https://dx.doi.org/10.4314/dujopas.v10i4a.10
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 10 No. 4a December 2024*

Assessing Mineral Potential of the Riruwai Complex, Nigeria, Using Gamma-Ray Spectrometry: Implications for Mineral Exploration and Development

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Abstract
Nigeria's aspiration to develop a competitive mineral sector that generates wealth and enhances social and human security can be realized through the effective discovery of more mineral resources. This study assesses the mineral potential of the Riruwai Complex using gamma-ray spectrometry data. The findings illustrate the effectiveness of gamma-ray spectrometric signatures in identifying changes linked to hydrothermal Nb-Ta-Sn mineralization, uncovering distinct spectral patterns of radioelement zoning that align with mineralogical variations within the granitic pluton. Reductions in K/Th and K/U ratios point to alterations in the granitoid plutons, ranging from aegirine arfvedsonite granite to albite arfvedsonite granite and biotite granite, which display more extensive alteration. This alteration results from the breakdown of potash feldspar and the depletion of radioelements during the late stages of magmatic differentiation, when highly felsic granites with potentially high concentrations of Sn, Nb, U, and Zn are emplaced. This study underscores gamma-ray spectrometry as a valuable tool in mineral exploration, with potential application in areas of similar geological settings with unknown mineralization. It will contribute to Nigeria's mineral database and support the country's progress toward domestic industrialization and a stronger position in the global market.

Keywords: Gamma-Ray Spectrometry, Mineral Exploration, Hydrothermal Mineralization, Riruwai Complex, Economic Development

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INTRODUCTION
Nigeria aims to develop a thriving mineral sector that can generate wealth and enhance social and human security by harnessing its mineral resources to boost domestic industries and compete globally. Gamma rays, a form of electromagnetic radiation, play a crucial role in mineral exploration due to their high energy and penetrating capabilities. Radiometric surveys utilize gamma rays to measure the natural radioactivity of rocks and soils, detecting emissions from radioactive isotopes like uranium-238, thorium-232, and potassium-40 (Broome, 1987; Dickson and Scott, 1997), which are present in varying amounts in different rock types. Airborne gamma-ray spectrometry surveys are particularly useful for exploring various commodities, including uranium, thorium, and also frequently for Sn, W, REE, Nb, and Zr. The interpretation of radioelement data has led to several mineral discoveries (Gnojek & Prichystal, 1985, Pires 1995, Hoover & Pierce 1990; Kuosmanen, 1994, Dickson & Scott 1997, Zhang et al., 1998 and Shives, et al. 2000)

Extensive studies (Abaa, 1976; Jacobson & Macleod, 1977; Ogunleye et al., 2006; Girei, 2019) have provided detailed geological insights into the Riruwai Complex, including the cassiterite mineralized lode associated with it. This lode extends 5 kilometers in an east-west direction, reaches a depth of over 400 meters, and dips southward at an angle of 85°. This current study examines airborne gamma-ray data over the Riruwai Complex to understand the distribution of potassium (K), uranium (U), and thorium (Th) within the complex, which are essential indicators for mineral exploration and discovery. This work will also contribute to Nigeria's mineral database, supporting economic development and business growth.

The Geology
The study of Mesozoic alkaline ring complexes, magmatic migration, and associated geological structures has been well-documented (Black & Liegeois, 1993; Ike, 1983; Kinnaird & Bowden, 1991). One notable example is the Riruwai Complex, which demonstrates the full cycle of magmatic activity characteristic of ring complexes within Nigeria's Younger Granite Province.

The magmatic evolution of the Riruwai Complex (Figure 1), as described by Jacobson and Macleod (1977), began with a volcanic phase marked by the eruption of substantial acid lavas and pyroclastic flows, with occasional basalt flows. This intense volcanic activity culminated in the formation of a large cauldron or caldera, approximately thirteen kilometers in diameter, where the bulk of the volcanic materials settled. The volcanic rocks from this phase are particularly well-preserved in the northwestern half of the Complex, while the underlying vent structures are exposed in the southeastern and extreme northwestern regions.

As the volcanic cycle came to an end, a significant geological event occurred: the emplacement of a large quartz-fayalite-porphyry plug at the center of the Dutsen Shetu vent Complex. This marked the transition to the plutonic phase, during which several key structural features were formed. Among these were the peripheral ring-dyke of granite-porphyry—a prominent structural element—and central granite plutons composed of biotite and arfvedsonite granite, which were emplaced beneath the volcanic layers. Over time, erosion has exposed all the major units of this cycle, revealing their intricate structural relationships.

Similar to other volcanic ring complexes within the Younger Granite Province, the lavas in the Riruwai Complex are confined within peripheral ring-faults. These faults likely played a crucial role in the preservation of the lavas, as they were probably maintained by down-faulting (Bonin, 1986; 2007). The subsidence that occurred during the volcanic stage, along with the subsequent intrusion of the ring-dyke, likely contributed to this preservation. Additionally, the early development of the ring-fault provided a pathway for the lava to reach the peripheral vents.

