

High Temperature Alteration Mineral Identification Using ATR Spectroscopy in Kenyan Geothermal Wells

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ABSTRACT

Understanding the formation and distribution of hydrothermal alteration minerals is essential for interpreting the thermal evolution, permeability, and fluid–rock interactions in geothermal systems. This study focuses on identifying high-temperature alteration minerals in selected Kenyan geothermal wells using Attenuated Total Reflectance (ATR) Spectroscopy.

The method provides a rapid, non-destructive approach for recognizing mineral phases through their diagnostic infrared absorption features. Drill cuttings and core samples collected from different depth intervals and geothermal fields within the Kenyan Rift were analyzed to investigate mineralogical variations associated with increasing temperature and alteration intensity.

The ATR spectra revealed prominent vibrational features characteristic of epidote, chlorite, quartz, garnet, and wollastonite, indicating progressive mineral transformations under high-temperature hydrothermal conditions. These spectral interpretations were verified using X-ray Diffraction (XRD) analysis, which confirmed the accuracy of ATR-based mineral identification. Integration of the spectral and mineralogical data delineated distinct alteration zones with depth, reflecting temperature gradients and fluid flow regimes within the geothermal reservoir.

The study demonstrates that ATR spectroscopy is a reliable and cost-effective analytical tool that complements traditional methods in geothermal exploration. Its minimal sample preparation, high spectral resolution, and ability to analyze fine-grained mixtures make it suitable for routine characterization of alteration assemblages. These results enhance understanding of the hydrothermal and thermal evolution of Kenyan geothermal systems and provide valuable input for resource evaluation and reservoir development.

1. INTRODUCTION

Alteration mineralogy in geothermal systems reflects subsurface thermal gradients, fluid–rock interaction, and permeability pathways, making it a pivotal parameter in system assessment and exploration (Reyes et al., 1990). Traditional modal mineralogical techniques, such as thin section petrography and X-ray diffraction, while robust, are time-consuming and require extensive sample preparation (Moore & Reynolds, 1997). ATR spectroscopy, a form of Fourier Transform Infrared (FTIR) spectroscopy, enables rapid, non-destructive acquisition of reflectance spectra that can be directly linked to mineral vibrational modes (Farmer, 1974).

Olkaria, located within the Kenyan Rift Valley, hosts a high-enthalpy geothermal resource with well-developed hydrothermal alteration zones (Wright et al., 1999). Prior studies have documented alteration assemblages ranging from propylitic to advanced argillic facies, with mineralogical distributions reflecting both magmatic degassing and meteoric fluid interaction (Torrens et al., 2004). This study focuses on high temperature zones (>250 °C) where alteration minerals provide insights into fluid evolution and reservoir conditions

2. PROBLEM STATEMENT

Which high-temperature minerals can we identify in OW-205 and OW-916 drill cuttings using ATR spectroscopy?

3. OBJECTIVES

The main objectives of the study:

To use Attenuated Thermal Reflectance (ATR) spectroscopy to identify high-temperature alteration minerals in Olkaria drill cuttings.

3.1. REGIONAL GEOLOGICAL SETTING

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 rig 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 1 below;

