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SUBSURFACE STRUCTURAL INTERPRETATION OF PARTS OF SOUTHERN BENUE TROUGH, NIGERIA USING AEROMAGNETIC DATA IMPLICATIONS FOR HYDROCARBON POTENTIAL

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Abstract
This study aimed at carrying out subsurface structural interpretation of parts of southern Benue Trough, Nigeria using aeromagnetic data for implications for hydrocarbon potentials. The study area is bounded by latitude 8º00^{l} N to 9º00^{l} N and longitude 9º00^{l} E to 10º00^{l} E with an area extent of 12,100 km^2. The methodology involves the use of four aeromagnetic data sheets namely; 211 (Kwolla), 212 (Shendam), 232 (Akiri) and 234 (Ibi) which were collected from Nigerian Geological Survey Agency and the data were contoured and analysed using Oasis-Montaj, Surfer and GeoRose softwares. The visual assessment of total magnetic intensity and residual anomaly maps of the study area reveal magnetic intensities ranging from -39.0 nT to 154.4 nT. The 3D surface map of the magnetic intensity of the basement reveals the presence of uplifts and depressions, a typical expression of folds. The result of qualitative interpretation of magnetic maps also reveals that the area is intensely faulted with major faults trending in northeast to southwest (NE-SW), whereas, the east to west (E-W) and northwest to southeast (NW-SE) are the minor trend in the area, which align with the major rift system of Benue Trough. The spectral analysis of the potential data revealed sedimentary thickness ranging from 0.47 km to 5.88 km with an average of 2.03 km, which could be investigated for further petroleum exploration. The generated geological model results revealed two geological layers in the area, namely the sedimentary layer and the basement layer. The result shows that the temperature at depth values obtained range between 39.95 ^{o}C and 167.56 ^{o}C with an average of 76.71 ^{o}C and they are shallower at the northern areas than the other areas. The study concludes that the southern and central parts of the study area are good for possible hydrocarbon accumulation in the region.
Keywords: *Magnetic lineaments, Fault, Rose Diagram, Spectral Analysis, and Sedimentary Thickness.*

Introduction

An aeromagnetic survey is a geophysical survey which is carried out using a magnetometer onboard or towed behind an aircraft. The principle is not different from that of a magnetic survey carried out with a hand-held magnetometer, though an aeromagnetic survey allows much larger area of the earth's surface to be covered quickly for regional reconnaissance. Geophysical methods provide fast, efficient and non-destructive reconnaissance techniques often required by archaeologists (Oyeyemi et al. 2014).

In order to search for the presence of buried magnetic materials and to determine the probable depth to basement, magnetic method has been very useful. Magnetic method can also be used in the location of shallow magnetic materials such as buried metallic containers and metallic pipes. Aeromagnetic method has its distinctive advantages which distinguishes it compared with other geophysical methods such that it exhibits a rapid rate of coverage and low cost per unit area covered. The main purpose of any magnetic survey is to detect minerals or rocks in the subsurface that possess unusual magnetic properties which reveal themselves by imposing some anomalies in the observed magnetic intensity of the earth.

Aeromagnetic surveys are used in mapping the above-mentioned anomalies in the earth's magnetic field which is then correlated with the underground geological structure of the study area. The presence of faults is usually identified by abrupt changes or close spacing in orientation of the contours as revealed by the magnetic anomalies. Also, for hydrocarbon exploration, residual magnetic anomaly maps are useful since they identify the presence of

intrusives, lava flows, or igneous plugs which are areas to be avoided in hydrocarbon exploration. Aeromagnetic data were employed in hydrocarbon exploration for regional reconnaissance survey because a large area can be covered quickly and is useful for providing first-hand information about the basement (Oladele et al. 2013). Also, during oil and gas exploration, the mapping of magnetic basement within sedimentary layered rocks is very important. The bedrock in Nigeria has been the source of solid minerals in the country as well as the lucrative hydrocarbon which has really prospered the oil sector.

The aeromagnetic survey is the oldest potential field method used for hydrocarbon exploration (Onuba et al. 2011). As a prerequisite, the thickness of sediment required for the generation or production of hydrocarbon is not generally constant as it varies from place to place. Generally, the minimum overburden thickness of sediment required for oil to form ranges from 2 km to 4 km, while for gas to form the minimum thickness required is between 3 km to 7 km (Onuba et al. 2011).

Benue Trough is geographically sub- divided into three major sub-divisions comprising of the Northern, Central and Southern Benue Trough. It stretches for a distance of about 1000 km and a width of 50- 200 km in places trending in general NE-SW direction covering a superficial area of about 216,000 km^2. Furthermore, the entire Benue Trough has been subjected to intensive petroleum exploratory investigations in the last two decades especially in the Upper Benue Trough and the Anambra Basin in a bid to build up oil reserves and to attain a higher production level thereby meet Federal Government's aspiration to hit the 40 billion barrels reserve target.

This research focuses on the mapping of subsurface structures, the mineral potentials and sedimentary thicknesses in parts of Southern Benue Trough, Nigeria using interpretation of aeromagnetic data.

According to Obaje (2009), the southern Benue Trough comprises of six stratigraphic successions that are dated within the Upper Cretaceous (Fig. 1). 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 (Offodile, 1976; 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.

