Geostatistical and radiogenic heat evaluation of aeroradiometric data of parts of the Upper Benue Trough, Nigeria: implications for geothermal hotspot delineation and sustainable power generation

Johnson U. Abangwu [1]*, John A. Yakubu [1], Mirianrita N. Ugwu [1], Oliver U. Ekwueme [2], Anthonia N. Nwobodo [3], Maximus C. Ugwuanyi [4]

[1] Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria
[2] Federal University of Technology Akure, Ondo State, Nigeria
[3] Department of Industrial Physics Enugu State University of Science and Technology, Nigeria
[4] Federal University of Allied Health Sciences, Enugu State, Nigeria

* Corresponding author E.mail: johnson.abangwu@unn.edu.ng

Abstract
Aeroradiometric data covering parts of the Upper Benue Trough, Nigeria, were processed and interpreted to evaluate the geostatistical characteristics of radioelements and their associated radiogenic heat production for geothermal energy assessment. The study area, encompassing Yuli, Futuk, Kaltungo, Guyok, Shellen, Bashar, Muri, Lau, Dong, and Numan, lies between latitudes 9.0°–10.0°N and longitudes 10.0°–12.5°E, covering approximately 30,250 km². High-resolution airborne radiometric datasets were processed using Oasis Montaj 8.4 software, and Total Count (TC), Uranium (U), Thorium (Th), Potassium (K), and ternary maps were generated through minimum curvature gridding. Geostatistical analysis was applied to quantify the spatial distribution of radioelements using statistical parameters such as mean, standard deviation, mode, median, skewness, kurtosis, and threshold values. The computed threshold values are 4.286 ppm (U), 21.987 ppm (Th), 3.254% (K), and 3187.5 cpt (TC). Areas exceeding these thresholds were considered anomalous and indicative of enhanced radiogenic contributions. Radiogenic heat production was estimated from U, Th, and K concentrations, yielding values ranging from 1.234 to 2.318 μWm^{-3}, with the highest values concentrated around the Dong and Lau areas. Ternary analysis further reveals high concentrations of the three radioelements (HC3R) predominantly within Dong and Kaltungo regions, suggesting the influence of acidic igneous intrusions. The coincidence of high radiogenic heat values with geostatistically anomalous zones highlights Dong and Lau as prospective geothermal hotspots. These findings demonstrate that the integration of geostatistical analysis and radiogenic heat evaluation provides a robust framework for geothermal resource assessment and sustainable power generation planning in the Upper Benue Trough.

Keywords: Aeroradiometric data, Geostatistical analysis, Radiogenic heat production, Geothermal energy, Power generation, Upper Benue Trough

Introduction

The increasing demand for sustainable and environmentally friendly energy sources has intensified global interest in geothermal energy as a reliable alternative to fossil fuels. Geothermal energy is derived from the Earth's internal heat, which originates mainly from primordial heat retained since Earth's formation and radiogenic heat produced by the decay of naturally occurring radioelements, particularly Uranium (U), Thorium (Th), and Potassium (K). In continental crustal settings, ra-

diogenic heat production constitutes a significant component of the terrestrial heat budget, making the spatial distribution of heat-producing elements a critical factor in geothermal resource assessment. Geothermal power has been successfully utilized to supplement electricity generation, demonstrating its viability as an alternative to conventional energy sources (Othieno and Awange, 2016; Macharia et al., 2018; Omenge et al., 2022; Nnaemeka et al., 2025). Aeroradiometric surveys offer an effective means of assessing the distribution of naturally occurring radioelements, specifically uranium, thorium, and potassium on the Earth's surface (Telford et al., 1990; IAEA, 2013). These elements are key indicators of radiogenic heat production, a crucial factor in geothermal energy potential. By using airborne spectrometric instruments to collect data across large and often inaccessible areas, aeroradiometric surveys provide valuable insights into subsurface characteristics that may indicate the presence of geothermal resources (Telford et al., 1990). However, interpretation of aeroradiometric data based solely on visual inspection of radiometric maps may be subjective and insufficient for robust geothermal assessment. Geostatistical analysis provides a quantitative framework for evaluating the spatial distribution, variability, and anomaly thresholds of radioelement concentrations. Statistical parameters such as mean, standard deviation, skewness, and kurtosis help to distinguish background values from anomalous zones that may reflect specific lithological units or geological processes. Integrating geostatistical analysis with radiogenic heat evaluation enhances the reliability of anomaly delineation and reduces interpretational uncertainty. The Upper Benue Trough of Nigeria is a major NE–SW trending intracontinental rift basin formed during the Early Cretaceous opening of the South Atlantic. It is characterized by complex geological evolution involving sedimentation, magmatism, and tectonic deformation. Several studies have demonstrated that parts of the Benue Trough are enriched in heat-producing elements and exhibit elevated geothermal gradients and heat flow values, suggesting significant geothermal potential. Despite these findings, detailed integration of geostatistical analysis and radiogenic heat production using high-resolution aeroradiometric data remains limited for many parts of the Upper Benue Trough. This study focuses on parts of the Upper Benue Trough covering Yuli, Futuk, Kaltungo, Guyok, Shellen, Bashar, Muri, Lau, Dong, and Numan. The objective is to integrate aeroradiometric mapping, geostatistical analysis, and radiogenic heat evaluation to identify zones of enhan-

ced geothermal potential. By statistically characterizing the distribution of U, Th, K, and Total Count and relating these to radiogenic heat production, the study aims to delineate geothermal hotspot zones and provide a scientific basis for sustainable power generation planning in the region. The novelty of this work lies in the combined application of geostatistical techniques and radiogenic heat modeling to high-resolution aeroradiometric data for geothermal assessment in the Upper Benue Trough. This integrated approach not only improves anomaly detection and interpretation but also contributes to the growing body of knowledge on geothermal resource evaluation in sedimentary–basement transition zones of West Africa.

Materials and Methods

Geology and location of the research area

The Upper Benue Trough is an intercontinental Cretaceous basin which has a length of about 1000 km, stretching in a NE-SW direction (Carter et al., 1963; Obaje, 2009). The stratigraphic divisions of the upper Benue Trough are characterized by rocks consisting of igneous and metamorphic materials which make up the Precambrian Basement. The Bima sandstone is the oldest sedimentary succession which is overlain by the Yolde formation (sandstone, shale and siltstone) which mark the transition from continental to marine sedimentation (Carter et al., 1963; Obaje, 2009). The research area is within latitude 9.0 to 10.0 °N and longitude 10.0 to 12.5°E with landmass of 30,250 km^2. Figure 1 is the geology map of the research area.

