Science Heritage Journal (GWS)

DOI: http://doi.org/10.26480/gws.02.2025.58.65

ZIBELINE INTERNATIONAL™
PUBLISHING

ISSN: 2521-0858 (Print)
ISSN: 2521-0866 (Online)
CODEN: SHJCAS

RESEARCH ARTICLE

ESTIMATION OF DEPTH TO MAGNETIC SOURCES IN SOUTHERN NIGERIA USING 2D SPECTRAL ANALYSIS OF HIGH-RESOLUTION AEROMAGNETIC DATA

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ARTICLE DETAILS

Article History:

Received 27 June 2024
Revised 24 July 2025
Accepted 29 July 2025
Available online 12 August 2025

ABSTRACT

Southern Nigeria encompasses diverse geological terrains that significantly influence its subsurface characteristics. Understanding the depth and distribution of magnetic sources is essential for advancing geological and hydrocarbon exploration in the region. This study aims to estimate the depth to magnetic sources across selected locations in Southern Nigeria using two-dimensional (2D) spectral analysis of high-resolution aeromagnetic data. Ten aeromagnetic sheets, obtained from the Nigerian Geological Survey Agency, were processed. Residual magnetic maps were generated by removing regional trends using first-order polynomial fitting. The residual anomalies were subjected to spectral analysis through Fourier transformation using Oasis Montaj and MATLAB environments. Results reveal two distinct magnetic layers: shallow magnetic sources at depths between 0.2 and 0.4 km, and deep sources ranging from 1.6 to 6.2 km. These depth estimates were utilized to construct 2D contour and 3D surface models of the magnetic basement topography. The analysis shows five distinct uplifts and depressions within the crystalline basement, with deeper basement regions concentrated in the central and western parts of the study area. These depressions correspond to thick sedimentary piles, indicative of promising zones for hydrocarbon exploration, particularly in Nsukka, Abakaliki, and Abeokuta. In conclusion, spectral depth modeling from high-resolution aeromagnetic data proves effective for delineating basement morphology in southern Nigeria. This study enhances resolution in subsurface geological mapping and identifies new prospective hydrocarbon zones by integrating advanced spectral techniques with 3D visualization, aiding exploration efforts in underexplored sedimentary basins.

KEYWORDS

Depth, Magnetic, spectral analysis, Aeromagnetic, Sedimentary, Basement

1. INTRODUCTION

Southern Nigeria is geologically diverse, encompassing a complex array of sedimentary basins and crystalline basement rocks, each shaped by prolonged tectonic and magmatic processes. This region forms part of the broader West African geological province and has been a focal point for resource exploration due to its abundant mineral and hydrocarbon potentials (Apeh et al., 2023). Understanding the structural and lithological characteristics of the subsurface is vital for assessing its mineralization potential, hydrocarbon prospectivity, and tectonic history. Among the various geophysical methods available for subsurface investigation, magnetic surveys, particularly aeromagnetic surveys, have emerged as one of the most effective non-invasive techniques for regional-scale geological mapping (Ishola et al., 2020).

The principle underlying magnetic surveys is the detection and interpretation of anomalies in the Earth's magnetic field caused by variations in the magnetic properties of underlying rocks. These variations are influenced by factors such as mineral composition, rock type, and structural configuration. Rocks containing ferromagnetic minerals such as magnetite and hematite tend to produce significant magnetic responses, allowing for the delineation of subsurface geological boundaries and structures (Elhussein et al., 2024). As noted, magnetic methods have evolved from their early use in mineral exploration to broader applications that include petroleum prospecting, groundwater exploration, geothermal studies, and crustal research by (Philip et al., 2002).

Over time, technological advancements have dramatically improved the resolution and coverage of magnetic surveys. The transition from low-resolution ground-based surveys to high-resolution aeromagnetic (HRAM) data acquisition has enhanced the ability to capture detailed subsurface variations, especially in regions with challenging terrain or limited accessibility (Bertrand et al., 2020). Aeromagnetic surveys are now the most widely used geophysical technique globally, both in terms of annual survey distance and total survey coverage (Paterson and Reeves, 1985). The advantages of airborne magnetic methods lie in their speed, cost-efficiency, and the ability to collect data over vast and remote areas consistently.

Aeromagnetic data acquisition involves measuring variations in the Earth's magnetic field along pre-defined flight lines using magnetometers mounted on aircraft. In earlier surveys, widely spaced flight lines and high terrain clearances limited the ability to resolve fine structural details. However, newer HRAM surveys conducted with reduced flight line spacing

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(typically around 500 m) and lower terrain clearance (~80 m) provide high-density datasets capable of resolving subtle anomalies associated with shallow and deep magnetic sources (Usman et al., 2024). These data are often presented as total magnetic intensity (TMI) maps, which allow for both qualitative and quantitative interpretation of subsurface structures.

In geologically complex regions such as southern Nigeria, the interpretation of aeromagnetic data requires robust processing techniques to isolate relevant geological signals. One such technique is spectral analysis, which utilizes the frequency domain characteristics of magnetic anomalies to estimate source depths. Spectral methods transform spatial magnetic data into frequency space using two-dimensional Fourier transforms. The slope of the logarithmic energy spectrum derived from this transformation provides estimates of the depth to magnetic source bodies (Usman et al., 2025). By analyzing both the high-frequency (shallow) and low-frequency (deep) components of the spectral curve, researchers can derive a two-layer depth model of the subsurface.

A key concept in magnetic interpretation is the identification of the "magnetic basement," which refers to the top surface of crystalline rocks beneath sedimentary cover. Since sedimentary rocks are generally non-magnetic, most of the magnetic anomalies measured at the surface are attributed to features within the basement (Liao et al., 2023). Mapping the magnetic basement depth is crucial in hydrocarbon exploration, as it provides insights into the thickness of sedimentary sequences and the structural framework of sedimentary basins (Reeves, 2005; Maxwell et al., 2012). Thick sedimentary sequences are significant as they are likely to contain source rocks, reservoir rocks, and seals essential for petroleum systems.

