

Sub-Surface Rock Alteration Mapping of OW 205 at Olkaria Geothermal system using Conventional Laboratory Techniques and Hyperspectral Imaging of Drill Cuttings

Mathew Kamau

Email: mwkamau@kengen.co.ke

Keywords: Petrographic, Binocular, Hydrothermal alteration, Hyperspectral data, Spectroscopy

ABSTRACT

Hydrothermal alteration is a common process in active geothermal systems. It can significantly change the physio-chemical properties of the parental rock material. The dissolution and transformation of primary minerals and the formation of hydrothermally altered minerals depends on the prevailing sub-surfaces conditions of a geothermal reservoir. Identification and characterization of the hydrothermal minerals is key to unraveling the predominant sub-surface conditions. In Olkaria, conventional techniques such as binocular and petrographic analysis have been used to identify hydrothermal alteration minerals. However, with introduction of spectroscopy technique in Olkaria, it is imperative to compare hydrothermal alteration minerals identified petrographically with those identified by infrared spectroscopy techniques. Hence, this study compares infrared spectroscopy and petrographic analysis of hydrothermal alteration minerals in OW 205 drilling cutting samples. The study will also include results from binocular observation of the drilling cuttings at the rig site. Binocular analysis was done by visually observing drilling cutting samples using a binocular microscope while petrographic analysis involved first preparing thin section with thickness of about 30 micrometers by mounting drilling cuttings on glass slides. Petrographic studies involved viewing samples in a thin section using a petrographic microscope. On the other hand, spectroscopy analysis was done by first imaging drill cutting sample using short wave infrared (SWIR) camera. Images of the samples were made by passing samples on a translation stage underneath a camera. Minerals such as chlorite, epidote, actinolite, zeolites were positively identified by the two techniques. However, minerals such as chalcedony, prehnite, quartz, and albite were only identified using petrographic analysis. Generally, the integrated use of binocular observations, thin section petrographic analysis, and infrared spectroscopy provide reliable data for hydrothermal alteration characterization in geothermal wells and development of a conceptual model.

1. INTRODUCTION

Hydrothermal alteration is a common process in active geothermal system and can significantly change the physiochemical properties of rocks (Weydt et al., 2022). Studies of hydrothermal alteration mineral is essential in defining the architecture of a geothermal system. The sensitivity of minerals to changes in temperature and chemical composition of hydrothermal fluids has enabled the evaluation of thermodynamic and compositional conditions in different stages in the evolution of hydrothermal system (Morata et al., 2023). It occurs when water, heated and ionized by shallow magma bodies or volcanic activities circulates in the surrounding rocks leading to the breakdown of primary mineralogy (Inoue, 1995). To improve reservoir assessment and modelling of high temperature geothermal resources linked to active volcanic setting, a detailed understanding of reservoir is need.

In borehole geology, rock cuttings provide a realistic picture of down-hole stratification and alteration. The study of these rock cuttings is essential in evaluating permeability, temperature size and depth of the geothermal borehole. In this respect, numerous studies have been done on hydrothermal alteration minerals in Olkaria geothermal systems. Notably, studies by ,Muehmi (1987), Omenda (1998) and Lagat (2007), identified, opaline, quartz, calcite, siderite, calc-silicates, clays, zeolite, pyrite, and albite minerals in various sub-fields of the greater Olkaria geothermal systems. Virtually, all these studies were based on the examination of drill cores/cutting using binocular and petrographic microscopes, XRD and fluid inclusion analyses.

Most recently, infrared spectroscopy studies have been done in Olkaria geothermal system. As described by Hauff, 2008, spectroscopy is the study of the interaction between energy as electromagnetic radiation and matter. Where in this case, radiation can be absorbed, emitted, or scattered by matter. It is a technique that uses energy in the visible (400-700nm), near infrared (700-1000nm) and Short-Wave infrared (1000-2500nm) wavelength region of the electromagnetic spectrum. According to Goetz et al, 1985, the science and techniques of reflectance spectroscopy are based on the spectral properties of materials. Atoms and molecules absorb energy as a function of their atomic structure.

In the Visible -Near Infrared (VNIR) region of the electromagnetic spectrum, mineral spectra are caused by electronic transitions while in the Short-Wave region, the absorption features are a functions of mineral composition (Hunt, 1977). Each mineral has a distinctive spectral signature consisting of several absorption features which are a function of composition, crystallinity, concentration, water content and environmental considerations (Pontual et al, 2008). This study integrates binocular observations, petrography, and infrared spectroscopy to identify and characterize hydrothermal alteration minerals in OW-205. The combined approach enhances confidence in hydrothermal mineral identification.

