Nigerian Journal of Physics (NJP)
ISSN: 1595-0611
Volume 32(1), March 2023

Spectral Transformation of Aeromagnetic data for Local Sub-Basin Delineation within Parts of the Cretaceous Middle Benue Trough

[1]Ugwu, J. U., *[2]Ayua, K. J., [1]Eze, M. O.

[1]Department of Physics, Michael Okpara University of Agriculture, Umudike
[2]Department of Physics, Federal University Lokoja, Kogi State Nigeria

*Corresponding author's email: kjayua@gmail.com

ABSTRACT

Spectral valuation of aeromagnetic data was undertaken within segments of the Middle Benue trough in order to delineate local sub-basin structures favourable to hydrocarbon accumulation; determine the depths to magnetic sources and hence estimate the thickness of the sedimentary materials within them. Standard processing and interpretation procedure involving coordinate system reprojection; regional-residual separation by means of least square polynomial smoothening and application of discrete Fourier Transform for the Spectral Analysis of (25) blocks carefully chosen to ensure inclusion of essential and interesting anomaly signatures were undertaken. Findings from the analysis show models with two-depth solutions, deep and shallow depth solution models. The deep depth-source model showed depth solutions varying between 0.65 km and 5.02 km and the shallow depth-source model revealed depth solutions ranging from 0.3 Km to 0.5 Km with the average magnetic source depth for the study area being 2.48 km. The deep depth sources are probably due to presence of thick sedimentary sequences with the thickest sedimentary sequences found around Tsuwa sub basins, SW of the study location and around Igbor sub basin, NW of the study location and on this basis; the two sub-basin structures were identified as most promising for hydrocarbon prospects. The shallow depth sources are hypothesized to be due to metallic ore deposits widely reported within the general vicinity. The results obtained have important implications for petroleum and mineral exploration.

Keywords:
Exploration,
Fourier Transform,
Sub-basin Structures,
Aeromagnetic Anomalies,
Least-Square Polynomial Smoothening.

INTRODUCTION

The application of Potential-field techniques like magnetics in geophysical investigations permits the delimitation of depth to basement and the mapping (at local and regional level) of such geologic structures like faults, lithologic contacts and other lineaments that do not appear on the surface (Ayua et al., 2023). The mapping of such features is of socio-economic significance as they can be indicative of mineralization veins, geologic structures and possible flow patterns of groundwater and hydrocarbons (Blakely and Simpson, 1986; Constant et al, 2010; Sultan et al., 2015). Aeromagnetic survey is particularly used as a reconnaissance survey in the petroleum industry, to determine the thickness of sediments. It provides information on the subsurface rocks and the geologic features capable of hosting and transmitting hydrocarbon.

The volume of sediment serves a significant purpose for hydrocarbon accumulation, because sediments function as source, reservoir and seal rocks for petroleum. It is therefore imperative that the sedimentary rocks should be of appreciable thickness for accumulation of hydrocarbon in quantities that would be of commercial interest.

The Middle Benue Trough is known to host geologic features favourable to hydrocarbon accumulation. In addition, it is distinctive in having the earth's field inclination close to zero (+/- 2°), this makes interpretation of magnetic data difficult and reduction to the pole very unstable; hence, we agree with (Nwosu, 2015) that it makes for an interesting case study. A lot of previous studies have been carried out by many researchers using aeromagnetic data in Nigeria. These include; Ofoegbu, (1984, 1985, 1986); Ahmed (1991); Nwachukwu (1985); Ofoegbu and Onuoha (1991); Nur et al., (1994); Onwuemesi (1997); Opara et al., (2012); Ogah and Jatau (2014); Nwosu (2014, 2015); Ayua, et al (2023) etc. However, some of these works made use of the aeromagnetic survey data from the Nigerian Geological Survey Agency commissioned in the 1970s. The ensuing data were of lower quality than the high resolution aeromagnetic data covering the whole of Nigeria lately acquired around 2009 (Ayua et al., 2023). Nwosu (2015) visually inspected and interpreted the features of surface contours and lineament maps with regard to the basement topography and structural trends within the study area. Although the study was carried out using the recent aeromagnetic data, the research was of a qualitative rather than quantitative nature. Nwosu (2014) on the other hand carried out quantitative estimation of the depth to top of basement using SPI but the work covered a larger area, thus leaving out significant local sub basins. Ayua, et al., (2023) attempted a re-assessment of the study area so as to assess the prospect for hydrocarbon and solid mineral emplacement. The study focused on the general thickness of sediments within the area without narrowing the scope to specific local depocenters of interest. This work therefore aims at delineating local sub-basins within the study area and estimating their sedimentary thickness using the Spectral Analysis technique developed by Spector and Grant (1970). The entire study area is divided into spectral blocks enabling the systematic appraisal of local sub-basins that may be otherwise overlooked. The study is significant in that it delineates specific local sub basins in the area within the general framework of the trough and examines their proclivity for hydrocarbon accumulation on the basis of sediment fill thickness and a priori geologic information about the basin.

Geological Setting of the Study Area

The study area is located within Benue State Nigeria. It lies within longitudes 8°30’00” E to 9°30’00” E and latitudes 7°0’00” N to 7°30’00” N (World Geodetic System (WGS) 1984). It covers an area of about 6, 558 Sq km (Figure 1). Geologically, the study area is within the Middle Benue trough. The Benue trough is a distinctive rift attribute on the African mainland whose tectonic evolution is related to the split-up of the African and South American continents in the Aptian (Grant, 1971). It is located intra-continentally and has a thickly folded cretaceous supracrustal fill formed from compression (Samuel *et al.*, 2011). It is 80 – 150 m wide and 800 km in length with NE - SW trending structures hypothesized to have originated as an aulacogen (Hoque and Nwajide, 1984). The Trough has a southern edge at the Northerly margin of the Niger-Delta Basin, while the Northern limit is at the southern boundary of the Nigerian portion of Chad Basin. The Benue Trough (Figure 1) is subdivided into the Southern portion which is also known as the Lower Benue Trough, the central section known as the Middle Benue and the Northerly segment known as the Upper Benue Trough (Samuel et al; 2011). There is no clear cut demarcation that delimits the distinct segments but major zones constitute the significant depocentre of the individual portions (Petters, 1982; Nwajide, 1990; Idowu and Ekweozor, 1993; Obaje *et al*, 1999; Burke et al, 1970).

