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EVALUATION OF SUBSURFACE STRUCTURES USING HIGH RESOLUTION AEROMAGNETIC DATASET FOR HYDROCARBON POTENTIAL PROSPECTIVITY IN PARTS OF THE ANAMBRA AND SOUTHERN BIDA BASINS, NIGERIA

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Abstract
This study focuses on the evaluation of subsurface structures using high resolution aeromagnetic dataset for hydrocarbon potential prospectivity in parts of the Anambra and Southern Bida Basins, Nigeria. Four high-resolution aeromagnetic data were collected, analyzed and evaluated to interpret the structural framework, assess basement topography, and evaluate the hydrocarbon potential of the study region. The datasets were interpreted using a combination of geophysical interpretation tools such as Oasis Montaj, Surfer, and Geo Rose software. Results from qualitative analysis of the residual anomaly map (RAM), the reduce to pole (RTP) map and the rose diagram reveals significant northeast to southwest (NE-SW) trending faults within the region, reflecting the regional tectonic regime. This conforms to the trend of the Benue Trough. The result also reveals evidence of other structural feature such as folds in the area. These faults form potential migration pathways and trapping mechanisms for hydrocarbon accumulation. Lineament analysis as reveal by the Analytical signal map showed dense fault networks predominately around the southern area, with prominent basement depressions that could serve as accommodation spaces for sediments. The identified structural traps, coupled with the thick sedimentary cover and fault-controlled migration pathways, suggest that the study area is prospective for hydrocarbon accumulation. The sedimentary thickness obtained through Spectral analysis ranges from 0.42 km – 5.24 km with average of 1.72 km across the study area. The deep sedimentary cover signifying deep depth to magnetic sources vary from 2.03km to 5.24 km, whereas the shallow sedimentary cover (shallow depth to magnetic sources) varies from 0.41 km to 1.85 km. The sedimentary cover map reveals deeper sedimentary cover in the southern and central parts of the study area while, the shallower sedimentary cover occurs in the northern parts. The result of the estimated oil and gas window is between 74.78 °C and 150.21 °C across the study area. The study concludes that there is likelihood of hydrocarbon generation in the southern and central regions of the study area, whereas, the northern and other parts of the study area appear plausible for mineral exploration.
Keywords: *Lineament, Rose Diagram,* Spectral Analysis, sedimentary cover, and Structural Trap

Introduction

The search for hydrocarbons has driven the development of advanced geophysical techniques, with high-resolution aeromagnetic surveys playing a pivotal role in mapping subsurface structures and understanding basin evolution. The Anambra Basin and the adjoining southern Bida Basin in Nigeria are of particular interest due to their strategic importance in Nigeria's hydrocarbon reserves (Chinwuko *et al.* 2016; Usman *et al.* 2024). These basins are situated within a tectonically inactive region and are characterized by complex subsurface structures, which necessitate robust analytical methods of exploration. The Anambra Basin, situated to the southeast, is a Cretaceous sedimentary basin developed during the Santonian tectonic episode. It overlies the Benue Trough and is characterized by sequences of sandstone, shale, and coal formations. While the adjoining Southern Bida Basin located in the central Nigeria, is a NW-SE trending intracratonic basin with sedimentary sequences dominated by sandstone and shale. The basins have undergone tectonic processes that created fault systems and structural traps essential for hydrocarbon accumulation. The integration of geophysical techniques like aeromagnetic surveys provides a cost-effective method to identify these critical subsurface features.

Aeromagnetic datasets are particularly valuable in hydrocarbon exploration because they provide insights into the distribution and depth of magnetic sources, which often correlate with key geological features such as faults, intrusions, and sedimentary thickness variations (Chinwuko *et al*. 2024). To enhance the interpretative power of aeromagnetic data, two methodologies stand out; Spectral Analysis and subsurface structural analysis using the Analytical signal and Reduce to Pole (RTP) Transformation. These techniques are indispensable for unraveling the subsurface structural framework and assessing the hydrocarbon potential of sedimentary basins. Spectral Analysis offers a quantitative approach to estimating the depth to magnetic sources by analyzing the frequency content of aeromagnetic anomalies.

This research focuses on evaluation of high-resolution aeromagnetic data over parts of Anambra and Bida Basins and its inference of Hydrocarbon prospectivity. The results of the interpretation give more insight on the configurations of the basins by determining their sedimentary thickness. It also establishes the structural features and possibly obtains a 3-Dimensional view of the Basins. The calculated sedimentary thicknesses across the study serve as input in computing the temperature gradient values which are used to calibrate the oil window regime within the study areas. Finally, the findings attempt to evaluate the petroleum prospectivity and delineation of prospect areas for petroleum exploration within the study areas.

