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Subsurface Structural Analysis Using High Resolution Aeromagnetic Data in Guyuk-Shani And Environs: A Geophysical Approach To Hydrocarbon Prospectivity

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Abstract : *The Investigation of depth to Magnetic Sources and Basement Topography in Guyuk-Shani and Adjoining Areas, Northeastern Nigeria, was carried out using High-Resolution Aeromagnetic (HRAM) data over the area to determine depth to Magnetic Sources, Basement Topography (BT), and its implications for Hydrocarbon potentials (HP). The Analysis of the High Resolution Aeromagnetic (HRAM) data was achieved through Source Parameter Imaging (SPI) and Modeling of Profiles to determine Sediment thickness and Basement Topography using Oasis montaj. The results of the findings revealed that, the Total Magnetic Intensity Map of the area has Magnetic susceptibilities varying from 9.2 to 253.9nT, and SPI depth to Magnetic Sources varying from 0.0703 to 15.5012km. The Basement Topography is the undulating type with Sub-Basins typical of Horst and Graben. The Modeled Profiles 1, 2, and 3 have deeper (D1) and Shallow (D2) Magnetic Source Depth varying from 8 to 12km, 5 to 15km and 8 to 12km, 1 to 3km, 0.8 to 1km and 0.1 to 0.25km, respectively. The findings revealed that the area has potential for Hydrocarbon exploration, especially the Sub-Basins with sediment thicknesses of 2 to 15km and above.*

Keywords: *High-Resolution Aeromagnetic data; Basement Topography; Source Parameter Imaging; Magnetic Source Depth; Sediment thickness; Hydrocarbon potential*

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1.0 Introduction

Nigeria's inland basins, particularly those within the Benue Trough, remain among the least explored regions for hydrocarbon accumulation despite their promising geological settings. Historically, hydrocarbon exploration in Nigeria has focused primarily on the Niger Delta, leading to over-reliance on that region while other basins such as the Gongola, Yola, and Bida Basins have received limited attention. The Benue Trough, a major Cretaceous sedimentary structure formed during the opening of the South Atlantic Ocean, exhibits complex tectonic and depositional histories that suggest potential for petroleum generation and accumulation. Understanding the subsurface geometry, basement configuration, and sediment thickness within these basins is therefore essential for evaluating their hydrocarbon potential.

Advancements in geophysical methods, especially High-Resolution Aeromagnetic (HRAM) surveys, have enhanced the ability to delineate subsurface structures where seismic data are unavailable or insufficient. HRAM data provide critical insights into magnetic anomalies that reflect variations in lithology, structural deformation, and basement topography. The Source Parameter Imaging (SPI) technique, derived from the analytic signal approach, has proven particularly effective in estimating magnetic source depths and identifying possible sub-basins that may serve as hydrocarbon traps.

Previous studies have demonstrated the usefulness of SPI and HRAM analyses in assessing sedimentary thickness and basement relief in several Nigerian basins, including Amper, Nasarawa, and Monguno. These studies revealed that areas with sediment thicknesses exceeding 3–5 km could support hydrocarbon generation. However, despite its strategic location within the Upper Benue Trough, the Guyuk–Shani area has not been adequately investigated using high-resolution aeromagnetic data. This lack of empirical geophysical evaluation represents a significant knowledge gap, as the structural characteristics and sedimentary architecture of the area remain poorly constrained.

Source Parameter Imaging (SPI) is a quick, easy, and powerful method for calculating the depth of magnetic sources. It is based on the extension of complex analytic signals to estimate magnetic depths and is also known as the local wavenumber method. The original SPI technique (Thurston & Smith, 1997) applies to two models: a 2-D sloping contact and a 2-D dipping thin sheet. This method has been widely used in recent years to estimate basement depth (Salako, 2014) and has proven reliable, with an accuracy of about ±20% in tests on real datasets with drill-hole control. Compared to Euler Deconvolution, SPI produces a more complete and coherent set of solution points and is easier to interpret, especially by experts familiar with local geology.

Globally, the SPI method has been adopted due to its effectiveness in subsurface imaging and magnetic depth estimation. For instance, Kasidi et al. (2016) used SPI to interpret HRAM data over Amper and its environs in North Central Nigeria, revealing shallow and deep magnetic sources ranging from 10–1490 m and 1500–4000 m, respectively. Similarly, Odidi et al. (2020) applied SPI to aeromagnetic data across the Benue Trough, covering the Gongola and Yola Basins, and estimated depths ranging from 0.12 to 12.26 km. Ayuba and Nur (2018) used HRAM data over Nasarawa and environs to assess hydrocarbon potential and reported sediment thicknesses of up to 5.297 km. Likewise, Akiishi et al. (2022) combined HRAM and aerogravity data over Monguno, revealing sediment thicknesses of about 3259.4 m and 4674.3 m, respectively.

