



# Existence of subsurface structures from aeromagnetic data interpretation of the crustal architecture around Ibi, Middle Benue, Nigeria

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## Abstract

Aeromagnetic data acquired over Ibi area within the Middle Benue Trough, Nigeria, has been interpreted to successfully mapped regional structural features that are favorable for economic mineral deposits. The 3D Euler deconvolution technique provided estimated depth values for the regional structural features while the deduced source parameter imaging gave depth estimates to magnetic basement of the study area. The latter map shows two major sub-basins with depth values between 2700 m and 3300 m. Since the magnetic basement depth estimates could be used as a proxy for the thickness of sedimentary formation of the region, the sedimentary formation is sufficiently thick for fossil maturation and therefore confirms that hydrocarbon exploration may be plausible within the region. The combined assessment of magnetic source edge location and magnetic basement depth values offers valuable information on the subsurface configuration, which is very important for mineral and hydrocarbon exploration within Ibi area.

**Keywords** Aeromagnetic data · 3D Euler deconvolution · Upward continuation · 3D Analytic signal · Reduction-to-pole · Source parameter imaging

## 1 Introduction

The magnetic method is widely used for mapping important targets in mineral and hydrocarbon exploration projects [1–3], and data can be acquired in the air, on the ocean, from the ground, and in borehole, for a wide range of geological purposes [4]. Modern aeromagnetic survey is capable of mapping valuable geologic structures on a regional scale including concealed terrains due to the sophistication of modern technology to provide high-quality data [5–7].

The interpretation of aeromagnetic anomaly data for improved sources depth estimates and locations of structural features such as faults, folds and contacts requires

the use of relevant standard techniques and good geological interpretation. The 3D analytic signal introduced by Nabighian [8] and further developed by Roset et al. [9] is one of the standard techniques used for the locations of structural features from aeromagnetic anomaly data. Other established techniques for source depth estimates include 3D Euler deconvolution [10, 11] and source parameter imaging [12].

In this study, we applied enhancement filters such as upward continuation and 3D analytic signal to map structural features. The 3D Euler deconvolution technique was used to estimate depth to the mapped structural features, while the source parameter imaging was used to estimate depths of magnetic basement. This approach is to unravel

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subsurface geologic information which is essential for mineral and hydrocarbon exploration projects within Ibi area of Taraba state.

## 2 Geologic setting

The study area is located in Ibi area of Taraba state which lies between latitude 8° 15' N and 8° 30' N and longitudes 9° 45' E and 10° 00' E. It is situated within the Middle Benue Trough, Nigeria, as shown in Fig. 1.

The Benue Trough is an intra-continental rift initiated in the Cretaceous during the opening of the South Atlantic Ocean. The formation of the trough has been associated with the opening of the southern Atlantic Ocean, and it is regarded as the failed arm or aulacogen of an RRR triple junction [14–16]. As a mainly structural basin of subsidence which was initiated as a product of basement disintegration, it was preceded by rifting during the Cretaceous continental split-up of South America and Africa plates [17, 18]. It is a major intra-continental sedimentary basin within the West to Central African region, spanning from Nigeria through Cameroon and eastwards to the Central African

Republic. The width ranges between 150 and 250 km in Nigeria where it has been divided into three geological provinces (Fig. 2). Lithologically, these sub-basins are dominated by black carbonaceous shale in the Lower Benue, platform carbonates in the Middle Benue and sandstones in the Upper Benue [16, 19–22]. The Middle Benue, where this research was conducted, is underlain by a sequence of sedimentary cover rocks of shale, limestone and siltstone units of the Asu River Group and the Eze-Aku Formations which lie unconformably on Pan-African porphyritic granites (Fig. 3).

### 2.1 Structures and mineralization

The Albian to Coniacian sediments in the study area have been affected by the Santonian tectonic events which transformed the basin into anticlinal and synclinal landform with series of folds and faults. These events were followed by mafic to intermediate volcanic activities which emplaced volcanic rocks such as sills and dykes within the sediments [16, 27–29]. Lead–zinc–barytes mineralization occurs as lodes and veins in faults within the Albian–Cenomanian sediments of Asu River Group, Awe,