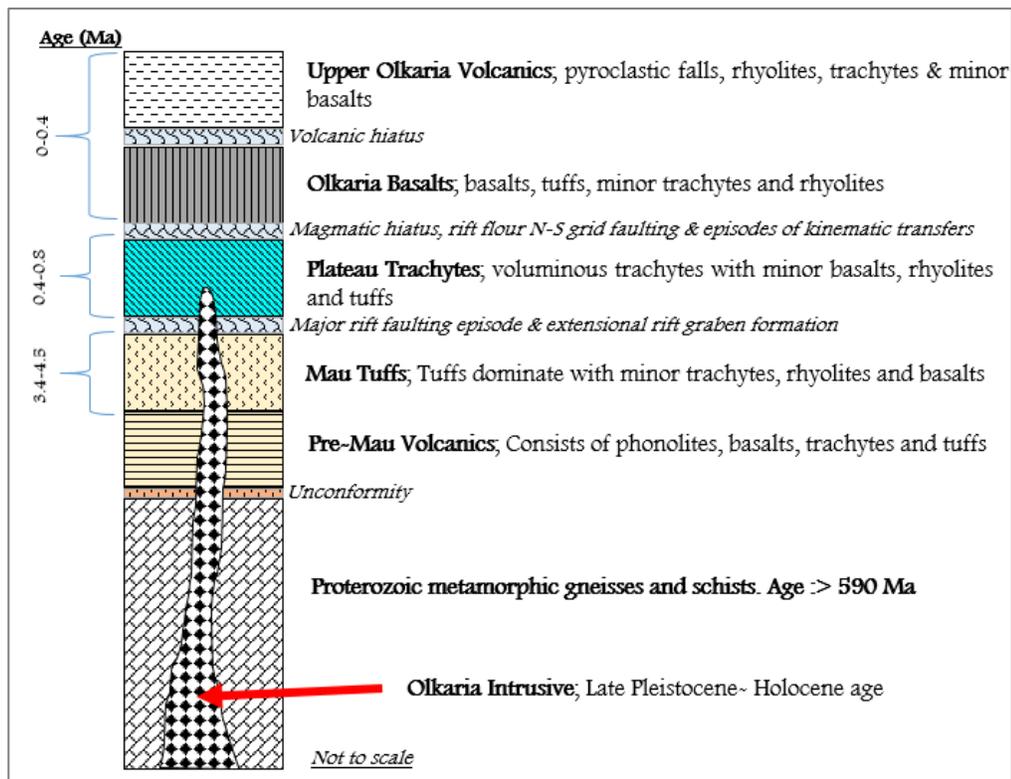


Figure 1: Stratigraphy of Olkaria Volcanic Complex (updated from Omenda, 1998) and with inputs from logs of drilled wells. However, the wells do not intercept any basement formation due voluminous nature of volcanic deposits.

3.2 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; Riaroh & 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.