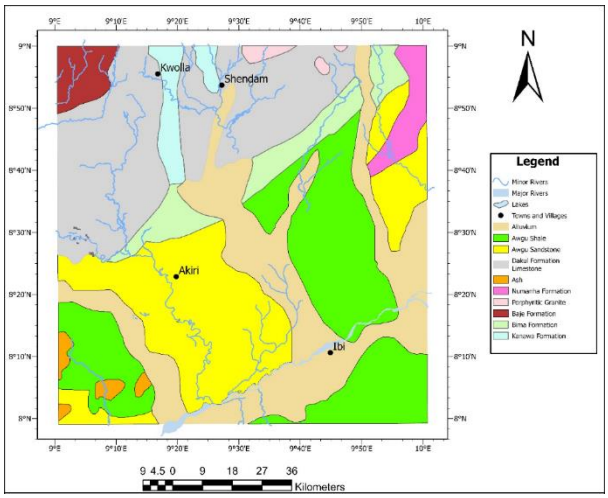


Fig.1: Location and geologic map of the study area

Methods

The procedure involved in this study will include merging of the four acquired aeromagnetic data sheets (Fig. 2, production of magnetic anomaly maps, generation of structural maps, analysis and modelling of magnetic anomaly data (Fig. 3). The integrated data sets shall be pre-processed, and the magnetic data reduced to the pole (RTP). The derived maps shall be 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 will be used. The structural trends within the study area shall be deduced using Rose diagram and the enhanced magnetic maps. The spectral analysis technique was found to be most suitable for basement depth estimation in this project, and was adopted for the purpose.

Furthermore, the magnetic anomaly maps will be interpreted qualitatively and quantitatively in order to achieved the set goals in this study. The qualitative interpretation will be done by visual inspection of the magnetic intensity maps, noting:

a) The trend of the contours;
b) The positive and negative values of the contours;
c) The minimum and maximum values of the contours and their areal extents.

Hence, there are three features that are important in qualitative interpretation, namely:

a. Sharp changes in contour gradient defines structural trend.
b. The alignment of lateral shift which off-set the main anomaly suggest faulting.
c. The alignment of closed anomalies suggests presence of magnetic bodies.

Additionally, the quantitative interpretation of the study area will be done by taking seven selected profiles on the residual anomaly map of the study area. Then, the graphs of the profiles will be plotted and the sedimentary thickness (depth to basement) across all the identified anomalies will be calculated using spectral analysis method (Fig. 3). Following this step will be the building of two and three dimensional models showing all the *in-situ* magnetic anomalies and sub-basin configuration in the area. With the available sedimentary thicknesses of the anomalies in the study area, the oil and gas window shall be calculated using temperature equation according to Onwuemesi (1997). Finally, the study will rank all the outcomes with

respect to the geology in order to determine the possibility of hydrocarbon generation within the study area.