METHOD

Airborne gamma-ray spectrometry determines the concentrations of Potassium (K), Thorium (eTh), and Uranium (eU) in rocks and weathered materials by detecting gamma-rays emitted from the natural radioactive decay of these elements. Potassium is measured directly by capturing the gamma-rays released during the decay of 40K to Argon. In contrast, Uranium and Thorium cannot be directly measured. Instead, the measurement focuses on the daughter nuclides produced during the decay process, from which the concentrations of the parent elements are inferred.

The distinct emission peaks of 208Tl and 214Bi are used to calculate the concentrations of Th and U, which are expressed in equivalent parts per million (eTh and eU). The airborne radiometric data was derived using a Gamma-ray spectrometer-1 Hz sampling at 500 m line spacing in a NW-SE orientation, acquired by Fugro Airborne surveys on behalf of the Nigerian Geological Survey Agency in 2005 (NGSA, 2005).

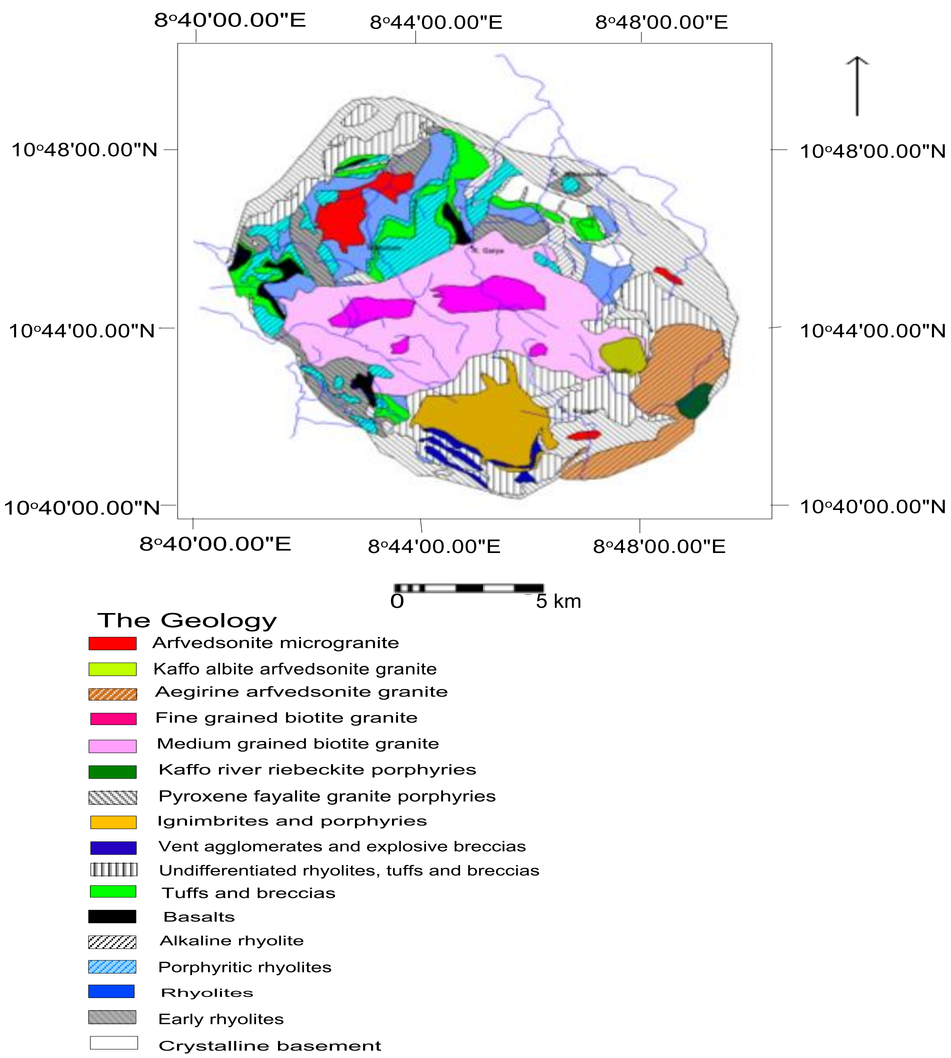

Figure 1 Geology map of the Riruwai Complex, modified after Ogunleye, et al. (2006)

RESULTS AND DISCUSSION

Radiometric Data Images

The airborne radiometric data images were designed to show the intensity distribution of elemental K, U, and Th. The method depends upon the fact that absolute and relative concentrations of the radioelement K, U and Th vary measurably and significantly with lithology. These values of radioelements are significant when compared with the mean from statistics of each radioelement in Table 1 across the entire country by Federal Republic of Nigeria, (2011).

