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# Radiometric Mapping for The Identification of Hydrothermally Altered Zones Related to Gold Mineralization in Ife–Ilesa Schist Belt, Southwestern Nigeria

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**Abstract:** This study presents the interpretation of airborne gamma ray spectrometric data to delineate hydrothermally altered zones related to gold mineralization in the Ife–Ilesa Schist belt. K/eTh, Kd and F–Maps highlighting Potassic alterations related to gold mineralization were processed on the Oasis Montaj software and subsequently integrated using fuzzy logic modeling to produce the hydrothermal alteration map of the study area. The C–A fractal analysis was applied to the final hydrothermal map and was able to classify the study area into background, very low, low, moderate, high and very high alteration. These classes reflect the pervasive hydrothermal alteration style of the study area. The hydrothermally altered areas are evident on granitoids and areas proximal to it indicating that granitoids are proxies of heat source. Occurrence of active mining sites in the area agrees with the generated hydrothermal alteration map of the study area with 81% agreement. It therefore shows that radiometric method is a veritable method in mapping hydrothermal alteration areas. The use of radiometric method only cannot reliably map areas of gold mineralization as mineralization can be associated with several other processes. Hence, other methods involving geochemical and magnetic methods including GIS tools can be employed for further prospecting.

**Keywords:** Orogenic; hydrothermal alteration; potassium enrichment; thorium impoverishment; Fractal analysis

## INTRODUCTION

Gold is one of the most important mineral resources on earth due to its ornamental value and importance in making a great hedge against inflation (KPMG, 2017). However, locating it is not easy majorly because they are found at great depths. Hence, geoscientists depend on mapping or detection of indices that are genetically linked to gold mineralization (Forson et al., 2022). Hydrothermal alteration is an important index in the mineral exploration of orogenic deposits with the inclusion of gold. Hydrothermal alteration process involves the introduction of hydrothermal fluids containing chemical composition complexes depending on the rock and fluid ratio (Rushmer, 1991; Robb, 2005). It is subsequently followed by the reworking and remobilization of mineral deposits through assimilation in country rocks under favorable temperature and pressure conditions. This in turn causes changes in the magnetic fabric, chemical composition and mineralogy of rocks (Phillips & Powell, 2010; McCauig & Hronsky, 2014). This then permits the mapping of anomalous changes in rocks caused by hydrothermal alteration using geophysical methods (Sanusi & Amigun, 2020). The mapping of hydrothermal alteration zones can thus be accomplished with the help of the radiometric and magnetic methods (Eleraki et al., 2017; Sanusi & Amigun, 2020). However, the radiometric approach offers the most detailed on the discovery and identification of alteration minerals that are indicators for mapping hydrothermal alteration zones (Maden & Akaryali, 2015; Eleraki et al., 2017). This is because direct identification of potassium enriched zones through potassic alteration, genetically linked to gold mineralization can be easily delineated through the distribution of radioelements like Potassium (K), Thorium (Th) and Uranium (U) (Graham & Bonham-Carter, 1993; Grasty & Shives, 1997; Wilford et al., 1997; Ford et al., 2000; Abd El Nabi, 2013; Eleraki et al., 2017; Sanusi & Amigun, 2020; Olomo et al., 2022).

Zones that have undergone hydrothermal alteration and are associated with mineralisation have been discovered in previous studies (Garba, 1988; Ranjbar et al., 2011; Tawey et al., 2022). Previous studies have shown that identifying and mapping hydrothermally altered zones can act as a guide for locating and mapping main mineralisation. However, it necessitates the identification and distribution of radioelements that are connected to hydrothermal alteration in order to identify zones that have undergone hydrothermal alteration. As a result, we can use the radiometric approach to establish the surficial distribution of various radioactive elements and then separate the hydrothermally changed zones (Sanusi & Amigun, 2020). The enrichment and depletion of specific radioelements in various lithological units, as well as their impoverishment, determine how reliable the mapping is (El Sadek, 2009; Abd El Nabi, 2013). As a result, it entails measuring the naturally existing radioactive elements uranium (U), thorium (Th), and potassium (K) for the outermost part of the earth's surface, where rock-forming minerals and soil profiles are present (Cook et al., 1996; Zhang et al., 2017). The radioelement contents of geological units that are undergoing deformation can alter in a variety of ways due to hydrothermal processes (Eleraki et al., 2017). Radiometric methods are useful for mapping potassic alteration, which is a significant aspect of hydrothermal alteration. Other important alterations like Argillic, Propylitic, Iron Oxide and Phyllic alteration are also genetically linked to orogenic gold mineralization (Andogma et al., 2020; Forson et al., 2022). It therefore means that the Potassic alteration delineation through radiometric method alone cannot be solely used for the delineation of orogenic gold mineralization (Di Tommaso & Rubinstein, 2007; Ranjbar et al,, 2011; Maden & Akaryali, 2015; Tawey et al., 2021). However, due to the success recorded in delineating gold mineralization through the identification of potassic alteration through radiometric mapping, the method offers an important clue as to the delineation and mapping of hydrothermally altered zones related to orogenic gold mineralization (Silva et al., 2003; Sanusi & Amigun, 2020; Forson et al., 2022).

However, in order to identify hydrothermally altered zones connected to gold mineralisation, mapping of potassium enrichment zones viz a viz potassium concentration is insufficient. This is due to the fact that additional factors, such as weathering, leaching, climate, and others, may contribute to potassium enrichment (Ranjbar et al., 2011; Tawey et al., 2022). In order to distinguish between potassium enrichment brought on by hydrothermal alteration from other processes, appropriate mathematical combinations of potassium concentrations and equivalent Thorium and Uranium concentrations are needed (Sanusi & Amigun, 2020). This therefore makes it possible to utilize the radiometric approach to identify and map the hydrothermal alteration reserves (including sericite, biotite, K-feldspars, and various K-bearing clay minerals). Due to its extensive coverage, speed, efficiency, and precision, the use of airborne radiometric data is crucial when mapping hydrothermally altered zones of huge areas (Abd El Nabi, 2013; Zhang et al., 2017; Sanusi & Amigun, 2020).

According to Garba (2002) and Obaje (2009), gold mineralisation is known to be generally associated with the Ife-Ilesa schist belt as well as other schist belts in Nigeria, including the Maru, Anka, Zuru, Kushaka, Zungeru-Birnin, Gwari, Karaukarau, Iseyin-Oyan, Malumfashi, and Egbe-Isanlu schist belts. These areas have also been found to contain hydrothermal alteration zones linked to gold mineralisation. There are numerous primary and alluvial gold workings in the Ife–Ilesa schist area. The primary gold often occurs in quartz veins across a variety of lithologies, and the host rocks for the veins include fine-grained mica schists, amphibolite schists, talc tremolite schists, and a number of other gneisses (Akande & Fakorede, 1988). Oyinloye (1997); Obaje (2009) and Olajide–Kayode et al. (2020) in different researches in the Ife–Ilesa schist belt identified primary gold deposits with the consequent identification of pathfinder elements like Zn, Ni, Sb, Co, Mo, Se and Pb often found in hydrothermally altered zones related to gold mineralisation.

The hydrothermal alteration often associated with magmatic differentiation is accompanied by Potassium emplacement. Furthermore, concentration of Potassium is often present alongside sulphide which is one of the scrubber elements of gold in the sericite zone. This was affirmed in the research of Olajide–Kayode et al. (2020) where hydrothermal alteration and sulphidization from petrological and geochemical studies were associated with the occurrence of gold in the Ife–Ilesa schist belt. This indicates that hydrothermal alteration is an important sub–system of the mineral system of gold mineralisation in the region, and for precise mapping of gold mineralisation, indices of hydrothermal alteration have to be taken into important consideration. However, the studies aimed at the identification of hydrothermal alteration zones in the Ife-Ilesa schist belt have mainly been centered on geological and geochemical sampling, requiring random sampling at chosen places (Akande & Fakorede, 1988; Akanmu et al., 2019; Olajide–Kayode et al., 2020). As a result, there is not much information available about the general hydrothermal alteration of the region to help with mineral prospectivity for gold in the area.

More than 90% of the gold extracted in the area is from artisanal mining, primarily because primary deposits' unique characteristics—such as the existence of gold deposits at depth—are given less attention than they deserve. The vast majority of the gold deposits are thus untapped mainly because of no indices to guide targeted exploration work of gold deposits. Therefore, large-scale mapping of hydrothermally altered zones is now essential because it has been demonstrated how important hydrothermal alteration is to primary gold mineralisation in the studied region. As a result, this study emphasizes the use of airborne radiometric data due to its vast coverage of the study region, speed, and capacity to recognize hydrothermally altered zones connected to gold mineralisation in the Ife–Ilesa schist belt. This will in turn aid in precise targeting of gold exploration in the area.