Materials

Ten high resolution aeroradiometric data sheets number 171, 172, 173, 174, 175, 192, 193, 194, 195 and 196, corresponding to Yuli, Futuk, Kaltungo, Guyok, Shellen, Bashar, Muri, Lau, Dong, and Numan, were obtained from the Nigerian Geological Survey Agency (NGSA) respectively. The survey was conducted by Fugro Airborne Surveys at a flight elevation of 80 m, with flight lines spaced 500 m apart. The flight line and tie line directions were 135° and 225°, respectively. The software applications employed in the analysis include Oasis Montaj 8.4, Golden Surfer.

Method

The analysis of the aeroradiometric data involves the merging and gridding of the data sheets to produce the Potassium, Uranium, Thorium, Total count maps using oasis montaj program. The quantitative interpretation of the data involved the geostatistical analysis, radioge-

Figure 1. *Geology map*
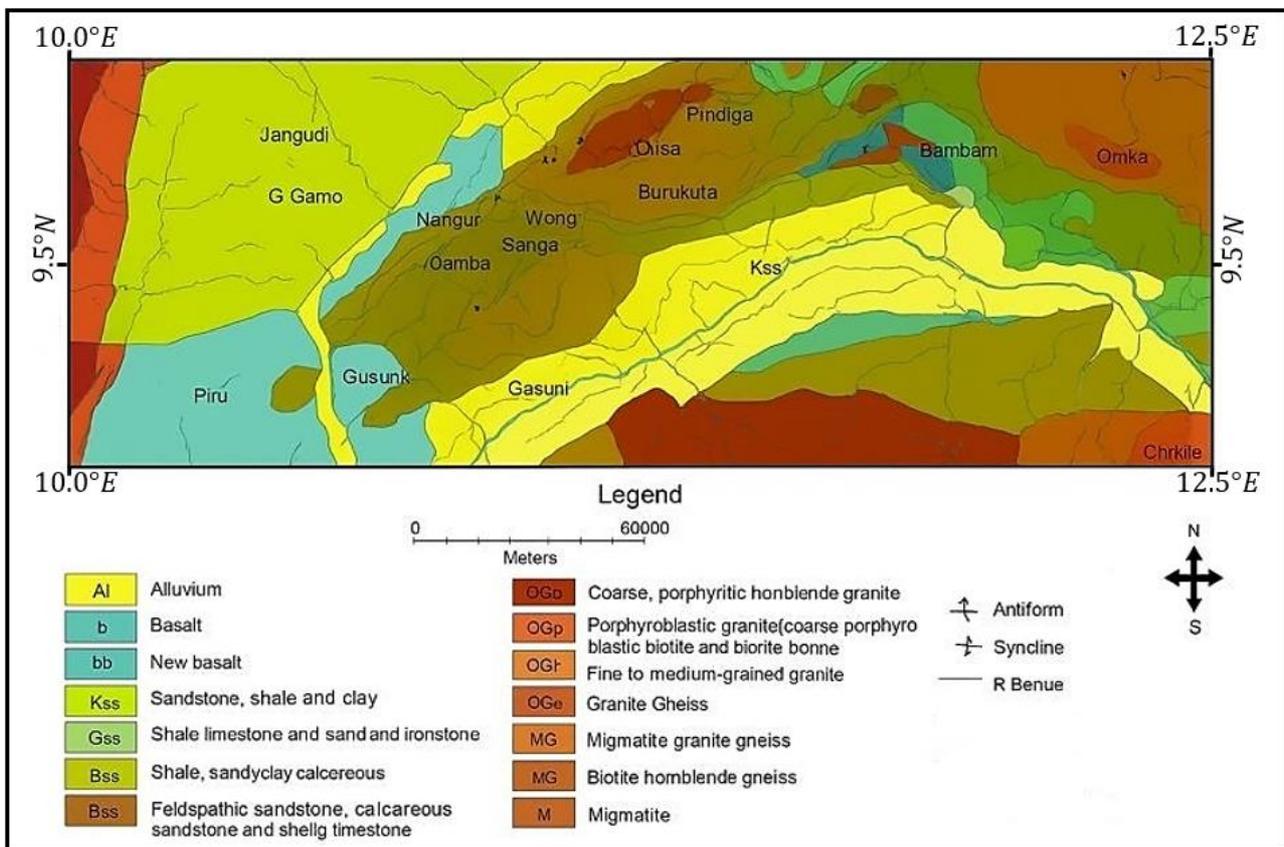
nic heat analysis and Ternary analysis.

Geostatistical analysis

The geostatistical technique employs the histogram analysis tool and kriging model to assess the statistical properties of geophysical data. Some of the geostatistical parameters are the mean, standard deviation (SD), kurtosis, mode, median. Equation [1] calculates the threshold value statistically as the sum of the mean and standard deviation; any result above the threshold is deemed anomalous (Mammoth Geophysical Inc., 2007; Yusuf, 2016; Adonu et al., 2022).

The threshold value = mean + Standard deviation [1]

Radiogenic heat production analysis

The radiogenic heat output of rocks is measured in $\mu W/m^3$ and is defined as the energy released in a unit of time from the breakdown of radionuclides present in a unit volume of rock (Sedara and Asere, 2020). Although rock contains a variety of radionuclides, the most intense heat in the crust is only produced by radioactive decay of the unstable isotopes of U, Th, and K (Ehinola et al., 2005; Bubu and Ononugbo, 2017). Equation [2] represents the radiogenic heat (H)

(Rybach, 1988; Holmberg et al., 2012; Eluwa et al., 2021).

$$H(\mu W/m3) = \varrho(9.52C_U + 2.56C_{Th} + 3.48C_K)10^{-5} \qquad [2]$$

where ϱ is the area's rock density (kg/m³), C_U, C_{Th} and C_K are the concentrations in U, Th and K respectively.

Ternary Analysis

A single representation of each of the three radioelement concentrations is displayed in the ternary image. Zones with significant amounts of U, K, and Th activity can be found using the map (Elawadi et al., 2004). High concentrations of the three radioelements appear white, while low levels look black in a typical ternary image, which is typically shown in blue, red, and green to represent uranium, potassium, and thorium anomalies, respectively (Yusuf et al., 2014).

