

AERO-RADIOMETRIC EVALUATION OF GEOTHERMAL POTENTIAL IN THE NUPE BASIN, NORTH-CENTRAL NIGERIA

AERORADIOMETRIJSKA PROCJENA GEOTERMALNOG POTENCIJALA U BAZENU NUPE U SJEVERNO-SREDIŠNJOJ NIGERIJU

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This study examined the spatial distribution of potassium, uranium, thorium, and radiogenic heat production (RHP) as indicators of subsurface thermal conditions in selected parts of the Nupe Basin, North Central Nigeria, using aero-radiometric data obtained from the Nigerian Geological Survey Agency. The corrected aero-radiometric datasets, representing the measured gamma radiation of the study area, were processed using Oasis montaj software to estimate potassium (K) in %, equivalent uranium (eU) in ppm, and equivalent thorium (eTh) concentrations in ppm. The total count, ternary, and elemental ratio maps were also generated. RHP values were subsequently calculated from the radioelement concentrations using established empirical relationships. The results indicated that elevated potassium concentrations, ranging from $0.08 \pm 0.02\%$ to $2.03 \pm 0.87\%$, are predominantly associated with crystalline basement rocks, particularly igneous and metamorphic lithologies. Thorium and uranium concentrations, with respective ranges of 14.0 ± 4.0 ppm to 21.0 ± 5.3 ppm and 3.2 ± 0.3 ppm to 5.7 ± 0.8 ppm, are more pronounced within weathered and sedimentary units. The estimated RHP across the study area yielded an average of $1.44 \pm 0.08 \mu\text{W}/\text{m}^3$, suggesting relatively weak heat generation from radioactive decay processes compared to the standard

threshold of $4.0 \mu\text{W}/\text{m}^3$ for geothermal lithologies. This study is limited to the radiogenic component of geothermal assessment and does not incorporate hydrogeological conditions, subsurface permeability, reservoir characteristics, or heat transport processes, which are essential for developing viable geothermal systems. Consequently, the analysed aero-radiometric data indicate a low to moderate radiogenic heat contribution.

KEYWORDS: aero-radiometric; radiogenic heat production; radioelement; geothermal energy; sedimentary; energy potential

U ovom je istraživanju analizirana prostorna raspodjela kalija, uranija, torija i radiogene proizvodnje topline (RHP) kao pokazatelja toplinskih uvjeta u podzemlju na odabranim dijelovima bazena Nupe u sjeverno-središnjoj Nigeriji primjenom aeroradiometrijskih podataka dobivenih od Nigerijske geološke službe (Nigerian Geological Survey Agency). Korigirani aeroradiometrijski skupovi podataka, koji predstavljaju izmjereno gama-zračenje na području istraživanja, obrađeni su u softveru Oasis montaj radi procjene koncentracije kalija (K) u postocima, ekvivalentnog uranija (eU) u ppm i ekvivalentnog torija (eTh) u ppm. Također su izrađene karte ukupnog intenziteta zračenja, ternarni prikaz i karte omjera pojedinih elemenata. Vrijednosti RHP-a potom su izračunate iz koncentracija radioelemenata primjenom utvrđenih empirijskih odnosa. Rezultati su pokazali da su povišene koncentracije kalija, u rasponu od $0,08 \pm 0,02 \%$ do $2,03 \pm 0,87 \%$, pretežno povezane s kristalinskim stijenama podloge, osobito magmatskim i metamorfnim litologijama. Koncentracije torija i uranija, u rasponima od $14,0 \pm 4,0 \text{ ppm}$ do $21,0 \pm 5,3 \text{ ppm}$ odnosno od $3,2 \pm 0,3 \text{ ppm}$ do $5,7 \pm 0,8 \text{ ppm}$, izražene su unutar trošnih i sedimentnih jedinica. Procijenjeni RHP na području istraživanja iznosi prosječno $1,44 \pm 0,08 \mu\text{W}/\text{m}^3$, što upućuje na relativno slabu proizvodnju topline procesima radioaktivnog raspada u odnosu na standardni prag od $4,0 \mu\text{W}/\text{m}^3$ za geotermalne litologije. Ovo je istraživanje ograničeno na radiogenu komponentu geotermalne procjene te ne obuhvaća hidrogeološke uvjete, propusnost podzemlja, značajke ležišta i procese prijenosa topline, koji su ključni za razvoj gospodarski iskoristivih geotermalnih sustava. Posljedično, analizirani aeroradiometrijski podaci upućuju na nizak do umjeren doprinos radiogene topline.

KLJUČNE RIJEČI: aeroradiometrija; radiogena proizvodnja topline; radioelementi; geotermalna energija; sedimentne stijene; energetski potencijal

INTRODUCTION

Inadequate production of electricity, which gives rise to poor distribution output, unstable power supply and other economic challenges, is a major problem in Nigeria (Adagunodo et al., 2026). It is imperative that the country engage in and improve the use of alternative renewable energy resources such as geothermal energy, since there is evidence of geothermal energy potential both in the basement and sedimentary part of the country to complement hydrocarbon (Salako et al., 2020; Salaudeen et al., 2024). To locate possible geothermal energy resource zones, the heat generated by radioactive decay of the natural radionuclide isotopes in the Earth's crust is an important parameter (Bezuidenhout, 2023). Radiometric methods involve measuring naturally existing radioactive elements such as uranium, thorium and potassium in rocks (Lawal et al., 2025; Oni et al., 2025; Youssef & Elkhodary, 2013).

The disintegration of these radioactive elements is followed by the release of ionization radiation (alpha ray, beta ray and gamma ray) from rocks, and it is measured using a spectrometer and a scintillation detector (Usman et al., 2022). Although many other naturally occurring elements have radioactive isotopes, only the radioactive isotopes of uranium, thorium, and potassium decay series release gamma rays with sufficient energy and intensity to be measured by a gamma-ray spectrometer (Adabanija et al., 2020). The reason for this is that the natural environment contains comparatively large amounts of the three elements (Eluwa et al., 2021). The energy of the gamma rays released by the decay of these natural radionuclides can theoretically range from zero to three MeV. However, the region of 0.2 to 3 MeV is more interesting for the geological survey (Ezekiel & Nur, 2022) and the decay of these radioactive elements is essential for geothermal resources (Ademila et al., 2018).

Aero-radiometric survey is a geophysical method used to measure the natural gamma radiation emitted from rocks and soils at the Earth's surface. The survey is usually conduct-

ed using detectors mounted on an aircraft or helicopter that flies along predetermined lines across an area of interest. Standard practice in aero-radiometric investigations requires corrections for aircraft altitude, cosmic background radiation, atmospheric effects, Compton scattering, and instrument calibration before quantitative interpretation can be carried out. International guidelines provided by the International Atomic Energy Agency (IAEA) emphasize that properly calibrated airborne gamma ray spectrometric data are essential for reliable estimation of radioelement concentrations and subsequent geological interpretation (IAEA, 2003). The guidelines further recommend the integration of radioelement distribution maps, ternary imagery, and ratio analysis for lithological discrimination and structural interpretation in regional studies. These procedures have become widely accepted in radiometric mapping and geothermal reconnaissance because they improve the consistency and comparability of aero-radiometric datasets (IAEA, 2003; Lawal, 2020; Ohaegbuchi et al., 2026).

Several researchers made use of radiometric analysis for examining the distribution of radioelement concentrations, production of radioactive heat in basement and sedimentary rocks, subsurface geological mapping, and evaluation of the health effects of these radioelements in various geographical areas (Ilori et al., 2024). The potential for radiogenic heat production in the Southern Anambra basin was examined using aero-radiometric data, with results showing that the sedimentary rock type that produces the most heat is shale (Kuforijimi & Aigbogun, 2017). Likewise, the radioactive heat generation and radioactive mineral concentrations in the Sokoto Basin are at low to moderate levels (Ezekiel & Nur, 2022). The radiogenic heat production in northeastern Nigeria over various petrologic units were also investigated, and it was observed that the porphyritic biotite-hornblende granites (OGp) rock has the greatest heat production output while the least was recorded in alluvium (AL) rock (Yusuf et al., 2023).

In addition, the surface geology and structural features that are essential for the development of mineral resources were investigated by analysing and interpreting aero-radiometric data of the Flamingo Field in Southwest Nigeria; according to the composite radioelements and image maps that were developed, bright zones which depict abnormal alteration zones and the most noticeable trend in the field, which corresponds to the northeast-southwest and northwest-southeast directions was observed (Lawal et al., 2025). Moreover, data from Aswan, Egypt's airborne gamma ray spectrometry show four comparatively high uraniferous zones with structural lineaments trending northwest, northeast, and east-northeast (Youssef & Elkhodary, 2013).

Previous research conducted in various parts of Nigeria highlighted various contributions of aero-radiometric data especially in the field of radiogenic heat production for geothermal energy investigation. However, there is still a knowledge gap about the unique radiogenic heat production properties of rocks in sedimentary zones as there are established facts of natural radionuclide isotopes being affected by geological and geographical causes (Baldik et al., 2011). Since a fault is a potential pathway for the migration of radionuclides from the subsurface rocks (Chen et al., 2018), it can therefore be an economically important structural feature in a geothermal potential site. The study area chosen for this research is the Nupe Basin, North Central Nigeria and researchers identified the study area to be a severely faulted formation; which trends majorly in the NE - SW, NNE - SSW and NW - SE, ENE-WSW direction, and the NNE-SSW being associated with the prominent Ifewara-Zungeru fault (Saleh et al., 2022). These structures may influence fluid migration, weathering intensity, and redistribution of radioactive minerals within the sedimentary sequence. Consequently, the Nupe Basin provides a suitable geological setting for examining the relationship between radioelement distribution, and crustal heat generation within an intracratonic sedimentary environment.