## GEOLOGICAL SETTING AND MINERALISATION

The Ife–Ilesa schist belt, one of the most important schist belts in Nigeria is located in Osun State, southwestern Nigeria. It lies east of the Ibadan Archaean to Lower Proterozoic massif. It has a N–S length of over 200 km and reaches its maximum width of 60 km in the south (Obaje, 2009). Rocks in the Ilesa schist belt are affected by two major fracture zones being the Iwaraja fault in the eastern part and the Ifewara fault in the west (Elueze, 1986; Folami, 1992; Kayode, 2006). The Ifewara fault stretches from the east of Ijebu Ode in the south to the Niger basin of the River Niger south of Lafiagi. Hubbard (1975) suggested a possible link between the fault and the subsurface Okitipupa Ridge in the Atlantic Ocean. Beyond the Nupe Basin, it extends north-eastwards through Zungeru as the Zungeru mylonites (Ajibade et al., 1988).

In the study area, the Ilesa schist belt is traversed by a major NNE-SSW fault zone that extends southwards to Omifunfun area and northwards to Ifewara–Iwaraja with a major bifurcation (Adelusi et al., 2013; Anifowose & Adetunji, 2015; Akinlalu et al., 2016; Akinlalu et al., 2021). The Ilesha schist belt's rocks showed signs of shearing, banding, and foliations in addition to favoured orientations, which suggest that the region has undergone more than one episode of deformation (Odeyemi, 1981; Ajibade et al., 1988; Odeyemi, 1993; Anifowose & Borode, 2007; Ademeso et al., 2013; Adeoti & Okonkwo, 2017). Optically examining the rocks as part of additional study revealed that they were primarily composed of talc, which appears as a mainly colorless mosaic in plane polarized light and as faint colors of pink and green under crossed polars. The secondary mineral in the samples is chlorite, which is a sign of low-grade metamorphism. Amphibolites in the study area are of the massive textural variety, occurring mostly as discontinuous lensoid bodies of small to large boulders, composed of hornblende, with subordinate plagioclase and epidote with accessory titanite observed in some of rocks (Oyinloye & Steed, 1996; Olajide–Kayode et al., 2020). The amphibolite, amphibolite schist, and pelitic schist that make up the western unit are closely related to the trondhjemitic granite, gneiss, and pegmatite. It displays a slightly open folding technique using N-S axes. Amphibolite facies is where metamorphism occurs most frequently, but greenschist facies occurs seldom (Obaje, 2009).

The eastern portion of the study region is dominated by quartzite. The quartzite is found in close proximity to minor iron-rich schists, quartz schist, and quartzo-feldspathic gneiss. Similar to the Anka meta-igneous complex in northwest Nigeria, the association of mafic and ultramafic rocks with metamorphosed granitic rocks and widespread pegmatites is present here. The Ilesha schist belt is well known for its potential for mineralisation, especially gold mineralisation. The granite-gneiss next to the gold-bearing veins has hydrothermally altered into a sericite-chlorite epidote assemblage (Akanmu et al., 2019). Amphibolites, amphibolite schist, quartz schists, quartzite intruded by granite now deformed into gneisses (Granite-gneiss), and migmatite gneiss compose the subsurface of the study area (Figure 1). The primary and alluvial gold mineralisations are the two main types of gold mineralisation that occur in the Ilesha Schist area (Akande et al., 1992; Ajayi & Ogedengbe, 2003). The gneisses or lithologies of the schist belt are related with the primary mineralisation, which is dispersed in quartz veins. Wright et al. (1985) hypothesized that veins, lenses, stringers, reefs, and other similar bodies of quartz, quartz-feldspar, and tourmaline rocks are where orogenic gold mineralisation occurs in the Ilesha schist belt. Galena and pyrite are the two most frequent sulphides found in quartz veins that contain gold. The veins are very often conformable with the general N–S to NNE–SSW structural grain of the basement and occur in a variety of geologic settings which suggests that there was more than one period of mineralisation.

Regionally, Woakes & Bafor (1984) noted that various schist belts in Nigeria, like the Ife-Ilesa schist belt, are linked to primary gold resources. Without any particular connection to the Older Granites, they are frequently geographically associated to amphibolites and regional NE-SW to N-S fault or shear zones.

Gold is present in the amphibolites in the Ilesha (Elueze, 1981) and Egbe (Garba, 1985) regions in quantities that are above the typical primary gold content for comparable rocks and are adequate to serve as the origin of some of the alluvial deposits. The alluvial deposits are found throughout the goldfields, not only in the current river channel deposits but also in ancient buried placers, which are the source of modern placers and have in some places been degraded by the current drainage system.

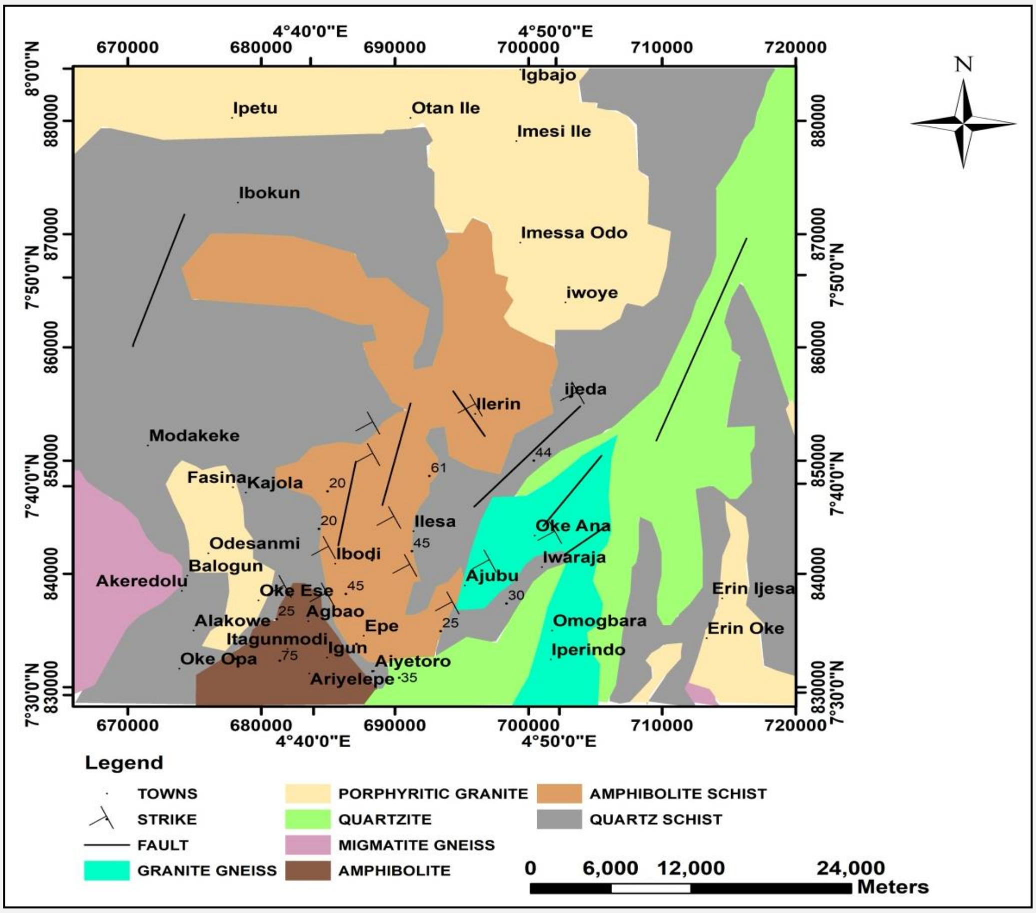

Figure 1. Geological Map of parts of Ife–Ilesa Schist Belt (Modified after Odeyemi, 1993)

Through geological and geochemical mapping, Elueze (1981), Garba (1985), Oyinloye & Steed (1996), and Olajide-Kayode et al. (2020) found that hydrothermal alteration and the presence of gold resources were closely related. This is supported by the existence of elemental compositions including Co, Mo, Pb, Ni, Zn, Se, and Sb that are above crustal levels and linked to hydrothermal alteration connected to gold mining in the region (Olajide-Kayode et al., 2020). However, for hydrothermal alteration to occur on a scale that facilitates mineralisation, the geologic environment must be permissible in the availability of geologic structures like fractures, faults, contacts, dykes, etc. that can facilitate the passage of hydrothermal fluids and the consequent passage of gold mineralizing fluids.

Geophysical techniques, including magnetic and electrical resistivity approaches, were used by Akinlalu et al. (2018) and Akinlalu et al. (2021) in several investigations in the study region to delineate geological structures assisting mineralisation. It was discovered that the structures identified by their analyses coincided with several artisanal workings in the region, indicating that the gold mineralisation in the region is predominantly structurally regulated and thus primary.