2. STUDY AREA

Olkaria geothermal field is located in Kenyan Rift valley to the south of Lake Naivasha about 120 km NW of Nairobi (Figure 1). It is a high-temperature geothermal system with an approximate area of about 240 km². This volcanic system is associated with an old central volcano which collapsed leaving a large caldera of approximately 5km diameter, defined in part by a ring fracture and by rhyolite domed (Clarke et al, 1990). The volcanic centers are structurally controlled with the main eruptive center being the Olkaria Hill. Others include Ololbutot and George farm fault. Olkaria fields has been divided into seven sub-fields with Olkaria Hill a prominent geological feature being the reference point (Otieno, 2016).

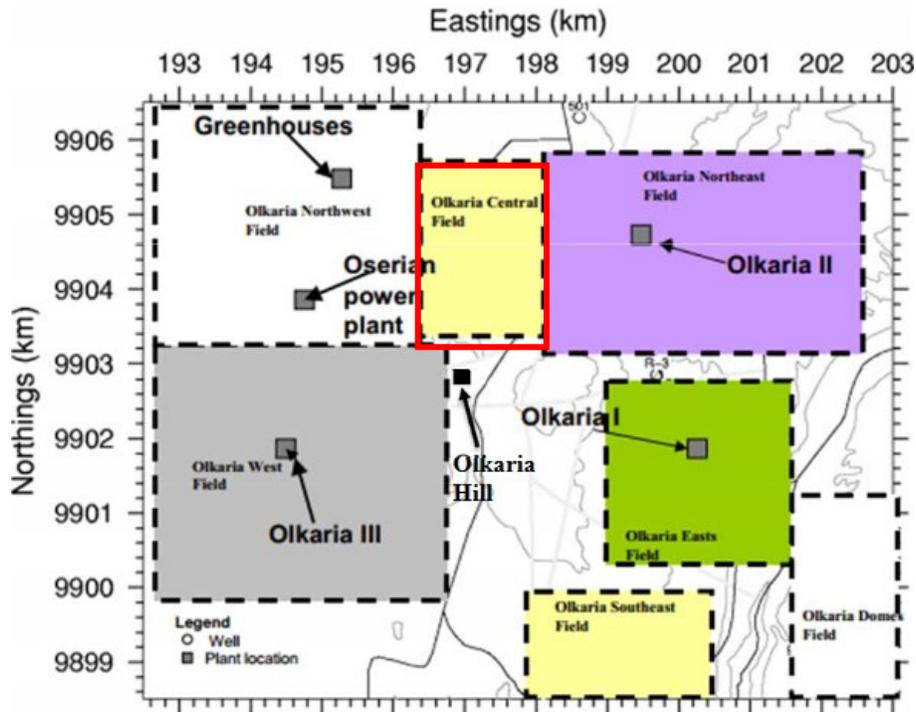


Figure 1: Olkaria geothermal field showing seven production sectors (Saitet, 2016).

OW 205 is located within Olkaria Central field (*bordered red*) at UTM coordinates E196609.3, N990398.9 and at an altitude of 1903.86 m.a.s.l (Katana, 2019). The field is the smallest in Olkaria and the least exploited compared to other fields. Consequently, borehole data within this field is scarce. Most of the wells were drilled during exploration activities of 1980 and 1997. They include OW 201, OW 202, OW 203, 204 and OW 205. Amongst these wells, OW 205 is the most recently drilled well in 2016.

2.1 Sub-surface Geology of Olkaria geothermal system

Detailed study of drill cuttings and cores obtained from the geothermal wells has resulted in the documentation of the sub-surface geology of the Olkaria geothermal complex over time. Studies by Muchemi (1987), described sub-surface geology of Olkaria as consisting thick volcanic pile of predominantly alkaline, silicic rocks and pyroclastic materials with minor basaltic intercalations. A study by Omenda (1998), showed sub-surface geology as consisting of six litho-stratigraphic units (

Figure). Continuous drilling of deep geothermal wells up to (3000 m) have contributed to an improved understanding of the downhole stratigraphy with six distinct groups described by previous studies being present. According to Lagat et al. (2005), the litho-stratigraphic sequence derived from wells drilled across all Olkaria fields are typically similar. As described by Omenda, 1998, the following lithostratigraphic sequence exists in Olkaria geothermal systems starting from the youngest to the oldest.