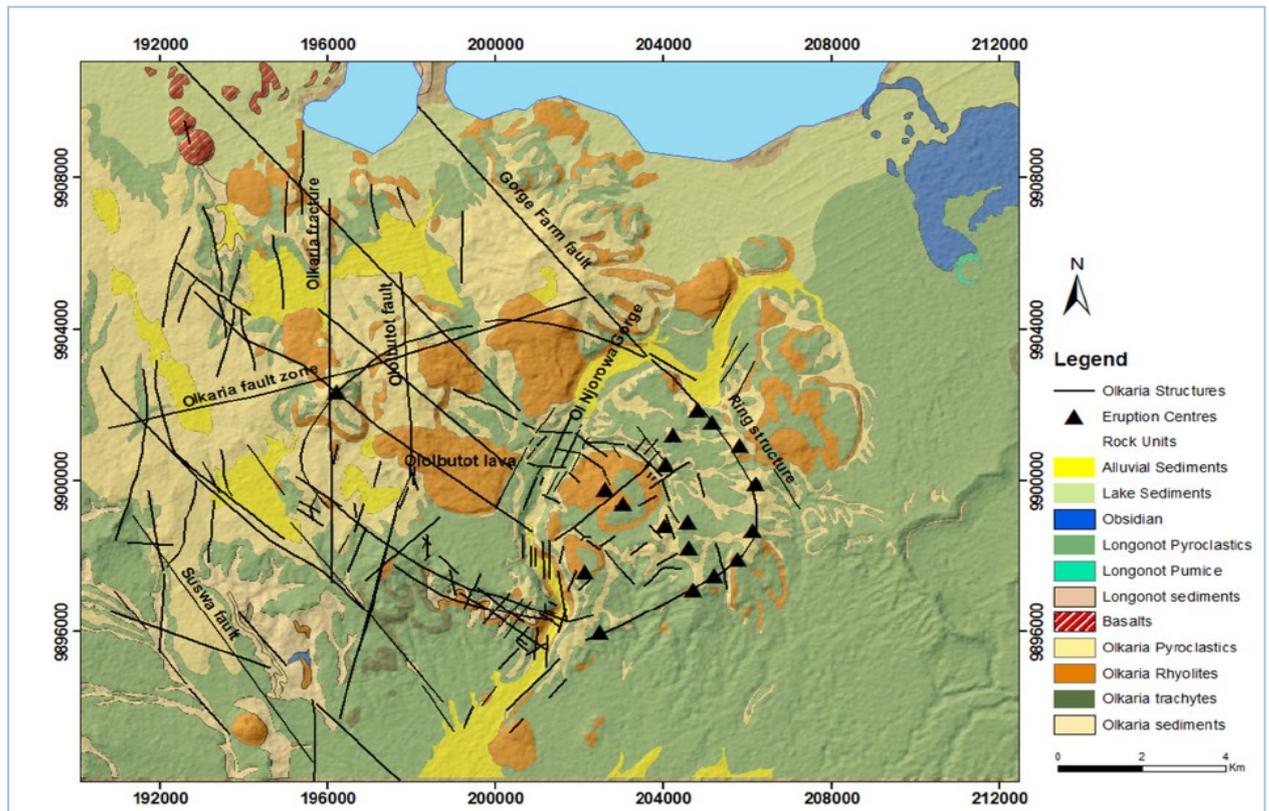


Figure 2: Geological and structural map of Olkaria Volcanic Complex (adopted Clarke et al., 1990; Muniyiri, 2016).

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.

4. METHODOLOGY

4.1 Sample Collection

Drill cuttings from two wells (OW205 & 916) in Olkaria were used during this research. The cuttings (about 500gms) were obtained at 2m intervals during the drilling phase of the two wells (KenGen standard procedure).