## Hydrothermal Alteration

Hydrothermal alteration has been recognized as a significant "player" in primary gold mineralisation in a variety of geologic contexts around the globe with the inclusion of the study area (Di Tommaso & Rubinstein, 2007; Maden & Akaryali, 2015; Sanusi & Amigun, 2020). Kinnaird (1979, 1985) recognized a number of hydrothermal processes in the Nigerian geological environment, including hydration, acid (hydrogen ion) metasomatism, sodic metasomatism, and potassic metasomatism. Other examples include silica metasomatism, argillic alteration, and chloritic (propylitic) alteration and fluorization (Obaje, 2009). Granitic and schist rocks, which are common in the research area, have been discovered to be altered by hydrothermal processes.

According to geochemical research done by Elueze (1981), Garba (1985), and Olajide-Kayode et al. (2020), each alteration process is defined by a shift in alkali element ratios together with enrichment in a particular trace element. Compared to unaltered granite, the early fluids that caused soda metasomatism also contained Fe mixed with Nb, Y, U, Th, Zr, and heavy rare earth element(s) (HREE) concentrations in addition to Na concentrations. Increases in $K_20$, Rb, Li, and Zn, as well as losses in $Na_2O$ and trace elements, are the hallmarks of potash metasomatism. Chemically, the formation of greisen and $H^+$ ion metasomatism is characterized by a sharp drop in K and Al because of the breakdown of feldspar and a corresponding rise in Si (Bowden, 1985; Kinnaird et al., 1985).

Obaje (2009) discovered that the hydrothermal activities in the study area and related geologic settings in Nigeria mostly affect the granites. In areas where these processes have been widespread, vein deposits of Sn, Zn, W, and Nb with Cu, Fe, Bi, U, and REE have formed in and around the roof and marginal zones of medium to fine-grained granite cupolas, with veins reaching up to 2 km into the surrounding rock. Additional research by Garba (1988, 2003); Gaboury (2019) revealed that fluids formed from iron-rich mineral assemblages (pyrite, chalcopyrite, galena) present in metavolcanics and metasediments formed under dehydration and devotalization during metamorphic process as magma melts and hydrothermal fluids are traversing geologic structures like faults are responsible for the precipitation of primary gold deposits in the study area (Tomkins, 2010).

## MATERIALS AND METHODOLOGY

### Radiometric Data

The airborne geophysical surveying of the study area was conducted by Fugro Airborne surveys between 2002 and 2009 by using the 512-channels gamma-ray spectrometers (NaI "Tl" crystals size of 2″ × 2″) (NGSA, 2009). Airborne gamma ray spectrometric data are classically displayed as images. Total count and individual radioelements are displayed as pseudo–colored images to show the supply of the three radioelements or as abundance ratio images. A thorough understanding of the effects of silicification, K–alteration, weathering processes and local lithological variations is required to evaluate the mineralisation potential associated with the radioelement anomalies in regards to hydrothermal alteration (Abd El Nabi, 2013). In identifying hydrothermally altered areas however, it is essential to isolate areas of Potassium enrichment caused by hydrothermal alteration from other processes such as weathering, leaching and weathering activities. In order to do this, areas enriched in Potassium are combined in ratios with equivalent Thorium and Uranium concentrations (eTh and eU). The abundance ratios, K/eTh and K/eU are often more diagnostic of changes in rock types and mineralogical changes caused by hydrothermal alteration (Erdi-Krausz et al., 2003). Using the mathematical expression available on Oasis Montaj™, the ratio maps were produced by applying the ratio function.

Ternary map facilitates various displays of different radioelements' data which are correlative in the same area. The ternary map is often used to get an indication of radioactivity distributions and, consequently, enables narrowing down favorable target areas for hydrothermal alteration associated with orogenic gold mineralisation. This was facilitated by the combination of concentrations of K, eTh and eU. The K count was assigned the red–cyan colour; and eTh, the green–magenta colour while the eU concentration was assigned the blue–yellow colour.

To evaluate the possibility of the gamma ray spectrometric method characterisation of areas of change linked with hydrothermal occurrences in the Ife-Ilesa Schist area, the F-parameter of Efimov approach (Efimov, 1978) was used. Due to two substantial correlations between the richness of K and the eTh/K ratio and the richness of eU and the eTh/K ratio, the F-parameter is particularly crucial in hydrothermal alteration mapping (Eq. 1) (de Quadros et al., 2003).

$$F = \frac{K*eU}{eTh} = \frac{K}{\frac{eTh}{eU}} = \frac{eU}{\frac{eTh}{K}} \tag{1}$$

As a reflection of the Th/U ratio and the concentration of potassium, the F-parameter that Efimov (1978) developed is a crucial marker of hydrothermal alteration in rocks (Maden & Akaryali, 2015). This is particularly important in distinguishing hydrothermally altered areas by eliminating processes other than hydrothermal alteration by the ratio combinations of K, eTh and eU. Hence, high anomaly is regarded as hydrothermally altered areas (Eleraki et al., 2017).

Furthermore, Potassium deviation (Kd) proposed by Saunders et al. (1987) has been found appropriate in delineating hydrothermal alteration haloes related to orogenic gold mineralisation prompting its application in the study area.

Based on the method proposed by Saunders et al. (1978) and Pires (1995), the nominal K value (Kn) in relation to the equivalent Thorium (eTh) concentration was extracted from Eq.2 (de Quadros et al., 2003):

$$K_n = \left(\frac{K\ map_{average}}{Th\ map_{average}}\right) * Th\ map \tag{2}$$

The statistics of the K and eTh grids yielded values for the K map average and eTh map average that were employed in this investigation were, respectively, 0.908 % and 10.582 ppm. Deviation from the nominal K values (Kd) were thought to signify potassium enrichment levels as they were obtained through hydrothermal alteration processes as obtained in Eq.3 (de Quadros et al., 2003):

$$K = \frac{K - K_n}{K_n} \tag{3}$$

It is important to note that high K/eTh, high F–parameter and high Kd values are indicative of hydrothermally altered zones accentuated by Potassium enrichment.

### Hydrothermal Alteration Map

The hydrothermal alteration map of the study area was produced by considering potassium concentration maps due to hydrothermal alteration. This involves the integration of K/eTh, Kd and F–Parameter maps using the fuzzy gamma operator, 0.9, after each input raster layer has been transformed by way of fuzzy logic modeling. The integration of these Potassium concentration maps ensures that potassic alteration genetically linked to orogenic gold mineralization is mapped by highlighting only areas of Potassium enrichment caused by hydrothermal alteration. The resulting hydrothermal alteration map from the integration of the transformed evidential maps was subjected to the concentration area (C–A) fractal analysis for the determination of the threshold of evidential values and classification of hydrothermal map on the degree of alteration intensities in a data driven way.

### Fuzzy Logic Modeling

The fuzzy logic modeling introduced by Zadeh (1965) works by way of logic by considering true or false alternatives. It also includes the transformation of unbounded values of raster layers into bounded values in the range of 0 and 1 (Yousefi and Nykanen, 2016; Almasi et al., 2017).

The transformation ensures easier classification of input layers and the resulting product. For this study, the transformation was done using the fuzzy membership function based on the fuzzy logic modeling proposed by Zadeh (1965). It is essentially based on the fuzzy set theory with evidential values in the range of 0 and 1, where 1 indicates membership of the set and 0 indicates non–membership of the set (eq.4).

$$A_{ij} = \{(X_{ij}.\,\mu_A)/X_{ij} \in X_i\}, 0 \leq \mu_A \leq 1 \tag{4}$$

Where $\mu_A$ is called the degree of membership function of x in A and X corresponds to a set of layers $X_i$ (I = 1, 2, 3, ……), and each layer to r classes defined as (j = 1, 2, 3,….r).

This was achieved by using the logistic fuzzy function available in the spatial analyst tool of the ArcGIS 10.3 software wherein the input raster layers involving K/eTh, Kd anomaly and F–Parameter maps were assigned the large fuzzy logistic functions because high anomaly indicating Potassic alteration is of interest in this study. Furthermore, the assignment of the fuzzy membership was also ratified using appropriate midpojnt and spread values.

The resulting transformed maps carried out using the process stated above were then integrated to produce the hydrothermal alteration map of the study area by making use of the fuzzy overlay function involving the gamma operator, 0.9, available on the spatial analyst tool of the ArcGIS 10.3 software. The fuzzy membership type and operator used in this study are shown in Table 1.