However, interpreting magnetic data in sedimentary regions is not without challenges. While the assumption that sedimentary rocks are non-magnetic holds in many cases, exceptions exist. For instance, certain iron-rich sedimentary deposits, volcanic intrusions, dykes, sills, and metamorphosed sediments within the basin can generate magnetic responses that may complicate interpretations (Eldosouky et al., 2021). Therefore, a comprehensive approach that includes data filtering, regional-residual separation, and imaging techniques is often necessary to enhance meaningful signals from magnetic noise (Gunn, 1997; Milligan and Gunn, 1997).

In the Nigerian context, the geological setting of southern Nigeria includes major sedimentary basins such as the Niger Delta Basin, the Anambra Basin, the Dahomey Basin, and the Lower Benue Trough. These basins have developed over millions of years through processes such as rifting, subsidence, sedimentation, and magmatism. Each basin exhibits distinct stratigraphic and structural characteristics (Aigbadon et al., 2023). For instance, the Niger Delta Basin, one of the most prolific hydrocarbon provinces in Africa, developed from early Tertiary deltaic progradation, while the Benue Trough represents a failed rift system with extensive sediment accumulation. The Dahomey Basin, on the other hand, comprises a mix of inland and offshore sedimentary sequences, separated from the Niger Delta by the Okitipupa Ridge (Ugwueze and Okengwu, 2023).

Despite the growing availability of geological data in Nigeria, significant gaps remain in the high-resolution mapping of basement morphology and sedimentary thicknesses across these basins. Earlier studies relied on low-resolution magnetic data or sparse seismic and well log information, limiting their accuracy and regional applicability. The use of high-resolution aeromagnetic data, however, provides a promising avenue to bridge this gap (Oretade et al., 2024). With improved resolution and broader spatial coverage, HRAM datasets can resolve structural discontinuities, basement topography, and intrabasement features critical for tectonic reconstruction and resource targeting.

In recent years, several studies have demonstrated the utility of spectral analysis for basement depth estimation in Nigeria. For example, applied 2D spectral methods to Abakaliki and derived depth estimates consistent with regional geological understanding (Anyanwu and Mamah, 2013). Similarly, utilized analytic signal and gradient-based methods in Ilesha, while extended these techniques to the Dahomey Basin and Abeokuta regions, respectively (Opara, 2011; Olurin et al., 2015; Ozebo et al., 2015). These studies collectively highlight the relevance of spectral methods in regional-scale geophysical assessments, especially where other geophysical tools such as seismic surveys may be logistically or economically prohibitive.

The potential for using magnetic depth models in hydrocarbon exploration lies in their ability to delineate areas of thick sediment accumulation, identify structural highs and lows, and assess tectonic history. Regions exhibiting significant basement depressions are considered promising targets due to their potential to host thermally mature source rocks (Falebita et al., 2020). In addition to petroleum prospectivity, magnetic data can be used to map potential zones of mineralization, particularly those associated with igneous and metamorphic basement rocks.

The study presented in this research seeks to build upon this foundation by employing high-resolution aeromagnetic data to estimate the depth to magnetic sources in southern Nigeria using two-dimensional spectral analysis. Ten aeromagnetic data sheets covering strategically selected locations across prominent basins and basement regions were processed and analyzed. The approach involved generating residual magnetic maps, computing energy spectra, and deriving depth estimates to both shallow and deep magnetic sources. These values were then used to model the topography of the magnetic basement using 2D contouring and 3D surface visualization techniques.

This research aims to estimate the depth to magnetic sources in selected regions of southern Nigeria using 2D spectral analysis of high-resolution aeromagnetic data. The objective is to delineate the crystalline basement topography and assess its implications for subsurface structure, sedimentary basin configuration, and hydrocarbon prospectivity across the study area.

2. THE STUDY AREA

2.1 Location of Study Area

The study area is located within the southern region of Nigeria and is geographically bounded by latitudes 5.20°N to 8.20°N and longitudes 3.10°E to 11.70°E. This spatial extent encompasses a significant portion of southern Nigeria, covering both sedimentary and crystalline geological formations. The area under investigation includes ten major cities: Abakaliki, Abeokuta, Auchi, Ibi, Ilesha, Kiri, Nsukka, Oban, Oyo, and Patani. These cities are strategically distributed across key geological terrains, including parts of the Anambra Basin, Niger Delta Basin, Dahomey Basin, Lower and Middle Benue Trough, and sections of the Basement Complex.

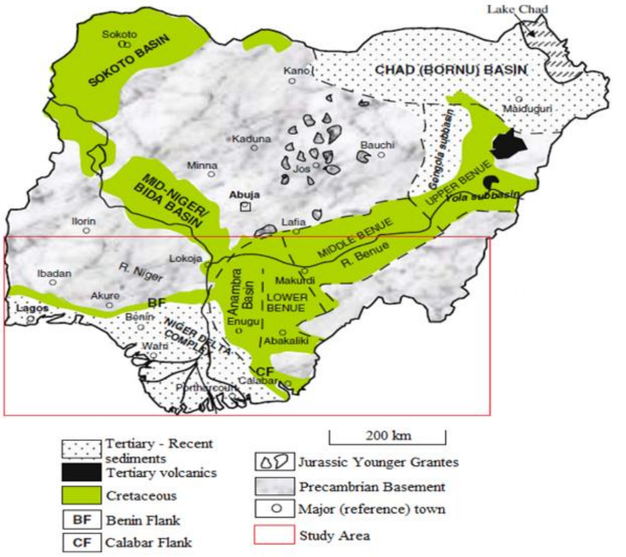

Figure 1: Geological sketch Map of Nigeria showing the major geological components; Basement, Younger Granites, and Sedimentary Basins (After Obaje, 2009).