This study therefore investigates the spatial distribution of uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) concentrations and estimates the associated radiogenic heat production within selected parts of the Nupe Basin using aero-radiometric data. The study specifically evaluates whether variations in radioelement concentration correspond to significant changes in radiogenic heat generation within the basin. The investigation is limited to the radiogenic component of geothermal assessment and does not incorporate hydrogeological conditions, permeability, reservoir properties, or subsurface heat transport processes that are also necessary for the establishment of viable geothermal systems.

MATERIALS AND METHODS

Study Area

The study area is the Nupe Basin, a NW-SE trending intracratonic basin in Nigeria, characterised by a gently down-warped depression filled with sedimentary rocks. Its coordinates are latitude $8^{\circ} 54'$ to $10^{\circ} 4' \text{ N}$ and longitude $5^{\circ} 28'$ to $6^{\circ} 36' \text{ E}$ and it is geographically located between the Benue Trough and the Anambra Basin. The basin is adjacent and nearly perpendicular to the major axis of the Benue Trough and the Niger Delta Basin of Nigeria. It forms the north-western extension of the Anambra Basin, and it is one of the inland basins in Nigeria that constitutes cretaceous and rift basins in Central and West Africa. The basin is a distinctive feature in the sedimentary landscape of Nigeria since it does not contain carbonate rocks, volcanics, and tertiary sediments (Opeloye et al., 2021). Figures 1 and 2 show geological and the location map of the study area. Furthermore, it was discovered that the Ifewara-Zungeru fault system, one of Nigeria's four major fault systems, extended across the research region.

Data Description

The aero-radiometric data used in this study consist of sheets 162 (Akerre), 163 (Zunge-

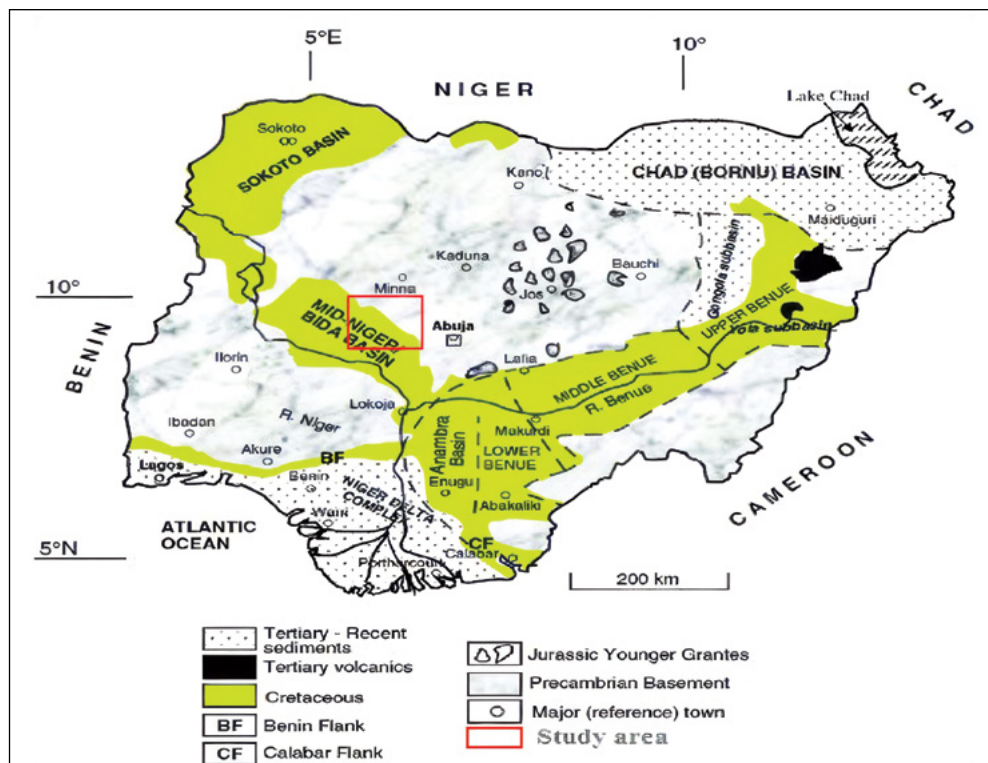


FIGURE 1 Geological map of Nigeria showing the location of the Nupe Basin

Source: modified according to Obaje, 2009

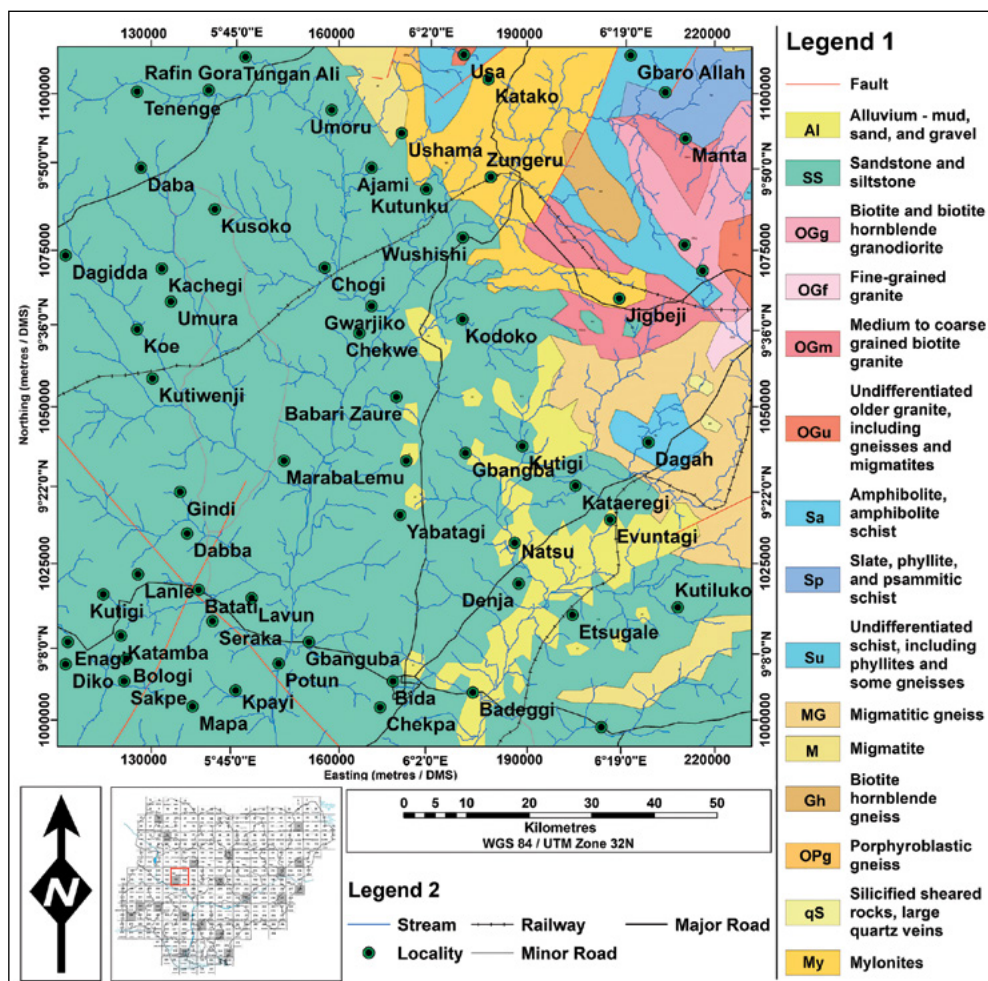


FIGURE 2 Lithological map of the study area

Source: according to Nigerian Geological Survey Agency (NGSA), 2006

TABLE 1 *Data parameters and specifications*

Survey Parameter	Radiometric Specification
Data Acquired by:	Fugro Airborne Survey
Time Range	2004-2009
Data Recording Interval	0.1 s or less
Sensor Mean Terrain Clearance	80 m
Flight Line Spacing	500 m
Tie Line Spacing	2000 m
Flight line Trend	135°
Tie line Trend	45°
Equipment: Aircraft	Cessna Caravan 208B ZS-FSA, Cessna Caravan 208B ZS-MSJ
Equipment:	(NaI (TI) crystals) 512-channels gamma-ray spectrometer

Source: NGSa (2009)

ru), 183 (Egbako), and 184 (Bida), located in the Nupe Basin, North Central Nigeria. It was acquired by Fugro Airborne survey Limited for the Nigerian Geological Survey Agency (NGSA) between 2004 and 2009. The acquisition, processing, and compilation of the new dataset were jointly funded by the Federal Government of Nigeria and the World Bank under the Sustainable Management for Mineral Resources Project. The survey was carried out using airborne gamma ray spectrometry with scintillation detectors employed as counters and a data recording interval of 0.1 s; a fixed-wing aircraft flying at mean terrain clearance of 80 m with 500 m line spacing and nominal tie line spacing of 2000 m. The trends for the flight line and tie line were 135° and 45° respectively. The data parameters and specifications are summarised in Table 1.