Despite these efforts, Guyuk–Shani and adjoining areas remain poorly investigated, leaving uncertainties regarding their basement configuration and sedimentary architecture. This research, therefore, seeks to bridge this gap by using HRAM data to determine sediment thickness and basement topography. Crucial parameters for assessing hydrocarbon potential. The study also responds to Nigeria's growing need to diversify its hydrocarbon exploration frontiers beyond the Niger Delta by evaluating inland basins with viable geological conditions.

This study aims to analyze subsurface structures and evaluate the hydrocarbon potential of Guyuk–Shani and environs using high-resolution aeromagnetic data through the Source Parameter Imaging (SPI) technique. Specifically, the study seeks to:

(i) Estimate the depth to magnetic sources and delineate basement topography;

(ii) Assess sediment thickness across the study area;
(iii) Identify potential sub-basins favorable for hydrocarbon accumulation; and
(iv) Contribute to the regional geological understanding of the Upper Benue Trough.

By providing new geophysical insights into the subsurface configuration of Guyuk–Shani, this study will enhance the understanding of structural trends within the Upper Benue Trough, contribute to Nigeria's hydrocarbon exploration database, and support informed decision-making in the country's quest for energy diversification.

1.1 Study Area

The study area lies in northeastern Nigeria, between longitudes 11°30′E and 12°30′E and latitudes 9°30′N and 10°30′N (Fig. 1). It covers an area of approximately 12,056.04 km², spanning about 109.8 km by 109.8 km, and is easily accessible through a network of roads and pathways. Geographically, it forms part of the Gongola Arm and Yola Arm of the Upper Benue Trough. The terrain varies in elevation from 140 to 800 meters, characterized by alternating high and low relief (Fig. 1). Drainage within the area is predominantly dendritic, with most streams converging into the River Gongola — a tributary of the River Benue.

The climate is typical of the West African Savanna, featuring distinct wet and dry seasons. Average temperatures range from 26.1°C during the cool months (December–January) to 33°C in the hottest months (April–May). Rainfall averages between 700–800 mm annually. The area lies within the Guinea Savannah Zone of Nigeria's vegetation regions, showing transitional characteristics between the Northern Guinea and Sudan Savannahs. Woodland vegetation dominates the river basins, with continuous grass cover and scattered trees (Adebayo & Tukur, 1999).

Geologically, the Benue Trough originated during the Lower Cretaceous as a result of the opening of the South Atlantic Ocean. Its evolution began in the Aptian era with the formation of isolated continental basins, followed by Albian and Turonian marine transgressions that facilitated sedimentation across the region. The tectonic development of the trough was influenced by transcurrent faulting along an axial fault system, producing alternating compressional and tensional regimes. These resulted in the formation of basins, horsts, and sub-basins aligned along the fault zones.

Two major compressional phases shaped the region. The Santonian event in the southern Benue (Abakaliki area) and a subsequent Cretaceous event in the Upper Benue Trough. The Cretaceous magmatism, often with alkaline affinities, was concentrated along these faults. Crustal thinning beneath the Benue Trough and the presence of an axial basement high, flanked by deep sub-basins, have been established through geophysical studies. The structural configuration of the trough is consistent with sinistral wrenching associated with the Equatorial Fracture Zones during the early stages of the opening of the Gulf of Guinea (Aliyu et al., 2020).

The Upper Benue Trough comprises two principal arms: the Gongola Arm and the Yola Arm**.** The Gongola Arm's stratigraphy includes the continental Albian Bima Sandstone, transitional Cenomanian Yolde Formation, and the marine Turonian–Santonian Gongila, Pindiga, and Fika Formations**,** overlain by the continental Campanian–Maastrichtian Gombe Sandstone and Tertiary Kerri-Kerri Formation. In contrast, the Yola Arm's stratigraphic sequence replaces these formations with the marine Dukul, Jessu, Sekuliye, Numanha, and Lamja Formations (Aliyu et al., 2020). Fig.s 2 and 3 illustrate the geologic map and stratigraphic framework of the study area.

2.0 Materials and Methods

2 1. Source of Data

The high-resolution Aeromagnetic data for this work were acquired from Nigerian Geological Survey Agency Abuja (NGSA), which is a digitized aeromagnetic data of four (4) sheets measuring one (1^o) degree and one (1^o) degree over the study region. Fugro Airborne Surveys conducted high-resolution aerial survey coverage in Nigeria for the Nigerian Geological Survey Agency from 2004 to 2009. Aeromagnetic Surveys were conducted at nominal flying height of 80 meters and along a sequence of 500-meter-spaced NW-SE flight lines with 2000-meter tie-line spacing in NE-SW direction. Data were captured every 0.1 seconds. The Survey's resolution of anomalies is better than that of traditional high-altitude surveys since it was conducted at a lower flying height (80 meters), with narrow line spacing, and a relatively short recording interval. Fugro Airborne Surveys performed all Magnetic data revisions. As part of the Sustainability Management for Mineral Resources Project in Nigeria, the Federal Government of Nigeria and the World Bank jointly funded the acquisition, processing, and compilation of the high-resolution Aeromagnetic data.

