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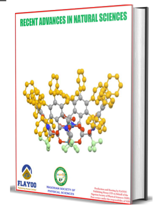

Depth estimation of the residual field of Patigi Area, Nigeria , using source parameter imaging and spectral depth analysis

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ABSTRACT

Aeromagnetic depth estimation was carried out over a one-half-degree sheet in the south-western Bida Basin, Northcentral Nigeria. The area, bounded by latitudes 8°30′–9°0′ N and longitudes 5°30′–6°0′ E, is underlain by Campanian–Maastrichtian sandstones and basement rocks of granite-gneiss and migmatites. Potential field methods were applied to investigate subsurface sedimentary thickness. Regional–residual separation was achieved using polynomial fitting, and the residual field was analyzed using source parameter imaging (SPI) and power spectrum techniques for depth estimation around Pategi and environs. The residual map was subdivided into nine spectral sections to examine depth variations from magnetic sources. SPI results revealed depths ranging from 53.4 m to 2766.5 m, with a mean of 284.3 m. Spectral analysis indicated shallow magnetic sources between 0.730 km to 1.359 km (average 1.100 km) and deeper sources between 1.927 km to 2.840 km (average 2.333 km). The maximum sedimentary thickness of 2.840 km was found in the north-central area, including Pategi, Baradogi, Wando, and Edogi. These results indicate significant hydrocarbon potential. Integrated geological and geophysical studies are recommended to validate reservoir structures and assess viability for exploration.

1. INTRODUCTION

An essential method for figuring out the magnetic basement depth under a sedimentary layer is aeromagnetic data analysis. The majority of valuable minerals, oil, gas, and groundwater are hidden beneath the surface of the earth. However, geophysical studies of the local subsurface structures can reveal the existence and extent of these resources. Magnetic data have become an invaluable and economical tool for studying geologic formations in the last few decades because of their accessibility and sensitivity to magnetic anomalies linked to a variety of subsurface characteristics [1, 2]. Analysing and interpreting geophysical measurements can unveil variations in the Earth's interior [3], both vertically and horizontally, providing valuable insights into the geological structures beneath the Earth's surface [4]. With the use of this data, a limited area of the upper crust may be explored

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for hydrogeological, engineering, and other human interests [5].

The purpose of this work is to determine the sedimentary thickness of Patigi and its environs using high-resolution aeromagnetic data. This has an impact on the ongoing petroleum exploration taking place in the Nigerian basins, which aims to increase the oil and gas reserves in the nation. Depth estimation is best resolved by establishing the shape and size of the anomaly [6].

In recent years, there has been growing interest among researchers in understanding the geothermal resource potential, paleogeography, depositional history, and mineral potential of the Nigerian Basins [7–11]. Previous studies by Sawuta *et al.* [12, 13], have contributed in this field, used high-resolution aeromagnetic survey data over parts of the upper Benue Trough in Northeast Nigeria, utilising Source Parameter Imaging (SPI) and Standard Euler Deconvolution to estimate sedimentary thickness for potential hydrocarbon maturation. The study found maximum sedimentary thicknesses of 4908 m (SPI) and 4050 m (Euler) around Wafango, Dong, and Lau areas, while the southern region showed shallower depths. These thicknesses suggest sufficient potential for hydrocarbon accumulation, and further geophysical investigations, like seismic studies, were recommended to confirm this potential. Anyadiegwu *et al.* [14] analysed Aeromagnetic data from Nsukka, Udi, Nkalagu, and Igunmale, located in the Lower Benue Trough and Anambra Basin in Southeast Nigeria, using various software tools. Qualitative analysis was reported to identify faults and magnetic anomalies, while quantitative analysis revealed depth ranges from 182 m to 8068 m. Spectral depth estimates showed deeper sources between 0.83 km and 6.17 km, and shallow sources between 0.39 km and 0.54 km. These depths, corresponding to the magnetic basement, are useful for exploring water resources, minerals, and hydrocarbons. Tijjani *et al.* [15] analyzed aeromagnetic data to determine sedimentary layer thicknesses in the northern part of the Bida Basin using spectral analysis, Euler deconvolution, and source parameter imaging (SPI). The spectral analysis revealed a maximum sedimentary thickness of 3.16 km, while the SPI method indicated a depth of 3.78 km, and the Euler Deconvolution (ED) method showed a depth of 3.34 km. They concluded that the northwestern (NW) region around Auna to the southeastern (SE) at Fashe exhibited the highest sedimentation, whereas the northeastern (NE) region at Kontagora to the southwestern of Kainji showed lower sedimentation rates. Salawu *et al.* [16] utilised aeromagnetic data and digital elevation models (DEMs) to map the structural framework of the southern margin of the Middle Niger Basin. By integrating these datasets, the study provided insights into the basin's subsurface geology, fault systems, and structural elements. This research significantly contributed to understanding the geological history and tectonic processes of the Middle Niger Basin, as well as identifying subsurface features with implications for resource exploration and land use planning.