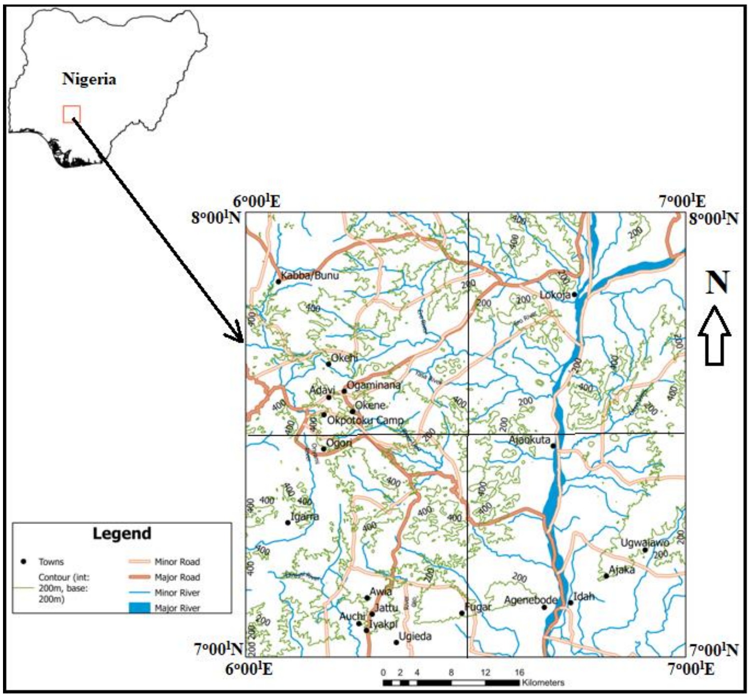

Fig.1.Location map of the study area

The area of study is in the parts of Anambra and its adjoining Bida Basins which is a major inland sedimentary basin located in the southern part of Nigeria. The study area lies between $7^{0}00^{1}$ and 80^{0} 00^{1} E of longitude and between $6^{0}00^{1}$ and $8^{0}00^{l}$ N of latitude, covering an area of approximately 12,100 km^{2}. The major towns are Kabba, Lokoja, Auchi and Idah (Fig. 1.1).

Geology of the study area

The Anambra/Bida Basins are part of the three major sub-divisions of Benue Trough, Nigeria with the other two as Upper and Lower Benue Trough border. According to Obaje (2009), the Middle Benue Trough comprises of six stratigraphic successions that are dated within the Upper Cretaceous (Fig. 2.2). This succession is made up the Asu River Group (ARG), Ezeaku Formation, Keana Formation, Awe Formation, Awgu Formation and Lafia Formation (From the oldest to the youngest). The Asu River Group is made up of Albian materials of Arufu, Uomba and Gboko Formations which consist of the lithologic composition of limestones, shales, micacous siltstones, mudstones and clays (Obaje, 1994). The average thickness is estimated to be about 1,800 m, overlying on top of the ARG is the Ezeaku Formation which is attributed to the beginning of marine transgression in the Late Cenomanian. The sediments are made up mainly of calcareous shales, micaceous fine to medium friable sandstones and beds of limestones which are in places shelly (Obaje, 2009). The deposition took place in a presumably shallow marine coastal environment.

The study area is composed of the following economic values; The South-eastern part of the study area is mostly endowed with sedimentary packages of Anambra Basin which favours the petroleum studies, while the Northern parts are covered by Basement Complex and little amount of sedimentary package of Bida Basin as evident in the geological map (Fig. 14a) also with these economic minerals; Beryllium Be, Tin Sn, Niobium Nb, and Tantalum Ta.

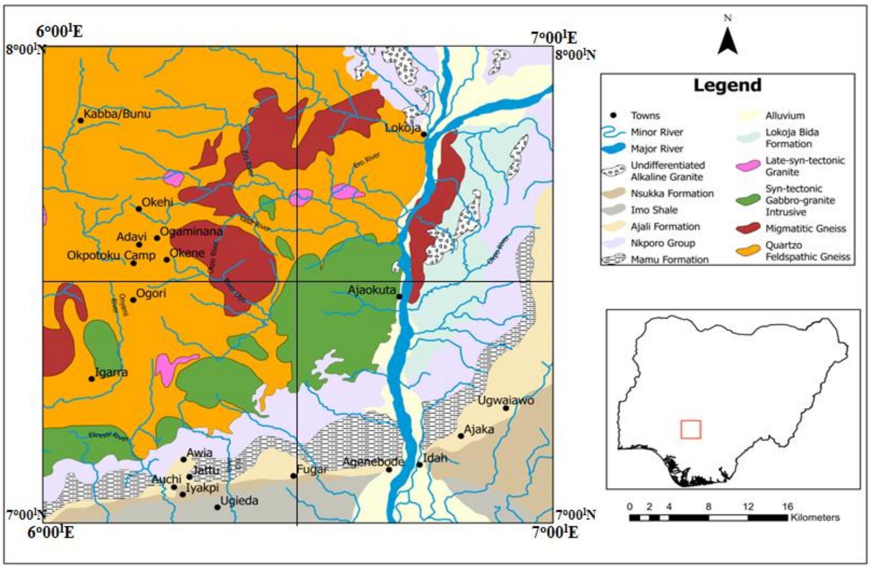

Fig.2. Geologic map of the study area

Methods

The procedure involved in this study includes integration of the four aeromagnetic data, production of magnetic anomaly map, generation of structural maps, analysis and modeling of magnetic anomaly data The data sets were pre-processed, and the magnetic data reduced to the pole (RTP). The derived maps were subjected to various transformation and enhancement procedures. The purpose of these procedures was both for enhancement and assessment of consistency of the various categories of anomaly and features. The upward continuation, analytical signal, tilt derivative, horizontal gradient of the tilt derivative, directional gradients (horizontal, vertical, directional cosine) and spatial frequency filtering techniques were mostly used. The spectral analysis technique was found to be most suitable for basement depth estimation in this project, and was adopted for the purpose.

The aeromagnetic data were obtained as part of the nationwide aeromagnetic survey sponsored by Geological Survey Agency of Nigeria. The data were acquired along a series of Northwest–Southeast flight lines with a spacing of 2km and an average flight elevation of about 150m while tie lines occur at about 20km interval. The geomagnetic gradient was filtered from the data using the International Geomagnetic Reference Field (IGRF). The data were made available in the form of digitized contoured maps on a scale of 1:100,000. The total area covered was about 12100 square kilometers.

