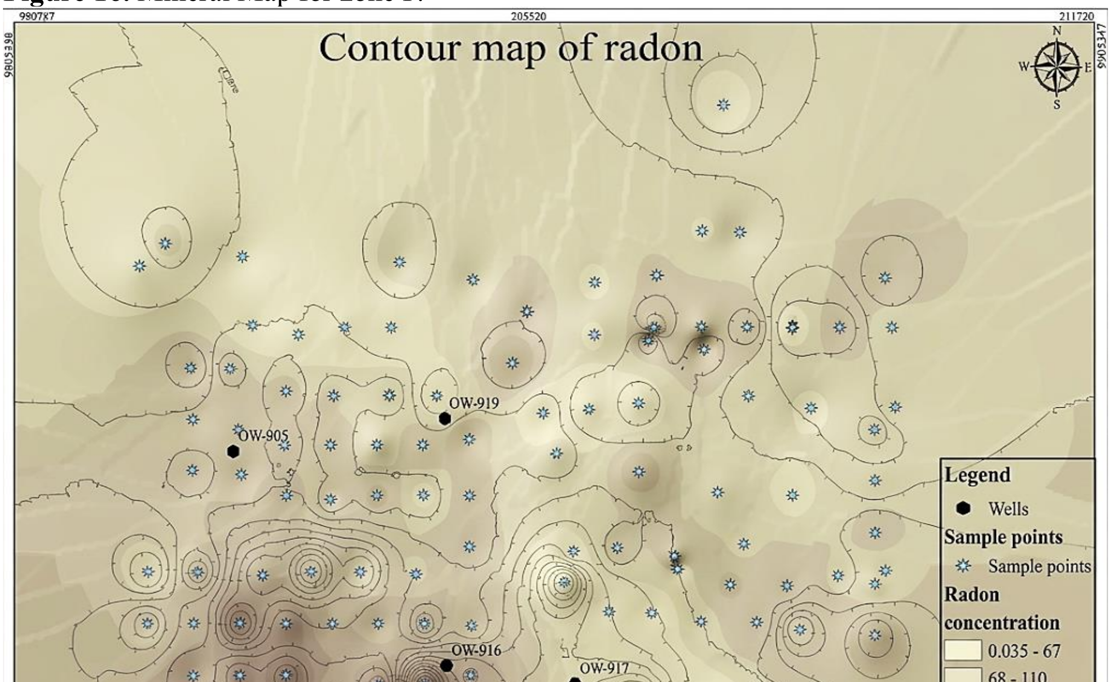

Figure 17. Map showing radon concentration in Olkaria domes field.

Zone C, with depths ranging from 800 to 1000 m, features hydrothermal alteration minerals such as clay, pyrite, calcite, quartz, chalcedony, hematite, epidote, and sphene. These minerals are characteristic of phyllic alteration facies associated with high temperatures and permeable geothermal zones. The predominant lithology in this zone is trachyte, which forms part of the reservoir rock in the Olkaria Geothermal System.

Mineral Maps for Zones D, E, and F

Introduction

The Olkaria geothermal system, located in the East African Rift, is characterized by a complex interplay of geological processes that contribute to its high-temperature potential. Among the various zones identified within this system, Zones D, E, and F are particularly noteworthy because of their mineralogical composition and associated geological features.

- *Zone D:* Contains chlorite, pyrite, calcite, quartz, and sphene.
- *Zone E:* Features pyrite, calcite, quartz, hematite, siderite, epidote, and sphene.
- *Zone F:* Comprises quartz, siderite, and sphene.

These zones are classified as belonging to the propylitic alteration facies, which are indicative of specific thermal and hydrochemical conditions that are prevalent in geothermal systems.

Mineral Composition and Characteristics

Zones D, E, and F are distinguished by the presence of several key minerals.