Table 1. Fuzzy membership parameters used for input layers and integration.

| Data Origin | Input Layer | Membership Type | Midpoint | Spread | Fuzzy Operator |
|---|---|---|---|---|---|
| SPECTROMETRY GAMMA DATASET | K/eTh | Large | 154.28 | 5 | 0.9 |
| | Kd Anomaly | Large | 125.75 | 5 | |
| | F–Parameter | Large | 127.5 | 5 | |

### Concentration Area (C–A) Fractal Model

The C–A fractal model proposed by Cheng *et al.* (1994) is a plot of the logarithmic area against logarithmic evidential values. This is because an inverse relationship exists between pixels (defined by evidential layer of interest) and area occupied (eq. 5).

$$\begin{cases} A(\rho \leq v) \alpha \rho^{\alpha 1} \\ A(\rho > v) \alpha \rho^{\alpha 2} \end{cases} \tag{5}$$

Here, A represents the area corresponding to less or greater than the concentration threshold, ρ represents concentration values, v represents the concentration threshold, ∝ represents proportionality, and α1 and α2 represent the feature indices corresponding to the smallest and largest singularities respectively.

According to fractal theory, the area is a decreasing function of the concentration. In the logarithmic graph of concentration–area fitting, the position where the decreasing slope of the line segment changes suddenly is the fractal threshold.

For this study, the occupied area of each transformed hydrothermal alteration values is obtained from the attribute table of the final hydrothermal alteration map on the ArcGIS 10.3 software. Subsequently, the logarithmic values of the occupied areas of each transformed hydrothermal alteration values and their corresponding pixel values were calculated. The fractal plot involves the plot of the log of the occupied area against the log of the transformed hydrothermal alteration values where the inflection points gives the number of classification and fractal threshold of the anomaly values for the final hydrothermal alteration map of the study area.

### Validation

The validation was done by posting mining sites of gold deposits on the hydrothermal alteration map to assess the spatial correlation of gold occurrence sites with hydrothermally altered mapped areas. This involves tracking the mining sites occurrences with areas of hydrothermal alteration and the determination of percentage occurrence with areas of hydrothermal alteration. A total of sixteen (16) active mining sites of gold deposits were therefore used for the validation in this study.

## RESULTS AND DISCUSSION

For the purpose of mapping and identifying hydrothermally altered areas in the study area, analyses of the potassium count (k percent), equivalent thorium concentration (eTh), equivalent uranium concentration (eU), concentration ratios related to potassium and other radioelements (K/eTh, K/eU), K-ternary, Kd (potassium anomalies), and F-parameter were conducted separately and in combination.

### K, Th and U Maps

High Potassium anomaly mainly due to high K–feldspar content is high over felsic rocks and intrusives such as granitoids. Hence, Potassium radiation is mainly due to K feldspar, especially microcline and orthoclase or micas such as muscovite and biotite, which are common in granites and are relatively low in basalts and andesites. Figure 2a shows the Potassium distribution of the study area. The Potassium distribution of the study area is observed to vary from 0.152 to 3.562 % reflecting a heterogeneous distribution of lithologies and varying form of responses to geological processes in the area. Four ranges of Potassium are observed in the study area. Very high Potassium count in the range of 1.951 to 3.562 % is observed to be notably isolated at the northern part of the study area with patches in the western and eastern flank of the study area while high Potassium count in the range of 1.023 to 1.951 % is observed at different parts of the western and eastern flank of the study area. This is especially prominent in areas around Otan Ile, Igbajo, Imesi Ile, Imessa Odo, Iwoye, Modakeke, Oke Opa, Akeredolu, Iperindo, Iwaraja, Omogbara, Ajubu, Itagunmodi and Aiyetoro. This anomaly appears as elongated signature having a NE–SW structural trend indicating the imprints of the pan–African orogeny (Akinlalu et al., 2018; Akinlalu et al., 2021). There is also a notable distended branching in form of a trellis configuration with high Potassium count at the north suggesting a flow of hydrothermal fluids from the source into geologic structures around Ibokun, Ipetu, Iwoye and Ilerin. The manner of the structural trend of this anomaly suggests that Potassium has migrated into structures such as faults, fractures, cracks and crevices indicating the presence of structures permitting the migration of hydrothermal fluids in the area. This anomaly is observed to be enclosed by rims of Potassium counts of medium concentration in the range of 0.463 to 1.023 % with the isolated anomaly observed to extend from the southern part to the central part of the study area with prominent features around Ilesa and Ilerin. Conspicuous low anomaly in the range of 0.152 to 0.463 % around Kajola, Agbao and Odesanmi is observed. However majorly in the central and southern parts of the study area with patches in the northern axis showing a very low concentration of Potassium counts and spatially coinciding with the schistose rocks in the area such as the amphibolite schist and quartz schist.

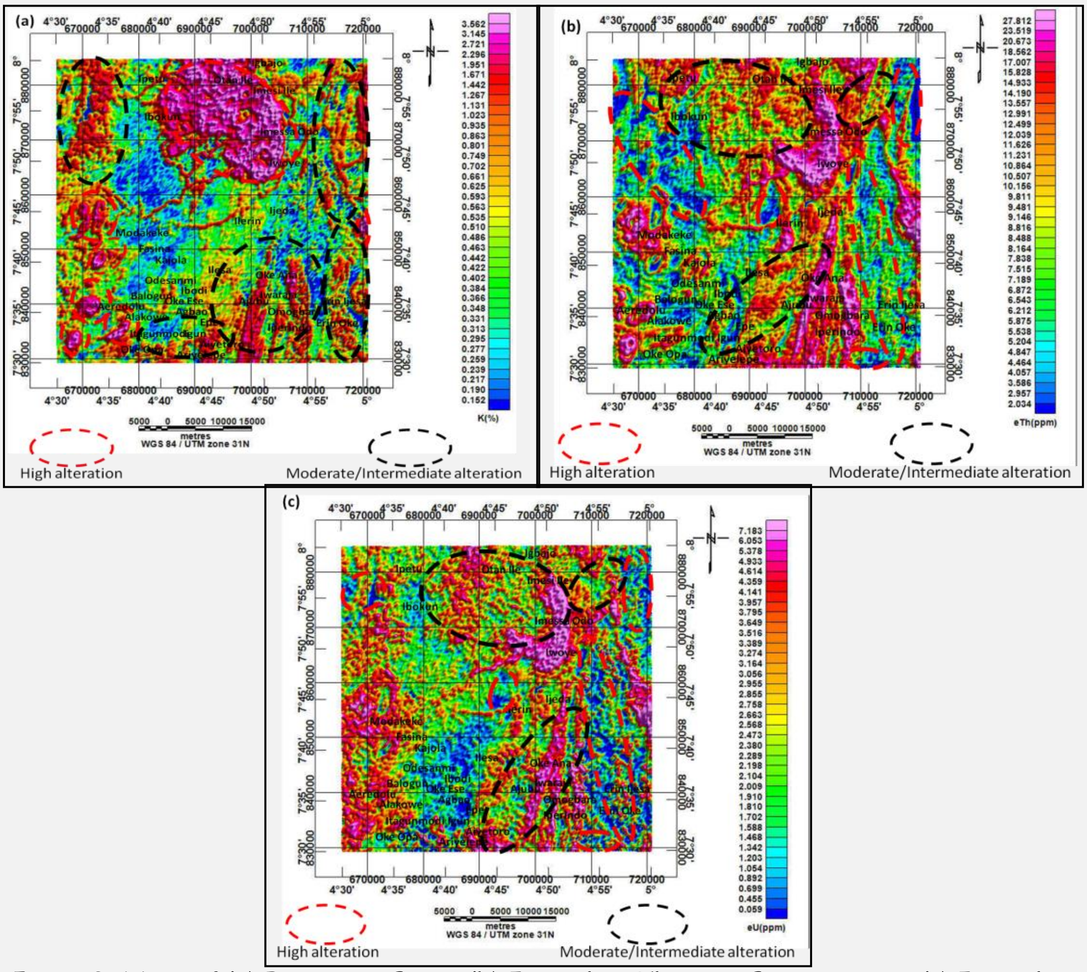


Figure 2. Maps of (a) Potassium Count (b) Equivalent Thorium Concentration (c) Equivalent Uranium Concentration of the Study Area

The very high count of Potassium distribution shows a constructive correlation with the positions of felsic rocks in the area, notably the porphyritic granite in the northern axis and patches in the extreme eastern flank and in locations where there are granite gneiss and migmatite gneiss (Figures 1 & 2a). This is mainly due to the high concentration of K–feldspar in the granitoids. Since hydrothermal alteration is associated with high heat content and high heat content is in turn associated with felsic rocks and granitoids which are proxies to heat source. It therefore means that areas of high Potassium count coinciding with and proximal to granitoids such as porphyritic granite, granite gneiss and migmatite gneiss are possible hydrothermally altered zones affirming the earlier works of Garba (2002) and Sanusi & Amigun (2020) in similar geologic environment.

