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Assessment of the Geothermal Source Potential Using Aero Radiometric Data in Parts of South-West and South-South, Nigeria

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ABSTRACT

Aeroradiometric surveys have recently become an invaluable resource for geothermal research. The Nigeria Geological Survey Agency (NGSA) provided the airborne radiometric data and other relevant information for the research area. For accurate detection of outliers, we recorded the data at 0.1 second intervals. Geographically, the research region covers the range of longitudes 5.0°E to 6.5°E and latitudes 6.0°N to 7.5°N. Radiogenic heat production (RHP), primarily caused by the decay of uranium, thorium, and potassium isotopes, and the tenary map were the main areas of investigation. We used Rybach's empirical equation to determine the relative heat production (RHP) by relating the rock's uranium (C_u), thorium (C_{Th}), and potassium (C_K) concentrations. The RHP values of six distinct profiles were calculated over the research area. Due to their higher RHP values (1.028928, 1.031824, and 1.023776 μW/m³, respectively), Profiles 2, 3, and 6 were deemed appropriate geothermal locations. There is a considerable lot of potential for geothermal energy production in Profile 3, which has the highest RHP, as well as in Profiles 2 and 6. Areas with large concentrations of radioactive elements were also shown by the ternary picture and concentration maps, along with regions with notable geothermal gradients and heat flow. Consequently, the regions around Edo State municipalities like as Okada, Okakpan, and Ugboku are ideal for geothermal energy. Geothermal exploration is most effective in areas with large concentrations of radiogenic elements, according to the study's results, which provide the groundwork for further investigation in these areas.

Keyword: Areoradiometric, geothermal, RHP, tenary.

INTRODUCTION

Geothermal energy is a sustainable and environmentally friendly energy resource that has gained significant attention globally due to its potential to provide a stable and continuous energy supply (Kabeyi & Olanrewaju, 2022). Unlike fossil fuels, geothermal energy is derived from the natural heat of the Earth's interior, which is virtually inexhaustible on a human timescale (Abas et al., 2015; Liu et al., 2015). This energy can be harnessed for various applications, including electricity generation, direct heating, and industrial processes (Zhang et al., 2019). The exploration and utilization of geothermal resources contribute to the diversification of energy sources, reduction of greenhouse gas emissions, and enhancement of energy security (Chandrasekharam & Bundschuh, 2008).

Globally, geothermal energy has been successfully harnessed in regions with favorable geological conditions, such as Iceland, the Philippines, New Zealand, and parts of the United States (Daniilidis & Herber, 2015). These regions benefit from the presence of volcanic activity, tectonic plate boundaries, and high heat flow from the Earth's interior. However, the potential for geothermal energy is not limited to these areas alone (Hammons, 2004). Advances in exploration technologies and methodologies have opened up new possibilities for identifying and utilizing geothermal resources in regions previously considered less favorable (Liu et al., 2015).

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Africa is endowed with significant geothermal resources, particularly in the East African Rift System (EARS), which stretches from the Horn of Africa down to Mozambique (Kombe & Muguthu, 2018). Countries such as Kenya, Ethiopia, and Djibouti have made notable strides in harnessing geothermal energy for electricity generation and direct use applications. Despite these successes, many parts of Africa, including West Africa, remain underexplored for their geothermal potential (Merem et al., 2019). The need for sustainable energy solutions in the face of growing energy demands and environmental challenges makes the assessment of geothermal resources in these regions imperative.

The Niger Delta region of Nigeria is renowned for its extensive petroleum resources, which have been a cornerstone of the country's economy for decades (Ovadia, 2014). However, the environmental and socio-economic impacts of oil and gas exploration and production have raised concerns and highlighted the need for alternative and sustainable energy sources (Omeje, 2005). The region's unique geological characteristics, coupled with its high energy demand, present an opportunity to explore geothermal energy as a viable alternative or complement to traditional fossil fuels (AgboniFo, 2016).

The geothermal potential of the Niger Delta has not been extensively studied, and existing data on the region's geothermal characteristics are limited (Yusuf et al., 2021). The complex geology of the region, characterized by sedimentary basins, fault systems, and varying heat flow, necessitates a comprehensive and systematic approach to geothermal exploration. Understanding the geothermal gradient, subsurface temperature distribution, and heat flow within the region is critical for identifying prospective geothermal resources (Ijeh et al., 2023).