- *Chlorite:* This phyllosilicate mineral is commonly formed under low-to moderate-temperature conditions and is indicative of hydrothermal alteration processes. Chlorite often indicates the presence of water-rich environments and can influence the permeability of the surrounding rock.
- *Pyrite:* As a common sulfide mineral, pyrite is often associated with hydrothermal systems. Its presence can indicate reducing conditions and is frequently found in association with other alteration minerals. Pyrite can also affect the geochemical environment by influencing the solubility of metals and other elements.
- *Calcite:* This carbonate mineral is typically formed by the precipitation of calcium carbonate in hydrothermal systems. Calcite can fill fractures and vesicles, contributing to the overall permeability of the rock mass. Its presence is often associated with the alteration of volcanic rocks and can indicate changes in fluid composition during hydrothermal activity.
- *Quartz:* A ubiquitous mineral in geothermal systems, quartz can form by the crystallization of silica in hydrothermal fluids. Its presence often indicates high-temperature conditions and can serve as a marker of the thermal history of the geothermal reservoir.
- *Sphene (Titanite):* This mineral is often found in igneous and metamorphic rocks and can form under high-temperature conditions. Sphene is significant for its role in the geochemical evolution of the system, particularly in relation to Ti and other trace elements.
- *Hematite:* As an iron oxide, it can form under oxidizing conditions and is often associated with the alteration of volcanic rocks. Its presence can indicate changes in the redox state of geothermal fluids and influence the mineralogy of the surrounding rock.

Alteration Facies and Thermal Conditions

The classification of Zones D, E, and F as propylitic alteration facies is significant for several reasons.

1. *Depth and temperature:* Propylitic alteration typically occurs at greater depths and is associated with higher temperatures than other alteration facies, such as argillic or phyllic. The presence of minerals such as chlorite and epidote suggests that these zones are situated in a thermal regime conducive to the circulation of hydrothermal fluids.
2. *Hydrothermal processes:* The formation of propylitic alteration facies is indicative of the interaction between hot fluids and surrounding rock. This interaction alters primary minerals and forms secondary minerals, which can enhance the permeability of the rock mass. The alteration processes are influenced by factors such as temperature, pressure, fluid composition, and the nature of the host rock.

3. *Reservoir characteristics:* The lithologies encountered in these zones (basalts, trachytes, and rhyolites) are integral to the reservoir formations of the Olkaria geothermal system. These volcanic rocks are typically characterized by their porosity and permeability, which are essential for the storage and movement of geothermal fluids.

The presence of secondary minerals, such as calcite and chlorite, can further enhance the capacity of the reservoir to hold and transmit fluids.

Geological Implications

The mineralogical and alteration characteristics of Zones D, E, and F have important implications for the exploration and development of geothermal resources in the Olkaria field.

- *Resource assessment:* Understanding the distribution and characteristics of propylitic alteration facies can aid in the identification of potential geothermal reservoirs. The presence of specific minerals can serve as indicators of high-temperature zones and permeable pathways for the movement of fluids.
- *Drilling strategies:* Knowledge of mineralogy and alteration patterns can inform drilling strategies, helping to target areas with the highest potential for geothermal production. By focusing on zones with favorable mineral assemblages, exploration efforts can be optimized.
- *Geochemical monitoring:* The mineral composition of these zones can provide insights into the geochemical evolution of the geothermal system. Monitoring changes in mineralogy and fluid chemistry can help assess the sustainability and productivity of geothermal resources over time.

CONCLUSION

In summary, Zones D, E, and F of the Olkaria geothermal system exhibit distinct mineral assemblages that highlight the intricate hydrothermal processes occurring within this geothermal field. The presence of key minerals such as chlorite, pyrite, calcite, quartz, sphene, and hematite underscores the importance of these zones as propylitic alteration facies, which are typically associated with greater depths and elevated temperatures.

The mineralogical characteristics observed in these zones provide valuable insights into the geological and thermal dynamics of geothermal systems. Specifically, the identification of these minerals is indicative of conditions that favor the formation of permeable pathways essential for the movement and storage of geothermal fluids.

Understanding the implications of this mineralogy for permeability and reservoir potential is critical for the effective exploration and development of geothermal resources in the Olkaria Field. By leveraging this knowledge, future geothermal projects can be better informed, leading to optimized drilling strategies and enhanced resource management, ultimately contributing to the sustainable utilization of geothermal energy resources in the region.

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

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

The minerals in Zone F were quartz, siderite, and sphene. It was concluded that the last three zones, that is, Zones D, E, and F, belonged to the propylitic alteration facies. Normally, the propylitic facies are associated with greater depths and higher temperatures in a geothermal system.