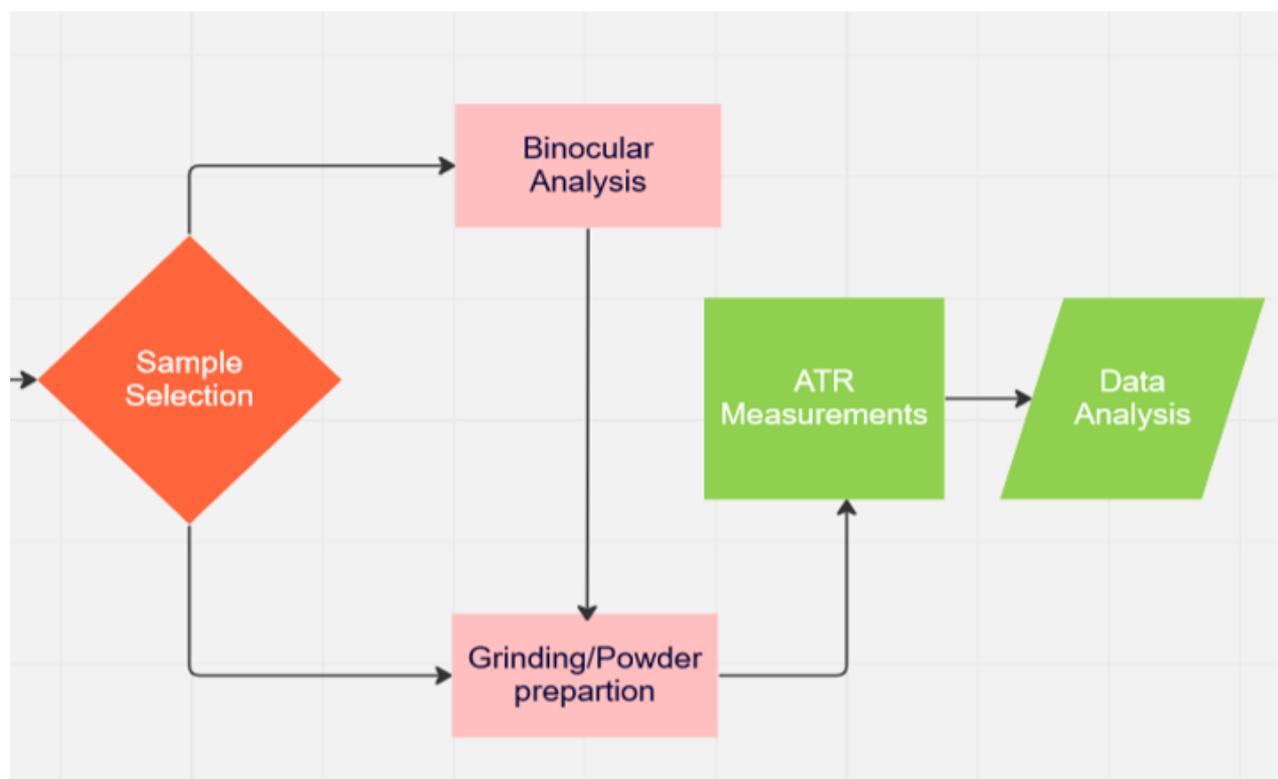


Figure 3: Workflow

4.2 ATR Spectroscopy

ATR (Attenuated Total Reflectance) spectroscopy is a widely used, simple, non-destructive sampling technique, often paired with FTIR (Fourier Transform Infrared Spectroscopy), that analyzes solids, liquids, and pastes by bringing the sample into direct contact with a high-refractive-index crystal, allowing an evanescent wave to penetrate shallowly, absorb light, and generate a spectrum of the sample's molecular structure with minimal sample preparation.

ATR spectra were acquired using a bench-top FTIR spectrometer equipped with a diamond ATR crystal. Powdered samples were gently pressed against the ATR element to ensure consistent contact. Spectra were collected over 4000–400 cm^{-1} at 4 cm^{-1} resolution with 64 co-added scans per sample.

4.3 Working Principle

(a) Contact: A sample (solid or liquid) is placed in direct contact with crystal (eg. Diamond, Ge, Si, ZnSe)-highly refractive-index material

(b) Internal Reflection: Infrared enters the crystal and reflects off its internal surface.

(c) Evanescent Wave: At the reflection point, the light creates an “evanescent wave” that extends a short distance (a few microns) into the sample. (electromagnetic waves that decay rapidly upon hitting a boundary at an angle greater than the critical angle.

(d) Absorption: The sample absorbs specific wavelengths from the wave, revealing its molecular structure.

(e) **Detection:**The internally reflected light,now modified by the sample's absorption, travels to a detector, generating the ATR -IR spectrum

4.4 Data Processing

Raw spectra were baseline corrected and normalized to facilitate comparison. Diagnostic absorption bands were identified following established spectral libraries (Clark et al., 1990) and previous geothermal spectral work (Christenson & Scott, 2003).

5. RESULTS

Two high-temperature alteration minerals, epidote and actinolite, were successfully identified through visual examination using a binocular microscope and subsequently confirmed by ATR spectroscopy. In addition to these, the ATR spectroscopic analysis enabled the identification of two other high-temperature minerals that were not readily observable under the binocular microscope. Notably, wollastonite was not detected during the binocular microscopic analysis, indicating either its absence or its occurrence in quantities or grain sizes below the detection limit of this method.