Results and Discussion

Total count (TC) anomaly results

Figure 2 is the total count map ranging from 650.0 to 4317.5 cpt. The map shows high concentrations of TC values mostly around Dong, Lau, Shellen, Kaltungo

Figure 2. *Total count anomaly map*
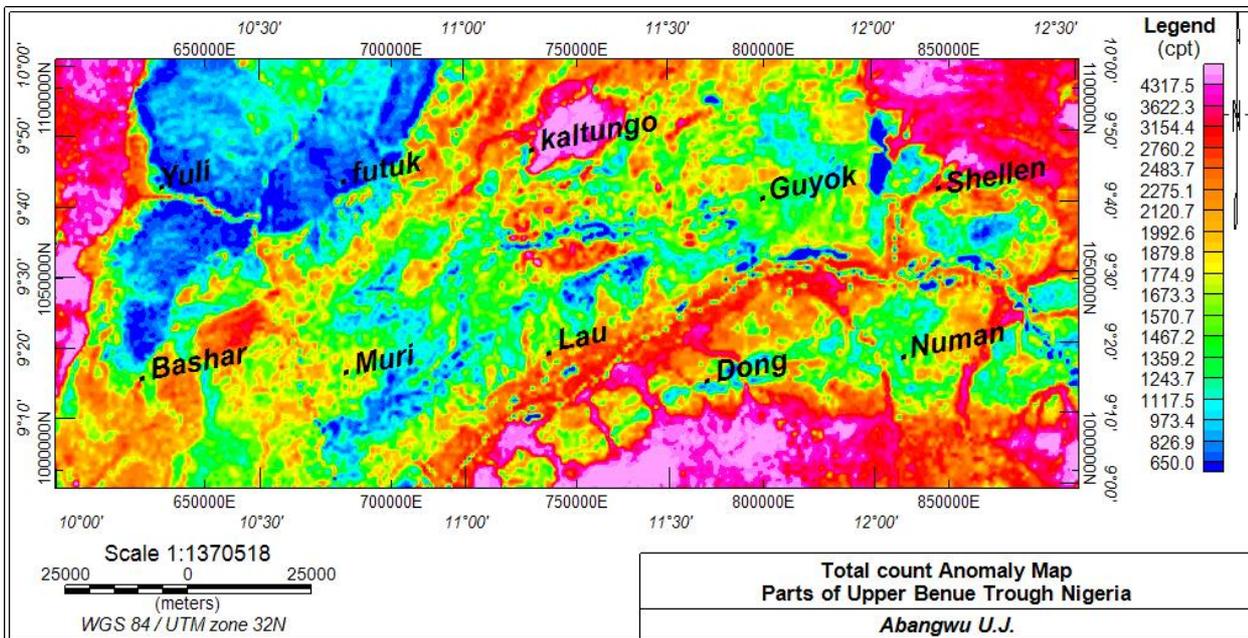
and Northwestern part of the Yuli area. There is low concentration of TC values around Futuk and Yuli area.

Uranium (U) anomaly results

Figure 3 is the map of U anomaly concentrations in the study area. Uranium abundances are in the range of 1.1 to 5.0 ppm (part per million). The discrete zones with relatively high levels (4.4 to 5.0 ppm) of uranium concentrations are distributed around Dong, Lau, Kaltungo and Northwestern part of Yuli and Bashar area. The

and Northwestern part of the Yuli area. There is low concentration of TC values around Futuk and Yuli area. map revealed high relative Uranium abundance (pink colour) in Dong, Lau, Kaltungo, Northwestern part of Yuli and Bashar area which are probably due to the presence of acidic igneous rocks such as granite while the intermediate values (2.1 - 3.3 ppm) of Uranium abundances are likely proportional to the presence of sedimentary rock such as limestone and sandstone (Galbraith and Saunders, 1983).
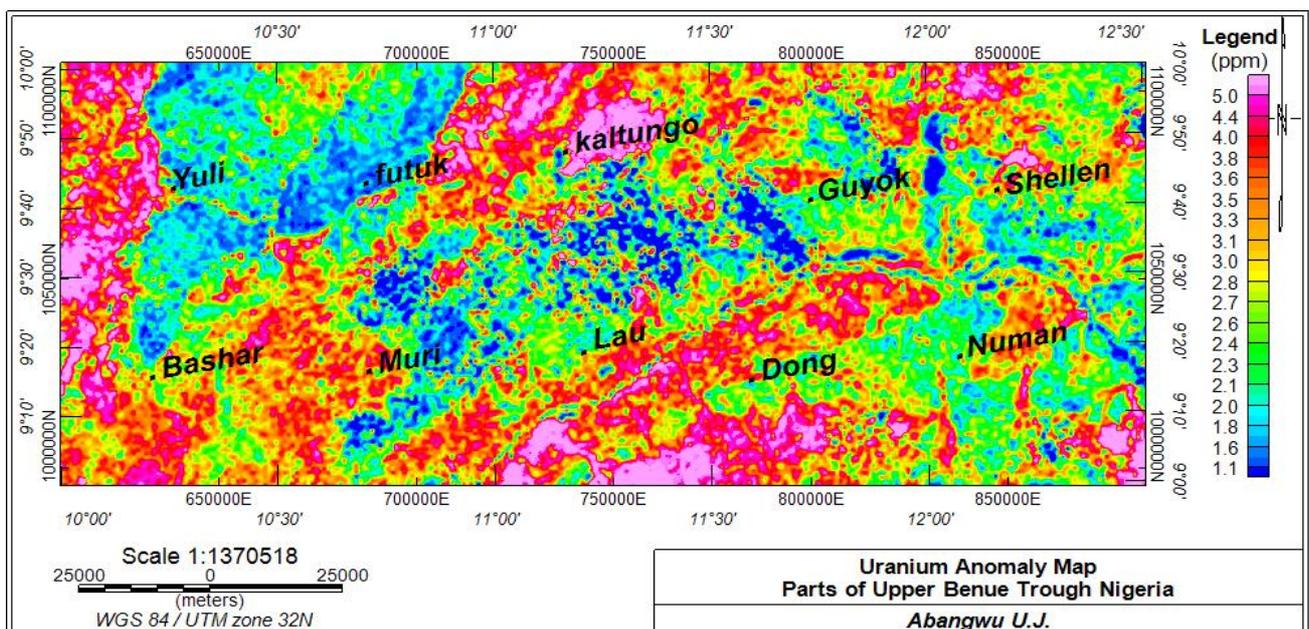

Figure 3. *Uranium anomaly map*

Thorium (Th) anomaly results

The map of Th concentration is shown in Figure 4. The map revealed wide range of anomalies in the area. The Th abundances are in the range of 4.5 to 27.9 ppm. The low thorium values of 4.5 to 6.5 ppm observed around Futuk, Yuli and Muri areas are possible attributes of sedimentary deposits such as sandstone while the intermediate thorium abundance values of 8.2 to 11.7 ppm are likely as a result of shale deposit in the

area (Galbraith and Saunders, 1983).