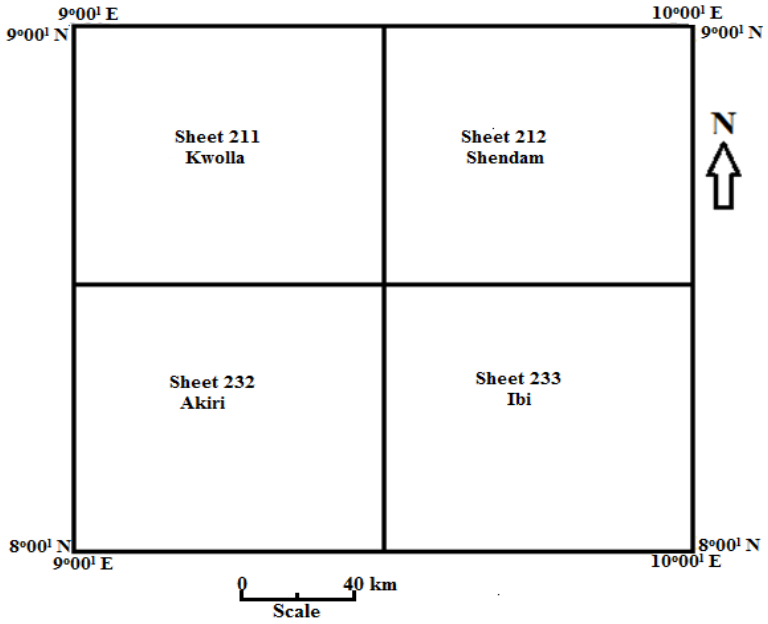


Fig. 2: Acquired four sheets of aeromagnetic data

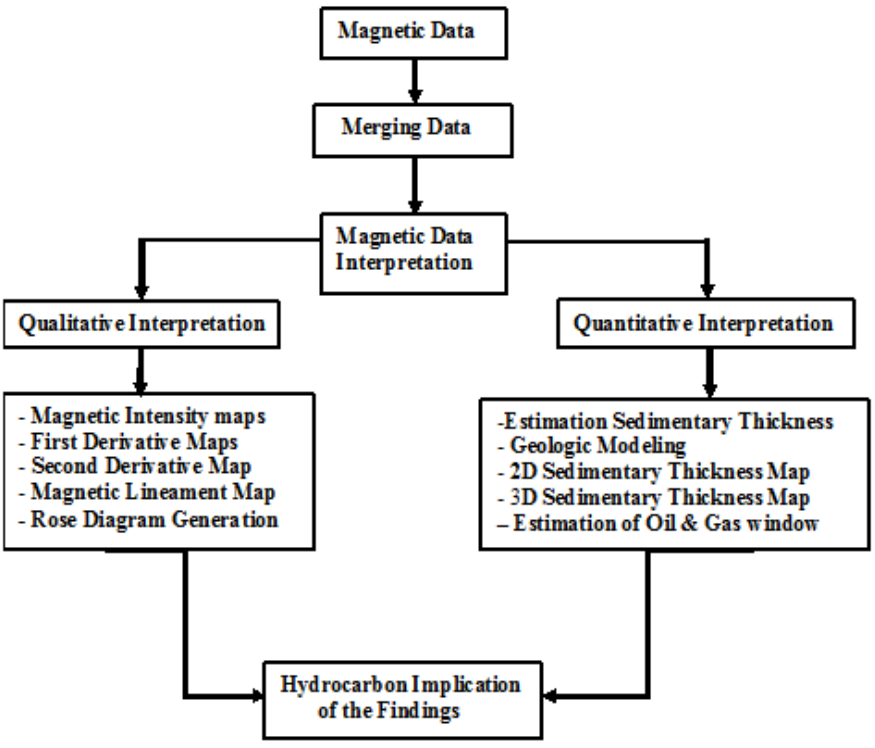


Fig. 3: Research workflow

RESULTS AND DISCUSSION

Qualitative Interpretation of the Aeromagnetic Maps

Magnetic Intensity Map and Reduction to Pole Maps

The visual assessment of residual magnetic anomaly and reduction to pole maps of the study area reveal complex pattern of magnetic signatures of both short and long wavelengths (Fig. 4 and Fig. 5). This varying amplitude of the anomaly suggests varying magnetic intensities from

different causative sources as established by Chinwuko *et al.* (2023); Chinwuko *et al*. (2024); Usman *et al*. (2025) and it is evident in the study area (such as magnetic intensity range between -39.0 nT and 154.4 nT). Around Ibi and below Akiri areas, the magnetic intensity maps depict the underlying basement as having magnetic intensities ranges from -39.0 to 5.4 nT. But around Kwolla and Shendam areas, there are strong evidences of igneous intrusion when juxtaposed with the geologic map of the area.

Indeed, these areas mentioned above possess mostly close-spaced contour lines, as such, these elliptical contours could be indicative of igneous intrusions or lineaments comprising a collection of economic and sub-economic mineral deposits as evident in the study area like Akiri, Kwolla and Shendam. However, from the central parts down to the southern parts of the study area, the contour lines are widely spaced signifying that the sedimentary infilling within these areas is thick (Fig. 4 and 5), unlike in the northern parts of the study area.

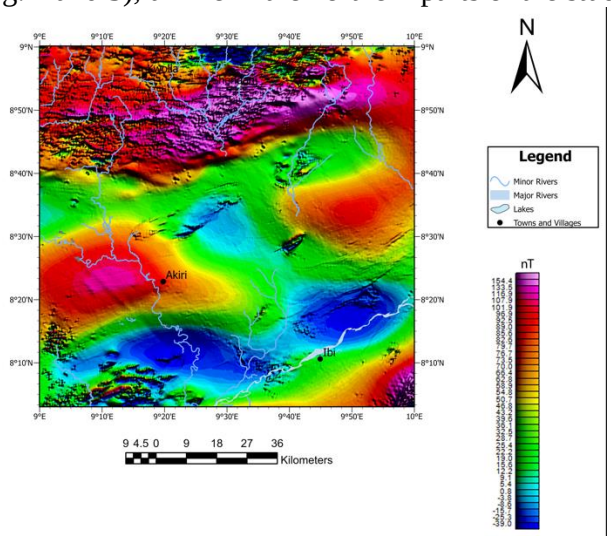


Fig. 4: Residual Magnetic Anomaly Map of the study area

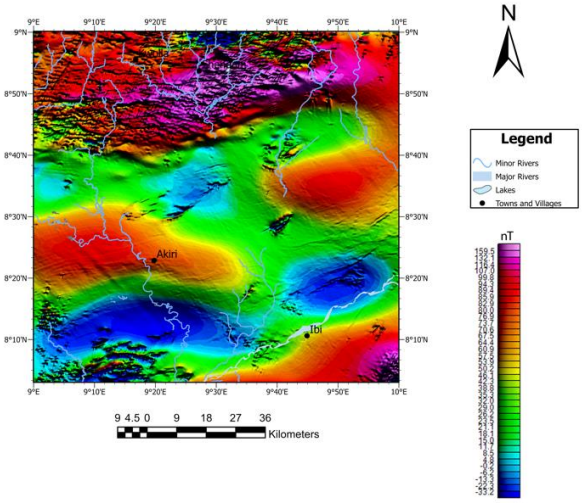


Fig. 5: Residual Magnetic Anomaly Map (Reduction to Pole) of the study area

3D Surface Map of the Residual Magnetic Anomaly

The 3D surface map of the magnetic intensity of the basement reveals the presence of magnetic spikes (uplifts) and magnetic lows (depressions), a typical expression of folds (Fig. 6). This folding could be linked to the basin fill which comprises of a northwestern trending belt of Upper Cretaceous sedimentary rocks that were deposited as a result of block faulting,

