

Solid Mineral Potential and Geothermal Energy Reserve of Northern Basement Complex, Nigeria

Možna prisotnost rude in geotermalna energija v Severnem bazalnem kompleksu, Nigerija

Okechukwu Stephen Ifeanyi*, Opara Alexander Ifeanyichukwu, Chikezie Peter Chidozie, Akaolisa Chukwuemeka Casmir, Okoli Austin Emeka, Agoha Chidebere Charles

Department of Geology, Federal University of Technology, Owerri, Nigeria

*Corresponding author: E-mail: stephen.okechukwu@futo.edu.ng

Abstract in English

The spectral analysis of aeromagnetic data over the study area (Northern basement complex, Nigeria) revealed the existence of two major source depths. The second segment of the spectrum layer shows shallow sources ranging in depth from 0.135 km to 0.201 km, with an average depth of 0.140 km. The depth to the basement or deeper source ranges between 1.655 km and 2.021 km, with an average depth of 1.882 km. The Precambrian basement is reflected in the deeper sources, beginning with the first segment of the power spectrum. Structural and topographic relief of the basement surface, lateral differences in basement susceptibilities, and intra-basement features such as faults and fractures contribute to the variation in basement composition. The mean thickness of sediments in the study area is represented by the D2 values obtained from the spectral plots. The depths revealed by this study appears to be reasonable and consistent with previous researchers' findings. Tectonically active regions have a major impact on heat flows. The average heat flow in thermally normal continental regions is reported to be above 60 mW/m². Values between 80 and 100 mW/m² indicate a good geothermal source; values in excess of about 80–100 mW/m² indicate anomalous geothermal conditions.

Keywords: 3-D Euler deconvolution, spectral inversion, magnetic basement depth, linear features, Nigeria

Povzetek

Spektralna analiza aeromagnetnih podatkov je na preiskanem območju razkrila obstoj virov v dveh glavnih globinah. Drugi segment spektralnega sloja kaže na plitve vire, ki ležijo na globini od 0,135 km do 0,201 km, s povprečno globino 0,140 km. Globina do podlage ali globljega vira je med 1,655 km in 2,021 km, s povprečno globino 1,882 km. Predkambrijska podlaga se odraža v globljem viru s prvim segmentom spektra moči. Strukturni in topografski relief površine predkambrijske podlage, lateralne razlike v susceptibilnosti podlage in njene notranje strukture, kot so prelomi in razpoke, prispevajo k razlikam v sestavi podlage. Srednjo debelino sedimentov predstavljajo D2 vrednosti, pridobljene iz spektralnih diagramov. Ocene globin na podlagi te raziskave so realistične in v skladu s predhodnimi ugotovitvami. Tektonsko aktivna območja imajo bistven vpliv na toplotni tok. Medtem ko je povprečni toplotni tok termično normalnih delov kontinentalne skorje nad 60 mW/m², vrednosti med 80 in 100 mW/m² predstavljajo dobre geotermalne vire, še višje vrednosti pa anomalne geotermalne pogoje.

Ključne besede: 3-D Eulerjeva dekonvolucija, spektralna inverzija, globina magnetne podlage, linearne strukture, Nigerija

Introduction

The Nigerian basement comprises the revitalized zone formed by plate collision between the West African craton's passive continental margin and the active continental margin [1]. The basement rocks are thought to be the consequence of at least four significant orogenic deformation processes.

The primary goal of the aeromagnetic survey is to identify minerals or rocks with peculiar magnetic characteristics that manifest themselves by producing anomalies in the strength of the earth's magnetic field [2]. The aeromagnetic survey is used to map abnormalities in the earth's magnetic field, which are connected to the subsurface geological structure. Faults are typically shown by magnetic anomalies as sudden shifts or close spacing in the orientation of the outlines. The premise of an aeromagnetic survey is similar to that of a magnetic survey conducted using a handheld magnetometer, but it enables far wider portions of the earth's surface to be covered swiftly for regional reconnaissance [3]. As the aircraft flies, the magnetometer registers slight variations in the intensity of the ambient magnetic field, which are due to both temporal impacts of the constantly shifting solar radiation and the geographic layout in the earth's magnetic field, the latter due to both the regional magnetic field and the local influence of magnetic minerals within earth's crust [4]. After removing solar and regional impacts, the subsequent aeromagnetic map depicts the global distribution and relative abundance of magnetic elements in the upper crust. Aeromagnetic methods may successfully map hidden and poorly exposed faults in a basin context. The magnetic basement is a group of rocks that reside under sedimentary basins and occasionally outcrop [5]. Linear features on aeromagnetic maps are plainly visible and often depict the form and position of particular folds, faults, joints, veins, lithologic contacts, and other geologic structures that may lead to the finding of specific mineral deposits [6]. They typically depict the general geometry of an area's underlying structures, resulting in a regional structural pattern. Certain lineament patterns have been identified as the most beneficial structural elements for mineral deposit

management. The analysis of variations in a region's Curie isotherm can provide useful information about the regional temperature profile at depth and the composition of surficial geothermal energy [7]. A geothermal energy-rich area is defined by an extremely large temperature gradient and heat movement, based on measurements. As a result, geothermically active sites are expected to have shallow Curie point depths [8]. It is also generally recognized that the bulk of the geodynamic processes visible on the surface are directly influenced by the temperature within the earth [9]. Heat flow measurements in various sections of the African continent have indicated that the mechanical structure of the African lithosphere is diverse in this regard [8]. Magnetic anomalies are investigated in order to calculate the depths to the bottoms of magnetized entities in the crust.

Several geologic formations and stratigraphic strata have been identified and recognized as a result of research on the northern basement complex. The current study has used high-resolution aeromagnetic data to analyze the structures that exist in the northern basement complex. The goal of this research is to employ various methods in the geological interpretation of the section of the basement complex from which data was collected and to use the data to estimate the Curie point depth, heat flow, and geothermal gradient of the region. The aim of this study is to interpret geological features of part of northern basement complex and to infer its solid mineral potential as well as its geothermal energy reserve.

Location and Geology of Study Area

The study area, which covers part of the Northern basement complex, lies between latitudes 9°00'N and 10°00'N and longitudes 7°30'E and 8°30'E (Figure 1). The study area is enclosed within four (4) aeromagnetic maps of the Geological Survey of Nigeria.

The area is well drained by streams and rivers, the sources for most of which are found in the surrounding hills. The drainage system in the area generally flows either northwards or westwards into the Kaduna and Gurara rivers,