This also includes those of high concentration of Potassium counts suggesting possible migration of Potassium since Potassium is more geochemically active than other radioelements. Therefore, areas of potassic alteration leading to orogenic gold formation are suspected in regions where there are very high and high counts of Potassium concentrations. Hence, Igbajo, Otan Ile, Imesi Ile, Imessa Odo, Iwoye, Modakeke, Oke Opa, Akeredolu, Itagunmodi, Aiyetoro, Iperindo and Omogbara are probable zones of orogenic gold occurrence due to the high potassium concentration observed in those areas.

Figures 2b & c show the distribution of equivalent Thorium concentration (eTh) and equivalent Uranium concentration (eU) with similar anomaly signature in the study area. The anomaly values range from 2.034 to 27.812 ppm and 0.059 to 7.183 ppm for eTh and eU maps respectively. Very high anomaly is observed in various parts of the study area especially in the northern and southern parts with patches in the eastern and western flank of the study area in Imesi Ile, Imessa Odo, Iwoye, Ipetu, Modakeke, Akeredolu, Aiyetoro, Oke Ana, Iwaraja, Omogbara and Iperindo. This indicates that those areas are not hydrothermally altered mainly because Thorium depletion is associated with hydrothermally altered areas. A conspicuous anomaly having the NE–SW structural trend traversing through Iwaraja axis is very evident resembling the structural geometry delineated by Salawu et al. (2021) as the Iwaraja fault. It is a bifurcation linked to the NNE–trending Kalangai–Zungeru transucrrent fault in the northern part of Nigeria known for its orogenic gold mineralisation (Garba, 2002; Dada, 2008; Sanusi & Amigun, 2020). This feature is more prominent on the eTh and eU maps than observed on the K–map (Figures 2a, b & c) because Thorium is considered to be less geochemically mobile than other radioelements. Also, because Thorium is commonly considered very immobile (Silva et al., 2003), thus the areas with low eTh concentration suggests that it was mobilized in hydrothermally altered systems since Thorium depletion is associated with hydrothermally altered areas. Consequently, the low eTh pattern appearing in large bits and patches at the western, eastern and central parts of the study area, notably around Ibokun (Figure 2b) indicates the leakage of Th elements by hydrothermal fluids through faults and shears.

Generally, the eTh and eU maps (Figures 2b & c) showed several high frequency local anomalies concentrated majorly in the central, northern, southern with patches in the eastern and western flank peripheral to the potassium anomalies. This infers the presence of geological discontinuities and the NE–SW orientated faults which could be related to mineralized veins.

However, individual analysis of the radioelements map cannot alone give information in isolating areas that are hydrothermally altered because the anomalies can be due to several processes other than hydrothermal alteration. Therefore, further integration of maps is needed to give detailed information on hydrothermal alteration of the area.

### Ratio Maps (k/eTh and K/eU)

The ratio maps involving Potassium counts as a ratio of equivalent Thorium and equivalent Uranium is useful in isolating areas that have undergone hydrothermal alteration from areas that have undergone other processes. Therefore, high K/eTh and K/eU anomalies are useful in identifying hydrothermally altered areas (Abd El Nabi, 2013; Maden & Akaryali, 2015; Elkhateeb & Abdellatif, 2018).

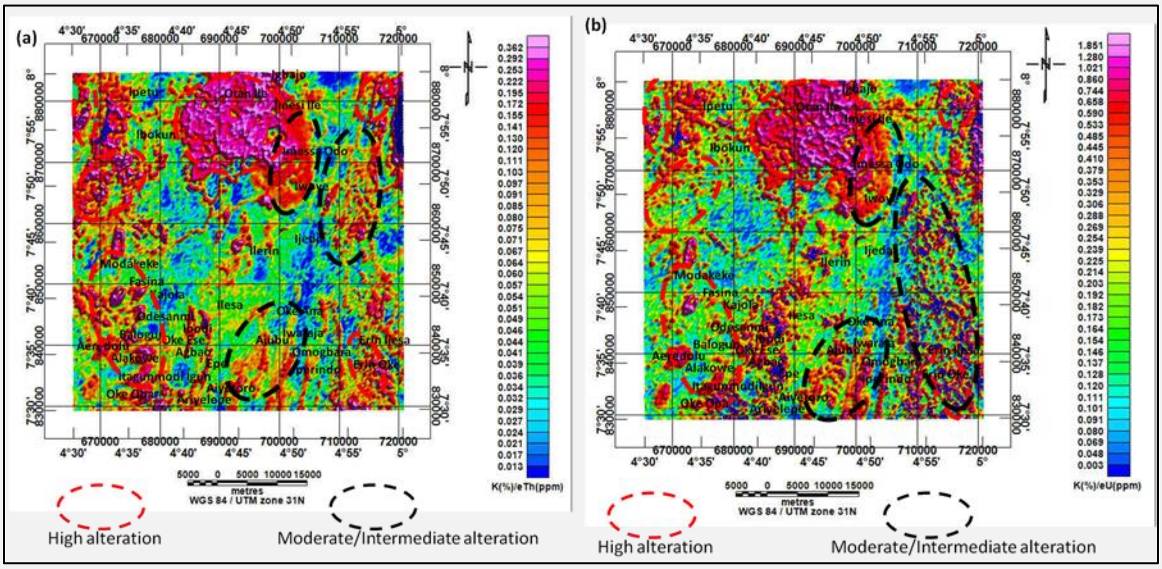


Figure 3. Ratio Maps of (a) K/eTh and (b) K/eU of the Study Area

Figures 3a & b shows the distribution of potassium concentration in the area caused by hydrothermal alteration with the K/eTh and K/eU showing similar signatures with anomaly values ranging from 0.013 to 0.362 (%/ppm) and 0.003 to 1.851 (%/ppm). Potassium enrichment is observed in the northern flank as a circular halo at Otan Ile, Imesi Ile, Igbajo and Imessa Odo, but with a distinctive reduction in diameter when compared with the K map (Figure 2a) indicating differentiation of anomalies caused by hydrothermal alteration from other processes. Nevertheless, areas around Iwoye and Imessa Odo with reduced anomaly at the rims of the highly anomalous region, characteristic of a hydrothermally altered zone is a strong indication that hydrothermal alteration process has taken place there. Also, areas having high concentration of Potassium on K map are also observed to have undergone different changes in anomaly reduction on the ratio maps especially in areas around Oke Ana, Iwaraja, Omogbara and Iperindo in the eastern axis. Furthermore, the ratio maps have also been able to accentuate new areas as possible hydrothermally altered zones coinciding with high Potassium concentration on the K map appearing as elongated patches of anomalies in the western flank and spurious patches on the eastern flank of the study area majorly in Ibokun, Ipetu, Modakeke, Fasina, Akeredolu and Oke Opa (Figures 2a, 3a & b). This is majorly because increase in K content and increase in K/eTh ratio is indicative of hydrothermal alterations. This is mainly due to the fact that K enrichments are not accompanied by eTh during hydrothermal alteration processes (Airo, 2002; Boadi et al., 2022).

Generally, K and other metal constituents are added to the mass rock by hydrothermal solutions, and it is easily observed in the felsic rock units such as granitoids or along lithologic contacts where hydrothermal alteration such as silicification is intensive. Hence, high K/eTh and K/eU coinciding with high potassium count is observed to occur in areas where granitoids such as the granitic rocks and migmatite gneiss are located indicating that areas proximal to granitoids which are proxy to heat source are hydrothermally altered and areas distal to them are not. However, an exception is seen on the quartz schist which is a probable indication of the occurrence of a near surface intrusion and the presence of geologic structures such as faults, dykes etc. responsible for the carriage of hydrothermal fluids from the granitoids. This correlates well with the works of Elkhateeb & Abdellatif (2018); Boadi et al. (2022); Forson et al. (2022) in similar geologic environments like the study area involving marginal basin and granitic intrusions.