The litho-stratigraphic succession of Middle Benue Trough (beginning from the oldest to the youngest) consists of the Asu River Group, the Awe, Keana, Eze-Aku, Awgu and Lafia Formations. The marine Asu-River group originated the sedimentation in the middle Benue trough (Obaje *et al.*, 2004). It is of Albian age and unconformably overlies the basement. The Asu River group is superseded by the Ezeaku Formation which is Turonian in age. Recent alluvial deposits are found along the river valleys and other low-lying areas (Jika and Mamma, 2014). Lafia Formation marks the end sedimentation in the Middle Benue Trough, and was followed by extensive volcanic activities in the Tertiary. Extensive report on the geology of Benue trough have been reported in the works of Cratchley and Jones (1965); Ofoegbu (1985); Burke *et al.* (1970); Grant (1971); Olade (1975); Offodile (1976); Obaje (2009). Figure 2 shows the geologic map of the study area.

MATERIALS AND METHODS

Data

Aeromagnetic data (Total magnetic intensity (TMI) (IGRF corrected)) (sheets 271 and 272) acquired from NGSA at scale 1:250,000. The total magnetic field data acquisition was undertaken by Fugro Airborne Survey Services with the 3 x Scintrex CS3 Cesium Vapour magnetometers in year 2007. The flight parameters are as follows: Flight line spacing; 500 metres; Profile sampling interval: 0.1 seconds; Terrain clearance: 80 metres; Flight direction: NW – SE; Tie line spacing: 2000 metres; Tie lines direction: NE – SW. The flight line direction was at 135º while the tie line direction was 225º.

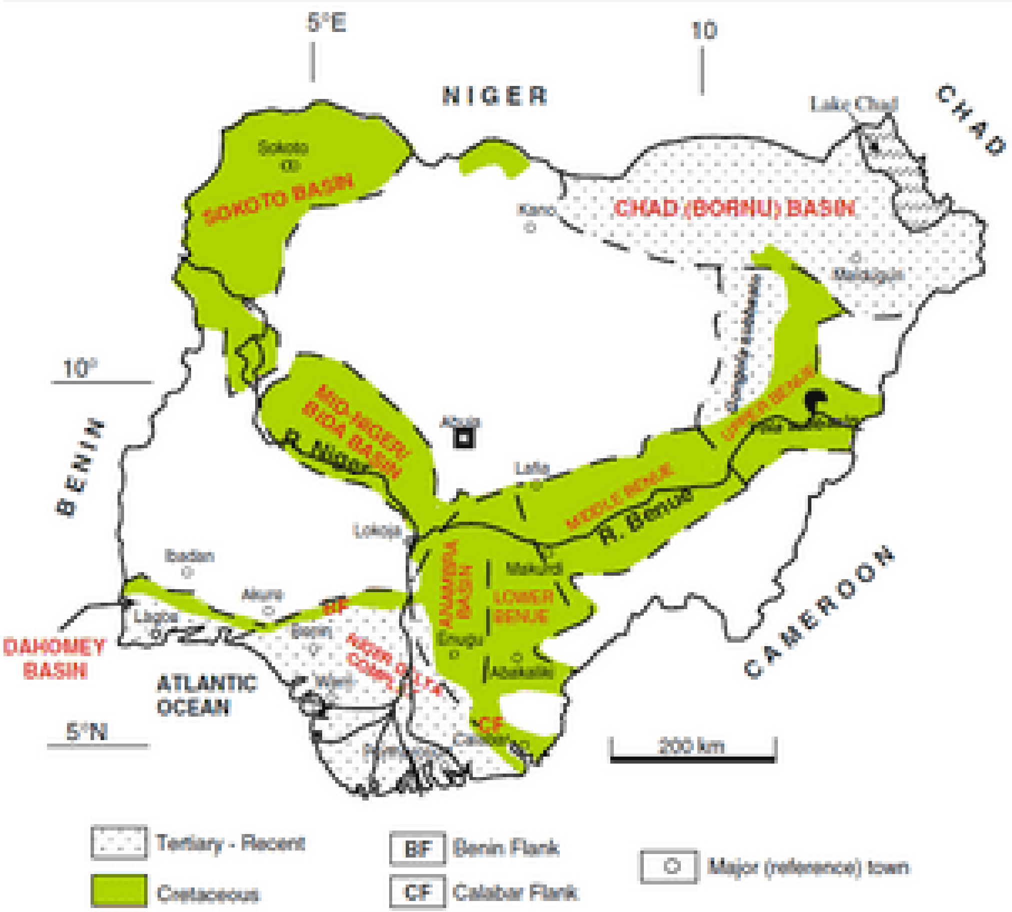


Figure 1: Geological Map of Nigeria (After Obaje, 2009)

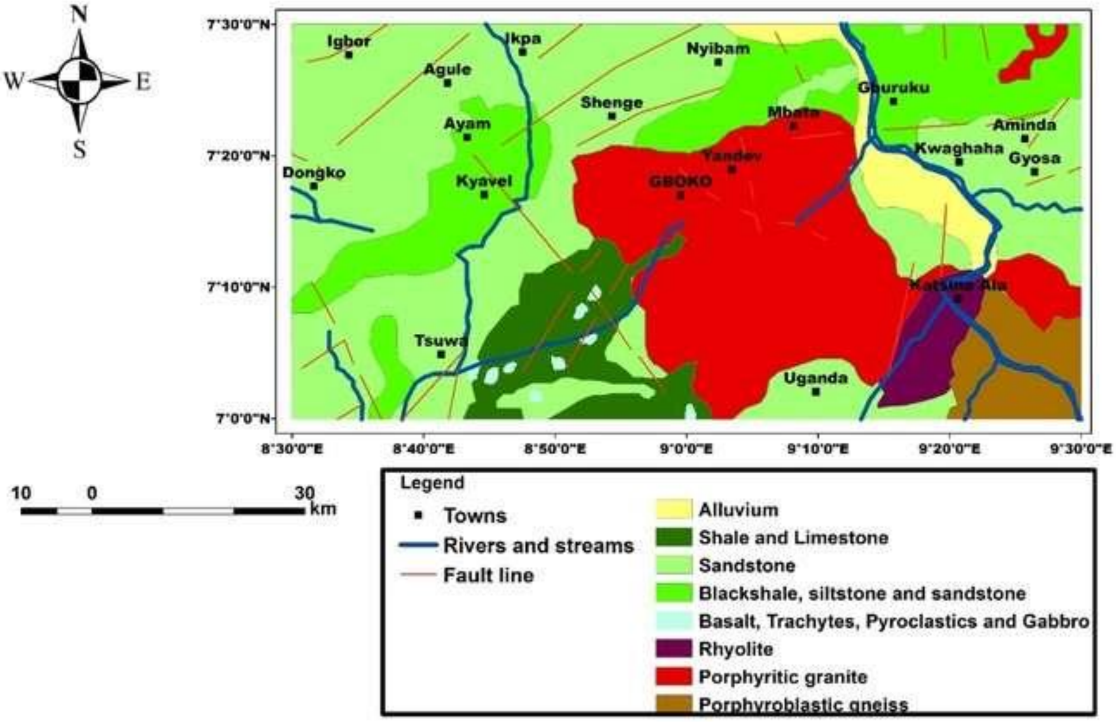


Figure 2: Geologic Map of the Study Area (Digitized from NGSA, 2006)

Data Processing

The input grid data was reprojected to UTM zone 32N of WGS 1984 to ensure a consistent coordinate system.