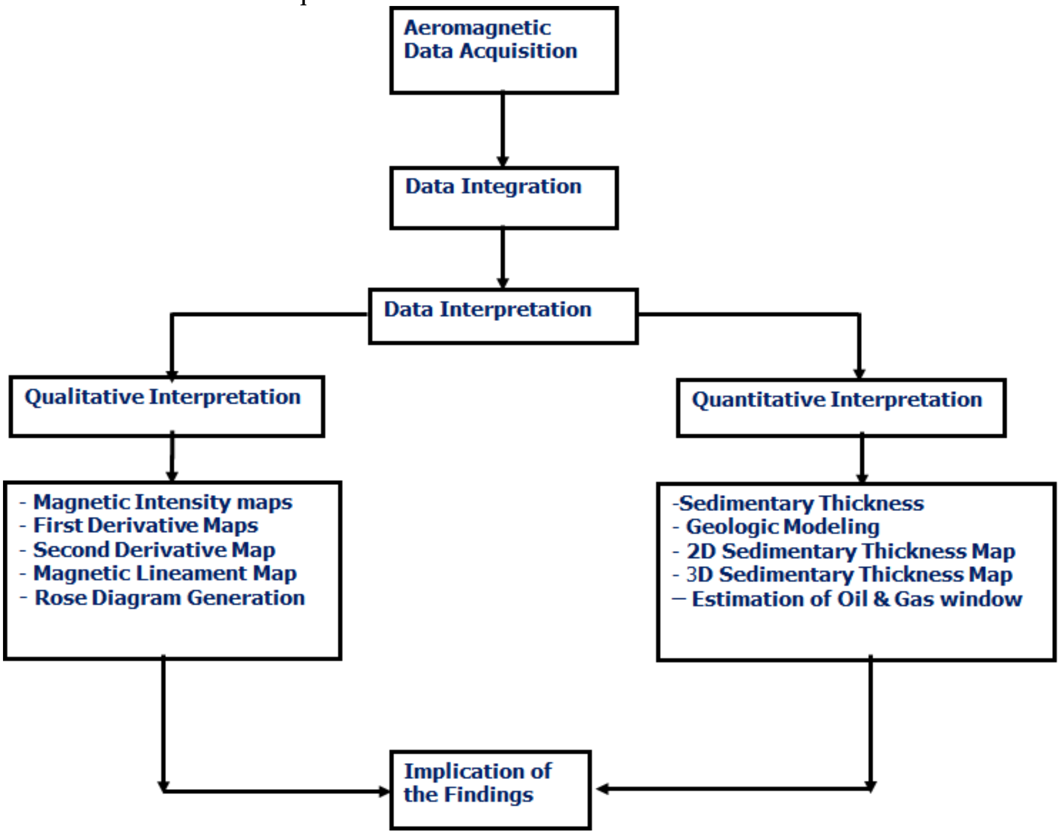

Fig. 3. Research workflow

Results and Discussion

The results from residual magnetic anomaly map (RMAM), residual magnetic anomaly map with reduction to equator (RMAM_RTE), and 3D model views how variations in magnetic field intensity ranging from -176.6 nTto 100 nT (Fig. 4 – Fig. 5). The bluish colour span within the magnetic maps depicts low magnetic values ranging from -176.6 nT to 100 nT revealed that the Southeastern part precisely around Idah area and some other parts suggest higher sedimentary thickness. There is a great deposition of a higher value of magnetic field strength as well as many intrusive objects in the northern and Southwestern regions (Lokoja, Kabba and Auchi) (Fig. 4 – Fig. 5). In addition, the contours are tightly packed in these regions of high magnetic strength values, meaning that the subsurface depths around these regions are quite shallow. The closely spaced linear sub-parallel orientation of contours in the eastern and southern parts of the study area suggests that faults or local fractured zones may possibly pass through these areas (Fig.4.).

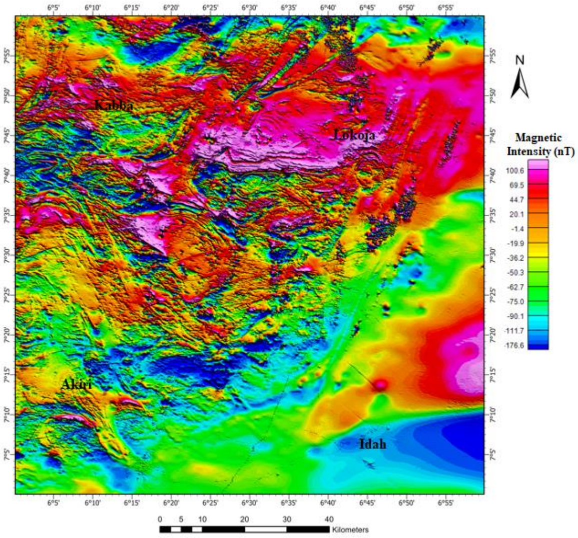

Fig.4: Residual Magnetic Anomaly map of the study area

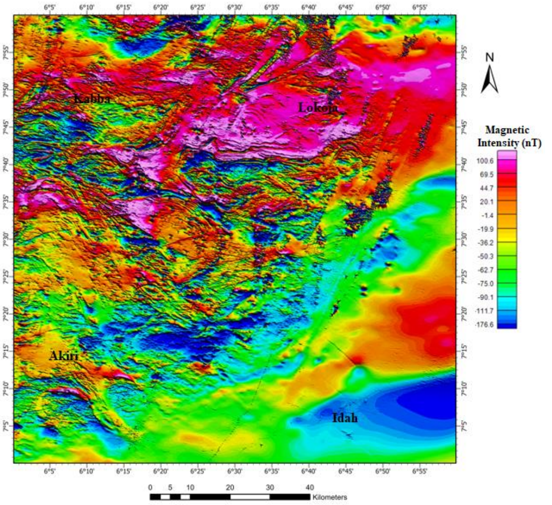

Fig.5: Residual Magnetic Anomaly map (Reduction to the Equator) of the study area

There is strong evidence of magnetic spikes and lows across the study area as shown in Fig.6. These magnetic spikes and lows are in conformity with the intense structural characteristics of the study area.