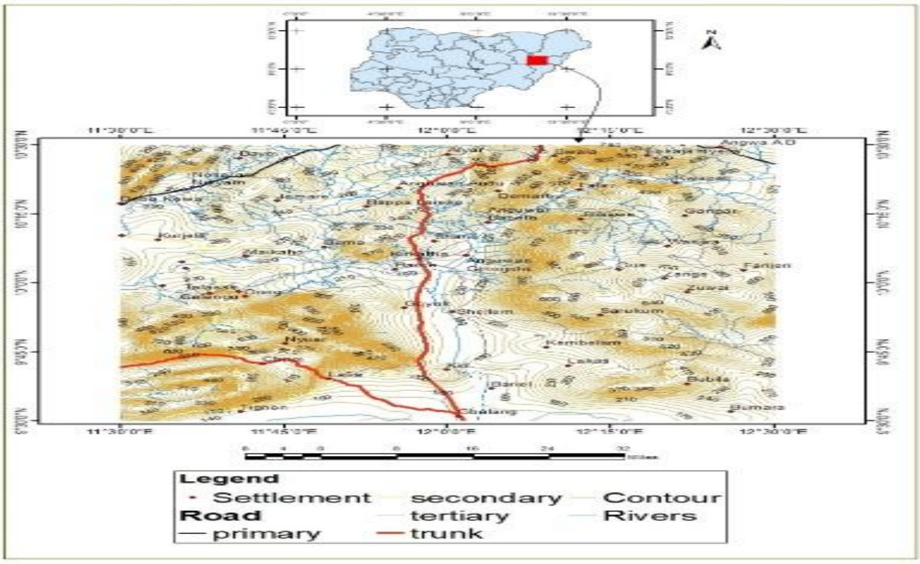

Fig. 1: Geologic Map of the Study Area (After Federal survey of Nigeria, 2006)

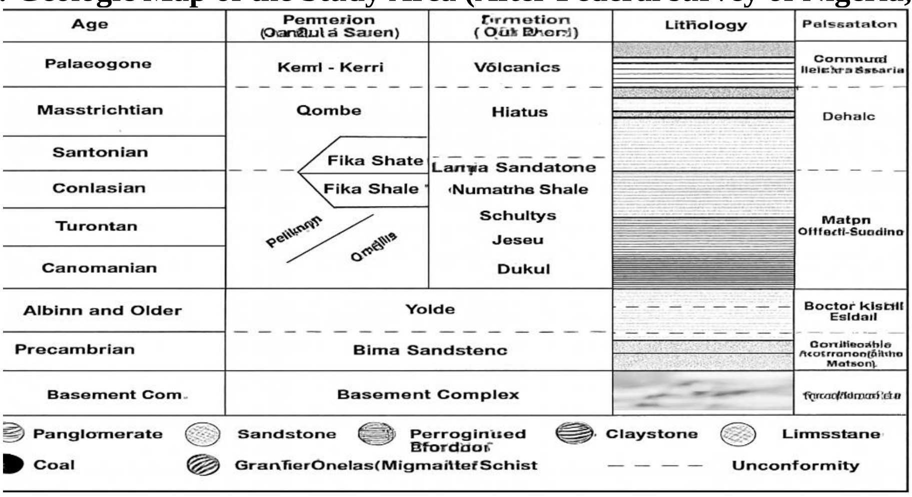

Fig. 2: Stratigraphic successions of Upper Benue Trough (After Aliyu *et al.*, 2020)

