

Spectral Interpretation of Geothermal Minerals

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ABSTRACT

Hyperspectral image spectroscopy (his) has revolutionized the spectral interpretation of minerals by providing non-destructive, high-resolution spectral data for precise mineral identification and mapping. This study explores the application of his in determining the wavelength of minimum reflectance, a critical spectral parameter for distinguishing minerals based on their unique absorption features. Wavelength mapping using his enhances the accuracy of mineral classification and spatial distribution analysis, making it a valuable tool in geological exploration and remote sensing applications. Compared to traditional analytical techniques such as x-ray diffraction (xrd) and x-ray fluorescence (xrf), his offers a rapid, large-scale, and non-invasive means of mineral characterization. While xrd is highly precise in identifying crystalline structures and phase compositions, it requires physical samples and extensive laboratory preparation. Xrf, on the other hand, is effective in determining elemental compositions but lacks the capability to directly identify mineral phases. In contrast, his enables remote, high-throughput mineral discrimination based on spectral signatures, making it particularly advantageous for field-based exploration, planetary studies, and resource assessment. The integration of his with xrd and xrf provides a comprehensive approach to mineral characterization, leveraging the spectral mapping capabilities of his alongside the structural and elemental insights offered by xrd and xrf. This synergy enhances the accuracy of geological interpretations and supports advanced mineral exploration and environmental studies. This study was focused on the analysis of a lithium pegmatite rock sample and the findings underscore the growing importance of hyperspectral data in complementing conventional mineralogical techniques for more efficient and precise geoscientific analyses. The minerals that were identified from the sample included; lepidolite, muscovite, topaz, quartz and albite.

1. INTRODUCTION

Mineralogical alteration in geothermal systems results from interactions between circulating fluids and host rocks under elevated temperature and pressure conditions. The resulting hydrothermal minerals preserve information on fluid chemistry, temperature, permeability, and structural controls (Browne, 1978; Reyes, 1990). Consequently, alteration mineralogy has long been used as a key indicator in geothermal exploration and reservoir assessment.

The Olkaria geothermal field, located within the Central Kenya Rift, is one of the most extensively developed high-temperature geothermal systems in Africa. Reservoir temperatures commonly exceed 300 °C, making Olkaria an ideal natural laboratory for studying hydrothermal alteration processes in volcanic geothermal environments (Mibei, 2012; Omenda and Karingithi, 1993).

Traditional mineral identification techniques, such as petrography and XRD, provide detailed mineralogical information but are limited by sample preparation requirements and analytical throughput (Reyes, 1990). Hyperspectral reflectance spectroscopy has emerged as an efficient complementary technique, capable of rapidly identifying hydroxyl-bearing and carbonate minerals based on diagnostic absorption features in the SWIR region (Clark, 1999; Hunt, 1977).

Previous studies have demonstrated the applicability of SWIR spectroscopy for geothermal alteration mapping at Olkaria (Kamau et al., 2020; Waweru, 2019). This paper builds upon these efforts by presenting a focused spectral interpretation of alteration minerals from drill cuttings and linking the results to geothermal processes and reservoir zonation

1.1 Objectives

The main objectives of the study are

- To determine mineralogical constituents of the rock sample based on visual inspection, analytical and Hyperspectral image spectroscopic techniques
- To produce mineral distribution map based on SWIR image data
- To understand diagnostic absorption of features of mineral constituents of the rock

2. GEOLOGICAL AND GEOTHERMAL SETTING

2.2 Regional Geological Setting

The volcanism and rift development in the Kenya rift started during the early Miocene with extensive basaltic and phonolitic volcanism on the crest of an uplifted dome. The early volcanic rocks crop out in the northern part of the rift and on the eastern rift shoulder (flood phonolite) (B. U. Baker & Wohlenberg, 1971; Ebinger & Scholz, 2011). These rocks overlie late Proterozoic schists and gneisses of the Mozambique mobile belt that occur at depths greater than 5 km within the central sector of the Kenya rift graben (Omenda, 1998).

The Great Olkaria Volcanic Complex (GOVC) is located within the central sector of the Kenya Rift Valley, where it is associated with a region of Quaternary volcanism. The GOVC has an estimated crustal thickness of 30-35 km beneath it (Riaroh & Okoth, 1994; Ring, 2014). The age of GOVC has been dated to be approximately 22-20 ka BP (Clarke et al., 1990; Macdonald, 2012). This is often characterized by different Similar Quaternary volcanic centers occur in the axial region of the rift and are potential geothermal resources (Omenda, 1998; Riaroh & Okoth, 1994).