Potassium (K) anomaly results

Figure 5 is the map of K anomaly concentrations. The map revealed varied degrees of K concentrations, which range from -0.18 to 4.99 % representing the area's various lithological units. The intermediate values of 0.29 to 0.80 % (green colour) in the area are possibly carbonate sedimentary deposits (Galbraith and Saunders, 1983).
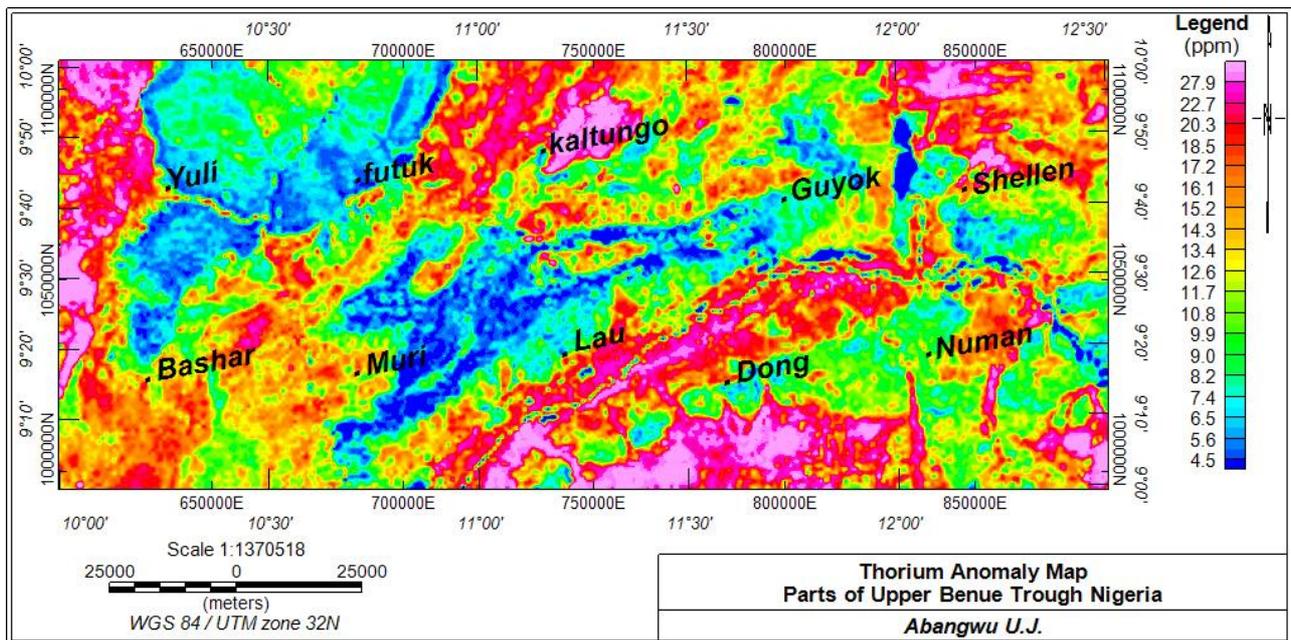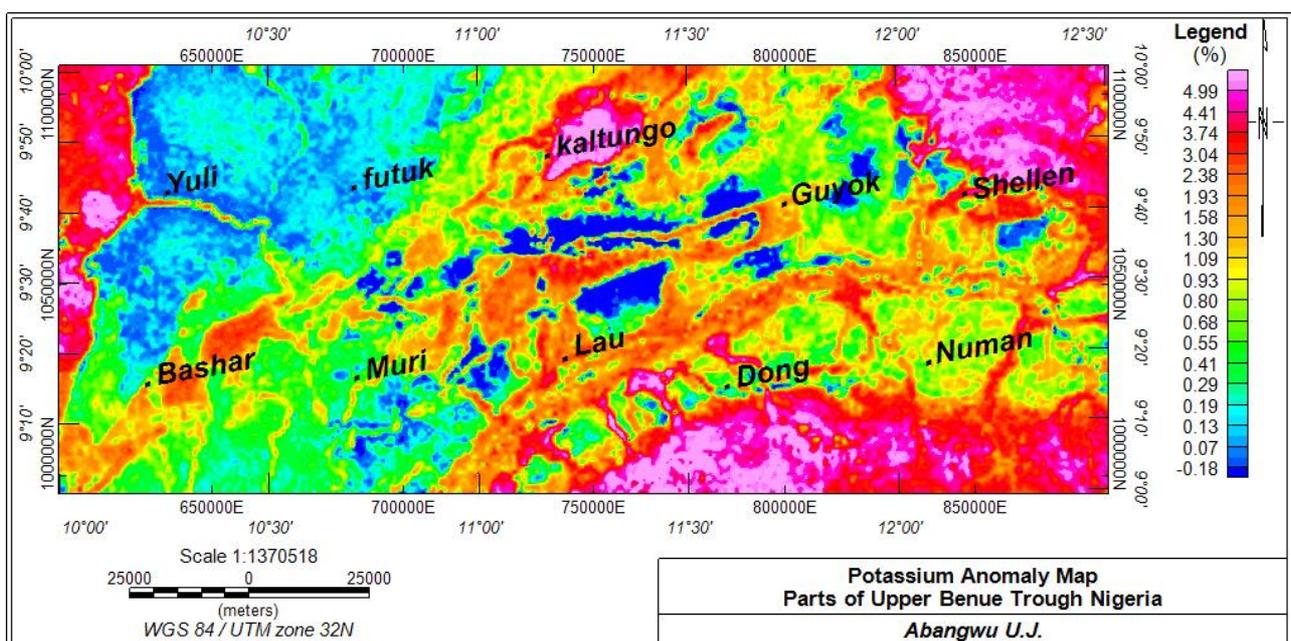

