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Assessment of sustainable geothermal potential in Patigi region, North-Central Nigeria

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Abstract. This study examines the geothermal potential in the Patigi region of Nigeria to address local and national power challenges. The study area and its environs are currently experiencing a power outage for the past three years. As energy is one of the most vital factors that facilitate development in a region or country at large, Aeromagnetic data were utilised to determine the geothermal potential, which could be added to the energy mix to boost the energy supply in the region. The geothermal parameters that were established from the study are the Curie point depth, geothermal gradient, and heat flow. The residual map was segmented into nine overlapping spectral blocks, and the logarithm of spectral energies was plotted against wave number. From these plots, the centroid depth (Z_0) and the depth to the top boundary (Z_t) were derived to calculate the Curie point depth (CPD), geothermal gradient (GG), and heat flow (HF). The results indicated that the Curie point depth values ranged from 34.09 km to 55.19 km, with an average of 41.87 km. The geothermal gradient values varied from 10.51 to 17.01 °C/km, averaging 14.13 °C/km. The heat flow values spanned from 26.27 to 42.53 mW/m², with an average of 35.32 mW/m². The deepest Curie point depth was observed in the central and northeastern parts of the study area, while shallower depths were found in other parts. Geothermal and heat flow contour maps highlighted hotspots in the southeastern and eastern regions, including Kusoji, Rogun, Ekopapo-Yagi, Etsufu, Sankwafuji, Momba, Koro, and Rodun. These hotspots are deemed suitable for geothermal energy exploitation, potentially addressing the power challenges in the study area and throughout Nigeria. Developing geothermal energy resources in Nigeria can significantly help achieve sustainable development goals 7, 9, 11, and 13. It could also enhance a reduction of unemployment and poverty in Nigeria.

Keywords: Geothermal resources, Aeromagnetic data, Energy mix, Bida Basin, Heat flow



1. Introduction

Nigeria national grid has been unable to supply sufficient power to the country. However, Nigeria depends mainly on hydrocarbon, which is fast depleting, as the main source of energy. Burning of these fossil fuels have resulted to the greenhouse gas effect which consequently leads to global warming and other health complicated issues. Nigeria possesses significant conventional oil and gas reserves, yet beneath its surface lies a substantial potential for clean, sustainable renewable energy in the form of geothermal energy [1], which if exploited and explored, can support the national grid or create a diversification/alternative in energy source. Geothermal energy is derived from the Earth's internal heat, a product of the cooling of the crust and the heating of the lower crust and mantle due to radioactive isotope thermal decay. This process increases the temperature gradient with depth [2]. Energy plays a critical role in the functioning of human society and ecosystems, facilitating various tasks and underpinning economic and social development. An adequate energy supply is fundamental to a nation's growth. Increasing environmental concerns over the use of hydrocarbons have heightened interest in environmentally safe energy sources, such as geothermal energy. Although geothermal energy is ubiquitous beneath the Earth's surface, its concentration varies geographically [3].

The utilisation of geothermal energy is gaining traction globally as countries seek to diversify their energy sources and reduce carbon emissions. Geothermal energy is considered highly reliable, providing a consistent power output compared to other renewable sources such as solar and wind, which are subject to weather conditions. Furthermore, geothermal power plants typically have a smaller land footprint than solar farms or wind parks, making them an attractive option for densely populated or land-constrained regions. The exploration and development of geothermal resources can significantly contribute to energy security, economic growth, and environmental sustainability.

Numerous studies have demonstrated that the thermal structure of the Earth's crust can be comprehensively determined using regional magnetic data across various geologic settings [4-8]. For example, the major magnetic minerals in the Earth's crust transition from ferromagnetic to paramagnetic states at a specific temperature known as the Curie-point temperature (CPT) [9]. Aeromagnetic data was used in this study because of its several applications, including noise reduction, enhancing specific features of the data, and integration with other geophysical data [10]. These data can be used to map subsurface structures, identify geothermal anomalies, and estimate geothermal parameters such as Curie-point depth (CPD), geothermal gradient, and heat flow.

This study investigates the geothermal system of the Patigi region and its surrounding areas, proposing that harnessing this energy could address the current power challenges in the region and the country at large, boost the economy, establish a business-friendly environment, and ultimately alleviate unemployment and poverty both locally and nationally. The Patigi region is situated in a geologically favourable area, characterised by significant geothermal potential due to

its crustal structure and thermal properties. By identifying geothermal hotspots, this research aims to provide a foundation for future geothermal exploration and development in the region.

Previous research by Nwankwo and Sunday [9] analysed aeromagnetic data from the Bida basin in North-central Nigeria to estimate Curie-point depth (CPD) and geothermal parameters using the conventional centroid approach. The findings indicate that the CPD ranges from 15.57 to 29.62 km, with an average of 21.65 km. The geothermal gradient varies between 19.58 and 37.25 °C km⁻¹, with an average of 27.25 °C km⁻¹, while the crustal heat flow ranges from 48.41 to 93.12 mW m⁻², with an average of 68.80 mW m⁻².

