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RESEARCH ARTICLE

AREAL AND DEPTH ESTIMATION OF SUBSURFACE ANOMALOUS STRUCTURES OF OYANDEGA AND ENVIRONS, PART OF THE ANAMBRA BASIN USING 2D MODELLING OF MAGNETIC DATA

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ABSTRACT

This study employed spectral analysis, Source Parameter Imaging (SPI), and Euler deconvulation techniques on two aeoromagnetic data sheets (Illushi 286 and Nsukka 287) to assess the depth to sub-surface structures and estimate the depth to magnetic sources at the transition region of Oyandega Area, Ibaji local government of Kogi state, part of lower Benue Trough (Anambra Basin). SPI techniques show minimum to maximum depth to anomalous source as 25.765m to 2533.293m. Euler deconvolution for contact body (Structural Index=1), indicate depth ranges from -473.70m to 751.11m, for extrusive body like thin layer, dyke (Structural Index =2) ranges from -619.74 to 1122.25m and for sphere (Structural Index =3), the depth to magnetic source obtained ranges from -800m to 1494.12m. From the spectral analysis, depth to the first layer (D1) in the study area varies from 1.3100 km to 5.6700 km with an average depth of 3.4900 km while second layer depth (D2) varies from 0.15300 km to 1.3200 km with the average depth of 0.7365 km. This result therefore indicates that the average basement depth of the study area as deduced from power spectrum inversion is 2.11325 km. The results favour the accumulation of petroleum around Agnosi, Annegbette, ijankuta and Uhro of the study area. The shallow magnetic sources around Nwajala, Adani, and Ogbo-uvuru are believed to be the resultant of basement rocks that were tectonically uplifted into the sedimentary overburden.

KEYWORDS

Aeromagnetic data; Anambra Basin; Spectral analysis; Subsurface anomalous structures.

1. INTRODUCTION

Geological structures such as folds and faults can tell us great deal about the history of the earth and are critical for the search of resources that include water, petroleum and minerals. Secondary structures are product of deformation that is the movement of parts of crust relative to one another. The buoyancy of any country's economy depends on it natural resources and those resource were mostly hosted by these subsurface structures, finding those hiding subsurface structures using geophysical method will ease the exploration and exploitation of geo-resources. Aeromagnetic survey is a passive method in the sense that no artificial energy is required to acquire data. This method was used because it covers large area of land and offers distinct parameter contrast, i.e magnetic susceptibility, which allows it to detect metalliferous deposits. This potential method has found wide applications in basin analysis schemes directed toward the exploration and exploitation of buried subsurface structures that hold resources, such as oil, gas, and solid minerals in several geologic provinces in the world.

The Anambra Basin is considered one of Nigeria's frontier basins. the Anambra Basin were classified as a frontier due to the difficulties in interpreting its stratigraphy and structure, primarily caused by the lack of subsurface data (Dim et al., 2019). Consequently, based on the geological context and rock characteristics, magnetic data can be useful for studying and characterizing the subsurface geological structure of the Basin.

Several researchers have utilized magnetic field methods to determine structural depths and sediment thicknesses in the Lower Benue Trough (Okereke et al., 1990; Nwogbo et al., 1991; Nur et al., 1994, 2003; Nur, 2002; Abbass and Mallam, 2013; Obiora et al., 2015, 2016; Oha et al., 2016; Obasi et al., 2017; Okpoli, 2019). Their findings estimate that sediment and structural lineament thicknesses in the Anambra Basin range from a minimum of 50 meters to a maximum of approximately 10 kilometers. The sedimentary section of the Anambra Basin consists of rocks with low magnetic susceptibility, which overlies deeper rocks with high magnetic susceptibility, thereby supporting the use of magnetic data in our study. This is supported by previous works based on aeromagnetic data interpretations that have identified high-magnetic-susceptibility basement and basic intrusive bodies into low magnetic susceptibility sedimentary cover as the two main sources of magnetic anomalies in the study area (Ofoegbu, 1984; Abbass and Mallam, 2013; Obiora et al., 2015; Okpoli, 2019).

In several studies, methods such as second vertical derivative, tilt-angle derivative, analytical signal (AS), standard Euler deconvolution, source parameter imaging, and forward and inverse modeling have been employed to interpret sediment thickness above the basement from magnetic maps or profiles. However, sometimes the anomalies' effects

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were not fully accounted for regarding basement topography, as more focus was given to intrusive bodies within the sediments. This study makes a significant effort to delineate the structural extent that could support structural traps in one of the major Cretaceous depocenters at Oyandega (i.e., the Anambra Basin) in the southern Benue Trough, southeast Nigeria. It uses aeromagnetic data analysis and interpretation to determine if sufficient sediment thickness exists for hydrocarbon generation, maturation, and expulsion. The workflow includes reduction-to-pole (RTP) transformation, regional-residual separation, trend analysis, and automatic basement depth estimations using analytical signal analysis (ASA) to properly reveal attributes of the magnetic basement. While aeromagnetic data alone cannot directly identify hydrocarbons, our research findings offer valuable insights into the basin's structure and its potential for hydrocarbon exploration. Our results reveal a varied terrain, with sediment layers overlaying a magnetic basement, reaching thicknesses of up to 8 km in certain regions. This substantial depth range suggests favorable conditions for the maturation and expulsion of hydrocarbon source-facies, aligning with previous studies (Selley, 1998; Obaje et al., 2004; Abubakar, 2014; Oluwajana and Ehinola, 2016). Similar to other basins within the Benue Trough, sediment thickness is likely to play a pivotal role in regulating hydrocarbon generation and maturation in our study area.