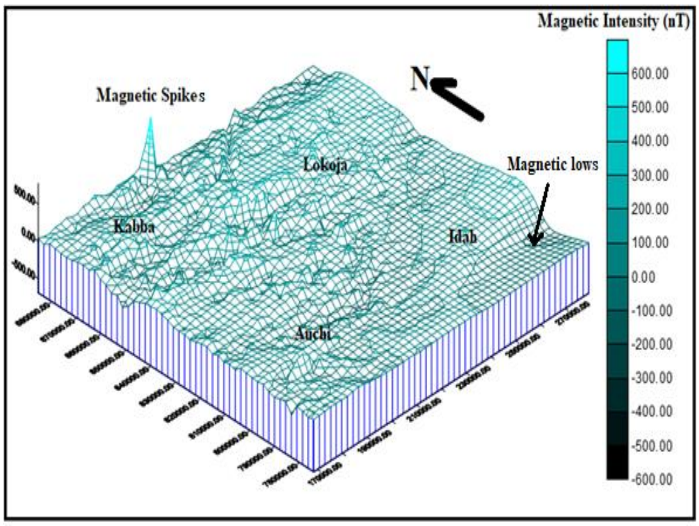

Fig.6: Earth model of the Residual Anomaly map of the study area

The obvious need to ascertain whether the magnetic anomalies found in this northern zone were triggered by crustal retreating or by intrusion prompted the use of analytical signal (AS) techniques (Fig. 4.4). The amplitude of the AS is mostly important for remnant magnetization, where the magnetic intensity is small, the sources of attention are highly localized, and the constraints are unidentified (Li, 2006).

Visual observation of (Fig. 7 – Fig.8) helps in the delineation of mineralized structures within the research region. In general, higher AS regions host the most mineral-bearing subsurface geologic structures (Usman *et al*., 2023), while lower AS values (0.0065 nT/m to 0.0759nT/m) suggest lower sedimentary infilling in the region (Fig. 6). It is worth noting that the fold structure around the northern and North western areas (Kabba, Auchi and Lokoja) changes trends around their inflection areas (Figs. 7 and 8), thus mimicking the trend of a different folding or deformation era, especially within a shear zone. With particular reference to the region, evidence of folds and faults are available with these features representing geologic structures that are indicated by circular and rectangular shapes represented in (Fig. 8.)

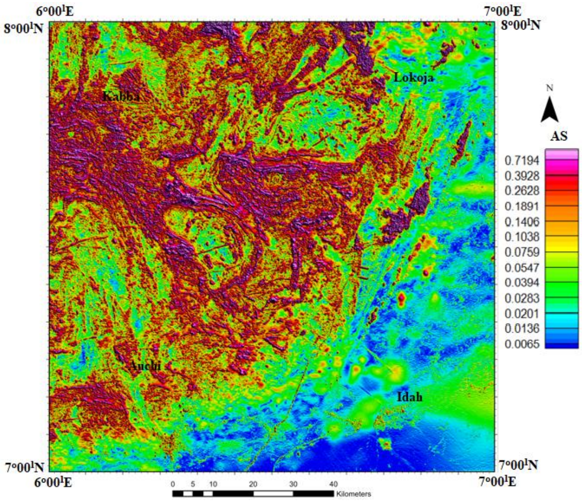

Fig.7: Analytical Signal Map showing the Magnetic Lineament within the study area

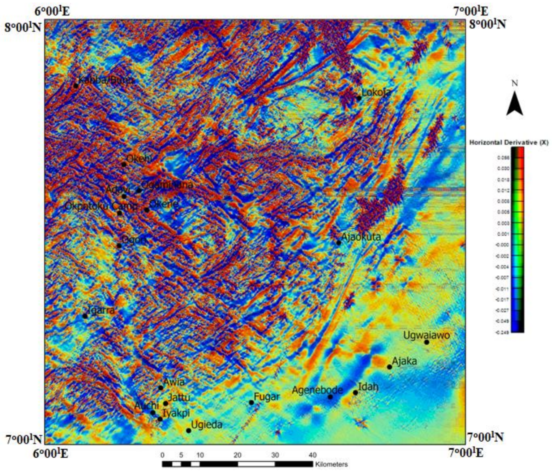

Fig.8: Horizontal derivative map showing magnetic lineament in the study area

Quantitative Interpretation

Aeromagnetic Profiles

Five (5) cross-sections namely D - D^{l}, E - E^{l}, F - F^{l}, G - G^{l}and H - H^{l} were taken in the northwest-southeast (NW-SE) direction, and used for detailed interpretation (Figure 4.9). The cross-sections were taken perpendicular to the direction of the contours so as to obtain clear information about the anomalies. Twenty-one (21) magnetic anomalies were identified along the five profiles and they were subjected to spectral analysis in order to obtain the sedimentary thickness across the study area. The method was chosen because of its advantage of filtering all the noise away from the data. Secondly, during the application of this method, information is not lost in the process unlike other methods.