The data were pre-processed by Fugro Airborne Surveys before delivery to the Nigerian Geological Survey Agency (NGSA) where the data was retrieved. The pre-processing procedure included several corrections which are usually made to the data when uranium, thorium, and potassium concentrations in surface rocks are estimated from the measured gamma rays using the airborne gamma survey. These corrections include aircraft background radiation, cosmic background radiation, Compton scattering in the potassium and uranium energy window, spectral overlap, and altitude variation. These

corrections were done using 1D non-linear filter. The calibration and correction procedures were designed to convert raw airborne gamma measurements into estimates of ground level radioelement concentrations suitable for geological interpretation.

Data Processing and Presentation

The corrected datasets were imported into *Oasis montaj* for further processing, visualisation, and interpretation. The equivalent uranium (eU) and equivalent thorium (eTh) concentrations were expressed in parts per million (ppm), while potassium concentration was expressed as percentage potassium (%). The total count was represented in counts per second (cps). Quality assessment of the supplied corrected dataset was performed during processing through visual inspection of line continuity, consistency between adjacent flight lines and tie lines, and assessment of anomalous spikes or striping effects that could indicate residual correction errors. Gridding of the radiometric variables was carried out using minimum curvature interpolation to produce continuous spatial distribution maps for potassium, uranium, thorium, and total count across the study area.

A ternary radiometric image was also generated from the combined potassium, thorium, and uranium grids. In the ternary image, red,

green, and blue colour channels were assigned to potassium, thorium, and uranium concentrations respectively to enhance lithological contrasts and spatial variations in radioelement distribution. In addition, K/eTh ratio maps were produced by the arithmetic combination of the radioelement grids. Ratio imaging is widely used in airborne radiometric interpretation because it minimises the influence of absolute count variations and enhances alteration patterns. The K/eTh ratio map was generated and displayed as an equalized histogram colour relief image to improve the visualization of relative potassium thorium concentration within the basin.

The dataset used in this study comprises 61 locations within the Nupe Basin, North Central Nigeria. These locations correspond to selected grid points extracted from the continuous airborne radiometric dataset to ensure adequate spatial representation of the study area. Gamma radiation was measured during the airborne radiometric survey, and the corresponding radioelement concentrations, together with their associated uncertainties arising from the gridding and interpolation procedures, were estimated after applying the appropriate correction techniques in Oasis montaj software. The selected locations provided representative

values of potassium, uranium, thorium, and radiogenic heat production across the different lithological units identified from the geological map of the basin.

Estimation of Radiogenic Heat Production

Radiogenic heat production is the physical property that describes the amount of heat emitted by the decay of unstable radioactive isotopes per unit of rock. It was evaluated from the aero-radiometric data and for correct computation and interpretation, the rock unit type present in the study area and their boundaries were well outlined. The computation of the radiogenic heat production from aero-radiometric data uses the expression below (Salem & Fairhead, 2011):

$$A(\mu / m^3) = \rho(0.0952C_u + 0.0256C_{Th} + 0.0348C_K) \quad (1)$$

where A is radioactive heat and ρ is the density of rock in g/cm^3 adapted from Telford et al. (1990). C_u and C_{Th} are the equivalent uranium (eU) concentration and equivalent thorium (eTh) concentration estimated in parts per million (ppm), while C_K is potassium concentration in %.

Table 2 and Figure 3 present the table and map of the rocks' density used for the computation of

TABLE 2 Average rock density for each unit of rock

S/N	Rock	Density (g/cm^3)
1.	Mylonites	2.7
2.	Silicified sheared rocks, large quartz veins	2.6
3.	Porphyroblastic gneiss	2.75
4.	Biotite hornblende gneiss	2.8
5.	Migmatite	2.7
6.	Migmatitic Gneiss	2.75
7.	Undifferentiated schist, including phyllites and some gneisses	2.75
8.	Alluvium – mud, sand, and gravel	1.8
9.	Sandstone and siltstone	2.4
10.	Biotite and biotite hornblende granodiorite	2.75
11.	Fine-grained granite	2.6
12.	Medium to coarse grain biotite granite	2.7
13.	Undifferentiated older granite, including gneisses and migmatites	2.6
14.	Amphibolite, amphibolite schist	3.0
15.	Slate, phyllite, and psammitic schist	2.76

Source: Telford et al. (1990)

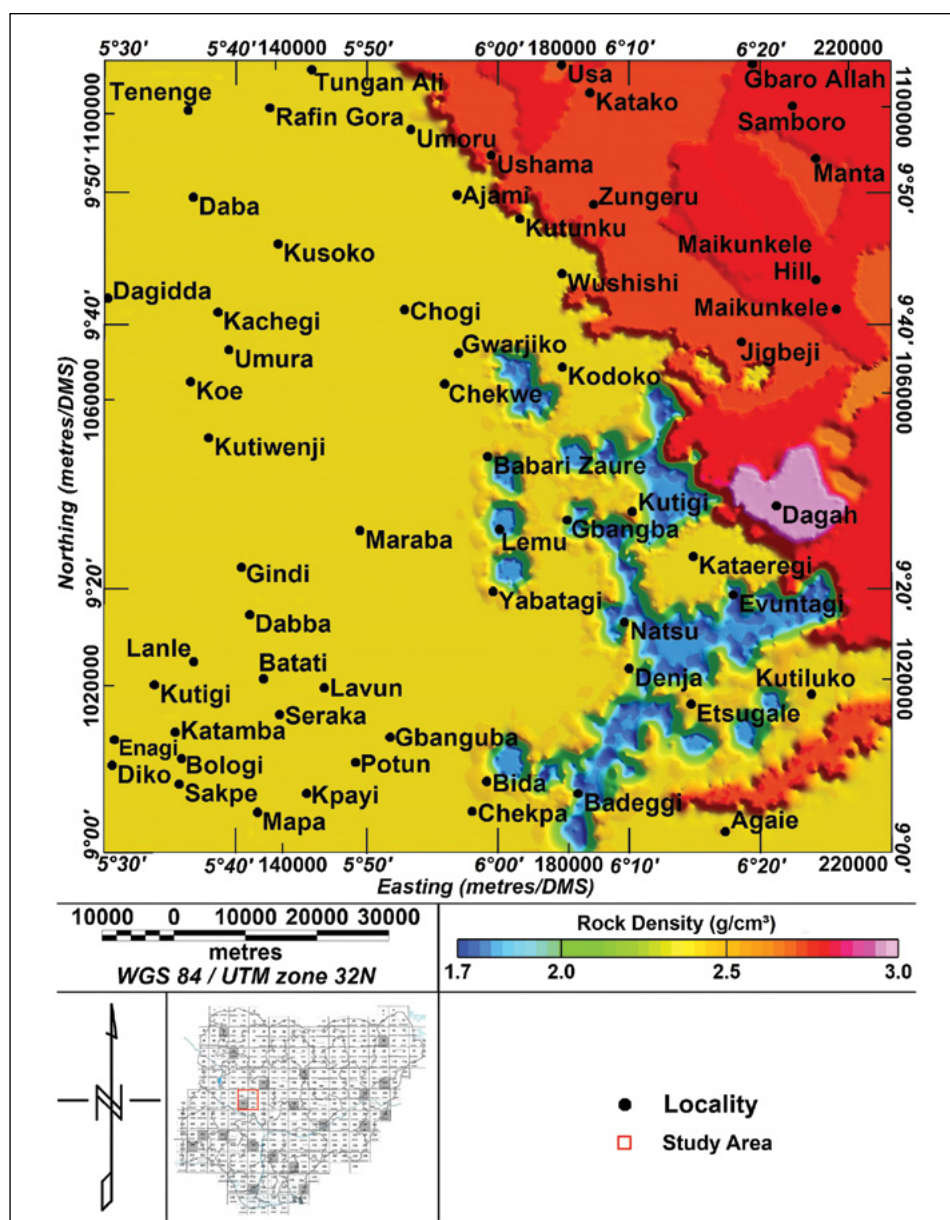


FIGURE 3 Average rocks' density for each unit of rock across the study area

Source: modified from Telford et al. (1990)

the radiogenic heat production of the study area according to Telford et al. (1990).

RESULTS AND DISCUSSION

Natural Radioelement Concentration Mapping

The result of the analysis of the aero-radiometric data, to obtain the concentration of uranium (eU), thorium (eTh), potassium (%), total counts and ternary image are displayed as maps. Values of each radioelement were presented in ranges with their standard error of the mean.

Potassium (K)

Potash feldspars which are mostly found in felsic igneous rocks like granite and are scarce in mafic rocks like basalts and andesite, are the primary source of potassium radiation (Gunn *et al.*, 1997). A few potassium anomalies ranging from 0.08 ± 0.02 to $2.03 \pm 0.87\%$ were observed on the potassium (^{40}K) anomaly map given in Figure 4. Medium and low concentrations of K were observed in areas with abundance of sandstone and siltstone as presented in Figure 2. These areas include Kusoko, Kutiwenji, Koe, Kachege, Tenenge, Rafin Gora, Lanle, Kutigi, Batati,

Sereka, Katamba, Bologi, Sakpe, Mapa, Bida, Yabatagi, and their environs. This confirms the description of Osae *et al.* (2006) concerning the sandstone and shale in Nupe basin as having relatively low concentration of K, since water bodies hide the potassium radiation from the basement rocks (Sawuta *et al.*, 2025).