The concept underlying magnetic prospecting is the existence of a magnetic dipole or monopoles within the rocks constituting the earth (Umeanoh, 2015). Magnetic force expression, F(Tesla) between two magnetic monopoles of strength P1 and P2 is given by

$$F_m = \frac{1}{\mu}\frac{P_1 P_2}{r^2} \quad (1)$$

where P1 and P2 are strengths of magnetic monopoles, r denotes the distance between the poles, and μ symbolizes the magnetic permeability (4πx10-7)

The research covers parts of Oyandega and environs, in the Kogi sector of the Anambra Basin (Figure 1). The study area is located between Latitudes 06°30'00"N to 07°00'00"N of the equator, and Longitudes 06°30'00"E to 07°30'00"E of the Greenwich meridian. It is located in eastern part of Kogi state (Figure 1) and has an extension of 6,174km² covering sheets 286 and 287 of the aeromagnetic sheets of Nigeria.

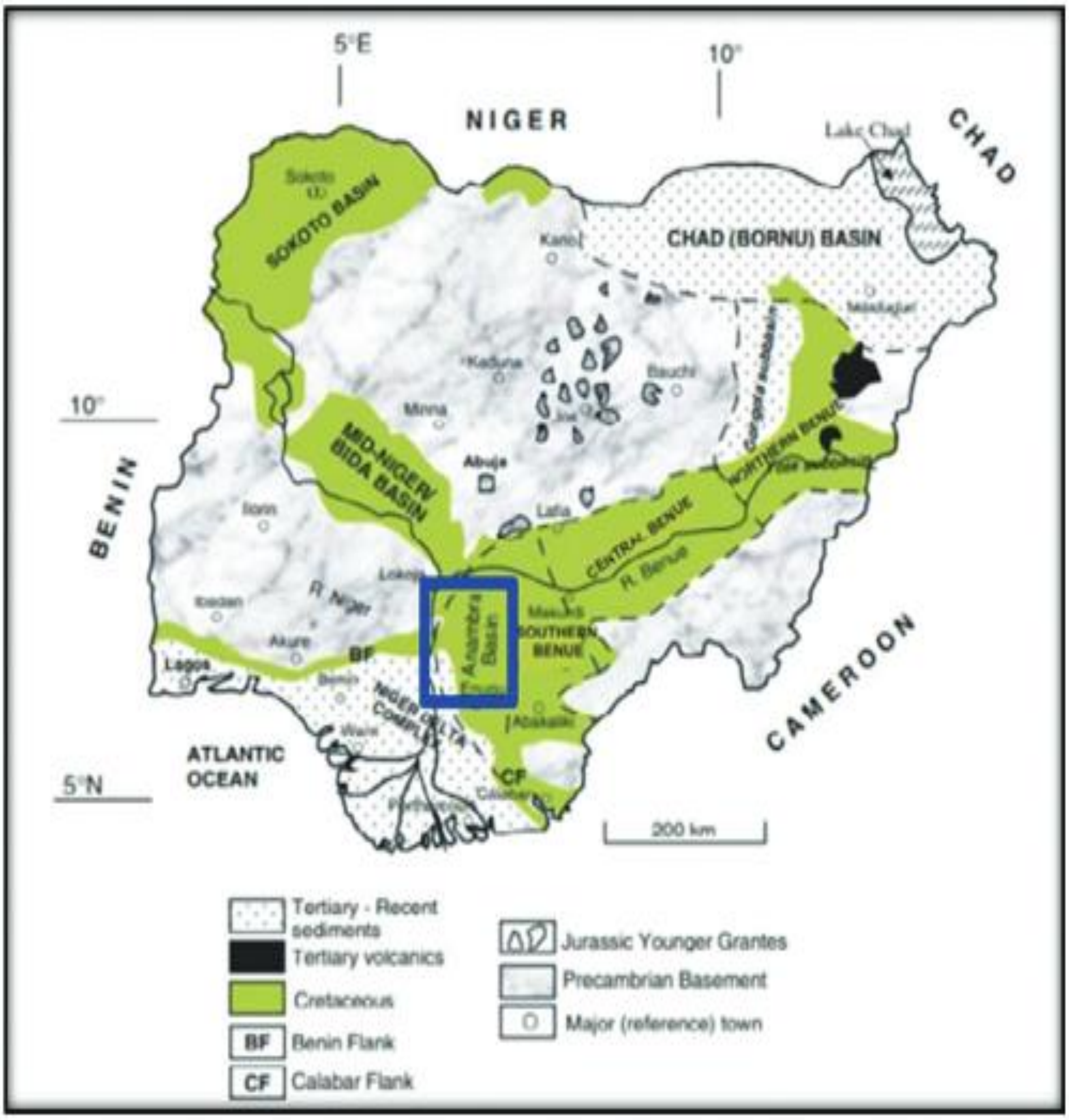

Figure 1: Geological Map of Nigeria showing the study area (Obaje et al., 2009)

This research work was carried out using magnetic method. It is limited to the analysis and structural investigation of the satellite gravity and aeromagnetic data of the study area.

2. Geology Of Study Area

The study area is situated at Lower part of the Benue Trough of Nigeria (Anambra Basin). The inland basin of Nigeria formed during separation of African and South American plate in late Jurassic. Geologically, the northeastern part of the study area was covered by Nsukka formation, Ajali sandstone trend from from central to the north and northeastern part of the study area, there's dominant exposure of alluvium across the southern part of the study area, then shale-limestone and mudstone predominantly cover the northwestern and southwestern part of the study area. Figure 2 presents the geological map of the study area