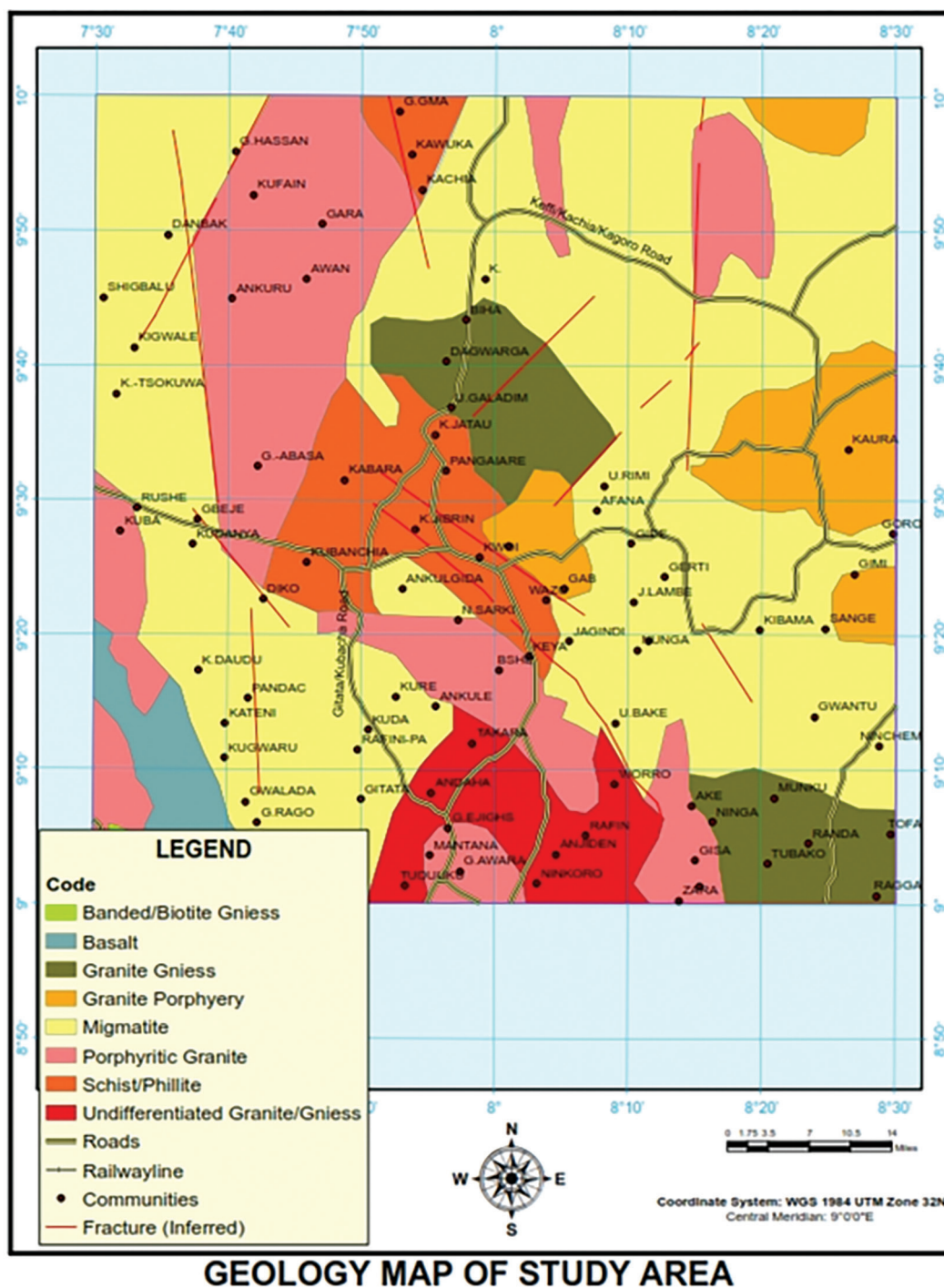


Figure 1: Geologic map of the study area.

which form part of the Niger basin, or southwards into the Mada River, which belongs to the Benue basin. The Farman range of hills forms the divide between the Gurara and Mada drainages. The Mada is represented by the Kogum River. The rivers and most of the smaller streams are perennial.

The relief of the area comprises the lowland and upland areas. The lowland is represented by the Kafanchan plain, which comprises the towns of Kafanchan, Matsirga, Madakia, Katsit, Garaje Kagoro, Tum, Fadan Daji, and Zakwa [10]. These areas have ground surface elevations above the mean sea level range of

between 594 m and 777 m. Examples of granitic rock are found in the Farman ranges, the Zuturung hill, Yariye Mutumbu Hill, Gatum Hill, and the Madauchi Hill [11]. The height of these hills above mean sea level ranged between 762 m and 996.70 m.

The Nigerian basement complex evolution took place over at least four orogenic cycles: the Liberian (2800 ± 200 Ma), the Eburnian (200 ± 200 Ma), the Kibaran (1100 ± 200 Ma), and the Pan-African (600 ± 150 Ma). The Pan-African orogeny is the most significant orogeny in Nigeria, its imprint being ubiquitous [12, 13]. The rocks in this zone (the Pan-African mobile belt) have witnessed a period of remobilization and reactivation that took place during the Pan-African thermo-tectonic event some 600 Ma ago. The study area's regional metamorphism, tectonism, and magmatism resulted in the formation of cracks and faults, and the deployment of intrusive and dyke-like structures [14].

Methods

Data source

The aeromagnetic maps used for the study were obtained from the Geological Survey of

Nigeria. Four digitized aeromagnetic maps covering the study area were acquired, digitized, and interpreted (Figures 2 and 3). This map was part of the nationwide aeromagnetic survey carried out by Fugro Airborne Surveys in 2009 and was sponsored by the Geological Survey Agency of Nigeria. The survey was carried out at 500-m line spacing in NW-SE orientation and 80-m mean nominal terrain clearance flying altitude above the terrain was 500 feet (approximately 152 m) with 5-km control line spacing in the NE-SW orientation. The survey also used measured horizontal gradients and gradient-enhanced gridding. The regional correction of the magnetic data was based on the International Geomagnetic Reference Field (IGRF, Epoch date 1 January 1974). In order to obtain the actual total field magnetic data, 32,000 gammas should be added to the contour values. Out of this, 25,000 gammas represent the regional field while 7000 gammas are arbitrarily removed from the contour values.

Aeromagnetic data analysis

Numerous analytical techniques and procedures are used to examine aeromagnetic data. Among them are aeromagnetic data

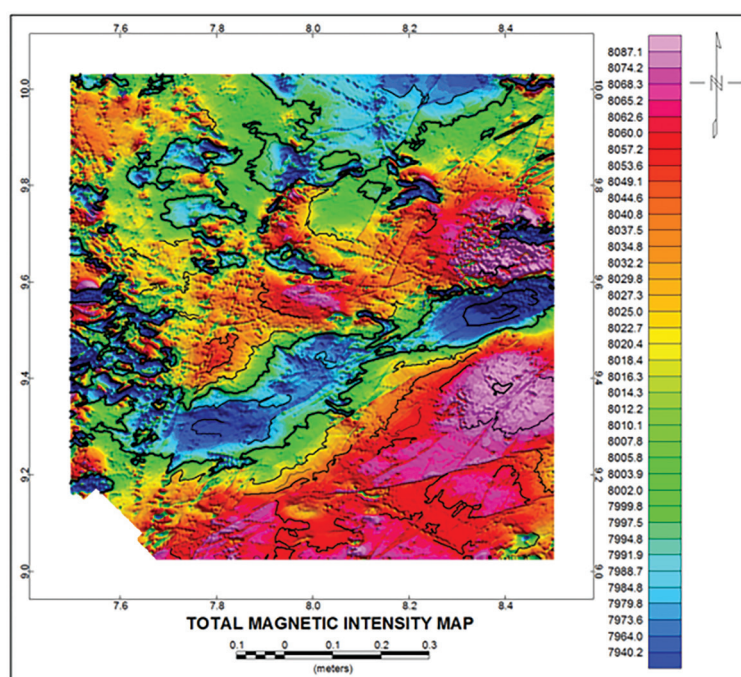


Figure 2: Aeromagnetic field over the study area as a color-shaded, contoured map.

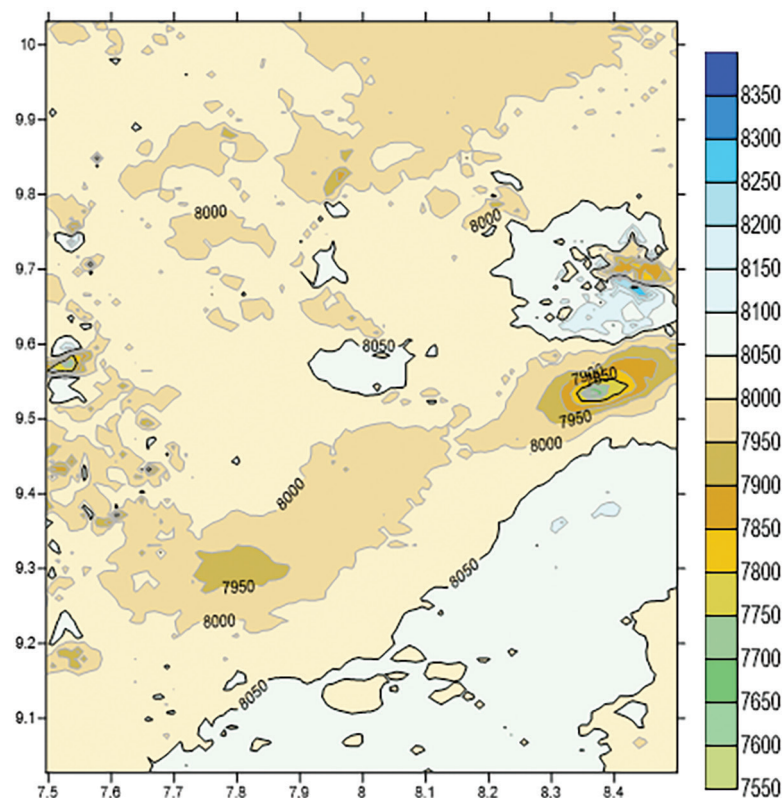


Figure 3: Color-coded pixel contour map of the total magnetic field of the study area in gammas.