- ❖ **Upper Olkaria volcanic:** They consists of comendite, rhyolites, trachyte and minor basalts together with pyroclastic materials (Clarke et al.; 1990). Previous studies show their occurrence from the surface to a depth of about 500 m below the surface with comendite being the dominant rock in this formation.
- ❖ **Olkaria basalt:** The formation consists of basaltic flows separated by thin layers of tuffs, minor trachytes and rhyolites. It underlies the Upper Olkaria volcanic and varies in thickness from 100-500 m.

- ❖ **Plateau trachyte:** This precede the Olkaria basalt and is mainly characterized by trachyte with minor intercalation of tuffs, rhyolites and basalts. Based on the boreholes drilled, the trachytic flows penetrated by the wells occurs in two petrographic variety where one is strongly feldspars-phyric and dense and the other one is fine-grained, aphyric with abundant feldspars.
- ❖ **Mau tuffs:** They are the oldest units of rocks cropping out and encountered during drilling process in the Olkaria geothermal system. The unit correlates with Mau ranges tuff on the western escarpment of the Kenyan rift. They are mainly composed of tuffs with minor interbeds of rhyolites, basalts and trachyte.

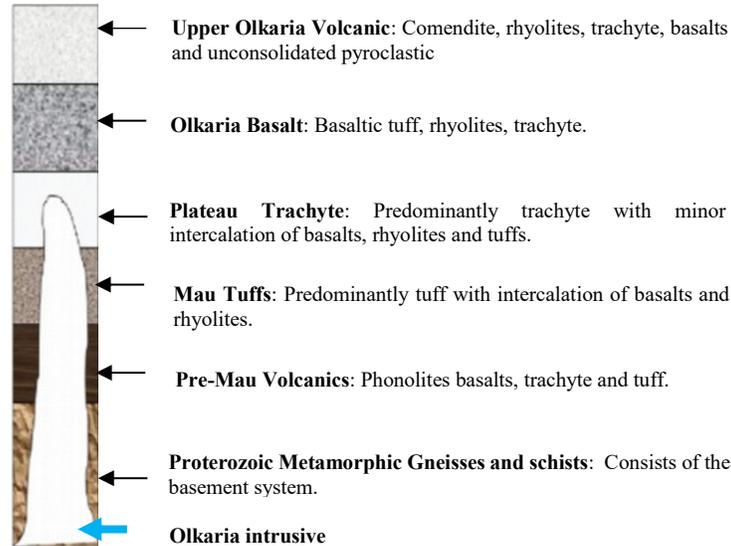


Figure 2: Stratigraphic units of Olkaria geothermal system (modified from Musonye, 2015)

Structurally, Olkaria is characterized by faults, fractures, dikes, domes/eruption centers, vents, plugs, sills and caldera among others. These structures are well exposed in the western part of the field. In the eastern side, the structures are not well exposed which is inferred as being buried by the thick layer of the Quaternary pyroclastic deposits.

2. SAMPLES AND METHODOLOGY

Drilling cuttings collected during rotary drilling of the geothermal well was used for this study.

2.1 Samples

Drill cuttings from OW 205 were used for this study. The samples were taken at 2m intervals but where inadequate or unrepresentative samples were encountered a 4 m sampling interval was used. Preliminary analysis of the sample was conducted at the rig site by the site geologist using a binocular laboratory. Samples were later packed and transported to the laboratory for washing, drying and storage in sample containers in readiness for detailed analysis using laboratory-based techniques. The selection put into consideration the grain size of the samples which varied from fine-grained, medium grained and coarse grained depending on the size of the drill cuttings and guidance from binocular observations.



Figure 3: Drill cutting samples

2.2 Methodology

2.2.1 Binocular Analysis

A binocular microscope was used for binocular analysis. The observation was utilized to delineate the rock lithology, primary and secondary minerals and alteration, fracture filling, oxidations, and intrusion. The results were used to decide which samples will be subjected to further investigation using other techniques.

2.2.2 Thin section Analysis

Observing samples with a petrographic microscope involves preparing thin sections at around 30 micrometers of rocks or minerals, mounting them on slides (Katana, 2019). Plane polarized light (PPL) was used to reveal unique optical properties like color, relief, birefringence, and interference colors while Crossed Polarized Light (XPL) was used to identify minerals and textures. This allowed detailed analysis of mineral composition, crystal structure, and rock textures, crucial for petrology. Mineral properties description was done based on the thin sections guidelines by (Raith et al, 2012).