The regions around Tungan Ali, Umoru, Usa, Katako, Ushama, Manta, Ajami, Zungeru, Kutunku, Mapa, Gwarjiko, Chekwe, Maraba, Lanle, Kutigi, Katamba, Bologi, Sakpe, and the surrounding area are characterised by high concentration of potassium with values ranging from 0.96 ± 0.21 to $2.03 \pm 0.87\%$. These regions co-

incide with the areas composed of migmatite, magmatic gneiss, amphibolite schist, slate, fine grained granite, medium to coarse grained granite, biotite hornblende gneiss, and undifferentiated older granite, as shown in Figure 2. According to Jones (1990) and Osae *et al.* (2006), migmatite is alkaline and contains a high concentration of potassium. Additionally, there is a high concentration of potassium in the central part of the area, corresponding to the alluvium (mud, sand, and gravel) region. This is consistent with Osae *et al.* (2006) description of the Bida Basin, which states that alluvium deposits emit more gamma rays than other sedimentary rocks in the area.

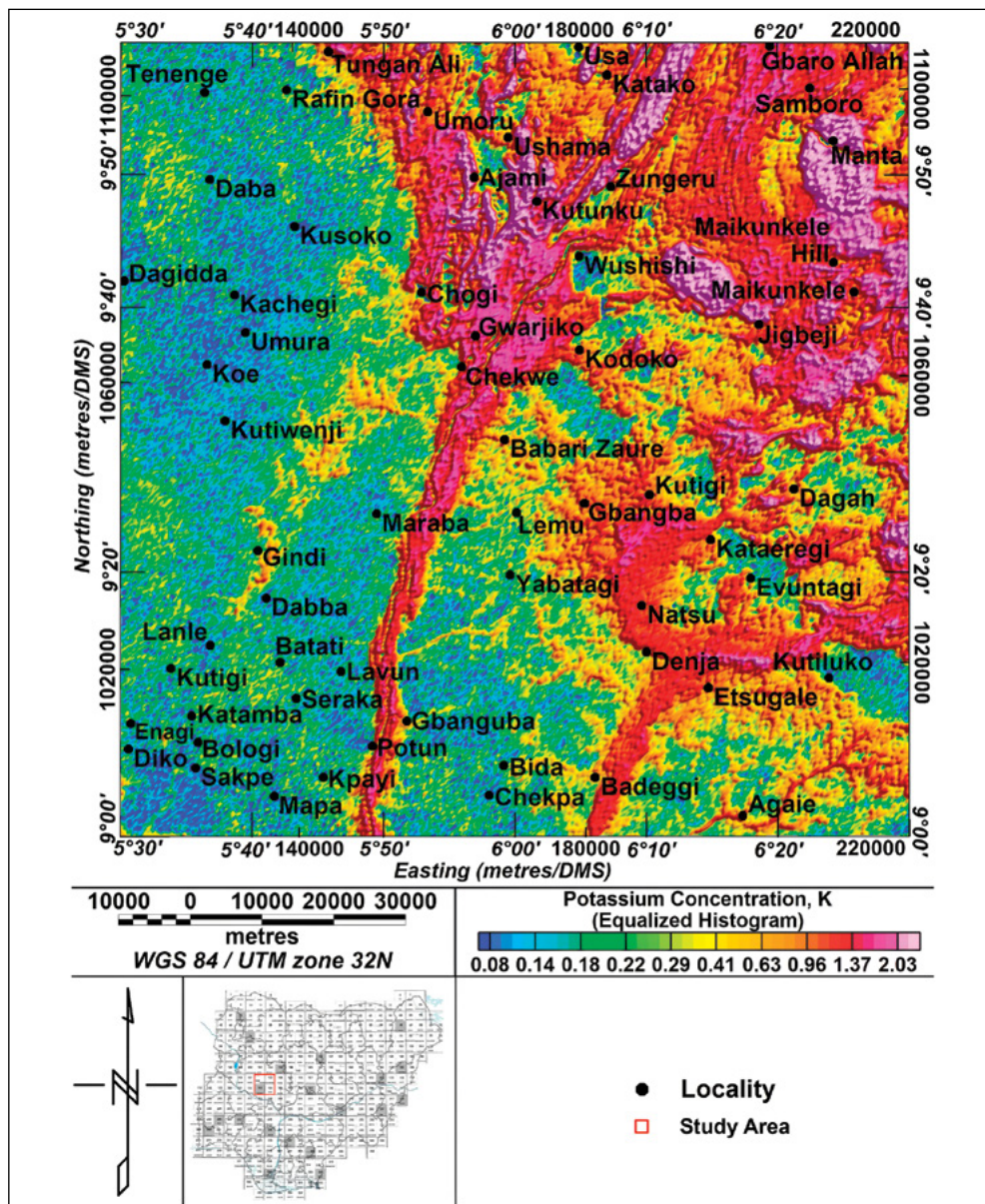


FIGURE 4 Potassium concentration across the lithological units of the study area

Source: Authors' analysis of aero-radiometric data obtained from the Nigerian Geological Survey Agency (NGSA) generated using Oasis montaj software.

Thorium (Th)

The Thorium (Th) concentration map is presented in Figure 5 with value of equivalent thorium (eTh) ranging from 4.0 ± 1.5 to 21.0 ± 5.3 ppm. Low to medium concentration of thorium was observed mostly in the north-eastern, western and eastern part of the study area, around Gbaro Allah, Samboro, Jigbeji, Daba, Tenenge, Kusoko, Kachegei, Umura, Koe, Dagah, Evuntagi, Kutiluko, Maikunkele, Wushishi, Zungeru, Kutiwenji and their environs. These areas coincide with the areas with amphibolite schist, slate, fine grained

granite, medium to coarse grained granite, biotite hornblende gneiss. High concentration of thorium with values ranging between 14.0 ± 4.0 ppm and 21.0 ± 5.3 ppm is depicted with red and pink and dominated in the northern, north-central, south-western and southern part of the study area. Those areas include Tungan Ali, Rafin Gora, Umoru, Ajami, Kutunku, Chogi, Bida, Kpayi, Mapa, Gwarjiko, Chekwe, Maraba, Lanle, Kutigi, Katamba, Bologi, Sakpe and their environs. The areas with high concentration of thorium correspond to the areas with sandstone and siltstone, alluvium mud, sand and gravel, and migmatite.

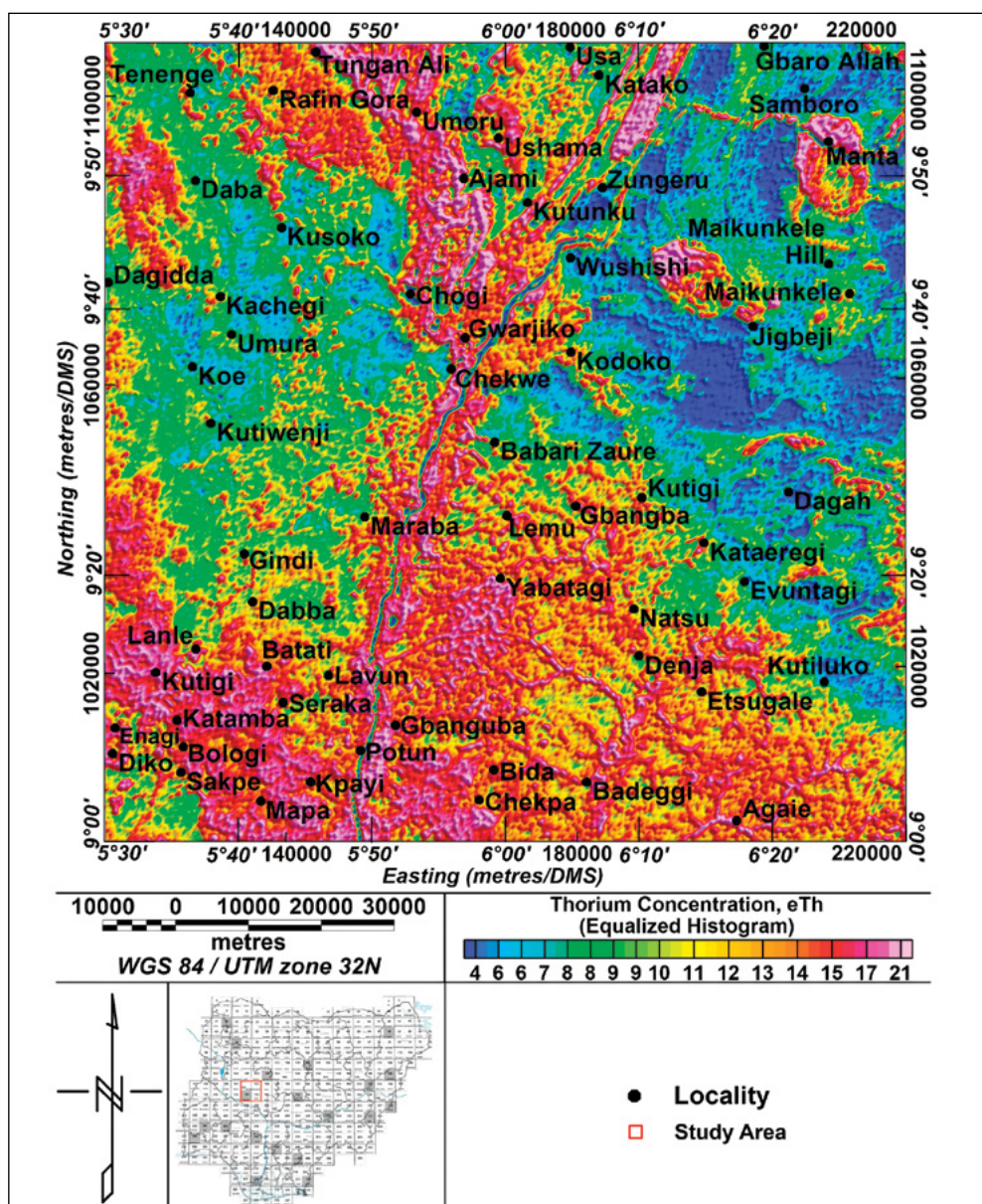


FIGURE 5 Thorium concentration across the lithological units of the study area

Source: Authors' analysis of aero-radiometric data obtained from the Nigerian Geological Survey Agency (NGSA) generated using Oasis montaj software