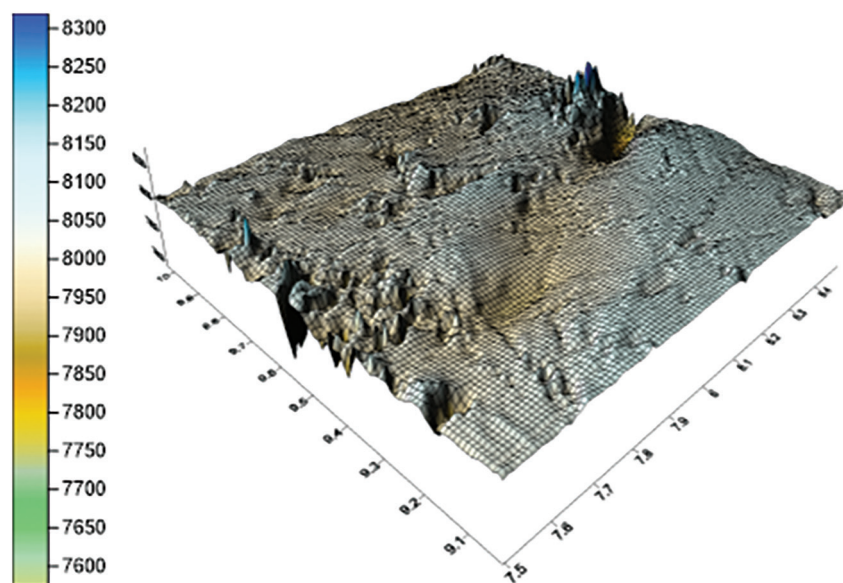


Figure 4: 3-D surface map of the total magnetic field of the study area in gammas.

filtering and convolution, reduction to pole, regional-residual separation, and depth estimate analysis (Figure 4). These tactics are thoroughly examined for improved clarity. The

major purpose of aeromagnetic data processing is to systematically differentiate between local and regional magnetic anomalies and to ameliorate these anomalies.

Aeromagnetic filters

Because not every signal in geophysical research is of interest, filtration methods are always required. Short-wavelength disturbance is often produced by near-surface or shallow, anomalous sources.

A low-pass filter is just a band-pass filter with a very big long-wavelength cutoff. A low-pass filter is called linear because it treats all data identically. When attempting to eliminate short-wavelength but high-amplitude characteristics, this might be an issue because relatively powerful filters may be necessary. Such filters have the potential to impact areas of the data that you did not plan to affect. A nonlinear filter, such as NLFILT, is another option.

A high-pass filter sharpens incoming data by using a convolution filter. This filter is referred to as a 'high-pass' filter because it enables high wave numbers (high frequencies) to pass through to the output channel. Longer-than-the-long wavelength cutoff features in the data will be deleted. Fraser's 1966 approach is used to create the convolution filter. The filter length can be supplied or computed by default. The default length will be established by subtracting the length of the longest wavelength. A band-pass filter is called linear because it treats all data equally. When attempting to eliminate short-wavelength but high-amplitude characteristics, this might be an issue because relatively powerful filters may be necessary. Such filters have the potential to impact areas of the data that you did not plan to affect. A nonlinear filter, such as NLFILT, is another option.

Nonlinear filters are extremely effective in removing high amplitude and short wavelength noise from data. A nonlinear filter can be followed by a linear low-pass filter to smooth out any low-amplitude noise that may remain. The decision process is based on the breadth and amplitude of characteristics in the data compared to a local backdrop. A feature must be smaller than a set width and have a bigger amplitude than a specified amplitude tolerance to be deemed noise.

Reduction to the pole and equator

The reduction to the pole (RTP) conversion compensates for the adjustment caused by the vector essence of the Earth's magnetic field in

between locations of anomalies (closed highs or lows on a contour map) and their causes. Although the symmetric 'highs' are directly centered on the body, the highest gradient of the antisymmetric dipolar anomalies completely matches with the body edges.

The amplitude portion of reduction to the equator is the $\sin(I)$ term, and the phase aspect is the $I \cos(I) \cos(D-q)$. North-south characteristics can blow up while lowering to the equator from low latitudes due to a quantitative error (from the term of $0/0$) in amplitude correction (the $\sin(I)$ component) that is applied when $(D-)$ is $/2$. (i.e., a magnetic east-west wavenumber). This complexity can be reduced or eliminated by choosing a larger latitude solely for amplitude correction, at the cost of substantially under-correcting the amplitudes of adjoining north-south features. Once the field has been decreased to the equator, the regional magnetic field will be horizontal, as will the majority of the source magnetizations.

Curie point depth, geothermal gradient, and heat flow

The Curie point depth is the depth at which the presence of magnetic mineral in the crust shifts from a ferromagnetic to a paramagnetic state, and its capacity to induce recognizable magnetic anomalies reduces as the temperature increases. It is also described as the moment at which some materials lose their permanent magnetic characteristics, allowing induced magnetism to take their place. Organized magnetic moments undergo ferromagnetic transformation and become chaotic paramagnetic [15]. The Curie point depth is calculated from aeromagnetic data as the basal depth of a magnetic source.

The upper limit and centroid of a magnetic layer are calculated using the slope of the power spectrum. The magnetic source's base depth is:

$$Z = 2Z_2 - Z_1 \quad (1)$$

where Z_2 is the centroid of the magnetic layer, and Z_1 is the top bound.

Heat flow estimations on the crust may thus be calculated using depth and thickness

data. The Curie point temperature at which rocks lose their ferromagnetic characteristics bridges the gap between thermal models and models based on magnetic source analyses [16].

Fourier's law is the fundamental relationship for conductive heat transmission. Under the premise that the temperature fluctuation is vertical and the temperature gradient $\left(\frac{\delta T}{\delta z}\right)$ is constant in one dimension, Fourier's law assumes the following form:

$$q = -k \frac{\delta T}{\delta z} \quad (2)$$

where, q is heat flow and k is thermal conductivity.

Curie temperature θ^0 can also be expressed as:

$$\theta = \left(\frac{\delta T}{\delta z} \right) d \quad (3)$$

where, d is the Curie-point depth (as obtained from the spectral magnetic analysis).

The surface temperature is 0°C , and $\frac{\delta T}{\delta z}$ will remain static if no heating systems or heat sinks exist between the earth's crust and the Curie-point depth. Magnetic mineralogy influences the Curie temperature.

Depth estimation by 3D Euler deconvolution

The standard 3D Euler method relies on Euler's homogeneity equation, which pertains to the potential field (magnetic or gravitational) and its gradient elements to the position of the causes via the extent of homogeneity N , which can be assumed to be a structural index. In addition to depth estimates, the method employs a structural index. On conventional maps, the Euler method observations are represented as point solutions that include the location (position of solution) and the depth (color range).

The located Euler 3D technique, which, unlike the standard Euler method, examines and restricts grid positions prior to actually computing depth estimations using Euler deconvolution, is another alternative for restricting the solutions discovered by the Euler method. The located Euler technique calculates the analytic signal (3p) and locates peaks in the

grid of analytic signals. The standard depth assessment centered on Euler deconvolution is then implemented only to these peak spots. Nevertheless, since it generates far fewer solutions than the standard Euler method, it is only appropriate for overwhelmingly clear anomalies and does not form solution clusters.

$$ASig = \sqrt{(dx.dx) + (dy.dy) + (dz.dz)} \quad (4)$$

Results and Discussions

Total magnetic intensity map

Magnetic anomalies of both short and long wavelengths were interpreted within the study area. The total magnetic field intensity map produced by digitization is displayed as both a total field intensity map and a three-dimensional map.

The total magnetic intensity after digitization ranged from 7940.2 nT to 8087.1 nT, indicating a magnetic signature. The northern part of the study area is dominated by magnetic lows, indicating that the area has low magnetic concentration and thus lower susceptibility. Magnetic highs can be found in the study area's south-eastern corner. The existence of granitic rocks that intruded through both the crystalline basement and metasediment belts might explain the magnetic high of magnitude 8087.1 nT. When likened to the geological map of the study area, the total magnetic map in gamma has closures in the northeastern part of the area that conforms with the granite porphyry. These closures are lineament expressions.

The wireframe map of the total magnetic field of the study area has a lot of undulation with a lot of highs, which is an indicator of a magnetic high, as shown in the 3-D surface map of the total magnetic field of the study area in gammas. The magnetic highs are represented by the colors seen in the undulation. This indicates that there is a higher concentration of magnetically susceptible minerals.