The diversity in geological setting across these locations makes the area suitable for regional geophysical studies aimed at estimating basement depths and understanding structural trends. Each city contributes unique geological characteristics to the study. For instance, Abakaliki lies within the Lower Benue Trough, Abeokuta in the Dahomey Basin, and Nsukka in the Anambra Basin, while Oyo and Ilesha lie within the Precambrian Basement Complex (Ani et al., 2023). The selection of these cities ensures a comprehensive coverage of southern Nigeria's geodynamic provinces, thereby enabling a comparative assessment of basement morphology across different tectonic environments. The regional map (Figure 1) illustrates the geographical distribution and geological context of these selected locations.

2.2 Geology of the Study Area

The study area encompasses selected regions within Southern Nigeria and includes portions of two major geological provinces: the Precambrian Basement Complex and the Cretaceous–Tertiary Sedimentary Basins.

The Basement Complex, which dates back to the Precambrian era, is primarily composed of the Migmatite-Gneiss Complex, Schist Belts, and Older Granites. Within the study area, the Schist Belts are the dominant lithological units, particularly in the southwestern part of Nigeria. States such as Osun and Oyo lie within this crystalline basement terrain, while Ogun State is part of an undifferentiated section of the Basement Complex (Samuel and Abraham, 2015). In contrast, the Sedimentary Basins in this region contain extensive sedimentary sequences that span from the Cretaceous to the Tertiary periods. These basins include the Niger Delta Basin, Anambra Basin, Lower Benue Trough, and Dahomey Basin—all of which fall within the study area (Obaje, 2009).

Sedimentation in the Lower Benue Trough began with the marine Albian-aged Asu River Group, which comprises shales, limestones, and sandstone lenses, notably represented by the Abakaliki Formation. Pyroclastic rocks from the Aptian–Early Albian have also been sporadically identified in this region (Ojoh, 1992). In the Calabar Flank, the Mfamosing Limestone is the equivalent of the Asu River Group. This sequence is overlain by the Nkalagu Formation—marine Cenomanian–Turonian black shales, limestones, and siltstones—and the regressive sandstones of the Agala and Agbani Formations. A major tectonic event during the mid-Santonian shifted the depositional axis westward, giving rise to the Anambra Basin.

The Anambra Basin subsequently experienced Campanian–Maastrichtian sedimentation characterized by the Enugu and Nkporo Formations (marine and paralic shales), succeeded by the coal-bearing Mamu Formation. The fluviodeltaic Ajali and Owelli Sandstones laterally correlate with the Mamu Formation. During the Paleocene, the Imo and Nsukka Formations (marine shales) were deposited, and the Nanka Sandstone of Eocene age eventually overlay these. Further basinward, these sequences transition into the Akata Shale and Agbada Formation of the Niger Delta Basin (Obaje, 2009).

The Niger Delta Basin represents a prolific Cenozoic depocenter located at the intersection of the Benue Trough and the South Atlantic Ocean, formed due to rifting and continental separation between South America and Africa during the late Jurassic (Whiteman, 1982). Subsequent subsidence of the continental margin and cooling of the oceanic lithosphere in the early Cretaceous facilitated marine transgression and sedimentation across the Benue and Anambra basins. The modern Niger Delta began to evolve in the early Tertiary, driven by increased fluvial sediment supply and delta progradation (Doust and Omatsola, 1989).

The Dahomey Basin is an onshore–offshore basin system that stretches from southeastern Ghana, through Togo and Benin Republic, into southwestern Nigeria. It is bounded to the east by the subsurface Okitipupa Ridge, which separates it from the Niger Delta Basin. Sedimentation in this basin generally follows an east–west trend. While the offshore portion of the Dahomey Basin is less understood, the onshore geology is better documented in neighboring Benin (Billman, 1976; De Klasz, 1977).

This geological diversity within the study area offers a unique opportunity to examine variations in basement morphology and sediment thickness, which are essential for hydrocarbon prospecting and geodynamic reconstructions.

3. METHODOLOGY

3.1 Data Source

Ten high-resolution aeromagnetic sheets—numbered 218, 233, 237, 241, 243, 260, 266, 287, 303, 319, and 324—were acquired for this study from the Nigerian Geological Survey Agency (NGSA). These maps were published at a scale of 1:50,000 and cover key geological zones across southern Nigeria. The survey, conducted between 2006 and 2007, was designed with a mean terrain clearance of 80 meters, a flight line spacing of 500 meters along north–south directions, and tie lines spaced 5 kilometers apart. This configuration provided a dense and detailed dataset suitable for resolving subtle subsurface features and mapping regional geological structures.

According to NGSA, the enhanced resolution and acquisition methodology represent a significant improvement over previous aeromagnetic surveys in Nigeria, offering greater accuracy in subsurface imaging and geological interpretation (Nwankwo and Shehu, 2015). Prior to interpretation, the data were subjected to geomagnetic correction using the International Geomagnetic Reference Field (IGRF) to eliminate global magnetic influences. Additionally, regional magnetic trends were removed from the Total Magnetic Intensity (TMI) data by applying a first-order polynomial trend surface fitting. This process yielded residual magnetic maps that better isolate local anomalies, forming the foundation for spectral analysis and depth estimation of magnetic sources.

3.2 Total Magnetic Intensity Map

Ten Total Magnetic Intensity (TMI) maps corresponding to the selected aeromagnetic sheets were generated and analyzed using Oasis Montaj software. These maps, presented in Figure 2, display the spatial distribution of magnetic anomalies across the study area. Each TMI map was processed independently to capture localized variations in magnetic intensity. Color gradients were applied to enhance visualization, with high magnetic intensity zones shown in warm colors—yellow, orange, red, and purple—while low intensity regions were represented by cool colors such as blue, sky blue, and green.

The maps revealed numerous subsurface geological structures, including lineaments and isolated anomalies that may indicate buried faults, intrusions, or contacts between lithological units. High magnetic intensity values are generally attributed to near-surface igneous intrusions or crystalline basement rocks possessing elevated magnetic susceptibility. These features typically signify the presence of magnetically active materials such as basalt, diorite, or granitic intrusions (Ishola et al., 2020). Conversely, low magnetic intensity zones are associated with sedimentary formations or other non-magnetic sources such as shale, limestone, or sandstone, which dominate many parts of southern Nigeria's sedimentary basins.