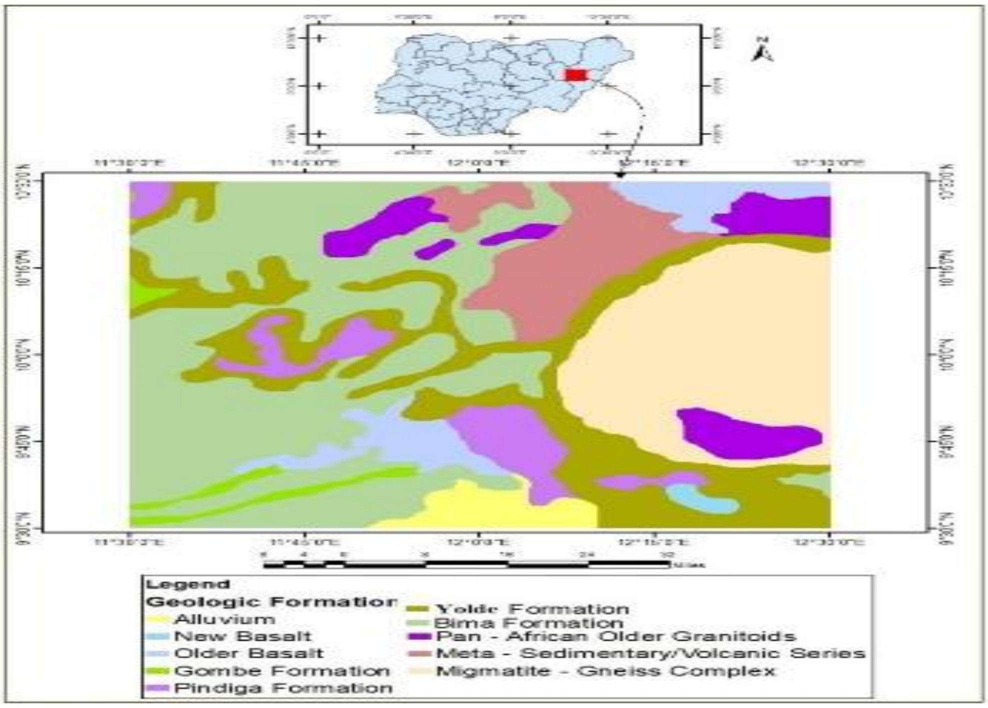

Fig 3: G.eologic Map of the Study Area (After Nigerian Geologic Survey Agency, 2006)

2.2 Source Parameter Imaging

The Source Parameter Imaging (SPI) is a technique using an extension of the complex Analytical Signal to estimate magnetic depths. This technique developed by Ndikum *et al*. (2024) sometimes referred to as the local wave number method is a profile or grid-based method for estimating magnetic source depths, and for some source geometries the dip and susceptibility contrast. The method utilizes the relationship between source and the local wave number (k) of the observed field, which can be calculated for any point within a grid of data via horizontal and vertical gradients (Odidi *et al*., 2020 & Nwosu, 2014).

The original SPI method (Thurston and Smith, 1997) works for two models: a dipping thin dike and a sloping contact. The local wave number has maxima located over isolated contacts, and depths can be estimated without assumptions about the thickness of the source bodies. Solution grids using the SPI technique show the edge locations, depths, dips and susceptibility contrasts. The local wave number, map more closely, resembles geology than either the magnetic map or its derivatives. The SPI method requires first and second order derivatives and is thus susceptible to both noise in the data and to interference effects.

The SPI method estimated the depth from the local wave number of the analytic signal. The analytic signal $A_1(x,z)$ is defined by Nwachukwu *et al*. (2020) as

$$A_1(x,z) = \frac{\partial M(x,z)}{\partial x} - j\frac{\partial M(x,z)}{\partial z} \quad (1)$$

Where $M(x,z)$ is the magnitude of the anomalous total magnetic field, j is the imaginary number and z and x are Cartesian coordinate for the vertical direction and the horizontal direction perpendicular to strike, respectively.

The local wave number k1 is defined by Thurston and Smith (1997) to be

$$\text{K1}=\frac{\partial}{\partial x}\tan^{-1}\frac{\partial M}{\partial z}\Big/\frac{\partial M}{\partial x} \quad (2)$$

The analytical signal A(x, z) is defined by Layade *et al*., (2023) as:

$$\text{A(x,z)} = \frac{\partial M(x,z)}{\partial x} - j\frac{\partial M(x,z)}{\partial z} \quad (3)$$

where M(x, z) is the magnitude of the anomalous total magnetic field, j is the imaginary number, z and x are Cartesian coordinates for the vertical direction and the horizontal direction respectively. Nabighian (1972) showed that the horizontal and vertical derivatives comprising the real and imaginary parts of the 2D analytical signal are Hilbert transformation pair

$$\frac{\partial M(x,z)}{\partial x} \Leftrightarrow \frac{\partial M(x,z)}{\partial z} \quad (4)$$

where ⇔ denotes a Hilbert transformation pair.

Edunjob *et a*l. (2023) define the local wave number k (in radian per ground unit) for this analytical signal to be

$$K = 2\pi f_0 \quad (5)$$

and

$$f_0 = \frac{1}{2\pi}\frac{\partial}{\partial x} tan^{-1}\left[\frac{\partial M(x,Z)}{\partial z} \Big/ \frac{\partial M(x,z)}{\partial x}\right] \quad (6)$$

where f_0 is cycles/ground unit and K is the wave number in radian per ground unit.

$$K = \frac{\partial}{\partial x} tan^{-1}\left[\frac{\partial M(x,Z)}{\partial z} \Big/ \frac{\partial M(x,z)}{\partial x}\right] \quad (7)$$

Nabighian (1972) gives the expression for the vertical and horizontal gradient of a sloping contact model as

$$\frac{\partial M(x,z)}{\partial z} = \frac{2\chi \boldsymbol{M} c\sin\beta \cdot x\cos(2I-\beta-90°) - h\sin(2I-\beta-90°)}{h^2+x^2} \quad (8)$$

$$\frac{\partial M(x,z)}{\partial x} = \frac{2\chi \boldsymbol{M} c\sin\beta \cdot h\cos(2I-\beta-90°) - x\sin(2I-\beta-90°)}{h^2+x^2} \quad (9)$$

where χ is the susceptibility contrast at the contact, M is the magnitude of the earth's magnetic field (the inducing field), c = 1-$\cos^2 i \sin^2\alpha$, α is the angle between the positive x-axis and magnetic north, *i* is the ambient-field inclination, tan I = sini/cos8, β is the dip (measured from the positive x-axis), *h* is the depth to the top of the contact and all trigonometric arguments are in degrees. The coordinate system has been defined that the origin of the profile line (x = 0) is directly over the edge.