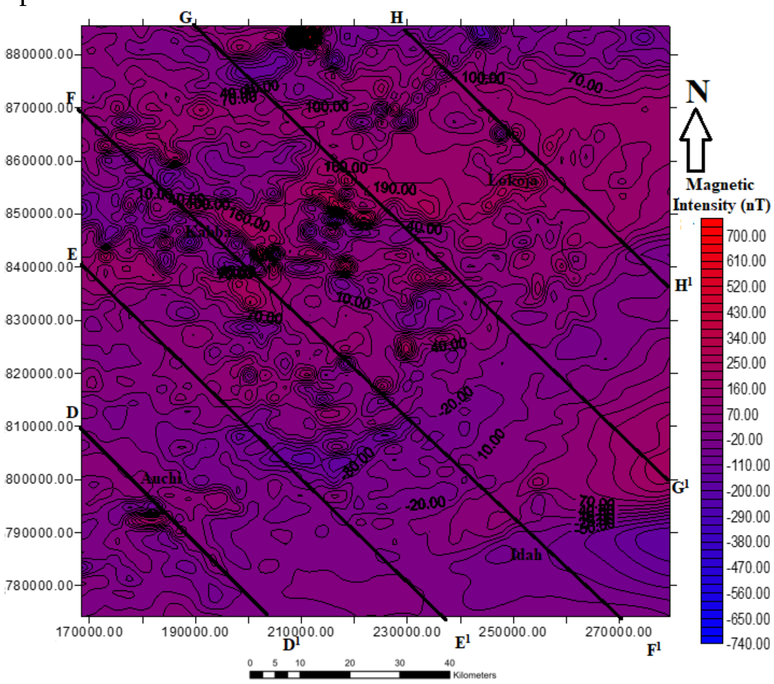

Fig. 9: Residual Anomaly Map of Study Area Showing the Profile Lines (Contour Interval ~ 45nT)

Calculation of Sedimentary Thickness

The graphs of the natural logarithms of the amplitude against frequencies obtained for the various profiles were plotted. Linear segments from the low frequency portion of the spectral, representing contributions from the deep-seated causative bodies were drawn from each graph. The gradient of the linear segments was evaluated and the depths to magnetic sources were determined along the selected profiles (Fig.10 and Table 1). The gradients of the line segments are negative because in spectral analysis, the graph decreases as the frequency increases. That is, the graphs must be negative and the points outside the line segments represent noise. This is in accordance with the laws of spectral analysis. The sedimentary thickness obtained through Spectral analysis ranges from 0.42 km – 5.24 km with average of 1.72 km across the study area (Table 1).

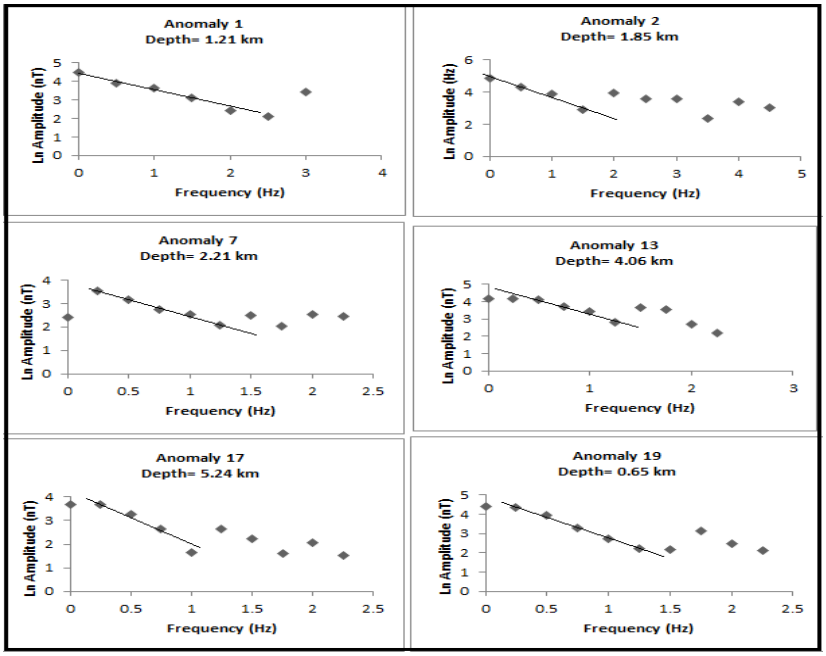

Fig.10: Spectral Graph within the study area

Table 1: Spectral Analysis Depth

Profile name	**Profile direction**	**Anomaly**	**Depth (km)**
D - D (Along Auchi)	NW-SE	1	1.214
	NW-SE	2	1.847
	NW-SE	3	2.033
	NW-SE	4	0.864
E-E (Along Auchi& Idah)	NW-SE	5	1.237
	NW-SE	6	1.754
	NW-SE	7	2.211
F – F (Along Kabba, Auchi & Idah)	NW-SE	8	0.641
	NW-SE	9	0.793
	NW-SE	10	0.417
	NW-SE	11	1.420
	NW-SE	12	2.970
	NW-SE	13	4.060

	NW-SE	14	1.471
G-G (Along Lokoja & Idah)	NW-SE	15	0.831
	NW-SE	16	2.283
	NW-SE	17	5.243
H-H (Along Lokoja)	NW-SE	18	1.581
	NW-SE	19	0.654
	NW-SE	20	0.932
	NW-SE	21	1.367
Average			1.724