Aeroradiometric surveys have emerged as a valuable tool in geothermal exploration. These surveys involve the measurement of natural gamma radiation emitted from the Earth's surface using airborne detectors (Yusuf et al., 2021). The data obtained can provide insights into the distribution of radioactive elements such as uranium, thorium, and potassium, which are indicators of geothermal activity. By analyzing aero radiometric data, researchers can infer the subsurface temperature distribution and heat flow patterns, thereby identifying areas with potential geothermal resources (Tende et al., 2021).

In the context of the Niger Delta, aeroradiometric data can play a crucial role in overcoming the challenges posed by the region's complex geology and limited surface manifestations of geothermal activity (Suleiman et al., 2020). The integration of aero radiometric data with other geophysical and geological data can enhance the accuracy and reliability of geothermal resource assessments. This approach not only reduces the risk and cost associated with traditional exploration methods but also provides a non-invasive means of investigating the subsurface (Gobashy et al., 2024).

The exploration and assessment of geothermal resources in the Niger Delta region using aero radiometric data represent a promising approach to unlocking the region's geothermal potential (Akinsunmade et al., 2020). This study aims to provide a comprehensive and systematic evaluation of the geothermal source potential using Radiogenic heat production (RHP), primarily caused by the decay of uranium, thorium, and potassium isotopes, and the ternary map to the broader goal of sustainable energy development in Niger Delta Nigeria.

LITERATURE REVIEW

Geothermal energy originates from the Earth's core and is manifested in the form of heat. This heat is continuously produced by the decay of naturally occurring radioactive isotopes such as uranium, thorium, and potassium within the Earth's crust (Yadav et al., 2022). Geothermal energy can be harnessed for various applications, ranging from electricity generation to direct use in heating and industrial processes. The utilization of geothermal energy typically involves the extraction of hot water or steam from geothermal reservoirs, which can be found in both high-enthalpy and low-enthalpy environments (Gobashy et al., 2024).

According to Ijeh et al. (2023), high-enthalpy geothermal resources are typically associated with volcanic regions and are characterized by high temperatures and pressures. These resources are commonly used for electricity generation in geothermal power plants. In contrast, low-enthalpy resources, which are found in sedimentary basins and other non-volcanic regions, have lower temperatures and are primarily used for direct

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heating applications, such as district heating, greenhouse heating, and industrial processes (Tende et al., 2021).

Elbarbary et al. (2018) used two components from aeromagnetic and aerogravity data to calculate the CPD values. This made understanding the geothermal potentials of Egypt's Western Desert's Frafra Oasis simpler. In addition to identifying favorable and unfavorable geothermal occurrence possibilities, the study looked at factors such as high heat flow, gravity inversion-determined shallow basement depth, and shallow CPD using magnetic data. However, when evaluating its geothermal potential, it fails to consider the impact of radiogenic heat. Additionally, Arafa-Hamed et al. (2023) used gravity and magnetotellurics to decipher the origin of the Hammam Faraun hot spring, which is located near the Sinai Peninsula in Egypt. The study made it feasible to map the structural features around the Hamman Faraun hot spring in the Egyptian Sinai Peninsula. However, the study suffers from flaws due to the inclusion of an insufficient number of assessment elements and the omission of some crucial characteristics from a more comprehensive prospectivity model. Also, Abuzied et al. (2020) looked at the geothermal energy of the Gulf of Suez in Egypt. They used temperature records from many oil wells spread out in the area, along with gravity and aeromagnetic data, to look into the subsurface structure pattern and how it relates to shallow geothermal points of interest like hot springs, etc. This research maps only buildings with geothermal effects, excluding other important assessment factors such as CPD and RHP. The more assessment criteria present, the more likely it is to precisely map a geothermal prospective zone, thereby reducing the reliability of the resulting findings.