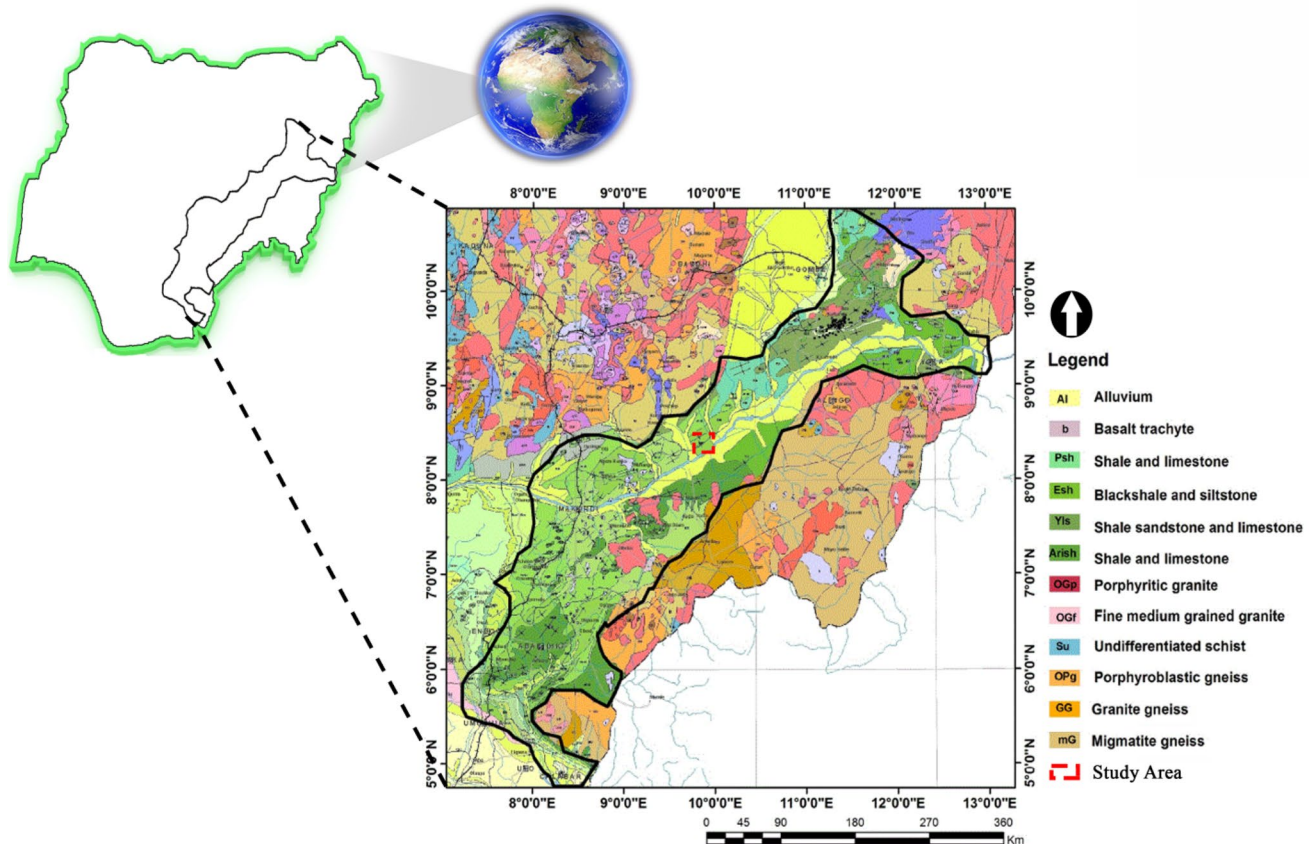


Fig. 1 Sectional geologic map of Nigeria showing the entire Benue Trough (modified after NGSA [13])