The 3D aeromagnetic plot indicates that there is an undulating topography and are areas of magnetic low, relatively speaking. The 3-D relief map revealed two distinctive features:

areas of low relief (plains) and areas of high relief. The high-relief area is also believed to be more tectonically active than the low-relief area and as such contains mineral deposits.

Digital filtering

A high-pass filter sharpens the input data through the application of a convolution filter. A high-pass filter emphasizes short wavelengths and eliminates wavelengths larger than the cut-off wavelength. Figure 5a clearly shows clusters of positive and negative anomalies. These anomalies are found to be distributed with varying trends. The prominent anomalies in the southeastern part of the study area and the other anomalies were retained.

The low-pass filter is defined as a filter that passes long wavelengths and rejects all wavelengths smaller than the cut-off wavelength. The low-pass filtering process is used to isolate the regional features from the local ones. The anomaly map with a low-pass magnetic filter (Figure 5b) shows that the well-defined trends of anomalies in the aeromagnetic map still persist. A band-pass filter changes channel data such that features longer than the long-wavelength cutoff and shorter than the short-wavelength cutoff will be removed. A band-pass filter is considered linear because all data is treated by the filter equally (Figure 5c).

Nonlinear filters are very good for removing high amplitude and short wavelength

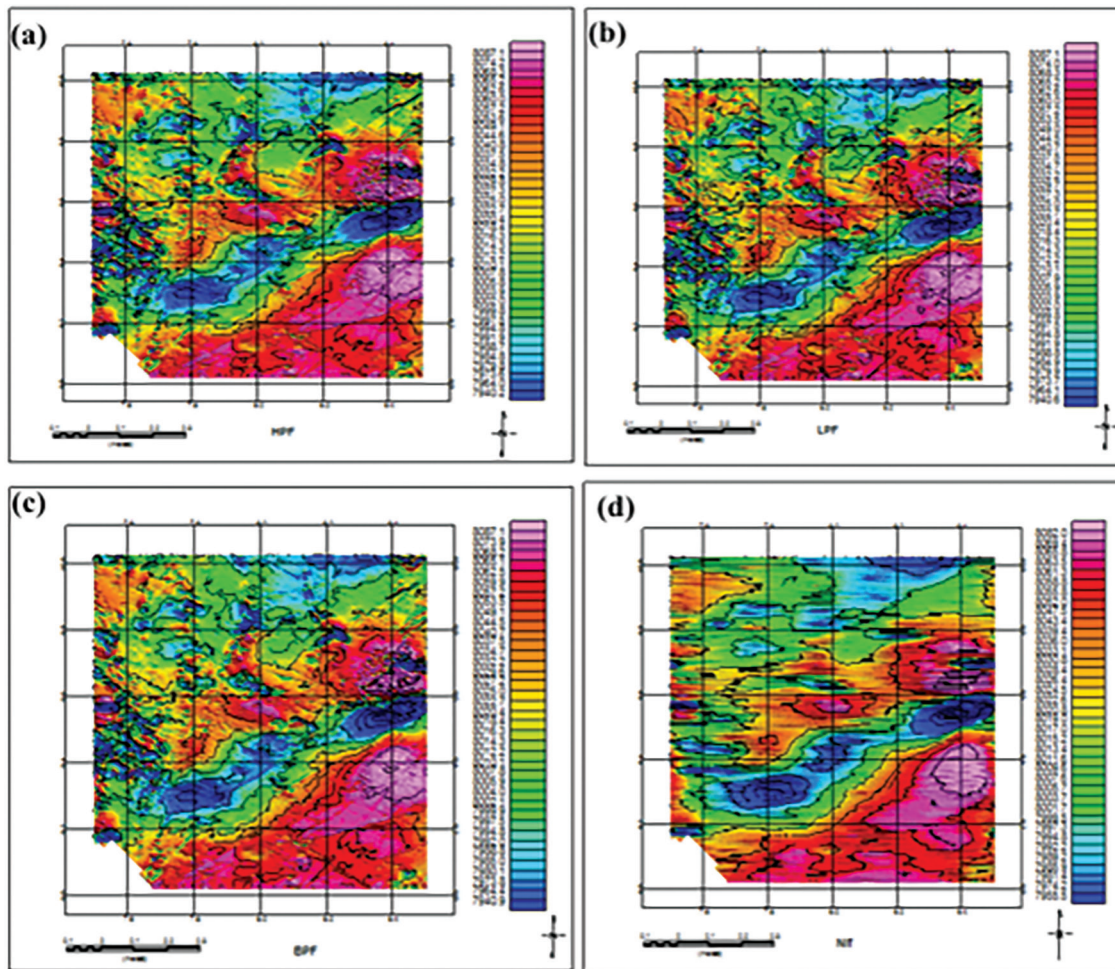


Figure 5: (a) High-pass filter, (b) low-pass filter, (c) band-pass filter, (d) non-linear filter map of the total magnetic field intensity of the study area.

noise from data. A nonlinear filter can be followed by a linear low-pass filter to smooth out any low-amplitude noise that may remain (Figure 5d).

Regional-residual separation

The regional gradients in the aeromagnetic data were removed using multi-regression least squares analysis to fit a plane surface to the data. The residual anomaly values are obtained by subtracting the regional field values from the observed data.

The residual magnetic intensity of the study ranges from -83.7 gammas to 70.2 gammas, as shown in Figures 6a-d. The study area is characterized by negative residual anomalies surrounded by positive residual anomalies, as shown by the figures. These negative

anomalies, surrounded by an elongated positive anomaly, reflect a significant magnetization zone surrounded by a lower magnetization zone. The residual anomalies in Kafanchan and Jema'a are primarily positive, according to the first, second, third, and fourth residuals.

The negative residual anomalies correspond to a low magnetization zone, whereas the positive residual anomalies correspond to a high magnetization zone. Such negative anomalies, surrounded by an elongated positive anomaly, reflect a significant magnetization zone surrounded by a lower magnetization zone. Even so, the occurrence of the elongated positive anomaly in the study area might be credited to magmatic activity, which led to a high concentration of magnetic minerals in the majority of near-surface

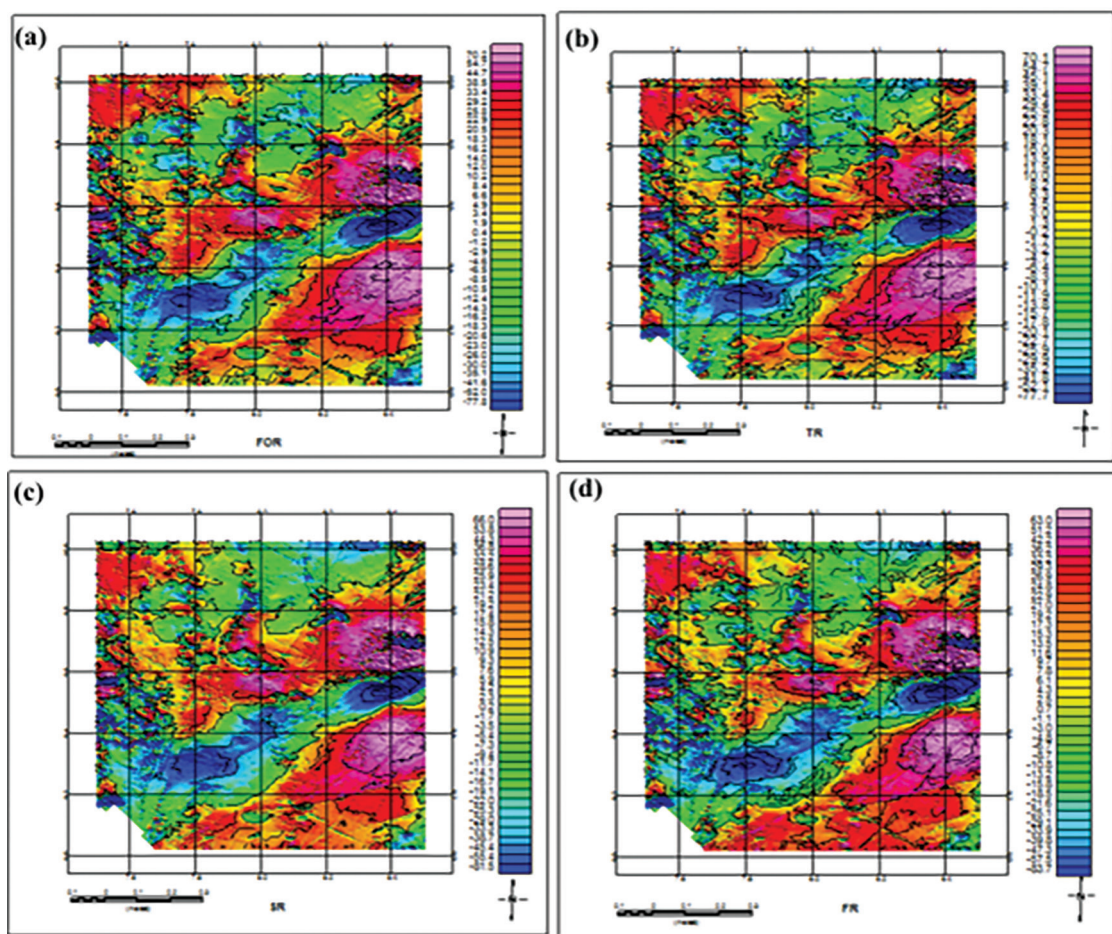


Figure 6: (a) First-degree residual, (b) second-degree residual, (c) third-degree residual, (d) fourth-degree residual field over the study area as a color-shaded contour map.

rocks. It should be noted that a strong magnetic anomaly in the vicinity of the study area might be influenced by mafic rocks.