Using gravity and magnetic data, Zaher et al. (2018) performed a geothermal study of the Siwa Oasis region in Egypt's Western Desert. Using the spectrum approach, the scientists calculated the CPD, heat flow, and geothermal gradient data over the Siwa. The Oasis region's anticipated geothermal potential will be revealed in its case study location. Nevertheless, this effort did not use the helpful GIS-based multicriteria integration technique. This can lead to an inefficient combination of digital theme layers, yielding unreliable and erroneous results. Ghoneim et al. (2023) used well, geophysical and geological data to generate a geothermal favorability map of Egypt using the GIS integration approach. The study found that locations with considerable crustal heat flow, shallow CPD anomalies, and near proximity to structural fault distributions had geothermal potentials that ranged from very low to very high. However, the model did not incorporate heat sources from radioactive sources when constructing its potential maps.

Isa et al. (2011) used a finite differences approach to create 2-dimensional estimates of temperature occurrences along the Aceh geothermal zones in Indonesia. Using the temperature monitoring technique, the study adjusted the model information and produced a two-dimensional representation of heat dispersion. Additionally, the research showed that an expected geothermal temperature of 180 °C correlated with a reservoir depth of more than 550 metres. Additionally, Srigutomo et al. (2007) used the very low frequency (VLF) technique to study the response of the electromagnetic field in the Sabang geothermal zone in Indonesia. The study's goal was to observe the hydrothermal fields' responses to variations in depth, form, and location. We found the biggest anomalies between 400 and 600 meters apart and between 10 and 14 meters below the surface.

The geological, petrological, and geochemical methods were used by Bolarinwa & Bute (2015), Okiyi et al. (2021), Salako et al. (2020), Obiora et al. (2016), and Jekayinfa et al. (2020) to pinpoint the locations, sources, and origins of uranium enrichment in the northeastern. Nigerian geology features, one important part of Earth's heat generation—radiogenic heat production (RHP)—was not addressed in the research (Sokari et al. (2022). This is why its calculation is essential to the current investigation. Geothermal energy has been successfully harnessed in several countries around the world, contributing to their energy mix and providing numerous environmental and economic benefits.

Location and Geology of the Study Area

The study area (Fig.1) is located in parts of south-west and parts of south-south of Nigeria, lying between latitudes 6°20'N and 7°10'N and longitudes 5°00'E and 6°00'E. It encompasses a diverse landscape characterized by various towns, rivers, railways, and natural land uses. This region is significant for a multitude of studies including environmental assessments, urban planning, and socio-economic analyses.

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The study area consist of many towns, marked with green dots, which are essential for understanding the human settlement patterns in this area. Prominent towns such as Owo, Akure, and Ekiti serve as key urban centers within this region. These towns are not only hubs of economic activity but also serve as focal points for cultural and social interactions. The distribution of these towns provides insight into the population density and urban sprawl within the study area.

