ADSUJSR 13 (2) (2025) 25 - 38
Adamawa State University Journal of Scientific Research (ADSUJSR)
https://www.adsujsr.adsu.edu.ng
ISSN: 2705-1900 (Online); ISSN: 2251-0702 (Print)

INTERPRETATION OF AERO-RADIOMETRIC DATA FOR GEOTHERMAL POTENTIAL ASSESSMENT IN YELWA AND ENVIRONS, NIGERIA

Kamureyina Ezekiel[a]* Mercy Abba[b] Barka Jonathan[c] Hayatudeen Musa[d]
[a]*Department of Geology, Adamawa State University, P.M.B. 25 Mubi, Nigeria*
[b]*Department of Geology, Adamawa State University, P.M.B. 25 Mubi, Nigeria*
[c]*Department of Geology, Gombe State University, P.M.B. 127 Gombe, Nigeria.*
[d]*Department of Applied Geophysics, Federal University of Kashere, P.M.B. 0182, Gombe, Nigeria.*
**Corresponding author email: ezekiel798@adsu.edu.ng*

Received in November 2025
Accepted December 2025

Abstract
This study presents a comprehensive radiometric analysis of the region within northwestern Nigeria, aimed at assessing its geothermal and mineral resource potential. Rock density values ranging from 2.00 to 2.99 g/cm³ indicate a heterogeneous lithological composition, comprising granite, basalt, and sedimentary formations. Gamma radiation intensity, measured in counts per second (–248.344 to 6285.020 cps), reveals generally weak emissions, likely due to low concentrations of radioactive elements or shielding effects from dense overburden. Radioelement concentrations exhibit wide variability, with Potassium (–0.282 to 4.925%), Thorium (–1.323 to 51.563 ppm), and Uranium (–4.928 to 17.914 ppm). Negative values are attributed to calibration errors, while elevated Th and U levels suggest the presence of felsic rocks and potential zones of radiogenic heat generation. Calculated radioactive heat production values (0.001991 to 0.005224 µW/m³) are consistent with continental crustal averages and correlate strongly with Th and U concentrations. These findings contribute to regional energy planning, mineral exploration, and a deeper understanding of crustal thermal dynamics.

Keywords: Aeroradiometric data, Geothermal Potential; Radioelement Concentration; Radiogenic Heat Production; Yelwa.

Introduction

Gamma rays are naturally occurring radiometric emanations from rocks and soils that are detected and mapped using radiometric surveys. The natural decay products of only three elements, uranium, thorium, and potassium are the source of all observable gamma radiation from Earth's materials. Only the decay series of potassium, uranium, and thorium have radioisotopes that produce gamma rays with enough energy and intensity to be measured by gamma-ray spectrometry, even though many naturally occurring elements have radioactive isotopes. This is a result of their comparatively high abundance in the natural world. The levels of uranium, thorium, and potassium in surface rocks and soils are measured by radiometric surveys, either in absolute or relative terms. Recent advancements in high-resolution Aero-magnetic and Radiometric data acquisition techniques, their data processing and interpretation methods could be able to identify the Earth's phenomena, with the emphasis on Mineral exploration, where those Minerals show considerable

Magnetic and Radiometric anomalies (Jha *et al.*, 2024; Karjalainen *et al*., 2025; DaPelo *et al*., 2024).

Different rocks have varying concentrations of radioactive elements; igneous rocks that are rich in silica (acid) have the highest concentration, whereas mafic (basic) rocks have the lowest. The most prevalent element found in K-feldspar, Muscovite, and Illite Clays is potassium (K). Thus, basalt has little or no potassium, but granite and rhyolite typically have high potassium. Pegmatite and some black shales are linked to uranium (U). The element thorium (Th) is linked to gneiss, pegmatite, and granite. Additionally, the three radioactive elements exhibit distinct behaviors throughout soil formation processes. Although potassium is easily weathered and leached, it can be absorbed by other clays and minerals and accumulates in illite clays. On the other hand, refractory minerals like zircon, titanite, apatite, and epidote are frequently linked to uranium and thorium. Therefore, they accumulate in highly weathered soil (Zapata *et al.,* 2024*;* Gawad *et al.,* 2024).

The concentration of heat-producing elements in the Earth's crust is estimated in counts per second using airborne gamma ray observations. Geothermal heat that is radiogenic in origin is produced by the decay of long-lived radioactive elements of relevance for geothermal resources, such as potassium (40K), thorium (232Th), and uranium (238U), in the Pre-Cambrian Basement, which is mostly covered by sedimentary and granitic rocks. Emissions of radiation, including beta, alpha, gamma, neutron, and proton particles, accompany it. High-energy electromagnetic radiation, the gamma particles have a distinct energy for every decay process. The concentration of various decaying isotopes can be ascertained using their spectrum (Jha *et al*., 2024).

The technique can be applied to assess the rate of radiogenic heat generation, which is the quantity of heat released by radiogenic isotope decay in a unit volume of rocks in a unit of time. Although it is only sensitive to a very small layer of the Earth's crust, its unit is Wm-3. Exploration for uranium, sedimentary features for oil and gas, radioactive contamination, and mineral exploration can all be done with radioactive heat. While some sources may be unique to a given location, radioactive decay is most likely the largest source of heat in the Earth's crust overall by a significant margin.

The portion of the Earth's heat that can be recovered and used by humans is known as geothermal energy. Earth’s heat comes from the molten magma that formed the planet as well as from the decay of long-lived uranium, thorium, and potassium isotopes that were present in the Precambrian Basement rocks. (Zou *et al*., 2024; Harrison, 2024). Geothermal energy encompasses both the engineering elements of using the earth's heating and cooling to generate electricity and the science that deals with the theoretical study of the earth's thermal regime. In many nations, geothermal energy has emerged as a sustainable and competitive alternative energy source. Therefore, this research work intends to use Aeroradiometric data over Yelwa and environs to investigate the radioactive Heat generation of the area for Geothermal energy.

The need to diversify from the use of Hydro, Fossil fuel and Solar as the major source of generating Electricity in the country necessitated this research. When explored, geothermal energy will be a better alternative when compared with the existing sources (Umar *et al*., 2024). It is in this regard that this research work intends to use Aeroradiometric data over Yelwa and environs to investigate the Radioactive Heat generation potentials of the area for Geothermal energy.

This work aims to investigate the Radioactive heat generation potentials of Yelwa and environs Northwestern Nigeria, using Aeroradiometric data to evaluate the Potassium concentration, concentrations of uranium, thorium, and radioactive heat production in the region. The region lies between latitudes 11°30' N and 12°00' N and longitudes 4°00' E and 5°00' E. Its aerial extent is 6,0374.902 km^2, or 54.9 km x 109.98 km. The main road and the pathways make it easy to get to.

Radioactivity is the process by which an unstable atom becomes stable through the process of decay, or breakdown of its nucleus. Alpha, beta, and gamma radiation are the three forms of radiation that are emitted as energy decays. These elements' average crustal abundances are reported to be between 2.5%

and 2.5 percent for K, 2 to 3 parts per million for U, and 8 to 12 parts per million for Th. Because airborne radiometric surveying can identify radioactivity resulting from the natural decay of elements like uranium, thorium, and potassium from the earth's composition, it is a useful tool for geologic mapping. According to El-Hadidy and Youssef (2024), this is among the fastest and most economical methods for geochemical mapping of the radioactive elements' thorium, uranium, and potassium.