The regional fields establish the major tectonic elements of a deeper and regional extent that affect and control the structural framework of the study area. First- to fourth-degree regional anomalies of the aeromagnetic data reveal a dominant regional trend of NE-SW trends and some E-W trends.

The structural trends suggested by the polynomial surfaces have trend directions of NE-SW, E-W, and NW-SE. The NE-SW trend is the dominant orientation in the study area, and it depicts the Pan-African orogeny. The fact that the structural trend is still dominant shows that there is little tectonic activity going on in the area. This agrees with the geologic literature that indicates the rocks in this zone (the Pan-African mobile belt) have witnessed a period of remobilization and reactivation that took place during the Pan-African thermo-tectonic event.

Equator reduction

In low magnetic latitudes, reduction to the equator is being used to focus the peaks of magnetic anomalies over their sources. This could improve the data's interpretability while preserving its geophysical relevance. The inclination and declination of the Earth's main magnetic field determine the shape of any anomaly. The same magnetic body will produce a different anomaly depending on where the anomaly occurs. The reduction to equator filter reconstructs the magnetic field of a data set as if it were at the equator.

The study area is located at a low latitude. At lower altitudes, a distinct amplitude adjustment is normally needed to avoid the north-south signal in the data from controlling the results. This explains why the trend orientation remains the same. It shows the most of the basement rocks have large remnant magnetizations similar to the present-day orientation.

The TMI data was reduced to the equator by assuming an inclination of $I = -0.47^\circ$ and a declination of $D = -6.78^\circ$ according to IGRF (International Geomagnetic Reference Field).

To reduce the field to the equator, the Geosoft package software V.6.3 has been used (transformation done in the Fourier domain). These algorithmic transformations correlate to space domain convolutions of the initial signal with a specific operator. Analyses have usually been done in the Fourier domain, for which convolution was replaced by simple multiplication. The magnetic field and magnetization would be horizontal, as with the majority of magnetized sources.

The RTE map (Figure 7) depicts various zones based on magnetic intensity variations that may be associated to structural variation zones based on geologic investigations. The study area's southeastern corner has the largest magnetic intensity values.

Horizontal and vertical gradient

A horizontal gradient map can be used to define the contacts between basement lithologies, which can represent individual basement blocks, faults and fault boundaries, and other linear features. However, keep in mind that the horizontal gradient method requires many assumptions, and that violations of these assumptions can result in contact displacement away from their true locations.

When compared to the TMI and RTE-TMI maps, the horizontal gradient method provides contact locations that are continuous, thin, and straight (Figure 8). The HGM map reveals significant anomalies in the ENE-SWS and NE-SW directions. The range of anomalies is -5446.9 gammas to 5460.9 gammas. The anomalies are associated with a geological contact zone with a significant magnetic susceptibility difference. The maxima of the HGM map are shown to highlight the contacts direction shown on the HGM map. This map reveals structural complexities, such as faults in the basement. As a result, the horizontal gradient method is used to locate physical property (magnetization) boundaries.

Derivatives do have influence in sharpening anomaly edges and improving simplistic features. To improve magnetic anomalies affiliated with faults and other structural discontinuities, the first vertical derivative of the residual map is used. The TMI map has been sharpened in

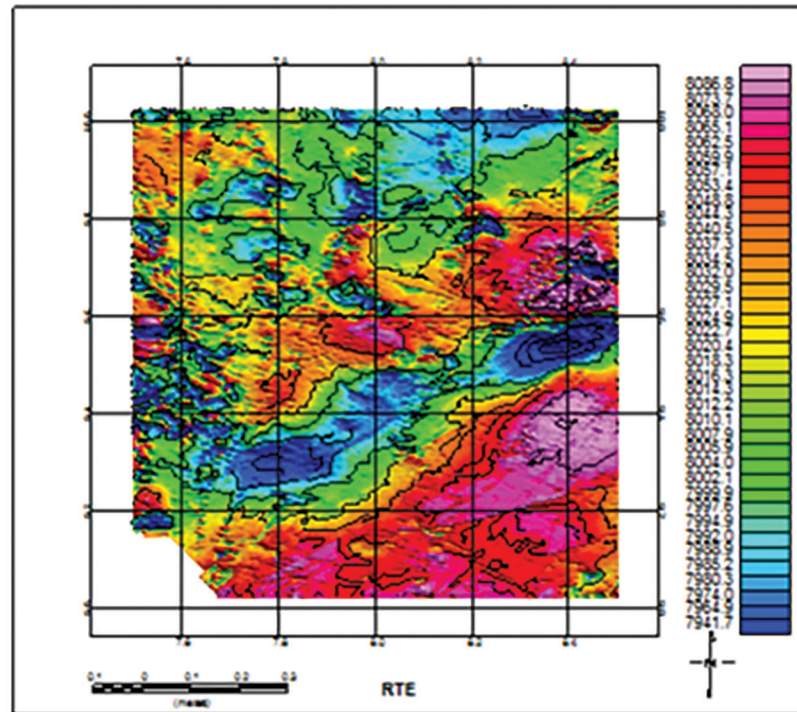


Figure 7: Reduction to equator of the aeromagnetic field over the study area as a color-shaded, contoured map.