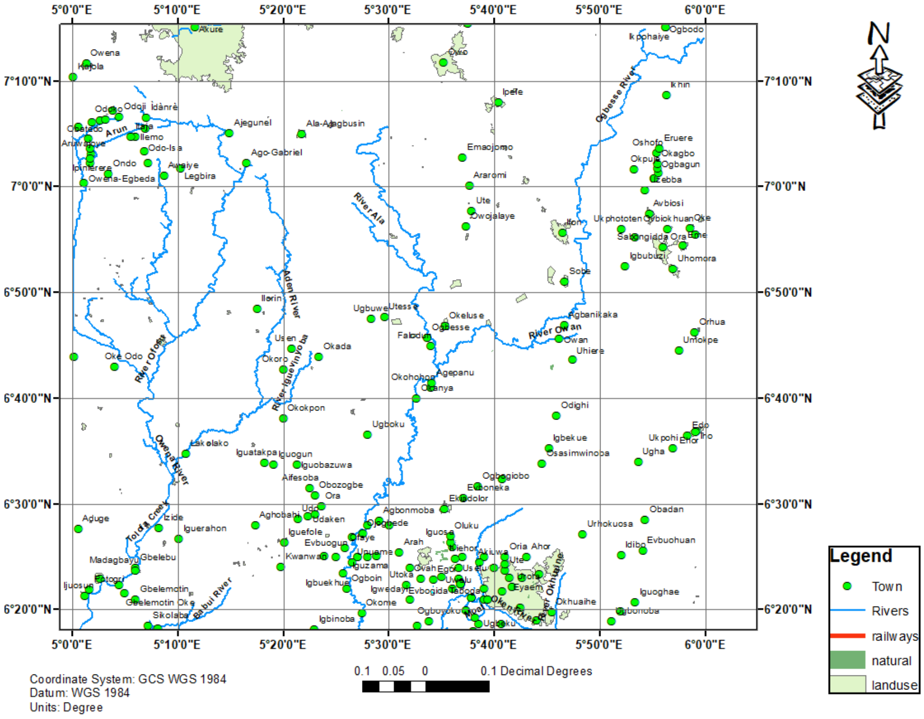

Fig 1: Study area map

The lithology of this region is diverse, comprising various rock types and geological formations that have significant implications for natural resource management, environmental studies, and urban planning (Olowofela et al., 2019). The southwestern region of Nigeria is characterized by several prominent geological formations, including sedimentary rocks, igneous intrusions, and metamorphic complexes. These formations are products of different geological processes, including sedimentation, magmatism, and metamorphism Akanabi and Olukowade (2018).

The study area includes portions of the Dahomey Basin, which features significant deposits of Cretaceous sediments. These sediments are primarily composed of sandstones, shales, and limestones. The sandstone formations are often cross-bedded, indicating ancient fluvial and deltaic environments, while shales suggest periods of low-energy, deeper marine conditions (Okeyode et al., 2021). Overlying the Cretaceous formations are younger Tertiary and Quaternary deposits. These include coastal and alluvial sediments, such as unconsolidated sands, clays, and gravels. These deposits are critical for groundwater resources and support various agricultural activities in the region (Rowland et al., 2022).

MATERIALS AND METHOD

Data

The Nigeria Geological Survey Agency (NGSA) provided the data for the research region, which included aero-radiometric measurements. With a notional flying height of 80 metres and a tie-line spacing of 2000 metres in a northeast-southwest direction, the aeromagnetic and aeroradiometric surveys were flown along a sequence of flight lines that were spaced 500 metres apart and from northwest to southeast. The data were collected at intervals of 0.1 seconds after this. The resolution of anomalies is far higher than that of traditional high-altitude surveys due to the fact that the survey was flown such that it was closer to the ground (at a flying height of 80 metres), with narrow line spacing, and with a very brief recording interval. The collection is comprised of nine different half-degree map sheets, each of which is outlined by geographical coordinates. To be more specific, the boundaries of the research region are between latitudes 6.0°N and 7.5°N and longitudes 5.0°E and 6.5°E. Considering the great spatial resolution of the aeromagnetic and aero-radiometric data, it is possible to get important insights into the geological and radiometric properties of the area.

Airborne Radiometric Method

The use of numerous geophysical technologies concurrently results in a significant improvement in the quality of the geophysical survey. An example of such synergy is the process of performing an aerial radiometric survey. In this survey, gamma ray flux measurements are obtained frequently using detectors that are placed on aeroplanes in a grid-like arrangement. The use of magnetic surveys is often used as a supplement to this strategy. The decay of radioactive isotopes beneath the crust of the Earth is the primary source of the heat movement that occurs across the continents. Consequently, the identification of places that have greater concentrations of radioactive isotopes makes it possible to estimate the generation of radioactive heat, which is correlated with regions that display enhanced heat flow (Jackson et al., 1987).

Radioactive Heat Analysis

More than 98% of the Earth's present-day heat production results from the decay of the uranium isotopes ^{238}U and ^{235}U, as well as thorium isotope ^{232}Th, and potassium isotope ^{40}K, which undergoes a single-step decay process. Uranium-235 (^{235}U) has a significantly shorter half-life compared to ^{238}U. Although other short-lived radioactive isotopes may have contributed substantially to the Earth's thermal history in its early stages, they are no longer detectable. Conversely, long-lived radioactive isotopes exist, but their decay rates are so slow that they have never made significant contributions to Earth's overall heat budget (Rybach, 1976).