**Composite Ternary Map**

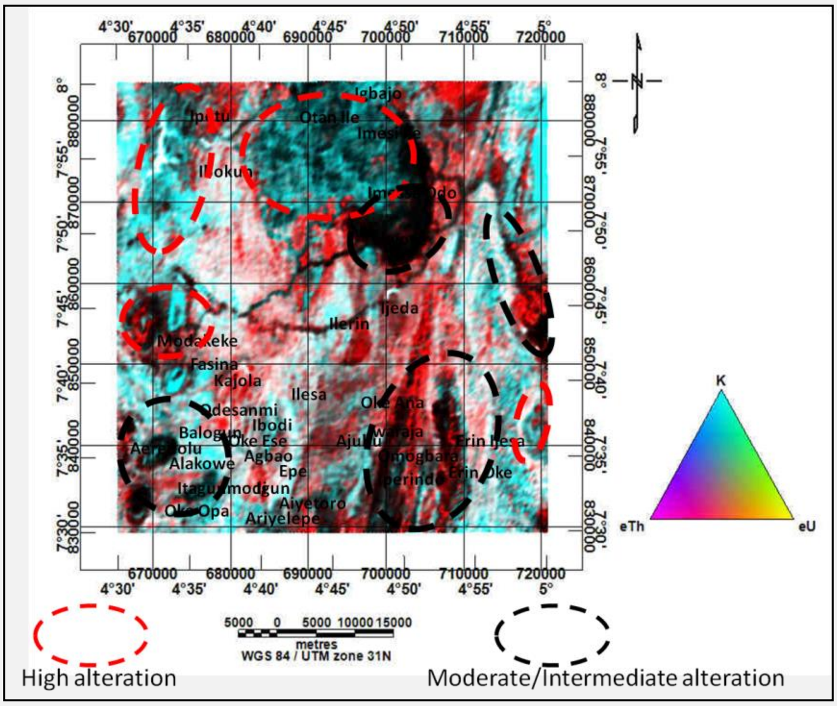


Figure 4. Composite Ternary Map of the Radioelements involving K, eTh and eU

The RGB ternary map of K, eU and eTh channels (Figure 4) provides additional information when compared to individual channel maps (Airo, 2002). Dark coloration on the map is indicative of areas where there are high concentration of K, eTh and eU. The enrichment of eTh in those areas especially in Iwoye and Imessa Odo does not reveal the effect of hydrothermal alteration process. Also, areas having red coloration are not regarded as being hydrothermally altered due to the enrichment of eTh, eU and the impoverishment of K in those areas. Same also goes for areas having light coloration as a result of the low concentration of K, eTh and eU. These are observed in areas around Ilerin, Ijeda, Kajola, Erin Ijesa and Erin Oke. The grey colored areas and light blue colored areas are observed as having coincidence with the granitic rocks on the north and migmatite gneiss on the west (Figures 1 & 4). Essentially, felsic rocks are observed to have grey with touch of light blue coloration showing a dominance of Potassium and low concentration of equivalent concentration of Thorium and Uranium in areas around Modakeke, Otan Ile, Igbajo, Imesi Ile, Oke Opa, Ariyilepe, Aiyetoro and Akeredolu. However, there is an exception on the anomaly observed on the granite gneiss having a lighter tone indicating reduced concentration of Potassium at Oke Ana, Iwaraja, Omogbara, Ajubu and Iperindo. This may probably be due to leaching or weathering.

Furthermore, a dark coloration having a tone of light coloration is observed to have a NE–SW structural trend at the southern flank representing the Iwaraja fault (Figure 4). The structural trend is also observed as dendritic pattern branching from the northern flank of the study area. This color mixture is indicative of minimal hydrothermal alteration as a result of the relatively high concentration of Potassium and considerable low concentration of Thorium.

Since Potassium enrichment is accompanied by Thorium depletion, the grey colored with light blue coloration, and light dark coloration are probable hydrothermally altered zones. These areas are coincident with the occurrence of granitoids and areas proximal to them, and geologic structures caused by the flow of hydrothermal fluids through them.

**Potassium Anomaly (Kd) Map**

The Kd (potassium anomalies) proposed by Saunders et al. (1987) map gives variable distribution of potassium to isolate hydrothermally altered areas with anomalously high Kd values are regarded as hydrothermally altered areas (Eleraki et al., 2017).

The ability of the Kd map to delineate probable hydrothermally altered areas due to the ratio combination of K and eU makes it a veritable means of identifying hydrothermally altered areas. Figure 5 shows the Kd map with anomaly values ranging from -0.851 to 3.220. High Kd anomaly appearing as concentric ring halo on the northern flank and elongated strips and patches on the western, eastern and southern flank having anomaly values ranging from 1.267 to 3.220 are delineated as hydrothermally altered areas. This signature is prominent at Igbajo, Otan Ile, Modakeke, Alakowe, Oke Opa, Itagunmodi, Igun, and Erin Oke. This signature bears semblance to that which was delineated on the K/eTh indicating the enrichment Potassium and depletion of Thorium in the areas.

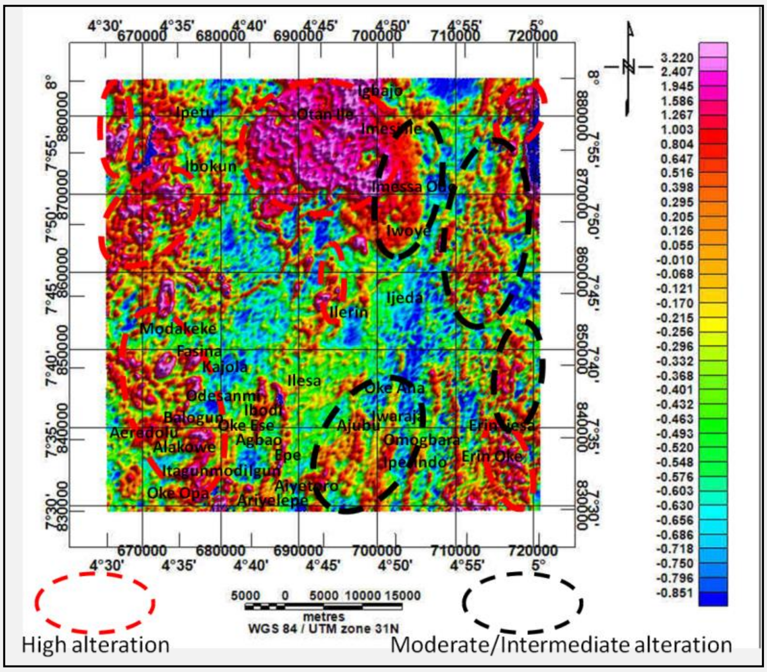


Figure 5. Potassium Anomaly (Kd) Map

This anomaly is also observed to coincide with the occurrence of granitoids in the area (Figures 1 & 5). Surrounding this anomaly at especially Imesi Ile, Imessa Odo, Ibokun and Iwoye, however, are anomaly values in the range of -0.296 and 1.003 appearing as rings and pockets of red and yellow color bands indicating minimum alteration has taken place as a result of proximity to high temperature areas. Evident structural trends in the NE–SW direction delineated as geologic structures from the earlier works of Akinlalu et al. (2021) is believed to be responsible for the transportation of hydrothermal fluids. Anomaly signature indicates that they have minimum alteration probably due to the reduced pervasive nature of the hydrothermal fluids. This could also be attributed to the reduced thermal energy during late stage transportation of the hydrothermal fluids.

## F–Parameter Map

Figure 6 shows the F–parameter map of the study area with anomaly values ranging from 0.152 to 3.562. According to Abd El Nabi (2012), highly altered rocks are always indicated with F–parameter values in the range of 2–5 and sometimes reaching 10, while moderate to intermediate altered rocks have anomaly values in the range of 0.5 and 2.

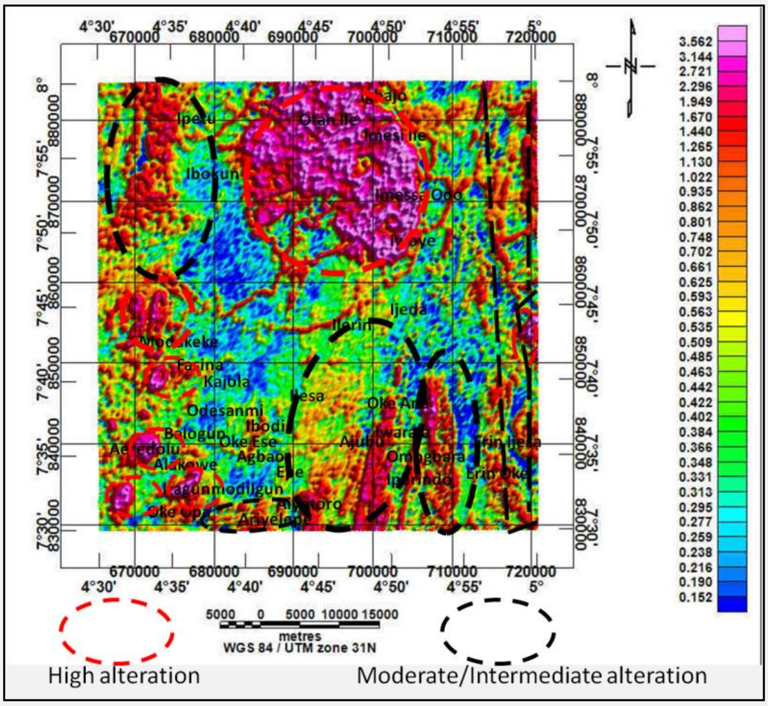


Figure 6. F–Parameter of Efimov (1978) of the Study Area

Therefore, very high anomaly values in the range of 2.296 and 3.562 are delineated as hydrothermally altered areas. These anomalous zones fall in the northern section of the study area as large concentric halo, with patches of occurrences in the southwestern and southeastern flank of the study area around Igbajo, Otan Ile, Imesi Ile, Imessa Odo, Iwoye, Akeredolu, Oke Opa, Modakeke, Oke Ana, Iwaraja, Ajubu, Ariyelepe, Omogbara and Iperindo.