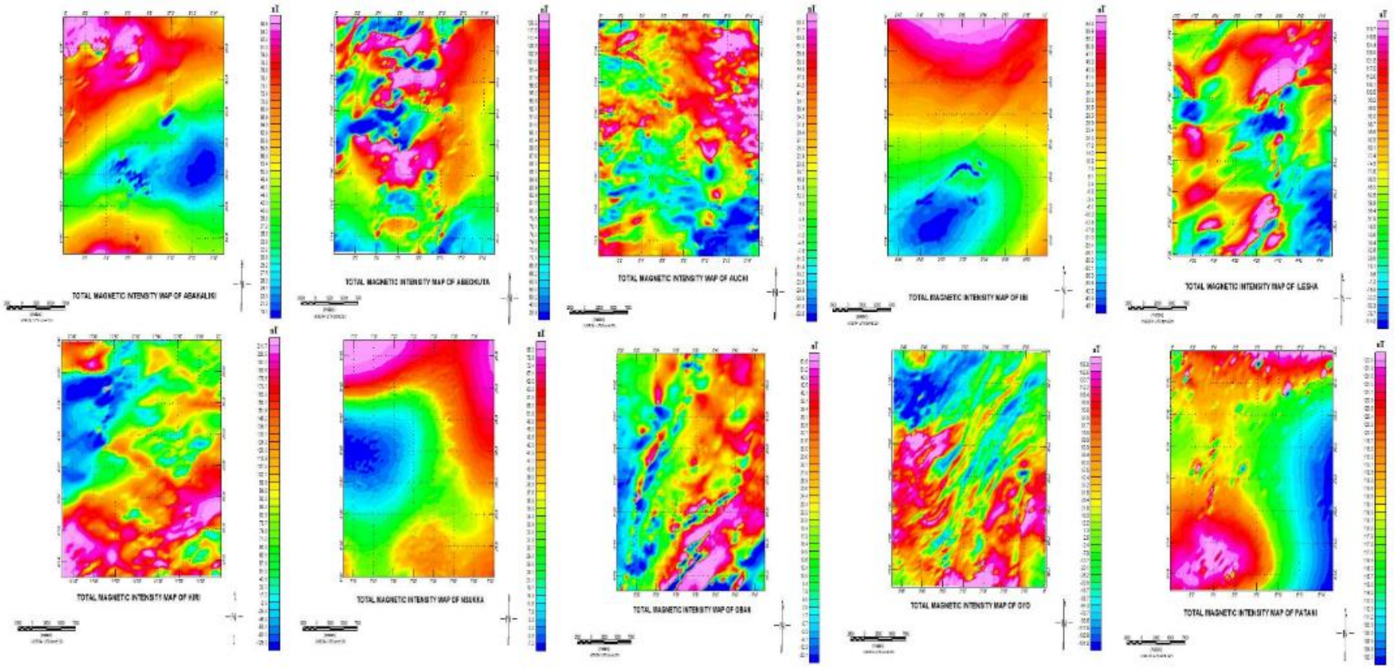

Figure 2: Total magnetic intensity maps of the study area.

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3.3 Estimation of the Magnetic Basement Depths

A two-dimensional Fourier transform technique was applied using the Geosoft Oasis Montaj software to convert the gridded magnetic data from the space domain into the frequency domain for each aeromagnetic sheet. Within the software environment, the radial average power spectrum of each dataset was computed and saved. These spectral energy profiles, which represent the distribution of magnetic signal strength across different frequencies, were then exported to MATLAB for further processing.

In MATLAB, logarithmic plots of spectral energy versus frequency were generated for each location. These plots typically exhibited two distinct linear segments corresponding to the high-frequency (shallow source) and low-frequency (deep source) components. The slopes of these segments were carefully extracted, as they are directly related to the depth of the magnetic sources (Pham and Eldosouky, 2024). By applying the appropriate spectral depth estimation equations, the depths to both shallow and deep magnetic anomalies were calculated. This method allowed for a systematic and consistent determination of magnetic basement depth across all study locations.

4. RESULTS AND DISCUSSIONS

4.1 Results

The spectral analysis of high-resolution aeromagnetic data across selected regions of southern Nigeria was conducted to estimate the depth to magnetic source bodies. As part of this process, the geographic center of each TMI map was determined by averaging the bounding latitude and longitude values. These central coordinates, along with the derived depth estimates, are presented in Table 1.

For each of the ten aeromagnetic data sheets analyzed, spectral density plots were produced and are shown in Figure 3. These plots represent the logarithm of the radial energy spectrum plotted against the spatial frequency (in cycles per kilometer). Typically, each plot displayed two distinct linear segments corresponding to low-frequency and high-frequency components. The slopes of these linear segments are inversely related to the depth of the magnetic sources. The low-frequency portion of the curve corresponds to deeper magnetic sources, while the high-frequency segment corresponds to shallower sources. These spectral features enabled a clear separation of magnetic anomalies into two depth categories: deep-seated and near-surface sources.

The results from this analysis revealed that the subsurface magnetic anomalies in the study area can be grouped into two major depth intervals: deep magnetic sources, which ranged from 1.6 km to 6.2 km, and shallow magnetic sources, which ranged from 0.2 km to 0.4 km. In Abakaliki, located in the Lower Benue Trough, the depth to the deep magnetic source was found to be 3.9 km, with a shallow source at 0.3 km. This suggests the presence of a moderately thick sedimentary sequence overlying the crystalline basement, consistent with the geologic structure of the trough. In Abeokuta, situated in the Dahomey Basin, the deepest magnetic basement was recorded at 5.3 km, with a shallow anomaly at 0.4 km. This represents one of the thickest sedimentary covers within the study, indicating strong hydrocarbon prospectivity in the area due to the increased potential for organic matter accumulation and maturation.