2.2.3 Hyperspectral Imaging

Imaging was done using SWIR camera (Specim ltd; Finland) with the following technical specifications.

Type of the stage	Lab stage
Spectral range (nm)	1000-2500
Distance of the sensor to sample (cm)	30
Pixel size(μm)	260
Image swath(mm)	98
Number of bands	288
Lens focal length(mm)	OLES30 (30 mm)
Spectral Sampling	5.6 nm
Spectral resolution FWHM	12nm

Images of the samples were acquired by first placing the sample on an aluminum container of an approximate height of 40 mm and a diameter of 60 mm ensuring a flat surface and then placed on a box containing silver sand. Images of samples were made by passing box containing samples on a translation stage which was then passed underneath the camera. Image cubes were constructed using the camera in a push-broom style where x-axis was the across track direction and the z-axis as the spectral direction. A white reference standard plate considered as a perfect reflecting surface (99%) of the incident light and a dark reference surface measurement were taken before the measurements were done and were used later for image calibration. After all the measurement were done, Specim data was converted to reflectance using the white reference and the dark current measurement.

3. RESULTS

3.1 Binocular Observations

Binocular observations of drill cuttings were used to provide a first-order assessment of lithology and visible hydrothermal alteration prior to detailed petrographic and spectroscopy analysis. The lithostratigraphic interpretation based on binocular observations of the drill cutting reflects a volcanic-dominated sequence that has undergone progressive hydrothermal alteration with increasing depth due to sustained interaction with geothermal fluids. The well is predominantly trachytic, with subordinate basalts, rhyolites, tuffs, and intrusive bodies, typical of the Olkaria geothermal system.

The following are main lithostratigraphic units identified by binocular observations in OW 205.

0–370 m: Pyroclastic and Rhyolitic Units: The upper section comprises pyroclastic deposits and rhyolitic tuffs, characterized by pumice, volcanic glass, and tuffaceous material. Minor oxidation is observed, with moderate alteration to clays and early secondary mineralization including quartz and zeolites infilling vesicles, indicating initial hydrothermal influence.

396–714 m: Tuffs and Trachyte: This interval transitions into tuffs and trachyte, displaying increasing porphyritic textures and vesiculation. Alteration intensity is generally weak to moderate, dominated by clay minerals, with minor pyrite dissemination and early veining by calcite and felsic minerals. Fracturing begins to develop, suggesting improving permeability.

714–1014 m: Basaltic and Mixed Volcanic Sequence: Basalts, tuffs, and rhyolitic units dominate this section, showing moderate to strong hydrothermal alteration. Vesicles and fractures are infilled with calcite, green clays, epidote, and pyrite, with localized zones of intense pyritization. Increased oxidation and mineral infilling indicate enhanced fluid–rock interaction and elevated temperatures.

060–1130 m: Trachyte–Rhyolite Intercalations: Trachyte interbedded with rhyolite exhibits moderate alteration, strong oxidation in places, and extensive veining by hematite, calcite, epidote, and secondary quartz. Vesiculation and mineralized veins suggest active fluid pathways, while sample heterogeneity reflects circulation-related mixing.

1158–2470 m: Thick Trachyte Sequence: This is the main lithological unit of OW-205, consisting of extensive trachyte flows with flow banding and weak porphyritic textures. The rocks are moderately altered to green and brown clays, with common epidote, pyrite, secondary quartz, and calcite veining. This interval represents a mature geothermal alteration zone, consistent with reservoir conditions.

