Delineation of Prospective Hydrocarbon Zones in Parts of the Central Benue Trough, Nigeria, Using High-Resolution Aeromagnetic Data

Ejike K. Nnaemeka, Uzochukwu C. Omoja, Gabriel N. Egwuonwu, Chigoziem C. Onyekwelu[1] and Nneji G. Ezenwa

Department of Physics and Industrial Physics, Nnamdi Azikwe University, Awka, Anambra State, Nigeria.

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ABSTRACT

Aeromagnetic data from parts of the Central Benue Trough were interpreted to determine sedimentary thickness and temperature at depth across the study area, with implications for hydrocarbon accumulations. Three depth estimation methods (Source parameter imaging (SPI), Standard Euler deconvolution, and Spectral analysis) were used, and the results were compared. The Source parameter imaging (SPI) ranged from -119.23 to -6045.08 m, and Standard Euler deconvolution for the structural index (SI) of 3 ranged from 608.67 to -4741.70 m. Spectral depth analysis revealed depths of deep and shallow magnetic sources, with deep sources ranging from 1.03 to 5.09 km and an average depth of 3.15 km, while shallow magnetic sources ranged from 0.21 to 1.84 km and had an average depth of 0.6 km. The temperature at depth over the study area was calculated and the results revealed temperature values ranging from 79.9 to 387.42 °C, with an average value of 154.61 °C. The southwestern, northern, northeastern and central parts were delineated as potential hydrocarbon targets areas due to appropriate sedimentary thickness and temperature. These areas corresponds to Otobi, Otukpo, Taraku, Nov, Moi Igbo, Igbor, Aliade, Ndeel, Ito, Wannune, Obi, Giringwe, Azare, and Wuse due to appropriate sedimentary thickness and temperature. Furthermore, clusters of structures, as revealed by the total horizontal gradient and first vertical derivative maps, trend predominantly NE-SW, with a cross-cutting NW-SE structure, suggesting a favourable structural system that may enable migration and entrapment of hydrocarbons within the area.

Keywords: Aeromagnetic data, Sedimentary thickness, depth estimations, temperature at depth, oil and gas window, and hydrocarbon potential.

INTRODUCTION

The continuous growth in global energy demand, coupled with the progressive depletion of conventional hydrocarbon reserves in mature petroleum provinces, has intensified the search for new exploration frontiers. Consequently, exploration activities have increasingly shifted toward frontier sedimentary basins, where advances in geophysical techniques have substantially reduced uncertainty in hydrocarbon exploration. In Nigeria, this renewed exploration strategy has extended beyond the prolific Niger Delta Basin to the inland sedimentary basins, particularly the Benue Trough, Chad Basin, Sokoto Basin, Dahomey Basin, and Anambra Basin, which possess significant geological characteristics favourable for hydrocarbon generation and accumulation (Osinowo & Taiwo, 2020; Hayatudeen et al., 2020). The Benue Trough has remained one of the most important frontier inland basins in West Africa because of its complex tectonic evolution, thick Cretaceous sedimentary succession, widespread structural deformation, and documented occurrences of hydrocarbon seepages and organic-rich source rocks. Since the discovery of commercial hydrocarbons in the Kolmani and Ebenyi areas within the upper and central Benue Trough, scientific and industrial interest in the petroleum prospectivity of the Benue Trough has increased considerably. These developments have stimulated renewed investigations aimed at understanding the basin architecture, structural evolution, sedimentary thickness, and petroleum systems using modern geophysical techniques (Osinowo & Taiwo, 2020; Hayatudeen et al., 2020). The High-resolution aeromagnetic data acquired by the Nigerian Geological Survey Agency (NGSA) have greatly improved the spatial resolution of magnetic investigations across Nigerian sedimentary basins. Compared with older regional magnetic datasets, the High-resolution aeromagnetic surveys provide enhanced anomaly definition, allowing more accurate mapping of lithological boundaries, basement relief, structural lineaments, and concealed tectonic features. The integration of derivative filters and depth estimation techniques has consequently become an effective approach for evaluating frontier hydrocarbon basins where seismic data are sparse or unavailable. Several recent investigations have reported encouraging evidence supporting the petroleum prospectivity of the central Benue Basin. Integrated geological, geophysical, and geochemical analyses have identified several structural leads characterized by adequate sedimentary thickness, favourable thermal maturity, and structural configurations suitable for hydrocarbon accumulation. Similarly, aeromagnetic studies have revealed sedimentary thicknesses exceeding 5 km in some parts of the basin, extensive fault systems aligned predominantly in the NE–SW direction, and localized regions relatively free from intrusive igneous bodies. These observations suggest that portions of the Central Benue Trough possess the geological conditions necessary for effective hydrocarbon generation and entrapment, although additional exploration is required to confirm commercial accumulations.

Despite these encouraging findings, the Central Benue Trough remain considerably underexplored compared with the Niger Delta Basin. The Central Benue Trough has received less attention compared to the Lower Benue Trough and Niger Delta by researchers, despite this evidence of hydrocarbon presence in the area. (Nnaemeka et al., 2024).

Many structural features controlling hydrocarbon migration and accumulation remain poorly constrained, while uncertainties persist regarding basement architecture, sedimentary thickness distribution, and the influence of magmatic intrusions on petroleum preservation. Consequently, detailed structural interpretation using modern high-resolution aeromagnetic data remains essential for reducing exploration uncertainty and identifying priority targets for subsequent seismic acquisition and exploratory drilling.

Therefore, this study aims to delineate potential hydrocarbon accumulation zones in parts of the Central Benue Trough, Nigeria, using high-resolution aeromagnetic data. Specifically, the study seeks to characterize the basement structural framework, estimate sedimentary thickness, calculate temperature at depth, identify structural traps and migration pathways, and integrate these parameters to delineate areas favourable for hydrocarbon potential. The findings are expected to provide valuable insights into the petroleum potential of the Central Benue Trough and contribute to future hydrocarbon exploration strategies in Nigeria's inland sedimentary basins.

Location and Geology of the Study Area

The study area, which is located between latitudes 7°00' and 8°30' North and longitudes 8°00' and 9°30′East is within Benue, Nasarawa and parts of Taraba states of the Central Benue Trough. It has a total coverage area of about 27,225 km^2. (Cratchley and Jone, 1965; Whiteman, 1982) stated that the Current research area, located within the Benue Trough in Nigeria, is an extensive Cretaceous folded rift basin that cuts across Nigeria with an extension of about 100 km from the fringe of the Niger Delta in the eastern part of the country through the Gongola Basin to the Bornu Basin in the North. The width of the basin is approximately 250km (Whiteman, 1982). The Benue Trough, as one of the inland sedimentary basins in Nigeria aligned in the NE-SW direction, is part of the long stretch arm of the Central African rift system that originated from the early Cretaceous rifting of the Central and West African basement uplift (Obaje, 2004). The basin is subdivided into the Lower, Middle (Central) and Upper Benue Trough. According to (Reyment, 1965; Short and Stauble, 1967; Murat, 1972; Nwachukwu, 1972; Olade, 1975), the depositional history of the Benue Trough is characterized by several phases of marine regression and transgression, which is mainly the Cenomanian and the Santonian deformations. The scholarly publication of Offodile (1976) stated six Cretaceous sedimentary formations in the Central Benue Trough, this includes; Asu River Group, Keana Formation, Awe Formation, Ezeaku Formation, Awgu Formation and Lafia Formation. The oldest formation, Asu River group being middle to Albian in age, and the youngest, Lafia Formation, is of

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Maestrichtian age (Obaje, 2004). However, the current study area, which is within the Central Benue Trough, is underlain by alluvial deposits along river coasts, and younger basalt flows encountered around Eze Aku Groups and Agwu formations. The Nkporo, Agwu, Lafia –Wukari, Eze-Aku, Asu-River and Bima formations consist of lithological compositions of shale, mudstone, limestone, sandstone, sandy shale, black shale, siltstone, feldspathic sandstone, calcareous sandstone, shelly limestone and sandstone intercalations. There are exposures of basement rocks which are mainly igneous intrusives; these are biotite granite, rhyolite, porphyritic granite, quartzite and undifferentiated schists, including phyllites, banded gneiss/ biotite migmatite, porphyroblastic gneiss silicified, sheared rocks and large quartz veins that intruded into the sedimentary overburden, as shown in Fig. 2.