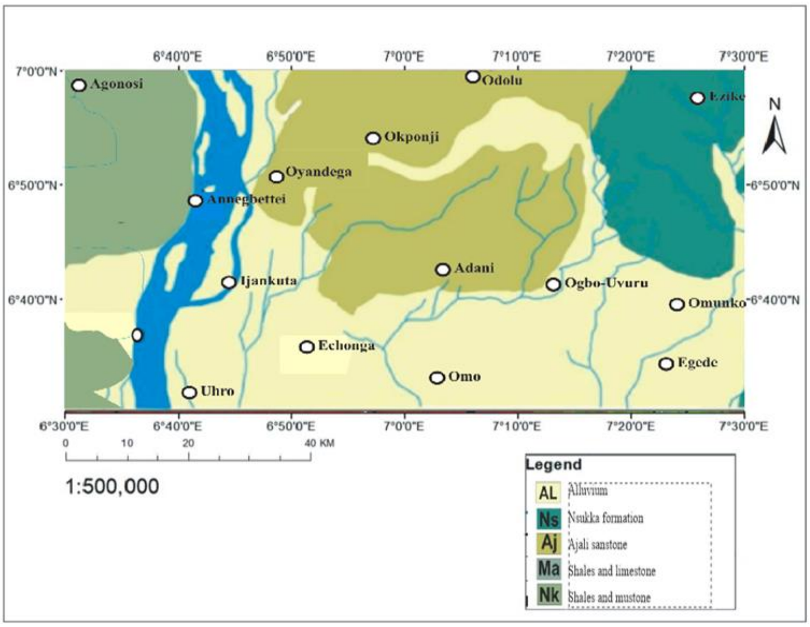

Figure 2: Geological map of the study area

The Anambra Basin is situated southwest of the Benue Trough, bordered by the Precambrian basement complex rocks to the west, the Abakaliki Anticlinorium to the east, and the northern portion of the Niger Delta petroleum province to the south (see Figure 1). The tectonic history of southeastern Nigeria's sedimentary basins traces back to the Late Jurassic era when the African and South American plates began to separate, instigated by the Y-shaped, RRR triple-junctionridge system (Burke et al., 1971; Benkhelil, 1982).

Sediment deposition within the Anambra Basin commenced during the Campanian period with a brief marine transgression that laid down the Nkporo Group formations (Owelli Formation, Nkporo Formation, Enugu Formation). These formations consist of carbonaceous shales and deltaic sandstone members (Nwajide and Reijers, 1996; Odunze and Obi, 2013). Subsequently, during the Late Campanian to Early Maastrichtian, the coal-be aring Mamu Formation was deposited, marking the onset of a regressive phase. This formation comprises alternating layers of sandstones, sandy shales, mudstones, and sub-bituminous coal seams (Akande et al., 2007). Overlying the Mamu Formation are the predominantly clay laminae of the Ajali Formation and the mid-to-late Maastrichtian age Nsukka Formation.

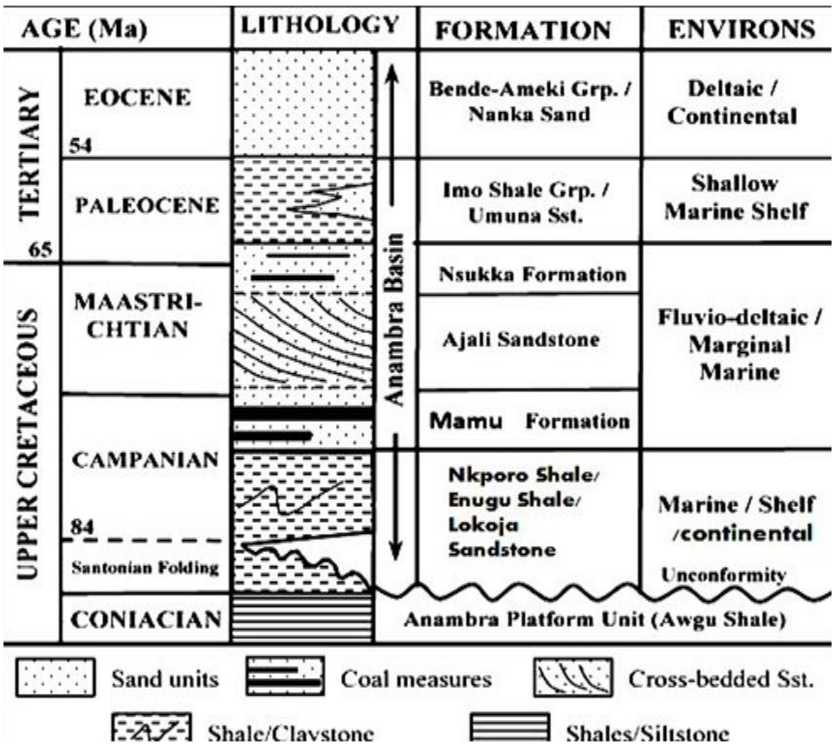

Figure 3: Stratigraphy of the Anambra Basin (after Nwajide and Reijers, 1996).

3. Materials And Methods

Two aeromagnetic data grids (Sheet 286 and 287) covering the study area were obtained from Nigeria Geological Survey Agency (NGSA) and merged into a single TMI grid. Oasis Montaj version 8.4 was used to analyze and develop the maps. The TMI sheets formed the basis for further application of enhancement filters needed for detail interpretation of the study area. TMI map was produced using computer software package Oasis Montaj. The software is an interactive computer program which places magnetic data according to their longitude and latitude bearing and gives a magnetic intensity map which is in colour aggregate.

The aeromagnetic sheet was divided into 32 cells in Microsoft Excel, with each cell covering a square area of 18.3 km by 18.3 km to explore depths up to approximately 6.0 km. Subsequently, each block was windowed into 20 min by 20 min segments.

Fast Fourier Transform (FFT) techniques were utilized in both Microsoft Excel and the Oasis Montaj program to convert the magnetic data into radial energy spectra for each block. The resulting average radial energy spectrum was then presented on a logarithmic scale of energy versus frequency.

The magnetic anomaly data, formatted in XYZ Geosoft format, underwent gridding using the minimum curvature method and the image tool of the Oasis Montaj software, generating a total magnetic intensity (TMI) grid for the study area at a grid size of 200. This grid size was chosen to prevent over or under sampling based on the data's sampling distance.