Uranium (U)

The uranium (^{238}U) content map presented in Figure 6 shows equivalent uranium (eU) values ranging from 0.5 ± 0.1 ppm to 5.7 ± 0.8 ppm. Low to medium concentration of uranium depicted by blue, green and yellow colour on the histogram map can be found in the north-eastern, western and eastern part of the study area. These areas include Gbaro Allah, Samboro, Jigbeji, Daba, Tenenge, Koe, Kusoko, Kachegi, Umura, Dagah, Evuntagi, Kutiluko, Wushishi, Zungeru, Kutiwenji and their environs. High concentration of uranium with value ranging

from 3.2 ± 0.3 ppm to 5.7 ± 0.8 ppm is depicted in red and pink and it is dominated in the northern, north-central, south-western and southern part of the study area. These areas include Enagi, Tungan Ali, Rafin Gora, Umoru, Ajami, Chogi, Chekpa, Gwarjiko, Chekwe, Bida, Maraba, Lanle, Kutigi, Katamba, Bologi, Sakpe and their environs. Elevated uranium concentrations correlate with geological formations rich in sandstone, siltstone, alluvial mud, sand, and gravel.

The geological feature observed to be lineament marked in the Th and K map is also noticeable in the uranium map. But unlike the K and the

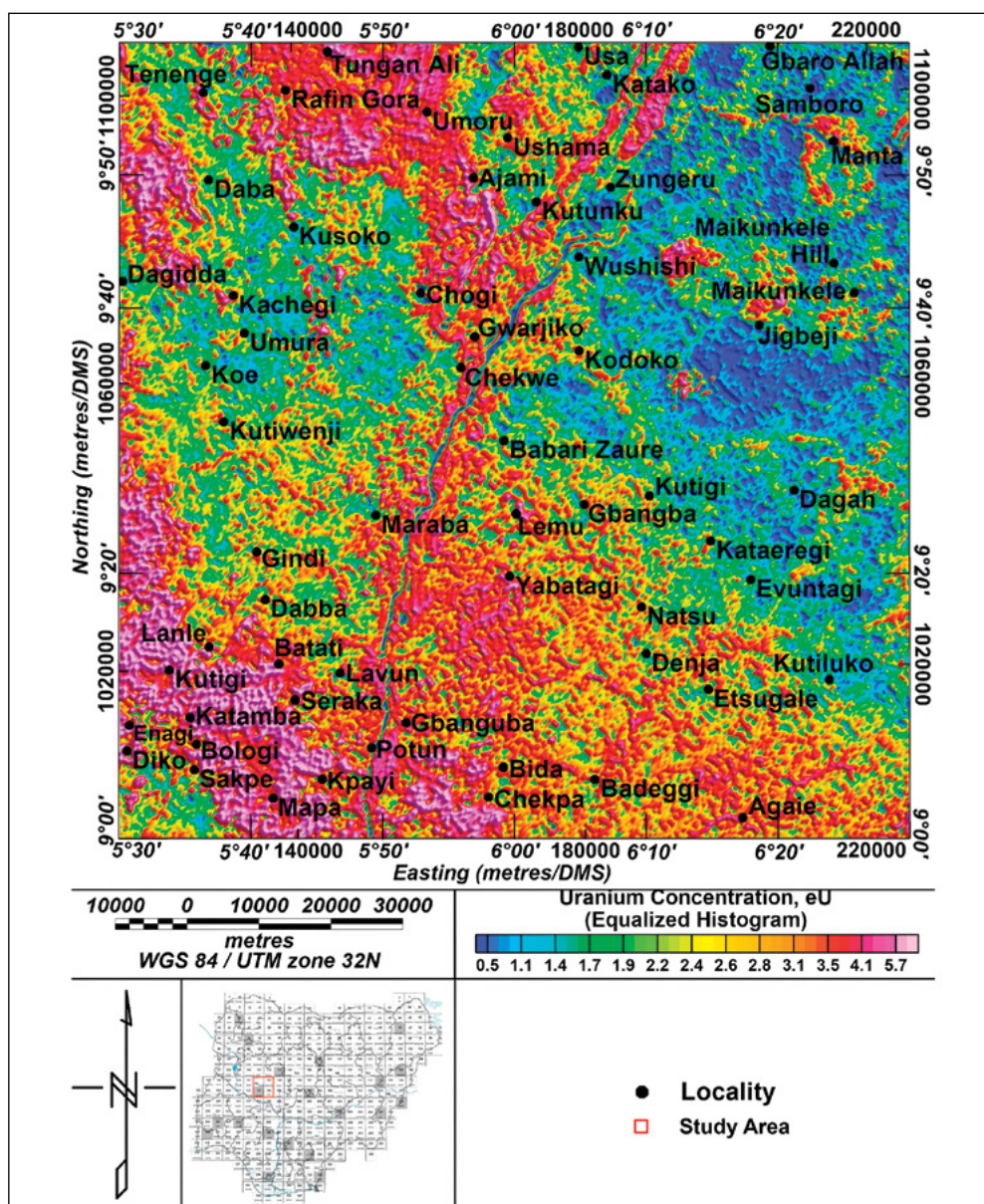


FIGURE 6 Uranium concentration across the lithological units of the study area

Source: Authors' analysis of aero-radiometric data obtained from the Nigerian Geological Survey Agency (NGSA) generated using Oasis montaj software

Th maps, the U map could not clearly delineate the distinct boundary between most lithological units in the area. The obvious boundary between the sandstone and the shale which was clearly seen in the thorium map (Figure 5) and potassium map (Figure 4) could not be observed on the uranium map (Figure 6). This is a typical feature found in uranium images despite the processing steps applied to the dataset (Minty, 1997).

Total Count

The total count map of the study area (Figure 7) illustrates the combined effects of ^{40}K , ^{238}U ,

and ^{232}Th , with measured values ranging from 651 ± 86 to 2517 ± 104 cps. The north (Tungan Ali, Rafin Gora, Umoru, Ushama, Ajami, Kutunku), north-central (Chogi, Gwarjiko, Chekwe, Zungeru, Maraba, Lemu, Yabatagi), south (Bida, Chekpa, Gbanguba, Potun, Badeggi), south-east (Natsu, Denja, Etsugale, Kutigi), and north-eastern (Manta, Maikunkele, Jigbeji) parts of the study area have high to medium concentration of the three radioactive elements. Meanwhile, there is low concentration of total count value in Kusoko, Koe, Kachegi, Wushishi, Dagah, Kutiluko areas. It was observed that the three elements are most abundant in areas dominated by sandstones