Potassium (%K),

The potassium (K) composite image map displays K (in red) highlighting the spatial distribution of potassium concentrations. High potassium levels appear as bright anomalous zones on the map, which align closely with the granitics of the ring complex. This information aids in distinguishing different rock units based on their unique chemical and physical properties (Ford & O'Reilly, 1985). The potassium concentration ranges from 1.70% to 5.32 %.

Thorium (eTh) maps

The eTh composite image map (Figure 3) highlights the relative distribution of eTh, drawing attention to areas of thorium enrichment (IAEA, 2003). The pale blue regions on the map effectively indicate parts of the Ring dyke, while pale green areas are linked to volcanic rocks of the complex. The red regions delineates the granitics which include both fine and medium grained granite, biotite granite, kaffo albite Arfvedsonite granite aegirine arfvedsonite granite . It was observed that the dark areas, representing low relative thorium values, are primarily associated with metasediments in the central part of the study area, with slight variations in the extent of these dark zones. The thorium value ranges from 17.17ppm to 80.96ppm

Equivalent Uranium (eU)

The eU composite image map (Figure 4) integrates eU (in red) with the ratios eU/eTh (in green) and eU/K (in blue). The relative concentrations of eU in relation to both K and eTh are crucial diagnostic factors for identifying potential uranium deposits (IAEA 1988). This map also reveals lithological variations and can be valuable in addressing geological mapping challenges (Broome, 1987; Dickson & Scott 1997). As such, it can help identify anomalous zones—highlighted as bright areas on the map—indicating regions of enriched uranium concentration. The uranium value ranges from 3.33 ppm to 13.57ppm (Figure 4).

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Table 1
Background values of airborne radioelements in Nigeria

Element	Minimum	Maximum	Mean	Standard Deviation
K%	-1.02	7.92	1.35	1.23
Th(ppm)	-2.01	203.21	13.89	8.68
U(ppm)	-3.32	27.65	2.70	1.65

Source: NGSA (2011)