In this study, spectral analysis will be carried out on the aeromagnetic data of Patigi and its environs in order to estimate the depths to magnetic basement rocks by dividing the composite aeromagnetic map of the study area into nine overlapping blocks. The blocks were overlapped in order not to lose any information. The depth to the basement was assessed using the Source Parameter Imaging (SPI) and Spectral Depth Analysis techniques. These approaches are among the most advanced automated source depth techniques available today to figure out the depth to magnetic bedrock.

2. LOCATION AND GEOLOGY OF THE STUDY AREA

The study area is located in the southwestern part of the Bida Basin (also called the middle Niger Basin or Nupe Basin) in the west of the Central part of Nigeria. It is situated in Kwara State and covers an area of approximately 2910.3 km^2. It is bounded by longitudes 5.50° E to 6.00° E and latitudes 8.50° N to 9.00° N. The area is filled with Campanian Maestrichtian sediments comprising mainly sandstones and silestones, which are underlain by the Precambrian rocks of the basement complex [17].

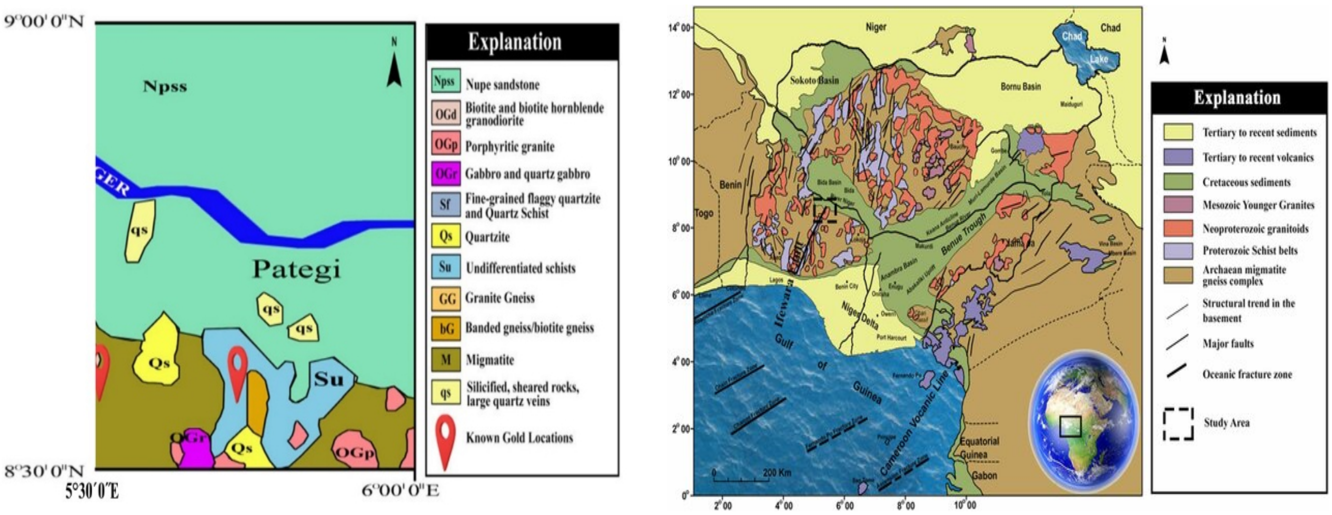
One of Nigeria's undifferentiated sedimentary basins is the Bida Basin. According to Nwankwo *et al.* [18], the Bida Basin's geology is thought to be a somewhat down-warped shallow trough that is filled with marine to fluviatile Campanian-Maastrichtian strata. The Batati, Agbaja, Lokoja, Patti, and Enagi formations are known to be included in the basin [19]. According to Obaje *et al.* [20], the Bida Basin is a trend of NW-SW intracratonic sedimentary basin that stretches from Kontagora in Niger State, Nigeria, to locations that are slightly after Lokoja in the south. The sedimentary formation's estimated length is 3.27 km [21]. With the estimated value of the sedimentary thickness, the basin may be viable for hydrocarbon exploration.