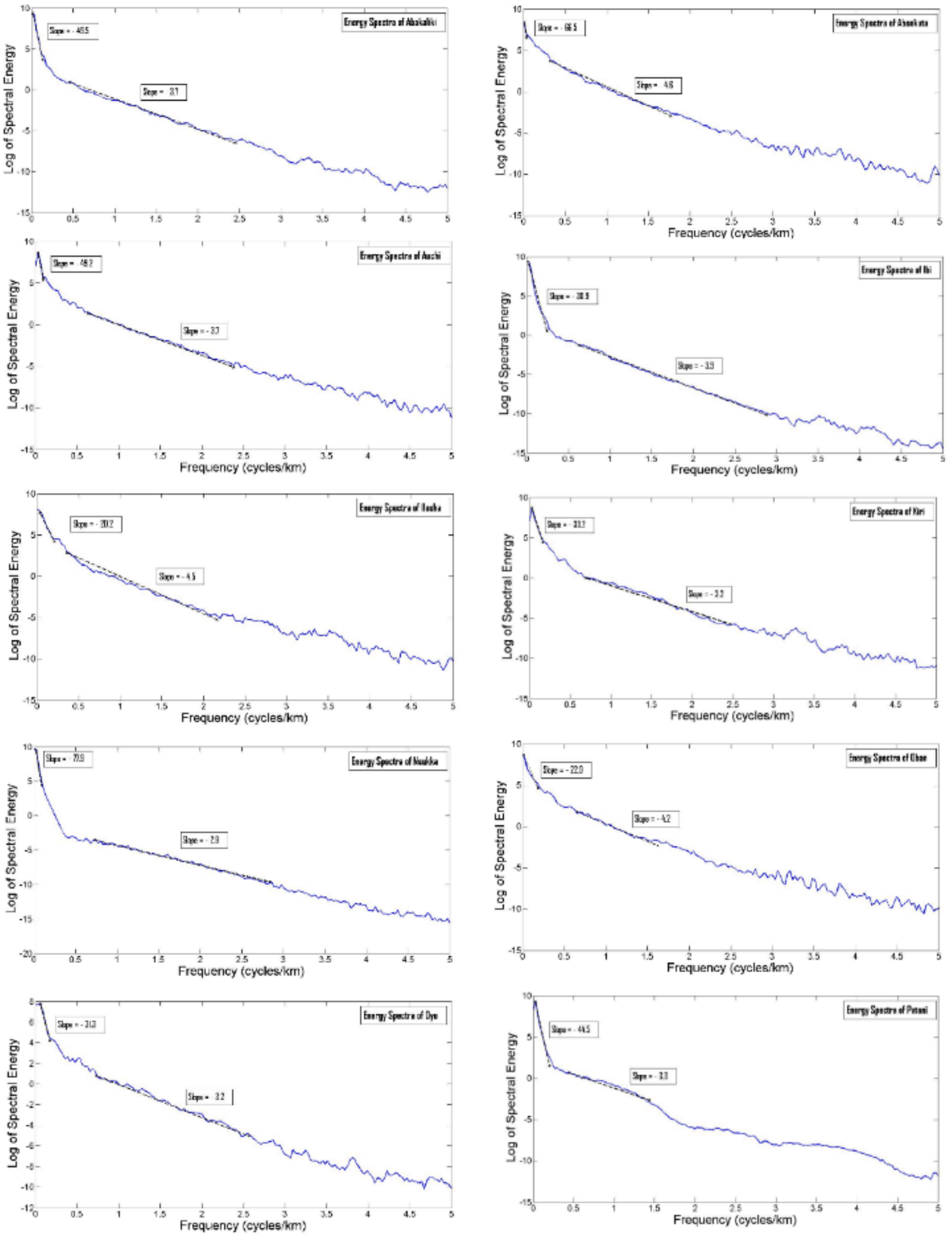

Figure 3: Spectral plots of log of energy against frequency (cycles/km) of study area.

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Auchi and Patani, both located within the Niger Delta and nearby sedimentary basins, also showed significant depths to magnetic basement—3.9 km and 3.5 km respectively—with shallow sources at 0.3 km. These results support previous geological interpretations indicating that these areas are underlain by substantial sedimentary thickness, making them favorable sites for hydrocarbon exploration. The deepest magnetic source was recorded at Nsukka in the Anambra Basin, at 6.2 km, while the shallowest was 0.2 km. This implies a very thick sedimentary package, which is favourable for the generation and entrapment of hydrocarbons. This result also highlights the basin's tectonic subsidence history and its potential as a petroleum province.

Table 1: Estimated depth to the deep magnetic sources and the shallow magnetic sources in km.

S/N	Selected Areas	Longitude (ºE)	Latitude (ºN)	Depth to deep Magnetic Sources (km)	Depth to Shallow Magnetic Sources (km)
1	Abakaliki	8.075	6.225	3.9	0.3
2	Abeokuta	3.075	7.225	5.3	0.4
3	Auchi	6.075	7.225	3.9	0.3
4	Ibi	9.725	8.225	3.1	0.3
5	Ilesha	4.375	7.375	1.6	0.4
6	Kiri	11.725	8.225	2.6	0.3
7	Nsukka	7.225	6.375	6.2	0.2
8	Oban	8.375	5.225	1.8	0.3
9	Oyo	3.725	7.725	2.5	0.3
10	Patani	6.075	5.225	3.5	0.3

On the other hand, areas such as Ilesha and Oban, which lie within or near the crystalline basement complex, showed shallow basement depths of 1.6 km and 1.8 km, respectively. These areas also had shallow magnetic source depths of 0.4 km and 0.3 km, suggesting limited sedimentary cover and hence lower hydrocarbon potential compared to other regions in the study. In Kiri and Ibi, located along the transition between basement and sedimentary terrain, the deep magnetic source depths were 2.6 km and 3.1 km, respectively. These moderate depths suggest transitional geological settings that may still be of interest for exploration, depending on the quality and thickness of the sedimentary fill. Oyo, within the southwestern basement complex region, had a deep basement depth of 2.5 km and a shallow source at 0.3 km, indicating a relatively shallow basement profile consistent with its known geology.