Furthermore, Adagunodo et al. [11] evaluated the potential for geothermal energy exploration in Nigeria using magnetic and gravity techniques, identifying regions such as the Benue Trough, Chad, Sokoto, and Dahomey basins as suitable for geothermal energy utilisation. They recommended prioritising the production of electricity through geothermal and other renewable energy sources to support Nigeria's sustainable development. Their findings underscore the importance of integrating geothermal energy into Nigeria's energy mix, which can enhance energy security, reduce greenhouse gas emissions, and foster economic development.

Adewumi et al. [7] estimated the Curie point depth (CPD) and heat flow using high-resolution aeromagnetic data over a section of the Bida Basin, which is bounded by longitude 5°00' E to 6°30' E and latitude 8°30' N to 9°30' N, covering an area of approximately 18,150 km². They applied regional/residual separation using polynomial fitting to the total magnetic intensity field of the study area, then divided the residual map into sixteen overlapping spectral blocks. From the plot of the logarithm of the power spectrum against wave number, they determined centroid depths (Z_0) and depth to the top of the basement (Z_t). The centroid depths ranged from 6.61 km to 20.30 km, while the depth to the top of the basement varied from 1.59 km to 6.38 km. The CPD ranged from 10.88 km to 35.51 km, with an average value of 23.22 km.

Odidi et al. [8] utilized the radially power spectrum on aeromagnetic data covering an area of 36,300 km², bounded by latitudes 7.5° N to 11.5° N and longitudes 7.5° E to 10.5° E. The area was divided into 35 square blocks with 50% overlap and approximately 64 by 64 data points. Their results indicated that the Curie point depths ranged from 17.711 km to 34.34 km, with a mean value of 26.21 km. The geothermal gradient ranged from 16.89 °C/km to 32.75 °C/km, with an average of 22.83 °C/km, and the heat flow ranged from 42.22 mW/m² to 81.87 mW/m², with a mean value of 57.07 mW/m². These findings aligned with the existing geothermal and geo-tectonic characteristics of the area, suggesting the potential existence and exploration of geothermal resources in the study area.

In Adagunodo et al. [11] results were obtained based on different researchers' reports. In this study, results will be based on the aeromagnetic data analysis of the study areas. Odidi et al. [8] utilized the radially power spectrum on aeromagnetic data but in this study centroid method will be utilized as it reduces error in the computation of the geothermal parameters.

Thus, this study on the Patigi region's geothermal system seeks to contribute to the growing body of knowledge on Nigeria's geothermal potential. By leveraging advanced geophysical techniques and building on previous research, this study aims to provide actionable insights for harnessing geothermal energy, thereby addressing the country's energy challenges and this will see to the achievement of sustainable development goals number 7, 11, and 13 [12], as this will create clean energy, sustainable communities, and favorable climate conditions as greenhouse effects, which is the primary cause of global warming, will be drastically reduced.

2. Geology of the Study Area

The study area is located in the southwestern part of the Bida Basin (Figure 1), also known as the Middle Niger Basin or Nupe Basin, in Kwara State, Nigeria. It covers approximately 2,910.3 km² and lies between longitudes 5.50° E to 6.00° E and latitudes 8.50° N to 9.00° N. The geological composition of this area includes Campanian to Maastrichtian sandstones and siltstones that rest atop the Precambrian basement complex rocks [13]. The Bida Basin is a shallow, down-warped trough characterized by a mixture of marine and fluvial sediments. Key formations within the basin include Batati, Agbaja, Lokoja, Patti, and Enagi [14]. The basin extends from Kontagora in Niger State to near Lokoja [15] and is considered potentially viable for hydrocarbon exploration due to its significant sedimentary thickness [16, 17]. This thickness, along with the basin's stratigraphic characteristics, suggests the presence of organic-rich layers that could generate hydrocarbons under suitable thermal conditions. Kwara State's geological setting is further distinguished by its ancient crystalline rocks, which include granites, gneisses, and migmatites [18-20]. These rocks are part of the Nigerian Basement Complex, which is known for hosting various economic minerals [21]. Notably, the basement complex contains valuable minerals such as mica and gemstones. The migmatite and migmatite-gneiss formations within this complex are particularly significant for their use as construction aggregates, providing essential materials for infrastructure development [22]. Overall, the geological diversity of the Bida Basin and its surrounding areas in Kwara State presents a complex interplay of ancient basement rocks and younger sedimentary formations. This interplay not only offers significant potential for natural resource exploration and extraction but also provides valuable information for understanding the geological history and evolution of this part of Nigeria.