Kwara State, where Pategi is situated, falls within the Nigerian basement complex. This basement complex is composed of ancient crystalline rocks such as granites, gneisses, and migmatites. The Precambrian basement complex rocks cover approximately half of Nigeria's territory [22]. Older granite formations are visible as dome-shaped isolated bodies scattered throughout the complex [23]. Younger granite series often appear as ring complexes containing minerals like soda pyroxenes, amphiboles, and biotite, sometimes accompanied by mafic rocks like diorites [24, 25]. The granite-gneiss formations typically exhibit a leucocratic composition with shades ranging from gray to greenish. Economic minerals such as mica and gemstones are found in the vicinity of the basement complex, with migmatite and migmatite-gneiss gaining economic importance recently [26], particularly for use as aggregates.

3. MATERIALS AND METHODS

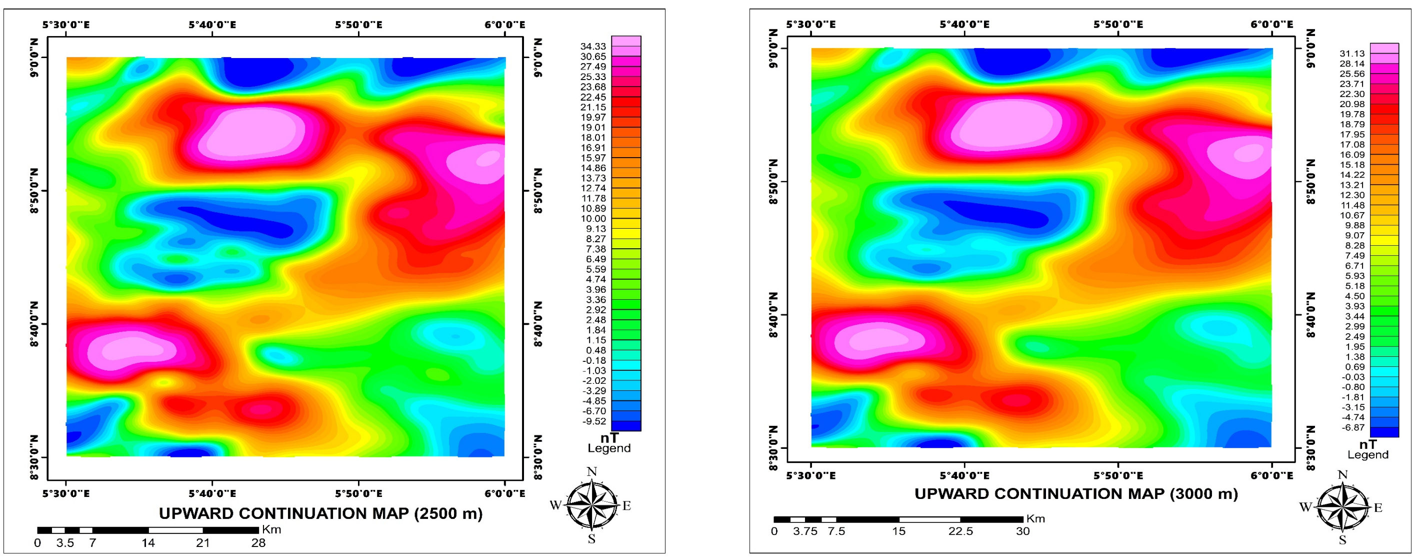
3.1. MATERIALS

An aeromagnetic map (Sheets 204) encompassing the Patigi area and its surroundings, situated within the southwestern portion of the Bida Basin, was procured from the Nigerian Geological Survey Agency (NGSA). This map was acquired as part of the nationwide aeromagnetic survey conducted in 2009, sponsored by the NGSA. The data collection involved flying along a series of NE-SW flight lines spaced at 200 m intervals, with an average flight elevation of approximately 80 m, and tie lines established at intervals of around 500 m. To ensure accuracy, the geomagnetic gradient was eliminated from the data using the International Geomagnetic Reference Field (IGRF) of 2005. The data was provided in grid format at a scale of 1:100,000 and processed using Geosoft Oasis Montaj version 8.4 software.