basement fragmentation, subsidence, rifting and drifting consequent to the Cretaceous opening of the South Atlantic Ocean. Major horizontal (sinistral) movements along the northeast–southwest axis of the adjacent Benue Trough appear to have been translated to the north-south and northwesterly trending shear zones to form the Mid-Niger Basin perpendicular to the Benue Trough (Benkhelil, 1989). The presence of numerous intrusive bodies present in the study area suggests that they are more tectonically active than the low relief areas. These intrusive generally occur as sills and dykes as established by Kogbe (1989). Similarly, tectonic structures such as faulted blocks yield broader and larger lows (Chinwuko *et al*., 2024) as seen in the 3D model map (Fig.6)

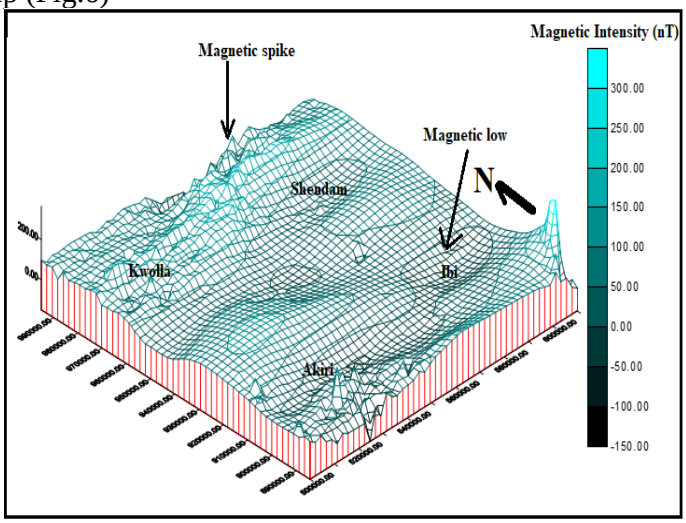


Fig. 6: Real view distribution of total magnetic field intensity in the area

Analytical Signal Map

The magnetic intensity maps are marked by numerous closed contours and the analytical signal map reveals northeast-southwest (NE-SW) as the prominent linear trend and East-West (E-W) as minor trend within the study area (Fig. 7). Okonkwo *et al.*, (2021), Ikumbur *et al.*, (2023), and Chinwuko *et al.*, (2024) believed there would always be a magnetic susceptibility contrast across a fracture zone due to oxidation of magnetite to hematite, and/or infilling of fracture planes by dyke-like bodies whose magnetic susceptibilities are different from those of their host rocks. Major faults are recognized by series of closed lows exhibiting a linear trend on the aeromagnetic intensity map (Onwuemesi, 1997).

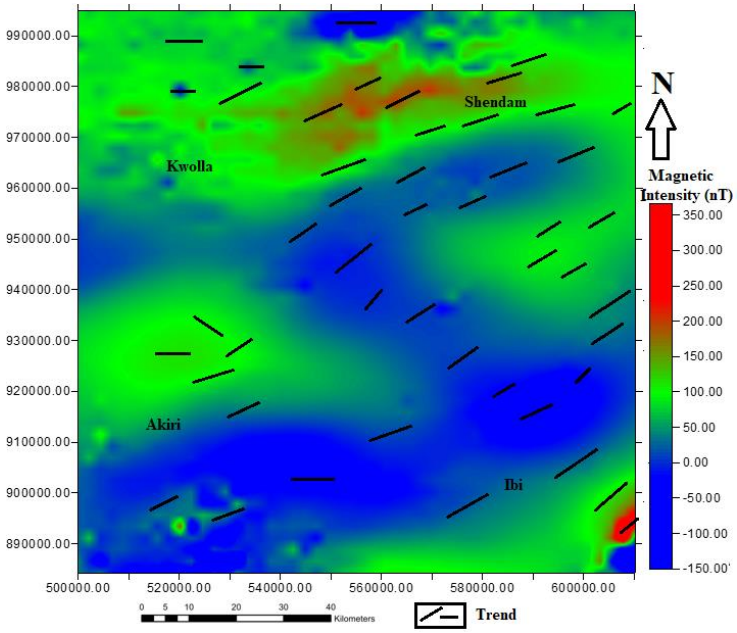
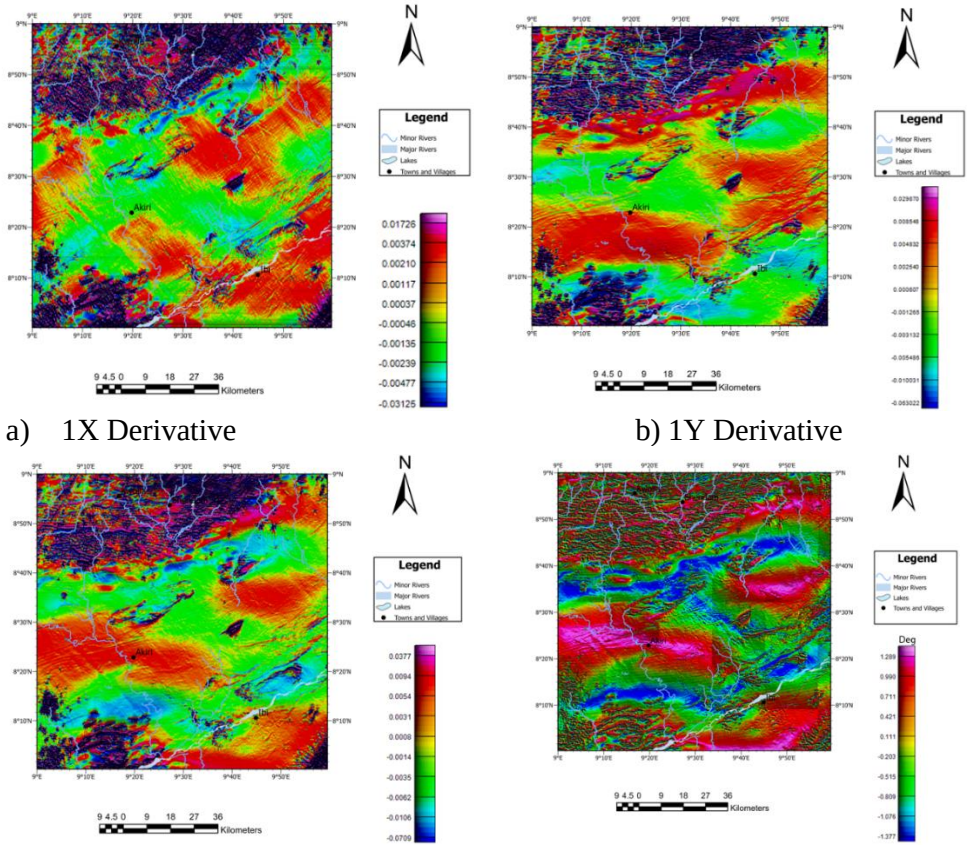