The lithologies encountered in the deeper zones, which were also permeable in the fractured sections, mainly comprised basalts, trachytes, and rhyolites, all of which formed part of the reservoirs in the Olkaria geothermal system.

Radon Concentration for the Domes Field

Radon measurements from 104 collection points in the Olkaria Domes field revealed a maximum concentration of 507 counts and a minimum concentration of 10 counts. The radon concentration map indicates significant anomalies trending west-southwest toward Drill Wells OW-905 and OW-917 and extending farther to the east-southeast. These elevated radon levels suggest substantial permeability, indicating that radon is migrating through a highly permeable zone characterized by elevated subsurface temperatures. This information is essential for the strategic siting and drilling of additional wells in the Olkaria field, as high radon concentrations reflect the potential for enhanced geothermal activity in these areas.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The Olkaria Domes field is a high-temperature geothermal system with significant potential for geothermal energy generation, characterized by interconnected structural fractures and faults that facilitate hydrothermal fluid movement. The regional E-W extensional forces have led to the development of faults trending NW-SE, N-S, and NE-SW, which enhance gas generation from magmatic intrusions. Key features observed in rock analysis include mineralogy, grain size, and alteration intensity, which indicate the permeability and porosity essential for geothermal reservoirs.

The study involved geological descriptions and geochemical data from six drill wells (OW-905, OW-912B, OW-916, OW-917, OW-918, and OW-919), highlighting the importance of combining geological facies identification with radon gas concentration measurements to map high-temperature and permeable zones. The analysis revealed that hydrothermal alteration minerals, particularly pyrite and calcite, were concentrated in specific zones, indicating potential reservoir areas.

CONCLUSIONS

1. Lithology mainly consists of pyroclastics, rhyolites, tuffs, basalts, and trachytes.
2. Hydrothermal alteration facies were categorized into argillic, phyllic, and propylitic.
3. Secondary mineral maps indicated concentrations of pyrite and calcite in specific zones.
4. The permeability in the domes field is lithologically controlled, with pore spaces formed from cooling magma.
5. The radon concentration contour map identified high-anomaly areas, particularly in the west-southwest and east-southeast directions.
6. High radon concentrations align with faults and fractures, confirming structural control over permeability.
7. Permeability is influenced by both structural and lithological factors.

Recommendations

Future studies should incorporate additional techniques to analyze the water, gas, and stable isotope compositions of geothermal fluids in the Domes field. Investigating the effects of water-rock interactions, secondary mineral formation, and gas exchanges (e.g., CO_2 and H_2S) will provide a more comprehensive understanding of geothermal systems and enhance field productivity.

Future Research Needed

Machine learning approaches: Develop machine learning models to predict permeability based on well log data, enhancing the ability to identify high-permeability zones and optimize drilling strategies.

Long-term tracer tests: Conduct long-term tracer tests using fluorescein and ammonium (NH_4^+) to better understand fluid movement and interactions within the reservoir, thus providing insights into the dynamics of permeability evolution over time.

These conclusions, recommendations, and future research directions aim to enhance the understanding and management of the Olkaria Domes geothermal field, ensuring sustainable and efficient geothermal energy production.

REFERENCES

1. Achini HN, Adeigbe OC, Rop BK. Characterizing permeability from geological and geochemical data in the Olkaria Domes Field in Kenya. East Afr J Environ Nat Resour. 2021;3(1):161-82. doi:10.37284/eajenr.3.1.429.