(a) (b)

Figure 1. Geological map of Nigeria and the study area [16].



(a) Map of the upward continuation 2500 m.

(b) Map of the upward continuation 3000 m.

Figure 2. Map of the upward continuation at 2500 and 3000 m.

3.2. METHODS

i Upward Continuation

Upward continuation is a mathematical technique employed to elevate data collected at a particular elevation to a higher altitude. This procedure leads to the attenuation of short wavelength characteristics as the data is shifted farther away from the anomaly. Essentially, it enhances broad-scale features, particularly those situated deeper within the surveyed region. An integral aspect of upward continuation is its ability to diminish anomalies relative to wavelength, thereby attenuating shorter wavelength anomalies to a greater extent. Moreover, this method tends to highlight anomalies originating from deep sources while reducing those originating from shallow sources [27]. The upward continued field ΔF (the total field magnetic anomaly) at a higher level ($z = -h$) is given by:

$$F(x, y, -h) = \frac{h}{2\pi} \iint \frac{\Delta F\,(x, y, 0)\,dxdy}{[(x - x_0)^2 + (y - y_0)^2 + h^2]^{\frac{3}{2}}}. \quad (1)$$

The process of calculating the field at a higher level from data at a lower level involves straightforward numerical integration of surface data. In practice, this computation is achieved by replacing the surface integral with a weighted sum of values taken on a regular grid. An empirical formula provided by Herderson *et al.* [28] relates the field at an elevation h, above the observed field ($z = 0$) plane, to the average value $\Delta F(r_i)$ within a circle of radius (r_i). This formula incorporates weighting coefficients, allowing for the accurate calculation of the upward continued field, typically within a 2 % margin of error [29].

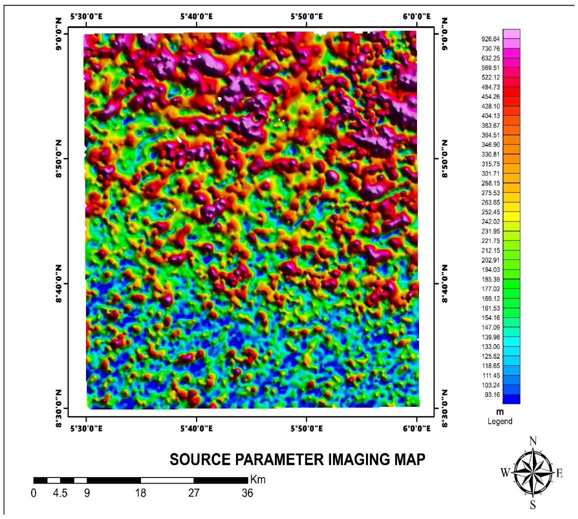


Figure 3. Source parameter imaging of the study area.

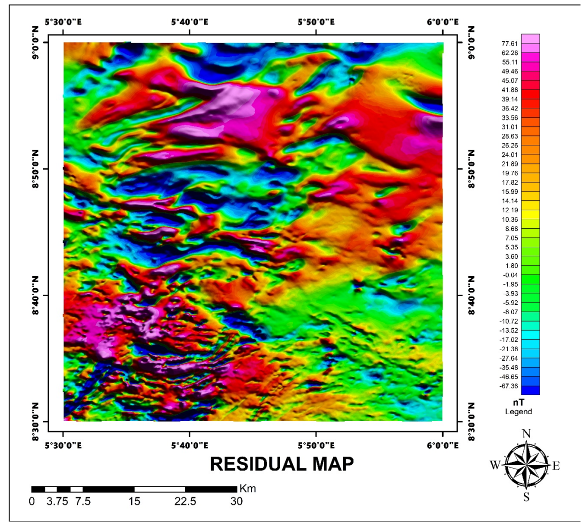


Figure 4. Residual map of the study area.