According to Cui et al. (2019), Yusuf et al. (2021), Rybach, (1976), and Liu et al. (2015), radiogenic heat production (H) primarily arises from the decay of radioactive isotopes ^{232}Th, ^{238}U, and ^{40}K. This production can be quantitatively estimated using an empirical equation formulated by Rybach (1976), which correlates heat production (H) with the concentrations (C_u, C_{Th}, and C_K) of uranium, thorium, and potassium in the rock:

$$H(\frac{\mu W}{m^3}) = \rho(9.52C_u + 2.56C_{Th} + 3.48C_k) \times 10^{-2}$$

H = radioactive heat production

ρ = density of rock adapted from Kuforijimi and Aigbogun (2017) and Cui et al. (2019).

C_u, C_{Th}, and C_K are the concentrations of Uranium, Thorium and respectively.

RESULT AND DISCUSSION

In Figure 2(a, b, c), the gamma decay data for potassium, thorium, and uranium are analyzed to show the distribution of radioactive elements within the study area. The radiation signals for potassium primarily originate from potassium feldspar, particularly in minerals such as mica and biotite (Taufiq et al., 2020). High anomaly signals for potassium are observed in the north-west and south-west part of the study area, indicating elevated concentrations of potassium-rich minerals (Fig 2a). This anomaly is attributed to the intrusion of various granitic rocks, which serve as sources of radioactive nuclei within the study area. Conversely, low anomaly signals are observed in the lower southern part of the study area, where potassium concentrations are comparatively lower.

Also, the concentration maps for thorium and uranium reveal high anomaly signals in the northern region of the study area (Fig. 2b and 2c). These anomalies are associated with fine-grained biotite granite formations, which are known to contain elevated concentrations of thorium and uranium. Conversely, low anomaly signals are observed in the southern lower part of the study area, indicating lower concentrations of these radioactive elements.

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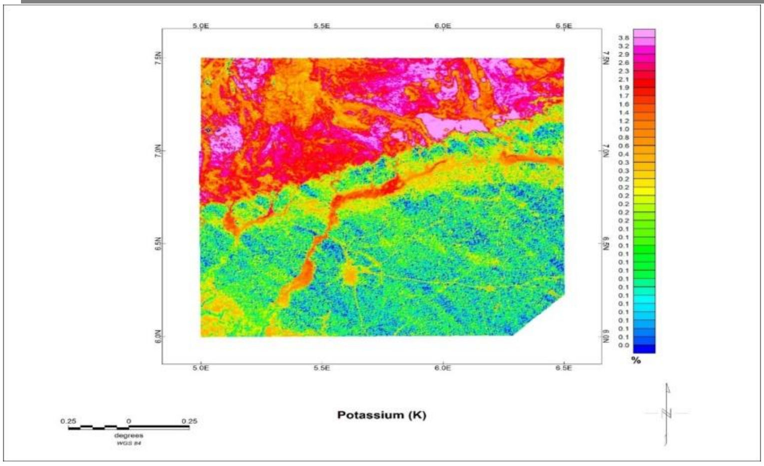