Substituting equations 10 and 11 into 12 gives the wave number for a contact profile as

$$K_{max} = \frac{1}{h} \quad (10)$$

$$Depth(h) = \frac{1}{K_{max}} \quad (11)$$

K is the wave number of the analytical signal

h is the depth to the point of contact.

From equation (14), it is evident that the wave number is independent of susceptibility contrast, the dip of the source, the inclination, declination, and the strength of the Earth's magnetic field (Hossein *et al*., 2023).

Equation 9 is the basis for the SPI method; it utilizes the relationship between source depth and the local wavenumber of the observed field, which can be calculated for any point within a grid of data through horizontal and vertical gradients. For vertical contacts, the peaks of the local wave number define the inverse of depth. The depth is displayed as an image (in colour aggregate). Image processing of the source-parameter grids enhances detail and provides maps that facilitate interpretation by non-specialists (Hossein *et a*l., 2023). In this work, after the source parameter image has been produced, profiles will be drawn on selected areas of the map using the Mag Map package in the Oasis Montaj, which will be modeled to obtain basement topography.

3.0 Results and Discussion

The Investigation of Depth to Magnetic Sources and Basement Topography in Guyuk-Shani and Adjoining Areas, Northeastern Nigeria was carried out to investigate sediment thicknesses and the Basement Topography of the area, with a view to having the knowledge of the implications of the sediment thicknesses and the Basement Topography to Hydrocarbon potentials.

The analysis of the Aeromagnetic data over the area using Source Parameter Imaging and Profile Modeling indicates that the Total Magnetic Intensity (TMI) Map (Fig. 4) has both low, moderate, and high Magnetic Intensity values that are characterized by dark blue-light blue, Green-Yellow-Orange, and

Red-Pink colours. Magnetic Intensity varies from 9.2 to 253.9nT.

The Source Parameter Image (SPI) Map (Fig. 5a) reveals the various thicknesses of sediments in the area. The sediments vary in thickness from 0.0703 to 15.5012km. It can be observed clearly that the depth to Magnetic Sources from the Source Parameter Imaging is inversely proportional to the Magnetic susceptibilities of the area.

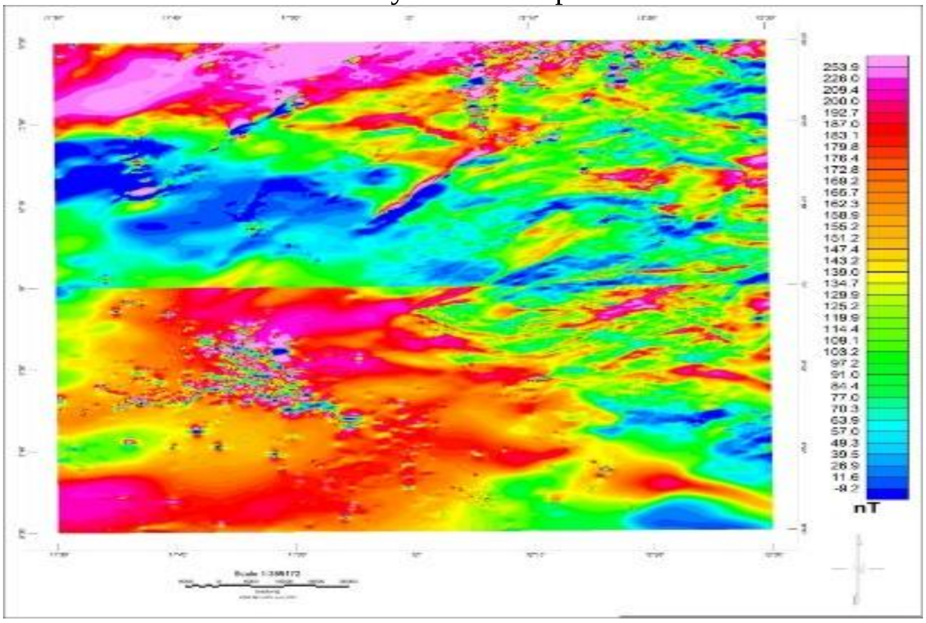

Fig. 4: Total Magnetic Intensity Map of the Area

In those areas with low Magnetic susceptibility, there are areas with high sediment thickness, while areas with high susceptibilities are the areas with low sediment thickness. This is an indication that the sediments are devoid of Magnetic Minerals and probably have non-magnetic Minerals. The result of the SPI relates to a certain extent to the work of Ndikum *et al.* (2024). A closer look of the sediment thicknesses in the area from the SPI result, the area has potential for hydrocarbons. According to Salako (2014), areas with sediment thickness of 2 km and above could be potential areas for Hydrocarbon if other conditions are met. Therefore, with the sediment thickness of the area based on the recommended range, the sediment thickness of potential areas varies from 2km to 15.5012km. These areas are potential areas for further Hydrocarbon studies to further confirm the thermal maturity of the sediments, total organic carbon content etc.