ii Source Parameter Imaging (SPI) Method

The source parameter imaging (SPI) method is commonly utilised to evaluate the depths to the top of magnetic source anomalies (Salawu *et al.*, 2020). This technique holds an advantage in determining these depths as it is independent of magnetization direction [30]. SPI relies on the correlation between source depth and local wavenumber to estimate the depths of magnetic source anomalies, as described by eq. (4) [31].

$$K = \frac{\frac{\partial^2 F}{\partial x \partial z}\frac{\partial F}{\partial x} + \frac{\partial^2 F}{\partial y \partial z}\frac{\partial F}{\partial y} + \frac{\partial^2 F}{\partial z^2}\frac{\partial F}{\partial z}}{|AS|^2}. \tag{2}$$

In the case of inclined magnetic geological interfaces, the high points of K are positioned directly over the margins of isolated contacts. Furthermore, the depth estimations are computed utilizing the inverse of the local wavenumber, as outlined in eq. (5):

$$Depth_{x=0} = \frac{1}{K_{max}}. \tag{3}$$

K_{max} represents the peak value of K (local wavenumber) across the magnetic source step. Hence, to ascertain the depth of magnetic sources, the SPI method was applied to the residual magnetic anomaly map covering various regions within the study area.

iii Spectral Analysis

An approach for automatically detecting the depth to a magnetic basement is spectral analysis. It converts magnetic data from the space domain to the frequency domain using the 2-D Fast Fourier Transform algorithm. This technique's main benefit is its capacity to remove nearly all noise from the data while ensuring that no information is lost during the interpretation process due to data overlap. [32] proposed the application of the power spectrum approach to potential field data, while Spector *et al.* [33] provided the depth to the magnetic body. The spectral analysis method utilised the Fourier Transform equation on the evenly spaced magnetic field dataset as depicted in eq. 2:

$$Y_i(x) = \sum_{N}^{n=1}\left[a_n \cos\left(\frac{2\pi n x_i}{L}\right) + b_n \sin\left(\frac{2\pi n x_i}{L}\right)\right]. \tag{4}$$

In the equation, Y_i represents the reading at the position x_i, where L denotes the length of the anomaly cross-section, n signifies the harmonic number of the partial wave N, and N represents the number of data points. Meanwhile, a_n denotes the real part of the amplitude spectrum, and b_n stands for the imaginary part of the spectrum, with i iterating from 0 to n. The linear segment slope was utilised to derive the depth to the magnetic source using eq. (2). Alternatively, if the frequency unit is expressed in cycles per kilometer, the correlation can be expressed as demonstrated in eq. (3):

$$Z = -\frac{M}{4\pi}. \tag{5}$$

In this context, Z represents the depth to the magnetic source, while M stands for the gradient of the linear segment (slope) [33].

4. RESULTS AND DISCUSSION

The upward-continued maps delineate how anomaly characteristics change as the distance to the magnetic source increases. Additionally, they serve as effective filters for low-wavenumber features. The upward continued data at 2500 m (Figure 2a) and 3000 m (Figure 2b) of the study area offer a comprehensive, undistorted view of the study area, as they have eliminated the local, high-amplitude, high-gradient anomalies from shallow magnetic sources. This process of upward continuation attenuates the shallow anomalies, resulting in a clearer and enhanced visualization of deeper anomaly sources [9]. At 3.0 km, the upward continuation map did not change significantly and has almost turned