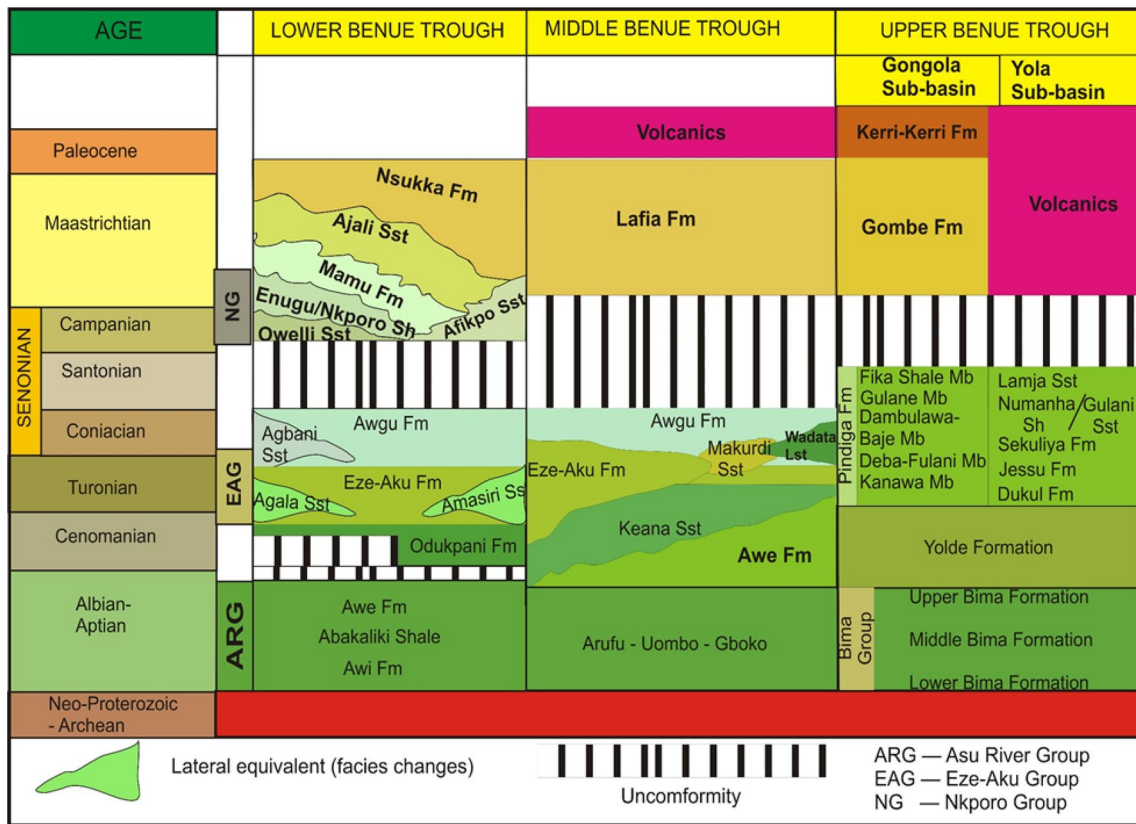


Fig. 2 Stratigraphy of the entire Benue Trough of Nigeria (modified after Carter et al. [22], Reyment [23], Offodile [24], Guiraud [25] and Zarborski [26])

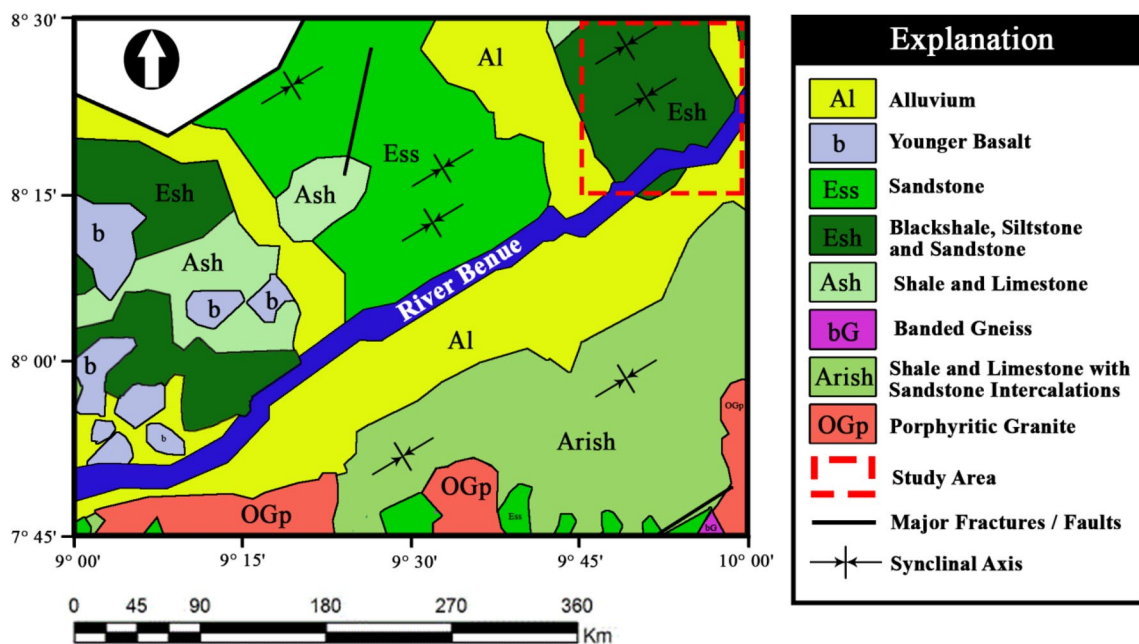


Fig. 3 Geological map of the Middle Benue Trough showing the study area indicated as red dashed lines (modified after NGSa [13])

Keana and Eze-Aku Formations. The fault patterns occur as linear structures or as different irregular faults that are interconnected and spaced over a considerable width and distance. The area of study in this paper around Wukari and Ibi is part of the known mineralized zones in the Middle Benue Trough [30]. Specifically, the area is located within the Wukari sub-basin [16] underlain by the Eze-Aku Formation which consists of hard gray and black cancerous shale, limestone and siltstone. This is overlain by bluish-gray bedded shale with fine-grained carbonaceous limestone bed of the Awgu Formation. These sediments along with the underlying older Albian Keana Formation were deformed during the Santonian episode that formed the Keana anticline. The study area lies within the adjoining synclinal axis generally referred to as the Giza syncline.