To separate the residual anomaly data from the regional magnetic field, a polynomial fitting method was applied to all grid values using Oasis Montaj 8.30 software. Subsequently, the residual anomaly data was interpolated using a minimum curvature gridding algorithm with a grid cell size of 250m.

The TMI grid for the study area was then reduced to the equator and upward continued by 1km using the MAGMAP tool of the Oasis Montaj software to mitigate the noisy effects of very shallow sources. The upward continued TMI grid, reduced to the equator, was divided into thirty-two equal spectral blocks using the utilities tool within the Grid and Image tools of the Oasis Montaj software. Potential maps underwent vertical derivatives (specifically First vertical derivatives) and were analyzed at the Center for exploration target to extract lineaments within the study area.

To investigate the depth to magnetic sources, three techniques were employed: Three Euler 3D maps were generated from the TMI for three different structural indices (1, 2, 3) as illustrated in Figure (7). The Source Parameter Imaging (SPI) depth map of the study area was produced. The SPI method calculates source parameters for gridded magnetic data, assuming either a 2D sloping contact or a 2D dipping thin-sheet model. It relies on the complex analytic signal and was developed to estimate magnetic depths (Thurston and Smith, 1997)

Spectral analysis involved using the discrete Fourier transform to analyze regularly spaced data, such as aeromagnetic data, to interpret the spectrum of the potential field. Graphs of the natural logarithms of the amplitude against frequency were plotted, and the gradient of the linear segments was computed to determine depths to the basement, following the equations of (Spector and Grant (1970):

$$M_1 = \frac{\Delta y(LogE)}{\Delta x(freq.)}$$

$$M_2 = \frac{\Delta y(LogE)}{\Delta x(freq.)}$$

$$D_1 = \frac{-M_1}{4\pi}$$

$$D_2 = \frac{-M_2}{4\pi}$$

Where M1 and M2 are the slopes of the first and second segments of the plots. The negative sign shows depth to the subsurface while D_1 (deep depth) and D_2(shallow depth) are the first and second depth segments, respectively.

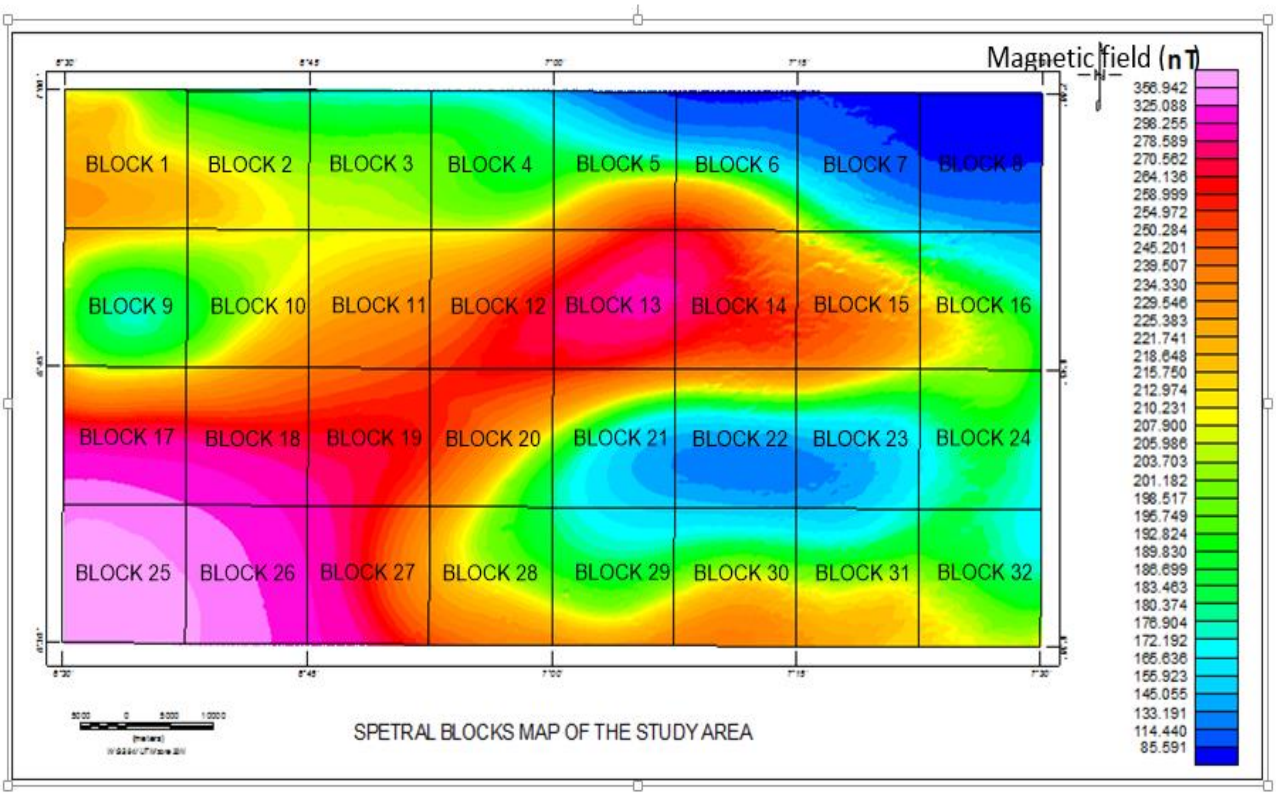

Figure 4: Spectral Block of the study area

4. Results And Discussion

4.1 Potential maps of the study area

Results from the regional/residual field are shown in Figures 4A-B. After filtering and removing the regional gradient of the study area still maintained the same linear trend and similar values all over the map. From the results derived regional field maps (Figure 4A), the structural trends observed to occur in the NNW – SSE direction. This NNW – SSE orientation occur dominantly in the polynomial surface. The regional field maps (Figure 4A) show intensity values ranging from 32749.579nT to 32882.510nT.