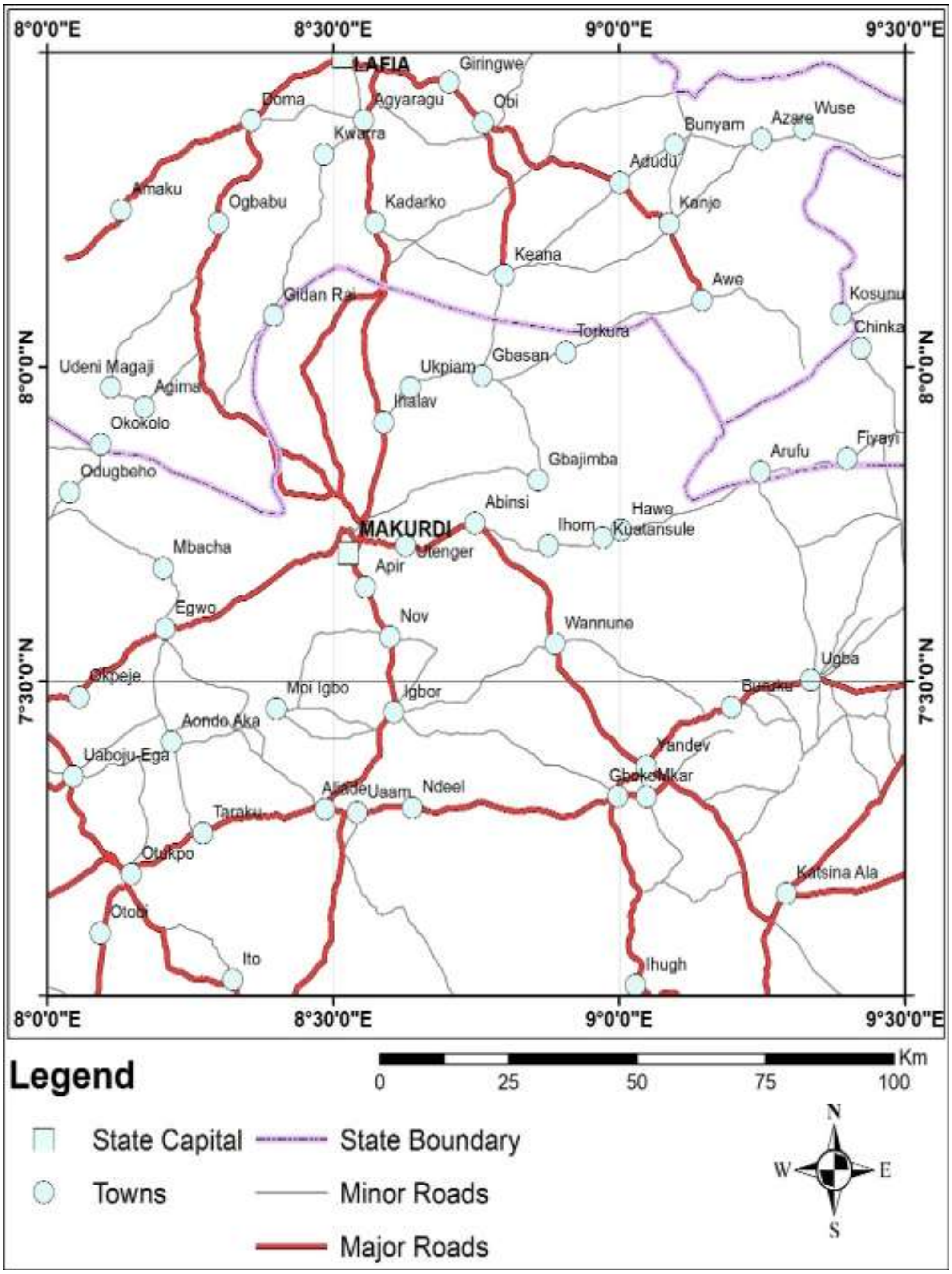

Fig. 1: Location map of the study area

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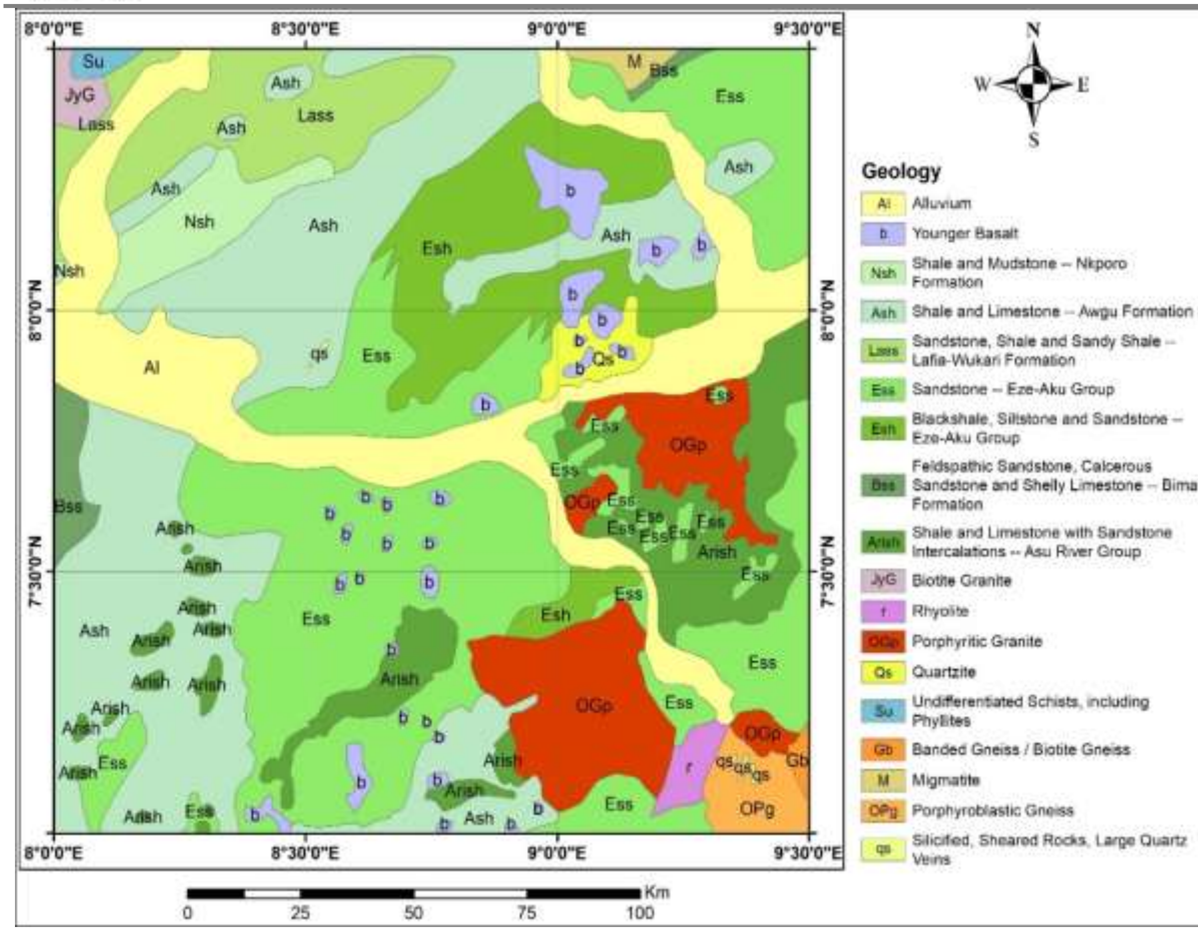

Fig. 2: Geology map of the study area

MATERIALS AND METHODS OF DATA ANALYSIS

Materials

The materials adopted in the current study are soft-copy digitized data sheets of Doma (230), Lafia (231), Akiri (232), Agana (250), Makurdi (251), Akwana (252), Otupko (270), Gboko (271) and Katsina Ala (271) carried out in Nigeria between the years 2005-2009 by the Nigeria Geological Survey Agency (NGSA). A flight altitude of 0.08 km, tie and flight line spacing of 2 km and 0.5 km were used for data acquisition. The digital data acquired was made available on a scale of 1:50000. The Software applications employed for the study are Oasis Montaj 8.4, ArcGIS, MATLAB, and Surfer 14.

Method of data analysis

The process started with merging the nine (9) aeromagnetic data sheets covering the study area to form a single database using the Oasis Montaj 8.4 software, such that the Total Magnetic Intensity (TMI) map of the area will be produced using the bi-directional line gridding method. Thereafter, the Total Magnetic Intensity map produced was reduced to the equator (TMI-RTE); this was done in accordance with the I.G.R.F 2005 standard reduction method using equation 1 below. Amplitude corrections of inclination -9.3 and declination of -1.7 were used as basic inputs. This is because reduction to the magnetic equator is specifically carried out in low magnetic latitude regions in which the study area falls (i.e. areas with geomagnetic inclination less than 15˚). This filtration technique centres the peaks of low magnetic anomalies over their sources or exact positions.

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$$T(\theta) = \frac{\{\sin I - i\cos I\cos(D-\theta)\}^2 \times \{-\cos^2(D-\theta)\}}{\{\sin^2 I_a + \cos^2 I_a \cos^2(D-\theta)\} \times \{\sin^2 I + \cos^2 I \cos^2(D-\theta)\}} \quad (1)$$

If $(/I_a/ < /I/)$

$I_a = I$

Where,

$T(\theta)$ = TMI reduced to the Equator, I = Geomagnetic inclination, I_a = Inclination for amplitude correction (never less than I), D = Geomagnetic declination, Sin I = Amplitude component and cos I cos (D - θ) = phase components.