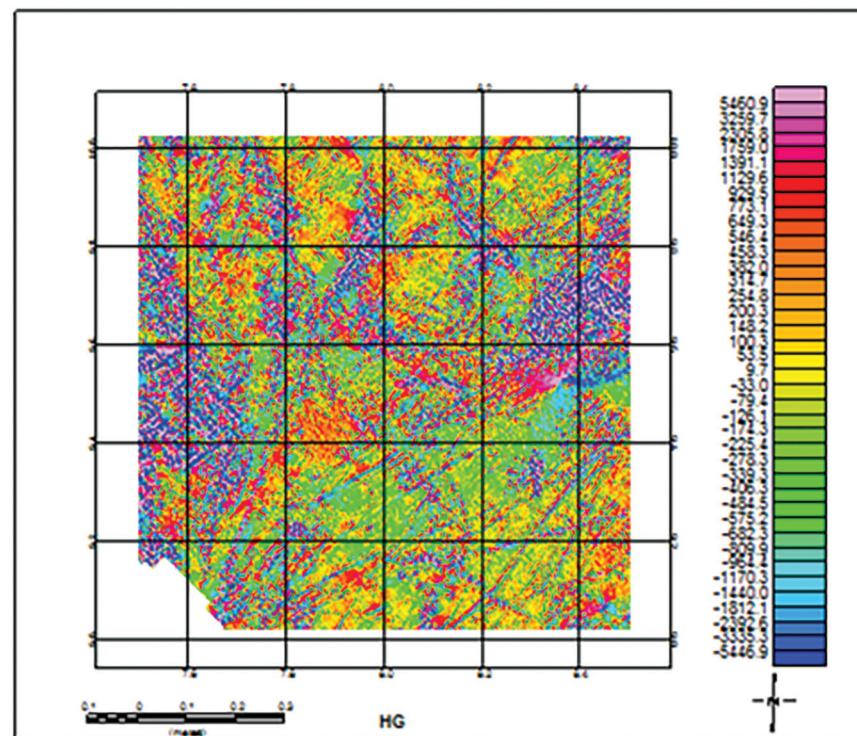
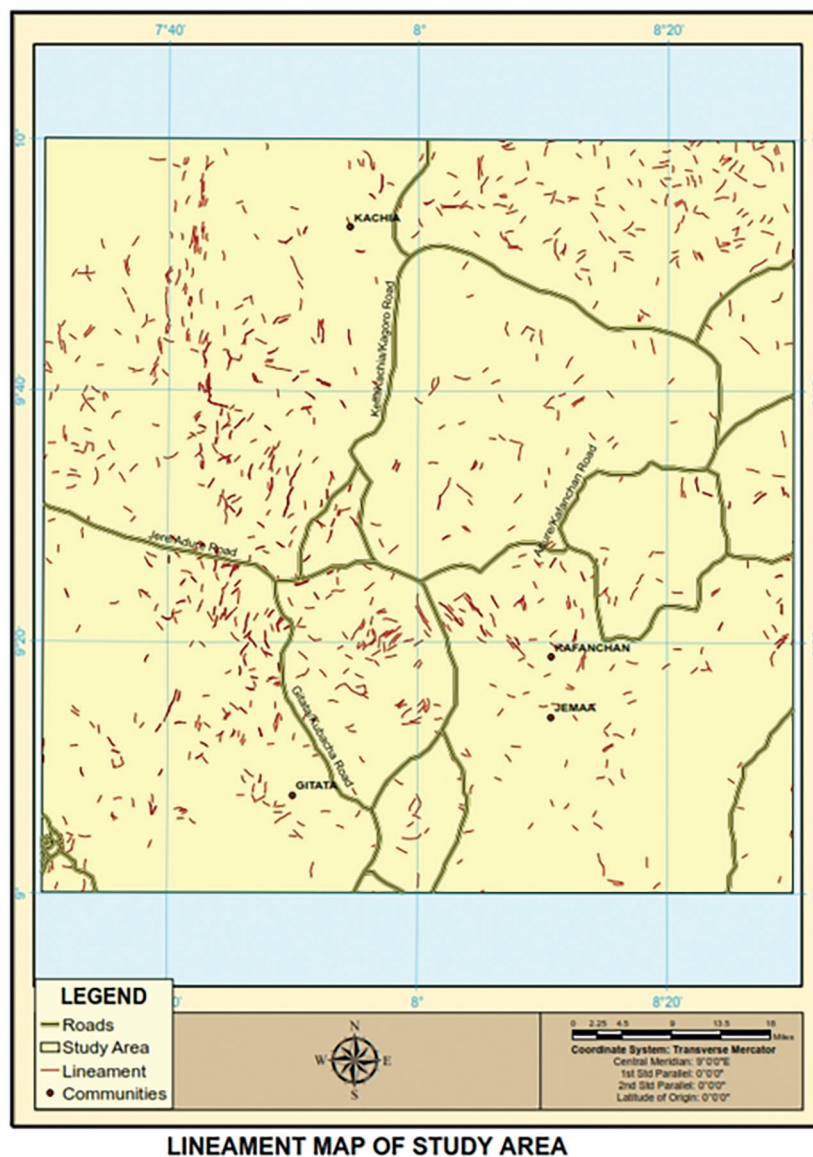


Figure 8: Horizontal gradient of the aeromagnetic field over the study area as a color-shaded, contoured map.



LINEAMENT MAP OF STUDY AREA

Figure 9: Lineament map of study area.

Figure 9. Concealed features such as fractures and dykes dominated. The geological contacts that are important for the structural framework of the study area are highlighted. Fractures and faults, and the formation of intrusive and dyke-like structures, are the effect of regional metamorphism, tectonism, and magmatism in the research region.

The lithologic limits between the various formations, primarily basement, were revealed by the zero contours of the second vertical derivatives. The dispersion of mafic and felsic rock-forming minerals was found to be linked

to positive and negative second vertical derivative anomalies in the research region.

Spectral depth estimation

SPECTRDEP, a FORTRAN program, was used to perform spectral analysis on the aeromagnetic data. To evaluate the depths of the anomalies to their magnetic sources, the study area was divided into 16 intersecting segments.

Using the power spectrum of the total intensity field, the spectral analysis plot calculates the average depth to buried magnetic rocks. In the spectral analysis, a two-layer (D1 and D2)

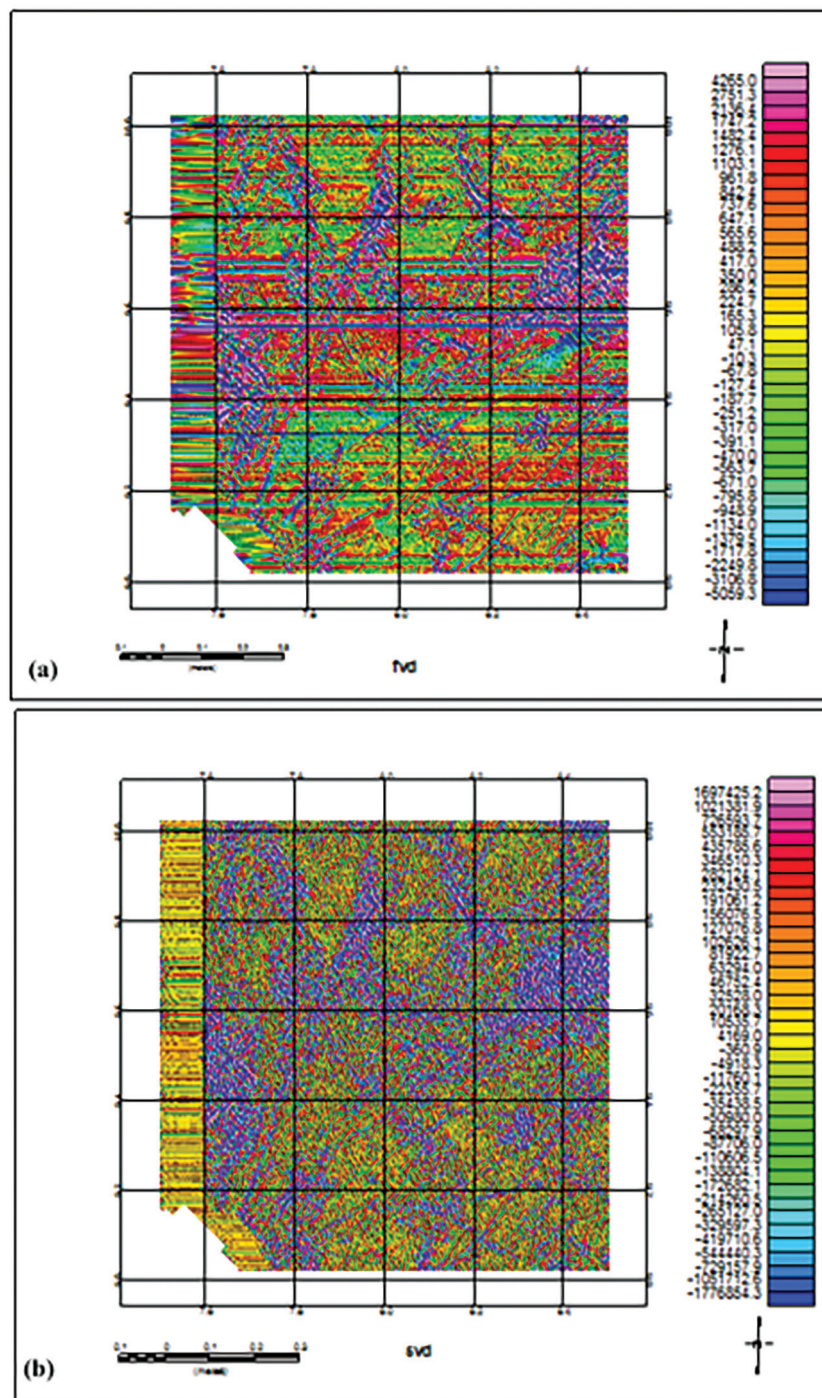


Figure 10: (a) D1 values (shallow magnetic basement depths) and (b) D2 (basement depths across the study area).

depth model is proposed. (Figure 10a and 10b). These depths have been calculated using the slope of the log-power spectrum at the lower end of the total wave number or spatial frequency band. The method estimates the depth

of a group of magnetized blocks with varying depth, width, thickness, and magnetization.