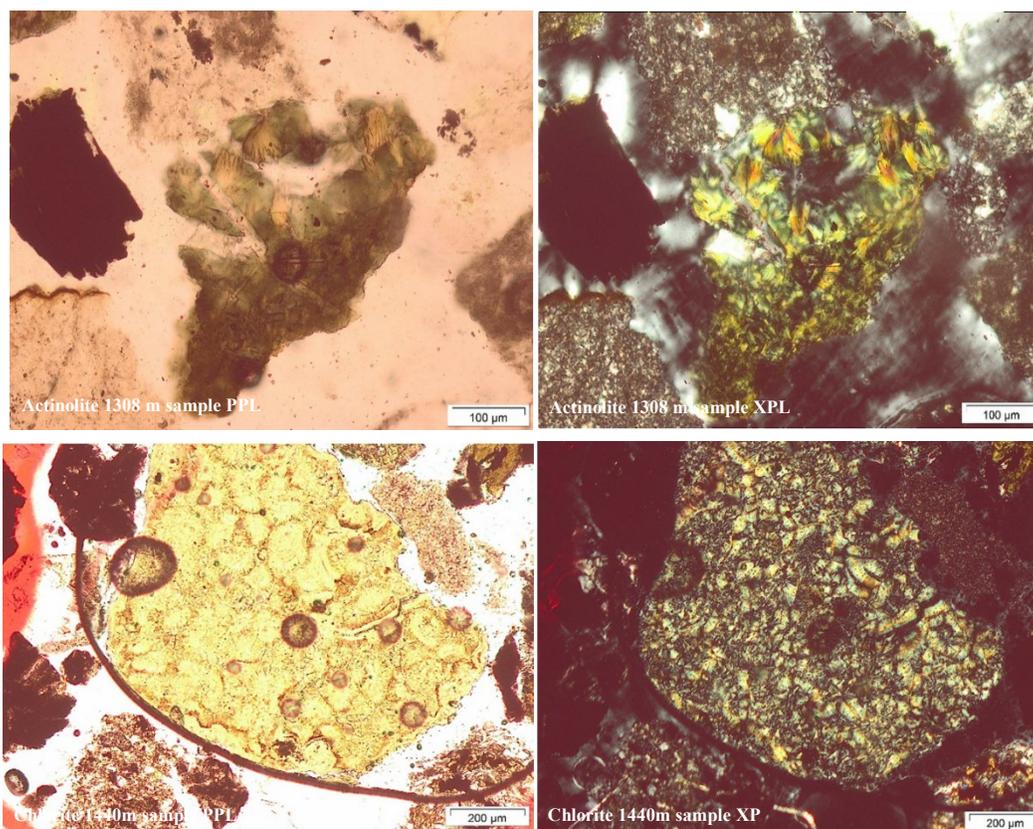
2488–2586 m: Basalt–Trachyte Alternations: Basalts and trachytes are interlayered, showing moderate alteration, vesiculation, and fracturing. Vesicles and veins are infilled with calcite, epidote, and clays, indicating continued hydrothermal circulation and permeability development.

2640–2666 m: Granitic Intrusion: A granitic intrusive body is encountered, relatively fresh but contaminated by overlying volcanic rock falls. Epidote associated with the intrusion suggests thermal overprinting rather than pervasive alteration.

2666–2944 m: Trachyte with Syenite Intrusion: The lower section returns to altered trachyte, moderately porphyritic and cut by numerous micro-veinlets infilled with calcite, quartz, epidote, and clays. A syenite intrusion (2864–2872 m) occurs within this interval and is only slightly altered. Overall alteration intensity remains moderate, with fracture-controlled mineralization indicative of sustained geothermal activity.

3.2 Thin section/Petrographic analysis

The petrographic assemblage in OW-205 reflects a progressive hydrothermal alteration sequence, transitioning from low-temperature minerals (zeolites and chalcedony) at shallow depths to more stable, higher-temperature phases (chlorite, epidote and actinolite at depth). This mineralogical evolution supports the interpretation of active geothermal fluid circulation and well permeability.