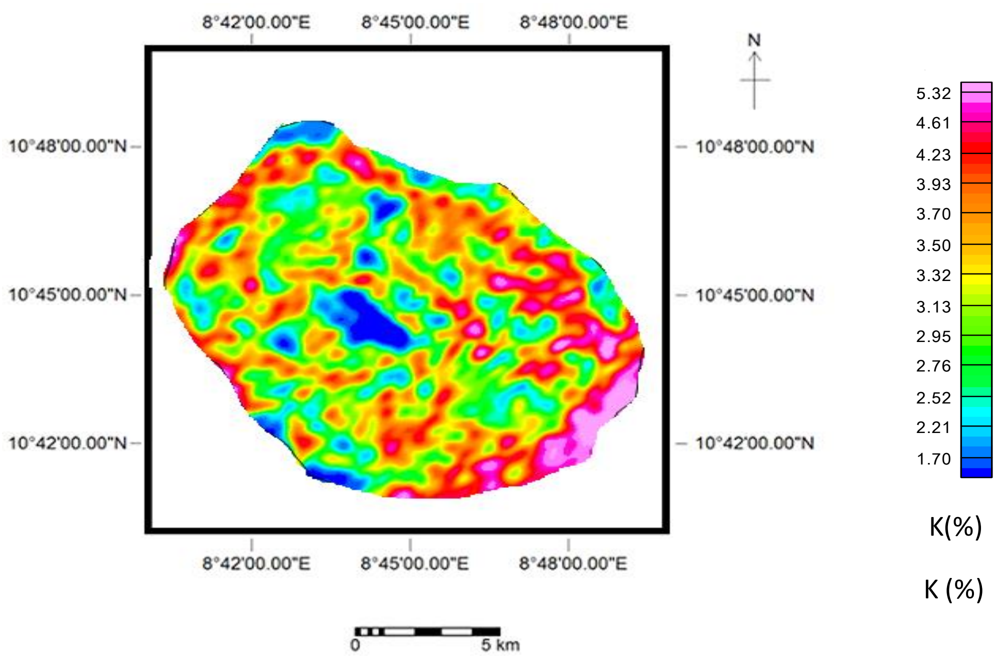


Figure 2 Airborne radiometric potassium anomalies of the study area

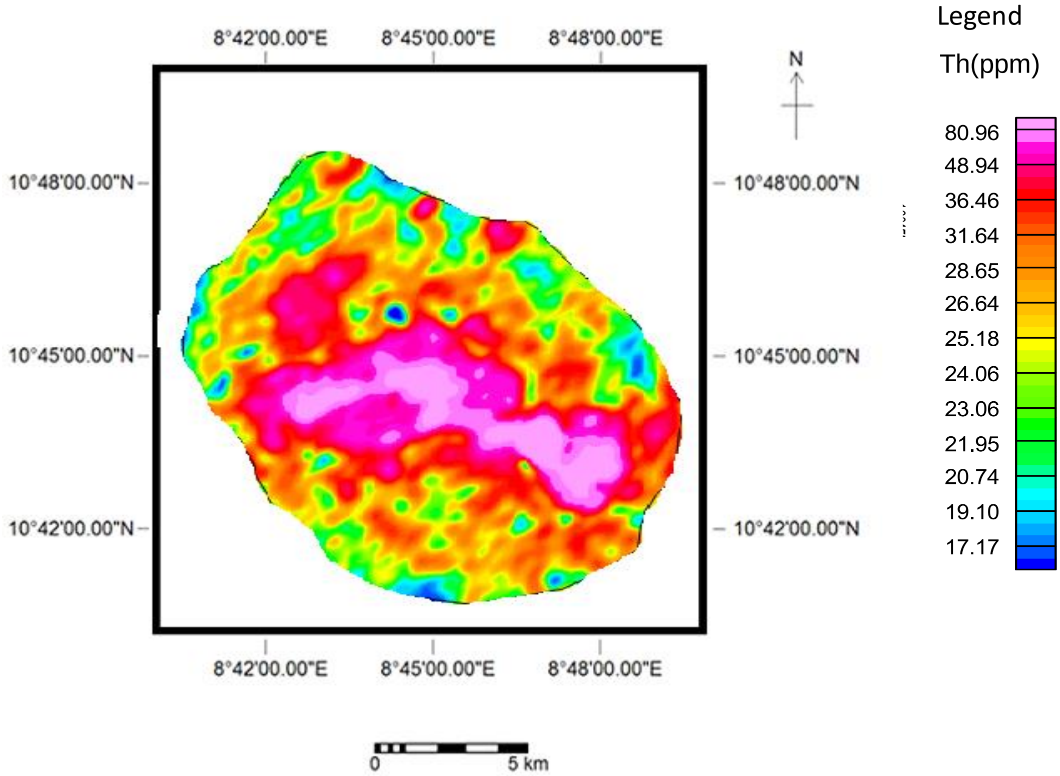


Figure 3 Airborne radiometric thorium anomalies of the study area

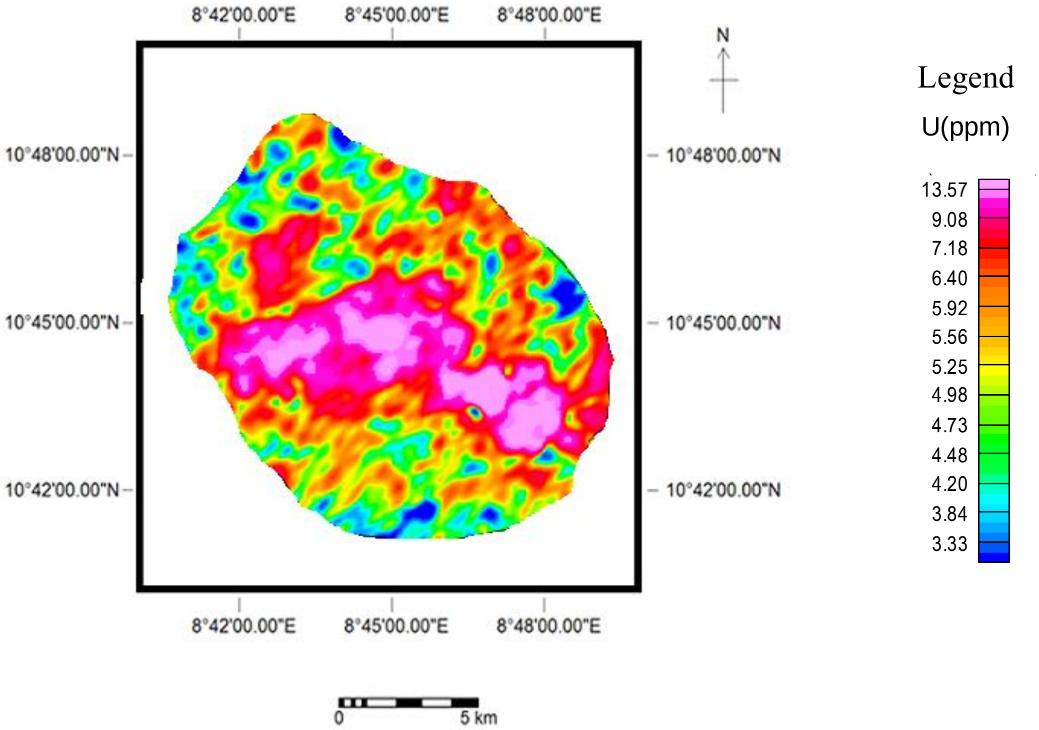


Figure 4 Airborne radiometric uranium anomalies of the study area

Ratio Contour Maps

The potassium enrichment in the area is evident from a potassium high, confirmed by low K/Th and K/U ratios, indicating preferential enrichment of potassium relative to thorium and uranium. This increase in potassium within the lithology is associated with mineralization processes. Figures 5 and 6 demonstrate that the hydrothermal system is characterized by the enrichment of potassium and uranium within the plutonic magmatic zone. The Sn, Zn, Nb, and U mineralizations in biotite granite and albite arfvedsonite granite are products of this hydrothermal system (Kinnard, 1985; Ogunleye et al., 2006).