These anomalously high areas also coincide with the occurrence of porphyritic granite, granite gneiss and migmatite gneiss and areas not distal to it in the study area (Figures 2 & 6). However, this anomaly is not observed over all the granitoids especially at Odesanmi and Balogun, with anomaly values below the threshold in the range of 0.238 to 0.331 with intermediate anomaly values. This may be due in large parts to the leaching of Potassium from the rock units and the high concentration of eTh and eU. Anomaly values ranging between 0.5 and 1.949 are also observed majorly on the schistose rocks due to their close proximity to the granitoids at the western, southern and eastern flank of the study area with conspicuous anomaly at Ilesa, Oke Ese, Ibodi, Agbao, Epe, Erin Ijesa and Erin Oke.

Generally, it is observed that potassic alteration and sericitization which are important in orogenic gold formation, has major occurrence on the granitoids, thereby making areas proximal to them to be hydrothermally altered (Grasty & Shives, 1997).

### Hydrothermal Alteration Map

The generated transformed hydrothermal alteration has anomaly values ranging from 0.001 to 0.991 showing varying degree of alterations in the study area (Figure 7a). The anomaly signature shows the nature and styles of the pervasion of hydrothermal fluid in the study area. The strongly pervasive alteration style is dominant in the northern axis of the study area around Igbajo, Otan Ile, Imesi Ile, Imessa Odo and Iwoye with the moderately pervasive alteration style punctuating at different areas of the study area. Areas of high hydrothermal alteration include Modakeke, Fasina, Akeredolu, Alakowe, Itagunmodi, Oke Opa, Ariyelepe, Ibodi, Ilesa, Igun, Iperindo, Ajubu, Omogbara, Erin Oke and Erin Ijesa. These areas are probable zones for gold mineralisation owing to the association of orogenic mineralisation to hydrothermal alteration. The weakly pervasive alteration style is also evident occurring along the circumference of the strongly pervasive alteration style showing that areas distal from granitoids are least affected by hydrothermal alteration. This is observed in regions around Odesanmi, Oke Ese, Ibokun and Epe. It is important to note that the strongly pervasive alteration style is evident on the granitoids and areas proximal to them (Figures 1 & 7a).

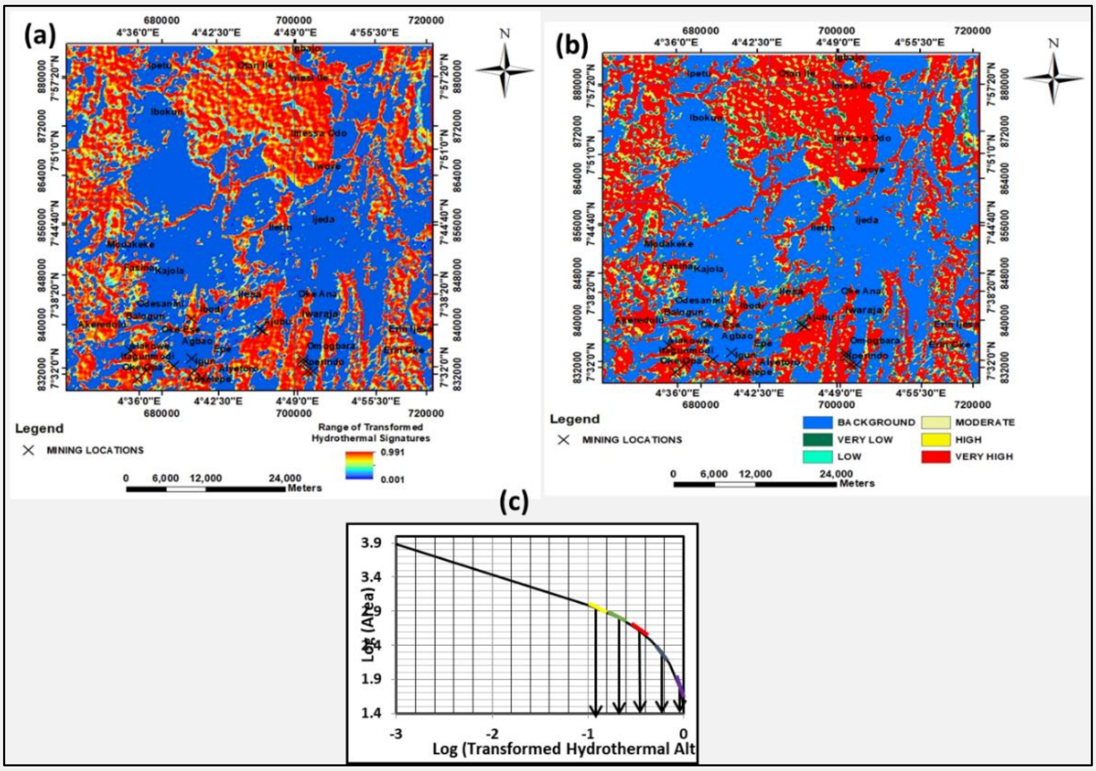


Figure 7. (a) Map of Transformed Hydrothermal Alteration; (b) Classified Hydrothermal Map of the Study Area after Fractal analysis; (c) log–log Plot based on the C–A Fractal Model for the Transformed Hydrothermal Alteration Values

Reclassification of the transformed hydrothermal alteration map was done by using the concentration area (C–A) fractal analysis. The resulting map was reclassified into five distinct classes based on the fractal analysis as very high, high, moderate, low and very low altered areas which are separated from the background anomaly (Figure 7c). The background anomaly indicates areas of potassium enrichment which are not necessarily as a result of hydrothermal alteration. They are majorly as a result of factors other than hydrothermal alteration. Hence, they have no contribution whatsoever to the hydrothermal alteration makeup of the study area. Highly hydrothermally altered areas are prominent in the northern, western, southern and eastern flanks of the study area with varying populated proportion of moderately high alteration occurring with the highly hydrothermally altered areas. Since hydrothermal alteration is an important criterion in the formation of orogenic gold deposits, areas that have the range of classification of very high to moderate alteration are important areas to be considered for further investigation for the mapping of gold deposits. Therefore, areas around Igbajo, Otan Ile, Imesi Ile, Imessa Odo, Iwoye, Ilerin, Modakeke, Fasina, Balogun, Akeredolu, Oke Ana, Ajubu, Ibodi, Aiyetoro, Ariyelepe, Oke Opa, Alakowe, Itagunmodi, Iperindo, Erin Ijesa and Erin Oke of high hydrothermal alteration are probable zones for the occurrence of gold.

Evidence of hydrothermal alteration is also observed on the NE–SW structural trend resembling the Iwaraja fault passing through Iwaraja at the eastern flank of the study area, howbeit having signature within the range of high to moderate. The anomaly signature observed over the fault is in tandem with the conclusion of Salawu et al. (2021) about the potential of the Iwaraja fault to aid in gold mineralisation in the area.

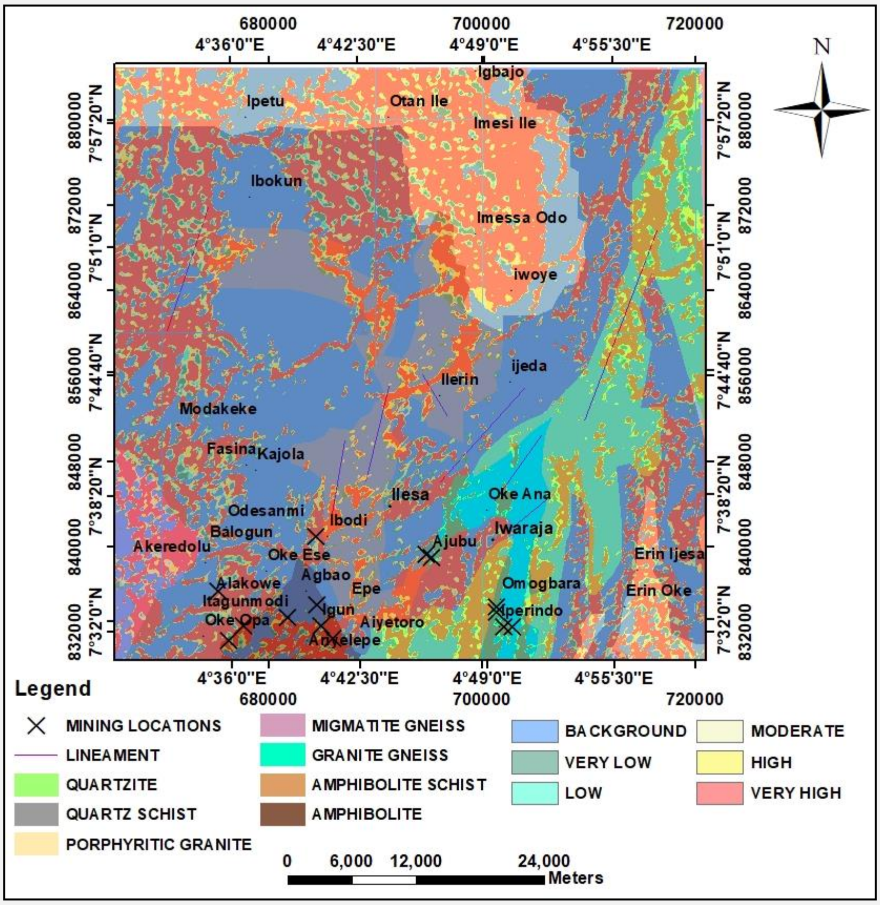


Figure 8. Overlay of the Geological and Hydrothermal Alteration Maps of the Study Area