Fig. 7: Analytical Map of the study the area

Lineament Trend Maps

Lineament orientation in the study area was delineated using the residual magnetic intensity derivative maps (Fig. 8) generated from the residual magnetic intensity map. The predominant structural trends were NE-SW with minor E-W and NW-SE trends. This result is in corroboration with earlier works carried out in the northern Benue Trough and other portions of the adjoining basement terrains (Ugwuoke and Chinwuko, 2023; Obaje *et al*. 2011, Chinwuko *et al.*, 2012). Juxtaposing these lineaments on the geological map of the study area, it depicts that the structural lineaments were slightly less concentrated in the Creataceous sedimentary rocks compared to the basement complex rocks (granites and biotite gneisses). The high concentration of structural lineament in the area portrays intense tectonic activity that affected the basement complex rocks and its abutting Cretaceous sequences.

The structural configuration of the study area is also confirmed by the generated Rose Diagram (Fig. 6), in order to date the events that produced the rocks from which they were obtained (Anudu *et al.*, 2012). As a result, NE-SW and NNE-SSW are depicted as prominent trend, whereas, the E-W, and NW-SE are the minor trend in the area (Fig. 8). According to previous works such as Usman *et al*., (2025); Chinwuko *et al*., (2024); Chinwuko *et al*., (2024); Okonkwo *et al*., (2021); Ikumbur *et al*., (2023); Obaje *et al*. (2011) propose that the NE-SW NNE-SSW and NW-SE within the study area are regarded as Pan-African Orogeny while the E-W may probably have been Pre-Pan-African Orogeny.



a) 1X Derivative b) 1Y Derivative

c) 1Z Derivative d) Tilt derivative

Fig. 8: Derivative maps showing Lineament trend in the area

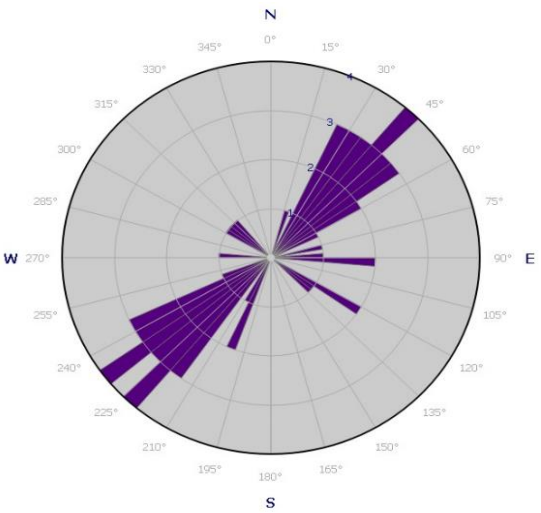


Fig. 9: Rose Diagram of structural Lineament trend in the area

Quantitative Interpretation of the Aeromagnetic data

Magnetic Profiles

In order to evaluate depths to basement (or sedimentary thickness) across the study area using the spectral analysis method, several profiles were taken on the residual aeromagnetic anomaly map of the study area (Fig. 10). These profiles were taken perpendicular to the direction of the magnetic anomalies. The method was chosen because of the fact that it is a good representative of the entire area and it has the ability of filtering all the noise away from the data unlike other

methods. Five selected magnetic profiles, namely O-O^1, P-P^1, Q-Q^1, R-R^{1}and S-S^1 reveals various magnetic anomalous bodies across the profile lines (Fig. 10). A total of nineteen (19) anomalies were identified along the profile lines.