The digitized aeromagnetic data of Gboko and Katsina - Ala (Sheets 271 and 272 respectively) were merged together to produce one sheet using Oasis Montaj ™ 6.4.2 software. The merged map was further subdivided into twenty – five (25) spectral cells using Arcgis software and was filtered for Spectral Analysis. Each cell was approximately 36.4 km by 18.4 km, thus ensuring the delineation of local features within each cell.

Reduction to the Magnetic Equator (RTE) is a magnetic field transformation technique that corrects for the asymmetry or distortion in the magnetic field anomaly, caused by the magnetic latitude at the point of measurement which depends on the dip angle of the magnetization vector in the body. It was accomplished by using magnetic parameters such as inclination (-10.809°), declination (-1.624°), magnetic field strength (33,324 nT). RTE replicated the anomalies as though they were located at the equator (Falebita and Ayua, 2022) with the consequences that anomaly peaks are centered over causative bodies.

Regional – residual anomaly separation was then undertaken in order to separate the effects that associated with geological features of interest (i.e. residuals - short wavelength) from those effects that were not of interest (i.e. regional - long wavelength). Residual maps are used extensively to better define local features which are otherwise annihilated by the expansive constitutes of the regional field (Alagbe and Sunmonu, 2014). Residual maps were used in this study for structural mapping based on visual inspection of the maps. For this purpose, the 2-Dimensional (2D) Least Square Polynomial Smoothening (LSPS) technique was adopted (Grant, 1957; Dobrin, 1976; Maxwell *et al.*, 2012; Opara *et al.*, 2015; Sultan *et al.*, 2015). The 2D LSPS is a purely analytical technique. In using this technique, it was assumed that the regional component of the field may be described by a low order polynomial of the general form:

$$B(x,y) = C_1 + C_2x + C_3y + C_4x^2 + C_5xy + C_6y^2 + C_7x^3 + C_8x^2y + C_9xy^2 + C_{10}y^3 \quad (1)$$

By considering the regional to be a 2D first degree polynomial, the equation (1) reduces to:

$$B = C_1 + C_2x + C_3y \quad (2)$$

By solving this equation in the least squares sense by minimizing the sum of the square of the differences, one can obtain the constants C_1, C_2 and C_3 (Press *et al.*, 1992). In this study, the first to fourth degree polynomials (regional fields) were calculated and the degree for which the regional profile best fits the RTE profile was selected.

Spectral analysis was then undertaken to estimate the depth of certain geologic features (bodies). The discrete Fourier Transform is the mathematical tool employed in Spectral Analysis. Onwuemesi (1997) expressed the Fourier Transform mathematically as

$$Y_i = \sum_{n=1}^{N}\left[a_n \cos\left(\frac{2\pi n x_i}{L}\right) + b_n \sin\left(\frac{2\pi n x_i}{L}\right)\right] \quad (3)$$

Where Y_i (x) is the reading atx_i, L is length of the cross section of the anomaly, n is harmonic number of the partial wave number, N is the number of data points, a_n is real part of the amplitude spectrum and b_n is imaginary part of the amplitude spectrum, for I = 0, 1, 2, 3, -- n.

Spector and Grant (1970) performed this analysis, by plotting natural logarithm of the amplitude against frequency. The gradient of the linear segments were computed and depths to the basement were also achieved using the equations.

$$M_1 = \frac{\Delta y(logE)}{\Delta x(freq)} \quad (4a)$$

$$M_2 = \frac{\Delta y(logE)}{\Delta x(logfreq)} \quad (4b)$$

$$D_1 = \frac{-M_1}{2\pi} \quad (5a)$$

$$D_2 = \frac{-M_2}{2\pi} \quad (5b)$$

Where M_1 and M_2 are slopes of the first and second segments of plots, the negative sign (-) indicates depth to the subsurface while D_1 and D_2 are the first and second depth respectively.

Plots of Log of Energy and the Frequency

Spector and Grant (1970) established the linear gradient relationship of the log energy spectrum of the source with magnitude dependent upon the depth of the source. Logarithms of the spectral energy was determined and plotted against frequency for the twenty – five (25) spectral blocks and the depth to the sources determined. In dividing the study area into the spectral blocks, care was taken to ensure that indispensible portions of each anomaly were retained in the blocks.

RESULTS AND DISCUSSION

Total Magnetic Intensity Grid

The Total Magnetic Intensity (TMI) map showed the general susceptibility of rocks in the area under study. The susceptibility map of these rocks was presented in colour shades for easy interpretation. The two dimension (2D) TMI map (Figure 3) of Gboko and Katsina – Ala have values ranging from – 109.58 nT (blue colour) to 120.53 nT (pink colour). The area is generally characterized by high, intermediate and low wavelength anomalies with different shapes of anomaly such as spherical, elliptical, rectangular etc. The region of very strong magnetic intensity values, ranging from 69.60 nT to 120 nT are probably caused by near surface igneous or metamorphic rocks of high magnetic susceptibility. They are found around the Kyavel area and suggest the presence of ferromagnesian minerals with high magnetic content. The region that has the intensity between -109.58 nT to -5.97 nT are most likely to be caused by deeply buried magnetic rocks. It also suggests the presence of basin structures with thick sedimentary rocks that accumulated within them. These features are found around the region of Tsuwa.

Reduction to the Equator (RTE)

Figure 4 shows the result of RTE operation on the TMI map. Comparing this map with the TMI shows clearer demarcation between anomaly shapes. The RTE map better reveals the major and minor rock contacts in the area separated with different colours.

Residual Magnetic Intensity Map (RMI)

The RMI map was obtained using the polynomial fitting method and presented as Figure 5. The 2D residual map has intensity values ranging from -137.63 nT (minimum) to 58.49 nT (maximum). The broad wavelength anomalies observed on Figure 3, which are representative of regional features, are attenuated on the RMI map. Features represented on the RMI are indicative of shallow magnetic sources originating from the crustal rocks.

In totality, the study area comprises positive and negative residuals, representative of high and low magnetic intensities. The positive residuals obtained could be as a result of near surface intrusive rocks (dykes or sills) that outcrop in some places, the presence of ferromagnesian mineral assemblages or could also be interpreted as the combined effects from the deep seated basement complex rock in the area.