The Miocene volcanics were subsequently faulted and then followed by massive and extensive Pliocene eruption of trachytic ignimbrites in the central area to form the Mau and Kinangop Tuffs (Clarke et al., 1990). The faulting later resulted in the development of a graben structure, and fissure eruptions, mostly of trachytes, basalts, basaltic trachyandesites, and trachyandesites, took place. Plateau rocks later filled the graben structure and were then faulted to form the high angle normal faults within the rift floor. The resultant fractures served as good conduits for Quaternary felsic and mafic volcanics (Omenda, 1998; Riaroh & Okoth, 1994; Smith & Mosley, 1993).

On the graben floor, fissure eruptions of trachytes and basalts occurred during the early Pleistocene and were followed by an extensive rift-floor grid-faulting event. Most of these volcanoes within the rift-system are associated with calderas of varying sizes; though the Olkaria volcanic complex does not have a clear caldera association. The presence of a ring of volcanic domes in the east and south, and southwest has been used to invoke the presence of a buried caldera (Clarke et al., 1990; Naylor, 1972). However, inference remain subtle in the context structural morphology and limited studies geared towards characterization of the caldera morphology to the northern part of the GOVC.

The petrochemistry of lavas within the Olkaria area attests that most of the lava flows were produced from discrete magma chambers (Omenda, 1998). Omenda (1998), further explains the caldera hypothesis associated with the rift structure to have been possibly produced by magmatic stresses in the Olkaria “magma chamber” with the line of weakness being loci for volcanism.

Several studies(e.g. Lagat et al., 2005; Omenda, 1998) have so far been conducted and correlated with subsurface data from the drilled wells, and six main lithological facies have been identified. These are summarized as shown in the figure 5 below;

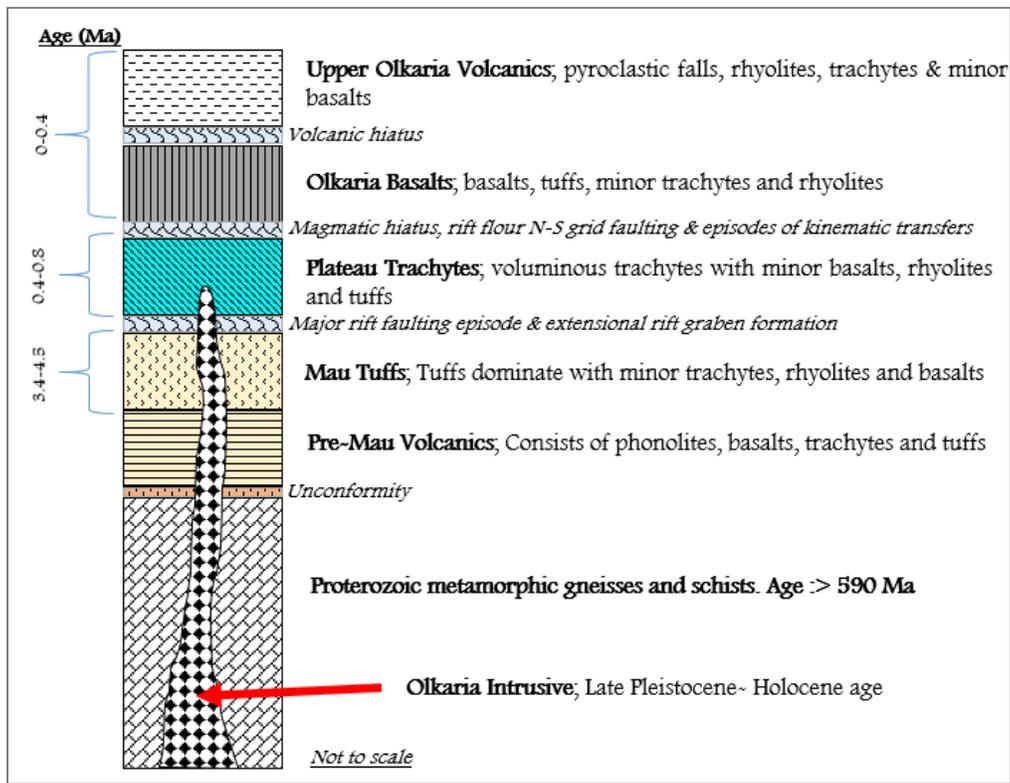


Figure 1: Stratigraphy of Olkaria Volcanic Complex (updated from Omenda, 1998) and with inputs from logs of drilled wells. However, the wells do not intercept any basement formation due voluminous nature of volcanic deposits.