First Vertical Derivatives (FVD): It is an enhancement technique that sharpens anomalies over bodies and tends to reduce these anomalies by allowing a clear visual imaging of the causative structures. The algorithm adopted for this method, as proposed by (Verduzco et al., 2004), is expressed mathematically as shown in equation 2.

$$FVD = \frac{\partial P}{\partial Z} \quad (2)$$

Where P is the magnetic field anomaly

Total Horizontal Gradient (THG): The derivative technique is designed to search for fault and contact features from potential field data. It complements the filtered and vertical derivative techniques. The equation for horizontal derivative techniques, as proposed by Cordell and Grauch 1985, is expressed mathematically as shown in equation 3.

$$THG = \sqrt{\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2} \quad (3)$$

Where P is the potential field anomaly and $(\partial P/\partial x)$ and $(\partial P/\partial y)$ are the x and y horizontal derivatives of the field.

Source Parameter Imaging (SPI)

This depth estimation technique was developed by Thurston and Smith (1997), and it is sometimes referred to as the local wavenumber method. Delineating solution grids using this technique shows the edge locations, depths, dips and susceptibility contrasts of potential field anomalies. This technique utilizes the relationship between source depth and the local wavenumber (*K*) of the observed field, which can be estimated for any point within a grid of data via horizontal and vertical gradients. The algorithm adopted for this depth estimation method, as proposed by Thurston and Smith 1997, is expressed mathematically as shown in equations 4- 6.

$$Depth = \frac{1}{K_{max}} = \frac{1}{\left(\sqrt{\left(\frac{\delta Tilt}{\delta x}\right)^2 + \left(\frac{\delta Tilt}{\delta y}\right)^2}\right)_{max}} \quad (4)$$

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Where the tilt is given as

$$Tilt = \arctan \frac{\frac{\delta T}{\delta z}}{\left(\sqrt{\left(\frac{\delta T}{\delta x}\right)^2 + \left(\frac{\delta T}{\delta y}\right)^2}\right)} \quad (5)$$

$$Tilt = \frac{\delta T / \delta Z}{HGRAD} \quad (6)$$

Where HGRAD is the horizontal gradient, T is total magnetic intensity (TMI), and are the first-order partial derivatives of the total magnetic intensity (T) in x, y and z coordinates.

Euler Deconvolution

Euler deconvolution is an inversion method employed during potential field data interpretation to estimate corresponding depths and locations of magnetic anomaly or geologic sources. The method also relates the magnetic field and its gradient components to the anomaly source, with its degree of homogeneity expressed as a structural index (El Dawi et al., 2004; Thompson, 1982; Reid et al., 1990; Moghaddam et al., 2015). The 3D form of Euler's equation as proposed by Reid et al. 1990 can be expressed mathematically as:

$$x\frac{\partial T}{dx} + y\frac{\partial T}{dy} + z\frac{\partial T}{dz} + \eta T = x_o\frac{\partial T}{dx} + y_o\frac{\partial T}{dy} + z_o\frac{\partial T}{dz} + \eta b \quad (7)$$

Where y and z are the coordinates of a measuring point; y_o and z_o are the coordinates of the source location whose total field is detected at y and z. b is a base level, η is the structural index, and T is the potential field.

The value of the structural index depends on the type of source body one intends to investigate (Whitehead and Musselman, 2005). A structural index of 3 was adopted for this study to estimate the depth of magnetic sources.

Spectral Analysis

The Spectral depth estimation technique developed by Spector and Grant (1970) entails estimating and interpreting the spectrum of potential field data (Rabeh, 2009). This technique is based on the principle that the magnetic field measured at the surface can be considered as an integral of signatures from all depths (Rabeh, 2009). The Fast Fourier Transform (FFT) algorithm, which computes the Discrete Fourier Transform (DFT), is a mathematical tool employed for spectral depth analysis and regularly spaced data such as aero potential field data (aeromagnetic). This algorithm is used for spectral analysis; when applied to the aerogeophysical data converts the spatial (real space) data to frequency data. The main signal (raw data) is composed of three parts: a linear trend (drift in the average of the signal), Signal (periodic or cyclic components) and Noise (random components). According to Telford et al. (1990), the major advantage of the spectral depth technique is its capacity to filter all the noise from the data and lose no information during the data processing by overlapping data operations, which are easier in the transform domain. The potential field data (magnetic or Bouguer) anomalies caused by shallow sources are specifically more dominant by higher wave number components than those emanating from deep structures. This effect was calculated by computing the power spectrum of the anomalies since the long power

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spectrum has a linear gradient whose magnitude is dependent upon the depth of the sources (Spector and Grant, 1970).

The analysis started with division of the Reduction to the Magnetic Equator (RTE) map into twenty-five overlapping blocks as follows: block 1 – 25 of spectral probe of 55 km by 55 km such that longer wavelengths can be accommodated and give room for the depth analysis of the area. Thereafter, each of the 25 blocks was subjected to a Log Power Spectrum (a filtering technique) of the Oasis Montaj software. This transformed the magnetic data from real space to the wavenumber or frequency domain via the Fast Fourier Transform (FFT) algorithm application. This art generated the spectral energies from which the depth values relating Z_0 (depth to the centroid) and Z_t (depth to the top boundary) were estimated from the slope of the first and second longest wavelength portions of the spectrum, adopting the algorithm of equations 1 and 2, respectively. The SPC files of the twenty-five blocks obtained from this analysis were exported into Microsoft Excel worksheets one after the other; thereafter, these 25 spectral (SPC) energy files were input into a spectral program plot (SPP) developed with MATLAB. The twenty-five spectral energies were plotted with the developed MATLAB program such that the depth values of (Z_0 and Z_t) were obtained. The SPP program is also designed to estimate the deep and shallow magnetic sources using the algorithm as stated in equations 3 and 4, respectively. This was used to estimate the depth of deep and shallow magnetic sources. A typical example plot of energy against frequency (wavenumber) is shown in Figure 7a to d.

$$\ln\left[\frac{\sqrt{P_{(s)}}}{|s|}\right] = \ln A - 2\pi|s|Z_o \quad (1)$$

Where $P_{(s)}$ is the radially mean power spectrum of the anomaly, A is a constant and $|s|$ is the wavenumber

$$\ln\left[\sqrt{P_{(S)}}\right] = \ln B - 2\pi|s|Z_t \quad (2)$$

Where B is the total amount of constant independent of $|s|$.

$$d_1 = \frac{-M_1}{4\pi} \quad (3)$$

$$d_2 = \frac{-M_2}{4\pi} \quad (4)$$

Where M_1 and M_2 are the slopes of the first and second segments of the plot, while d_1 and d_2 are the first and second depths

Estimation of Curie point Depth and Geothermal Gradient

Curie point depth: Curie point is the temperature at which spontaneous magnetization vanishes and magnetic minerals exhibit paramagnetic susceptibility. Curie point depth used to describe the depth to the inferred Curie point transition of magnetite. It is the depth at which the Fe-Ti Oxide minerals of the earth lose their ferromagnetic property (Nur *et al*., 1999). Therefore, the Curie point depth is given in expression 5:

$$Z_b = 2Z_o - Z_t \quad (5)$$

Where, Z_0 is depth to the centroid, and Z_t is depth to the top boundary

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Geothermal gradient: Geothermal gradient is the rate of increase in temperature per unit depth in the earth due to the outflow of heat from the centre (Lowrie, 1997). The Curie temperature (580°C) and the depth to the bottom of magnetic are connected Tanaka *et al.,* 1999; Tanaka and Ishikawa, 2005; Stampolidis *et al*., 2005, and can be calculated using the relation in equation 6

$$\theta = \left(\frac{dT}{dZ}\right) Z_b \qquad (6)$$

Rewriting equation 6, the geothermal gradient $\left(\frac{dT}{dZ}\right)$ can be obtained as;

$$\frac{dT}{dZ} = \frac{\theta}{Z_b} \qquad (7)$$

Where, $\boldsymbol{\theta}$=580°C (Curie temperature value)

Hence, the geothermal gradient of the area was calculated using equation (7)

Estimation of Temperature at Depth

In computing the various temperatures at depth within the study area, it was assumed that the temperature changes within the earth are linear of the form expressed in equation 8 as (Onwuemesi, 1997; Oguadimma and Aku, 2019).

$$T_d = G_{gd} D + T_s \qquad (8)$$

Where,

T_d = temperature in °C at individual depth (d), G_{gd} = Geothermal gradient at each depth

D = depth of interest and T_s = Surface temperature.