Overlay of the hydrothermal alteration maps and the geological map of the study area indicates that the geological grains of the study area can be genetically linked to the hydrothermally altered areas. Figure 8 shows the overlay of the geological map with the classified hydrothermal map of the study area. A close look at the map shows that areas that are hydrothermally altered especially regions showing strongly pervasive alteration styles are in close proximity to the granitoids such as Porphyritic Granite, Migmatite Gneiss and Granite Gneiss in the study area. This proves that the granitoids are majorly the heat source in the study area from which hydrothermal fluids originate, traversing through geologic structures and altering the mineralogy of country rocks accompanied by the subsequent emplacement of new minerals. Furthermore, areas of moderate to very high hydrothermal alteration have major occurrences on the metasediments and metavolcanics, coinciding with mining pits in the study area, thus confirming the earlier works of Sanusi & Amigun (2020); Boadi et al. (2022) in similar environment that materials carried by the hydrothermal fluids on reaction with the sulphur complexes in the metasediments and metavolcanics (being the source of gold mineralizing fluids) produces gold deposits in the study area. This is also in accordance with the earlier works of Olajide–Kayode et al. (2020) in some parts of the study area about the contribution of hydrothermal fluids to gold mineralisation especially when the Amphibolites and Amphibolite Schist were geochemically analysed.

### Validation

For the validation, the locations of mining sites were matched with the hydrothermally altered areas using 16 mining locations. The location of the mining sites showed 81 % correlation with the mapped hydrothermally altered regions in the study area (Table 2). This shows that orogenic gold is present in the study area and hydrothermal alteration plays an important role in the formation of orogenic gold deposits. All of the mining sites are located at the southern flank of the study area, this therefore has a strong implication on areas with similar signature where there are no mining activities taking place. Therefore, new areas like Otan Ile, Igbajo, Imesi Ile, Imessa Odo, Iwoye, Fasina, Akeredolu, Alakowe, Oke Opa, Aiyetoro, Erin Oke and Erin Ijesa are potential zones for gold prospecting (Figure 9). Also, new areas are delineated in locations where there are existing mining pits especially in Iperindo and Itagunmodi.

Table 2. Mining Sites with Correlation with Areas of Hydrothermal Correlation

| Pits | Easting | Northing | Background | Low | Moderate | High | Very High | Result |
|---|---|---|---|---|---|---|---|---|
| Pit 1 (Epe) | 684282 | 834072 | | | | | X | Passed |
| Pit 2 (Igun) | 684924 | 832612 | | | X | | | Passed |
| Pit 3 (Iperindo) | 702070 | 832436 | | | X | | | Passed |
| Pit 4 (Iperindo) | 701311 | 834393 | | | | X | | Passed |
| Pit 5 (Iperindo) | 702859 | 832495 | | | | X | | Passed |
| Pit 6 (Epe) | 683493 | 832553 | | | | X | | Passed |
| Pit 7 (Epe) | 681711 | 833371 | X | | | | | Failed |
| Pit 8 (Ajubu) | 695235 | 838979 | | | X | | | Passed |
| Pit 9 (Ajubu) | 694739 | 839242 | | | X | | | Passed |
| Pit 10 (Iperindo) | 701340 | 833868 | | | | | X | Passed |
| Pit 11 (Ibodi) | 686138 | 840907 | X | | | | | Failed |
| Pit 12 (Epe) | 687670 | 834539 | | | | | X | Passed |
| Pit 13 (Agbao) | 683522 | 835825 | X | | | | | Failed |
| Pit 14 (Itagunmodi) | 683590 | 831204 | | | X | | | Passed |
| Pit 15 (Ajubu) | 695205 | 837398 | | | | X | | Passed |
| Pit 16 (Iperindo) | 705323 | 837125 | | | | | X | Passed |
| % Agreement = 13/16 * (100) = 81 % | | | | | | | | |

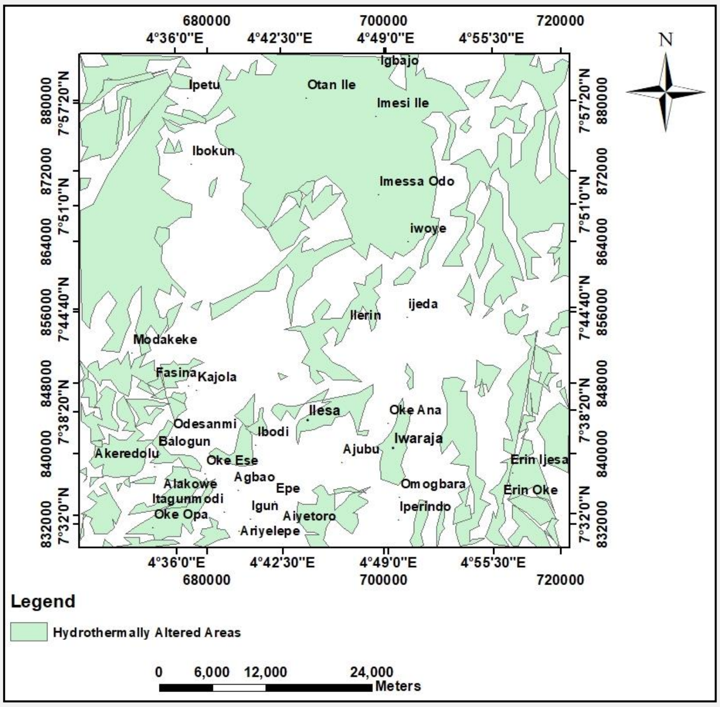


Figure 9. Hydrothermal Map of Unexplored Areas with Potential of Gold Occurrence

## CONCLUSION

The airborne gamma ray spectrometric data is helpful in delineating hydrothermal alteration zones of the study area. The use of radionuclides ratio combination has proven helpful in isolating areas that are hydrothermally altered. Although changes in the radioelement is slight, it is a useful aid in separating anomalies caused by Potassium enrichment as a result of hydrothermal alteration other than caused by other processes such as weathering, leaching, lithological changes and weather conditions. The results showed that hydrothermally altered areas are associated with granitoids and areas proximal to them with areas distal to them showing no or little alteration.

The hydrothermal alteration map was classified into six classes based on concentration–area (C–A) fractal analysis indicating the pervasive styles prevalent in the study area. The generated hydrothermal alteration map indicates prospective areas for further exploration work as only the southern flank of the study area is undergoing active mining activities with potential of occurrence of gold in the northern, western and along axis proximal to the Iwaraja fault. Therefore, the hydrothermal alteration map will be able to guide prospective investors, researchers and stakeholders on prospective areas for exploration of gold. Therefore, follow up investigation is needed to narrow down prospective zones using appropriate tools and methods especially in areas around Otan Ile, Igbajo, Imesi Ile, Imessa Odo, Iwoye, Fasina, Akeredolu, Alakowe, Oke Opa, Aiyetoro, Erin Oke and Erin Ijesa.

It should however be noted that despite the fact that this study has been able to show the importance of potassic alteration mapping to orogenic gold delineation, potassic alteration involving hydrothermal alteration mapping may not give a holistic view of the occurrence of orogenic gold deposits as there are several other indices that are linked to the occurrence of orogenic gold deposits. Therefore, other studies involving geochemical analysis including analysis of magnetic and remote sensing geographical information system data can be done to delineate indices that are spatially linked to the occurrence of orogenic gold deposits.

## DECLARATION OF INTEREST

Author declare that there is no funding for this research. Also, there is No Conflict of Interest.

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