Airborne radiometric maps reveal a wide range of element levels, reflecting the diverse rock compositions in the study area (Darnley & Ford, 1989). The notably low K/Th and K/U ratios (Table 2) highlight a strong contrast between the biotite granites and the Kaffo albite arfvedsonite granite within the lithological units. Decreases in these ratios suggest alterations in granitoid plutons, ranging from aegirine arfvedsonite granite through albite arfvedsonite granite to biotite granite, which is highly altered compared to the unaltered or weakly altered crystal-rich ignimbrites, porphyries, rhyolites, brecciated rhyolites, and undifferentiated rhyolites.

Increasing potassium levels (Figure 7) within the lithology indicate potassium enrichment linked to the mineralization. Additionally, the eTh vs. eU (Figure 8) concentration in the complex shows a positive increase, signifying a rise in eU within the lithology. This difference is attributed to the alteration of potash feldspar and the breakdown of radioelements during the late stages of magmatic differentiation, leading to the emplacement of highly felsic granites with potentially high Sn, Nb, U, and Zn concentrations (Plate 1-2). Uranium mineralization in the granites, particularly in the Kaffo albite arfvedsonite granite, is accompanied by sodium metasomatism mineralization (Kinnard, 1979; 1985). Under these conditions, sodium initially replaces potassium in rock-forming minerals, further exaggerating the K/U ratio, which tends to increase where significant uranium mineralization occurs. This phenomenon is corroborated by ternary images that highlight altered granitic areas.

These altered zones, rich in hydroxyls, are located near granitic intrusions and lineaments (Olasehinde and Ashano, 2013), which may have served as conduits for the mineralizing hydrothermal fluids. The mineralization zones are structurally controlled, like Gamma-ray spectrometric survey for mineral exploration at Baljurashi area, Saudi Arabia (Alhumimidi et al., 2013) with high gamma ray anomalies confined by the major geological faults. This also agrees with Pires (1995), who identified areas of hydrothermal alteration in the Crixás Guarinos region, Goias, Brazil, using anomalous potassium (Kd) signatures and other studies (Ferreira et al., 1998; Blum, 1999; Carvalho, 1999 and Biondi et al., 2001) demonstrating its effectiveness in mineral exploration.

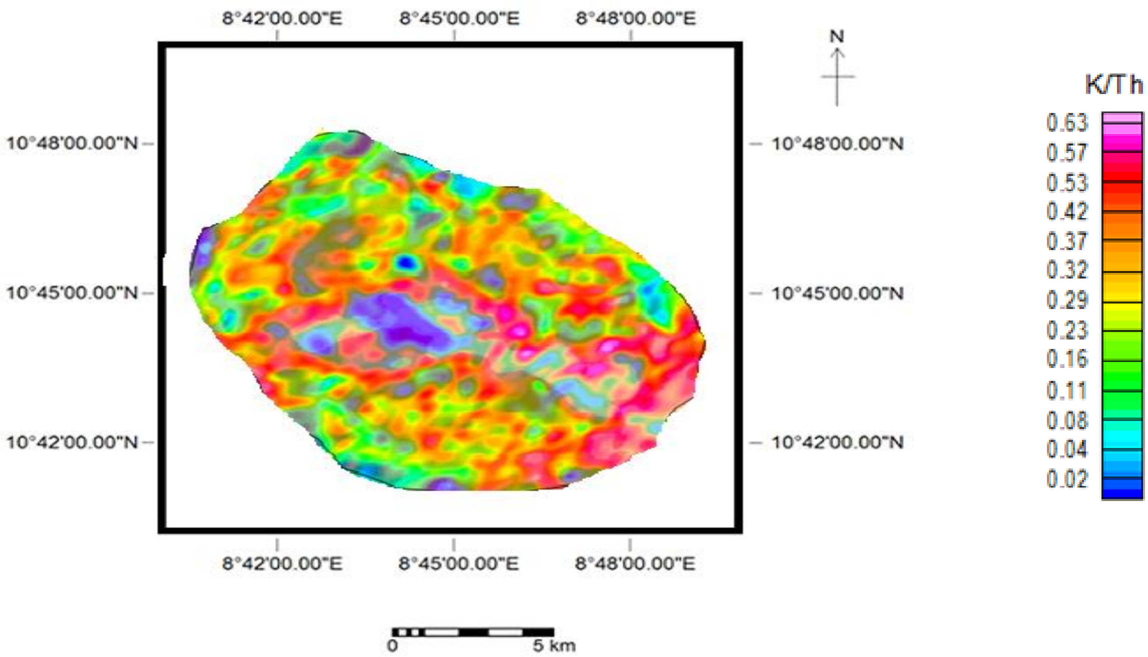


Figure 5 Potassium-Thorium ratio map of the Riruwai Complex outlining boundaries with potassium enrichment