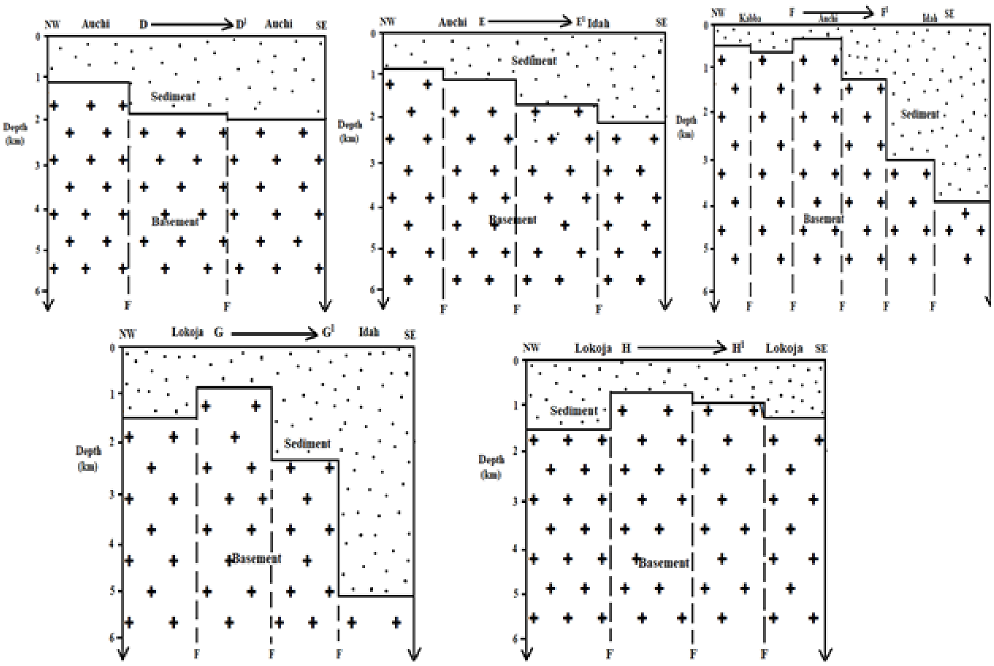

Fig. 11: 2D Geologic modelling along Profile (D - D^{l}, E - E^{l}, F - F^{l}, G - G^{l}and H - H^{l})

Quantitatively, five (5) cross-sections namely D - D^{l}**,** E - E^{l}, F - F^{l}, G - G^{l}and H - H^{l} were taken in the northwest-southeast (NW-SE) direction, to obtain clear information about the anomalies. Twenty-one (21) magnetic anomalies were identified along the five profiles and they were subjected to spectral analysis to obtain the sedimentary thickness across the study area. The method was chosen because of its advantage of filtering all the noise away from the data and no information is lost in the process unlike other methods. The sedimentary thickness obtained through Spectral analysis ranges from 0.42 km – 5.24 km with average of 1.72 km across the study area. The deep sedimentary cover signifying deep depth to magnetic sources vary from 2.03km to 5.24 km, whereas the shallow sedimentary cover (shallow depth to magnetic sources) varies from 0.41km to 1.85 km. The sedimentary cover is deeper in the southern and central part of the study area trending northwest-southeast direction and shallower in the northern parts of the study area.

Sedimentary Cover Configuration

Using the depth values determined from the spectral analysis method, two sedimentary cover models were established. The deep sedimentary cover signifying deep depth to magnetic sources vary from 2.03km to 5.24 km, whereas the shallow sedimentary cover (shallow depth to magnetic sources) varies from 0.41km to 1.85 km (Fig. 12). The sedimentary cover is deeper in the southern and central part of the study area trending northwest-southeast direction and shallower in the northern parts of the study area.

Based on the depth values determined, the depth to basement map (Fig. 12) and the 3-D surface map (Fig. 13) representing the topography of the study area were produced. These give the basement configuration as well as the sedimentary thicknesses within the study area. The 3-D surface plot shows a linear depression at the southeastern part of the study area indicating thicker sediments which trend northwest-southeast direction while the northern and other parts have shallower sedimentary thicknesses (Fig. 13).

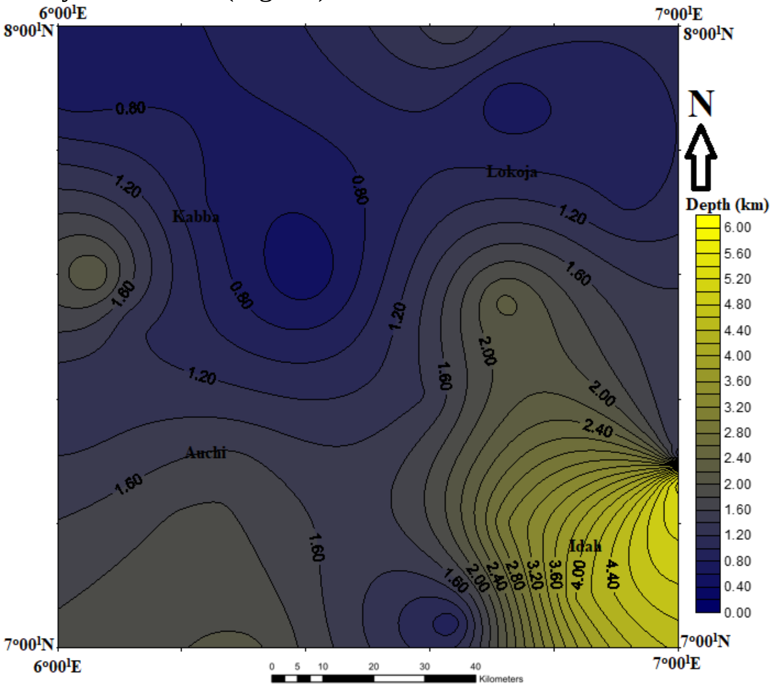

Fig. 12: Sedimentary cover model of the study area. (Contour Interval ~0.20km)