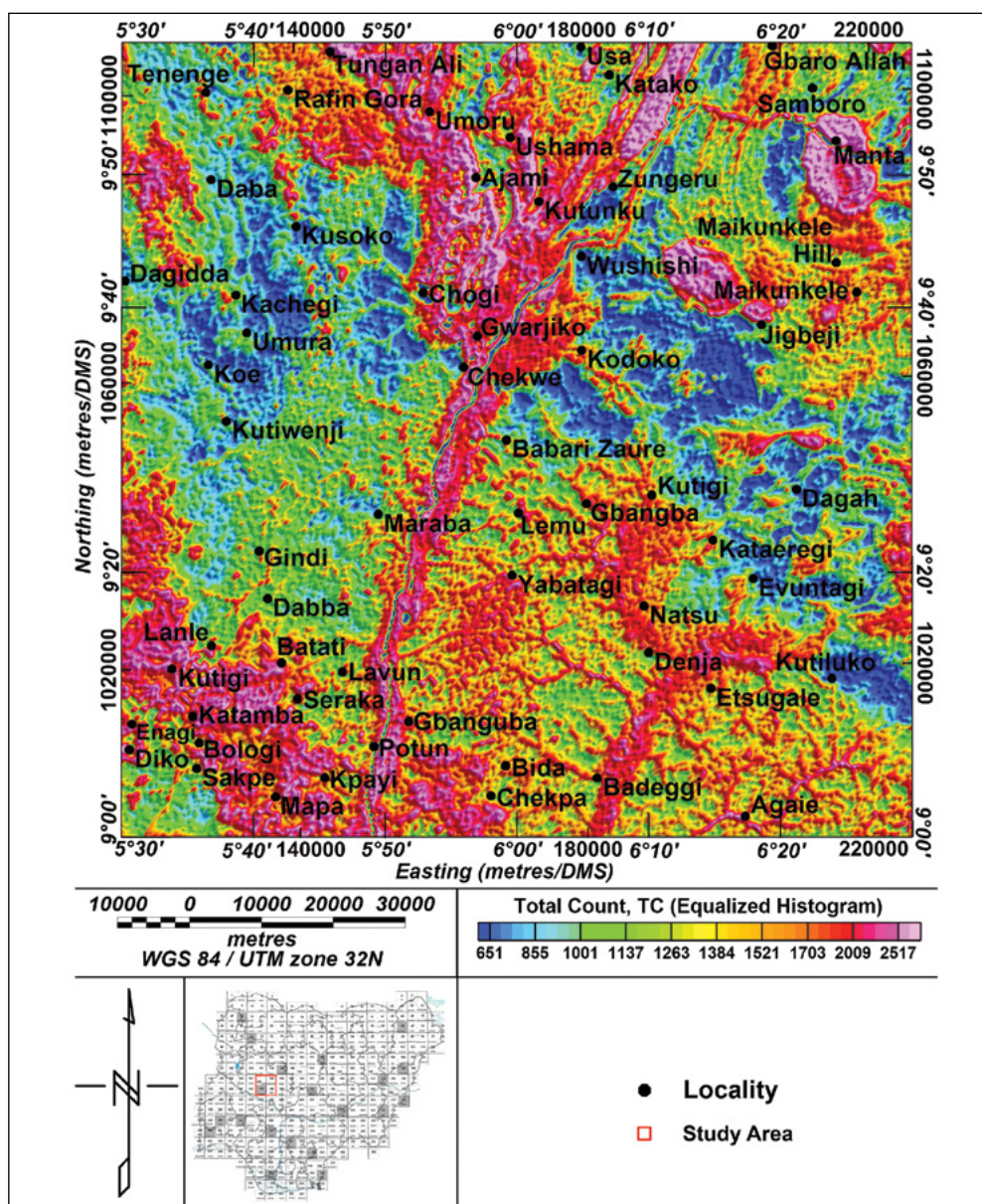


FIGURE 7 Total count (TC) of the radioelements (K, eU, and eTh) across the study area

Source: Authors' analysis of aero-radiometric data obtained from the Nigerian Geological Survey Agency (NGSA) generated using Oasis montaj software

and siltstones, alluvium (mud, sand and gravel), and metamorphic rocks such as mylonites and migmatites.

Ternary Image

Figure 8 presents the airborne radiometric data as a ternary map, in which equivalent uranium (eU), equivalent thorium (eTh), and potassium (K) concentrations are represented by blue, red, and green, respectively. The ternary map facilitates the interpretation of spatial variations in radioelement concentrations and their relationship with the underlying geology.

Elevated potassium concentrations are predominantly observed in the northern, northeastern, and eastern parts of the study area. The lithology of these regions includes fine-grained granite, biotite hornblende gneiss, medium-to-coarse-grained biotite granite, older granite that includes gneisses and migmatite, and amphibolite. Additionally, regions on the ternary plot that are coloured magenta indicate areas with concentrations of uranium and thorium. These areas are characterised by alluvium (mud, sand, and gravel), sandstone, and siltstone, and are in the north-western, western, south-western, and southern sections of the study area.

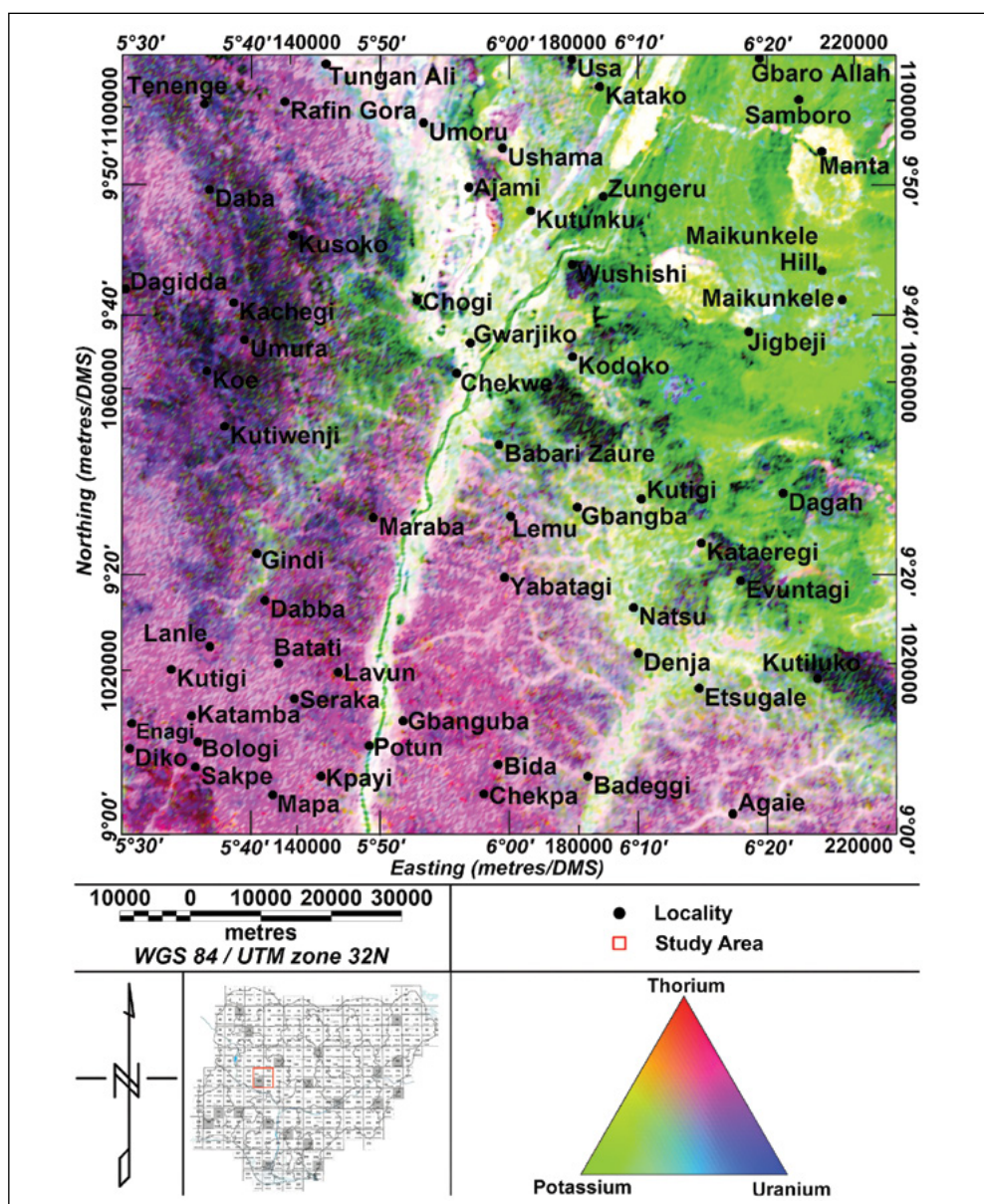


FIGURE 8 Ternary image of the study area

Source: Authors' analysis of aero-radiometric data obtained from the Nigerian Geological Survey Agency (NGSA) generated using Oasis montaj software

K/eTh ratio map

Ratio maps are a way to enhance geological features in the aero-radiometric datasets and compare the surface distribution of radioactive elements in a study area visually. Due to its significance in examining signals linked to hydrothermal alteration zones, the K/eTh ratio map is crucial to this investigation. Geothermal alteration is indicated by zones with high K/eTh ratio values, whereas low K/eTh ratio zones are indicative of low geothermal activity. The areas with a strong indicator of hydrothermal process, depicted with red and pink in Figure 9 exhibit K/eTh ratios ranging from 0.0067 ± 0.001 to 0.2311 ± 0.07 %/ppm, demonstrating that potassium is more mobile than thorium. They are mostly located in the north-eastern region of the study area. These areas are associated with grained biotite granite, amphibolite, amphibolite schist, migmatite, un-

differentiated older granite, mylonites, slate, and hornblende gneiss. The map shows that most of these alteration zones are trending from northeast to southwest (NE-SW).

Radiogenic Heat Production

The calculated radiogenic heat production (RHP) values for the 61 selected locations across the different lithological units of the study area are presented in Table 3.