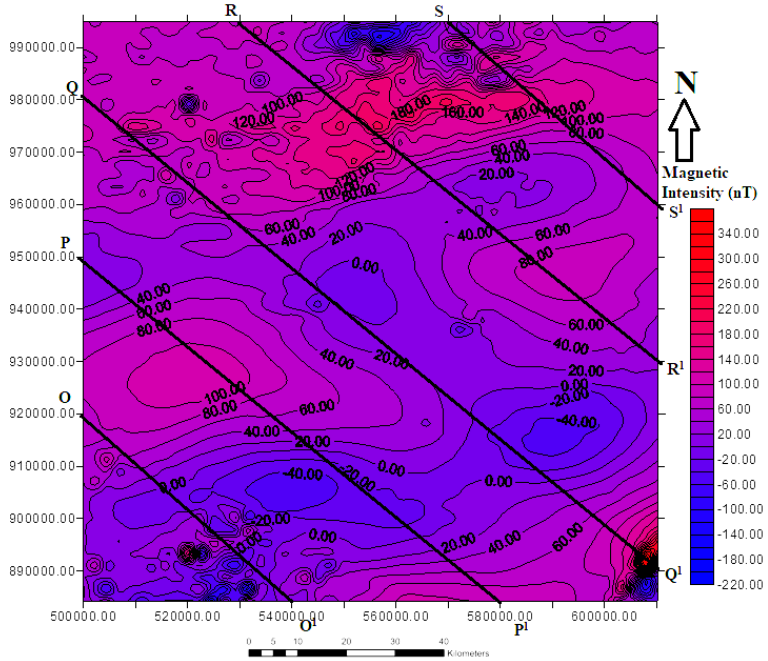


Fig. 10: Residual Anomaly map of the study area with profile lines (Contour Interval ~ 20 nT)

Estimating Sedimentary thickness

From the sedimentary thickness values calculated from the spectral analysis, two depth models were established. The deeper magnetic sources vary from 2.02 km to 5.88 km, whereas the shallow magnetic sources vary from 0.47 km to 1.96 km (Fig. 11). Deeper magnetic sources may probably represent depths to crystalline basement rocks, while the shallower magnetic sources may represent depths to basic intrusive and/or magnetized bodies within the sedimentary cover. The depth of basement is deeper in the southern and central part of the study area trending northwest-southeast direction whereas, at other parts of the area such as shendam and Kwolla areas have shallower sources depicting bluish colour (Fig. 11).

More so, the 3-D surface plot of sedimentary thickness shows presence of peaks (uplifts) and depressions (troughs). Around the central and southern parts such as Ibi and Akiri areas, there are visible linear depressions and these areas reveal higher sediments than the other parts such as Shendam and Kwolla areas which have prevalent uplifts (peaks) in conjunction with lower sedimentary thicknesses (Fig. 12). The presence of these peaks (uplifts) suggests that there are numerous intrusive bodies around these areas; as a result, they are more tectonically active than the areas associated with depressional feature. According to Kogbe (1989), these identified igneous intrusives generally occur as silly and dykes.

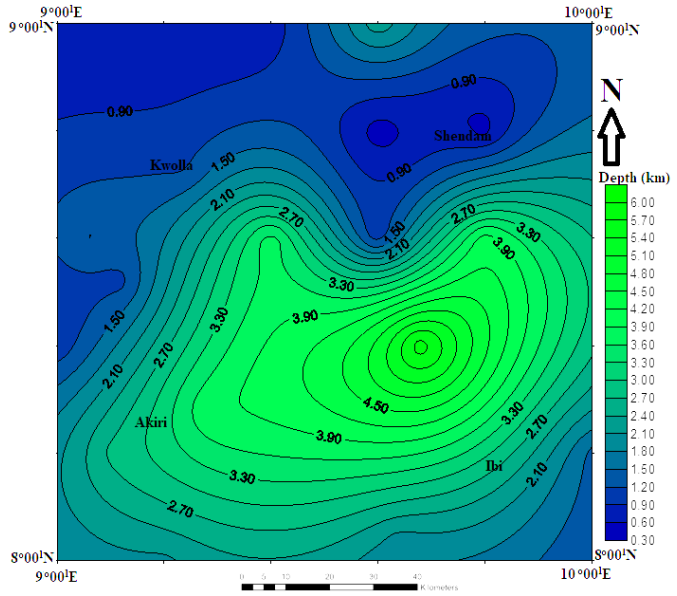


Fig. 11: Sedimentary thickness map of the area (Contour Interval~0.3km)