The goal of a radiometric survey is to recognize and understand Radiometric signatures associated with the host rocks important to mineralization and heat in the subsurface (Trivedi *et al*., 2024). Aeromagnetic and Aero Radiometric data were used to correlate the Geothermal Heat flow and radioactive heat generation of the Anambra basin to ascertain if areas with high Geothermal Heat flow values correspond with those of the radioactive Heat production (Ijeh *et al.*, 2024). Detecting uranium, identifying sedimentary features for oil and gas development, detecting radioactive contamination, and mineral exploration are additional uses for radioactive heat in addition to geothermal exploration. Although there are other sources that might be unique to locations, radioactive decay of rocks is most likely the largest overall source of heat in the Earth's crust by a significant margin (Ershov, 2024).

The most cost-effective way to comprehend a geophysical reconnaissance of any largely uncharted or inaccessible area is through a radiometric survey. With a focus on mineral exploration, when those minerals exhibit significant radiometric anomalies, recent developments in high-resolution aeroradiometric data collecting techniques are employed to identify earth's surface phenomena (Upadhyay, 2025).

The region is a part of the Northwestern Basement Complex in Nigeria. The crystalline rocks that comprise the Nigerian Basement Complex have experienced various stages of thermo-tectonic events, the most notable of which was the Pan-African event (Belts *et al*., 2024; Nweke *et al*., 2024). The Basement Complex is a component of the Togo-Benin-Nigeria Shield, which is the southern portion of the grouping of allochthonous terranes in West Africa. The widespread Pan-African Orogeny had an impact on the Togo Benin-Nigeria Shield, just like it did on other regions of the continent. Due to the reworking of the earlier crust caused by the Pan-African Orogenic event, which occurred across the whole continent, a Polycyclic Basement was created, and the region was forced to follow structural trends that are generally N to S. Granites and Charnockites were widely deposited as a result of the Pan-African magmatism, and the corresponding thermal activity left mineral ages of 500–600 Ma imprinted in practically all of the rocks in the region, including Nigeria (Belts et al., 2024; Oluyede *et al*., 2024).

Similarities between the petrology and geochronology of the Nigerian Basement Complex and neighboring Pan-African provinces have been reported. The volcanic and sedimentary rocks of the Tchilit paleorift (Air, Niger) are believed to be comparable to the Anka Schist Belt in Western Nigeria, much as the other Schist belts in Nigeria are strongly related to the Archean Greenstone belts in Pan-African Province. Notable similarities include size, synclinal structures, low-grade metamorphism, clastic and volcanic rock types, iron banded iron formation, and gold mineralization (Oluyede *et al*., 2024).

The Nigerian Schists, however, differ from many other belts within the province in that sedimentary Clasts predominate over Volcanic rocks. Deformation and metamorphism in the Himalayas of Asia and the Pan-African province of West Africa have also been correlated. Principal Shear and Transcurrent Fault systems that are oblique to the principal direction of propagation exhibit these commonalities. The Central Hoggar-Air block, located north of the Togo-Benin-Nigeria Shield, is like the Southern Province of the Pan-African belt in terms of the polycyclicity and diversity of the rocks that were created there. The Basement Complex's Evolution and Geochronology. There appears to be a lack of trustworthy radiometric data to adequately improve the comprehension and interpretation of the Nigerian Basement Complex's evolution, even though the rocks have benefited from significant geological field mapping. (Belts *et al.,* 2024).

The region is composed of the Gwandu Formation, the Rima group, which includes the Wurno, Dukamaje, and Taloka Formations; the Gundumi Formation; and the Basement, which includes the Pan-African Granitoids, the Migmatite-Gneiss Complex, and younger basalts (Figure 1a), according to the Geology of Nigeria (2006). On top of the Gamba Formation, the Gwandu Formation is noncomformable. It crosses the Nigeria-Niger border and drops at a low inclination northwest into the basin's center. It is the youngest Tertiary rock in the basin and is Eocene in age. In an area of roughly 22 km^2, the formation forms a huge crescent (Ola-Buraimo & Mohammed, 2024) west of the road connecting Jegal, Tambwel, Sokoto, and Illela.

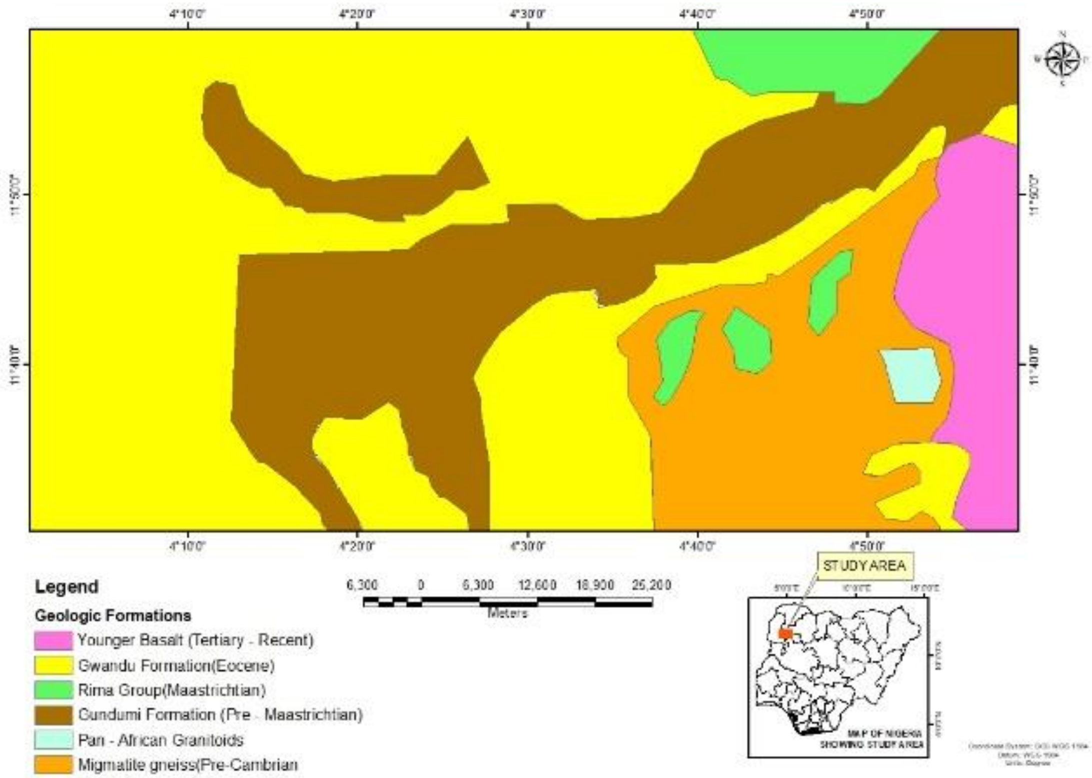

Figure 1a: Geologic Map of the Study Area (After Nigerian Geological Survey Agency, Abuja, 2006).