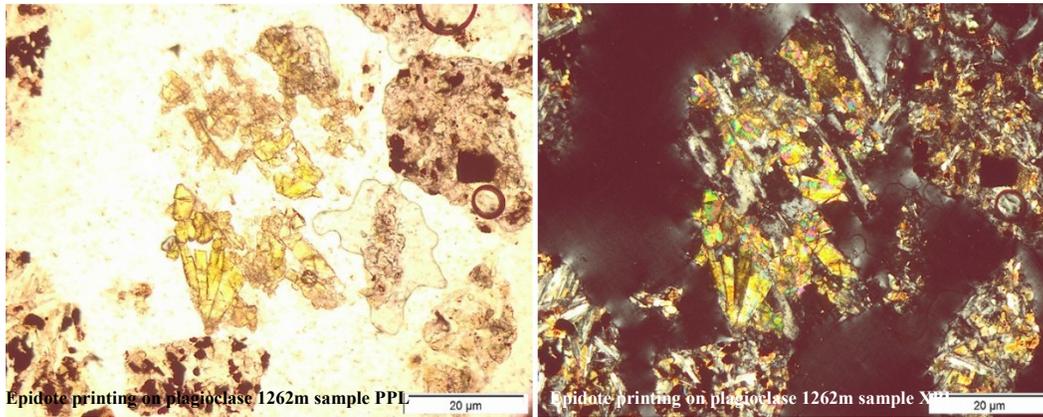


Figure 4: Thin section of actinolite, chlorite and epidote

3.3 Hyperspectral Imaging

Short-wave infrared (SWIR) region of the electromagnetic spectrum was used to map the distribution of alteration mineral assemblage in OW 205. Minerals were identified by comparison against a characterized spectral library. In this case US Geological Survey (USGS) spectral library. Several hydrothermal alterations minerals were identified using this technique. They include epidotes, actinolite and chlorites. Other minerals identified include zeolite, illite montmorillonite and calcites. Identification was by use of distinct absorption features in the mineral spectra. For instance, chlorites were spectrally identified by use of Fe-OH feature between 2245-2262 nm wavelength range. Epidotes were identified by use of absorption feature near 1540 nm and Fe-OH diagnostic feature located near 2256 nm and Mg-OH feature between 2335-2342 nm wavelength range. For amphibole, identification was done by use of Mg-OH characteristic feature which varied between 2314-2324 nm and 2326-2350 nm for actinolite and hornblende respectively.

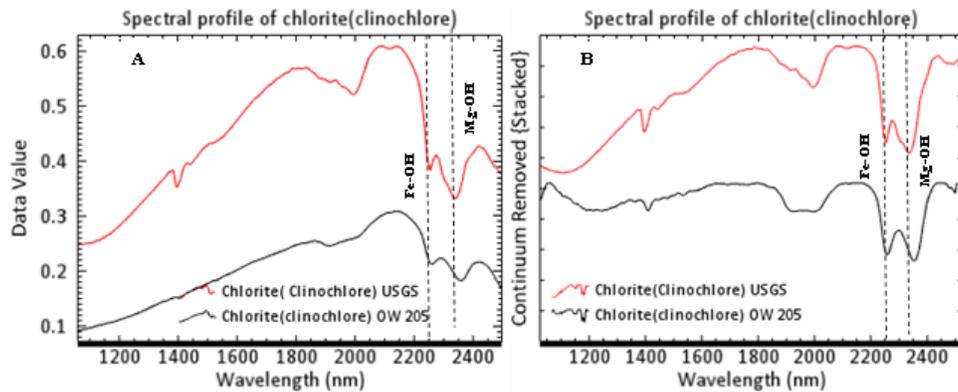


Figure 5: (A) Normal spectra of Chlorite (B) Continuum removed spectra of Chlorite