3. Materials and Methods

3.1 Materials

An aeromagnetic map (Sheet 204) encompassing the Patigi area and its environs in the southwestern Bida Basin was obtained from the Nigerian Geological Survey Agency (NGSA). This map is part of the comprehensive nationwide aeromagnetic survey conducted in 2009, which was funded by the NGSA to advance geological and geophysical investigations across Nigeria. The survey involved systematic data acquisition along NE-SW oriented flight lines, spaced 200

meters apart, at an average flight altitude of approximately 80 meters, with tie lines every 500 meters to ensure data continuity and accuracy [24]. To account for variations in the Earth's magnetic field, the geomagnetic gradient was corrected using the 2005 International Geomagnetic Reference Field (IGRF) [25, 26]. The collected data were provided in a grid format at a scale of 1:100,000, facilitating detailed analysis and interpretation. This data was processed and analysed using Geosoft Oasis Montaj version 8.4 software, which enable the enhancement of specific features and the integration of the aeromagnetic data with other geophysical datasets. This meticulous approach ensured high-resolution imaging of the subsurface, providing valuable insights into the geological structures and geothermal potential of the study area.

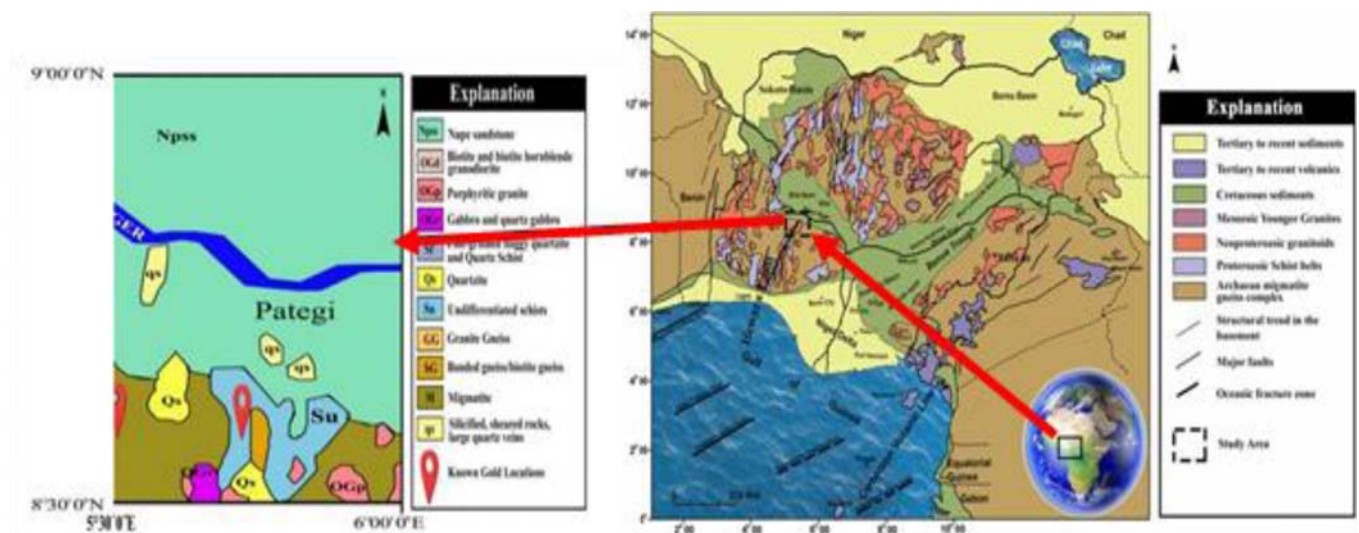


Figure 1: Geological map of Nigeria and the Study Area (Modified after [21]).

3.2 Methods

To estimate the Curie point depth, spectral analysis of the two-dimensional Fourier transform of aeromagnetic data was conducted utilising Oasis Montaj software (version 8.4). The residual magnetic field intensity map of the study area was segmented into nine overlapping blocks, and the logarithms of spectral energies versus frequencies for each block were plotted using MATLAB software. Additionally, graphs representing the Curie point depth, geothermal gradient, and heat flow were generated using Surfer 15 software. (Z_t).

3.2.1 Centroid Method

The mathematical models of the centroid method are based on the examination of the shape of isolated magnetic anomalies introduced by Bhattacharyya and Leu [27] and the study of the

statistical properties of magnetic ensembles by Spector and Grant [6]. Blakely [5] subsequently introduced the power spectral density of total magnetic field, $\phi\Delta(k_x, k_y)$ as;

$$\phi\Delta T(k_x, k_y) = \phi_M(k_x, k_y) \cdot 4\pi^2 C_M^2 |\theta_M|^2 |\theta_f|^2 e^{-2|k|Z_t} (1 - e^{-2|k|(Z_b - Z_t)})^2 \quad (1)$$