2. Fleury P, Bakalowicz M, de Marsily G, Cortes JM. Functioning of a coastal karstic system with a submarine outlet, in southern Spain. Hydrogeol J. 2008;16:75-85. doi:10.1007/s10040-007-0215-8.
3. Baker HB. Geology of the Olkaria geothermal field. Geothermics. 2024;101624. doi:10.1016/j.geothermics.2024.101624.
4. Bignall G, et al. The geology and geothermal potential of the Olkaria area, Kenya. Geothermics. 2000;29:257-76. doi:10.1016/S0375-6505(00)00006-5.
5. Burnside NM, Montcoudiol N, Boyce AJ. Surface and groundwater hydrochemistry in the mid-Gregory Rift, Kenya: first impressions and potential implications for geothermal systems. E3S Web Conf. 2019;98:07004. doi:10.1051/e3sconf/20199807004.
6. Chorowicz J. The East African rift system. J Afr Earth Sci. 2005;43:379-410. doi:10.1016/j.jafrearsci.2005.07.019.
7. Clarke J, et al. The geology of the Lake Naivasha Basin, Kenya. J Afr Earth Sci. 1990;10(1):1-12. doi:10.1016/0899-5362(90)90002-4.
8. Darling WG, et al. The use of stable isotopes in the study of geothermal systems: a case study from the Olkaria geothermal field, Kenya. Geothermics. 1996;25:1-20. doi:10.1016/0375-6505(95)00029-5.
9. Davis PM, Slack PD. The uppermost mantle beneath the Kenya dome and relation to melting, rifting and uplift in East Africa. Geophys Res Lett. 2002;29(7):1117. doi:10.1029/2001GL013676.
10. Hackman BD, Charsley TJ, Kagasi J, Key RM, Siambi WS, Wilkinson AF. Geology of Isiolo Area. Report No. 103. Republic of Kenya: Mines and Geological Department; 1989.
11. Kamau M, Hecker C, Lievens C. Use of short-wave infrared reflectance spectroscopy to characterize hydrothermal alteration minerals in Olkaria geothermal system, Kenya. In: Stanford Geothermal Workshop. Stanford: Stanford University; 2020. Available from: pangea.stanford.edu.
12. Karingithi C. Hydrothermal alteration and mineralization in the Olkaria geothermal field, Kenya. Geothermics. 2009;38(1):72-9. doi:10.1016/j.geothermics.2008.10.001.
13. Karingithi CW. Hydrothermal alteration and mineralization in the Olkaria geothermal field, Kenya. J Volcanol Geotherm Res. 2020;392:106120. doi:10.1016/j.jvolgeores.2020.106120.
14. Key RM, Rop BK, Rundle CC. Geology of the Marsabit Area: Report 108. Reconnaissance. Nairobi, Kenya: Ministry of the Environment and Natural Resources, Mines and Geological Departments; 1987. 42 p.
15. Link K, Koehn D, Barth MG, Tiberindwa JV, Barifaijo E, Aanyu K, et al. Continuous cratonic crust between the Congo and Tanzania blocks in western Uganda. Int J Earth Sci. 2010;99:1559-73. doi:10.1007/s00531-010-0548-8.
16. Lagat JK. Geology: Hydrothermal Alteration and Fluid Inclusion Studies of the Olkaria Domes Geothermal Field [master's thesis]. Iceland: University of Iceland; 2004.
17. Chardot L, Jolly AD, Kennedy BM, Fournier N, Sherburn S. Using volcanic tremor for eruption forecasting at White Island volcano (Whakaari), New Zealand. J Volcanol Geotherm Res. 2015;302:11-23. doi:10.1016/j.jvolgeores.2015.06.001.
18. Mwania MM. Evaluation of subsurface structures using hydrothermal alteration mineralogy—a case study of Olkaria South East field. GRC Trans. 2015;39.
19. Rop BK, Mwanganga FR, Kiprotich KP. Evolutionary dynamics of the East African Rift System: implications for hydrocarbon exploration. J Geotech Eng. 2023;9:1-17.
20. Rop BK. Stratigraphic and Sedimentological Study of Mesozoic–Tertiary Strata in Loiyangalani Area, Lake Turkana District, NW Kenya [dissertation]. Windsor, Canada: University of Windsor; 1990. 146 p. Paper 3602. ISBN 0-315-61857-4.
21. Kwelwa SD, Sanislav IV, Dirks PHGM, Blenkinsop T, Kolling SL. Zircon U-Pb ages and Hf isotope data from the Kukuluma Terrain of the Geita Greenstone Belt, Tanzania Craton: implications for stratigraphy, crustal growth and timing of gold mineralization. J Afr Earth Sci. 2018;139:38-54. doi:10.1016/j.jafrearsci.2017.11.027.
22. Smith MC. A history of hot dry rock geothermal energy systems. J Volcanol Geotherm Res. 1983;15:1-20. doi:10.1016/0377-0273(83)90093-8.
23. Warega J. Geothermal prospecting of Olkaria Dome areas in Naivasha, Nakuru County, Kenya using gravity method. J Earth Environ Sci. 2020;12(4):45-58. doi:10.15406/jees.2020.12.0045.