2.3 Structural setting

Geological structures play a vital role as conduits for the movement of fluids. In particular, faults are considered to have two-fold effects on fluid flow dynamics; they may facilitate flow by providing channels of high permeability, or they may prove to be barriers to flow by offsetting zones of relatively high permeability (Calais et al., 2008; Chorowicz, 2005; Omenda, 1998). Within the Rift Valley, the main direction of faulting is along the axis of the rift, and this has a significant effect on the flows across the rift. It is apparent from the high hydraulic gradients that are developed across the rift escarpments that the effects of the major fault are to act as zones of low permeability.

The structural pattern of the greater Olkaria volcanic complex area is characterized by the following fault trends: the Ol-Njorowa gorge, N-S, NW-SE, NNW-SSE, ENE-WSW Olkaria fault and the ring structure (Lagat et al., 2005; Omenda, 1998; Riarioh & Okoth, 1994), (see figure 6). These faults are undoubtedly considered to have substantial effect on the geothermal fluid flow systems of the area. In the Greater Olkaria Geothermal Area (GOGA), there is evidence of near vertical step-faulting. These fault scarps are often well preserved and marker horizons can be progressively traced on lower slopes. It is notable that the greater portion of the fault blocks plunge southwards. There are other faults striking NW linking the parallel rift basins to the main extensional zone.

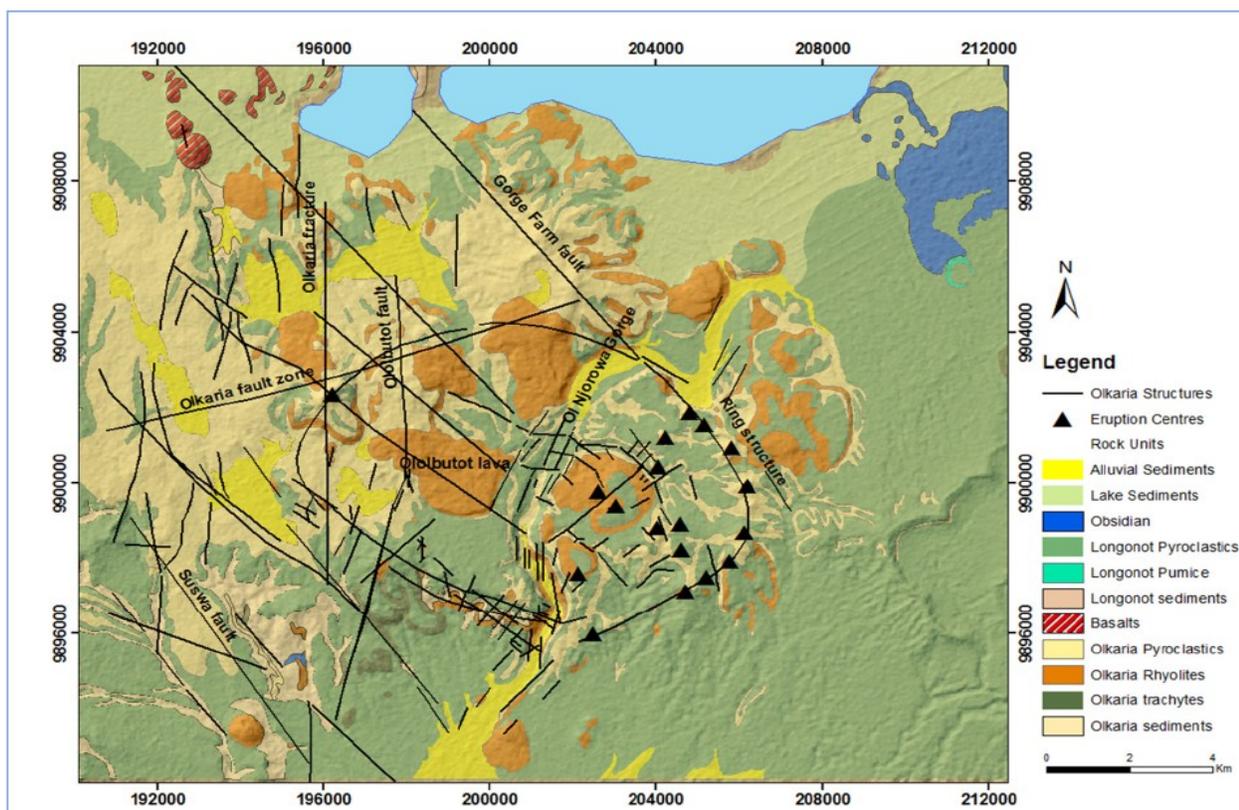


Figure 2: Geological and structural map of Olkaria Volcanic Complex (adopted Clarke et al., 1990; Munyiri, 2016).