### 3 Data and methods

#### 3.1 Data

The total magnetic intensity (TMI) anomaly data covering parts of Ibi area of Taraba state, Middle Benue Trough Nigeria, were provided by the Nigerian Geological Survey Agency (NGSA). The aeromagnetic survey was carried out by Fugro Airborne Surveys Limited for NGSA between 2004 and 2009, using 3 × Scintrex CS3 Cesium Vapor magnetometer along a series of NW–SE flight lines with a spacing interval of 500 m and sensor mean terrain clearance of 80 m while tie lines occur at about 2-km interval. A typical initial correction such as diurnal correction was applied to the aeromagnetic data and then gridded using minimum curvature technique with a grid cell of 100 m to produce the TMI data of the study area. The TMI is the vector sum of the two horizontal and the vertical components of the magnetic field [31]. TMI differs within various locations due to the strength and inclination of the Earth's magnetic field. The International Geomagnetic Reference Field (IGRF) correction was applied to the TMI data to remove the regional effect of the geomagnetic field. The resulting diurnal and IGRF-corrected TMI aeromagnetic anomaly map is shown in Fig. 4. At low-latitude regions such as the study area, magnetic geologic sources would be characterized normally by low magnetic anomalies.

#### 3.2 Methods

The TMI aeromagnetic anomaly map was enhanced to estimate depth to magnetic basement and geometry of structural features (such as faults, fractures and dykes) within the study area. Standard enhancement techniques utilized include the upward continuation and

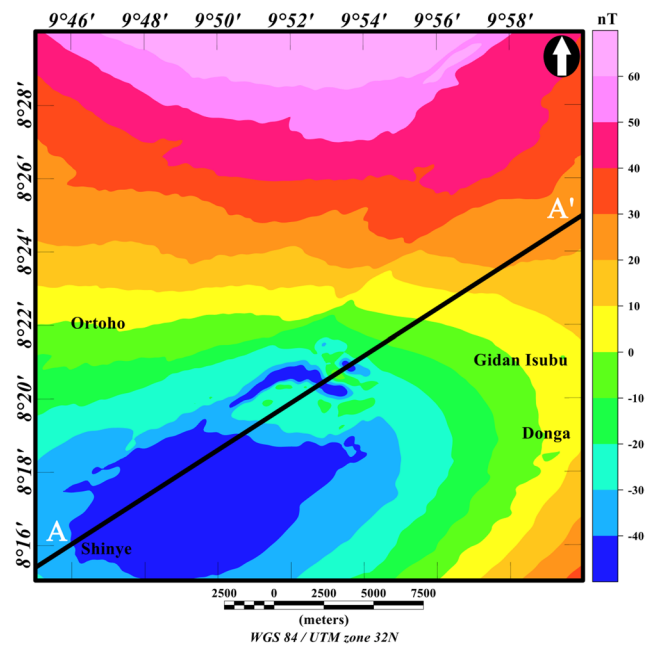
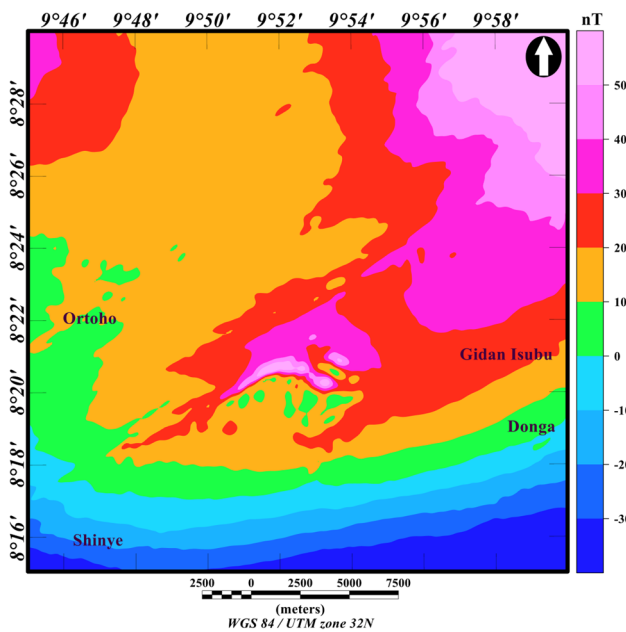