Similarly, the negative residual anomalies are magnetic low regions with thick sedimentary rocks. The regions around Katsina-Ala are characterized by an intermediate wave-number, which could occur as a result of near surface intrusion of dyke or sills.

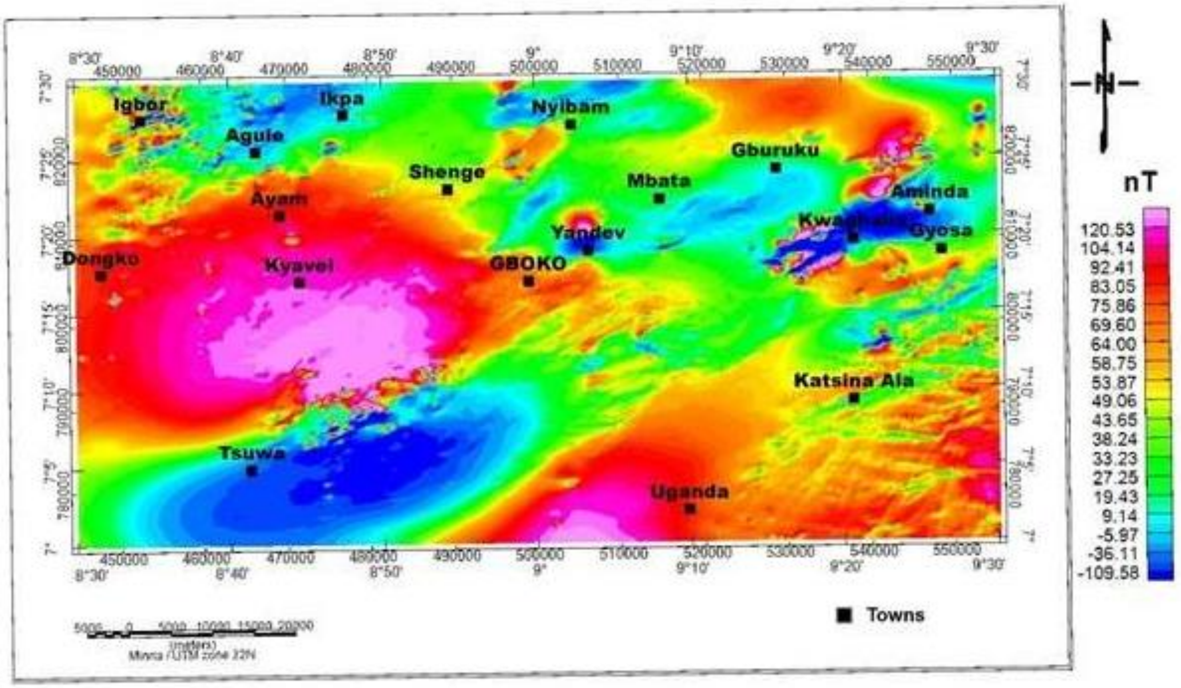


Figure 3: Two dimensional (2D) view of the total magnetic intensity (TMI) of the study area.