where k_x and k_y are wave numbers in x and y direction, $\phi_M(k_x, k_y)$ is the power spectra of the magnetization, C_M is a constant, θ_M and θ_f are factors for magnetization direction and geomagnetic field direction, and Z_b and Z_t are depths to bottom and top of magnetic layer respectively. If the layer's magnetization, (x, y) is a random function of x, y , y implies that $\phi_M(k_x, k_y)$ is a constant, and therefore the azimuthally averaged power spectrum, $\phi(|k|)$ would be given as;

$$\phi(|k|) = A e^{-2|k|Z_t} (1 - e^{-2|k|(Z_b - Z_t)})^2 \quad (2)$$

The initial step involved estimating the depth to the top (Z_t) of the magnetic source based on the slope of the high-wave-number portion of the power spectrum, expressed as:

$$\ln(P(k)^{\frac{1}{2}}) = X - |k|Z_t \quad (3)$$

where Z_t represents the depth to the top of the magnetic sources, X is a constant, k is the wave number ($2\pi \text{ km}^{-1}$), and $P(k)$ is the azimuthally averaged power spectrum. Additionally, the centroid depth of magnetic sources can be determined from the low-wavenumber region of the wave-number scaled power spectrum [28]:

$$\ln(P(k)^{\frac{1}{2}}/k) = Y - |k|Z_o \quad (4)$$

where Y is a constant and Z_o is the centroid depth of the magnetic sources. The depth to the bottom of the magnetic source (Z_b) can then be calculated using the relationship [29]:

$$Z_b = 2Z_o - Z_t \quad (5)$$

With the depth to the bottom of the magnetic sources (Z_b), determined, the geothermal gradient ($\frac{dT}{dz}$) can be estimated using the formula [28, 30]:

$$\frac{dT}{dz} = \frac{\theta_c}{Z_b} \quad (6)$$

where θ_c is the Curie temperature. Subsequently, using Z_b and the geothermal gradient $\frac{dT}{dz}$, the heat flow (q_z) can be estimated as [29]:

$$q_z = -\sigma \frac{\theta_c}{Z_b} = -\sigma \frac{dT}{dz} \quad (7)$$

where σ is thermal conductivity. For this research, a thermal conductivity value of $2.5 \text{ Wm}^{-1}\text{C}$ and a Curie temperature of 580°C [31] were utilised as standard values.

4. Results and Discussion

The residual map (Figure 2), marked by positive and negative anomalies, was divided into nine equal overlapping spectral blocks. For each block, the logarithm of spectral energies was plotted against the wave number to determine the Centroid depth (Z_0) and the depth to the top boundary (Z_t). These values were then used to calculate the Curie point depth (CPD), which in turn was used to compute the geothermal gradient (GG) and heat flow (HF) of the area. Table 1 presents the results from the nine blocks, detailing the variations in CPD, GG, and HF. Sample graphs of spectral energy versus frequency (wavenumber) from the blocks are shown in Figure 3. This analysis provides a clear visual representation of the data and the derived geothermal parameters for each spectral block:

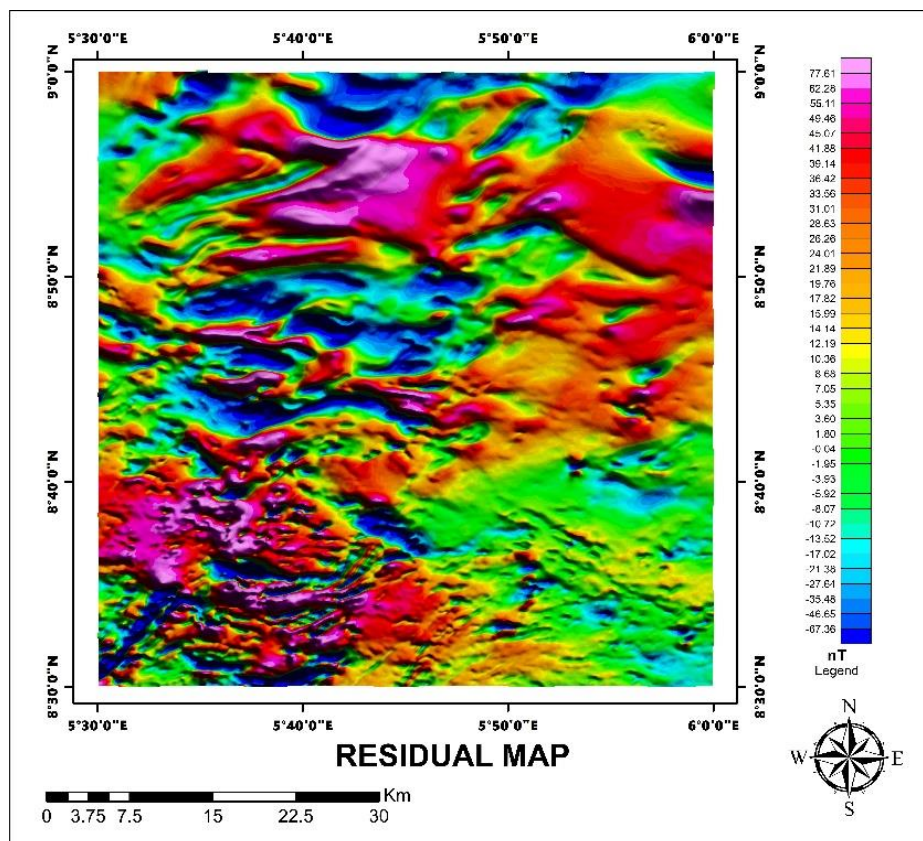


Figure 2: Residual Map of the Study Area

Table 1: The estimated result of the spectral analyses of the study area for each block

Blocks	Long (°E) ^a	Lat (°N) ^a	Centroid depth Z _o (km)	Depth to top Z _t (km)	Basal depth Z _b /CPD (km)	Geothermal gradient (°C/km)	Heat flow (mW/m ²)	Block Areas
1	5.625	8.875	23.57	4.87	42.26	13.72	34.31	Gonagi, Kagwa,
2	5.75	8.875	23.36	5.51	41.20	14.08	35.19	Lahagi, Kusodo
3	5.875	8.875	26.93	4.19	49.67	11.68	29.19	Lamfa, Kpatagi,
4	5.625	8.75	20.33	3.27	37.39	15.51	38.78	Gazhe, Dangi
5	5.75	8.75	29.68	4.16	55.19	10.51	26.27	Agegi, Ebagi,
6	5.875	8.75	19.5	4.91	34.09	17.01	42.53	Doko, Lancika
7	5.625	8.625	20.24	3.32	37.15	15.61	39.03	Lade, Rani, Ekate,
8	5.75	8.625	21.08	1.97	40.19	14.43	36.08	Podoge
9	5.875	8.625	22.56	5.43	39.69	14.61	36.54	Pategi, Baradogi,
								Wando, Edogi
								Kusoji, Rogun,
								Ekopapo-Yagi,
								Etsufu
								Danikun, Ndanaku
								Okolushe-Egboro,
								Erufu, Matokun
								Sankwafuji,
								Momba, Koro,
								Rodun
Average			23.03	4.18	41.87	14.13	35.32	

Note: ^a indicates Centre of the blocks

The Curie point depth (CPD) values in the study area ranged from 34.09 km to 55.19 km, with an average depth of 41.87 km. To illustrate these findings, a two-dimensional contour map (Figure 4) was generated, visually representing the spatial distribution of CPD values across the study area. This map reveals that the deepest CPD values are concentrated in the central parts of the study area, encompassing locations such as Pategi, Baradogi, Wando, Edogi, and others. Conversely, the shallowest depths are observed in the eastern regions, including areas like Kusoji, Rogun, Ekopapo-Yagi, and Etsufu. According to Bhattacharyya and Leu [27] and Tanaka et al. [28], the CPD is significantly influenced by the mineralogical and geological conditions of the region. Shallow depths are typically found in volcanic and geothermal fields due to the high thermal activity and the presence of geothermal anomalies. The presence of shallow CPD values in the eastern part of the study area may be attributed to igneous intrusions. These intrusions elevate the geothermal gradient, leading to a reduction in the Curie point depth. This phenomenon occurs because the heat from the intrusions increases the temperature of the surrounding rocks, causing the magnetic minerals to reach their Curie point at shallower depths.