Figure 2a: Potassium concentration map of the study area

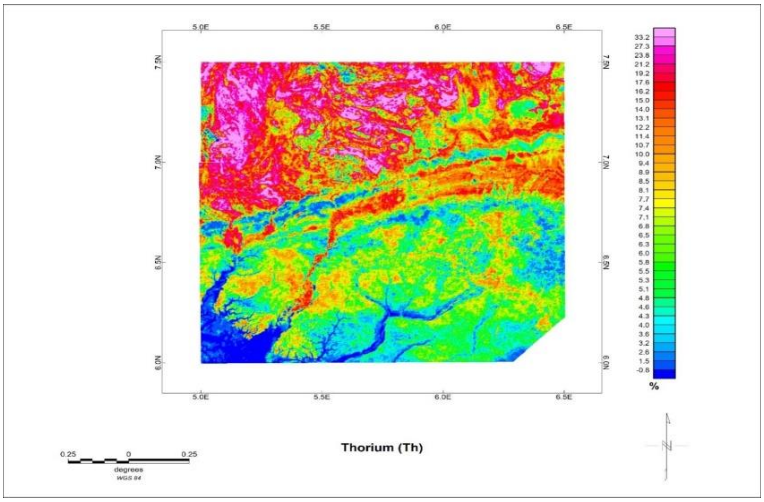

Figure 2b: Thorium concentration map of the study area

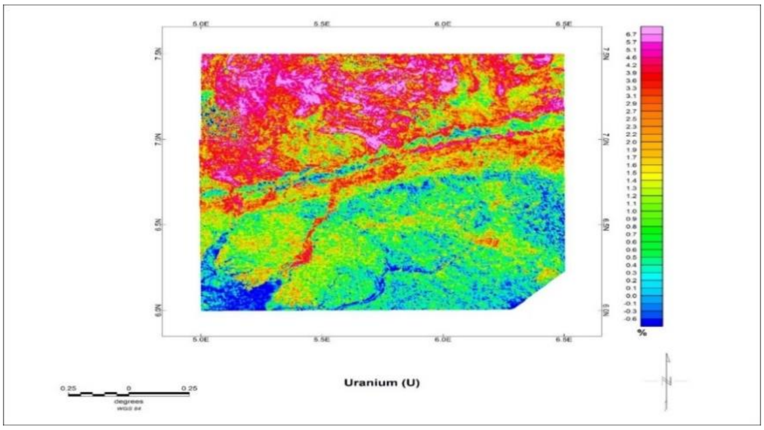

Figure 2c: Uranium concentration map of the study area

The Ternary map presents a composite image combining the concentrations of Potassium, Thorium, and Uranium, with corresponding Red, Blue, and Green colorations, respectively (Fig 3). This map serves to show subtle variations in the relative concentrations of gamma radiation within the study area, depicting specific levels of radiation intensity. Regions characterized by undifferentiated porphyritic granite, exhibit high potassium concentrations, as indicated by the red areas on the composite map. In the composite image, red areas signify high potassium concentrations, while blue areas indicate strong uranium content combined with relatively weaker potassium and thorium concentrations. White regions represent areas with significant indications of uranium, thorium, and potassium content, predominantly located in the eastern regions of the study area.

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Areas displaying strong indications of uranium and thorium content but weaker potassium concentrations are denoted by cyanide on the composite map. Dark blue sections, attributed to nearby migmatite formations, suggest lower potassium and thorium concentrations but substantial uranium levels.

According to the findings of this study, areas exhibiting high concentrations of potassium, thorium, and uranium are deemed most favorable for geothermal investigation. therefore, the areas bounded by Okada, Okakpan, Ugboku, Ekiadolo, Ugha, Ukpahi, Igeghudu, Ojagba, Ebelle, Ewallo, Idumujuno, Uku-Nzu, Igo Onaghaleo, Ebulen, Ugbalo, Ewuh, Ekeke, Ozalla, Owan, Okeluse, Ugbuwe and Usen towns of Edo State of the research area emerges as a promising location for such investigations, coinciding with regions where high geothermal gradients and heat flow were detected. Also, areas encompassing Udachi, Fugar, Ayaguri, Auchi, Usua, Ipe Iyaju and Iwaiaro towns of Edo state also displayed suitability for geothermal energy source for further geothermal exploration.

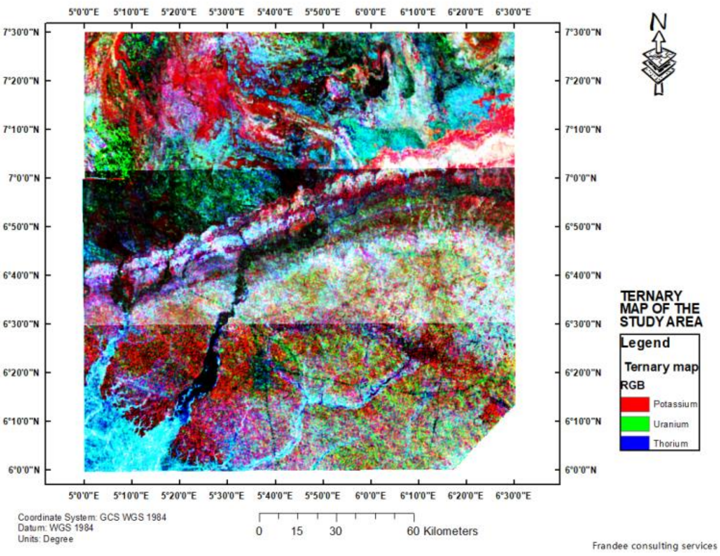

Figure 3: Ternary map of the study area.