Figure 4. *Thorium anomaly map*

Figure 5. *Potassium anomaly map*

Geostatistical analysis results

Geostatistical analysis of the aeroradiometric data (Fig. 6(a-d)) reveals that the radioelement distributions are positively skewed, with mean values of 2.986 ppm (U), 13.980 ppm (Th), 1.578% (K), and 2051.462 cpt (TC). The calculated threshold values effectively discriminate background levels from anomalous concentrations. In particular, the threshold value of 3187.462 cpt for the Total Count, in agreement with Uwah (1984) and Nwobodo et al. (2020), delineates anomalous zones that are predominantly concentrated around Dong, Lau, Shellen, Kaltungo, and the northwestern part of Yuli. These anomalies are considered significant and may be associated with radioelement mineralization
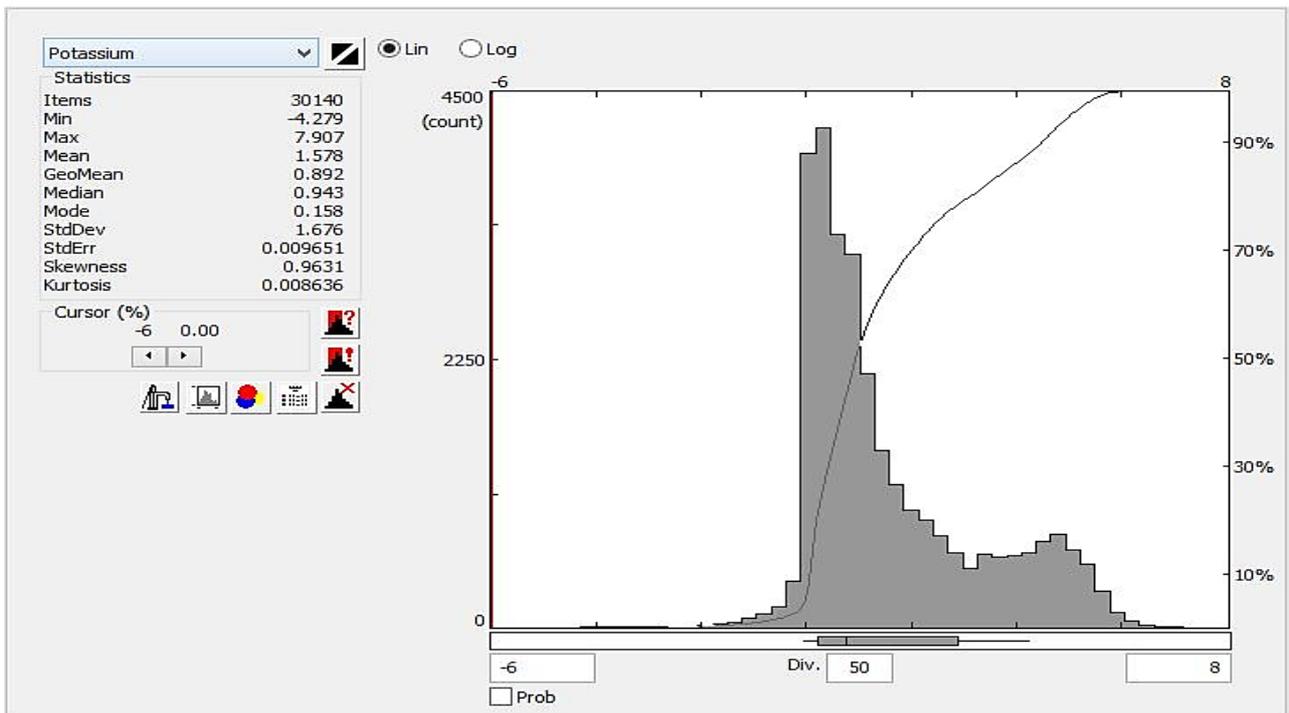

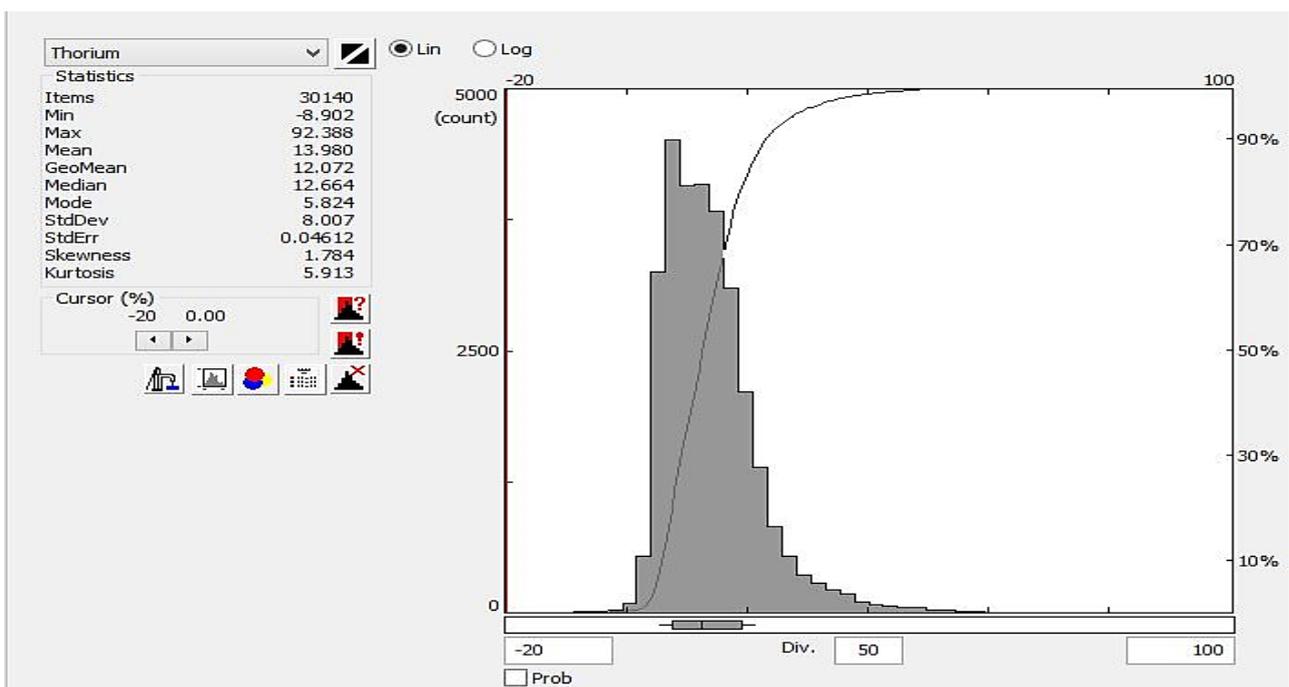**Figure 6.** (a) *Potassium geostatistical histogram plot*

Figure 6. (b) *Thorium geostatistical histogram plot*

and enhanced geothermal prospects (Levinson, 1974). Table 1 is the summary of the geostatistical analysis results. From Table 1, the threshold value of U concentrations was found to be 4.286 ppm. Those areas (pink colours) where U concentrations exceeded 4.286 ppm mostly Dong, Lau, Kaltungo, Northwestern part of Yuli and Bashar area were considered anomalous in