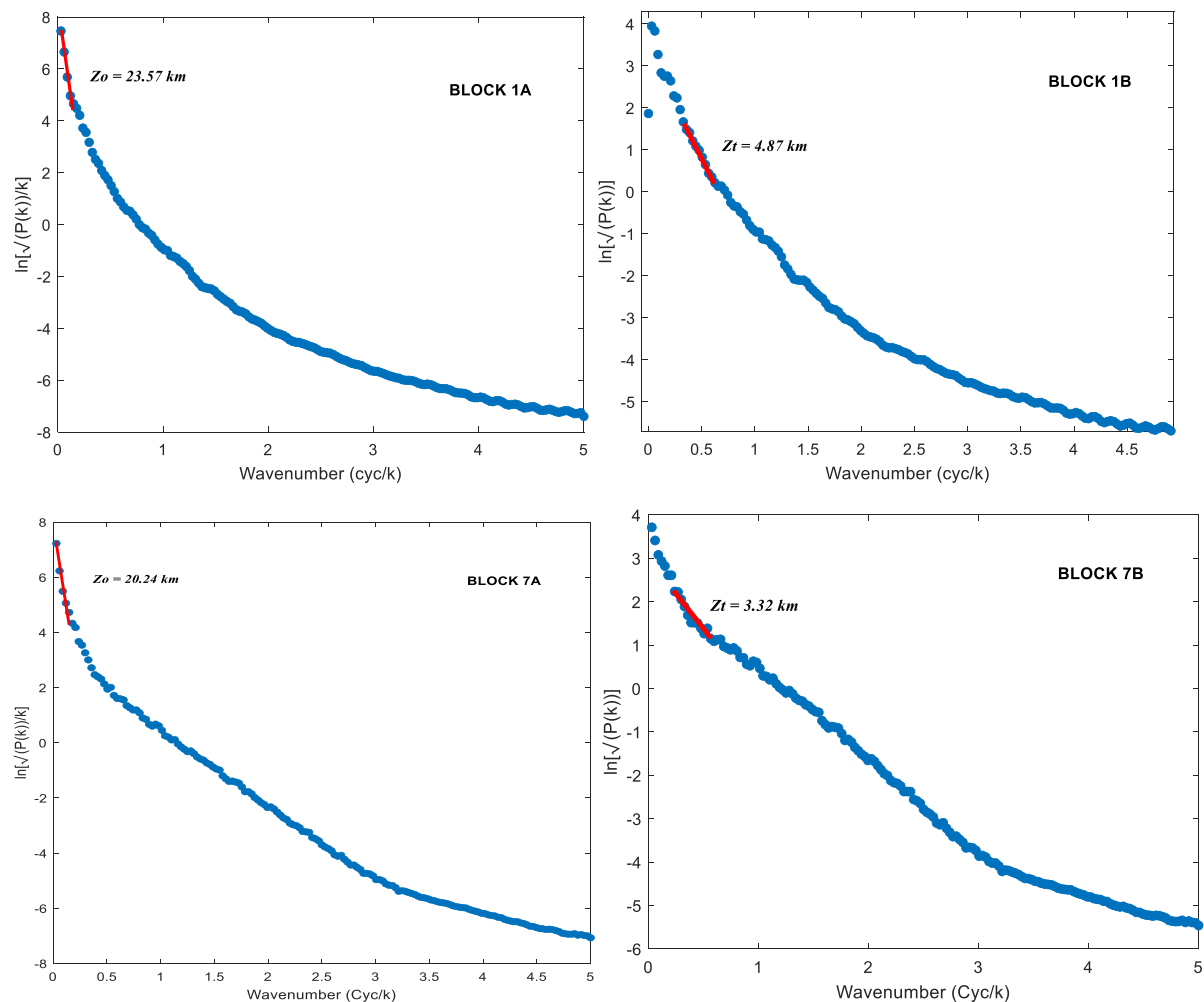


Figure 3: Samples of Averaged power spectral plots for blocks 1 and 7

The correlation between CPD values and geological formations provides essential insights into the geothermal potential and subsurface characteristics of the region. The areas with shallow CPD values indicate regions where geothermal energy can be more readily harnessed, making them prime targets for further exploration and development. These findings align with previous studies, reinforcing the validity and reliability of the results. The contour map (Figure 4) serves as a valuable tool for visualizing the geothermal landscape of the study area. By highlighting the variations in CPD, the map allows researchers to identify key areas for potential geothermal energy exploitation. The deeper CPD values in the central region suggest a more stable thermal regime, whereas the shallow CPD values in the eastern regions point to areas of heightened geothermal activity. Understanding the distribution of CPD values is crucial for assessing the geothermal energy potential of the study area. Regions with shallow CPD values are likely to have higher geothermal gradients and heat flow, making them more suitable for geothermal

energy projects. The identification of these regions can guide future exploration efforts, helping to prioritize areas with the highest potential for successful geothermal energy extraction. Moreover, the study's findings have broader implications for the region's energy strategy. By tapping into the geothermal resources identified through this analysis, the area can reduce its reliance on conventional fossil fuels, promote sustainable energy practices, and contribute to the overall energy security of Nigeria. The integration of geothermal energy into the local energy mix can provide a stable and reliable power source, fostering economic growth and development.