These findings, summarized in Table 1, provide key insight into the magnetic basement architecture of southern Nigeria. The depth variations observed across the study area reflect the underlying tectonic history, basin development, and sedimentation patterns. The spectral analysis method used in this study proved effective in delineating the structural variations and has significant implications for regional geological modeling and hydrocarbon exploration.

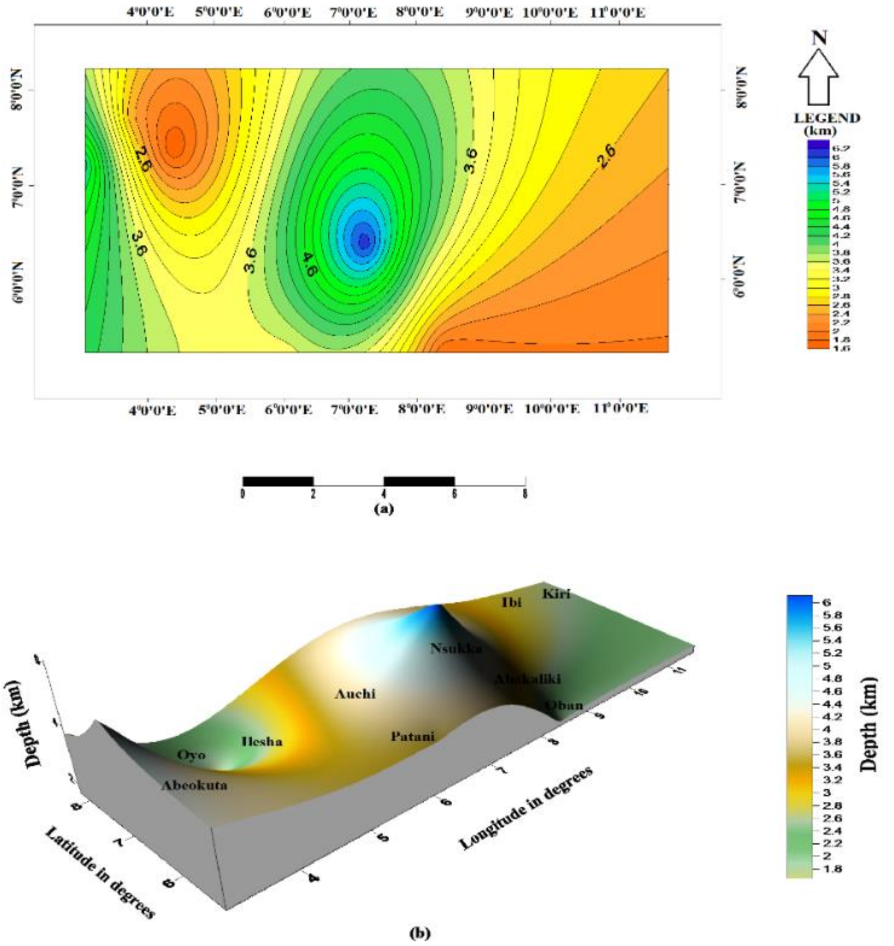

Figure 4: (a) 2-D Contour Map of the deep magnetic source (contour interval is 0.2km) (b) 3-D Surface model of deeper magnetic source depth area.

Figure 4 presents a visualization of the depth to deep magnetic sources in the study area using two models: (a) a 2-D contour map and (b) a 3-D surface model. The 2-D contour map (Figure 4a) displays the spatial distribution of basement depths, with depth values ranging from 1.6 km to 6.2 km and a contour interval of 0.2 km. The map shows clear structural variation, with several depression zones (in blue and green tones) indicating deeper basement areas. The deepest region, marked by a closed concentric contour in the central part of the map, reaches a maximum depth of 6.2 km and is associated with Nsukka and Abakaliki. Shallower zones, represented by yellow to red colors, are primarily located in the eastern and western extremes of the map, notably around Ilesha, Oban, and Oyo.

The 3-D surface model (Figure 4b) complements the 2-D map by offering a three-dimensional perspective of basement undulations across the study area. The model highlights five major structural depressions and corresponding uplifts, with visible tectonic features aligned with known sedimentary basins such as the Anambra and Dahomey Basins. Areas with greater sediment thickness, including Abeokuta, Nsukka, and Abakaliki, exhibit significant hydrocarbon exploration potential due to their deeply buried magnetic basement, while uplifted zones like Ilesha and Oban suggest basement exposure or minimal sedimentary cover.

Figure 5 illustrates a bubble map of Nigeria generated using ArcGIS, showing the geographic distribution and estimated depths to magnetic basement at selected locations across southern Nigeria. Each bubble corresponds to a specific study area and is scaled proportionally to the depth of the underlying magnetic source. The depth classification ranges from less than 1.6 km to greater than 6.2 km, with larger circles representing deeper basement levels. From the map, the deepest basement depths are observed in Nsukka and Abeokuta, represented by the largest bubbles, indicating depths exceeding 6.2 km and around 5.3 km, respectively. These areas lie within the Anambra and Dahomey Basins and are characterized by significant sediment accumulation, suggesting favorable conditions for hydrocarbon generation and maturation. Similarly, moderate to deep basement depths are noted in Abakaliki, Auchi, Ibi, and Patani, reflecting sedimentary environments with considerable potential for hydrocarbon exploration.