Markedly, the faults are more exposed in the East, Northeast and West Olkaria fields but rare in the Olkaria Domes area due to the thick pyroclastics cover (Lagat et al., 2005). The NW-SE and WNW-ESE faults are thought to be the oldest and are associated with the development of the rift. The most prominent of these faults is the Gorge Farm fault, which bounds the geothermal fields in the northeastern part and extends to the Olkaria Domes area and is envisaged to be a major recharge zone for GOGA. The most recent structures are the N-S and the NNE-SSW faults. Hydroclastic craters located on the northern edge of the Olkaria Domes area mark magmatic explosions, which occurred in a submerged environment.

Among the many faults is the ENE-WSW Olkaria Fault. This is one of the major faults that run through the Olkaria geothermal area. Omenda (1998) inferred that the ENE-WSW Olkaria fault to be an older and rejuvenated structure. The fault manifests itself on the surface as a linear zone of intense geothermal manifestations and highly altered grounds, about 50-100 m in width. Fumaroles in this area are at boiling point with sulphur and silica deposits observed on the surface. This fault has a surface displacement of about 5 m with a down throw to the north (Omenda, 1998). A system of fissures and faults running E-W are believed to control the bulk of fluid movement and permeability properties of the reservoir rocks in Olkaria West Field and Domes areas.

3.0 MATERIALS AND METHODS

3.1 Sample Collection

A rock sample was collected from Olkaria geothermal field from a lithium pegmatite outcrop for this study. The rock was subjected to the following analyzes:

- Physical description: color, texture, visible mineral
- XRF- Elemental composition analysis
- XRD-whole rock mineralogical analysis
- Hyperspectral Image Spectroscopy-Wavelength of Minimum and wavelength mapping