Figure 4B displays the residual magnetic intensity map of the study area. The fluctuations observed in the residual magnetic field signify the presence of diverse geological, magnetic, and chemical compositions of anomalous bodies. Regions exhibiting negative magnetic values are likely characterized by low magnetization, whereas those with positive residual anomalous areas suggest high magnetization. Consequently, areas showing positive residual values indicate the presence of shallow to near-surface magnetized bodies. Conversely, locations such as Uhro, Agonosi, and Aliko, with low residual values, are presumed to be underlain by deep-seated magnetized bodies.

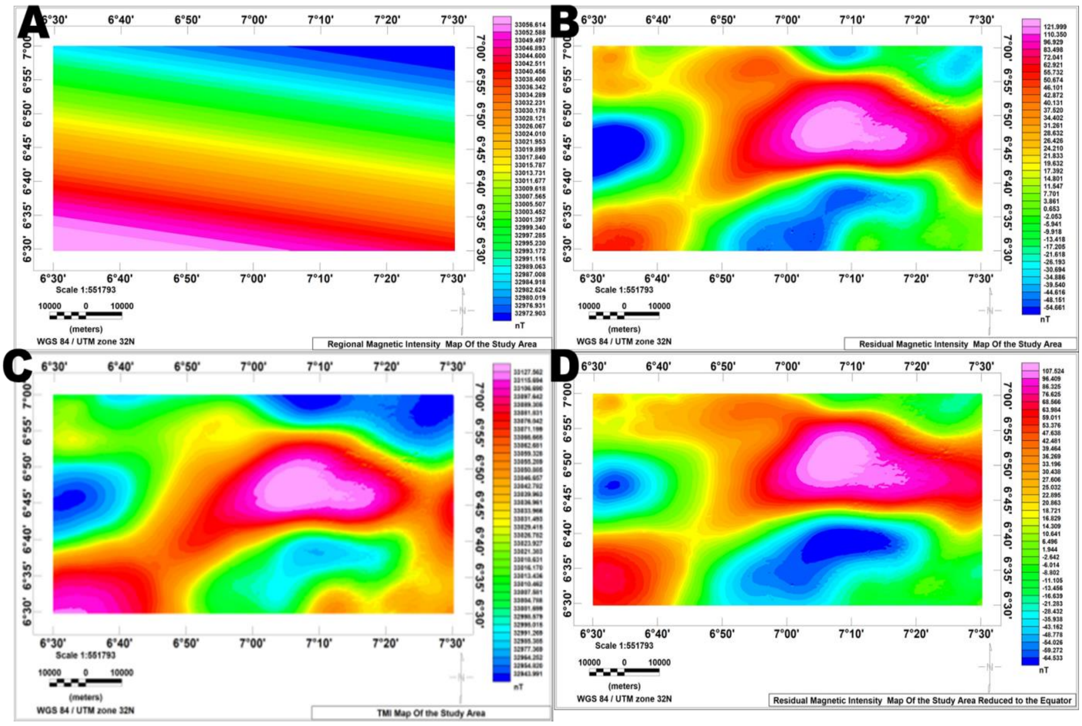

Figure 4: (A) Regional Map (B) Residual Map (C) TMI Map (D) TMI RTE Maps of the study area

In Figure 4C, the magnetic intensity across the study area spans from 32943.735 to 33126.239 nanoteslas (nT). Both high (depicted in pink) and low (depicted in blue) magnetic signatures are observed within the area. This variation in magnetic intensity may stem from factors such as the degree of strike, differences in depth, variations in magnetic susceptibility, discrepancies in lithology, as well as variations in dip and plunge angles.

High magnetic signature zone ranging from about 33088.721nT to 33126.239nT, coloured pink are observed to occur more prominently at the Northern part of the areas and areas that lie within Longitudes 7°00E and 7°20E and Latitudes 6°40N and 6°40N. Geologically, this high anomalous signature is seen to occur in areas around Adani and Ogbo-Uvuru area. Low magnetic signature values ranging from 7880.7nT–8005.7nT coloured blue occur prominently at the South-West and South-East of sheet 286.

Figure 4D, after reducing the UC TMI map to magnetic Equator, we obtained magnetic intensity for the study area ranging from 85.591nT to 356.942nT. We used this filtered TMI grid for our quantitative interpretation of depths to magnetic anomalies.

4.2 Enhancement techniques

4.2.1 First Vertical Derivatives and Center for Exploration Target

The first vertical derivative (FVD) effectively highlights high-frequency features, particularly in regions where they might be obscured by large amplitude, low frequency anomalies. Throughout the VD map, associations of both positive and negative values were noted. Among the most notable occurrences are those observed in the northern section of the map, specifically around the Annegbette and Ijankuta Areas. These positive and negative values correspond closely to the Shale-Limestone rocks of the Nsukka formation, as depicted in the geological map of the study area. The Lineament map from the FVD map show the structural lineaments are dominantly trending NW-SE, SW-NE and E-W direction.