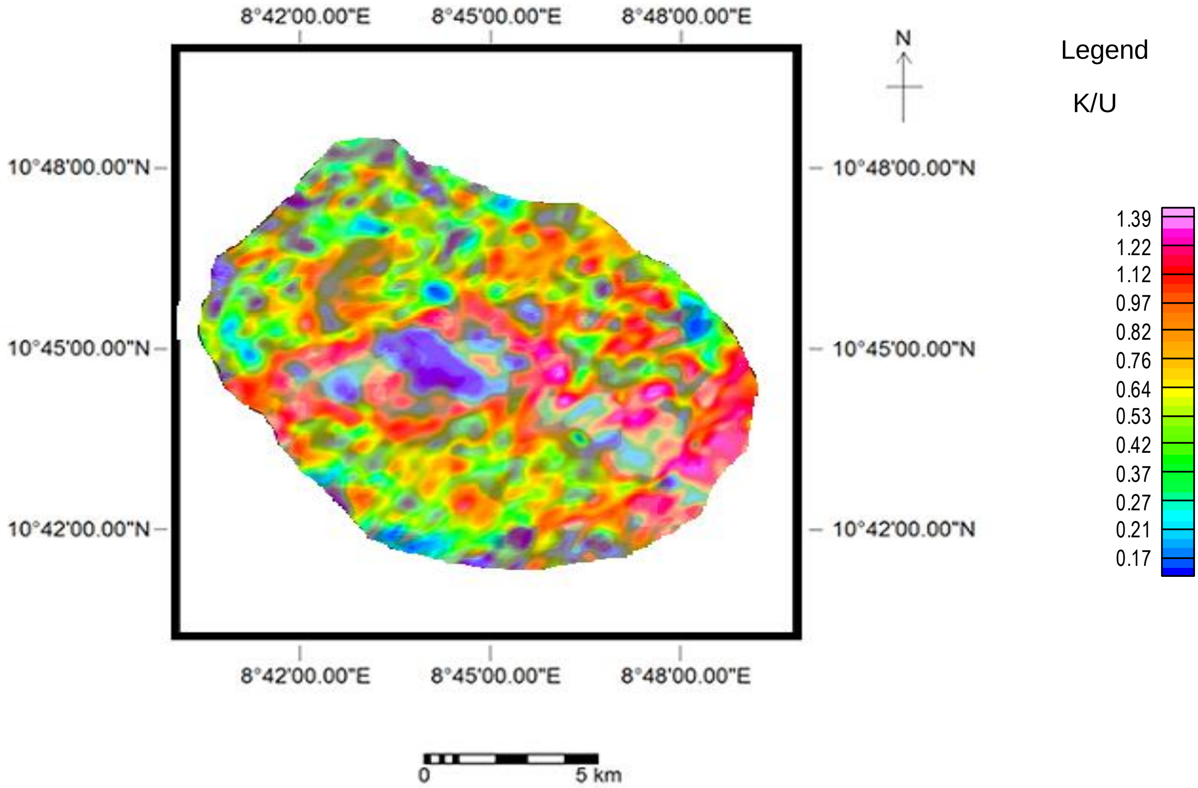


Figure 6 Potassium-Uranium ratio map of the Riruwai Complex reflecting areas with potassium enrichment with the mineralisation