The sediments are partially cemented sands and clays that are interbedded and have a continental origin. Typically, the clay beds are large, thick, white, red, grey, black, and brown. Sands range from fine to extremely coarse. The formation also contains lignite beds. The thickness of the formation varies from about zero at the eastern edge to roughly 300 meters northwest, toward the center of the basin's downdip. About 25 to 50 meters of pale fine sand and occasional silt make up the Wurno formation, which is the uppermost member of the Rima Group. Well-sorted fine white sand is detected in borehole samples from Sokoto, Rabah, and Wurno, together with dark gray lignite clay that contains pyrites. Shale, some limestone, and mudstones make up the Dukamaje Formation. Near the base are several shally bone beds that include many pieces of fossilized vertebrae, limbs, and skulls. The Formation's thickness ranges from less than 0.5 m in some locations to 23 m at the type of area. The Rima River Valley next to Wurno has good exposures (Aigbadon & Igbinigie, 2024; Ogbesejana *et al*., 2024).

With a maximum thickness of 180 meters, the Taloka Formation is the oldest in the group. In essence, it is made up of mudstones and sandstones. Shinaka, Taloka, and Guronyo all have good exposures. It is composed of siltstones and white, fine-grained, friable sandstones with intercalated shale and mudstone (Tijjani, 2025). The Gundumi Formation consists of Clays, Sandstones and Pebble beds, thought to be lacustrine and fluvial in origin. The maximum thickness of the Formation is reported to be up to 300 m near the Niger border. The base is marked by Conglomeritic beds, which are well preserved and exposed by the roadside at Tureta and Ruwan Kalgo (Ezekiel *et al*., 2023). These basal beds contain rounded Quarts Cobbles and Pebbles and attain a thickness of about 3 m. The Formation is the oldest Sedimentary rock in the northern part of the study area, and it lies uncomformably on the Basement Complex.

The four main orogenic cycles of deformation, metamorphism, and remobilization, the Liberian (2,700 Ma), Eburnean (2,000 Ma), Kibaran (1,100 Ma), and Pan-African (600 Ma) cycles, are thought to have produced the Basement rocks. Intense deformation and isoclinal folding, along with regional metamorphism and widespread migmatization, were the hallmarks of the first three cycles. Alongside the Pan-African deformation, there was widespread granitization and gneissification, migmatization, and regional metamorphism, resulting in the production of homogeneous gneisses and syntectonic granites (AF, 2024). The latter stages of this last deformation were accompanied by the late tectonic emplacement of granites and granodiorites as well as related contact metamorphism. Faulting and fracture signaled the end of the orogeny (AF, 2024).

MATERIALS AND METHODS

Data Acquisition

Two 30-by-60 sheets of digital high-resolution aeroradiometric data were employed in this investigation. The data was gathered from the Nigerian Geological Survey Agency, Abuja. Fugro Airborne Surveys collected the data for the Nigerian Geological Survey Agency from 2004 to 2009. The surveys were conducted with a notional flying height of 80 meters and a sequence of NW-SE flight lines that were 500 meters apart, with a 2000-meter tie-line spacing in a NE-SW orientation. As part of the Sustainability Management for Mineral Resources Project in Nigeria, the World Bank and the Federal Government of Nigeria jointly funded the collection, processing, and compilation of the high-resolution aeroradiometric data. Nigeria.

Techniques for Processing Aeroradiometric Data

The Oasis Montaj software was used to analyze digital data, which was obtained as a total count map for the research region that displays the combined effects of ^{40}K, ^{232}Th, and ^{238}U for the area. The maps were then divided into three categories: potassium content, uranium content, and thorium content. The energy emitted from the Alpha, Beta, and Gamma decay of rocks was used to compute the radioactive heat values (Alabi *et al*., 2024) using an empirical equation that looks like this:

$\rho(9.67C_U+2.56C_{Th}+2.89C_K)\times10^{-5} = A(\mu Wm^{-3})$ where A = radioactive heat and ρ = rock density was taken from Telford *et al*. (1990). The quantities of uranium (ppm), thorium (ppm), and potassium (%) are denoted by C_U, C_{Th}, and C_K, respectively.

RESULTS AND DISCUSSION

Rock density values, based on the prevalent lithology in each grid of the geological map (Fig. 1b), vary from 2.00 to 2.99 g/cm³ (Table 1), indicating that the research area exhibits considerable variation in both geological and radiometric features. This variety illustrates how the subsurface geology is diverse, containing both felsic and mafic rock types.

Figure 2 shows data on total gamma counts, which range from -248.344 to 6265.020 counts per second (cps). With negative values most likely due to instrumental noise or background adjustment, these data show comparatively low gamma radiation intensity throughout the region.

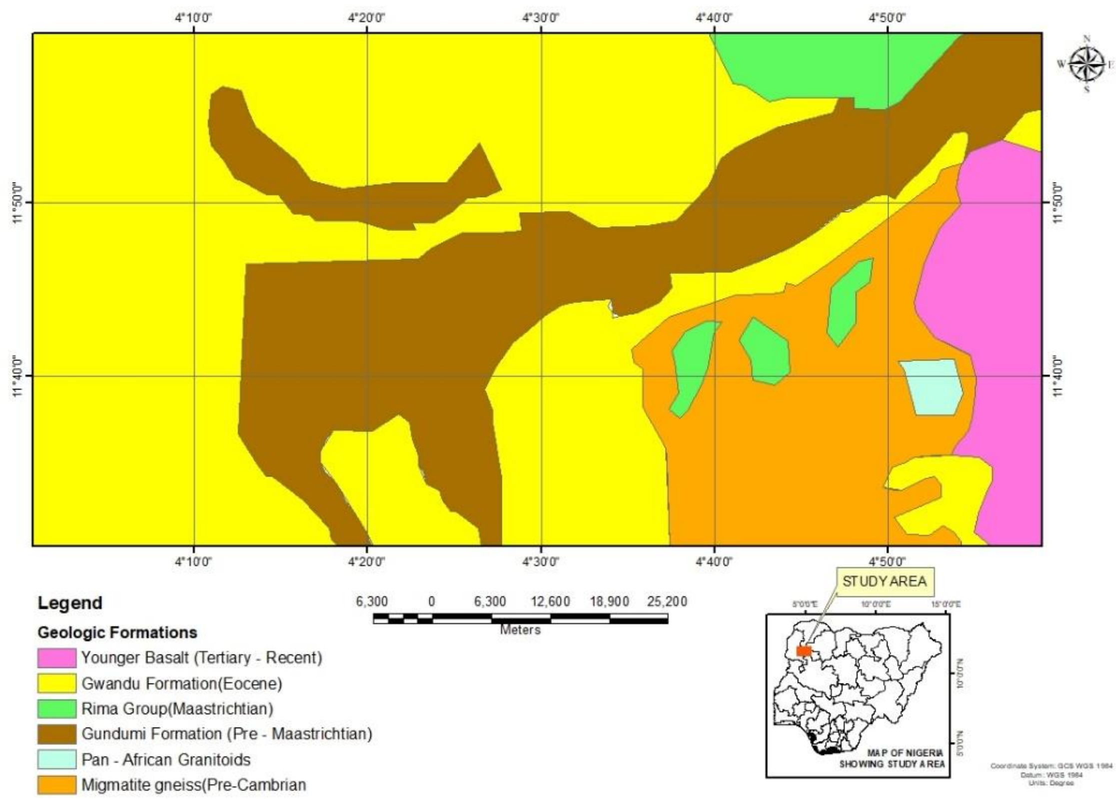

Figure 1b: Gridded geologic map of the area.