The estimated depths to magnetic basement are shown as D1 and D2, respectively (Table 2). The depth to the shallower source

represented by the second segment of the spectrum is represented by the first-layer depth (D1). The depth of this layer (D1) ranges from 0.135 km to 0.201 km, with an average depth of

0.140 km. The depth of the second layer (D2) varies between 1.655 km and 2.021 km, with an average depth of 1.882 km. Magnetic rocks that have intruded onto the basement surface may be responsible for this layer. As a result, the D2 values obtained from the spectral plots represent the average depths to the basement complex (sedimentary thickness) in the blocks under consideration.

Table 1: Computed spectral depths.

Portions	Depth 1 (m)	Depth 2 (m)
1	136.34	1659.50
2	200.53	1618.28
3	135.85	1585.18
4	136.15	2021.74
5	136.37	1615.90
6	136.36	1864.81
7	136.41	1933.89
8	136.39	1770.43
9	136.36	1655.05
10	136.34	1657.43
11	136.30	1810.54
12	135.98	1784.44
13	136.42	1850.81
14	138.17	1999.46
15	135.50	1756.11
16	135.61	1871.02

Curie point depth, geothermal gradient, and heat flow

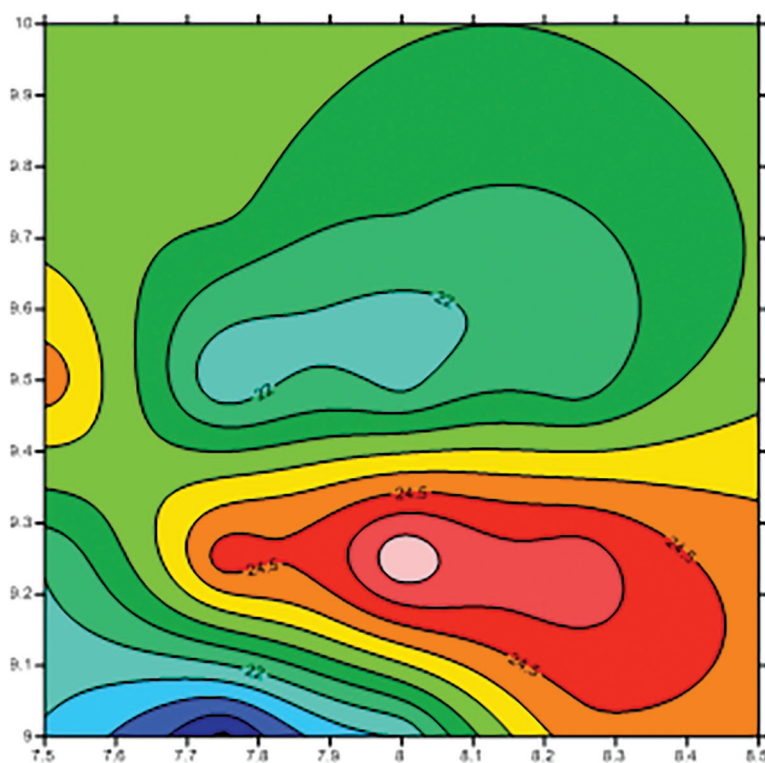
From Table 3 below, we observed that the Z_0 centroid of the magnetic source ranges from 12.120 to 15.426 and the depth to the top boundary Z_t ranges from 1.585 to 2.022. The basal depth (Z_b) of the magnetic source was calculated. The obtained basal depth (Z_b) of magnetic sources is assumed to be the Curie point depth. The obtained Curie point depth, which ranges from 22.306 to 29.234, reflects the average local curie depth point values beneath each block. The obtained Curie point was also used to construct curie isotherm as well as the 3-D Curie point depth in the study area. The shallow depth to bottom of magnetic sources indicates a concentration of major geologic

Table 2: Computed spectral depths in km according to sheets.

Sheets	Spectra L Block	Longitude		Latitude		Depth (km)	
		X_1	X_2	Y_1	Y_2	D_1	D_2
Kachia	13	7.50	7.75	9.75	10.00	0.136	1.851
	14	7.75	8.00	9.75	10.00	0.138	1.999
	9	7.50	7.75	9.50	9.75	0.136	1.655
	10	7.75	8.00	9.50	9.75	0.136	1.657
	15	8.00	8.25	9.75	10.00	0.136	1.756
Kafanchan	16	8.25	8.50	9.75	10.00	0.135	1.871
	11	8.00	8.25	9.50	9.75	0.136	1.810
	12	8.25	8.50	9.50	9.75	0.135	1.784
Gitata	5	7.50	7.75	9.25	9.50	0.136	1.616
	6	7.75	8.00	9.25	9.50	0.136	1.864
	1	7.50	7.75	9.00	9.25	0.136	1.660
Jema'a	2	7.75	8.00	9.00	9.25	0.201	1.618
	7	8.00	8.25	9.25	9.50	0.136	1.934
	8	8.25	8.50	9.25	9.50	0.136	1.770
	3	8.00	8.25	9.00	9.25	0.136	1.585
	4	8.25	8.50	9.00	9.25	0.136	2.021

Table 3: Computed spectral depth, Curie temperature and heat flow.

	Longitude		Latitude					CPD (km)	Geothermal Gradient (°Ckm ⁻¹)	Heat Flow (mWm ⁻²)
SPECTRAL LINES	X ₁	X ₂	Y ₁	Y ₂	Z _t	Z ₀	Z _b		dT/dZ	q
1	7.50	7.75	9.00	9.25	1.660	14.354	27.048		21.44336	53.6084
2	7.75	8.00	9.00	9.25	1.618	15.426	29.234		14	49.5997
3	8.00	8.25	9.00	9.25	1.585	14.286	26.987		21.49183	53.7296
4	8.25	8.50	9.00	9.25	2.022	12.950	23.878		24.2901	60.7253
5	7.50	7.75	9.25	9.50	1.616	13.980	26.344		22.01639	55.0409
6	7.75	8.00	9.25	9.50	1.865	12.620	23.375		24.81283	62.0321
7	8.00	8.25	9.25	9.50	1.934	12.120	22.306		26.00197	65.0049
8	8.25	8.50	9.25	9.50	1.770	12.340	22.91		25.31646	63.2912
9	7.50	7.75	9.50	9.75	1.655	12.734	23.813		24.35644	60.8911
10	7.75	8.00	9.50	9.75	1.657	14.320	26.983		21.49501	53.7375
11	8.00	8.25	9.50	9.75	1.811	14.240	26.669		21.74809	54.3702
12	8.25	8.50	9.50	9.75	1.784	13.980	26.176		22.15770	55.3943
13	7.50	7.75	9.75	10.00	1.851	13.410	24.969		23.22880	58.072
14	7.75	8.00	9.75	10.00	1.9996	13.510	25.0204		23.18108	57.9527
15	8.00	8.25	9.75	10.00	1.756	13.720	25.684		22.58215	56.4553
16	8.25	8.50	9.75	10.00	1.871	13.340	24.809		23.37861	58.4465

**Figure 11:** Plot of the geothermal gradient of the study area.

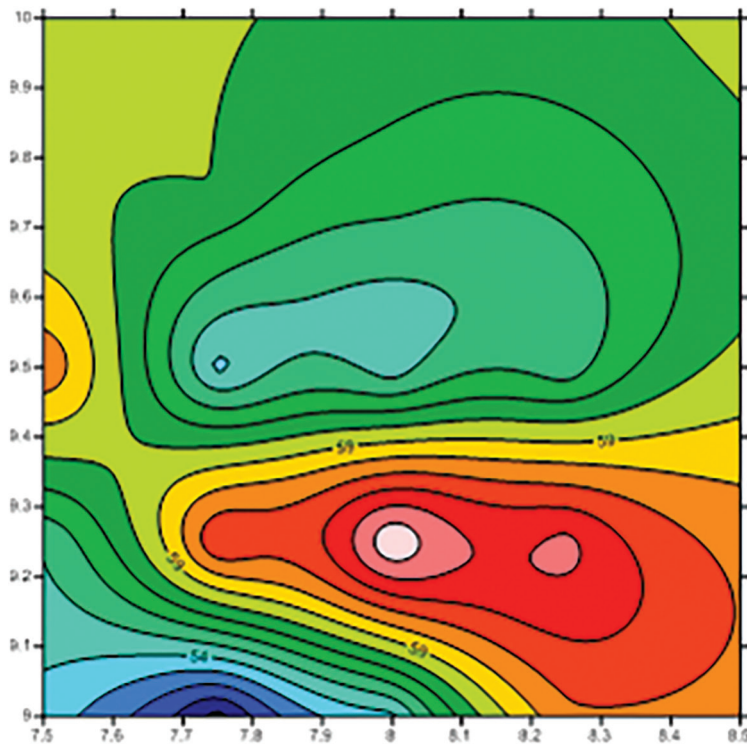


Figure 12: Plot of the heat flow.

lineaments (faults and fractures) is noticed in these regions and this is a result magnetic intrusion at depths.