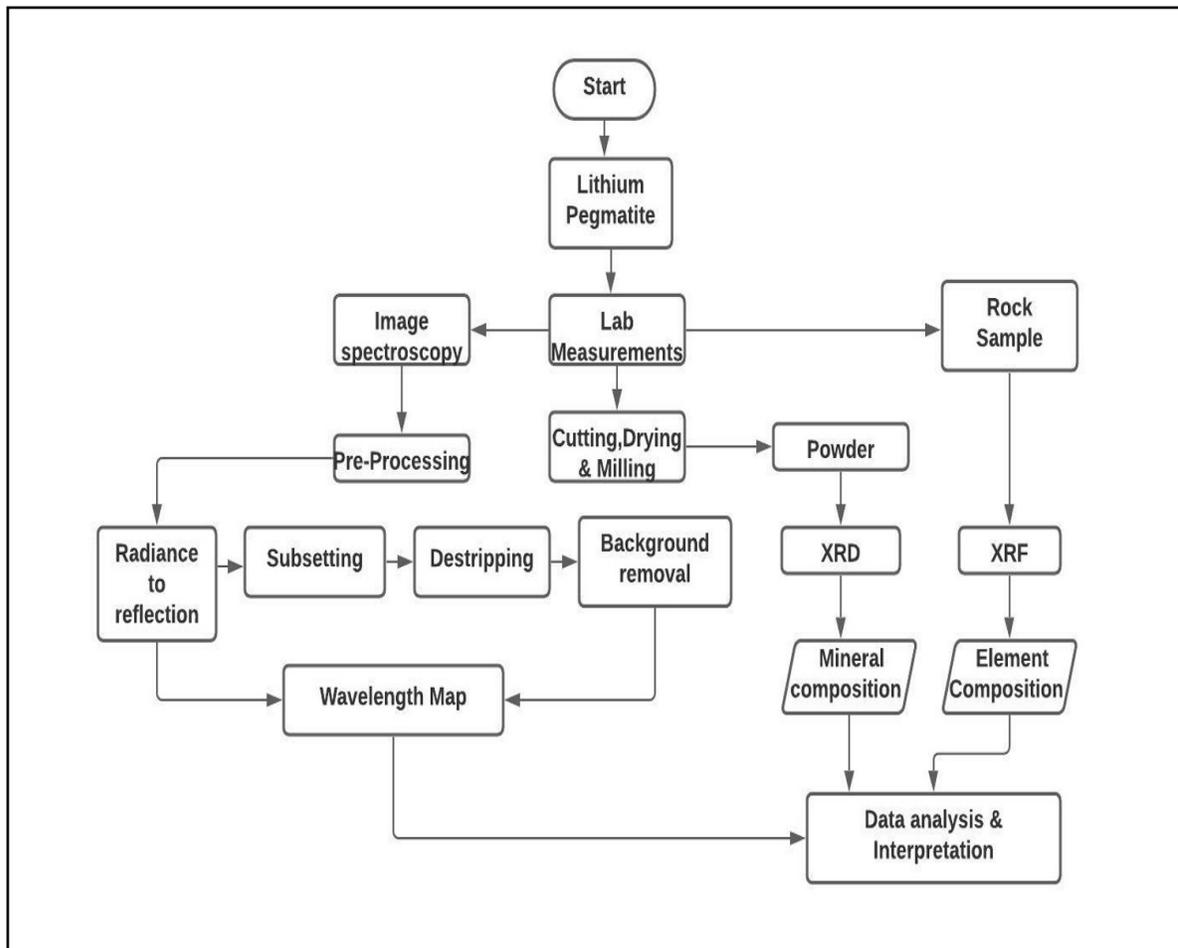


Figure 3: Workflow

1.2 3.2 Spectral Processing and Mineral Identification

Spectral preprocessing included noise reduction, continuum removal, and normalization to enhance diagnostic absorption features (Clark and Roush, 1984). Mineral identification was performed by comparing sample spectra with reference spectra from the USGS spectral library using visual matching and the Spectral Angle Mapper (SAM) algorithm (Kruse et al., 1993).

Key absorption features used for interpretation included:

- ~1400 nm and ~1900 nm: molecular water and hydroxyl groups
- ~2200 nm: Al-OH absorption typical of illite and smectite

- ~2250–2350 nm: Fe-OH and Mg-OH absorptions characteristic of chlorite and amphiboles

4.RESULTS

4.1 Alteration Mineral Assemblages

Spectral analysis identified several hydrothermal alteration minerals across the studied wells. Smectite and zeolites were dominant in shallow sections, indicating low-temperature alteration (<150 °C). Illite and chlorite were widespread at intermediate depths, consistent with temperatures between 180 °C and 280 °C (Reyes, 1990; Kamau et al., 2020).

4.2 Physical Interpretation

The sample shows whitish, purple, and brownish color and its medium to to coarse grained

Visible minerals include;

Leucocratic-whitish and light gray minerals 45% (quartz and feldspar)

- Brownish mineral (topaz) ~ 20%
- Purple mineral(lepidolite) ~ 10%,
- Shiny mica mineral (muscovite) ~ 15%