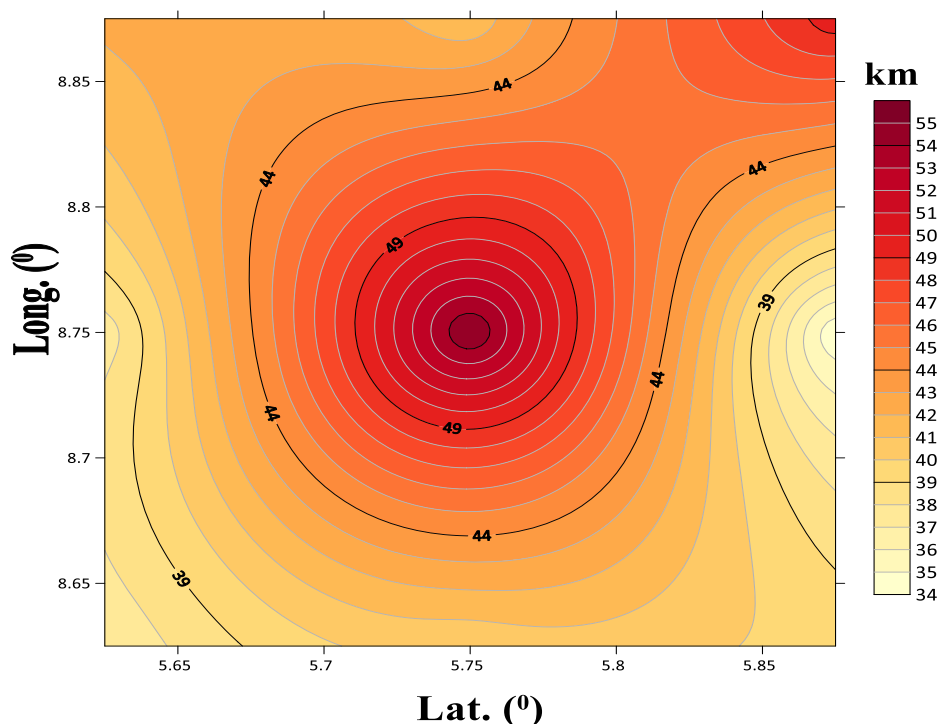


Figure 4: CPD map of the study area.

The geothermal gradient values calculated in the study range from 10.51 to 17.01 °C/km, with an average of 14.13 °C/km. The heat flow values span from 26.27 to 42.53 mW/m², averaging 35.32 mW/m². These results align closely with previous studies conducted by Nwankwo and Sunday [9] and Megwara et al. [10] in the Bida Basin, Nigeria, confirming the reliability and consistency of the data. To provide a comprehensive visual representation of these findings, contour maps for both geothermal gradient and heat flow were generated (Figure 5 and Figure 6). These maps clearly indicate the presence of geothermal energy hotspots in the southeastern and eastern parts of the study area. Specific locations identified as geothermal hotspots include Kusoji, Rogun, Ekopapo-Yagi, Etsufu, Sankwafuji, Momba, Koro, and Rodun. These hotspots are characterised by geothermal gradient values ranging from 14 to 17 °C/km and heat flow values between 36 and 43 mW/m²; marking them as promising regions for geothermal resource exploration.

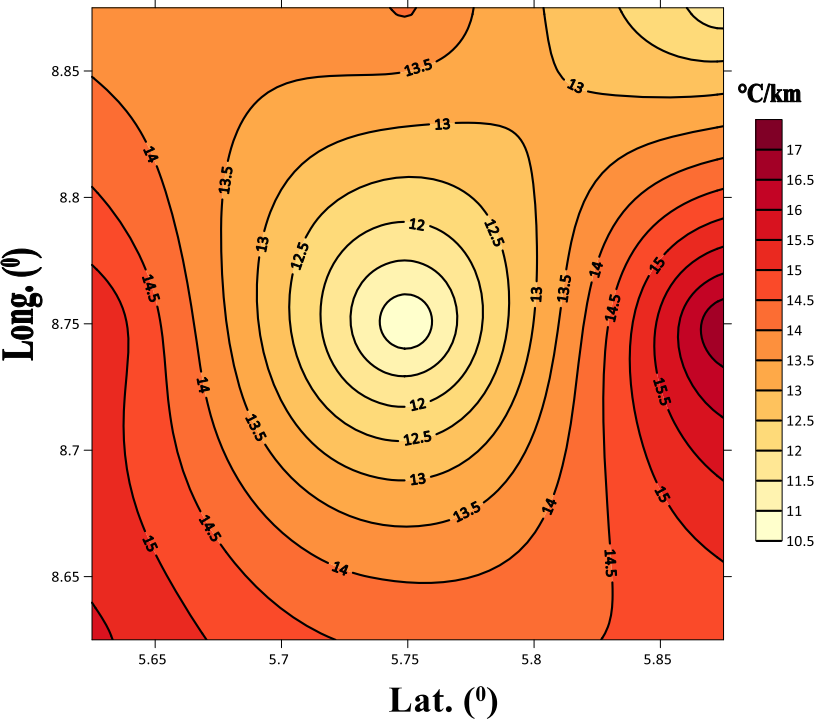


Figure 5: Geothermal gradient map of the study area.