Radiogenic Heat Production (RHP)

A connection was made between the maps of the research area's uranium, thorium, and potassium concentration, as well as the map of the total magnetic intensity. In Figure 4, there are six profiles that run in a southwest-northeast direction, with the exception of profile 5 and 6, which travels in a northwest-southeast direction. The computations included determining the average concentration of each isotope along each profile. There are eight different rock units, including alluvium, the Akata Formation, the Agbada Formation, the Nun and Focados River Group. The southwestern region of Nigeria is characterized by several prominent geological formations, including sedimentary rocks, igneous intrusions, and metamorphic complexes. These formations are products of different geological processes, including sedimentation, magmatism, and metamorphism.

In order to do further calculations about the creation of radiogenic heat, their average specific gravity or density, in addition to the average concentration of each isotope throughout each profile, were used. For each profile, the RHP values were calculated using Equation (1). These data are shown in Table 1. According to Jaupart et al. (2001), the average heat production of the Precambrian shield is 0.77 ± 0.08 μWm^{-3}. This shield has a higher heat production than average. Even though they acknowledged that the deviation from their value could be significant on a local scale, they still made this statement. The region's high radioelement concentrations could potentially account for the variation in the RHP of the area under investigation in this study.

According to the findings presented in Table 1 and Fig 4, Profile 1 has an RHP of 0.856288 $\mu W/m^3$, with C_K at 2.34 ppm, C_{Th} at 18.68 ppm, and C_u at 4.44 ppm. Despite the high C_{Th}, the RHP is moderate. Profile 2 shows an RHP of 1.028928 $\mu W/m^3$, with C_K at 4.76 ppm, C_{Th} at 15.81 ppm, and Cu at 4.90 ppm. This profile has a

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higher RHP, indicating good potential for geothermal energy. Profile 3 has the highest RHP at 1.031824 $\mu W/m^3$, with C_K at 5.09 ppm, C_{Th} at 13.55 ppm, and C_u at 5.77 ppm. The high RHP makes this profile the most suitable for geothermal applications. Profile 4 has an RHP of 0.816336 $\mu W/m^3$, with C_K at 1.56 ppm, C_{Th} at 19.38 ppm, and Cu at 4.87 ppm. The lower RHP makes it less favorable for geothermal energy. Profile 5 shows an RHP of 0.861832 $\mu W/m^3$, with C_K at 2.32 ppm, C_{Th} at 18.99 ppm, and C_u at 4.44 ppm. Like Profile 1, it has moderate heat production. Profile 6 has an RHP of 1.023776 $\mu W/m^3$, with C_K at 5.07 ppm, C_{Th} at 16.67 ppm, and C_u at 3.20 ppm. The high C_K and decent RHP suggest good geothermal potential.

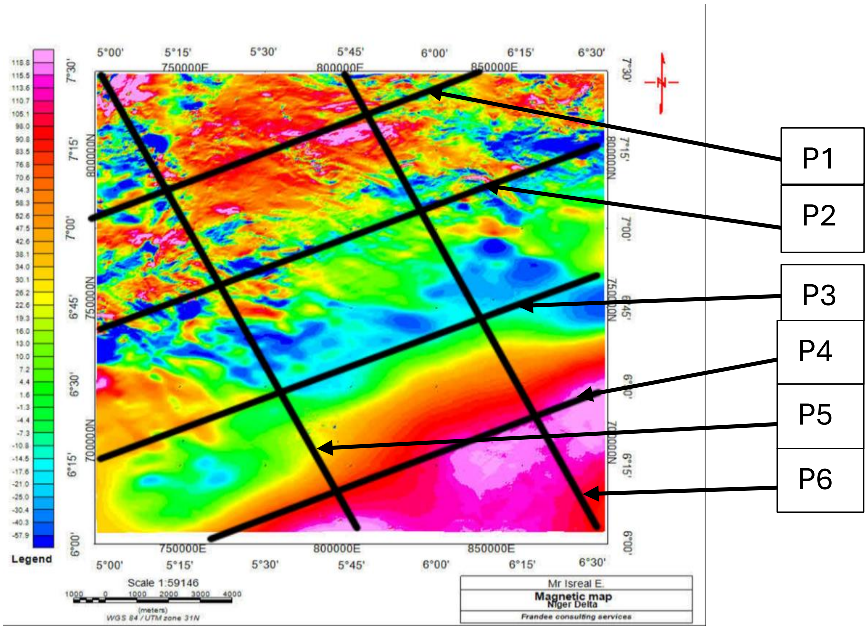

Fig. 4. Total Magnetic Intensity Map showing radiometric model drawn.