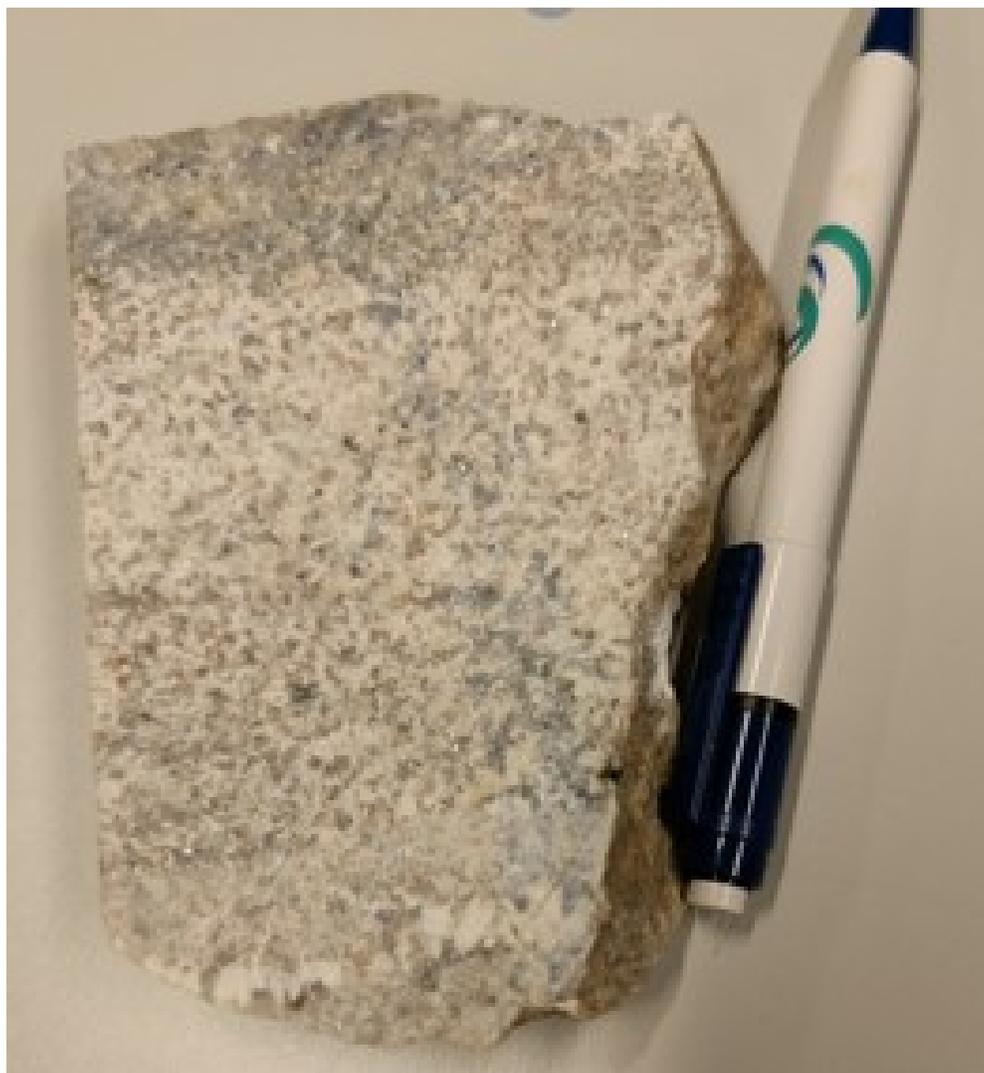


Figure 4: The rock Sample that was analyzed

4.2 XRD Results

A fresh, unaltered portion of the rock is cleaned, crushed, and ground to a fine powder (commonly $<63 \mu\text{m}$) to reduce grain-size effects and minimize preferred orientation of platy minerals (Moore & Reynolds, 1997). The powdered sample is then mounted in a sample holder with a smooth, randomly oriented surface and analyzed using an X-ray diffractometer, typically employing Cu-K α radiation, over a selected 2θ range appropriate for common rock-forming minerals (Brindley & Brown, 1980). The resulting diffractogram below show the strong peaks of Quartz and Albite.