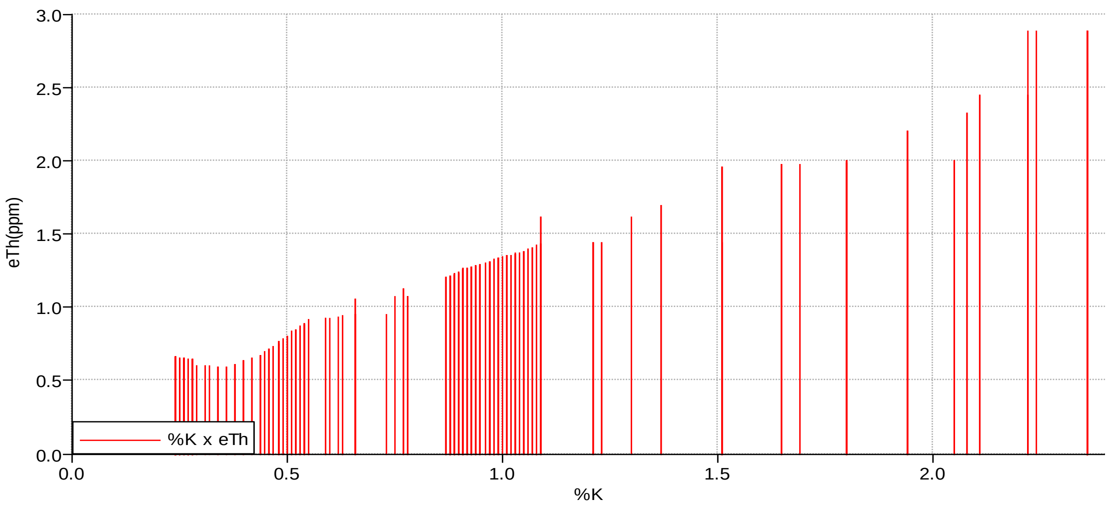


Figure 7: Potassium versus thorium concentrations determined by gamma ray spectrometry, from the Riruwai Complex. Increasing potassium within the lithology reflects the potassium enrichment associated with the mineralization

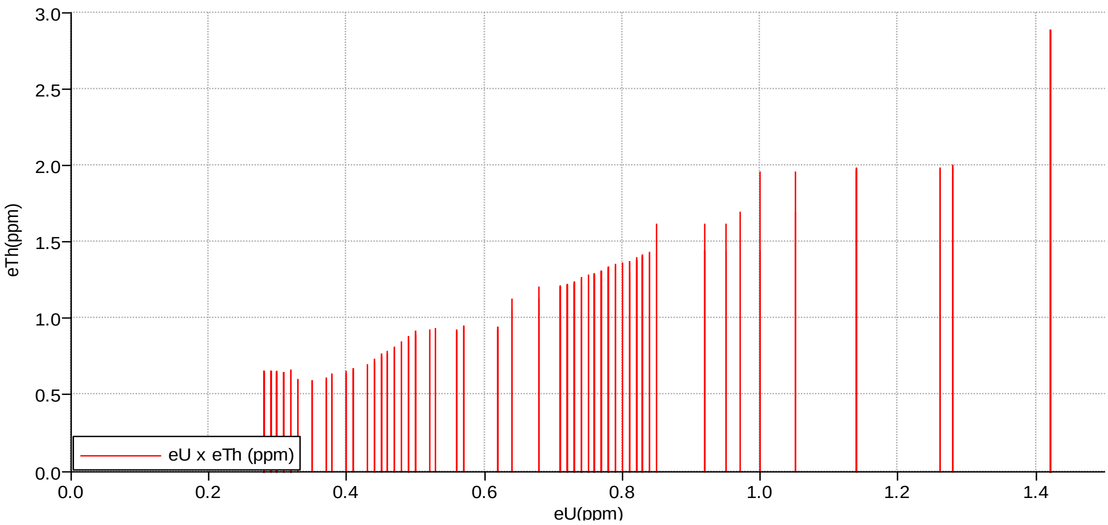


Figure 8: eTh vs eU concentration from the complex also shows a positive increase signifying an increase in the eU in the lithology

Plate 1a

Plate 1b

Plate 1(a &b) Alteration and mining activities within biotite granite of the study area

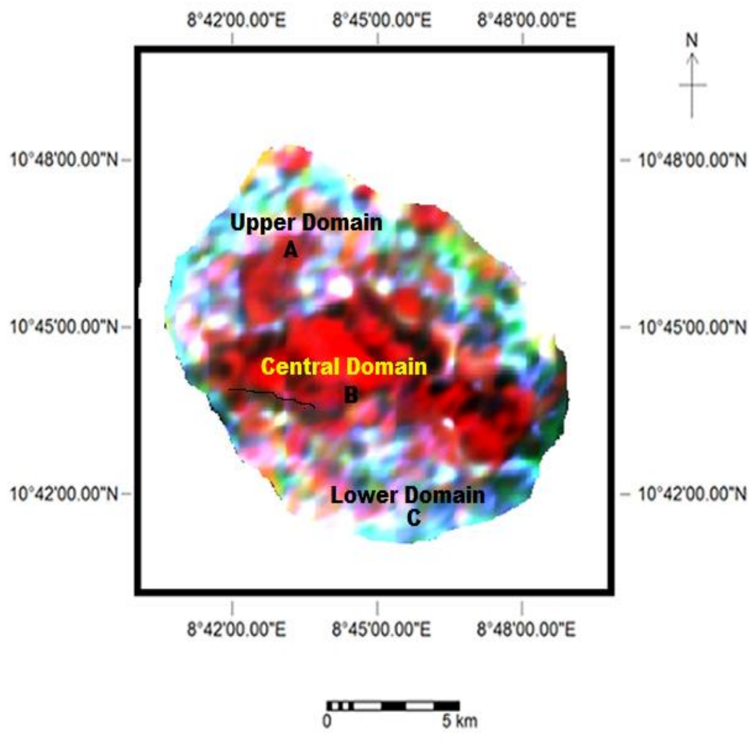
Plate 2 Exploration activity within the Kaffo arfvedosonite granite