Table 1: Density and concentration of each blocks K, Th, and U

Block	Density of Rocks	K (%)	Th (ppm)	U (ppm)
1	2.3	4.82	21.58	12.14
2	2	0.51	14.83	12.14
3	2	0.74	21.58	12.14
4	2	0.74	21.22	12.14
5	2.35	0.74	12.52	12.14
6	2.35	1.23	12.52	12.14
7	2	4.82	21.58	12.14
8	2.35	1.23	21.58	12.14
9	2.35	4.82	21.58	4.18
10	2.35	0.87	21.58	4.18
11	2.8	4.82	21.58	12.14
12	2.99	4.82	12.53	2.13
13	2	0.87	21.58	12.14
14	2	4.82	11.1	12.14
15	2	0.24	21.58	12.14
16	2	4.82	21.58	12.14
17	2.8	4.82	21.58	12.14
18	2.99	4.82	12.52	2.43

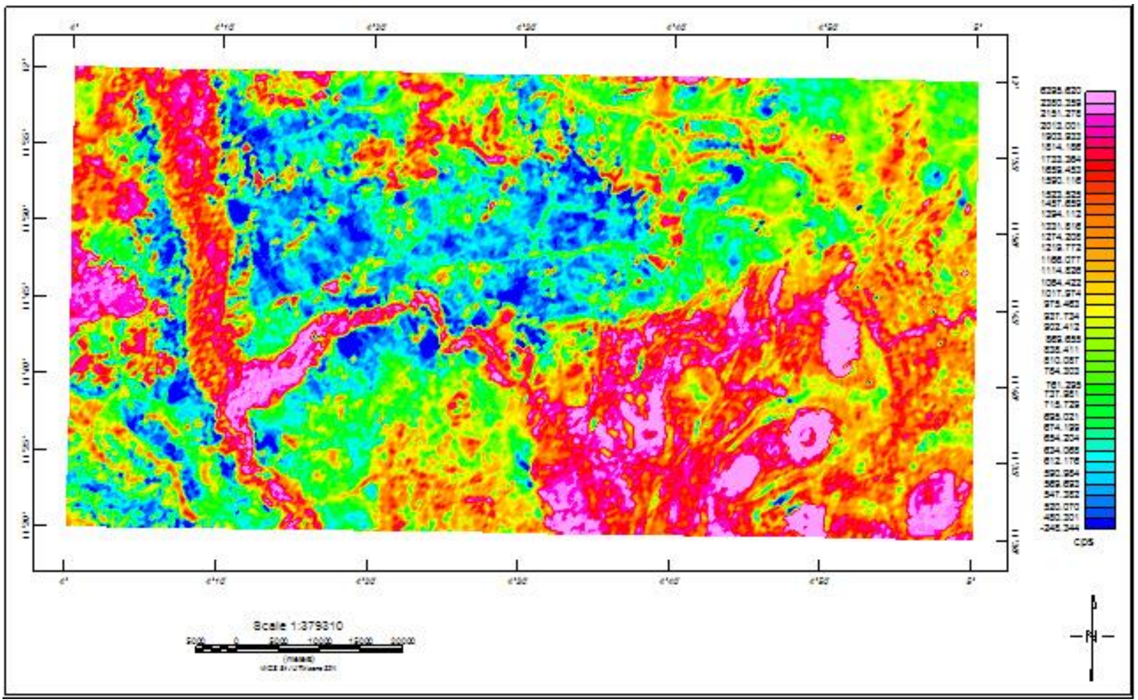

Figure 2: Map of the area's radioactive total count.

There is significant regional diversity in the amounts of the three main radioactive elements, uranium (U), thorium (Th), and potassium (K). Thorium (Th) (-1.323 to 51.563 ppm), Uranium (U) (-4.928 to 17.914 ppm), and Potassium (K) (-0.282 to 4.925%). (Figures 3a, 4a, and 5a). While the upper ranges indicate zones of enhanced radiogenic minerals, especially in felsic lithologies, negative readings could be the result of calibration mistakes.