Table 1. Summary of the result for radioactive heat analysis.

Isotope	C_K (ppm)	C_{Th} (ppm)	C_u (ppm)	RHP ($\mu W/m^3$)
Profile 1	2.34	18.68	4.44	0.856288
Profile 2	4.76	15.81	4.90	1.028928
Profile 3	5.09	13.55	5.77	1.031824
Profile 4	1.56	19.38	4.87	0.816336
Profile 5	2.32	18.99	4.44	0.861832
Profile 6	5.07	16.67	3.20	1.023776

Based on the RHP values, Profiles 2, 3, and 6 are the most suitable for geothermal site selection. Profile 3, with the highest RHP of 1.031824 $\mu W/m^3$, stands out as the best candidate, followed closely by Profiles 2 and 6. These profiles indicate a strong potential for geothermal energy production due to their higher radiogenic heat production.

The Ternary map, combining the three elements (K, Th, and U), revealed areas with strong concentrations of potassium, thorium, and uranium (the white sections). The regions exhibiting strong concentrations of these elements coincided with profiles of high RHP values particularly in areas bounded by Okada, Okakpan, Ugboku, Ekiadolo, Ugha, Ukpahi, Igeghudu, Ojagba, Ebelle, Ewallo, Idumujuno, Uku-Nzu, Igo Onaghaleo, Ebulen, Ugbalo, Ewuh, Ekeke, Ozalla, Owan, Okeluse, Ugbuwe and Usen towns of Edo State Also, Udachi, Fugar, Ayaguri, Auchi, Usua, Ipe Iyaju and Iwaiaro towns of Edo state exhibited strong concentrations of these

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elements (Fig. 5). In conclsion, the regions demonstrating strong concentrations of the three radiogenic elements appear to be the most promising for geothermal exploration, aligning with areas where high RHP were observed.

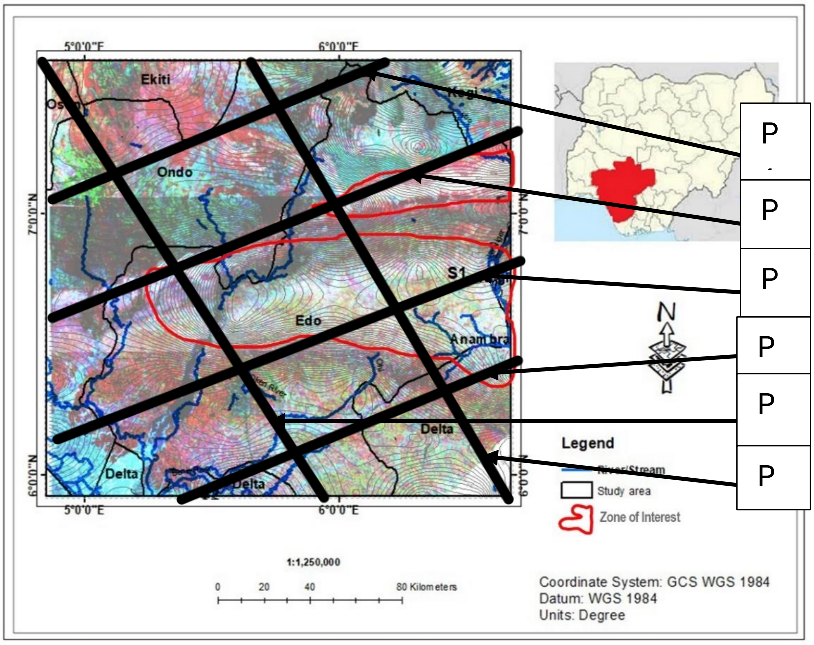

Fig. 5: Ternary Map

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