The Ternary map

The Ternary Image (Figure 9) is composed of a Thorium anomaly image in the Red channel, a Uranium anomaly image in the Green channel and potassium anomaly in Blue channel. In this ternary image, dark red colors are representing granites, pink color without any mixed color represents volcanics and the rest of the dull blue colored portion represent the ring dyke. The Ternary Image composed of Thorium anomaly image in Red channel, Uranium anomaly image in Green channel and potassium anomaly in Blue channel.

In this ternary image, dark red colors are representing as granites, pink color without any mixed color represents volcanics and the rest of the dull blue colored portion representing the ring dyke This corroborated the work of Solomon, (2005) who reported the Riruwai complex as one of the complexes in the province with a high level of radiation. Thorite ($ThSiO_4$) and Zircon ($ZrSiO_4$) are radioactive and usually occur as accessory minerals in albite arfvedsonite granite, biotite granites and riebeckite granite that constitutes part of the lithologies within the study area.

The radiometric signatures especially the Uranium and Thorium maps define the boundaries of the intrusives (biotite granite, kaffo albite Arfvedsonite granite aegirine arfvedsonite granite) within the complex which are also areas with high values of these elements. Table (2) shows the three spectral domains signatures of the Riruwai Complex. The gamma ray response permits the identification of anomalous responses within lithological units that may represent mineralization. These variable increases were observed among the highly altered rocks of the younger granite which are also rich in radioactive minerals compared with the unaltered or weakly altered counterpart rocks.



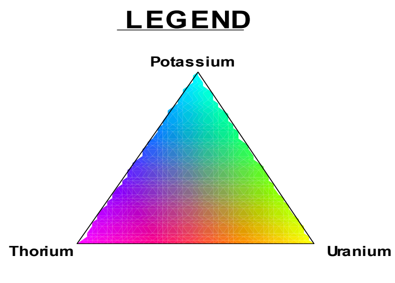


Figure 9 Ternary radiometric image of Riruwai Complex. K, Th and U in RGB ternary image. The deep red regions are the areas associated with the mineralisation

Table 2: Spectral domains of the Riruwai Complex

Domain	Tenary map Hue	Radioelement	Remarks
Upper Domain A	white,red, dull blue hue, light green	- modeate to low k, eU, eTh. -Low K relative to eU & eTh. -low K/eU/, K/eTh	A strong hue appears to be primarily associated with the volcanic and ring dyke formations.
Central Domain B	Strong red hue, blue	-High K, eU, eTh. -relatively high eTh, eU –High K/eU/, K/eTh ratios	Strong hues appear primarily associated with biotite granite, kaffo albite Arfvedsonite granite aegirine arfvedsonite granite, characterized by high Zr, Nb, Y, Th, U, HREE
Lower Domain C	white, red, light blue hue, light green	low eU, moderate eTh. -moderate K relative to eU & eTh. Moderate to low K/eU, K/eTh	A strong hue appear primarily associated with the volcanic and the ring dyke

CONCLUSION

In conclusion, the study reveals the following:

1. The area shows significant potassium enrichment, confirmed by low K/Th and K/U ratios, which indicates preferential potassium enrichment relative to thorium and uranium. This enrichment, associated with mineralization processes, is evident in the hydrothermal system, particularly within the plutonic magmatic zone where Sn, Zn, Nb, and U mineralization are found in biotite granite and albite arfvedsonite granite.
2. Airborne radiometric maps reveal diverse rock compositions, with notable contrasts between different granitic units due to variations in K/Th and K/U ratios. These variations suggest alterations in granitoid plutons and are linked to the alteration of potash feldspar and breakdown of radioelements during late-stage magmatic differentiation.
3. Uranium mineralization, especially in the Kaffo albite arfvedsonite granite, is associated with sodium metasomatism, which further increases the K/U ratio. Ternary images support these findings, highlighting altered granitic areas near intrusions and lineaments, possibly serving as conduits for mineralizing hydrothermal fluids.
4. This study underlines gamma-ray spectrometry as an effective tool in mineral exploration, with potential applications in areas with similar geological settings that have unknown mineralization. It will contribute to Nigeria's mineral database and bolster the country's advancement toward domestic industrialization and a more competitive position in the global market.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support and contributions of various individuals and the Nigeria Geological Survey Agency for the data that made this research possible. Special thanks go to the communities around the Riruwai Complex for their cooperation and hospitality during the fieldwork.

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