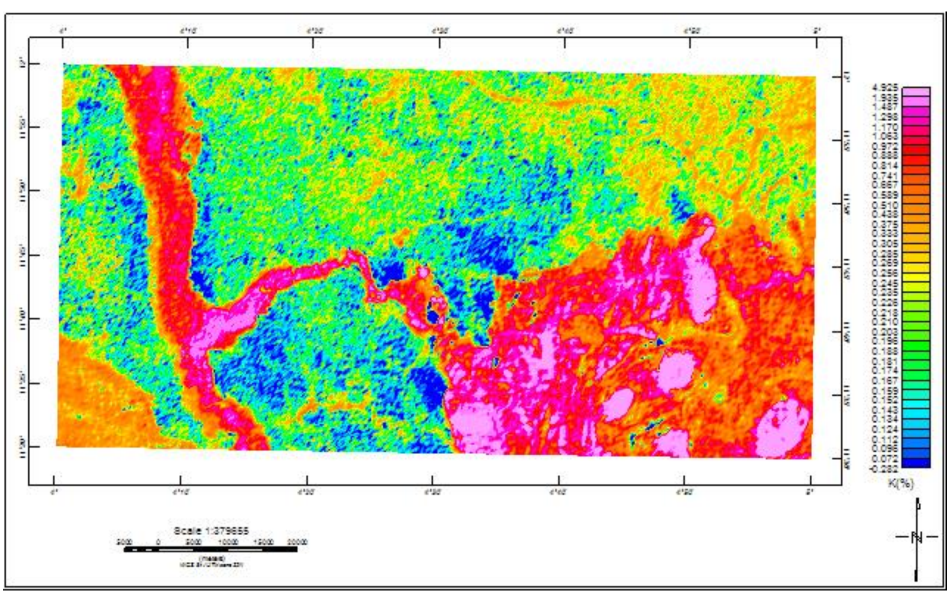

Figure 3a: Potassium concentration map

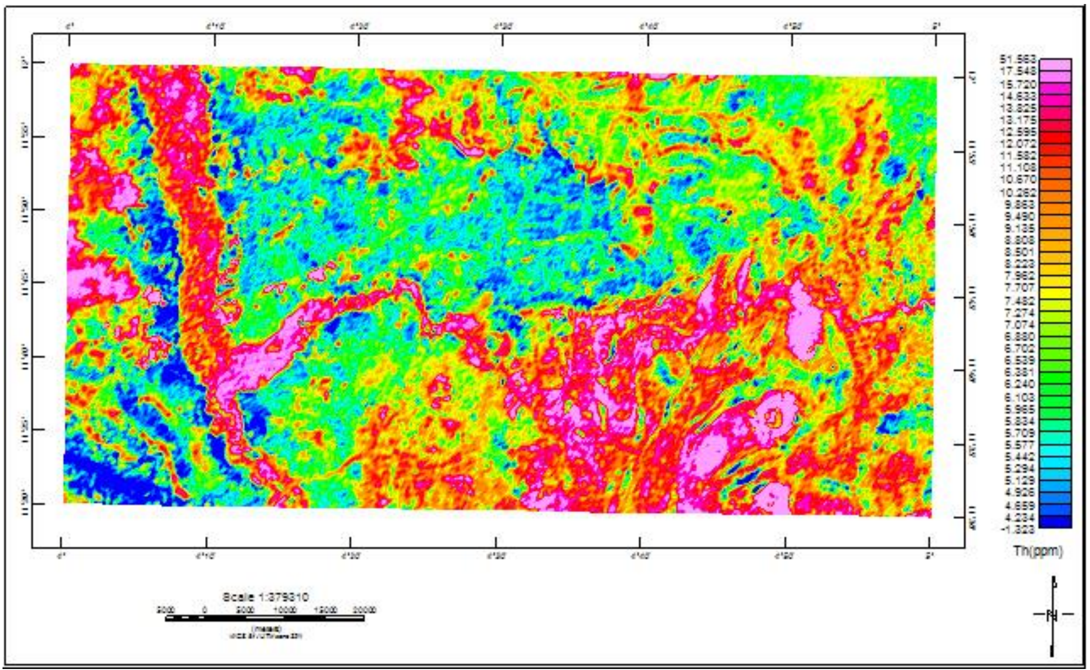

Figure 4a: Thorium concentration map.

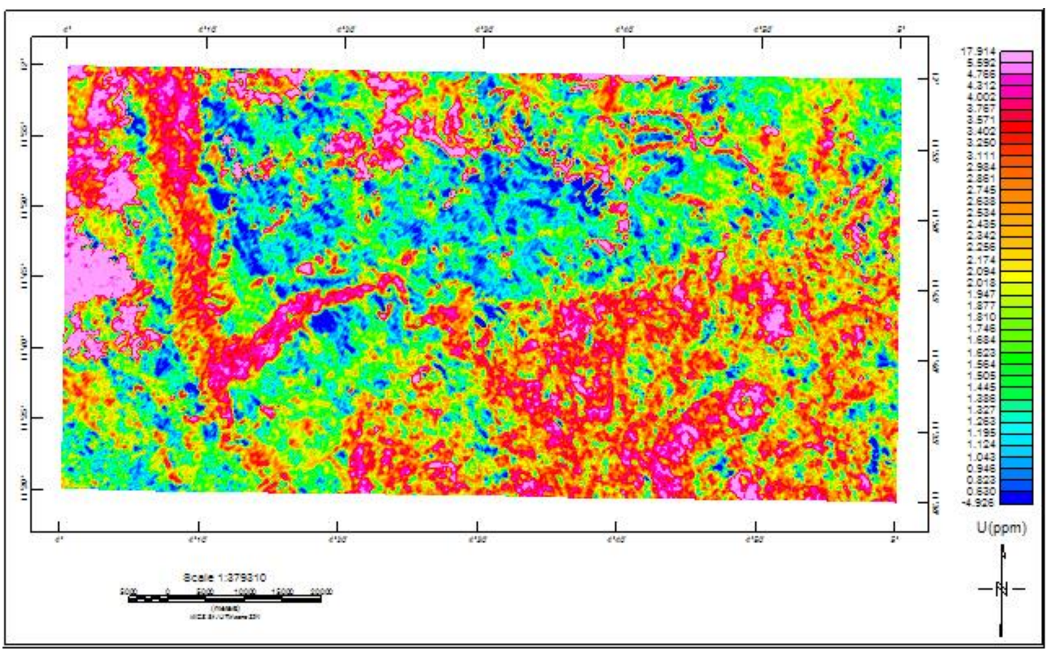

Figure 5a: Uranium concentration map.

An empirical method that accounts for rock density and the K, Th, and U concentrations in each grid cell was used to determine the amount of radioactive heat produced (Figures 3b, 4b, 5b, and Table 2). The resultant values (Table 2, Figure 6) range from 0.001991 to 0.005224 μW/m³. These numbers indicate isolated areas of increased geothermal potential and are in line with the average continental crustal heat production.