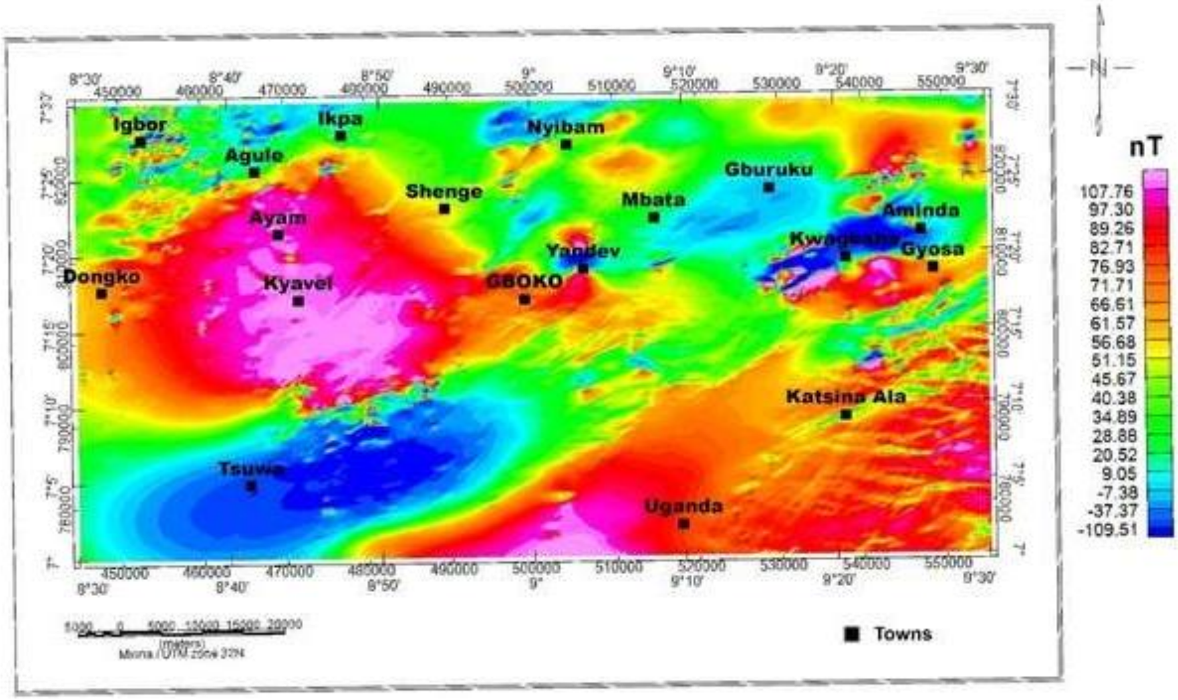


Figure 4: Reduction to the Equator Map

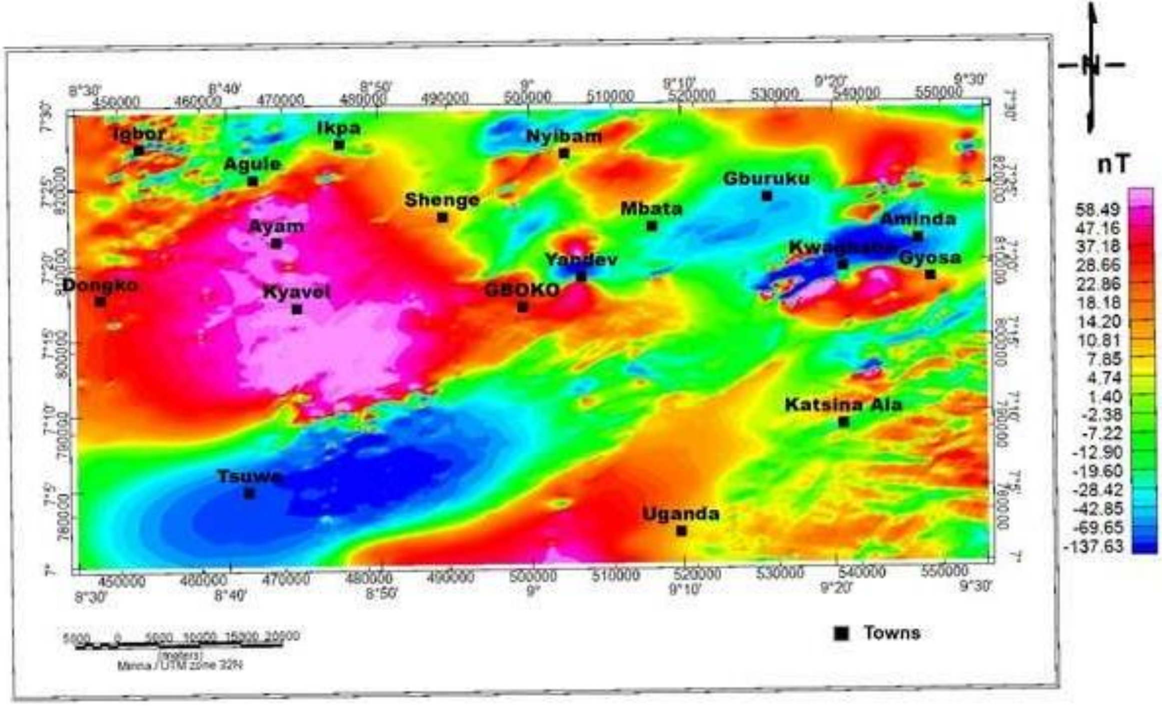


Figure 5: Residual Magnetic Intensity Map

Specral Analysis

Divisions of the study area into spectral blocks

The division of the study area into twenty – five (25) overlapping and equal spectral cells is presented as Figure 6. Each profile covers a rectangular area of approximately 36.4 km by 18.4 km in order to accommodate longer wavelength. This cell size allows maximum depth to the basement to be determined.

Generation of the Radial Energy Spectrum

The average radial energy spectrum was calculated using the Fast Fourier Transform (FFT) and the results displayed as a logarithmic plot of energy against frequency. The FFT was used to transform the magnetic data into a radial energy spectrum for each spectral block and the results for two representative blocks are presented as Figure 7.

Plots of Log of Energy and the Frequency

The gradient m = $\frac{\Delta \log E}{\Delta frequency}$ for each line segments in the Figure 7 were calculated. The average depth D of the buried material was also calculated using Equations 5a and 5b. The results of the two depth estimates (D_1 *and* D_2) for each of the twenty – five (25) spectral blocks are given on Table 1 below.

The results suggest the existence of two main source depths as also reported in some literature for the area (Nur et a;., 1994) for all the blocks (see Table 1) thus implying the existence of a deeper sub-basin. The deeper source (of the two depth-source model) lies at a depth that varies between 650 m (Block 13) and 5015 m (Block 6). Depth to top of basement in excess of 2500 m were obtained in Blocks 21, 16, 9, 8, 7, 6, 4, 3, 2 and 1 South West and North West of the area. The thickest sedimentary sequences were found to overly the following areas: Tsuwa area, South West of the study area (block 1, 2, 3, 6, 7 and 8), and NW of the study area around Igbor area (Block 21). The average depth for the study area was 2475 m. The work of Wright et al, (1985) reported that the minimum thickness of the sediment required to achieve the threshold temperature of 115 ^{o}C for the commencement of oil formation from marine organic remains would be 2.3 km. The results obtained indicate that the thicknesses of the sub-basins meet the depth thickness for hydrocarbon accumulation.

From the point of view of sediment thicknesses alone, the sub-basins south and SW of Gboko should provide good prospects for hydrocarbon exploration.

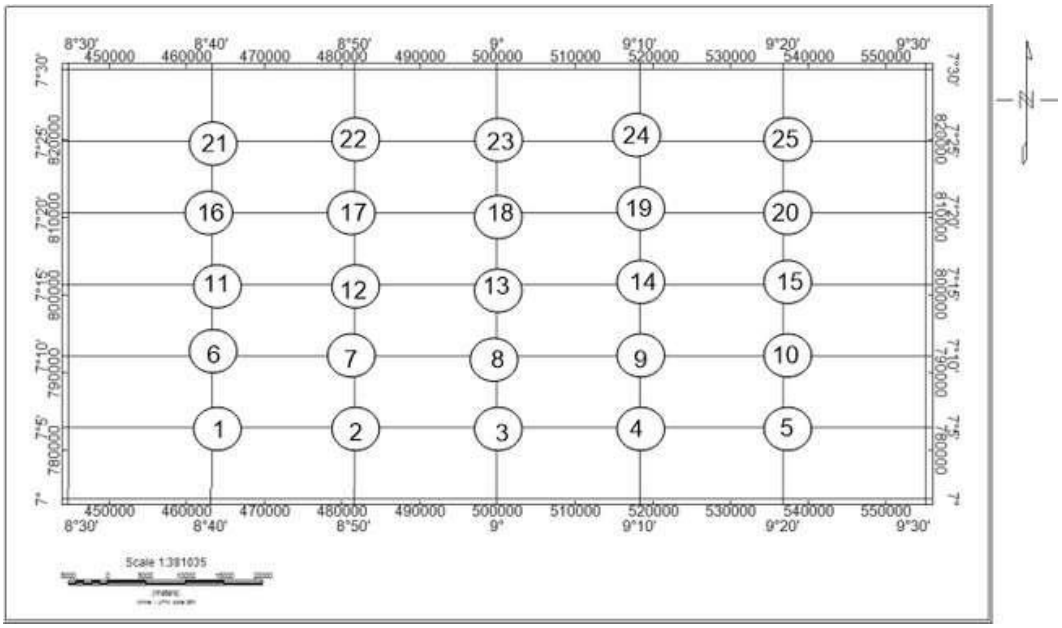
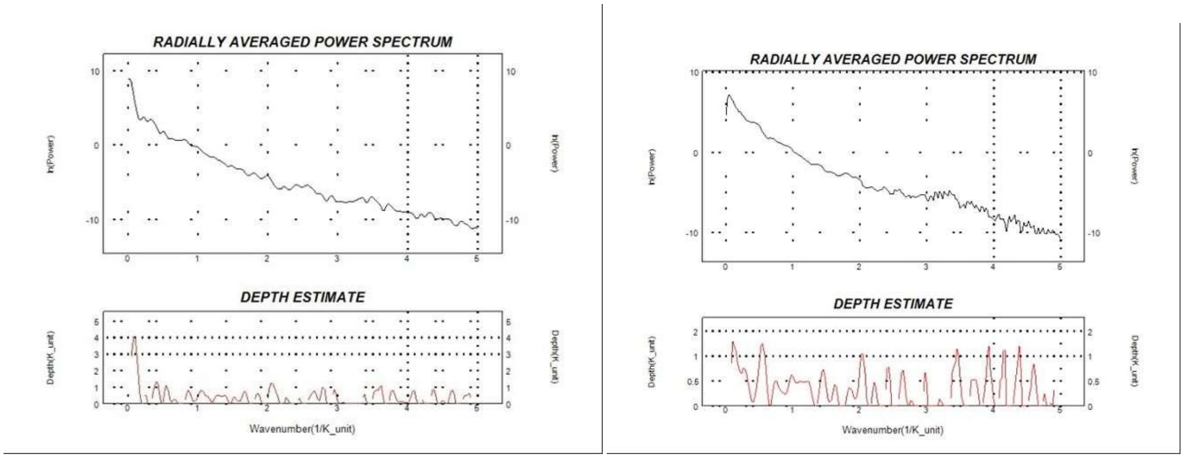