Figure 3. From the geostatistical analysis the threshold value of Th radiometric data was found to be 21.987 ppm (Table 1). Those areas (Dong, Lau, Kaltungo, Shellen and northwestern part of Yuli area) where Th concentration exceeded 21.987 ppm were considered anomalous in Figure 4. From Table 1, the threshold value for the K concentration was found to be 3.254 %.
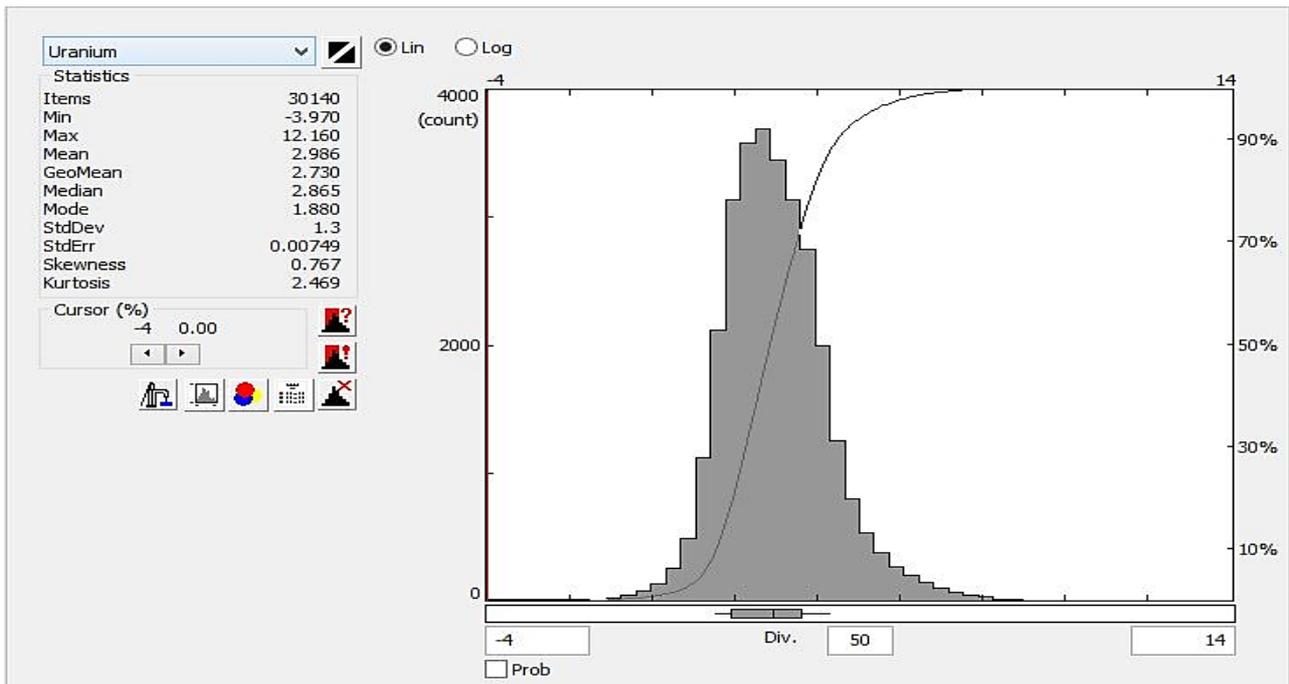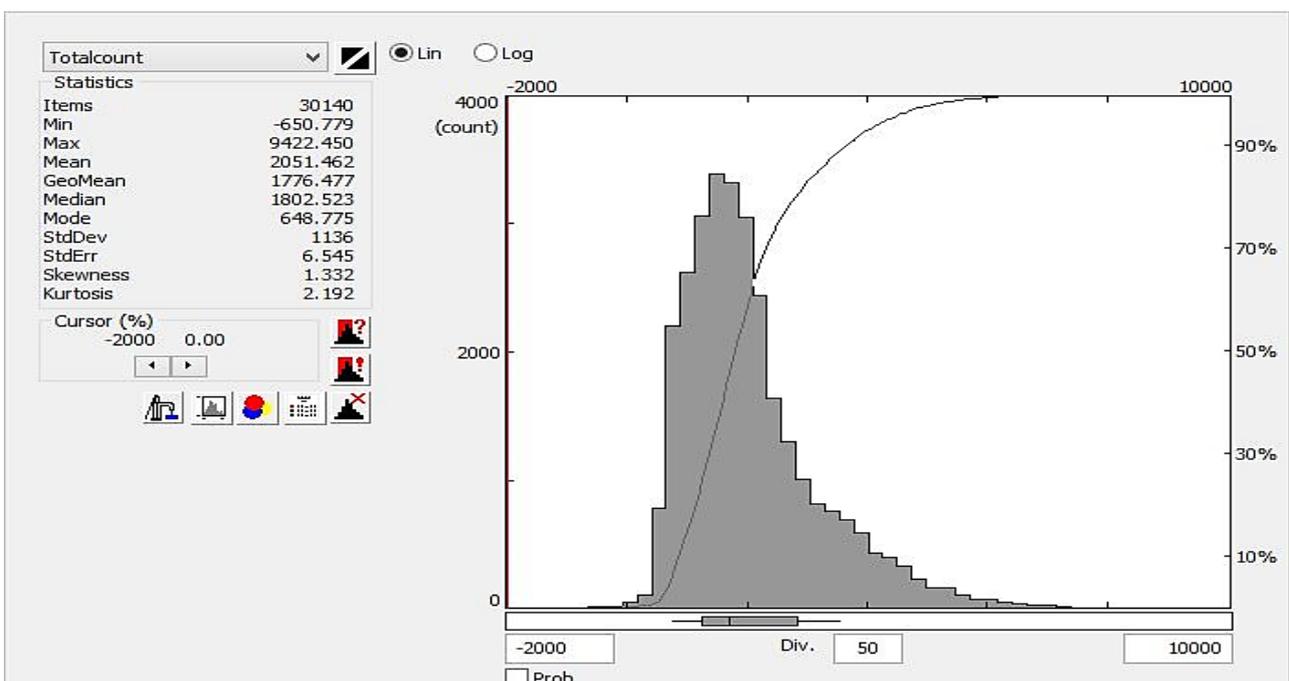

Figure 6. (c) *Uranium geostatistical histogram plot*

Figure 6. (d) *Total count geostatistical histogram plot*

S/N	Parameters	U (ppm)	Th (ppm)	K (%)	Total Count (cpt)
1	Min	-3.970	-8.902	-4.279	-650.779
2	Max	12.160	92.388	7.907	9422.450
3	Mean	2.986	13.980	1.578	2051.462
4	Mode	1.880	5.824	0.158	648.775
5	StdDev	1.300	8.007	1.676	1136.000
6	StdErr	0.007	0.046	0.010	6.545
7	Median	2.865	12.664	0.943	1802.523
8	Skewness	0.767	1.784	0.963	1.332
9	Kurtosis	2.469	5.913	0.009	2.192
10	Threshold value	4.286	21.987	3.254	3187.462

Table 1
Summary of the geostatistical analysis results

In Figure 5, those areas (especially Dong, Lau, Kaltungo, Shellen, Numan and northwestern part of Yuli area) where K % concentrations exceeded the threshold value of 3.254 % were considered anomalous.

Radiogenic heat production results

Table 2 summarizes the results of the radiogenic heat analysis. The radiogenic heat values range from 1.234 to 2.318 $\mu W m^{-3}$ with a mean value of 1.731 $\mu W m^{-3}$.