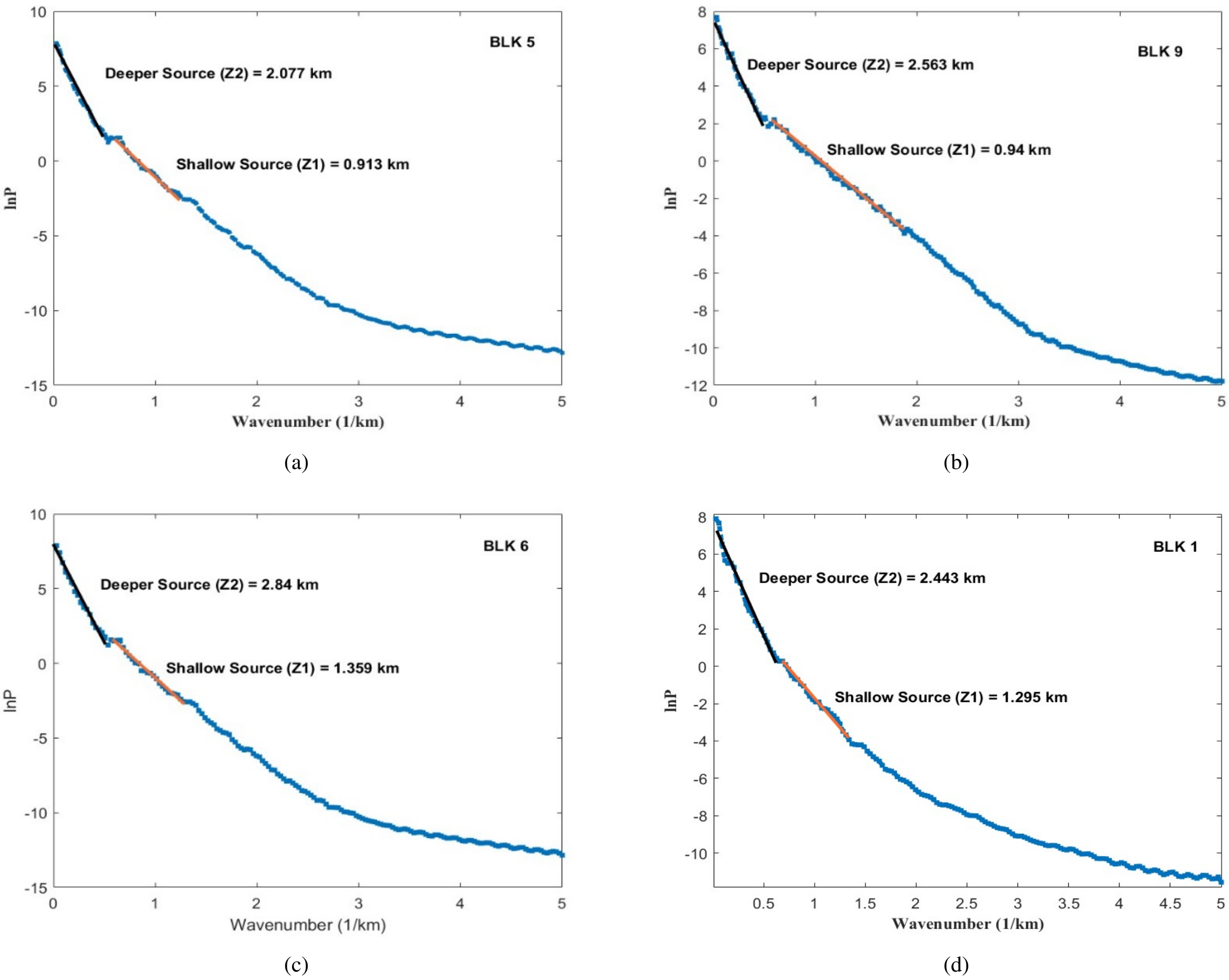


Figure 5. Samples of spectral plots for estimation of deeper source and shallow source depths.

Table 1. Spectral blocks with coordinates and depth measurements.

S/N	SPECTRAL BLOCKS	LATITUDE (degrees)		LONGITUDE (degrees)		Z_1 (km)	Z_2 (km)	AREAS
		X_{min}	X_{max}	Y_{min}	Y_{max}			
1	BLK1	5.500	5.750	8.750	9.000	1.295	2.443	GONAGI, KAGWA, LAHAGI, KUSODO
2	BLK2	5.625	5.875	8.750	9.000	1.316	1.927	LAMFA, KPATAGI, GAZHE, DANGI
3	BLK3	5.750	6.000	8.750	9.000	1.512	2.252	AGEGI, EBAGI, DOKO, LANCIKA
4	BLK4	5.500	5.750	8.625	8.875	1.064	2.222	LADE, RANI, REATI, PODOGE
5	BLK5	5.625	5.875	8.625	8.875	1.359	2.840	PATEGI, BARADOGI, WANDO, EDOGI
6	BLK6	5.750	6.000	8.625	8.875	0.913	2.077	KUSOII, ROGUN, EXOPAPO-YAGI, ETSUFU
7	BLK7	5.500	5.750	8.500	8.750	0.775	2.380	DANIKUN, NDANAKU
8	BLK8	5.625	5.875	8.500	8.750	0.730	2.300	OKOLUSHE-EGBORO, ERUFU, MATOKUN
9	BLK9	5.750	6.000	8.500	8.750	0.940	2.563	SANKWAFUJI, MOMBA, KORO, RODUN
Average Mean Value						1.100	2.333	