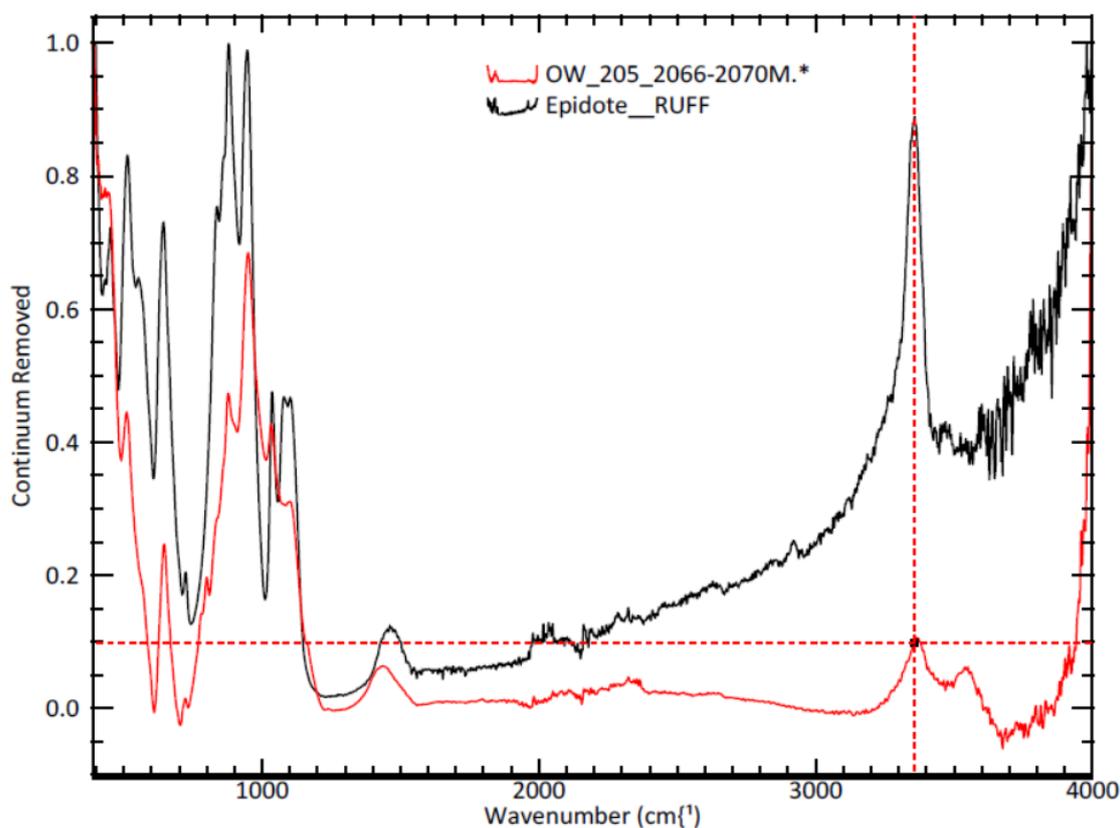


Figure 3: Acquired Epidote spectra and RUFF library spectra.