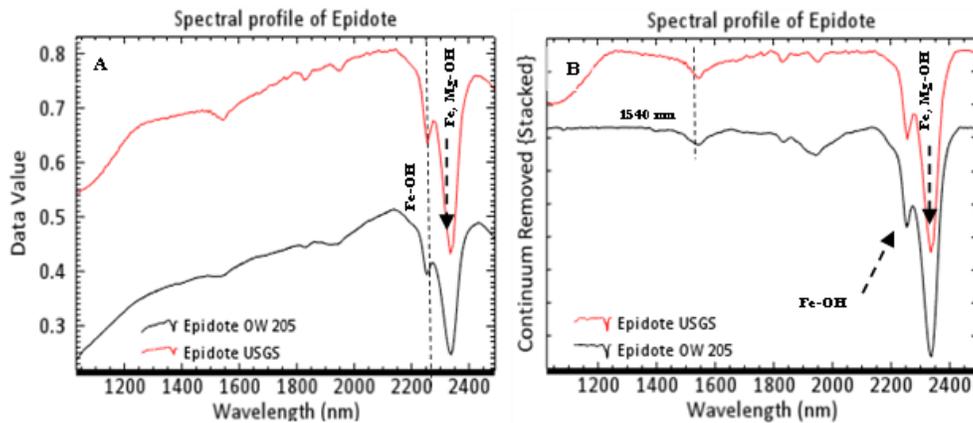


Figure 6: (A) Normal spectra of Epidote (B) Continuum removed spectra of Epidote

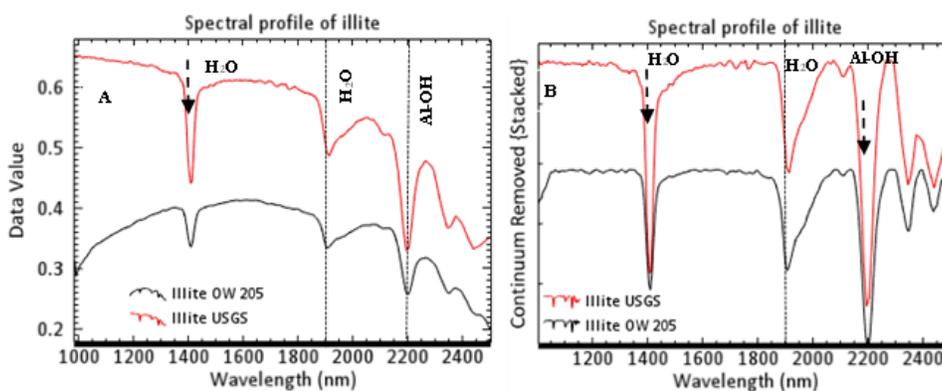


Figure 7: (A) Normal spectra of Illite (B) Continuum removed spectra of Illite

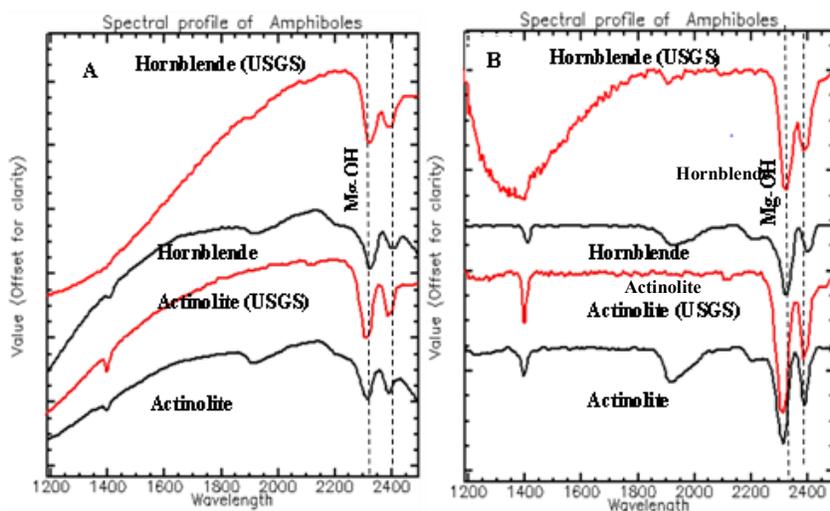


Figure 8: (A) Normal spectra of Amphibole (B) Continuum removed spectra of Amphibole

3. DISCUSSION

Mineralogical characterization of OW 205 was conducted using a combination of binocular observations, thin section petrographic analysis, and infrared (IR) spectroscopy. Binocular examination of drill cuttings and hand specimens provided a rapid, first-order assessment of lithology, colour changes, fracture density, veining, and visible hydrothermal alteration. These observations guided sample selection for detailed laboratory analyses and assisted in identifying zones of significant alteration. Thin section and petrographic analysis were subsequently carried out to identify primary and secondary minerals and to evaluate textural relationships such as mineral replacement, vein infilling, and alteration intensity under plane- and cross-polarized light. Infrared spectroscopy was used to complement petrographic observations by identifying fine-grained alteration minerals, particularly clay minerals and zeolites. The technique is based on diagnostic absorption features related to molecular vibrations and enables rapid mineral identification with minimal sample preparation. Minerals such as chlorite, epidote, and amphiboles were identified using both thin section petrographic analysis and infrared (IR) spectroscopy. Petrographic examination confirmed these minerals based on their diagnostic optical properties and textural relationships, including mineral replacement and vein infill. The concurrence of both techniques enhances confidence in mineral identification and confirms the presence of moderate- to high-temperature hydrothermal alteration within the geothermal system.

4. CONCLUSION

The integrated use of binocular observations, thin section petrographic analysis, and infrared spectroscopy provides a reliable and comprehensive framework for hydrothermal alteration characterization in geothermal wells. The combined application of these methods improves confidence in alteration mineral identification and supports the delineation of alteration facies corresponding to temperature gradients within the geothermal system, including the transition from low-temperature smectite-rich assemblages to higher-temperature illite, chlorite, and epidote assemblages. This integrated approach enhances assessment, supports reservoir temperature estimation, and supports drilling operations at the rig by enhancing quick decision making. Consequently, this contributes to informed geothermal resource assessment and development of a conceptual model.

ACKNOWLEDGEMENT

Special thanks to KenGen for facilitating this study and my colleague Christine Katana for providing petrographic study data.