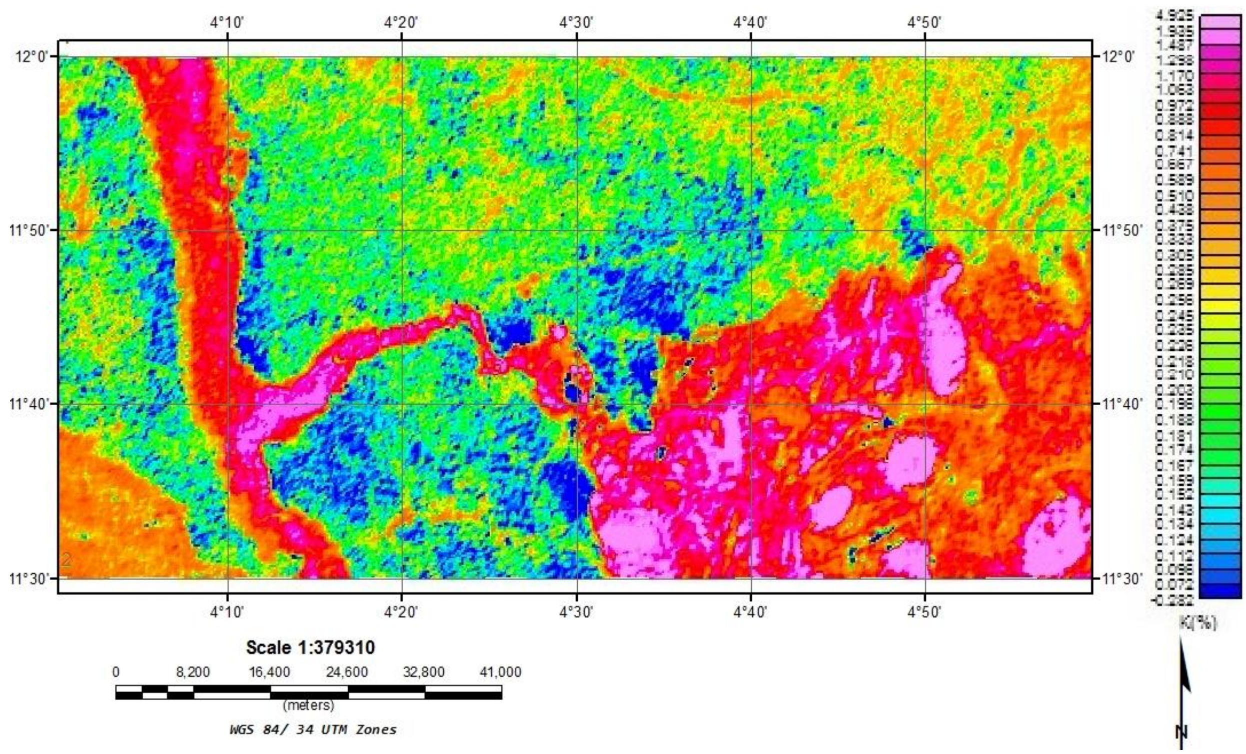

Figure 3b: Potassium concentration gridded map

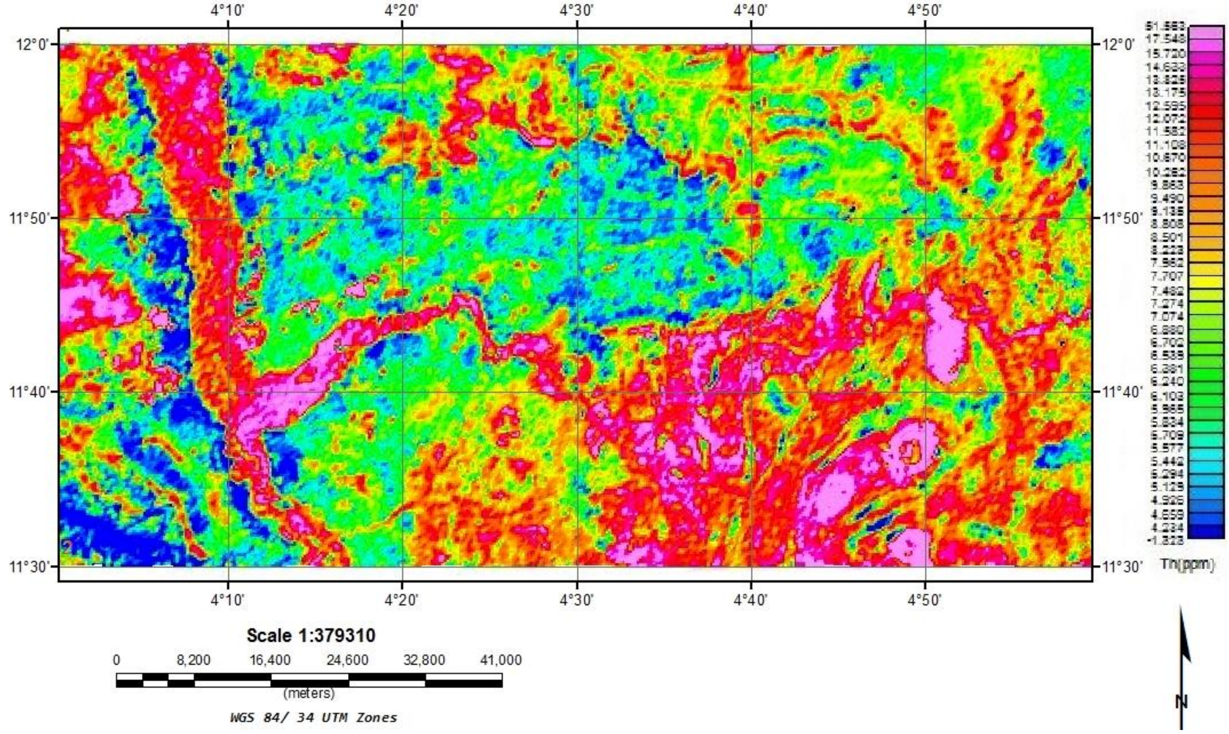

Figure 4b: Thorium concentration gridded map.

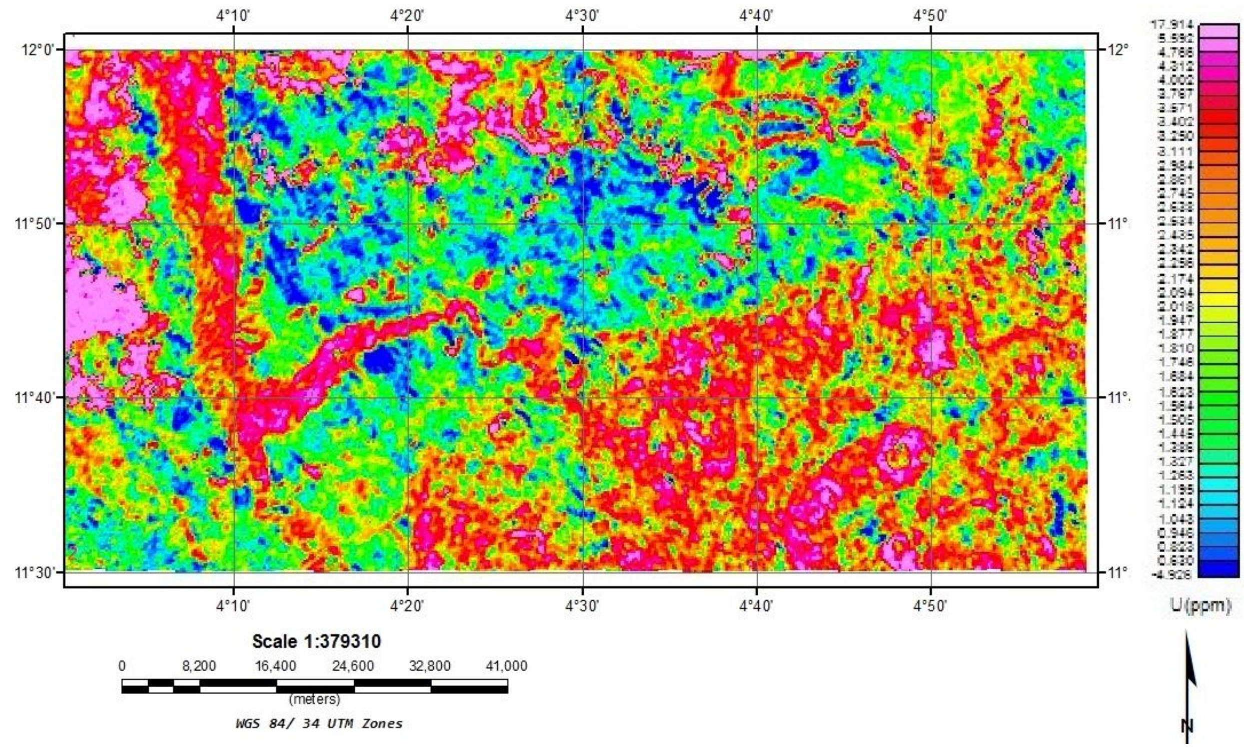

Figure 5b: Uranium concentration gridded map.

Table 2: Computed Radioactive Heat production of the Area

Block	$\rho(2.89C_K)$	$\rho(2.56C_{Th})$	$\rho(9.67C_U)$	$\rho(2.89C_K) + \rho(2.56C_{Th}) + \rho(9.67C_U)$	Heat flow = $\rho(2.89C_K) + \rho(2.56C_{Th}) + \rho(9.67C_U) \times 10^{-5}$
1	32.3709	127.063	270.0057	429.43967	0.004294396
2	2.9474	75.9296	234.7876	313.6646	0.003136646
3	4.2772	110.4896	234.7876	349.5544	0.003495544
4	4.2772	108.6464	234.7876	347.7112	0.003477112
5	5.02571	75.32032	275.8754	356.22146	0.003565521
6	8.35355	75.32032	275.8754	359.552175	0.003595521
7	27.8596	110.4896	234.7876	373.1368	0.003731368
8	8.35355	129.8253	275.8754	414.054255	0.004140542
9	32.735	129.8253	94.98841	257.54872	0.002575487
10	5.90861	129.8253	94.98841	230.722295	0.002307222
11	39.0034	154.6854	328.7026	522.39152	0.005223915
12	41.6501	95.90963	61.58533	199.145063	0.00199145
13	5.0286	110.4896	234.7876	350.3058	0.003503058
14	27.8596	56.832	234.7876	319.4792	0.003194792
15	1.3872	110.4896	234.7876	346.6044	0.00346604
16	27.8596	110.4896	234.7876	373.1368	0.003731368
17	39.0034	154.6854	328.7026	522.39152	0.005223915
18	41.6501	95.83309	70.25932	207.742509	0.002077425