The minimum value of 1.234 $\mu W m^{-3}$ is seen at Futuk area while the maximum value of 2.318 $\mu W m^{-3}$ is at Dong area (Fig. 7). Radiogenic heat production values exceeding approximately 2.25 μW m⁻³ are regarded as anomalous and indicative of favorable geothermal conditions (Rybach, 1976; Yakubu et al., 2022; Nnaemeka et al., 2025). Consequently, the Dong area, with a maximum RHP of 2.318 μWm⁻³, is identified as a significant geothermal hotspot within the Upper Benue Trough.

Locations	Long (°)	Lat (°)	Lithology	K mean (%)	Th mean (ppm)	U mean (ppm)	Radiogenic Heat ($\mu W m^{-3}$)
Yuli	10.253	9.754	Granite	1.291	13.791	2.920	1.724
Futuk	10.756	9.754	SS, shale	0.349	10.520	2.558	1.234
Kaltungo	11.255	9.754	Granite	1.543	15.384	3.236	1.965
Guyok	11.753	9.754	SS, LS	0.842	11.408	2.654	1.326
Shellen	12.252	9.754	Shale, LS, SS	3.113	14.799	2.750	1.723
Bashar	10.253	9.255	Granite	1.043	15.079	3.334	1.886
Muri	10.756	9.255	Shale	0.634	10.901	2.795	1.435
Lau	11.255	9.255	Granite	1.947	16.045	3.422	2.091
Dong	11.753	9.255	Granite	2.754	18.162	3.331	2.318
Numan	12.252	9.255	Shale	2.237	13.774	2.809	1.605
Average				1.575	13.986	2.981	1.731

Table 2
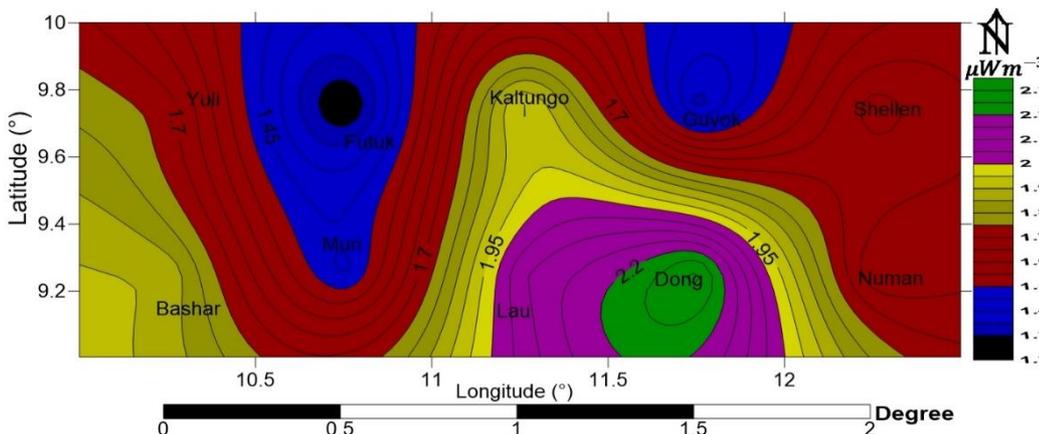*Results of radiogenic heat analysis (SS=Sandstone; LS=Limestone)*

Figure 7
Radiogenic heat map (contour 0.05)

Ternary anomaly results

The ternary map presented in Figure 8 depicts the relative abundance distributions of the three radioelements. The U, Th and K are represented in blue, green and red colour respectively. Low concentrations of the three radioelement concentrations mainly at northwestern Futuk and Northeastern Yuli area are displayed inblack colour (indicated by LC3R) which may be attributed to sedimentary deposits such as sandstone, limestone and shales, while the white colour mainly at Dong and Kaltungo area denotes high concentrations of the three radioelements (HC3R) and these areas are possibly as a result of acidic igneous intrusions (Galbraith and Saunders, 1983), which are generally enriched in heat-producing elements (Yusuf et al., 2014).

Figure 8. *Ternary anomaly map*
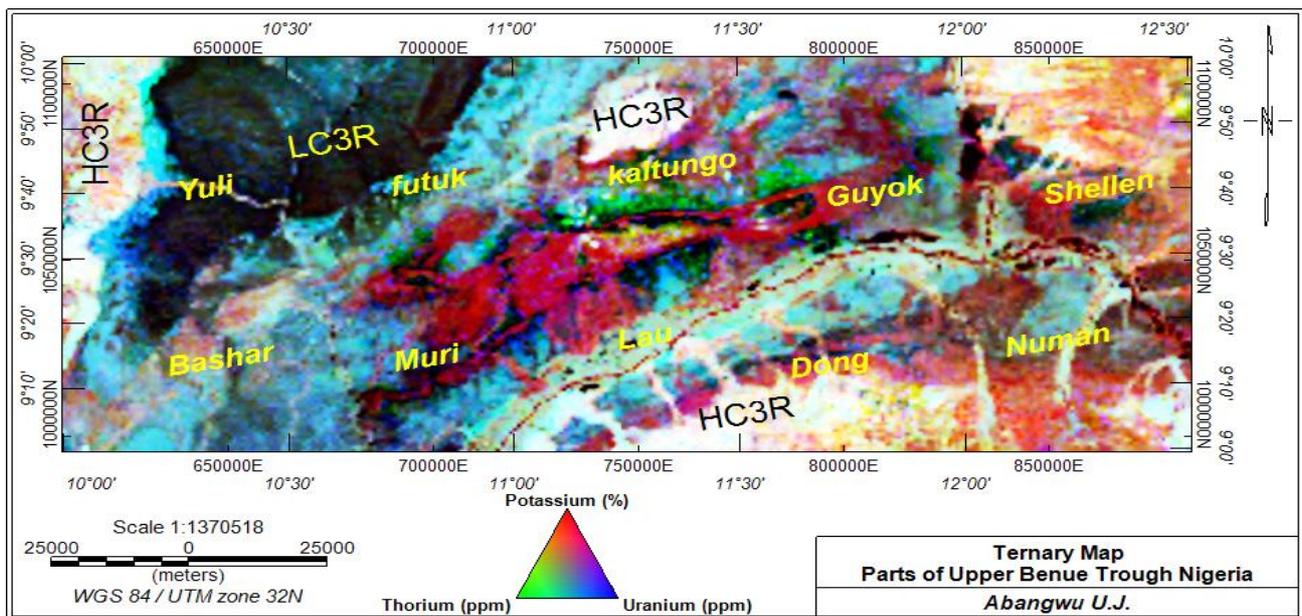
Conclusion

The integration of geostatistical analysis and radiogenic heat evaluation of aeroradiometric data has provided a comprehensive assessment of geothermal potential in parts of the Upper Benue Trough, Nigeria. Statistically significant anomalies in Uranium, Thorium, Potassium, and Total Count correspond spatially with elevated radiogenic heat production values ranging from 1.234 to 2.318 μWm^{-3}. The Dong and Lau areas exhibit the highest radiogenic heat values which spatially coincide with the Total count anomaly threshold and HC3R zones on the ternary map, suggesting strong radiogenic contributions from acidic igneous rocks. These areas are therefore identified as viable geothermal hotspots with potential for sustainable electricity generation.