REFERENCES

- Clarke, Woodhall, A. & D. (1990). *Geological, volcanological and hydrogeological controls on the occurrence of geothermal activity surrounding Lake Naivasha, Kenya*. Nairobi.
- Goetz, a. F. H., Vane, G., Solomon, T. E., & Rock, B. N. (1985). Imaging Spectrometry for Earth Remote Sensing Author (s): Alexander F . H . Goetz , Gregg Vane , Jerry E . Solomon and Barrett N . Rock. *Science*, 228(4704), 1147–1153.
- Hauff, P. (2008). An overview of VIS-NIR-SWIR field spectroscopy as applied to precious metals exploration. *Arvada, Colorado: Spectral International Inc*, (January).
- Hunt, G. R. (1977). Spectral signatures of particulate minerals in the visible and near infrared. *Geophysics*, 42(3). <https://doi.org/10.1190/1.1440721>
- Inoue, A. (1995). Formation of Clay Minerals in Hydrothermal Environments. In *Origin and Mineralogy of Clays* (pp. 268–329). Berlin, Heidelberg: Springer Link. https://doi.org/10.1007/978-3-662-12648-6_7
- Katana, C. (2019). Borehole Geology and Alteration Mineralogy of Well 205, Olkaria Geothermal Field, (8), 83–109.
- Lagat, J. (2014). Hydrothermal alteration mineralogy in geothermal fields with case examples from Olkaria domes geothermal field, Kenya. In *Short Course IX on Surface Exploration for Geothermal Resources*. Naivasha: UNU-GTP,Kengen and GDC. Retrieved from <http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-05-10.pdf>
- Lagat, J., Arnorsson, S., & Franzson, H. (2005). Geology, hydrothermal alteration and fluid inclusion studies of Olkaria domes geothermal field , Kenya. In *Proceedings, World Geothermal Congress 2005, Antalya, Turkey* (pp. 24–29). Antalya,Turkey. Retrieved from <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0649.pdf>
- M.Raith, Peter R,J.A. (2012). A guide to Thin Section Microscopy.pdf. Retrieved from http://www.minsocam.org/msa/OpenAccess_publications/Guide_Thin_Sctn_Mcrscopy/Thin_Sctn_Mcrscopy_2_prnt_eng.pdf
- Morata, D., Gallardo, R., Maza, S., Arancibia, G., López-Contreras, C., Mura, V., ... Reich, M. (2023). Hydrothermal Alteration in the Nevados de Chillán Geothermal System, Southern Andes: Multidisciplinary Analysis of a Fractured Reservoir. *Minerals*, 13(6). <https://doi.org/10.3390/min13060722>
- Muchemi, T. M. L., & G.G. (1987a). Geology and Hydrothermal Alteration of the North and West exploration wells in Olkaria, Kenya. *Proceeding 9th NZ Geothermal Workshop*, 82, 187–192.
- Muchemi, T. M. L., & G.G. (1987b). Geology and Hydrothermal Alteration of the North and West exploration wells in Olkaria, Kenya. In *Proceeding 9th NZ Geothermal Workshop* (Vol. 82).
- Musonye, X. (2015). *Sub-Surface Petrochemistry , Stratigraphy and Hydrothermal alteration of the Domes area , Olkaria geothermal filed, Kenya*. United Nations University.
- Omenda, P. A. (1998). The geology and structural controls of the Olkaria geothermal system, Kenya. *Geothermics*, 27(1), 55–74. [https://doi.org/10.1016/S0375-6505\(97\)00028-X](https://doi.org/10.1016/S0375-6505(97)00028-X)
- Otieno, V. O. (2016). Borehole geology and sub-surface petrochemistry of the Domes area, Olkaria geothermal field, Kenya, in relation to well OW-922.
- Pontual, S., Merry, N., & Gamson, P. (2008). GMEX1-Spectral Interpretation Field Manual.pdf. AusSpec International Pty. Ltd.
- Saitet. (2016). Update of the Conceptual Model of the Olkaria Geothermal System, 40, 97–104. Retrieved from <http://pubs.geothermal-library.org/lib/grc/1032313.pdf>
- Weydt, L. M., Lucci, F., Lacinska, A., Scheuven, D., Carrasco-Núñez, G., Giordano, G., ... Sass, I. (2022). *The impact of hydrothermal alteration on the physiochemical characteristics of reservoir rocks: the case of the Los Humeros geothermal field (Mexico)*. *Geothermal Energy* (Vol. 10). Springer Berlin Heidelberg. <https://doi.org/10.1186/s40517-022-00231-5>