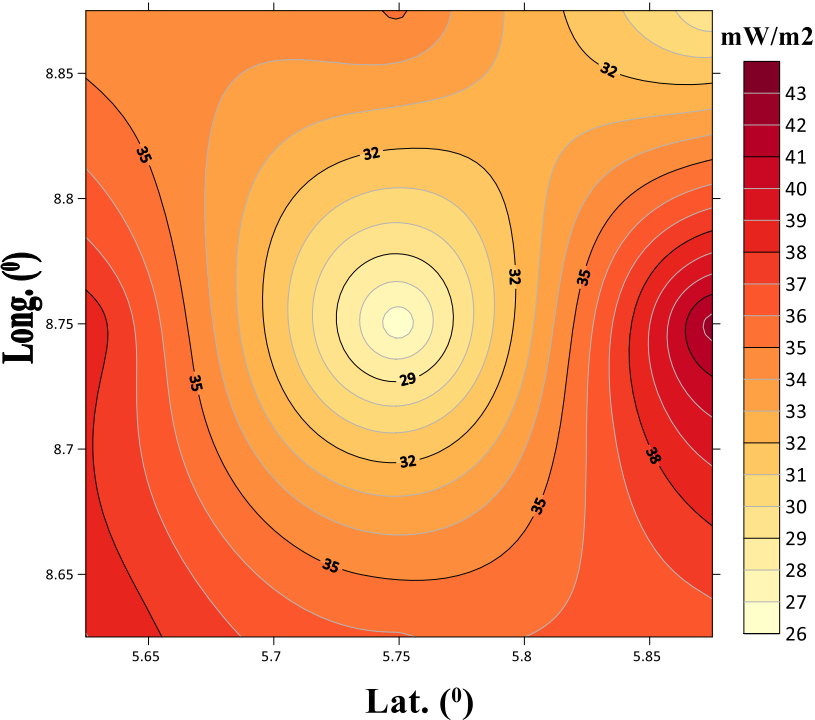


Figure 6: Heat flow map of the study area.

According to Jessop et al. [32], heat flow values exceeding 80 mW/m² are indicative of anomalous geothermal conditions. Although the current study did not record such extreme values, the identified hotspots still represent significant geothermal potential. The contour maps reveal a linear relationship between geothermal gradient and heat flow, illustrating the areas with high, and low geothermal gradients correspond to similar levels of heat flow. This correlation underscores the importance of both parameters in assessing the geothermal energy potential of a region. The identification of these hotspots is significant for several reasons. First, it provides a clear direction for future geothermal energy exploration and development efforts. By focusing on areas with favourable geothermal gradients and heat flow characteristics, stakeholders can optimise resource allocation and increase the likelihood of successful geothermal energy projects. Second, the exploitation of these geothermal resources could have substantial economic and social benefits for the region. Geothermal energy is a clean, sustainable, and renewable energy source that can contribute to the diversification of Nigeria's energy portfolio. By reducing reliance on fossil fuels, geothermal energy development can help mitigate environmental impacts and promote a more sustainable energy future. Furthermore, the development of geothermal energy resources in these identified hotspots can provide a stable and reliable power supply, addressing existing power shortages and fostering economic growth. The availability of continuous and affordable electricity can attract investments, boost industrial activities, and improve the overall business environment in the region. This, in turn, can create job opportunities, reduce unemployment, and enhance the standard of living for local communities. The detailed analysis of geothermal gradient and heat flow values, supported by contour mapping, highlights the significant geothermal energy potential in the southeastern and eastern parts of the study area. The consistency of these findings with previous research reinforces their validity and underscores the importance of these hotspots for future geothermal exploration. By harnessing these geothermal resources, Nigeria can make strides towards achieving energy security, economic development, and environmental sustainability.

5. Conclusions and Recommendation

The spectral analysis of the aeromagnetic data proved highly effective in identifying regions with significant and anomalous geothermal sources. Specific areas, including Kusoji, Rogun, Ekopapo-Yagi, Etsufu, Sankwafuji, Momba, Koro, and Rodun, were highlighted as geothermal energy hotspots. The study's findings for key parameters such as Curie point depth (CPD), geothermal gradient (GG), and heat flow (HF) are consistent with the results of previous research by Nwankwo and Sunday [9] and Megwara et al. [10]. These identified areas demonstrate considerable potential for geothermal energy exploration, which could be harnessed for electricity generation. The development of these geothermal resources presents a promising solution to address the power shortage in the study regions. Furthermore, exploiting geothermal energy could create a more business-friendly environment by ensuring a reliable and sustainable

power supply. In a broader context, the successful development of geothermal energy resources has the potential to significantly contribute to the achievement of sustainable development goals number 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), and 13 (Climate Change), which can also lead to the drastic reduction of unemployment and poverty across Nigeria. By fostering economic growth and stability, geothermal energy development could play a crucial role in boosting the national economy. The alignment of this study's findings with prior research underscores the reliability and significance of the identified geothermal hotspots, highlighting their strategic importance for Nigeria's energy future. It is recommended that the exploration of geothermal energy should be considered for generating an alternative source of electricity in regions with moderate to relatively high heat flow values. Exploiting this renewable energy resource could enhance the economic viability of the region and its environs.

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