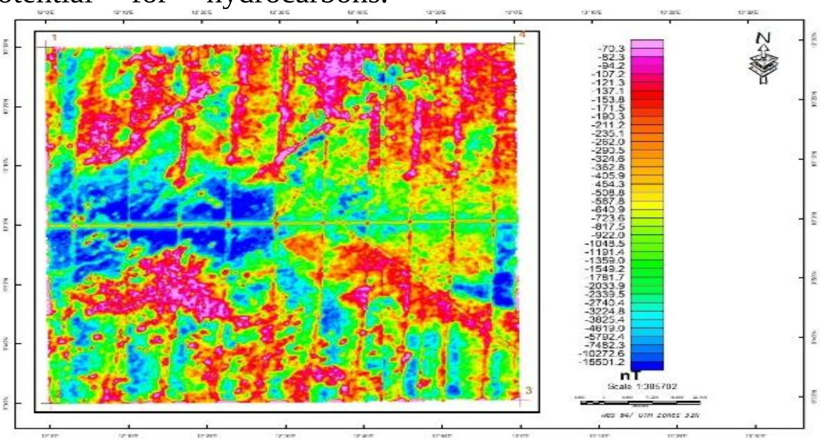

Fig. 5a: Source Parameter Image Map of the Area

The SPI Map was further subjected to modeling of three Profiles (Fig. 5b), which were carefully selected based on areas of prominent anomalies. The essence of the Modeling of the Profiles was to observe the Basement Architecture (Topography), which is crucial to the understanding of the Basement surface. The result of the Modeling of the three (3) Profiles (Fig.s 6a, 6b & 6c) revealed that the Basement surface is not flat, but rather it has an undulating surface that is characterized by Host and Grabens that have resulted from Tectonic activities that affected the area. The Grabens are simply referred to as Sub-Basins as observed on the Profiles.

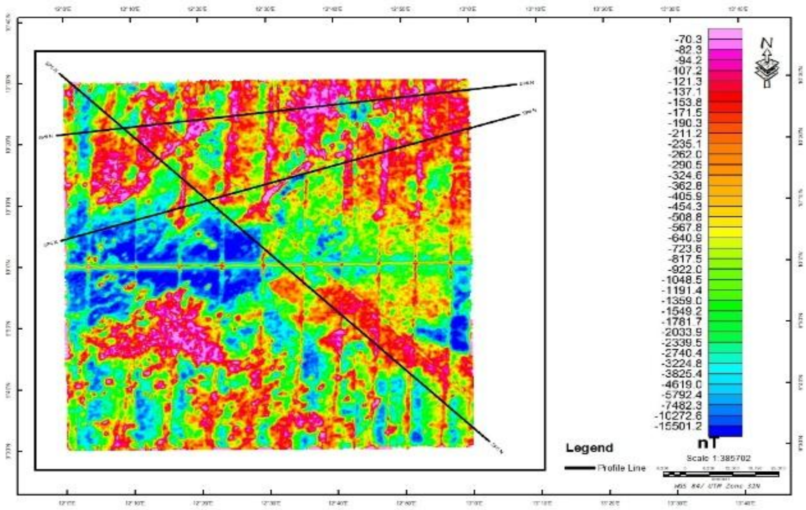

Fig. 5b: Source Parameter Image Map of the Area Showing Profiles.

Profile 1 (Fig. 6a & Table 1a) extends from SW-NE with a length of approximately 16.5 km. The profile is characterized by an undulating surface with two major Sub-Basins, which are identified on the profile as D1, signifying Deeper Sediment thickness (Deeper Magnetic Source depths). While the Shallow Sediment thicknesses are identified as D2, indicating areas with Shallow Sediment thickness. From the SPI modeling, the Profile revealed Sub-Basins of D1 and Shallow areas of D2 as shown on the Profile. Table 1 shows that the thickness of D1 and D2 varies from 8 to 12km and 1 to 3km, respectively. This indicates that the Sub-Basins of D1 that vary from 8 to 12km are potential areas for further hydrocarbon studies.