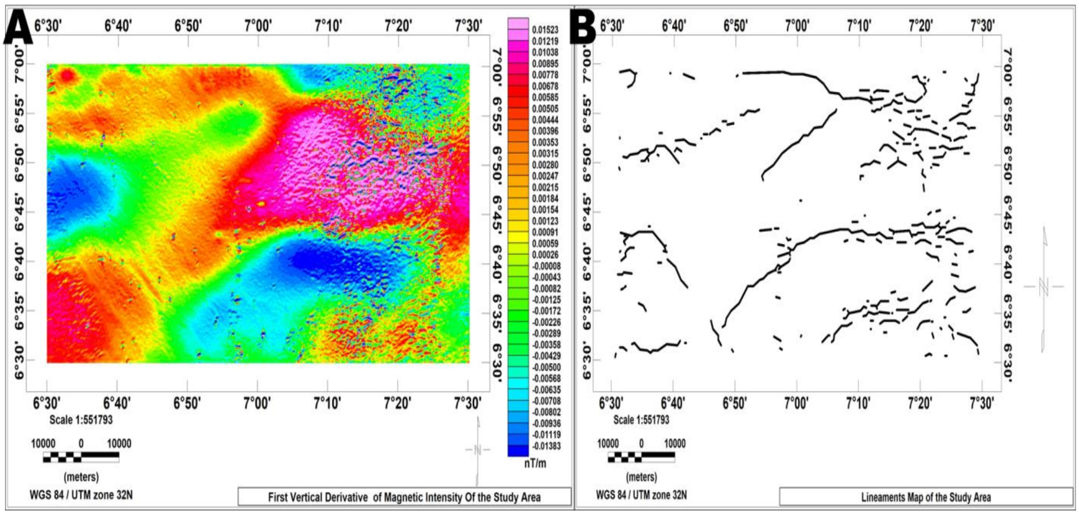

Figure 5: (A) FVD map of the study area (B) Lineament Map of the study area

4.3 Depth estimation

4.3.1 Sources parameter imaging (SPI)

The depth to the basement, estimated using Source Parameter Imaging (SPI) and illustrated in Figure 6, varies across the range of 32.571 meters (0.032571 kilometers), denoted by a blue color, to a maximum depth of

2533.293 meters (2.533293 kilometers), indicated by a deep pink color. Within the map, the Janakuta area, situated between latitude 605''N to 604''N and longitude 603''E to 604''E in the study area, exhibits a notably high SPI depth exceeding 2533 m.

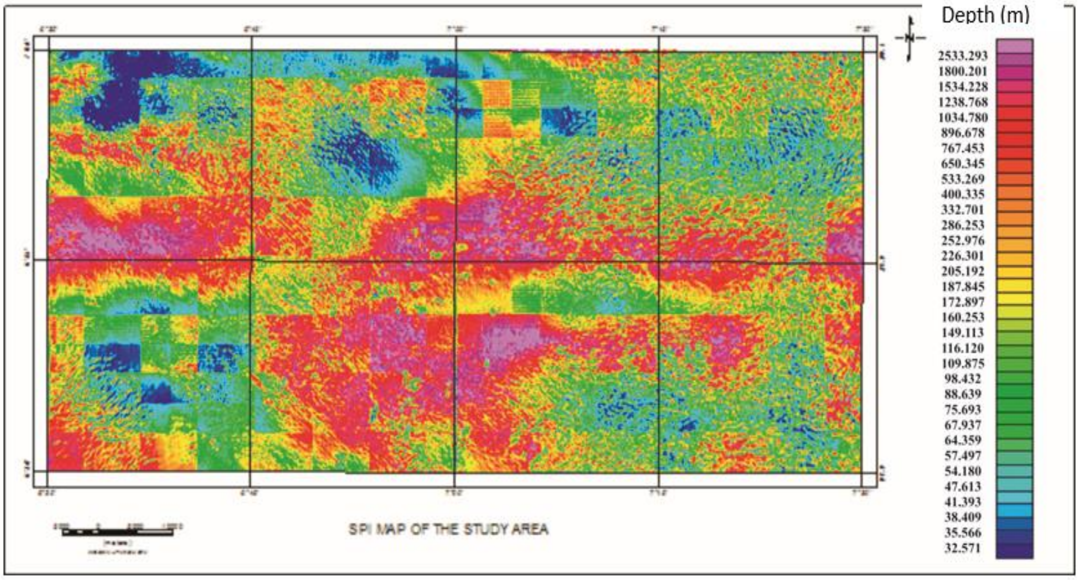

Figure 6: SPI Depth Map of the Study Area.

4.3.2 Euler Depth Estimation

Three Euler 3D maps were created from the Total Magnetic Intensity (TMI) data for three different structural indices (1, 2, 3), as depicted in Figures 7A, 7B, and 7C. Regions within the maps lacking magnetic signatures or color represent areas where no Euler solution for depth was obtained with the respective structural index used. In these maps, deep lying magnetic bodies are represented by the color blue, while shallow magnetic bodies are depicted in pink.