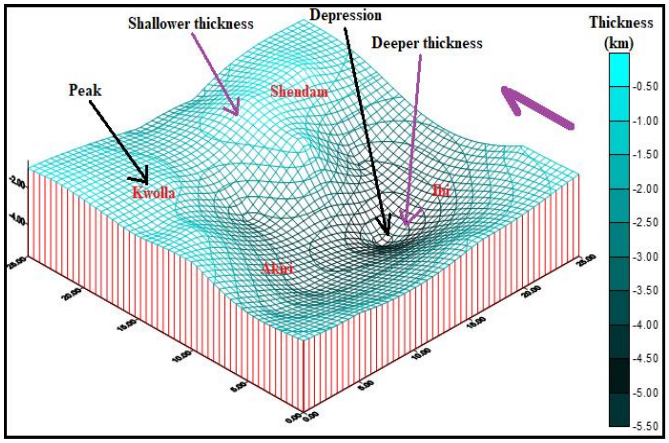


Fig..12: Real view model of sedimentary thickness of the area

Estimation of Temperature at Depth

Usually, the oil window is often found in the 60 ^{o}C - 120 ^{o}C interval with approximate depth of 2 km – 4 km (Anakwuba and Chinwuko, 2012; Chinwuko *et al.*, 2013). In order to estimate the various temperature at depth within the study area, it was assumed that the temperature changes within the earth are linear and of the form (according to Onwuemesi, 1997):

$$T_h = mh + T_0 \quad (1)$$

Where,

T_h = temperature at depth(h); m = geothermal gradient
h = depth of interest; T_o = surface temperature

It was further assumed that the surface temperature was 28.88 ^{0}C while the average geothermal gradient in the study area was given by Ikumbur *et al.* (2023) as 23.58 ^{0}C/km. From the values of the sedimentary thicknesses obtained, which vary from 0.4694 km to 5.8814 km, the temperatures at depth for each anomaly block were estimated from equation 4.1 by solving for the unknown T_h (temperature at depth h). The values obtained range between 39.95 ^{o}C and 167.56 ^{o}C with an average of 76.71 ^{o}C. The distribution map of the temperature at depth

produced shows the viability of possible generation of hydrocarbon in the southern and central parts of the study area (Fig. 13).

More so, the 3-D surface plot of temperature at depth shows presence of peaks (uplifts) and depressions (troughs) across the study area (Fig. 14). Around Ibi and Akiri areas, there are visible linear depressions and these areas reveal possible oil and gas window than the other parts such as Shendam and Kwolla areas which have prevalent uplifts (peaks) in conjunction with lower values.

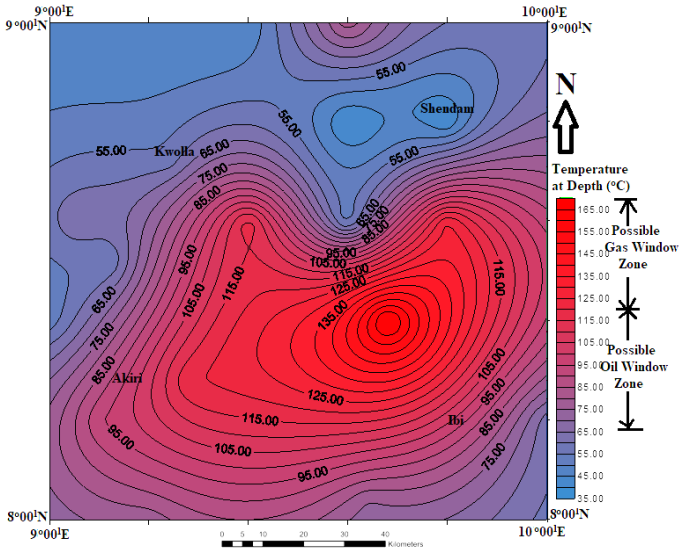


Fig. 13: Temperature at depth in the study area (Contour Interval~5.0°C)

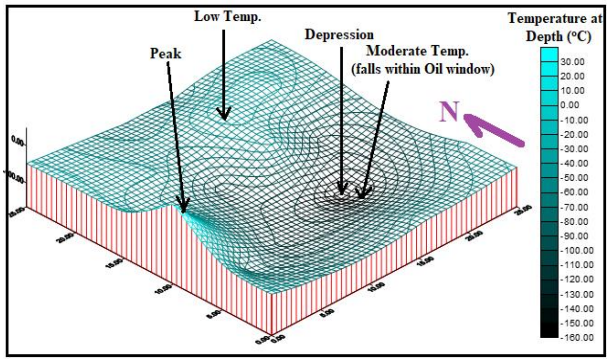


Fig. 14: Real view model of temperature at depth in the area

Hydrocarbon Potentials Implication

The sedimentary thickness within the study area have been delineated along five different profile lines using Spectral analysis of aeromagnetic data. Integrating all the results and deductions obtained in this work, it can be deduced that those regions (such as Shendam and Kwolla) with shallow or low sedimentary thicknesses are possible areas that are associated with magnetic mineral ore deposits like oolitic iron ore identified in Shendam-Kwolla area (Fig. 15). Actually, these areas might not support hydrocarbon generation.

However, the sedimentary infillings around Ibi and Akiri area is relatively high in conjunction with the high geothermal gradient and heat flow; will possibly pave way for hydrocarbon potential in this area provided that all other conditions for hydrocarbon generation are available (Fig. 15). Previous workers such as Obaje (2009) and Ikumbur *et al*. (2023) suggest that the

study area contains potential source rock which is composed of carbonaceous shales intercalated with sandstones and clay.

In addition, qualitative interpretation reveals that the area is highly fractured with most of the fracture trending in the NE-SW direction and minor ones in NW-SE and E-W directions. These fractures can serve as migrating pathway for both geothermal gradient and fluids such as hydrocarbon (Fig. 15). In fact, the stratified nature of the shales and sandstones may likely favour migration of fluids into the potential reservoir rocks that are made up mainly of fluvial, shelf and flood plain sandstones in the Lokoja and the Patti Formations (Obaje *et al.*, 2009).