to regional variation, therefore, the depth 3.0 km may be construed as the depth to the deeper magnetic sources. As depicted in Figure 3, the pre-processed grids *dx*, *dy*, and *dz*, derived from the residual grid, were used as input for computing the source parameter imaging (SPI). This process employed the algorithm within the Oasis Montaj software. The SPI method, demonstrated by the SPI images generated from the residual field data in Figure 4, significantly aids in interpreting magnetic data. Variations in magnetic depths and susceptibilities across the study area were observable in the gridded SPI depth map and accompanying legend. In the SPI map, the northern parts of the study area show depths of buried magnetic bodies, potentially including deep-seated basement rocks or near-surface intrusions. In contrast, the southern parts show outcropping magnetic bodies. The SPI depth result ranges from 0.0534 km (indicating outcrops or shallow magnetic bodies) to 2.7665 km (representing magnetic bodies at greater depths), with an average mean value of 0.2843 km.

Spectral analysis was carried out using the power average spectrum module on Geosoft Oasis Montaj software version 8.4. The graph of spectral energies against frequency was plotted using MATLAB (version 9.13.0.2049777) 2022b Software. Each of these graphs presents two clear segments due to deeper and shallower sour, The depth Z_1 is the first depth segment (layer) that corresponds to the shallow magnetic sources. Meanwhile, the depth Z_2 is the second depth segment (layer) which corresponds to the deep magnetic source. The depth to the first layer, Z_1, in the study area varies from 0.730 – 1.359 km, with an average depth of 1.100 km, with the second layer, Z_2, varies from 1.927 – 2.840 km, with an average depth of 2.333 km.

The result of the depth estimated in the present study agrees with the results of some previous researchers who had worked within the area of the study. Tsepav *et al.* [34] Comparatively analysed the subsurface magnetic structures in some parts of Bida Basin using the source parameter imaging and the spectral depth analysis. The basement depths from spectral analysis gave an average value varying from 0.923 km (shallow sources) to 2.706 km (deeper sources) for Patigi and its Environs. The study area was divided into 9 blocks/regions (Figure 5) so as to know the basement depth variations of each region. Table shows the estimated results of depths with their corresponding blocks.

5. CONCLUSION AND RECOMMENDATIONS

Upward continuation filtering technique and two enhancement techniques (source parameter imaging and spectral analysis) were employed on high-resolution aeromagnetic data of Patigi and environs with the purpose of estimating the depth to magnetic sources in the study area. The results obtained from the methods were in agreement with each other as upward continuation gave 3.0 km (deeper sources), SPI gives 0.0534 km (shallow sources) and 2.7665 km (deeper sources) with an average mean value of 0.2843 km and spectral analysis gives an average of 1.1 km (shallow sources) and 2.333 km (deeper sources). The depth to shallow magnetic sources may result from tectonic activities that gave rise to basement rocks intruding into the sedimentary formation. The deeper magnetic sources may be characterised by lateral inversion and basement structural deformations, such as faults and fractures [35]. The results indicate that the study area is a transition zone. A sedimentary depth of around 2.3 kmis necessary to achieve the temperature threshold for the commencement of hydrocarbon maturation [36]. However, the results of the sedimentary thickness obtained from this study agree with previous research work carried out within the area, such as Tsepav *et al.* [34] who reported an average depth to the magnetic basement of 2.7 km. Hence, hydrocarbon exploration is said to be feasible in this study area, especially areas such as Pategi, Baradogi, Wando, and Edogi (where the sedimentary thickness is higher than 2.840 km). Continued geophysical and geological investigations, including seismic surveys and geochemical analysis, are encouraged to delineate reservoir structures and confirm hydrocarbon presence.

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DATA AVAILABILITY

The data used for this paper will be made available on request.

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