Figure 6: Twenty – five (25) spectral blocks for the spectral analysis.



(a) Block 6 (b) Block 14

Figure 7: Spectral plot of logarithm of energy against Frequency for blocks 6 and 14

Table 1: Depth Estimates of the First and Second Magnetic Layer for the Twenty-Five (25) Spectral Blocks

	SPECTRAL BLOCKS SECTIONS	**Coordinates (UTM)**		**DEPTH SOURCE VALUE (KM)**	
S/N		**X (Longitude)**	**Y(Latitude)**	$DEEP\ D_1$	$SHALLOW\ D_2$
1	1	463175.5	782959	4.936917	0.382479
2	2	481489.5	782959	4.51207	0.404275
3	3	499950.9	782959	3.22417	0.515301
4	4	518363.2	782959	3.250012	0.400263
5	5	536775.4	782959	1.383082	0.347231
6	6	463175.5	792140.6	5.015791	0.410423
7	7	481489.5	792140.6	4.746487	0.440669
8	8	499950.9	792140.6	3.382216	0.417028
9	9	518363.2	792140.6	2.665264	0.390495
10	10	536775.4	792140.6	1.563036	0.344306
11	11	463175.5	801371.3	1.620416	0.339467
12	12	481489.5	801371.3	1.885208	0.313229
13	13	499950.9	801371.3	1.634321	0.424757
14	14	518363.2	801371.3	0.651853	0.323416
15	15	536775.4	801371.3	0.967016	0.375322
16	16	463175.5	810602	2.922327	0.405769
17	17	481489.5	810602	2.216455	0.449272
18	18	499950.9	810602	1.252446	0.41627
19	19	518363.2	810602	1.316387	0.451689
20	20	536775.4	810602	1.518367	0.533093
21	21	463175.5	819783.6	4.050784	0.348012
22	22	481489.5	819783.6	2.342758	0.387269
23	23	499950.9	819783.6	1.836447	0.373653
24	24	518363.2	819783.6	1.253891	0.373716
25	25	536775.4	819783.6	1.744044	0.421779
		Average depth (km)		2.475671	0.399567
		Maximum depth (km)		5.015791	0.533093

Minimum depth (km)	0.651853	0.313229

Depth to Magnetic Basement

The magnetic basement depth map was plotted and contoured using Surfer 11 software. A cross section profile was taken from A to B to obtain the deepest magnetic sources of the area. The results of the contoured depth map and the profile are presented as Figure 8.

From the results, it was observed that the deep magnetic source varies from 0.5 to 5.5 km, with an average depth of 2, 475 m whereas the shallow magnetic source varies from 0.31 to 0.51 km from the computed value. Areas South East of Katsina-Ala has the shallowest sources delineated. This zone borders the transition zone between the sediments of the Middle Benue Trough and the Eastern Nigerian Basement Complex, an extension of the Congo Craton. This is not surprising since the basement complex outcrops near the surface in parts of this area, and the regolith in most places is quite thin here. The deepest depth to basement (blue colour) was found around Tsuwa, which is South-west of Gboko area, of the study area.

The profile along AB shows the gradient as one moves from the basin, SW of the study area to regions around Buruku, North and East of the study area. The results also show that nature of the floor of Benue valley is irregular, with sub-basin structures being separated by horst-like features or basement ridges. This confirms the 'horst and graben" structure of the floor of the Benue Trough as obtained from previous gravity and aeromagnetic studies (Cratchley and Jones, 1965; Adighije, 1981; Ofoegbu, 1984; Nur et. al., 1994).

A 3D image view of the basement topography of the study area is shown as Figure 9. The 3D image verifies the irregular nature of the basement topography of the study area. The 'horst and graben" structure of the floor of the Benue Trough is evident with a prominent horst structure around Dongko and Kyavel area separating the sub-basinal structures at Igbor and Tsuwa. The sub-basinal structures of the Middle Benue trough are generally separated by horst-like features or basement ridges.