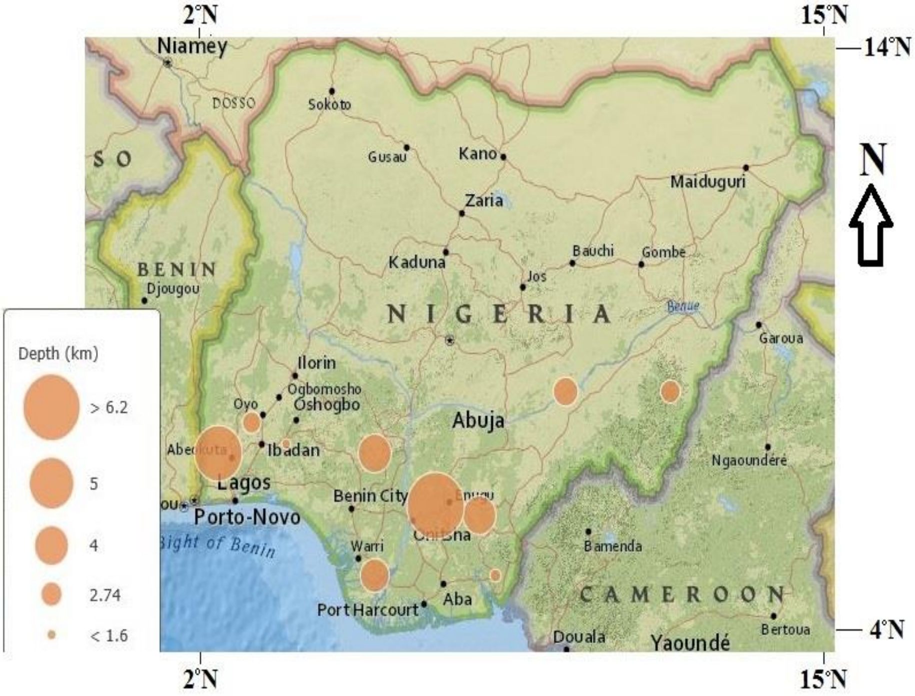

Figure 5: Map of Nigeria showing selected location and their estimated depths (ArcGIS).

In contrast, smaller bubbles indicating shallower depths are visible over areas like Ilesha, Oban, and Oyo, which lie within or near the crystalline basement complex. These regions exhibit thinner sedimentary cover, suggesting lower hydrocarbon prospectivity but may hold potential for mineral exploration due to proximity to the exposed basement. The spatial variation in bubble sizes effectively conveys regional differences in sedimentary thickness and basement topography. This visualization aids in identifying structurally depressed zones of economic interest and contributes to basin modeling and strategic resource exploration in southern Nigeria.

4.2 Discussion

The interpretation of spectral analysis results from high-resolution aeromagnetic data in southern Nigeria revealed significant variations in both shallow and deep magnetic anomaly source depths. The shallow magnetic sources were identified within the depth range of 0.3 to 0.4 km across most of the study locations. These shallow anomalies are typically attributed to near-surface magnetic rock bodies, likely intrusive or extrusive igneous formations, that have penetrated the sedimentary layers. Such anomalies are common in tectonically active regions or areas with historical magmatic activity (Ike et al., 2024). Their limited depth range suggests localized geologic events that influenced only the uppermost crustal levels, possibly through magmatic intrusions, fault-associated mineralization, or structural deformations.

In contrast, the deep magnetic anomaly sources display a much broader variation in depth, ranging from 1.6 km to 6.2 km, according to Table 3.1. These deeper magnetic sources are interpreted as the magnetic basement, underlying the overlying sedimentary cover. The variation in depth is attributed to the lateral changes in magnetic susceptibility of the basement rocks, which may be controlled by geological structures such as faults, fractures, and intrabasement lithological heterogeneity (Ezeh et al., 2022). This inference aligns with the interpretations, who emphasized that intrabasement features strongly influence the configuration of magnetic anomalies in southern Nigerian basins (Nwankwo, 2015). The deep basement depths derived from the spectral analysis were employed to construct both 2D contour and 3D surface maps (Figure 3.2), effectively delineating the topography of the crystalline basement across the study region. These maps provided valuable insights into the geomorphological character of the basement terrain beneath the sedimentary cover. The contour and surface representations illustrate a basement landscape marked by alternating uplifted and depressed zones, suggesting structural complexity and possible tectonic reactivation in the region's geological past (Adebiyi et al., 2020).

In particular, the 3D surface model revealed that the magnetic basement is significantly deeper in the central and western regions of the study area. These include Nsukka within the Anambra Basin (6.2 km), Auchi and Patani in the Niger Delta Basin (3.9 km and 3.5 km respectively), Abakaliki in the Lower Benue Trough (3.9 km), Ibi in the Middle Benue Trough (3.1 km), and Abeokuta in the Dahomey Basin (5.3 km). These locations are associated with thick sedimentary sequences, which make them geologically favorable for hydrocarbon generation and accumulation. The thick sedimentary cover suggests sufficient thermal maturation of organic matter, thus highlighting their potential as viable hydrocarbon exploration targets (Arogundade et al., 2020). On the other hand, the regions with shallower magnetic basement depths include Ilesha (1.6 km), Kiri (2.6 km), Oban (1.8 km), and Oyo (2.5 km). These areas fall within the Basement Complex terrain and are therefore less prospective for hydrocarbon exploration due to their thinner sedimentary cover and lack of extensive organic-rich formations. Nonetheless, their geophysical signature may hold interest for other mineral exploration activities, particularly for magmatic-hosted mineral deposits (Daudu et al., 2022).

The validity of these interpretations is supported by cross-referencing with previous studies. For instance, applied 2D spectral analysis to assess the subsurface structure in Abakaliki (Anyanwu and Mamah, 2013). Their findings revealed depth values ranging from 1.585 km to 4.136 km, with an average of 3.096 km, comparable to the current study's result of 3.9 km. This agreement affirms the robustness of the 2D spectral approach in capturing regional basement depth variations with high precision. Similarly, employed both Horizontal Gradient Method (HGM) and Analytic Signal Method (ASM) in Ilesha to estimate magnetic source depths (Ozebo et al., 2015). Their results for ASM ranged between 1.46 km and 2.55 km (average: 2.01 km), while the HGM approach yielded deeper values between 2.92 km and 5.48 km (average: 4.20 km). These are reasonably close to the 1.6 km value obtained in this study for Ilesha using spectral analysis, thereby validating the spectral technique's applicability across diverse geophysical terrains.