An empirical relation, which is a one-dimensional heat-conductive transport model, is used to estimate heat flow and geothermal gradient. The model is based on Fourier's law. In a one-dimensional case under assumptions, the direction of temperature variation is vertical, and the temperature gradient is assumed to be constant. Using a Curie point temperature of 580 °C [9], the geothermal gradient was calculated, and it ranges from 19.839 to 26.002 °Ckm⁻¹ with an average geothermal gradient of 22.959 °Ckm⁻¹ (Figure 11).

The heat flow in the study area ranges from 49.608 to 65.005 mW/m². The average heat flow obtained in the study area is 57.397 mW/m² (Figure 12). This may be considered as typical of continental crust. And this is also consistent with the values of Curie point depth noted in this area. The areas with a high heat flow correspond to areas where we have anomalies. This depicts magnetic anomalies or areas where the crust is thin due to magmatic

activities that took place during the tertiary period. The quantitative change in Curie depth observed in the study area implies that the heat flow in the study area is not uniform.

Measurements have shown that a region with significant geothermal energy is characterized by an anomalous high temperature gradient and heat flow. It is expected that geothermically active areas will be associated with shallow Curie points.

3D Euler deconvolution depth estimation

Figure 13a – d show the depth estimate solutions as colored point solutions. Four geological models' standard Euler solutions are presented. The figure shows the depth estimates for structural indexes of 0.0, 1.0, 2.0, and 3.0. The Euler solutions used for the plots were calculated using a variety of geologic models defined by contacts, dike and sill structures, pipes, and spheres. As a consequence, structural indices with values ranging from 0 to 3 were used. Whereas solutions for the standard Euler deconvolution were acquired using diverse structural indices, all of the solutions

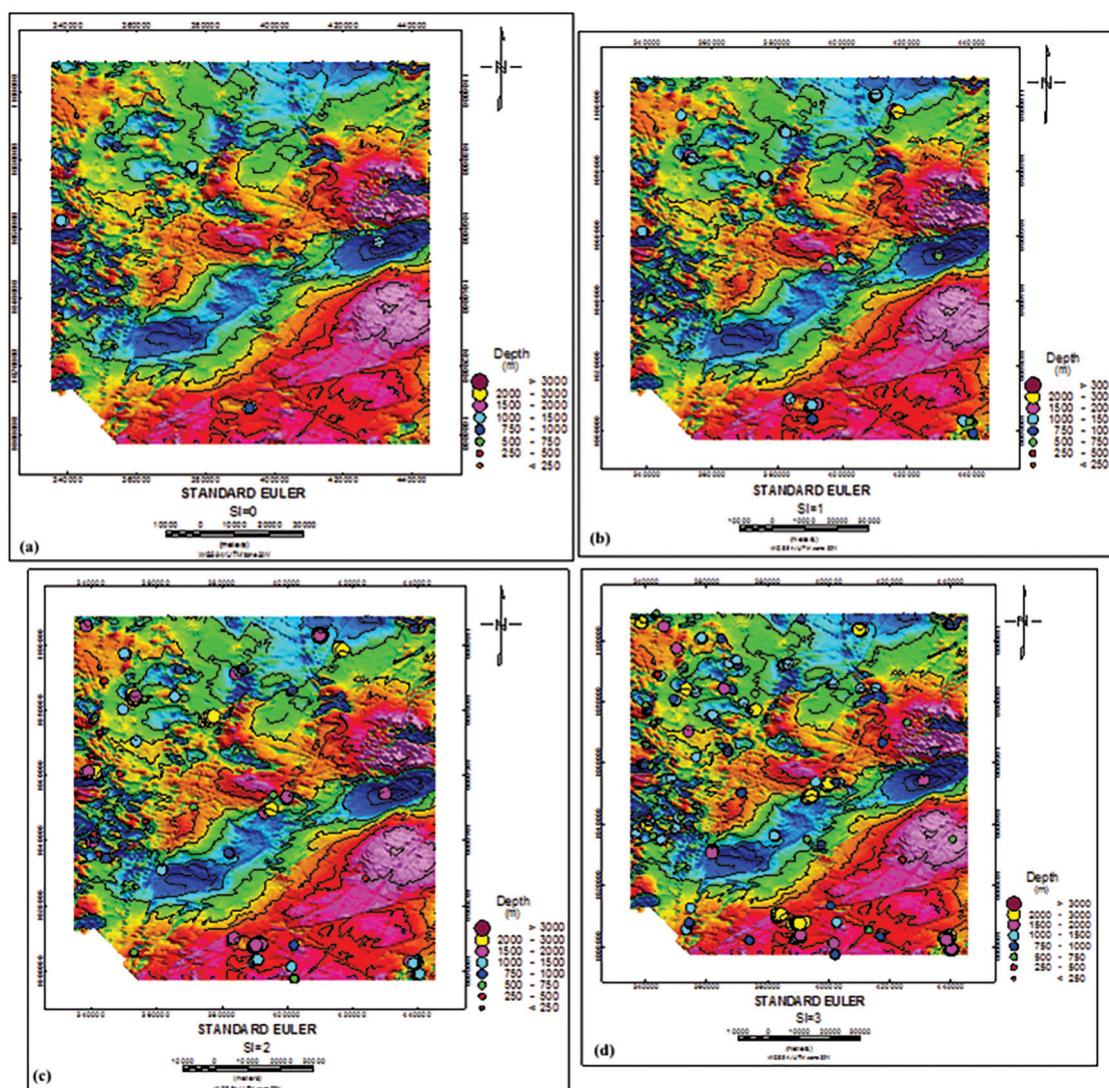


Figure 13: 3D Euler deconvolution depth solutions of the study area: (a) structural index = 0, (b) structural index = 1, (c) structural index = 2, (d) structural index = 3.

are similar. As a result, Euler I values of 2.0 and 3.0 were considered too high to be expressly interrelated with recognized source bodies in the study region, and the correlating solutions were discarded.

When these depth estimates are compared to the information obtained from the spectral analysis, the results from both depth estimation methods show a positive correlation.

Conclusion

The magnetic basement is a group of rocks that underpin sedimentary basins and may

occasionally outcrop. Onyedim et al. [17] believe that if magnetic units occur at the basement surface, then depth determinations for these will accurately map the basin floor morphology and structure. Nigeria has a complex network of fractures and lineaments with dominant NE-SW, NW-SE, and N-S axes [18]. A single-digitized total magnetic field map of the study area was created using the aeromagnetic analysis. The map has made the geology and basement topography of the study area clearer.

The study area has an average heat flow of 57.397 mW/m², which is less than 60 mW/m², but in the southwest region, heat flow increases significantly and can be termed as a

good geothermal source and as such should be investigated through further work to ascertain the cause of the anomaly. The knowledge of the depth to Curie point and its heat flow are of interest and can be related to the thermal history of an area. This study illustrates that surface magnetic data can be used to produce Curie depth estimates even for regions with a paucity of heat flow and geothermal gradient data. On the basis of this result, we then conclude that, the most plausible mechanism responsible for the moderate heat flow observed in this study is tectonically induced rifting and magmatism that occurred during the cretaceous, tertiary period and Pan-African orogeny.

The result of the Euler deconvolution suggests that there could be a presence of geologic structures such as dykes and sills in the area. This is substantiated by the many clusters in the Euler deconvolution map. This suggests the possibility of deep-seated intrusive rocks in the area.

A region with significant geothermal energy has an anomalous high temperature gradient and heat flow. It is expected that geothermically active areas will be associated with shallow active points. Geothermal energy can also be found in areas where basement rocks with reasonably mild heat flow are surrounded by a thick layer of thermally insulated sediments. As there is no indication of volcanic activity in the study region, it can be deduced that geothermal prospect areas in this study could be areas in which a thick blanket of thermally insulated sediment covers basement rocks; thus, these areas with high heat flow might be geothermal sources and reservoirs and will aid in defining the presence of productive geothermal reservoirs at desirable temperatures and depths in the study region. The pattern of the Curie point depths is useful as an index of geothermal structure.

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