Conflict of interest

The authors declare that they have no conflict of interest.

References

ADONU I.I., UGWU G.Z., ONYISHI G.E. (2022) Interpretation of airborne radiometric data of part of the Middle Benue Trough, Nigeria for mineral deposits. IOSR Journal of Applied Geology and Geophysics, 10(1):58–62. https://doi.org/10.9790/0990-1001025862

BUBU A., ONONUGBO C.P. (2017) Radiogenic heat production due to natural radionuclides in the sediments of Bonny River, Nigeria. Journal of Scientific Research & Reports, 17(6):1–9. https://doi.org/ 10.9734/JSRR/2017/39159

CARTER J.D., BARBER W., TAIT E.A., JONES G.P. (1963) The geology of parts of Adamawa, Bauchi and Borno Provinces, northeastern Nigeria. Geological Survey of Nigeria Bulletin, 30:1–109.

EHINOLA E.A., JOSHUA E.O., OPELOYE S.A., ADEMOLA J.A. (2005) Radiogenic heat production in the Cretaceous sediments of the Yola Arm, Benue Trough, Nigeria. Journal of Applied Sciences, 5(4):696–701. https://doi.org/ 10.3923/jas.2005.696.701

ELAWADI E., AMMAR A., ELSIRAFY A. (2004) Mapping surface geology using airborne gamma-ray spectrometric survey data: A case study. Proceedings of the SEGJ International Symposium. Nuclear Materials Authority of Egypt,

Airborne Exploration Department.

ELUWA N.N., OPARA A.I., OKEREKE C.N., ELUWA J.C., ONWE R.M. (2021) Estimation of radioelement concentration in Sokoto Basin using airborne radiometric data. World Journal of Advanced Research and Reviews, 12(1): 315–325. https://doi.org/10.30574/wjarr.2021.12.1.0514

GALBRAITH J.H., SAUNDERS D.F. (1983) Rock classifycation by characteristics of serial gamma-ray measurements. Journal of Geochemical Exploration, 18(1):49–73. : https://doi.org/ 10.1016/0375-6742(83)90080-8

HOLMBERG H., NAESS E., EVENSEN J.E. (2012) Thermal modeling in the Oslo Rift, Norway. Proceedings of the 37th Workshop on Geothermal Reservoir Engineering. Stanford University.

INTERNATIONAL ATOMIC ENERGY AGENCY (2013) Guidelines for radioelement mapping using gamma-ray spectrometry data (IAEA-TECDOC-1363). IAEA, Vienna.

LEVINSON A.A. (1974) Introduction to exploration geochemistry. Applied Publishing Ltd.

MACHARIA M., MUNDIA C., KURIA D., GACHARI M., NICHOLAS N. (2018) A GIS-based approach for exploring geothermal resources along part of the Kenyan Rift. Geoscience Letters, 3:1–34.

MAMMOTH GEOPHYSICAL INCORPORATED (2007) Geophysical exploration, oil and gas field, Barrackville, West Virginia (Technical Report No. 304).

NNAEMEKA E.K., EGWUONWU G.N., OBINWA O., ONYEKWELU C.C., EZENWA N.G. (2025) Assessment of geothermal resource potentials at some parts of Central Benue, Nigeria, using aeromagnetic and radiometric data. Applied Journal of Physical Science, 6(3):73–90. : https://doi.org/ 10.31248/AJPS2025.116.

NWOBODO A.N., IKERI H.I., CHIKELEZE P.C. (2020) Geological studies on uranium, thorium and potassium based on airborne radiometric geophysical data of Wukari and Donga, Middle Benue Trough, Nigeria. The International Journal of Engineering and Science, 9(1):34–41. https://doi.org/ 10.9790/1813-0906013441.

OBAJE N.G. (2009) Geology and mineral resources of Nigeria. Springer. https://doi.org/10.1007/978-3-540-92685-6.

OMENGE P.M., OBWOYERE G.O., ESHIAMWATA G.W., MAKINDI S.M. (2022) A review of the quality of environmental and social impact statements: The case of geothermal energy projects in Kenya. East African Journal of Environment and Natural Resources, 5(2):144–163. : https://doi.org/ 10.37284/eajenr.5.2.1027

OTHIENO H., AWANGE J. (2016) Energy resources in western and central Africa. In Earth resources and environmental remote sensing/GIS applications. Springer. https://doi.org/ 10.1007/978-3-319-25187-5_4

RYBACH L. (1976) Radioactive heat production in rocks and its relation to other petrophysical parameters. Pure and Applied Geophysics, 114(2):309–317. https://doi.org/ 10.1007/BF00878955

RYBACH K. (1988) Equation for radiogenic heat production. In An introduction to geophysical exploration. McGraw-Hill.

SEDARA S.O., ASERE A.M. (2020) Review of radiogenic heat properties of some rock types for geothermal characterization in Nigeria. Global Journal of Earth and Environmental Science, 5(4):82–92. https://doi.org/ 10.31248/GJEES2020.073.

TELFORD W.M., GELDART L.P., SHERIFF R.E. (1990) Applied geophysics (2nd ed.). Cambridge University Press.

UWAH J.E. (1984) Investigation of radiometric anomalies by nuclear and other methods: A case study of the Sokoto Basin of Nigeria (PhD thesis). Ahmadu Bello University, Zaria.

YAKUBU M.B., LAWAL K.M., DEWU B.B.M., IKPOKONTE A.E. (2022) Investigation of geothermal energy potential using aeromagnetic and aeroradiometric data of Kano, Nigeria. FUDMA Journal of Sciences, 6(1):296–307. https://doi.org/ 10.33003/fjs-2022-0601-900

YUSUF D.B., AHMED A.L., KOLA M.L., ARABI A.S. (2014) Ground scintillometric investigations of parts of the Kerri–Kerri Formation, southwest Gombe, northeastern Nigeria. Global Journal of Geological Sciences, 12:53–62. https://doi.org/ 10.4314/gjgs.v12i1.6

YUSUF B.D. (2016) Ground radiometric investigation in the southern part of the Kerri–Kerri Formation, Gombe State, northeastern Nigeria (PhD thesis). Ahmadu Bello University, Zaria.