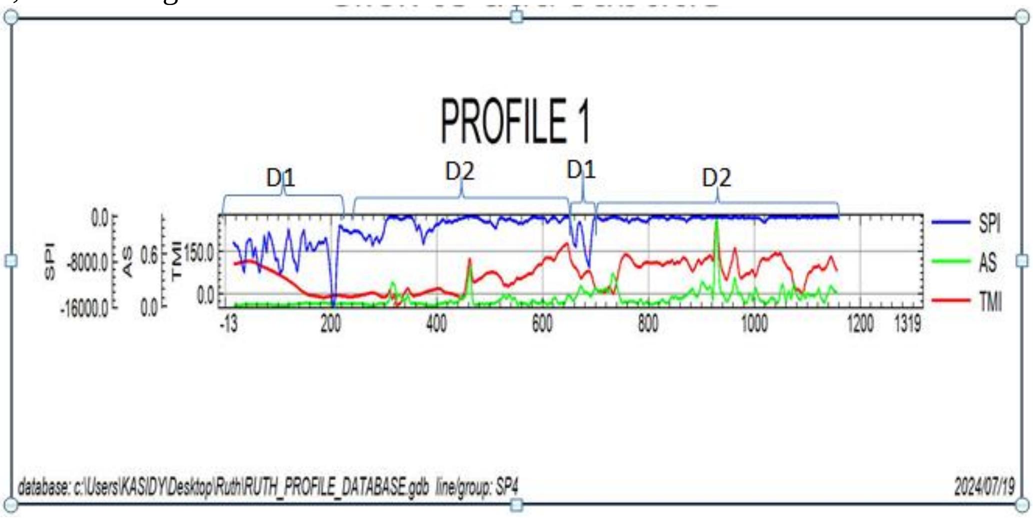

Fig. 6a: Profile 1 of the Area

Table 1a: Source Parameter Image Depth of Deeper (D_1) and Shallow (D_2) Magnetic Sources

Profile	D_1 (km)	D_2 (km)
1	12	3
	8	1
Total	**20**	**4**
Average	**10**	**2**

Profile 2 (Fig. 6b & Table 1b) extends from SW-NE with a lateral extent of approximately 18km. The Profile is also characterized by an undulating surface with two major Sub-Basins identified as D1 and D2. The Sub-Basins, which are known as areas with thick sediments, vary from 5 to 15km, while areas with Shallow Sediment thickness vary from 0.8 to 1km. Sediment thickness of 5 to 15km is a potential area for Hydrocarbon exploration.

Profile 3 (Fig. 6c & Table 1c) is an undulating surface with a lateral extent of approximately 24.5km. The Profile has three Sub-Basins (D1) that vary in Sediment thicknesses from 8 to 12km, which are potential areas for further Hydrocarbon studies. The three shallow areas (D2) vary from 0.1 to 0.25km.

Table 1b: Source Parameter Image Depth of Deeper (D_1) and Shallow (D_2) Magnetic Sources

Profile	D_1 (km)	D_2 (km)
2	15	1.0
	5	0.8
Total	**20**	**1.8**
Average	**10**	**1.4**