The quantity of heat extracted from rocks due to radioactive decay of elements like potassium (K), thorium (Th), and uranium (U) defines the study area's Radiogenic Heat Production (RHP). The estimations in Table 3 were contoured to obtain the map in Figure 10 where values are colour-coded in red, pink, yellow, green, and blue. The average calculated RHP is $1.44 \pm 0.08 \mu\text{W}/\text{m}^3$, with values ranging from 0.62 ± 0.01 to $3.12 \pm 1.02 \mu\text{W}/\text{m}^3$. Low and intermediate RHP val-

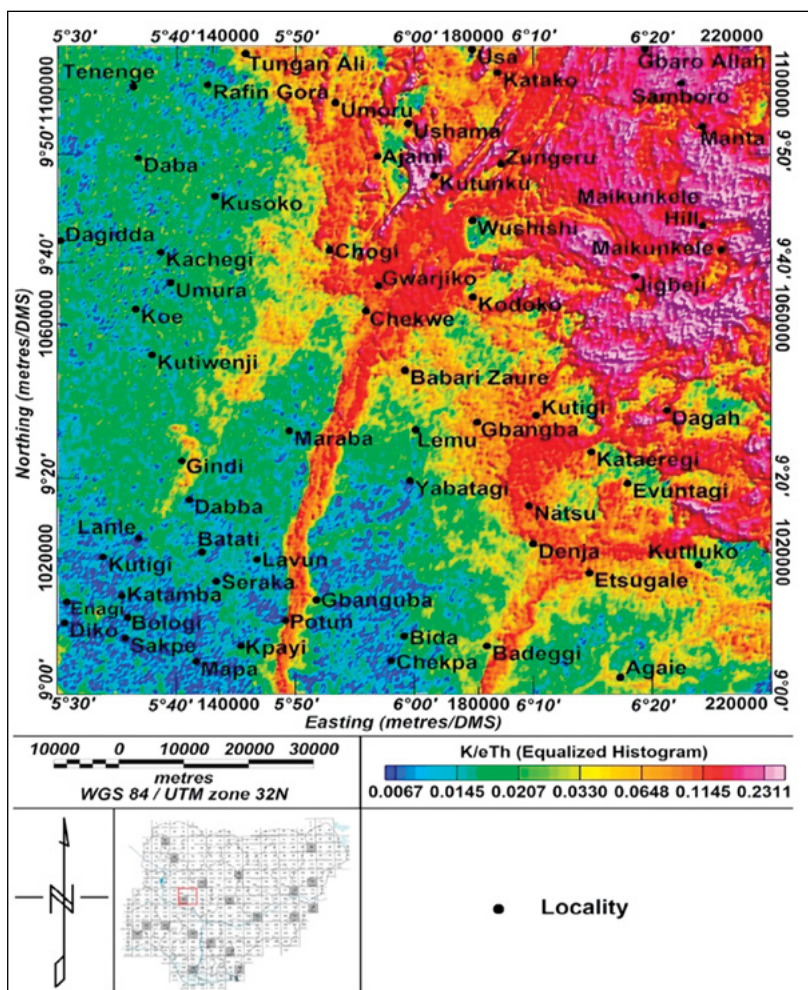


FIGURE 9 *K/eTh ratio map of the study area*

Source: Authors' analysis of aero-radiometric data obtained from the Nigerian Geological Survey Agency (NGSA) generated using Oasis montaj software

TABLE 3 *Radiogenic heat production values computed across various geological units of the study area*

S/N	Location	Lithology	RHP ($\mu\text{W}/\text{m}^3$)
1	Tungan Ali	Sandstone and Siltstone (SS)	3.08 ± 0.64
2	Tenenge	Sandstone and Siltstone (SS)	0.78 ± 0.01
3	Rafin Gora	Sandstone and Siltstone (SS)	1.91 ± 0.01
4	Umoru	Sandstone and Siltstone (SS)	1.87 ± 0.04
5	Daba	Sandstone and Siltstone (SS)	1.02 ± 0.02
6	Ajami	Sandstone and Siltstone (SS)	1.74 ± 0.06
7	Kusoko	Sandstone and Siltstone (SS)	0.79 ± 0.06
8	Kutunku	Sandstone and Siltstone (SS)	1.57 ± 0.02
9	Dagidda	Sandstone and Siltstone (SS)	0.90 ± 0.01
10	Kachehi	Sandstone and Siltstone (SS)	1.19 ± 0.05
11	Chogi	Sandstone and Siltstone (SS)	0.96 ± 0.02
12	Wushishi	Sandstone and Siltstone (SS)	0.75 ± 0.01
13	Kodoko	Sandstone and Siltstone (SS)	1.78 ± 0.02
14	Gwarjiko	Sandstone and Siltstone (SS)	1.74 ± 0.04
15	Umura	Sandstone and Siltstone (SS)	0.78 ± 0.03
16	Koe	Sandstone and Siltstone (SS)	0.83 ± 0.01
17	Chekwe	Sandstone and Siltstone (SS)	0.73 ± 0.01
18	Kutiwenji	Sandstone and Siltstone (SS)	1.64 ± 0.06
19	Babari Zaure	Sandstone and Siltstone (SS)	1.32 ± 0.05
20	Maraba	Sandstone and Siltstone (SS)	1.79 ± 0.07
21	Lemu	Alluvium – mud, sand, and gravel (AL)	1.35 ± 0.01
22	Gbangba	Sandstone and Siltstone (SS)	1.51 ± 0.04
23	Kutigi	Sandstone and Siltstone (SS)	1.79 ± 0.06
24	Kataeregi	Sandstone and Siltstone (SS)	1.31 ± 0.07
25	Gindi	Sandstone and Siltstone (SS)	1.05 ± 0.02
26	Dabba	Sandstone and Siltstone (SS)	1.17 ± 0.03
27	Yabatagi	Sandstone and Siltstone (SS)	1.95 ± 0.09
28	Evuntagi	Alluvium – mud, sand, and gravel (AL)	1.35 ± 0.01
29	Natsu	Alluvium – mud, sand, and gravel (AL)	1.12 ± 0.09
30	Denja	Sandstone and Siltstone (SS)	1.18 ± 0.06
31	Kutiluko	Sandstone and Siltstone (SS)	0.81 ± 0.02
32	Etsugale	Sandstone and Siltstone (SS)	1.22 ± 0.07
33	Agaie	Sandstone and Siltstone (SS)	2.64 ± 0.09
34	Badeggi	Alluvium – mud, sand, and gravel (AL)	1.65 ± 0.06
35	Bida	Sandstone and Siltstone (SS)	1.59 ± 0.05
36	Chekpa	Sandstone and Siltstone (SS)	1.48 ± 0.01
37	Lanle	Sandstone and Siltstone (SS)	1.52 ± 0.05
38	Kutigi	Sandstone and Siltstone (SS)	3.12 ± 1.02
39	Batati	Sandstone and Siltstone (SS)	2.19 ± 0.06
40	Lavum	Sandstone and Siltstone (SS)	1.29 ± 0.03
41	Sereka	Sandstone and Siltstone (SS)	1.31 ± 0.08
42	Katamba	Sandstone and Siltstone (SS)	1.90 ± 0.05
43	Enagi	Sandstone and Siltstone (SS)	1.56 ± 0.04
44	Diko	Sandstone and Siltstone (SS)	2.36 ± 0.06
45	Bologi	Sandstone and Siltstone (SS)	1.55 ± 0.01

S/N	Location	Lithology	RHP ($\mu\text{W}/\text{m}^3$)
46	Sakpe	Sandstone and Siltstone (SS)	1.28 ± 0.02
47	Mapa	Sandstone and Siltstone (SS)	1.87 ± 0.05
48	Kpayi	Sandstone and Siltstone (SS)	2.16 ± 0.02
49	Potun	Sandstone and Siltstone (SS)	1.43 ± 0.09
50	Gbanguba	Sandstone and Siltstone (SS)	1.46 ± 0.06
51	Usa	Undifferentiated older granite, including gneisses and migmatites (OGu)	1.17 ± 0.02
52	Gbaro Allah	Undifferentiated older granite, including gneisses and migmatites (OGu)	1.31 ± 0.04
53	Ushama	Migmatite (M)	1.60 ± 0.09
54	Samboro	Undifferentiated older granite, including gneisses and migmatites (OGu)	0.67 ± 0.02
55	Katako	Mylonites (My)	1.01 ± 0.03
56	Manta	Medium to coarse grain biotite Granite (OGM)	3.06 ± 1.06
57	Zungeru	Mylonites (My)	0.88 ± 0.06
58	Maikunkele Hill	Biotite and biotite hornblende granodiorite (OGg)	0.76 ± 0.03
59	Maikunkele	Biotite and biotite hornblende granodiorite (OGg)	1.40 ± 0.06
60	Jigbeji	Mylonites (My)	0.62 ± 0.01
61	Dagah	Amphibolite, amphibolite schist (Sa)	0.77 ± 0.02
Mean			1.44 ± 0.08

The $\pm$ values for individual locations represent the uncertainty in the gridding and interpolation procedure while the $\pm$ on the mean signifies the standard error of mean for the RHP

Source: Authors' analysis of Radiogenic Heat Production (RHP) using the obtained Radioelement concentrations