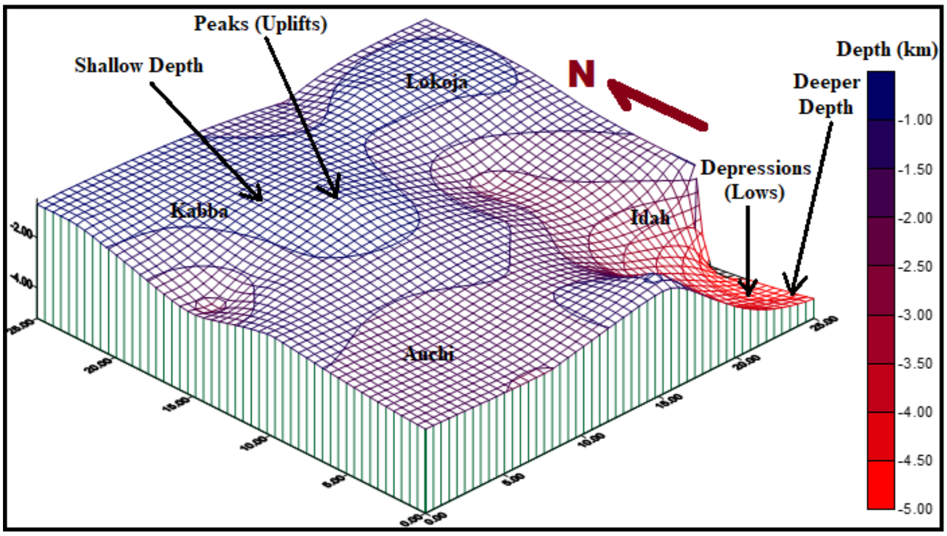

Fig. 13: 3D model of sedimentary cover of the study area

Estimation of Oil and Gas window

The result of the oil and gas window across the study area was estimated using a linear equation postulated by Onwuemesi, 1997:

$$\mathbf{T_h = mh + T_0} \quad (1)$$

Where,

T_h = temperature in ^{0}C at depth (h); m = geothermal gradient; h = depth of interest; T_o = surface temperature

Consequently, the investigation posited that the surface temperature was 27 °C, while the average geothermal gradient within the study region was reported by Ikumbur *et al*. (2023) as 23.50 °C/km. Utilizing the sedimentary thickness measurements acquired, which range from 0.41km to 5.24 km, the temperatures at various depths for each anomaly block were deduced from equation 1 by resolving for the unknown T_h (temperature at depth h). The resultant values span from 36.80 °C to 150.21°C, yielding an average temperature of 67.09°C.

Thus, the sedimentary cover within the designated study area exhibits a significant elevation towards the southern sections, thereby suggesting a potential for hydrocarbon generation. Indeed, any prospective sedimentary environment must encompass a high-quality source rock, suitable reservoir and seal lithologies, as well as favourable regional pathways and trapping mechanisms. Correspondingly, for any region to be deemed viable for hydrocarbon generation, the sedimentary thickness should reach a minimum of 2.0 km, alongside other requisite conditions essential for hydrocarbon formation (*Chinwuko et al.*, 2012). Given the calculated sedimentary thickness ranging from 2.03 to 5.24km and the temperature at depth between 74.78 °C and 150.21 °C, the likelihood of hydrocarbon generation in the southern and central regions of the study area appears plausible (Fig. 14).

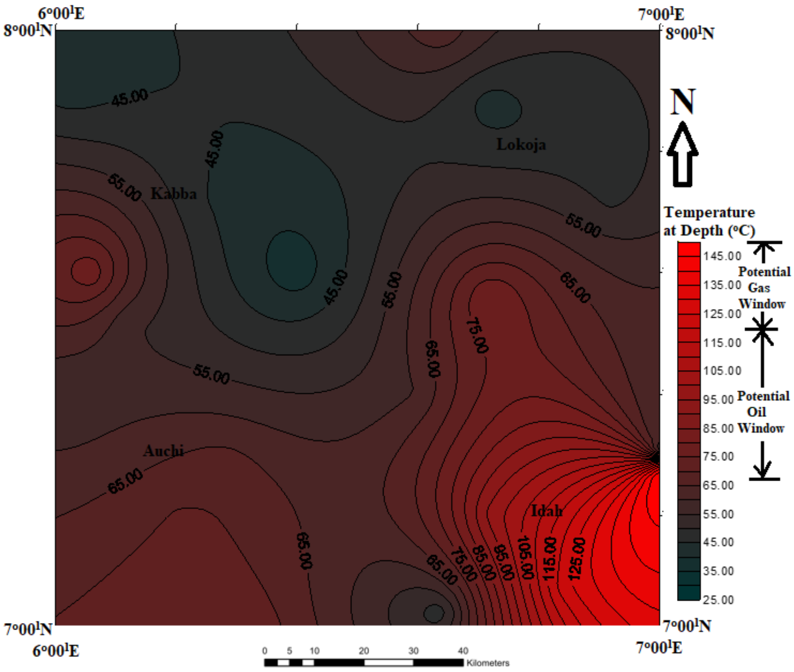

Fig. 14: Oil and Gas window map of the study area

Implication of Hydrocarbon Potential

The southeastern part of the study area is mostly endowed with sedimentary packages of Anambra Basin while the northern parts are covered by Basement Complex and little amount of sedimentary package of Bida Basin as evident in the geological map (Fig. 15a). Dim *et al.* (2019) conducted research on the signatures of key petroleum system elements using outcrop examples from the Anambra Basin, Southeastern Nigeria and the study aligned with the present study on the ground of existence of oil and gas in the Campanian to Maastrichtian strata of the Anambra Basin, which it is still considered a frontier basin due to the challenges associated with interpretation of stratigraphy and structures rising from non-availability of subsurface data.