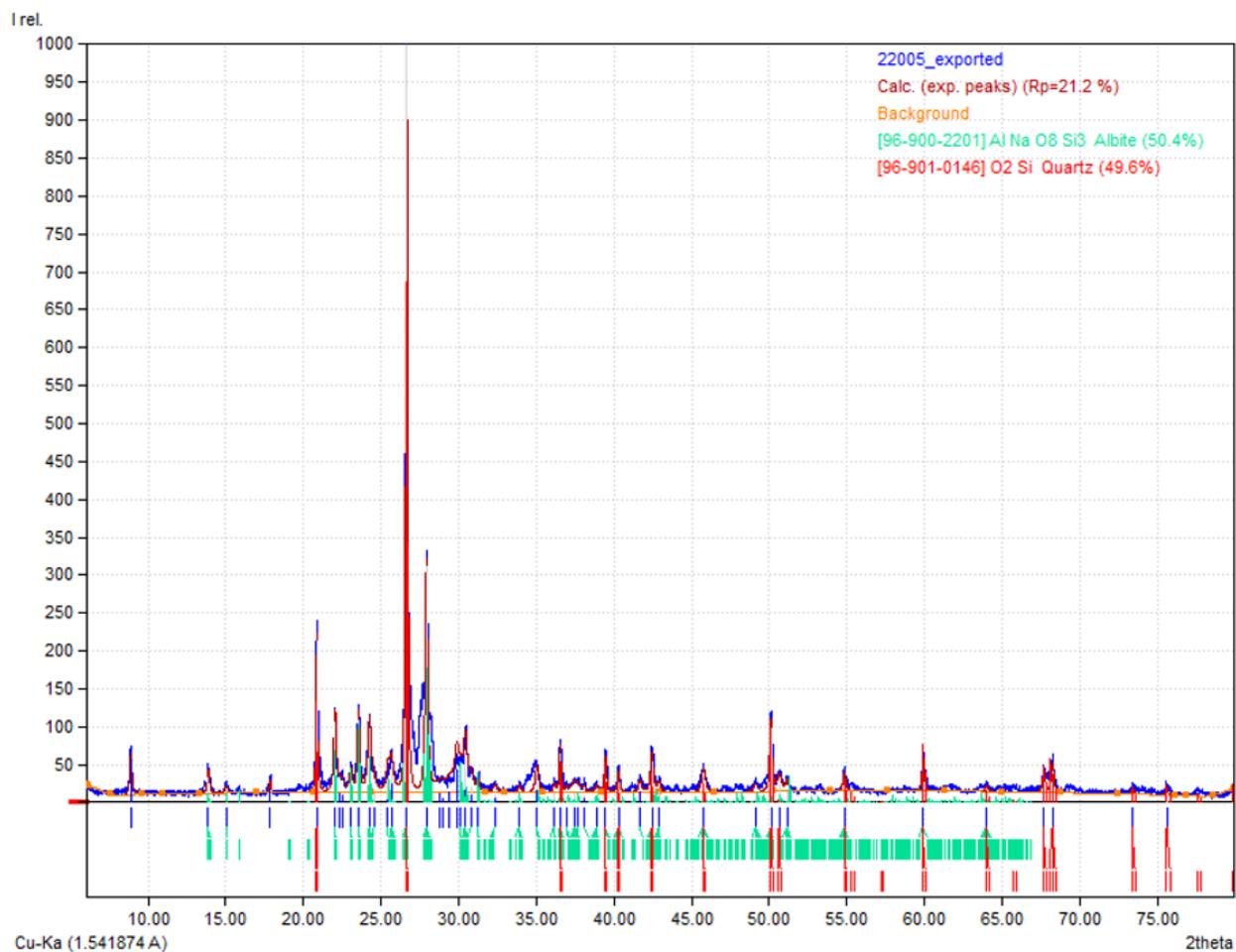


Figure 5: XRD Diffractogram Result showing strong peaks of Quartz and Albite

XRF Result

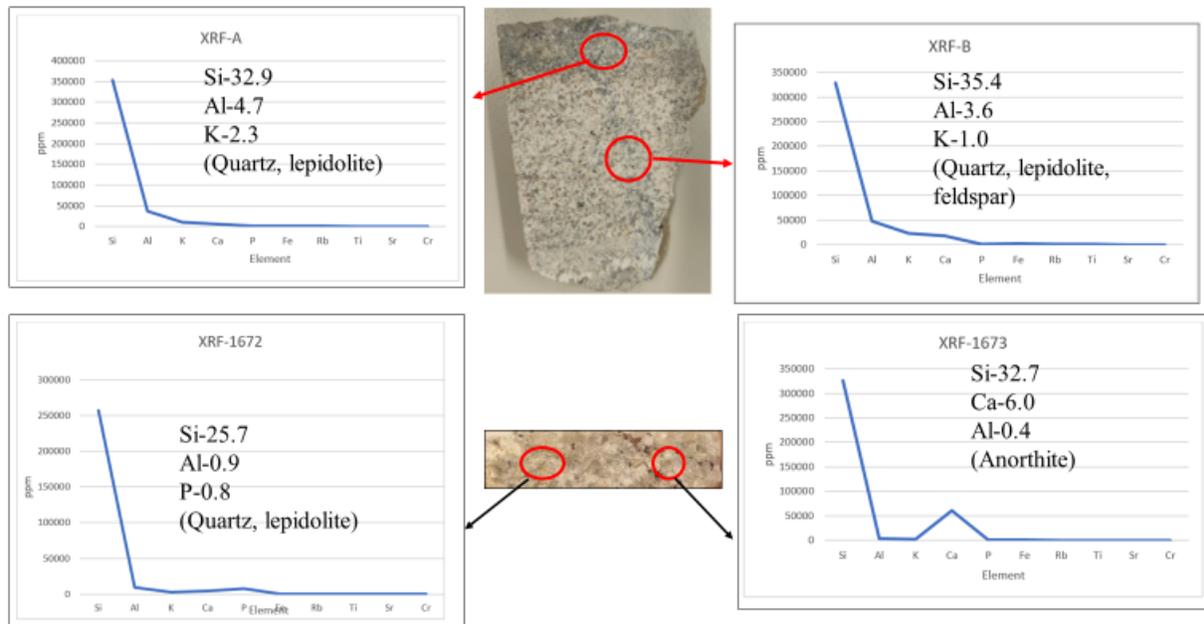


Figure 6: XRF Results showing elemental composition of the rock at different spots.