As studied Abeokuta using multiple techniques: ASA yielded depths between 0.554 km and 2.49 km, HGM gave 0.503 km to 2.34 km, and LWN method indicated depths between 0.931 km and 4.90 km (Olurin et al., 2015). The current study's depth estimate of 5.3 km in Abeokuta falls within the range suggested by the LWN method and represents one of the thickest sedimentary sequences in the region. This finding supports Abeokuta's potential as a frontier zone for petroleum exploration, especially when coupled with thermal maturity assessments and source rock characterization. Furthermore, the study in the Kogi-Auchi region, employing slope analysis of aeromagnetic data, identified deep magnetic source depths ranging from 2.3 km to 4.9 km (Chinwuko et al., 2014). This aligns well with the current study’s depth estimate of 3.9 km for Auchi, strengthening the regional consistency of magnetic basement interpretations. Additionally, analyzed part of the Dahomey Basin using 2D spectral analysis and found basement depths varying between 4.22 km and 6.99 km, with an average depth of 6.04 km (Opara, 2011). The 5.3 km depth obtained in this study at Abeokuta, a city within the Dahomey Basin, corresponds well with these findings.

The collective agreement between current results and previous studies indicates that the spectral analysis technique employed is both reliable and effective in delineating subsurface structures across southern Nigeria. The obtained depths fall within the expected range of sedimentary basin thicknesses typical of southern Nigerian geological settings. Notably, the 3D surface map unveiled a basement topography defined by five distinct depressions and uplifts, which are likely controlled by crustal-scale fault systems and tectonic subsidence. These structural lows, particularly in Nsukka, Abakaliki, Auchi, and Abeokuta, act as sediment traps and could potentially host mature petroleum systems. Their correspondence with known basins such as the Anambra, Benue Trough, Niger Delta, and

Dahomey Basin further substantiates this interpretation.

The embedded depth data on the Nigerian map facilitates visualization of spatial basement variations and assists in prioritizing areas for further exploration. Such visual data integration using GIS enhances the spatial understanding of depth distribution and allows for multi-criteria decision-making in exploration planning. Moreover, the outcomes of this study underscore the geological evolution of the Nigerian southern basins. The variability in basement depths reflects a complex tectonostratigraphic history involving rifting, subsidence, and magmatic intrusions. These processes have shaped the present-day morphology of the basement and influenced the development of sedimentary environments across the study area.

In summary, this discussion highlights several key insights:

- The shallow magnetic anomalies indicate near-surface igneous or metamorphic features;
- The deep magnetic sources represent the undulating crystalline basement and show significant depth variations across southern Nigeria;
- Thick sedimentary sequences identified in Nsukka, Abeokuta, Abakaliki, and Auchi offer favorable conditions for hydrocarbon generation;
- The findings corroborate well with previous research, reinforcing the reliability of the spectral analysis technique for geophysical investigations.

Ultimately, this study contributes valuable information to the understanding of sedimentary basin architecture in southern Nigeria. It provides a foundational dataset that can guide hydrocarbon exploration, basin modelling, and future geophysical investigations. Given the observed variability in basement depths and structural features, follow-up studies integrating gravity data, seismic reflection surveys, and petrophysical logging are recommended to validate these findings and refine hydrocarbon prospectivity assessments.

5. CONCLUSION

The application of spectral analysis on high-resolution aeromagnetic data has proven highly effective in estimating the depth to magnetic sources across southern Nigeria. This geophysical approach has provided critical insights into the subsurface structure and stratigraphic framework of the region. By identifying two distinct magnetic layers, shallow sources ranging from 0.3 to 0.4 km and deeper sources ranging from 1.6 to 6.2 km, the study contributes substantially to understanding the geomorphology of the magnetic basement and the tectonic evolution of the sedimentary basins in this part of the country. The resulting two-dimensional (2D) contour and three-dimensional (3D) surface maps reveal a basement topography marked by distinct uplifts and depressions. These structural variations delineate areas of significant geological interest. In particular, the central and western regions, namely Nsukka, Abakaliki, Abeokuta, Auchi, and Patani, are characterized by deeper magnetic basement depths, implying a thicker sedimentary pile that is favorable for hydrocarbon accumulation. This aligns with findings from previous studies and reinforces the petroleum prospectivity of these regions, particularly those overlapping the Niger Delta Basin, the Dahomey Basin, and the Anambra Basin. Furthermore, the accuracy of the depth estimates derived from the spectral method has been validated through comparison with results from other geophysical approaches and studies. The consistency of these findings across various geological settings demonstrates the reliability of spectral analysis as a cost-effective, non-invasive tool for regional exploration and geological mapping. In addition to its hydrocarbon implications, this study also holds relevance for mineral exploration and geological modeling. The observed anomalies and structural features may correspond to zones of mineralization or basement intrusions that are significant for resource development. Future research efforts could build upon this foundation by incorporating complementary geophysical techniques such as gravity surveys, seismic reflection data, or magnetotellurics, to enhance the resolution and interpretative power of subsurface models. Investigations could also be extended to contiguous areas, allowing for a broader regional synthesis of basement architecture and sedimentary evolution. This study enhances our geoscientific understanding of southern Nigeria’s subsurface, offering valuable implications for hydrocarbon exploration, mineral prospecting, and basin evolution analysis. The methodologies and insights provided herein will serve as a reference point for subsequent geophysical and geological investigations in the region and beyond.

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Cite The Article: Babatola, Babatude Keji, Adebayo, Samuel, Ajide, Adeolu Bamidele, Abiona Mujidat Ayobami, Olushola Ebenezer Oluwatobi (2025). Estimation of Depth to Magnetic Sources in Southern Nigeria Using 2D Spectral Analysis of High-Resolution Aeromagnetic Data. *Science Heritage Journal, 9(2): 58-65.*