The average surface temperature was assumed to be 27°C. Using the geothermal gradient and sedimentary thickness values obtained, which vary from 16.09 to 70.81 °C/km and 1.38 to 6.93 km, respectively, the temperatures at depth for each anomaly block were calculated by determining T_d (temperature in °C at individual depths). The values obtained range from 79.9 to 387.42 °C, with an average of 154.61 °C.

RESULTS AND DISCUSSION

Total magnetic intensity and Reduction to the magnetic equator

The total magnetic intensity and reduction to the equator maps (Fig. 3 and 3b) are characterized by positive and negative anomalies ranging from -58.49 to 99.80 nT and -53.92 to 96.97 nT, respectively, indicating high (pink to red colours), moderate (yellow) and low (blue) in magnitude, depicting that the area is magnetically heterogeneous. The high/positive anomalies may be attributed to shallow basements and regions of igneous intrusions within the sedimentary basin or basement resulting from magmatism, as observed in the geologic map of the study area, whereas the low/ negative anomalies depicted sedimentary terrains as well as deep-seated structures in the area. The variations in the anomalies noticed may be related to magnetic susceptibility, depth, degree of strike, lithology or basement complex rocks harbouring varying amounts of magnetic minerals.

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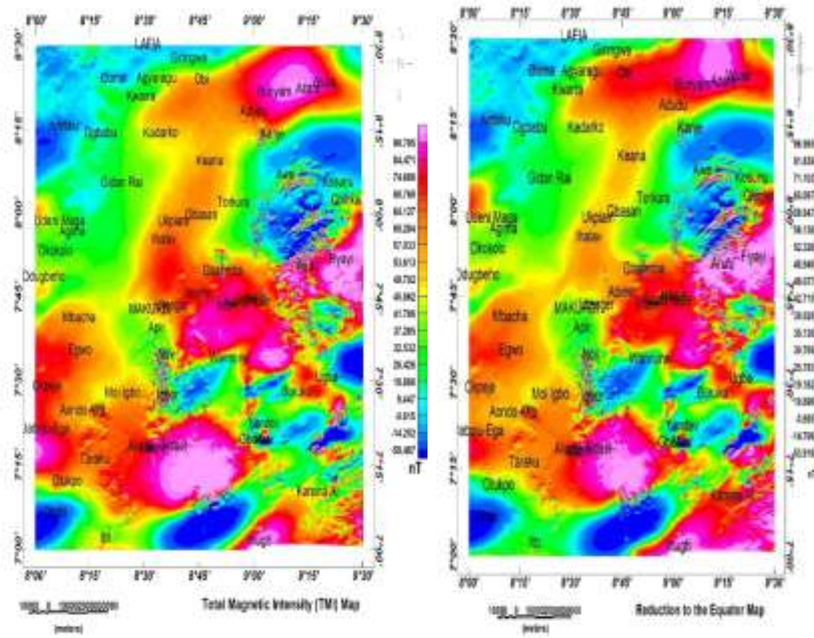


Fig. 3a: Total Magnetic Intensity Map of the area. (3b) Reduction to the Equator Map of the area.

Total horizontal gradient (THG) and First vertical derivative (FVD)

The total horizontal gradient and the first vertical derivative maps (Fig. 4a & 4b) revealed areas of structural deformation (ASD) trending mainly at NE-SW and cross-cutting at NW-SE directions, which is consistent with the structures of the Central Benue Trough. These structures support the migration and entrapment of hydrocarbon within the area and also possible favourable fault systems for other mineralization.

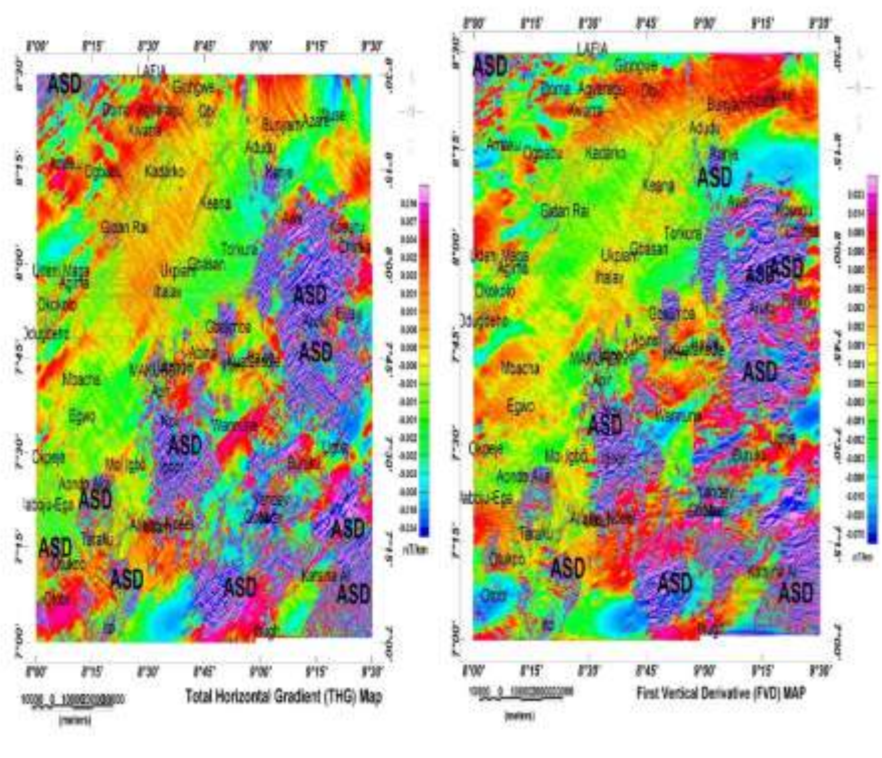
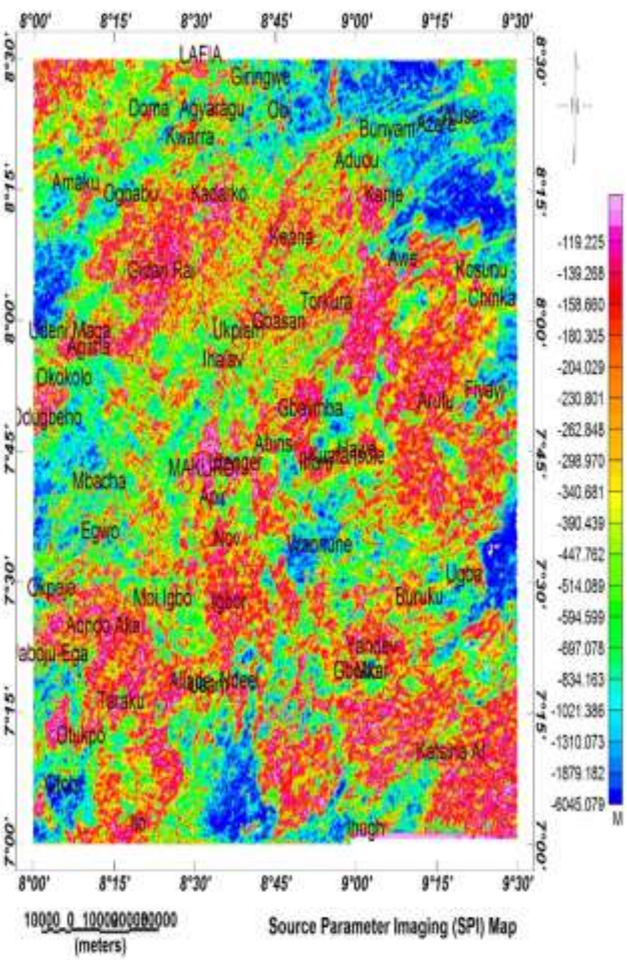


Fig. 4a: Total Horizontal Gradient map of the area. (4b) First Vertical Derivative map of the area

Depth estimations

The SPI depth weighting solutions (Fig. 5a) revealed negative depth values ranging from -119.23 to -6045.08 m. This negative values seen on the maps depict depths of buried magnetic bodies, which could be deep basement rocks. The Euler depth (Fig. 5b) yielded depth values of 608.67 m to -4741.70 m, representing shallow and deep magnetic sources. The shallow magnetic bodies are occupied by (pink to shaded red areas), while the blue colour depicts areas of deep magnetic bodies.