Thus, the sedimentary cover within the study area is generally high towards the southern parts and therefore may support hydrocarbon formation. Actually, any prospective sediment must have a good quality source rock, good reservoir and seal lithologies, favourable regional pathways and trapping mechanisms. In line with this, for any area to be viable for hydrocarbon formation, the thickness of sediment must be up to 2.0 km as well as other conditions necessary for hydrocarbon formation (Wright *et al*., 1985 and Chinwuko *et al.*, 2012). Based on the computed sedimentary thickness (2.02 km – 5.88 km) and temperature at depth (76.59 – 167.56 ^{o}C), the possibility of hydrocarbon generation in the southern and central parts of the study area is realistic (Fig. 15).

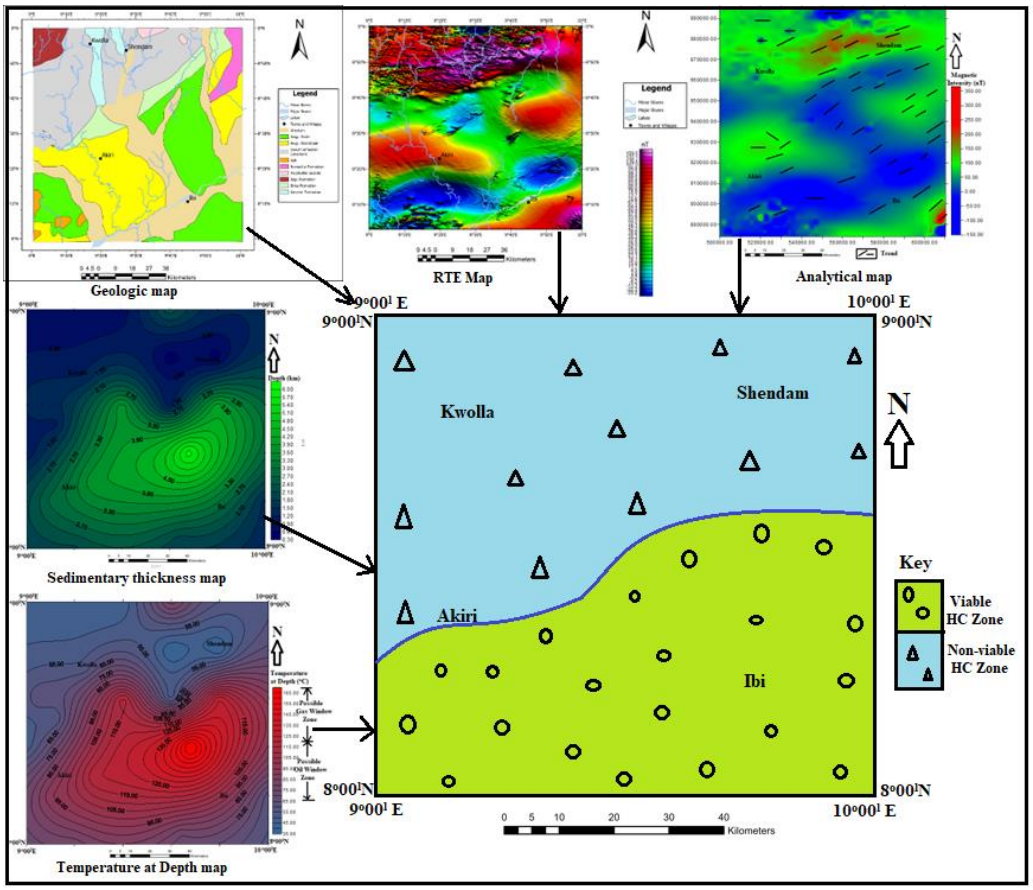


Fig. 15: Possible zone of hydrocarbon generation in the study area

5.2 Conclusions

Subsurface structural interpretation of parts of southern Benue trough, Nigeria using aeromagnetic data implications for hydrocarbon potential has been carried out and the following conclusions have been reached:

1. The visual assessment of total magnetic intensity (TMI) and residual anomaly maps of the study area reveal magnetic intensities ranging from -39.0 - 154.4 nT.
2. The 3D surface map of the total magnetic intensity of the basement reveals the presence of uplifts and depressions, a typical expression of folds. This folding could be linked to the basin fill which comprises a northwestern trending belt of Upper Cretaceous sedimentary rocks.
3. The result of qualitative interpretation of magnetic maps also reveals that the area is intensely faulted with major faults trending in NE-SW and NNE-SSW, whereas, the E-W and NW-SE are the minor trend in the area.
4. Two layers depth model were delineated: the shallower bodies varied from 0.47 to 1.97 km while the deeper bodies varies from 2.02 to 5.88 km with average sedimentary thickness of 2.03 km.
5. The geologic model reveals two geological layers namely the sedimentary layer and basement body across the area.
6. The result shows that the temperature at depth values obtained range between 39.95 and 167.56 ^{o}C with an average of 76.71 ^{o}C and they are shallower at the northern areas than the other areas.
7. The computed sedimentary thickness (2.02 km – 5.88 km) and temperature at depth (76.59 – 167.56 ^{o}C), the possibility of hydrocarbon generation in the southern and central parts of the study area is realistic.

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