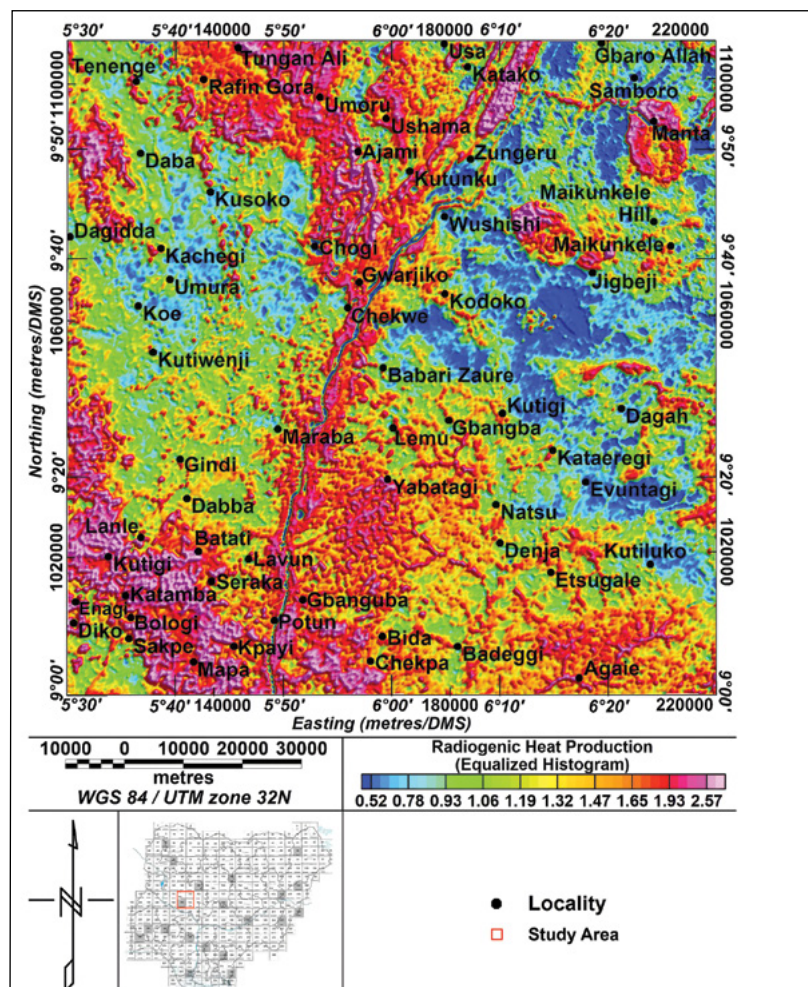


FIGURE 10 Radiogenic heat production map (RHP) of the study area

Source: Authors' analysis of the RHP results using Oasis montaj software

ues are represented in blue, green and yellow, and ranging from 0.62 ± 0.01 to $1.64 \pm 0.06 \mu\text{W}/\text{m}^3$. These are predominantly observed in the north-eastern, eastern, and western parts of the study area, which are geologically characterised by mylonites, migmatite, biotite hornblende gneiss, silicified sheared rock, migmatitic gneiss, slate, and amphibolite schist.

High levels of radiogenic heat production, with values ranging from 1.65 ± 0.06 to $3.12 \pm 1.02 \mu\text{W}/\text{m}^3$, were displayed in red and pink. They are found to be most prevalent in the north, north-central, south, south-east, and some parts of the south-west. As revealed by the RHP map overlaid on the geological map in Figure 11, high RHP occurs around Kutigi and Manta, where the lithology is characterised by medium- to coarse-grained biotite granite. These regions coincide with areas of elevated concentrations of potassium, uranium, and thorium identified on the total count map.

The RHP values for the sedimentary portions of the study area, which ranged from 0.62 ± 0.01 to $3.12 \pm 1.02 \mu\text{W}/\text{m}^3$ were found to be greater than the range of 1.11 to $2.11 \mu\text{W}/\text{m}^3$ as recorded by Yusuf *et al.* (2023). Likewise, the average value of $1.44 \pm 0.08 \mu\text{W}/\text{m}^3$ obtained in this study was found to be lower than the sedimentary average of $1.48 \mu\text{W}/\text{m}^3$, $1.67 \mu\text{W}/\text{m}^3$, and $1.58 \mu\text{W}/\text{m}^3$ reported by Obaje (2009), Zhang *et al.* (2020), and Yusuf *et al.* (2023) respectively. It was also observed to be relatively higher than $0.44 \mu\text{W}/\text{m}^3$ and $0.90 \mu\text{W}/\text{m}^3$ as reported by Abbady (2010) and Bute (2013) respectively. The lowest RHP value of $0.62 \pm 0.01 \mu\text{W}/\text{m}^3$ was recorded at Jigbeji, where the lithology is represented by mylonite, while the highest RHP value of $3.12 \pm 1.02 \mu\text{W}/\text{m}^3$ was identified in the sandstone and siltstone outcrops surrounding Kutigi.

In the igneous and metamorphic rock-dominated sections of the study area, RHP value ranged

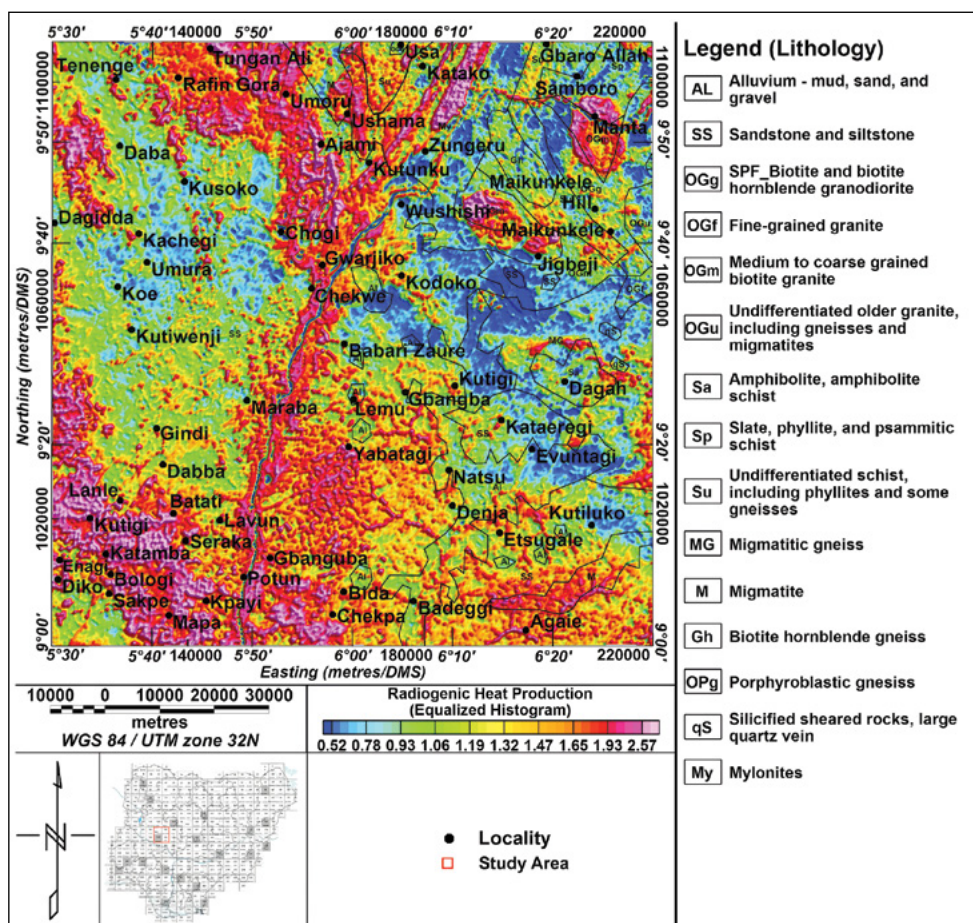


FIGURE 11 Radiogenic heat production across the lithological units of the study area

Source: Authors' analysis of RHP results overlaid on the lithological map of the Nigerian Geological Survey Agency (NGSA, 2006), generated using Oasis montaj software

from 0.62 ± 0.01 to $1.19 \pm 0.05 \mu\text{W}/\text{m}^3$. However, the medium-to coarse-grained biotite granite in the eastern part of Wushishi and around Manta exhibits higher values of about $3.06 \pm 1.06 \mu\text{W}/\text{m}^3$. This exceeds the ranges of $0.40 \mu\text{W}/\text{m}^3$ to $2.34 \mu\text{W}/\text{m}^3$ for gneissic rocks and $1.10 \mu\text{W}/\text{m}^3$ to $1.50 \mu\text{W}/\text{m}^3$ for younger granites, reported by Aisabokhae and Adeoye (2020); while remaining relatively close to $3.20 \pm 1.07 \mu\text{W}/\text{m}^3$ obtained by Zhang *et al.* (2020) for basal granitic rocks.

In summary, the maximum obtained RHP value of $3.12 \mu\text{W}/\text{m}^3$ falls below the minimum average threshold of $4.0 \mu\text{W}/\text{m}^3$ for geothermal lithologies as stated by Yusuf *et al.* (2023) and Huston *et al.* (2010). Therefore, the study area can be classified as having low or minimal radiogenic heat production.

CONCLUSION

This reconnaissance-level study explored the distribution of natural radioelements and their contribution to radiogenic heat generation across the study area. Given that radioactive isotopes are critical contributors to geothermal energy, elevated average crustal abundances of these elements compared to typical background levels may explain localized increases in heat flow and geothermal gradients.

The analysis revealed that potassium concentrations are predominantly higher in the northern, north-eastern, and eastern parts of the area. In contrast, elevated levels of thorium and uranium are more concentrated in the north-central, south-western, and southern regions. Estimated radiogenic heat production (RHP) ranges from 0.62 ± 0.01 to $3.12 \pm 1.02 \mu\text{W}/\text{m}^3$, with an average of $1.44 \pm 0.08 \mu\text{W}/\text{m}^3$. The highest RHP val-

ues were recorded at Kutigi, within sandstone and siltstone, and at Manta, within medium- to coarse-grained biotite granite, reaching $3.12 \pm 1.02 \mu\text{W}/\text{m}^3$ and $3.06 \pm 1.06 \mu\text{W}/\text{m}^3$, respectively.

Despite these localized elevations, the overall average RHP remains below the commonly cited minimum threshold of $4.0 \mu\text{W}/\text{m}^3$ for geothermal lithologies. As such, the preliminary geothermal reconnaissance, based solely on radiogenic heat production, appears limited. While these findings provide a preliminary framework for understanding subsurface heat generation in the area, they are exploratory in nature and should be supplemented by more detailed geophysical, geochemical, and subsurface investigations to fully evaluate the region's geothermal potential.

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Data Availability Statement: The data were obtained from the Nigerian Geological Survey Agency (NGSA) and are available upon request.

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Conflicts of Interest: The authors declare no conflict of interest.

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