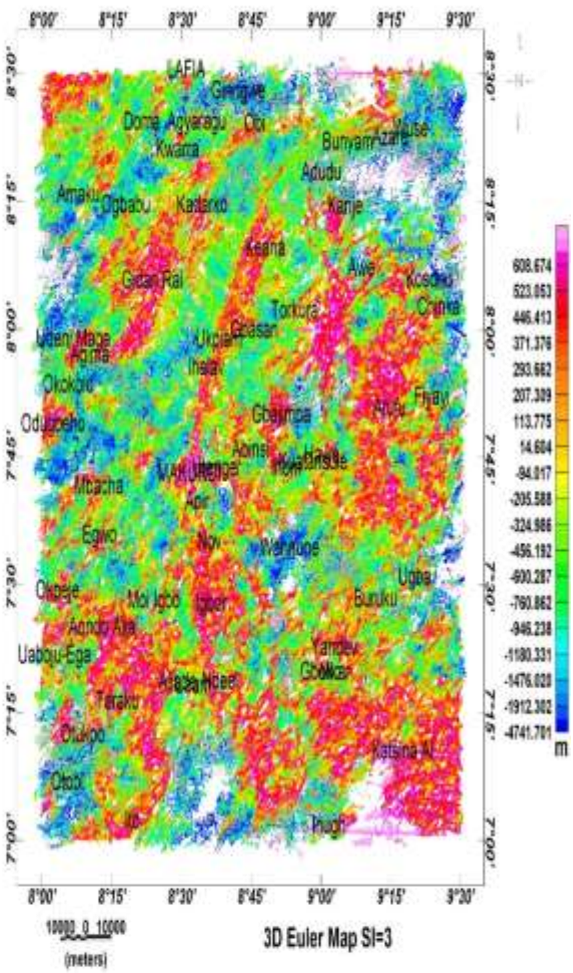


Fig. 5a: SPI Map of the Study Area.

Fig.5b: Euler depth map of the Study Area

Spectral Analysis

The division of the spectral results (Fig. 6) showed two source depths, shallow and deep depths. The contour map of the deep depth magnetic sources (Fig. 8a &b) ranged from 1.03 to 5.09 km with a mean depth value of 3.15 km, whereas the contour map of shallow magnetic sources (Fig. 9a & b) ranged from 0.21 to 1.84 km with an average depth of 0.60 km as given in Table 1. The Table further summarizes the results from the 25 overlapping blocks. The samples of graphs of spectral energy against frequency (wavenumber) obtained from blocks 1-25 are shown in (Fig. 7a-d). The contour map of temperature at depth (Fig. 10) showed values ranging between 79.9 ˚C and 387.42 ˚C with an average value of 154.61 ˚C. The South western, north-north eastern, parts of central and north western of the study area, covering about 60% of the total area, showed good temperature and depth and were delineated as potential hydrocarbon zones.

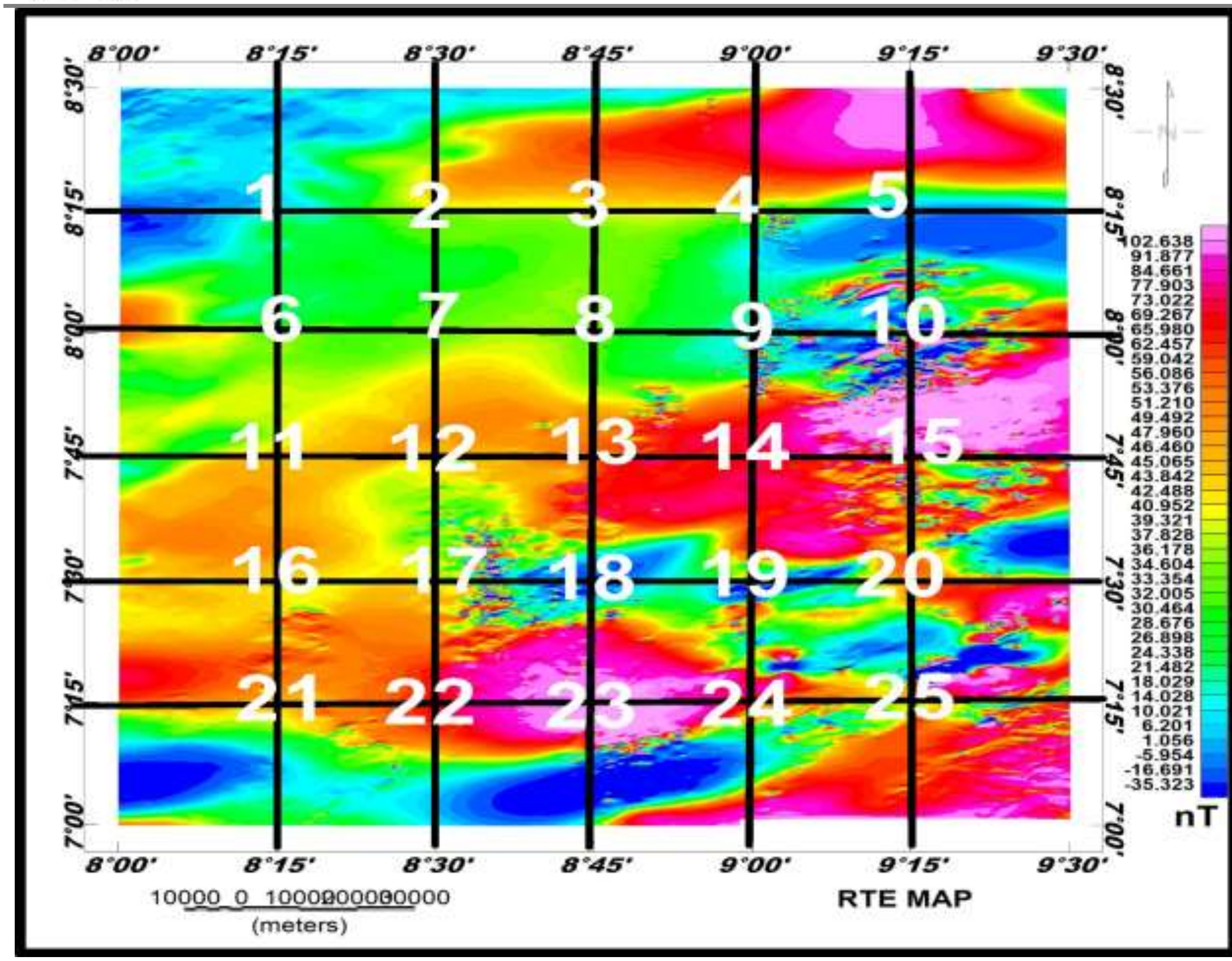


Fig.6: Division into 25 spectral blocks for estimation of the depth to basement.

Table 1. Summary of the results of spectral analysis from the 25 overlapping spectral blocks

Blocks	Long.(°)	Lat. (°)	Depth to centroid Z_0 (Km)	Depth to top Z_t (Km)	Curie Point Depth Z_b (Km)	Geothermal Gradient (°C/Km)	Deeper depth (d_1) km	Shallow depth (d_2) (km)	Temp. at depth (°C)
1	8.25	8.25	8.41	1.61	15.21	38.13	1.68	0.43	91.06
2	8.50	8.25	9.41	2.20	16.62	34.90	2.77	0.77	123.67
3	8.25	8.25	10.70	3.50	17.90	32.40	3.04	0.25	125.49
4	9.00	8.25	8.90	3.37	14.43	40.19	3.47	0.21	166.46
5	9.25	8.25	8.27	4.53	12.01	48.29	4.49	0.39	243.52
6	8.25	8.00	5.96	3.31	8.61	67.36	3.52	1.84	264.11
7	8.50	8.00	5.86	2.45	9.27	62.57	4.98	1.76	338.59
8	8.75	8.00	6.08	2.06	10.10	57.43	3.22	0.88	211.92
9	9.00	8.00	6.99	1.66	12.32	47.08	2.01	0.34	121.63

10	9.25	8.00	6.89	1.38	12.40	46.77	1.51	0.32	97.62
11	8.25	7.75	5.66	3.13	8.19	70.81	5.09	1.51	387.42
12	8.50	7.75	6.02	3.36	8.68	66.82	3.02	0.24	228.79
13	8.75	7.75	6.22	2.65	9.79	59.24	3.52	0.26	235.52
14	9.00	7.75	7.57	2.29	12.85	45.14	2.53	0.27	141.20
15	9.25	7.75	8.14	2.59	13.69	42.37	3.00	0.35	154.11
16	8.25	7.50	5.88	2.77	8.99	64.52	3.69	0.75	265.08
17	8.50	7.50	13.00	2.89	23.11	25.09	4.33	0.81	135.64
18	8.75	7.50	17.20	4.70	29.71	19.52	4.35	0.38	111.91
19	9.00	7.50	8.12	5.84	10.40	55.77	2.08	0.35	143.00
20	9.25	7.50	5.88	2.10	9.66	60.04	1.69	0.49	128.47
21	8.25	7.25	14.90	6.93	22.87	25.36	3.61	0.87	118.55
22	8.50	7.25	19.60	3.16	36.04	16.09	4.06	0.39	92.33
23	8.75	7.25	11.20	3.96	18.44	31.45	4.23	0.29	160.03
24	9.00	7.25	6.56	1.83	11.29	51.37	1.03	0.35	79.91
25	9.25	7.25	9.93	2.30	17.56	33.03	1.86	0.38	88.44
					Av. = 14.81	Av.= 45.39	Av.= 3.15	Av. = 0.60	Av. = 154.61