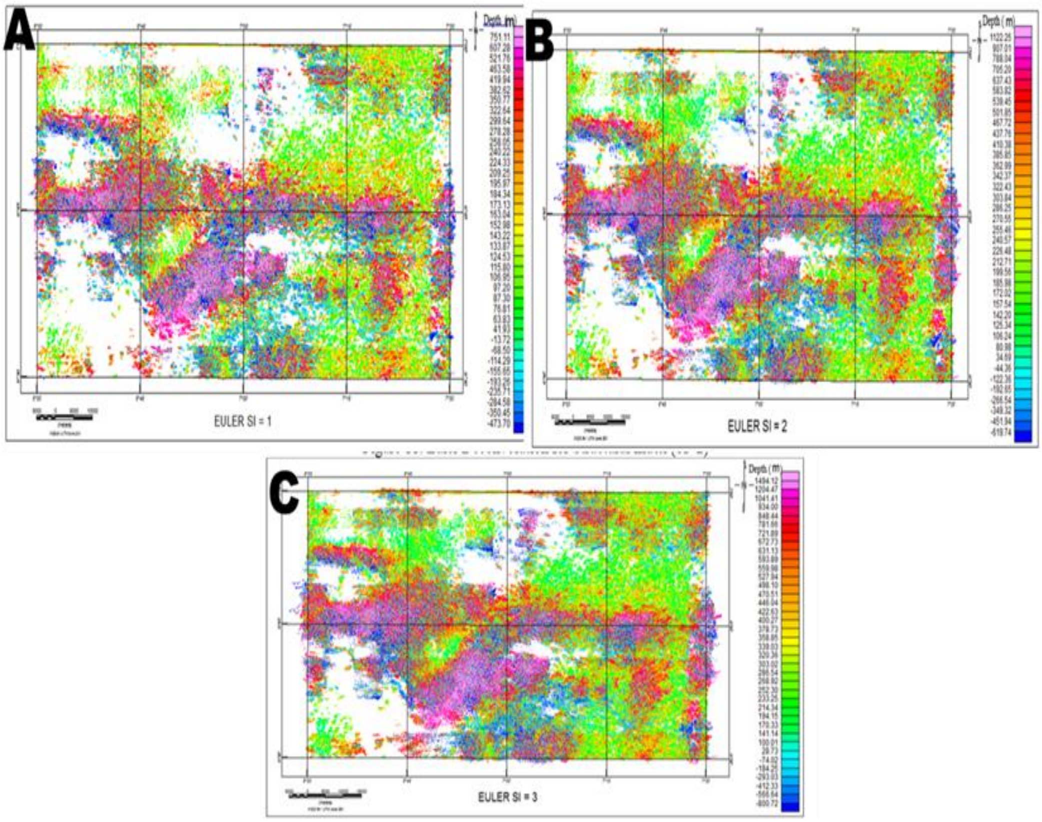

Figure 7: (A) Euler Map for SI 1 (B) Euler Map for SI 2 (c) Euler Map for SI 3

For the Euler solution with dyke and sills as the source (structural index = 1), depths were found to range from -473.70 meters to 751.11 meters. Clustering solutions were observed throughout the map (Figure 7A). However, maximum depths, ranging from 607.28 meters to 751.11 meters, were noted in areas surrounding Ogbo-uvuru, which are underlain by Ajali sandstone, shale-sandy, and the Nsukka formation.

In the case of the Euler solution for horizontal cylinders and pipes as the source (structural index = 2), depths ranged from -619.74 meters to 1122.25 meters. Evenly spread clustered solutions were observed across the entire map (Figure 7B). The maximum depth, exceeding 1122 meters, was identified around two areas trending in a NE-SW direction near Ijanaku. Lastly, the Euler solution for structural index 3 (spheres) revealed a concentration of clustered solutions throughout the study area. Depths of the interpreted cluster of solutions ranged from below -800 meters to above 1494 meters, as depicted in Figure 7C.

4.3.3 Spectral Analysis for depth estimation

In the study area, the depth to the first layer (D1) ranges from 1.3100 kilometers to 5.6100 kilometers, with an average depth of 3.4600 kilometers. The second layer depth (D2) varies from 0.1530 kilometers to 1.3200 kilometers, with an average depth of 0.7365 kilometers, as depicted in Table 1.

Table 1: Spectral Estimates to the Magnetic Source Depth Layers for Illushi Sheets 286 and Nsukka Sheets 287 of the study area

S/NO	BLOCK	LONG(km)	LAT(km)	D_1 (km)	D_2(km)
1	1	6.567476	6.932418	3.24	0.830
2	2	6.689572	6.932418	3.74	0.801
3	3	6.809780	6.932418	5.45	1.090
4	4	6.934590	6.932418	2.14	1.320
5	5	7.064826	6.932418	1.43	0.339
6	6	7.171999	6.932418	1.83	1.030
7	7	7.303592	6.932418	4.44	0.826
8	8	7.427045	6.932418	4.31	1.180
9	9	6.558804	6.809603	5.43	1.090
10	10	6.690397	6.809603	1.52	0.178
11	11	6.811137	6.809603	1.47	0.427
12	12	6.923737	6.809603	3.20	0.843
13	13	7.060756	6.809603	5.02	0.979
14	14	7.185566	6.809603	2.36	0.549
15	15	7.300879	6.809603	5.12	0.386
16	16	7.425689	6.809603	3.84	0.153
17	17	6.553378	6.686787	2.38	0.705
18	18	6.684971	6.686787	1.31	0.245
19	19	6.805710	6.686787	1.38	0.186
20	20	6.927807	6.686787	1.23	0.362
21	21	7.062113	6.686787	3.62	0.969
22	22	7.186922	6.686787	4.80	0.921
23	23	7.307662	6.686787	3.57	0.917
24	24	7.432472	6.686787	2.97	0.552
25	25	6.553378	6.566701	5.61	1.000
26	26	6.686327	6.566701	3.36	1.110
27	27	6.805710	6.566701	2.74	0.975
28	28	6.926450	6.566701	2.50	0.758
29	29	7.058043	6.566701	2.06	0.881
30	30	7.186922	6.566701	5.25	0.867
31	31	7.309019	6.566701	1.78	0.747
32	32	7.433828	6.566701	2.34	1.050

The average basement depth derived from power spectrum inversion in the study area is approximately 2.1133 kilometers. Shallow magnetic sources are thought to originate from basement rocks that underwent tectonic uplift into the sedimentary overburden. On the other hand, deeper basement depths may be linked to lateral variations in basement susceptibilities and structural deformations within the basement, such as faults and fractures.