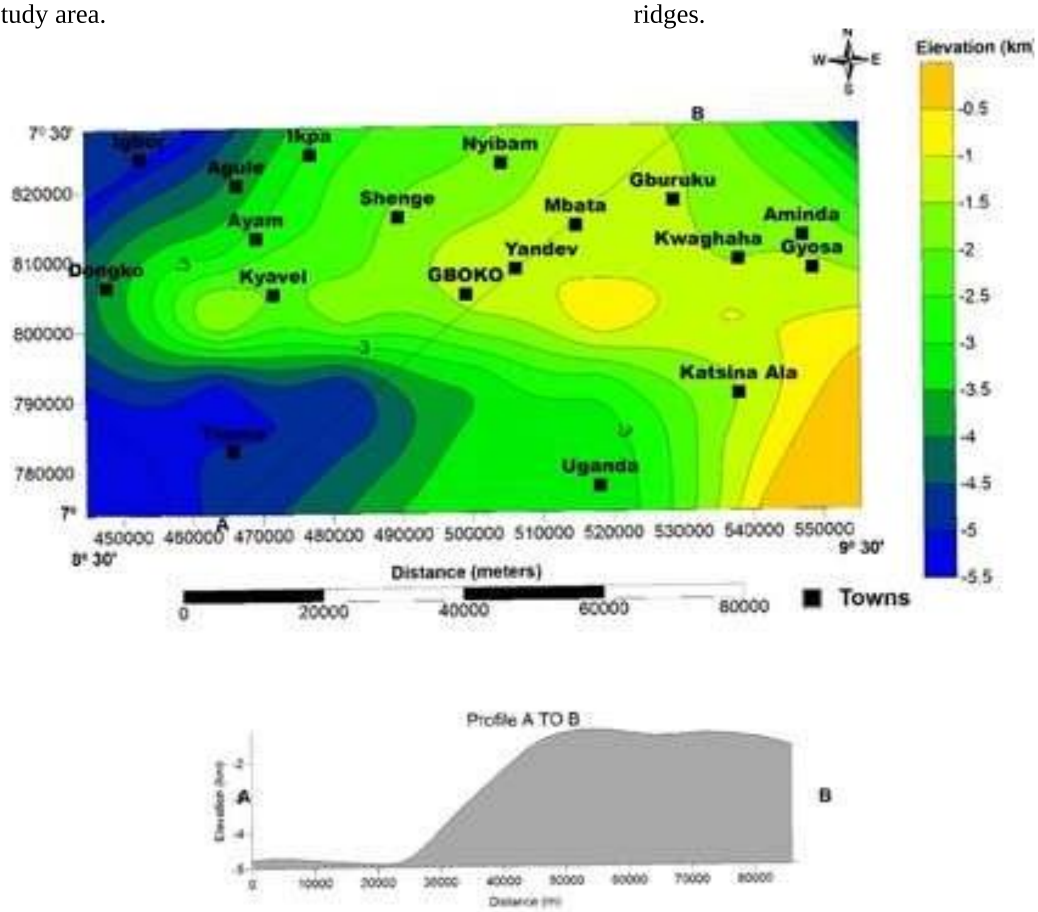


Figure 8: Deep depth to basement map of the study area (contour interval 0.5 km)

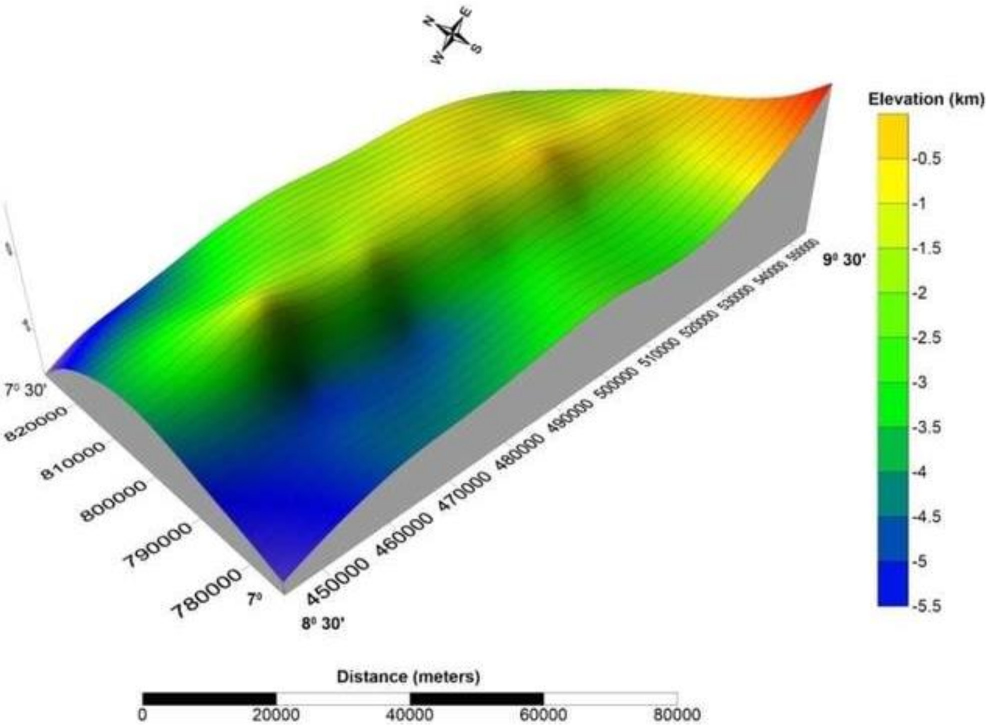


Figure 9: 3D map of the study area showing basement Topography.

CONCLUSION

Local sub-basin structures in the central Benue trough were delineated and the depths to the top of basement within them estimated from the spectral analysis of aeromagnetic data. Result from the spectral analysis showed two depth-source models, a deep depth-source and shallow depth-source model. The deep depth to magnetic source model revealed depth solutions ranging from 0.652 km to 5.016 km and an overall average depth of 2.476 km and was hypothesized to be due to deeply buried basement; thus implying thick sediment cover while the shallow depth model with depth solutions ranging from 0.313 km to 0.533 km with an overall average depth of 0.40 km was postulated to be due to magnetic sources significant for mineral exploration or surficial basement rocks. On the basis of basement topography, two sub-basin structures in the Northwest around Igbor area and Southwest, around Tsuwa area were delineated and results indicates that the deepest depths to the basement are found around the Tsuwa region with depths in excess of 4.0 km. The sub-basin structures are adjudged to have sufficiently thick sedimentary cover and are likely areas for more detailed hydrocarbon prospecting since the sediments are geologically likely to be good source rocks.

ACKNOWLEDGEMENT

The authors wish to acknowledge the Nigerian Geological Survey Agency for the provision of HRAM data.

CONFLICT OF INTEREST

The authors wish to declare that there are no conflicts of interests in the research.

SOURCES OF FUNDING

The authors wish to state that the research was self-funded.

REFERENCES

Adighue, C. (1981) A gravity interpretation of the Benue Trough Nigeria. *Tectonophysics*, 79, pp. 126 -136.

Ahmed, N.M. (1991). Spectral Analysis of Aeromagnetic Data Over the Middle Benue Trough, Nigeria; research publication; M.Sc. thesis University of Nigeria Nsukka.

Alagbe, O.A. and Sunmonu, L.A. (2014). Interpretation of Aeromagnetic Data from Upper Benue Basin, Nigeria Using Automated Techniques. *IOSR Journal of Applied Geology and Geophysics*, 2(5), 22-40. https://doi.org/10.9790/0990-0252240

Ayua, K.J., Ugwu, J.U. and Hassan, Y. (2023). Re-evaluation of HRAM data of Gboko and Katsina-ala area for hydrocarbon and solid mineral potential, *World Scientific News*, 178 (2023), pp. 56-78. Available online at www.worldscientificnews.com

Blakely, R.J. and Simpson, R.W. (1986). Approximating Edges of Source Bodies from Magnetic or Gravity Anomalies: *Geophysics* 51(7), pp. 1494 - 1498.

Burke K, Dessauvagie TFJ, Whiteman A (l 970). *Geological history of the Benue Valley and Adjacent areas*: In T.F. J. Dessauvagie and AJ. Whiteman (eds), African Geology. University of Ibadan Press, Nigeria. Pp. 187-205.

Constant, T.N., Fidele, K., Eliezer, M.D. (2010). Structural Features of South-Adamawa, Cameroon Inferred from Magnetic Anomalies: Hydrogeological Implications. *Comptes Rendus Geoscience*, 342, pp. 467 – 474.