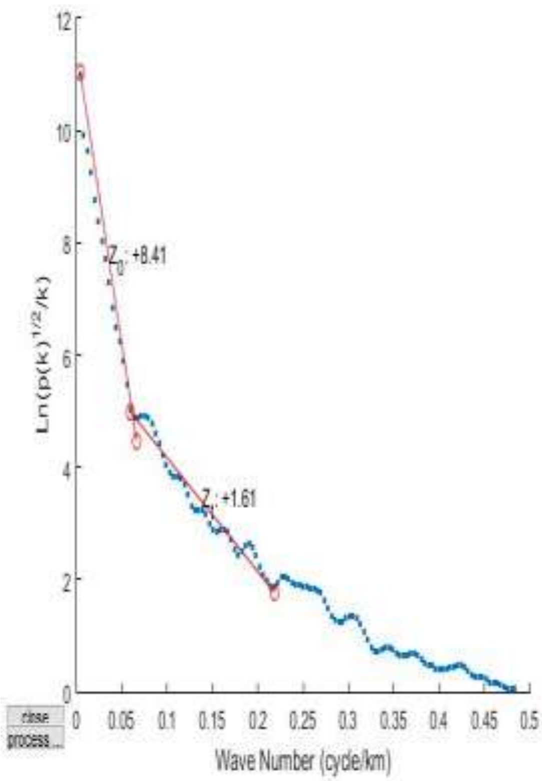


Fig.7a: block 1

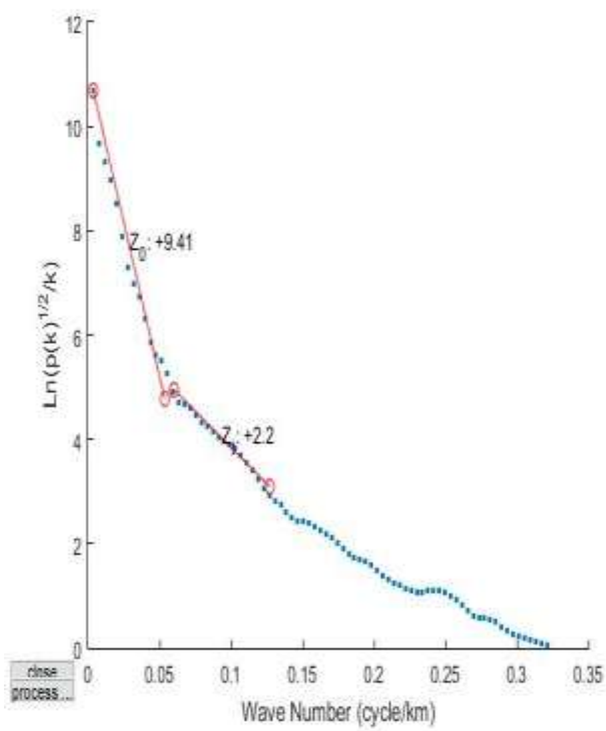


Fig.7b: block 2

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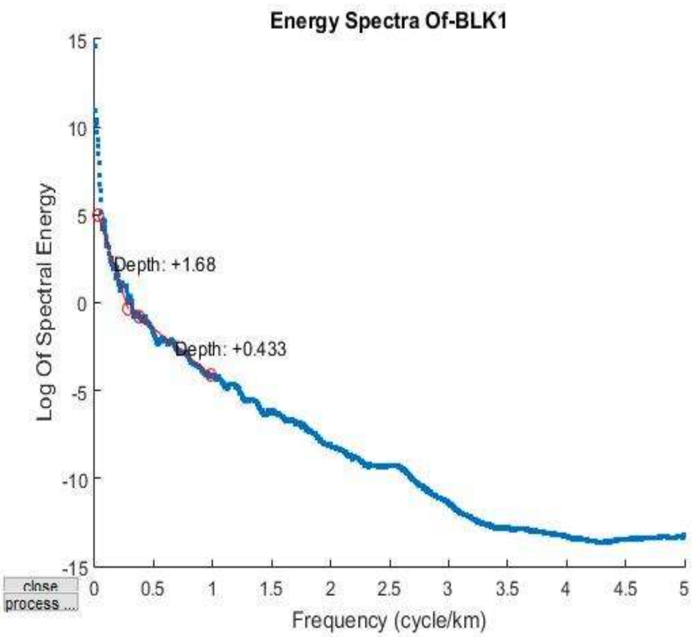