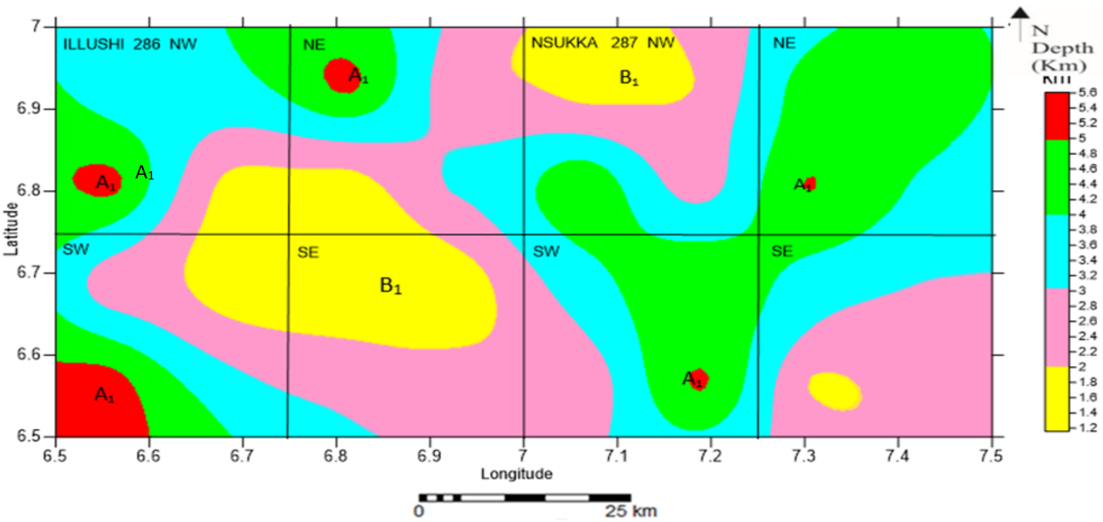

Figure 8: Map of Magnetic Depths from Deeper Sources (D_1) of the study area

The depths to the shallower magnetic sources and the magnetic basement depths were observed to increase from the western part of the study area towards the eastern parts, where they decrease notably, as depicted in the magnetic contour map. This suggests that basement outcrops may be visible around the Agonosi, Opkongi, and Echonja areas, where the basement depth is low, while sediment thicknesses are greater in the Uhro, Annegbette, and Ogbo Uvuru areas along latitudes 60.5''N to 60.9''N and longitudes 60.5''E to 60.9''E.

The lower Benue trough, underlain by thick sedimentary deposits in the Basement complex, has led to the formation of various geological features, as depicted in Figures 8 and 9. The deeper source D1 contains geological features labeled A1, with depths ranging from 5.0 km to about 5.6 km. Similarly, along the southeast of the maps, feature B1 contains similar geological characteristics.

The shallow depths observed in the study area are a result of uplift from the deeper source rocks, which are characterized by sandstone, shale, and mudrock. The depth of the study area is approximately 2.11325 km, with depths ranging from 1.2 km to 2.0 km and 0.2 km to 0.5 km, respectively.

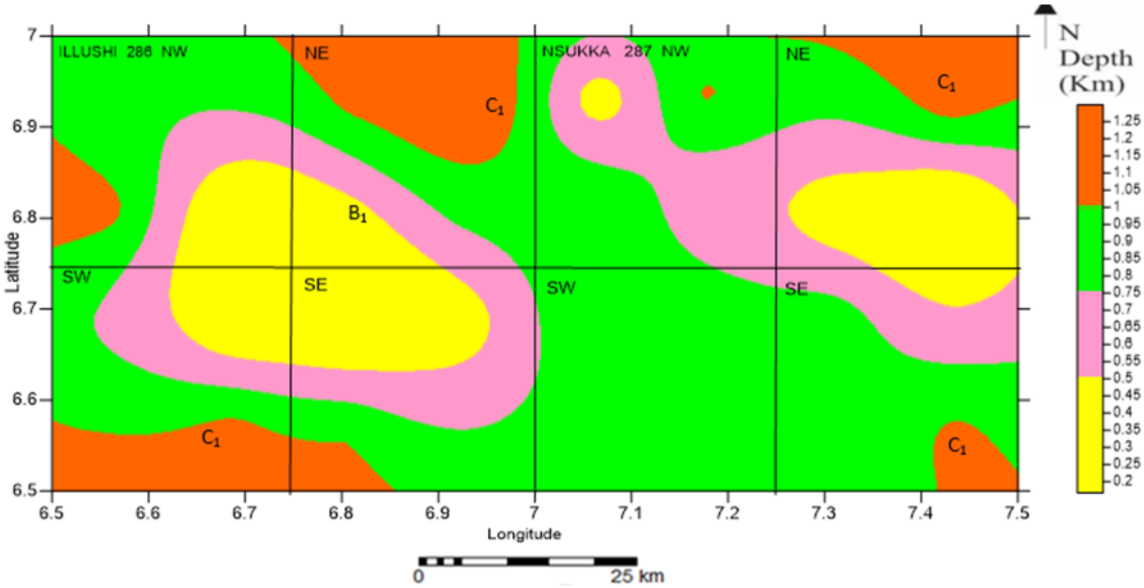

Figure 9: Map of Magnetic Depths from Shallow Sources (D_2) of the Study Area

5. Conclusion

Investigation of subsurface structures of the study area was done using magnetic method. The interpretation was done qualitatively and quantitatively using the Spectral analysis, standard Euler deconvolution, and source parameter imaging (SPI). The depth estimated using the three methods are within the same range. Three methods adopted for depth estimation agrees with Wright et al., (2017) which reported that the minimum thickness of the sediments required for the commencement of oil formation from marine organic remains would be 2.3 km deep. The SPI depth results range from a minimum of 25.765 meters (indicating shallow magnetic bodies) to a maximum of 2533.293 meters (representing deep lying magnetic bodies). The study area exhibits thick sedimentary layers, suggesting favorable conditions for hydrocarbon accumulation and mineral deposits. Additionally, results from spectral analysis indicate that the average basement depth in the study area, as deduced from power spectrum inversion, is approximately 2.11325 kilometers, further supporting the potential for petroleum accumulation. In areas such as Nwajala, Adani, and Ogbouvuru, shallow magnetic sources are thought to result from basement rocks that were tectonically uplifted into the sedimentary overburden. Conversely, deeper basement depths may be attributed to lateral variations in basement susceptibilities and intra-basement structural deformations such as faults and fractures.

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