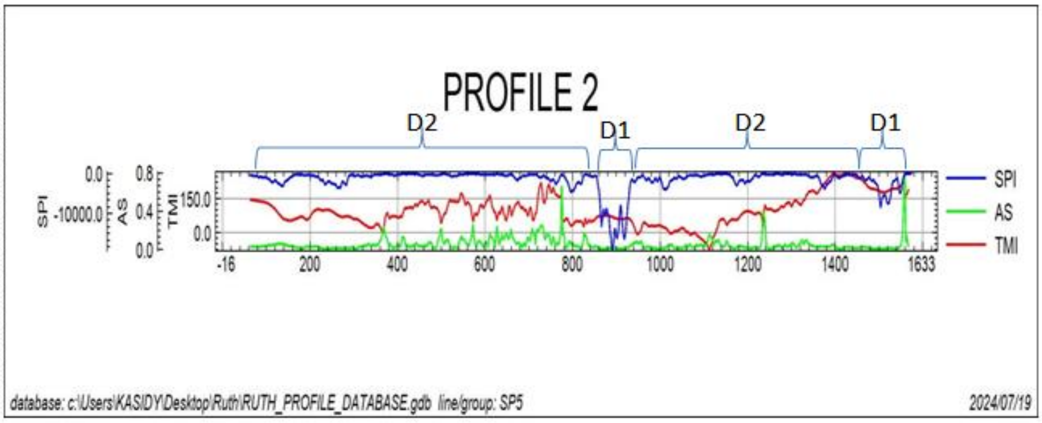

Fig. 6b: Profile 2 of the Area

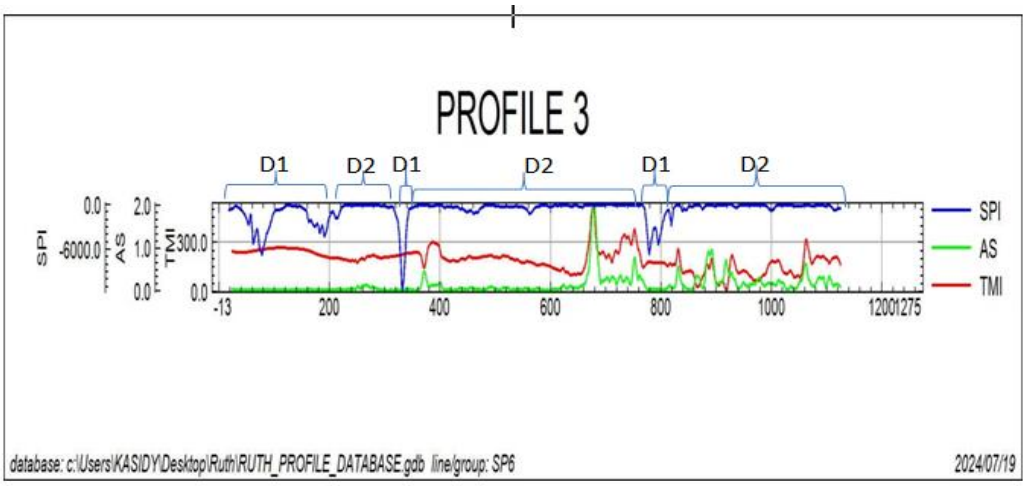

Fig. 6c: Profile 3 of the Area

Table 1c: Source Parameter Image Depth of Deeper (D_1) and Shallow (D_2) Magnetic sources

Profile	D_1 (km)	D_2 (km)
3	8	0.10
	12	0.20
	8	0.25
Total	**28**	**0.55**
Average	**9.33**	**0.18**

The findings of this research indicate that the Sediment thickness obtained from the Source Parameter Imaging is worthy enough to say that the specified areas of high thickness, as revealed by the SPI Map and Modeling of Profiles, are potential areas for Hydrocarbon exploration.

The investigation of depth to Magnetic Sources and Basement Topography in Guyuk-Shani and Adjoining areas, Northeastern Nigeria, was carried out to determine depth to magnetic sources and Basement Topography and its implications for Hydrocarbon potentials. From the result obtained, the Total Magnetic Intensity Map of the area has Magnetic lows and highs varying from 9.2 to 253.9nT, the Residual Magnetic Intensity Map with values from -85.7 to 74.0nT, the Regional Magnetic Intensity Map with values from 23.8 to 230.3, and SPI depth to Magnetic Sources vary from 0.0703 to 15.5012km. The Basement Topography was observed and found to be the undulating type with Sub-Basins typical of Horst and Grabben with Profiles 1, 2, and 3 of D1 and D2 varying from 8 to 12km, 5 to 15km, and 8 to 12km, 1 to 3km, 0.8 to 1km, and 0.1 to 0.25km, respectively.

4.0 Conclusion

This study investigated the depth to magnetic sources and basement topography in the Guyuk–Shani and adjoining areas of Northeastern Nigeria to assess sediment thickness and hydrocarbon potential using aeromagnetic data, Source Parameter Imaging (SPI), and profile modeling.

The Total Magnetic Intensity (TMI) values range from 9.2 to 253.9 nT, reflecting variable subsurface magnetic compositions. The SPI results show sediment thicknesses between 0.07 and 15.5 km, with low magnetic susceptibility zones corresponding to thick, non-magnetic sediments typical of potential hydrocarbon-bearing formations. These findings align with earlier studies in the Upper Benue Trough, emphasizing strong structural control on sedimentation.

The basement structure is undulating, comprising alternating horsts and grabens that resulted from tectonic deformation. Modeled profiles confirm this variability: Profile 1 shows sediment thicknesses of 8–12 km in deeper sections and 1–3 km in shallower parts; Profile 2 indicates depths of 5–15 km, while Profile 3 reveals 8–12 km in deeper zones and 0.1–0.25 km in shallow areas. These structural variations define several sub-basins that could serve as hydrocarbon depocenters.

The relationship between low magnetic intensity and high sediment thickness indicates promising hydrocarbon zones, particularly where sediment thickness exceeds 2 km, consistent with thresholds for hydrocarbon generation. However, confirmation requires geochemical and thermal maturity studies to validate hydrocarbon presence.

In conclusion, the study delineates three major sub-basins with significant sediment accumulation and a structurally complex basement favorable for hydrocarbon exploration. The integration of aeromagnetic interpretation, SPI, and profile modeling reveals that the Guyuk–Shani region holds strong potential for hydrocarbons. Future work should combine seismic, gravity, and geochemical analyses to refine basin models and confirm reservoir viability. This research enhances understanding of the Upper Benue Trough's tectono-sedimentary evolution and supports its evaluation as a frontier for hydrocarbon exploration.

Acknowledgement

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Not applicable

Data availability

The microcontroller source code and any other information can be obtained from the corresponding author via email.

Authors' Contribution

Ezekiel Kamureyina designed and supervised the study, coordinated data interpretation, and prepared the initial manuscript. Justine Ruth Ija processed HRAM data and assisted with anomaly interpretation. Na'Allah Victor Gambo contributed to SPI depth analysis and geological evaluation. Salihu Idris Jauro supported basement modelling and structural interpretation. Benjamin Brian prepared maps, validated results, and improved the presentation of findings.