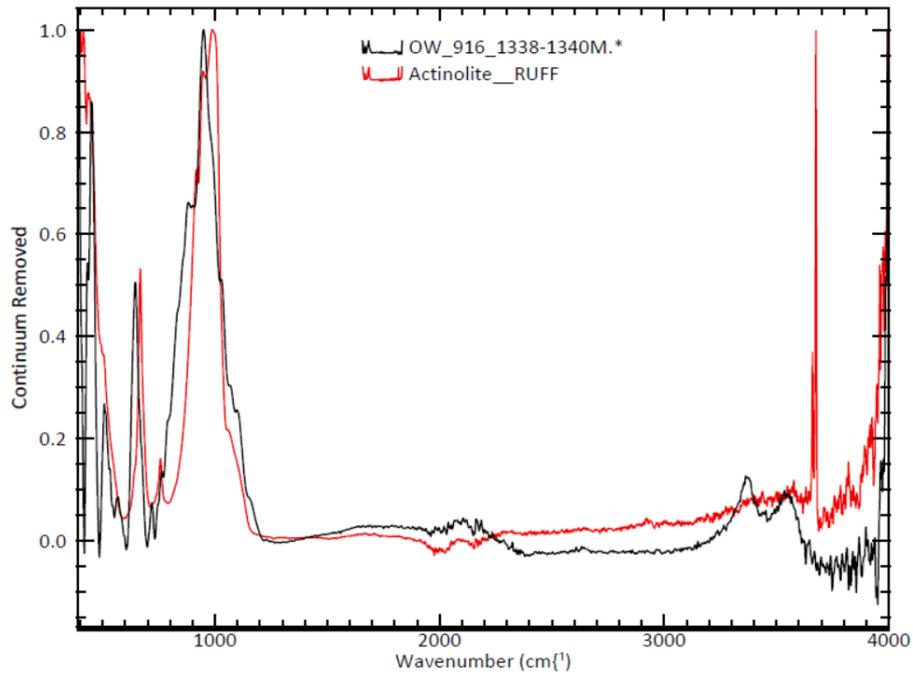


Figure 4: Acquired Actinolite and RUFF library spectra

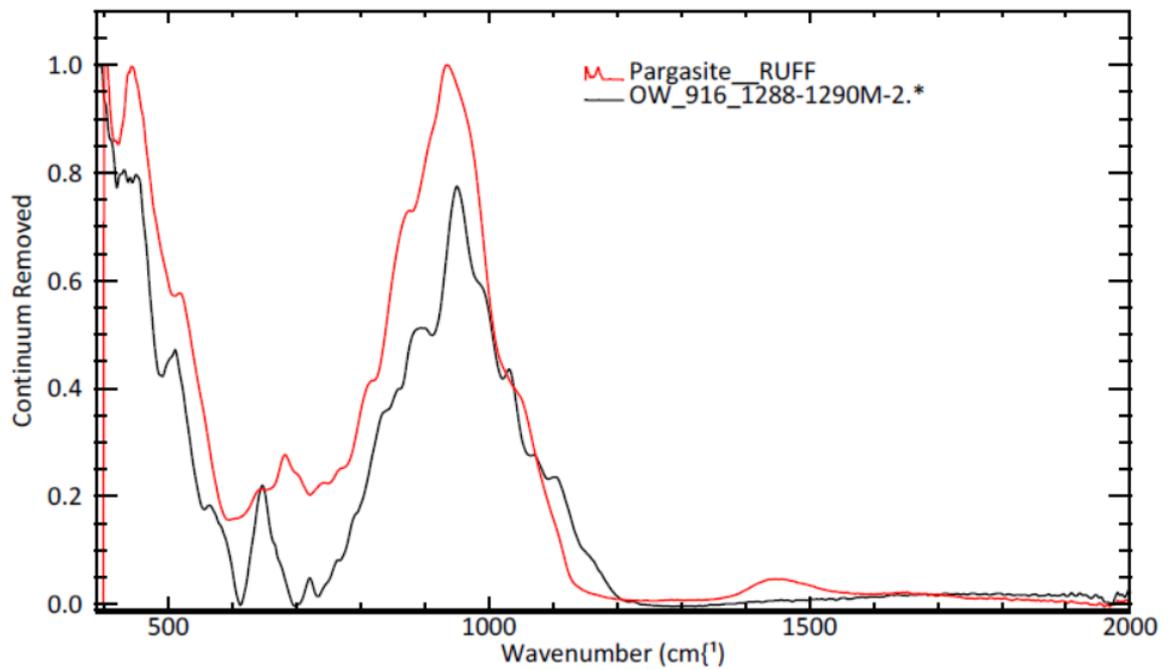


Figure 5: Acquired Pargasite and RUFF library spectra

6. DISCUSSION

The available data proved to be useful and sufficient for achieving the study objective, and the research question was successfully addressed upon completion of the investigation. However, the preliminary stage of mineral grain picking using a binocular microscope was found to be time-consuming and labor-intensive, requiring

approximately three hours to obtain a representative quantity of mineral grains from a single sample. Additionally, some minor spectral shifts or mismatches observed during spectral interpretation may be attributed to the use of the RRUFF mineral library, which is largely based on spectra acquired from pure mineral crystals, whereas natural samples often contain compositional variations, impurities, or mixed phases.

7. CONCLUSIONS

ATR spectroscopy is a powerful tool for identifying high-temperature alteration minerals in geothermal wells. In the Olkaria field, ATR spectral analysis successfully distinguished alteration phases consistent with subsurface temperature gradients and fluid interactions. These results reinforce the value of ATR for rapid mineralogical characterization in geothermal exploration and reservoir management.

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