Both the tilt derivative and fault density maps (Figs. 15b and 15c) reveal the presence of key petroleum elements such as the structural traps like the folds and faults. This assertion is supported by Dim *et al*. (2019), which stated that the key petroleum elements within Anambra Basin are traps, seal, source, and reservoir rocks. More so, Dim *et al*. (2019) established that the shales of Enugu Formation and Mamu Formation serve as the potential source rocks; the sandstones of the Mamu Formation and Ajali Formation offered potential reservoir rocks; the shales with interstratified sandstone of the Nsukka Formation provide potential cap and overburden rocks.

In addition, for any area to be viable for hydrocarbon potential, the thickness of sediment must be up to 2.0km as well as other conditions necessary for hydrocarbon formations (Chinwuko, *et al*. 2012; Anakwuba *et al.*, 2011; Anakwuba and Chinwuko, 2012). Based on the sedimentary thickness (2.03 km - 5.24km) along with the calculated oil/gas window (74.78 °C and 150.21 °C), the likelihood of hydrocarbon generation in the southern and central regions of the study area appears plausible and some parts of the study area have been demarcated for detail hydrocarbon exploration (Fig. 15).

However, the northern and other parts of the study area appear plausible for mineral exploration (Fig. 15), because these zones possess low sedimentary packages and low oil/gas window in alliance with the works of Roest *et al.* (1992) and Usman *et al.* (2018), which stated that areas with high sedimentary infilling, high heat flow and high geothermal gradient should be avoided during mineral exploration.

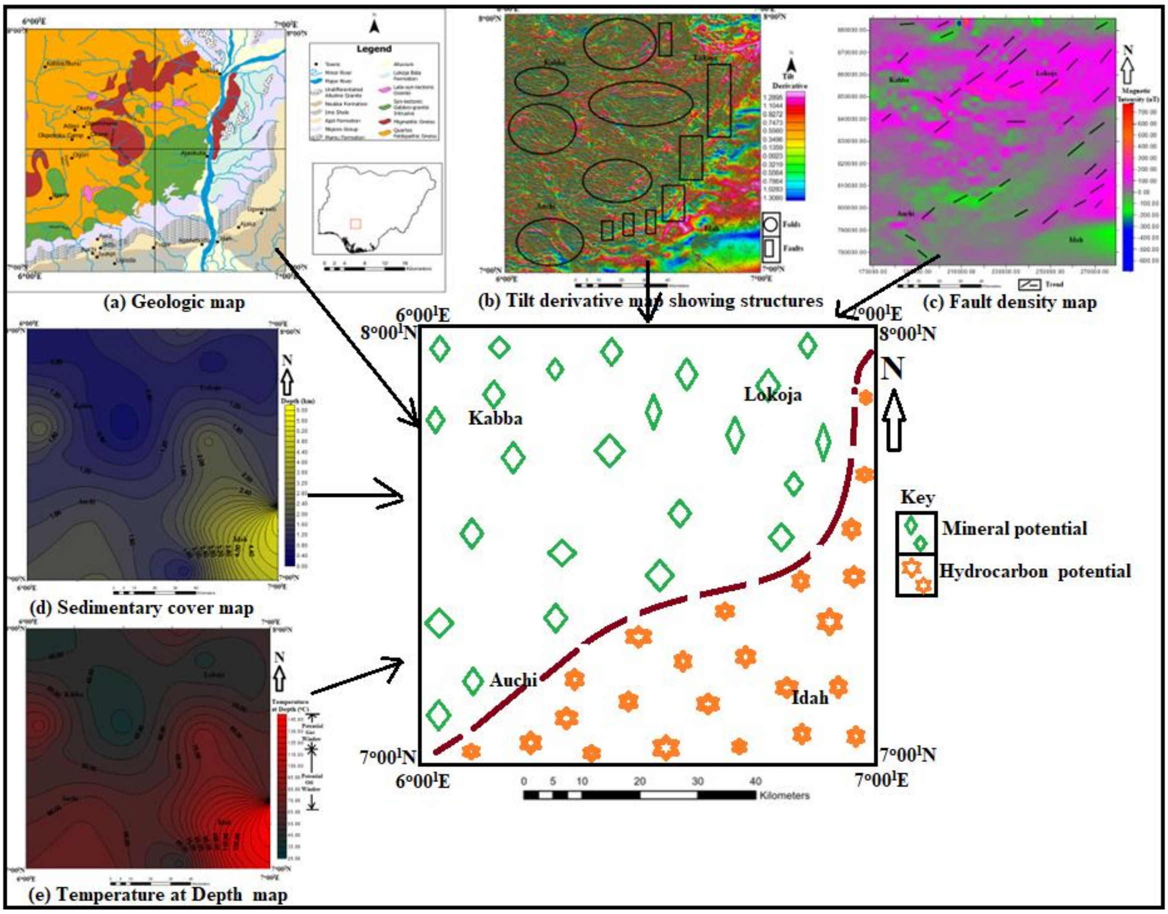

Fig. 15: Possible area of hydrocarbon generation

Conclusions

Spectral analysis has been applied in the interpretation of aeromagnetic anomalies over the parts of Anambra and Southern Bida Basins, Nigeria. The conclusions are as follow:

1) The result of the qualitative interpretation shows evidence of structural features such as folds and faults representing geologic structures that are indicated by circular and rectangular shapes.
2) The area is intensely fractured with major regional faults trending in NE-SW direction. This conforms to the trend of the Benue Trough.
3) The sedimentary thickness obtained through Spectral analysis ranges from 0.42 km – 5.24 km with average of 1.72 km across the study area.
4) The estimated oil and gas window is between 74.78 °C and 150.21 °C across the study area.
5) The likelihood of hydrocarbon generation in the southern and central regions of the study area appears plausible, whereas, the northern and other parts of the study area appear plausible for mineral exploration.

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