Spectral matching with USGS library

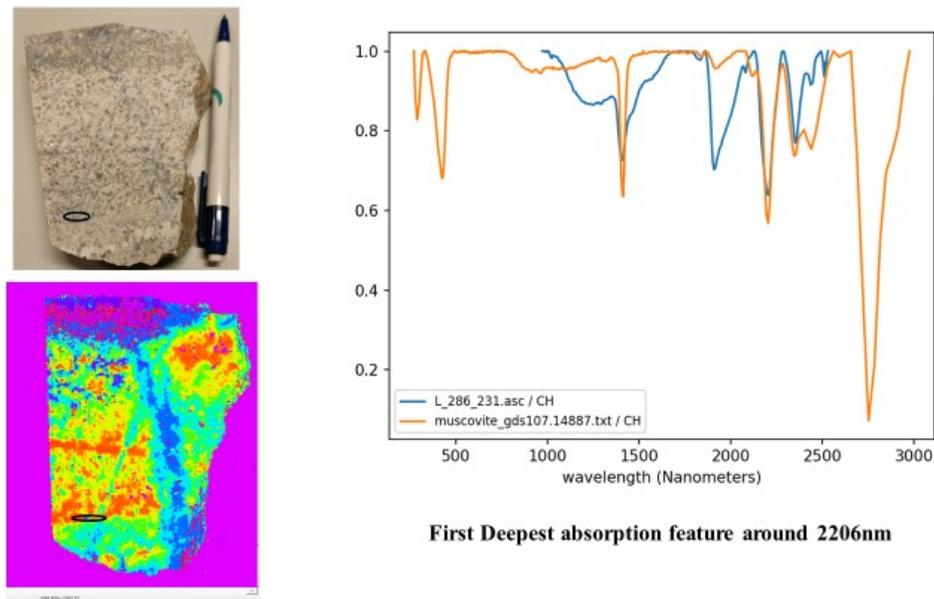


Figure 7: Hyperspectral Image and the corresponding Spectral Signatures for Muscovite.

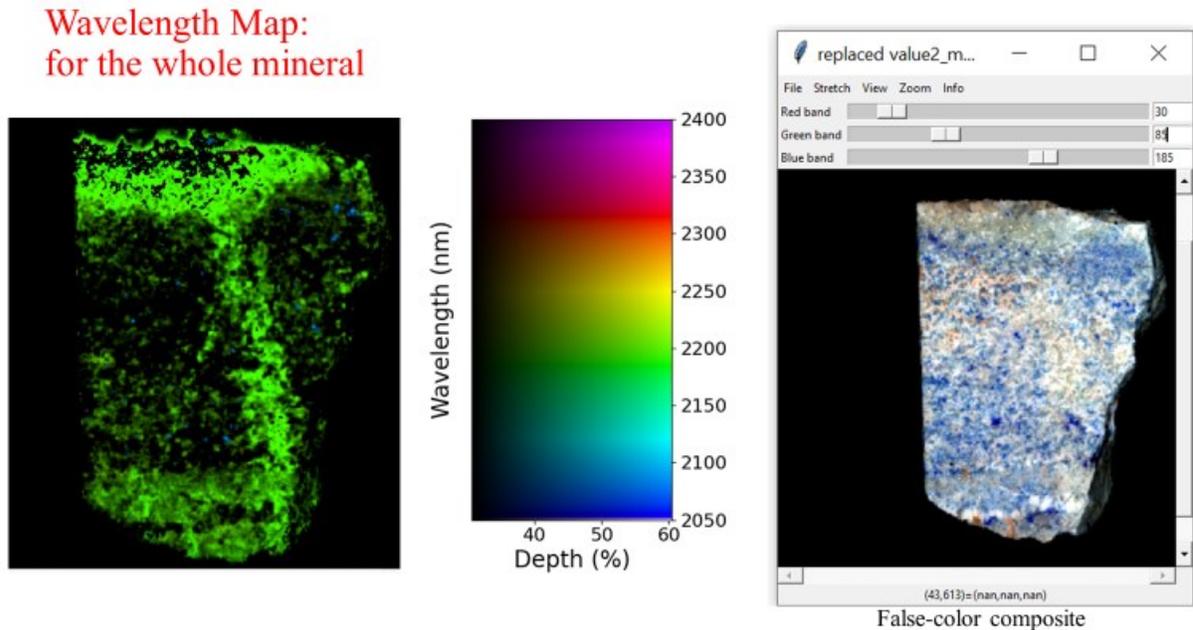


Figure 8: The resulting Wavelength map of the rock sample.

5. DISCUSSION

The results confirm that SWIR hyperspectral spectroscopy is highly effective for rapid identification of geothermal alteration minerals. The technique is particularly sensitive to hydroxyl-bearing minerals, which dominate geothermal alteration assemblages (Hunt, 1977; Clark, 1999).

1.3 5.2 Implications for Reservoir Characterization

Spectral mineral zonation provides valuable constraints on subsurface temperature distribution and fluid flow paths. When integrated with geological, geochemical, and geophysical data, hyperspectral analysis enhances geothermal reservoir models and supports informed drilling decisions (Kamau et al., 2020; Waweru, 2019).

6. CONCLUSIONS

This study demonstrates that SWIR hyperspectral spectroscopy is a robust and efficient tool for interpreting geothermal alteration mineralogy in the Olkaria geothermal field. The identified mineral assemblages and their vertical distribution correlate strongly with known thermal regimes and reservoir structures. Spectral interpretation therefore represents a valuable addition to geothermal exploration and reservoir management workflows, particularly in volcanic rift

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