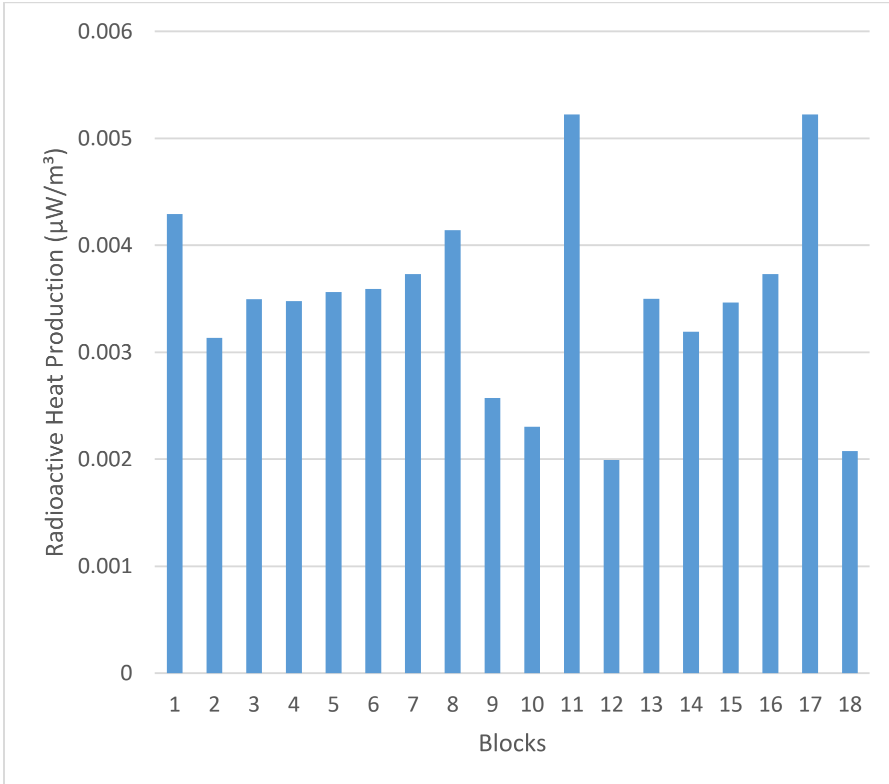

Figure 6: Histogram showing the radioactive Heat production of each Block of the Area.

These findings offer a rich insight into the geological and radiometric characteristics of the study area. Rock Density (2.00 to 2.99 g/cm³) is typical for common crustal rocks, such as granite, basalt, and sedimentary formations. The variation suggests a heterogeneous lithology across the mapped grids, which may influence both radiometric readings and heat production. Higher densities often correlate with more mafic or compact rocks, while lower densities may indicate more felsic or porous materials.

Total Count Data (-248.344 to 6285.020 cps), Counts per second (cps) reflect gamma radiation intensity. The presence of negative values may indicate data correction artifacts or background subtraction. The relatively low cps values suggest weak gamma emissions, possibly due to low concentrations of radioactive elements or shielding effects from dense overburden. The interpretation of the variation is shown in Table 3.

Table 3: Radioactive Element Concentrations

Element	Range	Interpretation
Potassium (K)	-0.282 to 4.925%	Negative values are likely due to calibration errors or noise. Positive values up to 4.925% are within expected limits for granitic rocks.
Thorium (Th)	-1.323 to 51.563 ppm	High Th values suggest the presence of felsic rocks or heavy mineral concentrations.
Uranium (U)	-4.928 to 17.914 ppm	Elevated U levels may indicate potential for radiogenic heat production or even economic interest in uranium exploration.

The wide range and presence of negative values imply extreme variability in elemental distribution.

In general, radioactive heat production is divided into three categories: low (less than 1 μW/m³), moderate (between 1 and 3 μW/m³), and high (more than 3 μW/m³). The region's radioactive heat output, which varies between 0.001991 and 0.005224 μW/m³, is comparatively modest yet in line with averages for the continental crust. The K, Th, and U concentrations weighted by rock density and an empirical formula are used to calculate the heat generation. Regions probably make greater contributions to the upper end of the heat production spectrum with higher Th and U concentrations.

The geological map reveals a complex terrain with variable lithology and radiometric properties. The presence of high Th and U concentrations in some grids suggests zones of elevated radiogenic heat, which could influence geothermal gradients and subsurface temperature profiles. These findings are valuable for: Geothermal energy assessment, Mineral exploration, and understanding crustal composition and thermal structure.

Correlating the findings of this research with other radiometric and geothermal studies conducted in northwestern Nigeria, particularly within the Iullemmeden Basin and surrounding Precambrian basement zones, helps validate the results and highlight broader geological implications. Aisabokhae and Adeoye (2020) conducted a radiometric survey across the Precambrian basement transition zone in NW Nigeria. According to their analysis, radiogenic heat output ranged from 0.002 to 0.006 μW/m³, while potassium levels ranged from 4.6 to 18.9%, uranium levels from 0.7 to 4.9 ppm, and thorium levels from 4.6 to 18.9 ppm. These figures support the region's geothermal potential because they closely match the research's findings, particularly about heat output and Th/U concentrations.

Tijjani (2018) applied radiometric techniques to estimate heat production around the Rafin Rewa hot spring. Though focused on a hydrothermal system, the study supports the use of airborne radiometric data for geothermal assessment in northern Nigeria. In other parts of the country such as Ikogosi Warm Spring (Southwest Nigeria) Ayilola *et al.* (2025) found similar radioelement concentrations and heat production values using aero-radiometric data. Their methodology and findings offer a useful benchmark for interpreting low-enthalpy geothermal systems. The heat production values (0.001991 to 0.005224 μW/m³) are consistent with this research and other works in NW Nigeria. Elevated Th and U concentrations are common in the basement complex and basin margins. These results lend credence to the region's continued mineral prospecting and geothermal exploration.

CONCLUSION

This study emphasizes the region's complex radiometric landscape, which is characterized by varying gamma radiation intensity, varied lithology, and a range of radioactive element concentrations. The possibility of radiogenic heat generation in the area is highlighted by the observed rock densities and elemental distributions, especially the elevated quantities of uranium and thorium.

Although small, the estimated heat production values support the area's viability for geothermal energy exploration and are consistent with continental crustal averages. Prospects for the development of mineral resources are further supported by the existence of mineral-rich zones and felsic rocks.

The validity of aerial radiometric techniques and the geothermal potential of the Iullemmeden Basin and surrounding Precambrian Basement zones are confirmed by correlations with earlier investigations conducted in northwest and southwest Nigeria. These discoveries have a significant impact on mineral exploration, regional energy planning, and our understanding of crustal thermal dynamics in general.