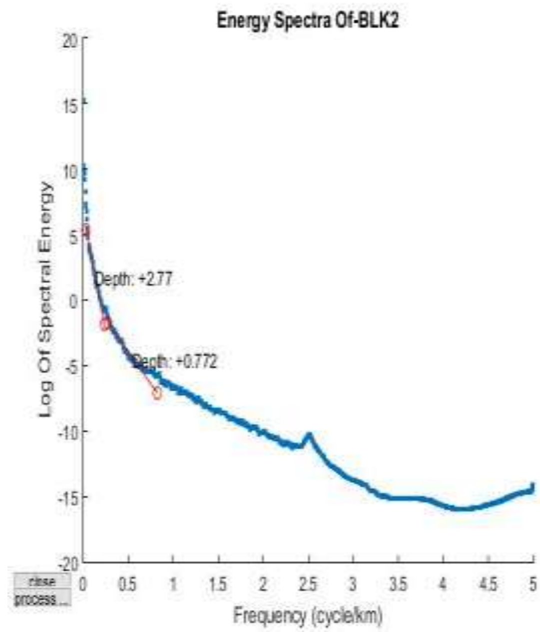

Fig.7c: block 3

Fig.7d: block 4

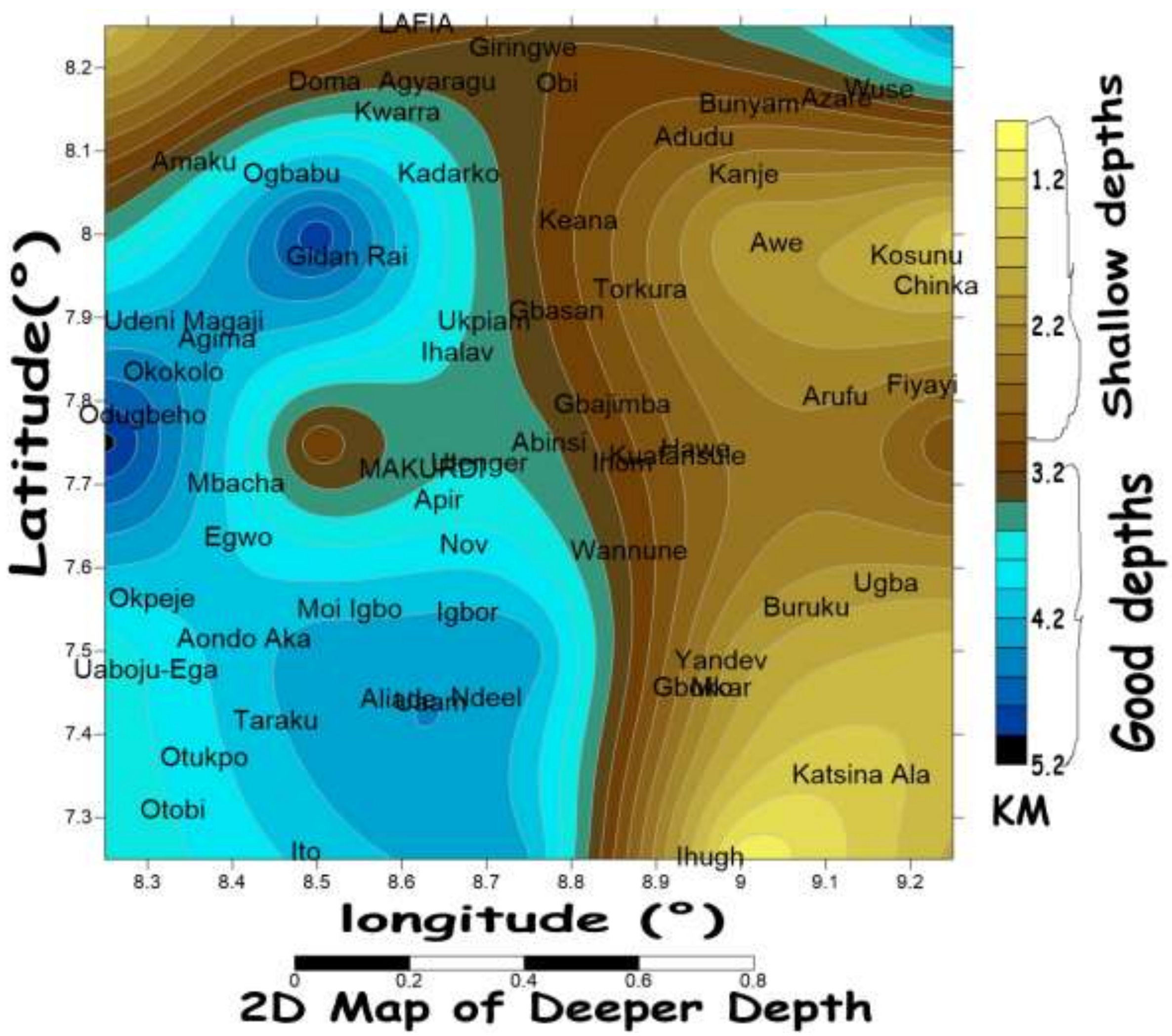

Fig 8a: 2D contour map of the depth of deep magnetic sources

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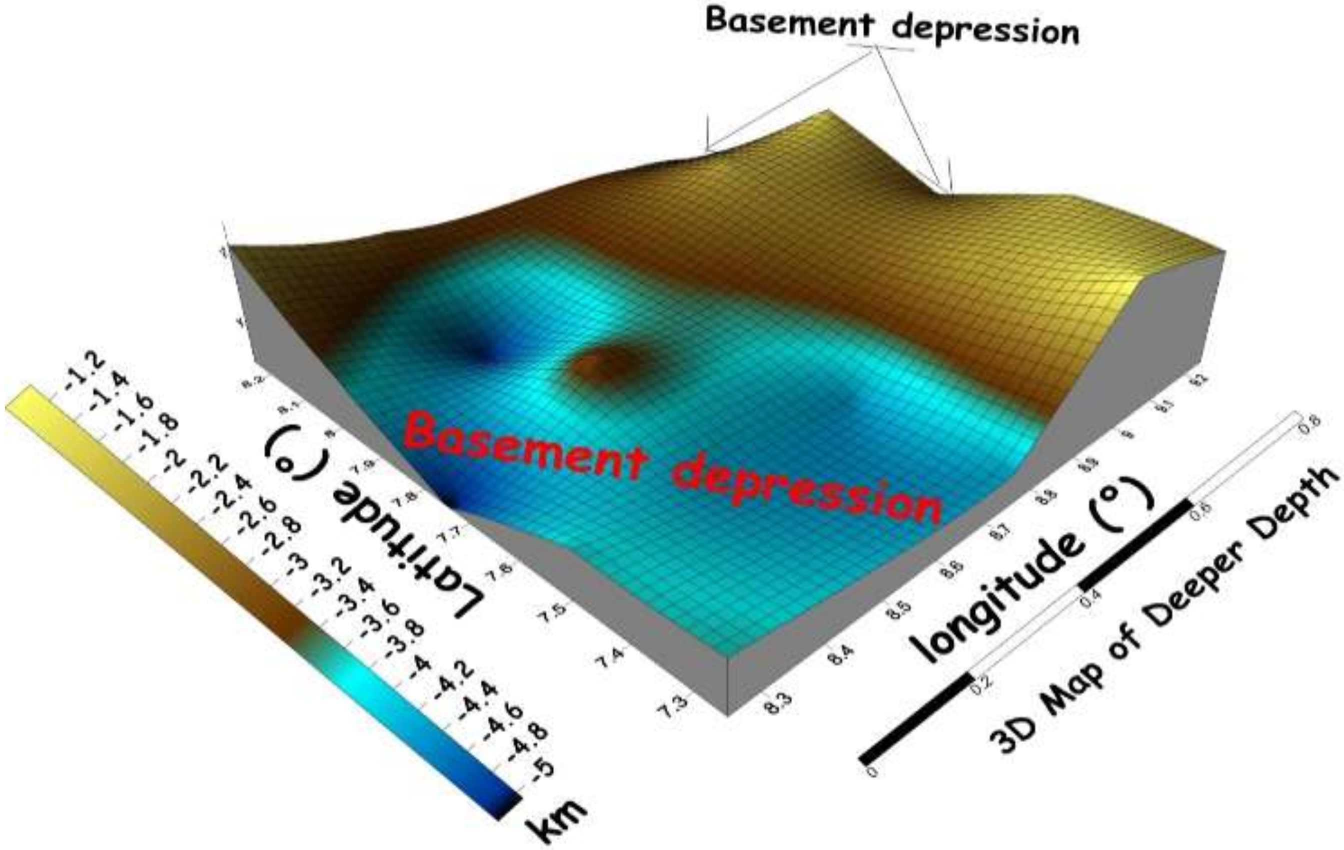