Cratchley C.R. and Jones G.P. (1965). An interpretation of Geology and Gravity anomalies of the Benue Valley Nigeria. *Geophy. Pap. Overseas Geol. Surv*. London, 1, pp. 17-25.

Dobrin, M.B. and Savit, C.H. (1988). *Introduction to Geophysical Prospecting*. McGraw-Hill Book Co. Singapore, pp. 633 - 635.

Falebita, D.E. and Ayua, K.J. (2022). Appraisal of lineaments for groundwater prognosis in the Middle Benue Trough, Nigeria – A Case Study. *Sustainable Water Resources Management.* https://doi.org/10.1007/s40899-022-00791-1

Geological Survey of Nigeria. (2006). Geologic Map of Nigeria. Geological Survey Department: Ministry of Petroleum and Mineral Resources: Abuja, Nigeria.

Grant, N.K. (1971). A compilation of radiometric age from Nigeria. *Journal of Mining Geology*, 6, pp. 37-54.

Hoque, M. and Nwajide, C.S. (1984). Tectono-Sedimentological evolution of an elongate Intracratonic basin {aulacogen}: The case of the Benue Trough of Nigeria. *Journal of Mining and Geology*, 21(1&2), pp. 19-26.

Idowu, J.O. and Ekweozor, C.M. (1993). Petroleum Potential of Cretacious Shales in the Upper Benue Trough, Nigeria. *Journal of Petroleum Geology*, 21, 105-118. https://doi.org/10.1111/j.1747-5457.1993.tb00337.x

International Geomagnetic Reference Field (IGRF-12) model, (2015). Magnetic Field Calculator: http://geomag.nrcan.gc.ca/calc/mfcal-en.php. Accessed 08th September, 2017.

Jika, H. T. and Mamah, L. I. (2014). Application of electromagnetic method and electrical resistivity sounding in hydrogeological studies, a case study of Vandeikya area, central Nigeria. *International Journal of Scientific & Technology Research*, 3(2), pp. 179-190.

Nur, M. A., Onuoha, K. M. and Ofoegbu, C. O. (1994). Spectral Analysis of Aeromagnetic Data over the Middle Benue Trough, Nigeria. *Journal of Mining and Geology*, 30(2), pp. 211-217

Nwachukwu JI(1985). Petroleum Prospects of Benue Trough, Nigeria. *Am Assoc. Pet. Geol. Bull*. 69 (4): 601-609.

Nwajide, C.S. (1990). Cretacious Sedimenatation and Paleogeography of the Central Benue Trough. In: Ofoegbu, C.O.; (Ed.), The Benue. Tough Structure and Evolution. *International Monograph Series. Braunschweig*, pp. 19-38.

Nwosu, O.B (2014). Determination of Magnetic Basement Depth over Parts of Middle Benue Trough by Source Parameter Imaging (SPI) Technique Using HRAM. *International Journal of Scientific & Technology Research*. 3 (1), 2277-8616

Nwosu, O.B. (2015). Qualitative interpretation of aeromagnetic data over parts of Middle Benue Trough Nigeria using HRAM, *Standard Scientific Research and Essays*, 3(2), pp. 026-032.

Obaje, N. G. (2009). *Geology and Mineral resources of Nigeria*. Springer Dordrecht Heidelberg London New York, 224 pp.

Obaje, N.G., Wehner, H., Scheeder, G., Abubakar, M.B. and Jauro, A. (2004). Hydrocarbon prospectivity of Nigeria's inland basins: from the viewpoint of organic geochemistry and organic petrology. *AAPG Bull*, 87, pp. 325–353.

Offodile, M.E. (1976). The geology of the middle Benue Nigeria. Dissertation, Univ. of Uppsala Sweden.

Ofoegbu, C.O. (1985). Long Wavelength anomalies and the crustal structure underneath the Benue Trough and surrounding regions, *Nig. J. Min. Geol*. 22: 45 - 50.

Ofoegbu, C.O. (1984). Aeromagnetic anomalies over the lower and middle Benue Trough Nigeria; *Nig. J. Min. Geol.* 21: 103- 108.

Ofoegbu, C.O. (1986). A preliminary result of a pseudogravity study of the Benue Trough, *Nigeria. J. Afr. Earth Sci*. 5: 187- 192

Ofoegbu, C.O., and Onuoha, K.M. (1991). Analysis of magnetic data over the Abakaliki Anticlinorium of the Lower Benue Trough, Nigeria. *Marine and Petr. Geol*. 8:174-183.

Ogah, V.E. and Jatau, B.S. (2014). Airborne Magnetic Study of Otukpo Area. *International research Journal of Pure and Applied Physics*. 2(3), 15-24.

Olade, M.A. (1975). Evolution of Nigerian Benue trough (Aulocogen): A tectonic model. *Geol. Mag*. 112: pp. 575 -583.

Onwuemesi, A.G. (1997). One-dimensional spectral analysis of aeromagnetic anomalies and curie depth isotherm in the Anambra basin of Nigeria. *J. Geodynamics.* 23(2): 95-107.

Opara, A.I., Ekwe, A.C., Okereke, C.N., Oha, I.A. and Nosiri, O.P. (2012). Integrating Airborne Magnetic and Landsat Data for Geologic Interpretation over part of the Benin Basin, Nigeria. *Pacific Journal of Science and Technology*. 13(1), 556-571.

Petters, S.W. (1982). Central West African Cretacious-Tertiary Benthic Foraminifera and Stratigraphy. *Palaeontographica Abteilung*, 179, 1-104.

Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P. (1992). *Numerical recipes in C: The art of scientific computing*. Second Edition. Cambridge University Press.

Samuel, O.A., Olusola, J.O. and Olabisi, A.A. (2011). Stratigraphic Evolution and Petroleum Potential of Middle Cretaceous Sediments in the Lower and Middle Benue Trough, Nigeria: Insights from New Source Rock Facies Evaluation. *Petrol. Technol. Devel. J*. 1, pp. 81 – 87.

Spector, A. and Grant, F.S. (1970). Statistical models for interpreting aeromagnetic Data; *Geophy*. 25: 293-302.

Sultan, A.S.A., Hassan, S.S. and Wael, R.G. (2015). Integrated Geophysical Interpretation for Delineating the Structural Elements and Groundwater Aquifers at Central Part of Sinai Peninsula, Egypt. *Journal of African Earth Sciences*, 105, pp. 93 - 106.

World Geodetic System, 1984

Wright, J. B., Hastings, D., Jones, W.B. and Williams, H.R. (1985). *Geology and Mineral resources of West Africa*. George Allen and Urwin, London. 90-120, 1985.