ACKNOWLEDGEMENTS

The high-resolution aeromagnetic data were made accessible by the Nigerian Geological Survey Agency, for which the authors are thankful.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

AF, A. (2024). Application of Aeromagnetic Data to Delineate the Mineralization Zones within Shanga (Sheet 96), Northwest Nigeria. *Asian Journal of Geological Research*, *7*(1), 74-87.

Aigbadon, G. O., & Igbinigie, N. S. (2024). Lithological Characteristics, Petrographic and Ostracods Analyses of Carbonate Rocks in Parts of Sokoto Basin, Nigeria: Implications for Exploration Efforts and Petroleum Geology. *Ilorin Journal of Science*, *11*(1), 34-51.

Aisabokhae, J., & Adeoye, M. (2020). Spatial distribution of radiogenic heat in the Iullemmeden basin – Precambrian basement transition zone, NW Nigeria. *Geology, Geophysics and Environment*, 46(3), 239–250. https://doi.org/10.7494/geol.2020.46.3.239.

Alabi, O. O., Sedara, S. O., Ajah, D. T., & Akanni, I. A. (2024). Modification of radiogenic heat production equation due to radioactive disequilibrium in rock samples from gamma-ray spectrometry. *Journal of the Indian Geophysical Union, 28*(2), 84–98. https://doi.org/10.59321/jigu.2024.02802.84

Ayilola, O. O., Tamunobereton-Ari, I., Amakiri, A. R. C., & Israel-Cookey, C. (2025). Radiogenic heat production and its effects on the geothermal potentials of Ikogosi Warm Spring, South-West Nigeria. *American Journal of Sciences and Engineering Research*, 8(3). https://iarjournals.com/upload/83260273.

Belts, S., Nigeria, N., Oluyede, K., Garba, I., Danbatta, U., Ogunleye, P., & Klötzli, U. (2024). 8 Origin and Geological Setting. *Geology and Natural Resources of Nigeria*, 124

DaPelo, S., Aghdam, M. M., Dentoni, V., Loi, A., Randaccio, P., & Crowley, Q. (2024). Assessment of natural radioactivity and radon release potential of Silurian black shales. *Radiation Physics and Chemistry*, *215*, 111347.

El-Hadidy, S. M., & Youssef, M. A. (2024). Exploring geothermal energy prospects through radioelement enrichment zones in Gabal Abu Hashim area in southeastern Aswan by geophysical and remote sensing data integration. *Scientific Reports*, *14*(1), 27043.

Ershov, B. G. (2024). Natural radioactivity of the crust as an important factor of the chemical evolution of the early Earth. *Precambrian Research*, *406*, 107400.

Ezekiel, K., Peter, S. & Garba, M. A. Aeromagnetic Data Investigation of Geothermal Energy Potentials in Ramfashi and Environs Zamfara State, Nigeria.

Federal Survey of Nigeria (2006) Topographical Map of the Study Area, Latitudes 11°30'- 12°00'N and longitudes 4°00'-5°00'E

Gawad, A. E. A., Masoud, M. S., Khandaker, M. U., & Hanfi, M. Y. (2024). Radiological hazards assessment associated with granitoid rocks in Egypt. *Nuclear Engineering and Technology*.

Harrison, T. M. (2024). We don't know when plate tectonics began. *Journal of the Geological Society*, *181*(4), jgs2023-212.

Ijeh, B. I., Anyadiegwu, F. C., Onwubuariri, C. N., & Eze, M. O. (2024). Evaluation of geothermal resource potential of the Lower Benue Trough using aeromagnetic and radiometric data. *Modeling Earth Systems and Environment*, *10*(1), 695-721.

Jha, S. K., Patra, A. C., Verma, G. P., Iyer, I. S., & Aswal, D. K. (2024). Natural Radiation and Environment. In *Handbook on Radiation Environment, Volume 1: Sources, Applications and Policies* (pp. 27-72 Singapore: Springer Nature Singapore)'

Karjalainen, V., Malinen, J., & Tokola, T. (2025). Comparison of two gamma-ray datasets measured with different methods and assessment of their performance to predict soil properties. *International Journal of Forest Engineering*, *36*(1), 29-42.

Nigerian Geological Survey of Nigeria (2006) Geological Map of the Study Area, Latitudes 11°30'- 12°00'N and longitudes 4°00'-5°00'E

Nweke, N. D., Ugwuonah, E. N., Onuba, L. N., & Egbueri, J. C. (2024). The occurrences, characteristics, and implications of chaotic rocks (accretionary rocks) within the Trans-Saharan orogenic belt in Nigeria. *Discover Geoscience*, *2*(1), 1-24.

Ogbesejana, A. B., Muaz, L. A., Gobirawa, N. S., Radda, F. D., Akinyemi, S. A., Areguamen, O. I., ... & Yandoka, B. M. S. (2024). Major, Trace, and Rare Earth Elements Geochemistry of the Late Paleocene Shales from Gamba Formation, Sokoto Basin, Northwest Nigeria.

Ola-Buraimo, A. O., & Mohammed, A. T. (2024). Palynological zonation and age dating of the Gamba (Middle Eocene) and Kalambaina (Early Maastrichtian-Paleocene) Formations, Sokoto Basin, northwestern Nigeria. *Savanna*, *6*(1), 45-53.

Oluyede, K., Garba, I., Danbatta, U., Ogunleye, P., & Klötzli, U. (2024). Origin and Geological Setting of Magmatic Rocks within the Kushaka and Birnin Gwari S chist Belts, Northwest Nigeria. In *Geology and Natural Resources of Nigeria* (pp. 124-159). CRC Press

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (1990). *Applied geophysics*. Cambridge university press.

Tijjani, I. (2018). Application of radiometric method to determine radiogenic heat around Rafin Rewa hot spring, Lere, Kaduna State, Nigeria (Master's thesis, Ahmadu Bello University, Zaria). Retrieved from ABU Repository

Tijjani, R. D. (2025). Occurrence, Quality, and Challenges in Nigeria. *Groundwater Frontiers-Techniques and Challenges: Techniques and Challenges*, 149.).

Trivedi, A., Kumar, U., Patra, S. N., Shrivastava, H. B., & Mondal, R. K. (2024). Gamma Ray Spectrometry–An indispensable tool for Uranium Exploration. *Indian Journal of Pure & Applied Physics (IJPAP)*, *62*(10), 940-950.

Umar, M., Awosusi, A. A., Adegboye, O. R., & Ojekemi, O. S. (2024). Geothermal energy and carbon emissions nexus in leading geothermal-consuming nations: Evidence from nonparametric analysis. *Energy & Environment*, *35*(5), 2726-2752.

Upadhyay, R. K. (2025). Exploration of Mineral Resources. In *Geology and Mineral Resources* (pp. 655-723). Singapore: Springer Nature Singapore.

Zapata, S., Cardona, A., Jaramillo-Ríos, J. S., Siachoque, A., Peverelli, V., Chew, D., ... & Glodny, J. (2024). Repeated structural reworking in the basement of the Central Colombian Andes unraveled by a multi-chronometric approach. *Tectonics*, *43*(10), e2024TC008340.

Zou, F. H., Santosh, M., Deng, L. H., Wu, C. L., Gao, D., & Gao, Y. H. (2024). Granitoids indicating moderate to high heat production associated with oceanic subduction system in the NE Tibetan Plateau. *Bulletin*, *136*(1-2), 597-618.