Fig 8b: 3D contour map of the depth of deep magnetic sources

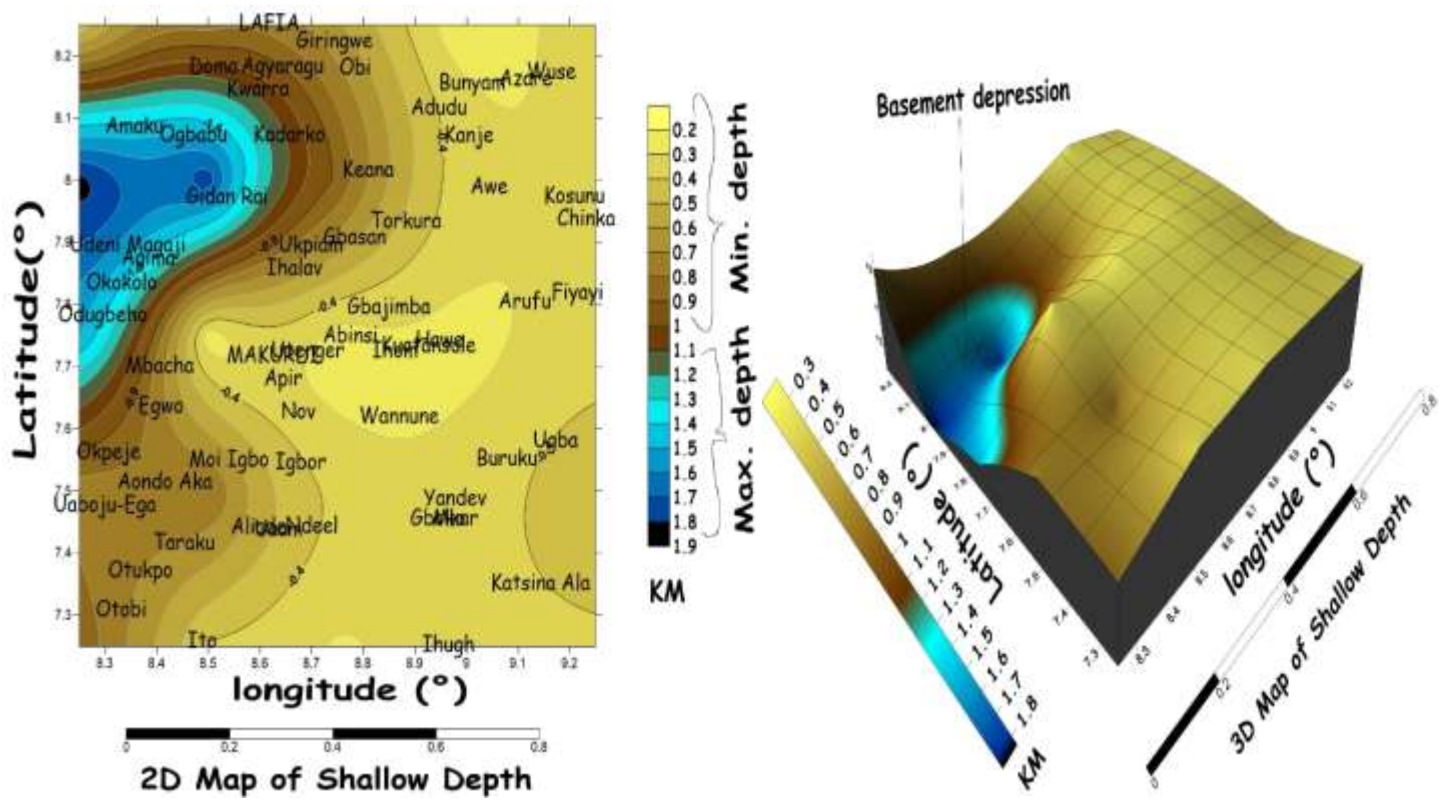

Fig 9a and 9b: 2D &3D contour map of the depth of shallow magnetic sources

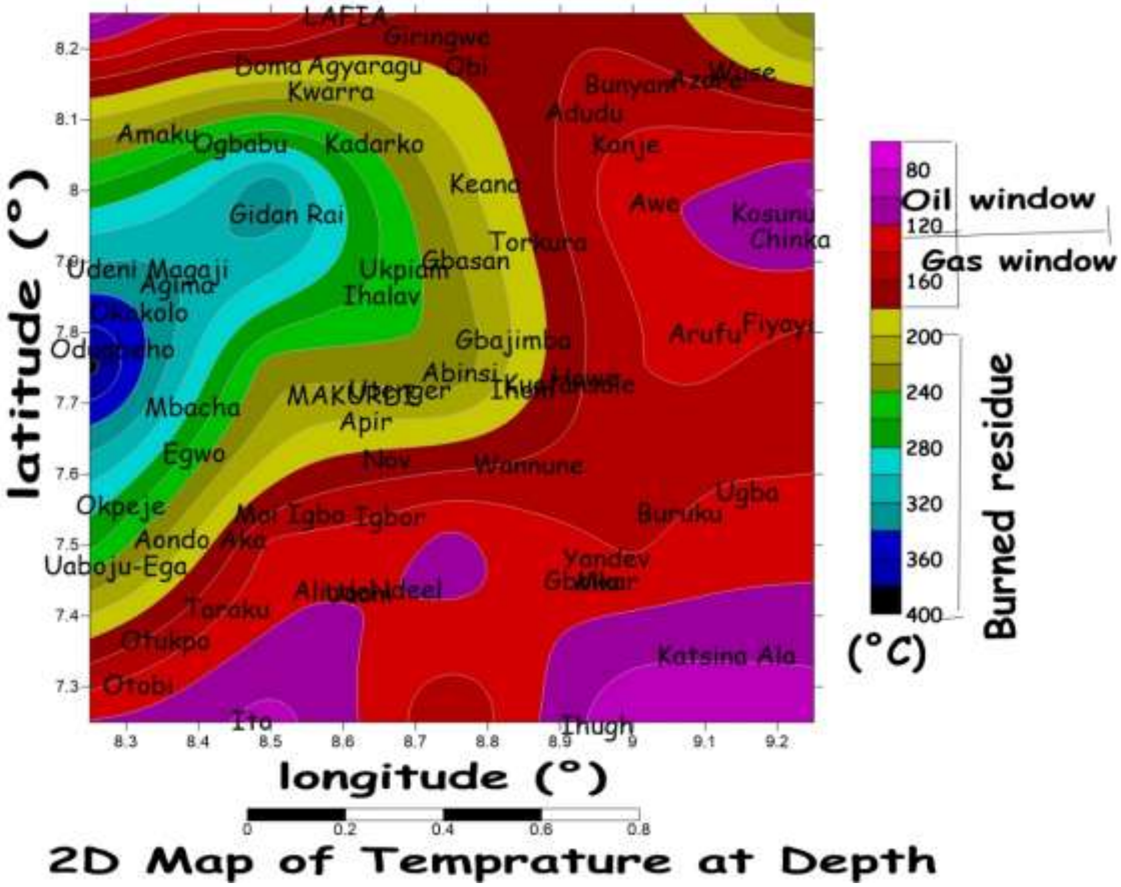

Fig 10: 2D contour map of the distribution of temperature across the study area

Discussions

The visual inspection of the geology, total horizontal gradient (THG) and first vertical derivative maps of the area shows abundant structures of NE-SW and a cross-cutting NW-SE structure, suggesting a favourable structural system that may have enabled migration and entrapment of hydrocarbon within the area. A good correlation was noticed from the depth estimation methods of (3D Euler, SPI and spectral analysis) employed. The three methods obtained maximum depths of 4.74 km, 6 km and 5.09 km and minimum depths of 0.61 km, 0.12 km and 0.67 km. The depth results of the our study, compares favorably alongside depth results estimated by previous researchers who have worked within the Central Benue Trough Nigeria (Nwosu and Onuba, 2013; Opara et al., 2018; Oguadinma and Aku, 2019; Onyishi and Ugwu, 2019; Okwesili et al., 2020; Abdusalam et al., 2022; Omenikolo et al., 2022; Ugwuoke and chinwuko, 2023; Ekwok *et al*., 2024). The maximum depths of 4.74 km, 6 km and average sedimentary thickness of 3.15 km obtained from spectral analysis showed sufficient depth for maturation of hydrocarbon. The temperature at depth model for the oil and gas window and geology map (Fig. 2) position the corresponding areas of Otobi, Otukpo, Taraku, Nov, Moi Igbo, Igbor, Aliade, Ndeel, Ito, Wannune, Obi, parts of Keana - Torkura, Giringwe, Azare and Wuse as potential hydrocarbon areas for further hydrocarbon studies due to their favourable depth to sedimentary thickness and temperature. These potential hydrocarbon areas mentioned correspond with geologic formations of Awgu, Asu River and Eze Aku Groups (rocks of shale, limestone and sandstone) which are said to be the most prospective formations with potential to generate oil and gas in the Central Benue Trough (Nwachukwu, 1985; Obaje and Hamza, 2000; Akande et al., 2012; Adedosu et al., 2015; Musa et al., 2022; Obaje et al., 2022). Also, Nwachukwu (1985) in his early studies stated the Middle Benue Trough is considered the most prospective Trough for hydrocarbon within the Benue Trough because of its moderate depths to mature zones of (2-4 km). This depth also agrees with the depths from our study for hydrocarbon potential areas. While areas like Gidan Rai, Okokolo, Udani Magai, Agima, Odugbeho Mbacha,

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Egwo, Makurdi, Abinsi, Apir, Okpeje Uaboju-Egu, Aondo-Aka, Ihalav, Ukpiam, Gbajimba ,Gbasan, Kakarko, Amaku, Ogbabu,Kwara and Doma Ayaragu met good depths but are posed with a high temperature history which is capable of overcooking the source rocks and expelling the oil and gas accumulated to burned residues. This is because the maturation of sedimentary organic matter into hydrocarbons and its hydrocarbon conversion is basically controlled by the temperature history of sedimentary basins. Potential areas for detailed hydrocarbon investigations are listed in Table 2 below.

Table 2: Potential further hydrocarbon study areas

Blocks	Longitude (°)	Latitude (°)	Depth (km)	Temp. at depth (°C)	Possible Window	Locations	Geologic formation	lithology
3	8°30′- 9°	8°- 8°30′	3.04	125.49	Oil	Obi & Giringwe	Eze- Aku Group	Sandstone
4	8°45′- 9°15′	8°- 8°30′	3.47	166.46	Gas	Azare &Wuse	Agwu Formation	Shale & limestone
15	9°- 9°30′	7°30′- 8°	3.00	154.11	Gas	Parts of Wannune	Eze- Aku Group	Sandstone
17	8°15′- 8°45′	7°15′- 7°45′	4.33	135.64	Gas	Nov, Wannune, Moi -Igbo, Igbor, Taraku, Aliade, Ndeel & Otukpo	Eze- Aku Group, Agwu Formation & Asu-River Group	Shale, Sandstone & limestone
18	8°30′- 9°	7°15′- 7°45′	4.35	111.91	Oil	Nov, Wannune, Moi- Igbo, Igbor, Taraku, Aliade, Ndeel & Otukpo	Eze- Aku Group, Agwu Formation & Asu-River Group	Shale, Sandstone & limestone
21	8°- 8°30′	7°- 7°30′	3.61	118.55	Oil	Parts of Taraku, Aliade, Parts of Ndeel, Moi- Igbo & Igbor	Eze- Aku Group, Agwu Formation & Asu-River Group	Shale, Sandstone & limestone
22	8°15′- 8°45′	7°- 7°30′	4.06	92.33	Oil	Igbor, Ndeel & Parts of Aliade	Eze- Aku Group, Agwu Formation	Shale, Sandstone & limestone

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							& Asu-River Group	
23	8°30′- 9°	7°-7°30′	4.23	160.03	Gas	Otobi, Ito, Taraku, Otukpo, Aliade & Moi- Igbo	Eze- Aku Group, Agwu Formation & Asu-River Group	Shale, Sandstone & limestone

CONCLUSION AND RECOMMENDATIONS

The aeromagnetic data proved very useful in estimating the depth to sedimentary thickness and hydrocarbon potential of the area. The presence of NE-SW and NW-SE fault systems in the total horizontal gradient (THG) and first vertical derivative maps shows that the area is tectonically active. It is also evident from the results that the areas which reflect the structural patterns of NE-SW and NW-SE trends from the total horizontal gradient (THG) map correlate well with those of the first vertical derivative (FVD) of the area. These NE-SW and NW-SE structures will serve as conduits and pathways for hydrocarbon migration and entrapment in the area. The results of the three estimation methods employed gave sufficient and moderate depths of 2-6 km required for hydrocarbon formation. More so, adopting the temperature at depth evaluation, in estimating the temperature of the area, provided us with assistance in understanding the temperature history of the area. The recent discovery and exploration of a significant quantity of hydrocarbon in Obi and Keana environs of Nasarawa State of the Central Benue Trough, by the Nigeria National Petroleum Corporation (NNPC), which falls within the study area, is strong support for its occurrence in the Central Benue Trough (CBT). Therefore, we recommend that the Federal Government draw the attention of the Nigeria National Petroleum Corporation (NNPC) to the prospective areas favourable for hydrocarbon accumulations so that further seismic studies will be carried out to evaluate and sufficiently model the hydrocarbon potential of the areas.

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