Fig. 4 Total magnetic intensity anomaly map of the study area. The 2D model for profile A–A' is shown in Fig. 10

3D analytic signal methods as well as 3D Euler deconvolution to obtain locations and depths of structural features. Furthermore, the source parameter imaging (SPI) technique was used to estimate depth to magnetic basement. All analyses were performed using commercial software package Oasis Montaj (Geosoft™). The applied techniques have different advantages in various geologic situations. Utilizing multiple standard techniques to the same anomaly region improved the reliability of the deduced results. Since the analysis of observed anomalies is usually complicated by the lateral displacement of the magnetic anomalies with regard to their magnetic sources at nonpolar and non-equatorial latitudes, we first apply the reduction-to-pole (RTP) filter to the TMI anomaly map, assuming the magnetization of the sources is induced. Magnetic field intensity, inclination and declination are the parameters used for the application of the RTP filter. We select these parameter values at the midpoint of the study area (longitude 9° 52' and latitude 8° 22'): total magnetic field value of 33,516 nT, inclination of  $-7.564^\circ$  and declination of  $-1.471^\circ$ . Also, we used amplitude correction inclination of  $-90^\circ$  to stabilize the result of the RTP transformation, which is not stable for low-latitude regions. After applying the RTP filter, the anomalies on the resulting RTP aeromagnetic anomaly map (Fig. 5) are shifted such that they are repositioned directly over their respective magnetic sources.



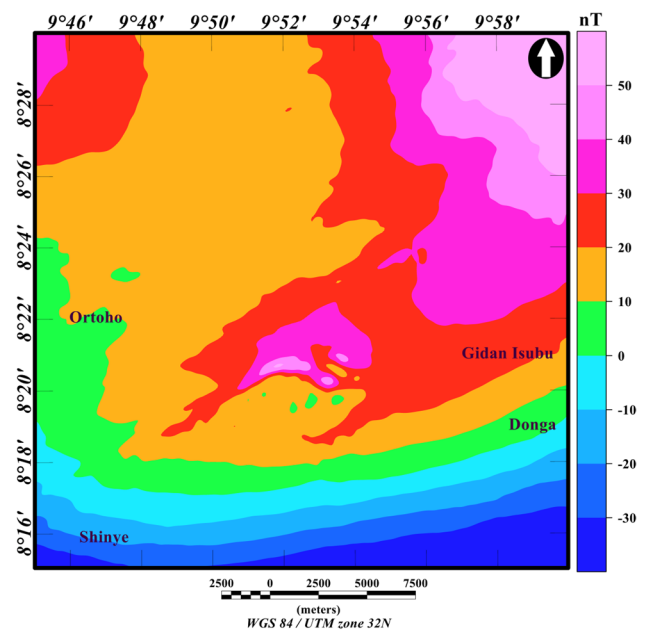
**Fig. 5** Reduced-to-pole aeromagnetic anomaly map of the study area

### 3.2.1 Upward continuation and subtraction from RTP anomaly data

Upward continuation of aeromagnetic anomaly data is commonly used by geophysicist to enhance the signal of deep and extended sources [32–34]. The upward continuation filter is considered a clean filter because it produces almost no side effects that may require the application of other filters or processes to correct. We applied the upward continuation filter (using 100 m increment) to the reduced-to-pole anomaly data (initially at 80 m above the ground) to produce a regional magnetic anomaly field, which would be measured on another surface with a total elevation of 180 m. The resulting regional magnetic field grid (see Fig. 6) was subsequently subtracted from the RTP aeromagnetic anomaly grid to produce a residual magnetic anomaly map (see Fig. 7a). Most anomalies that are shown in the RTP anomaly map (see Fig. 5) continues to the regional aeromagnetic map (Fig. 6).

### 3.2.2 3D analytic signal

Structural filters are crucial tools for outlining the edges, and hence the horizontal extent of magnetic sources and in Ibi area, these could be potential locations for mineral exploration targets [35]. The edges of magnetic sources within Ibi area can be examined by applying the 3D analytic signal (AS) filter. The major advantage of the 3D AS technique initially established for profile magnetic data by Nabighian [36] is that the 3D AS produces maxima over



**Fig. 6** Reduced-to-pole regional aeromagnetic anomaly map upward continued to a total elevation of 180 m

linear structural features (such as fractures, faults or dykes) and is independent of Earth's magnetic field parameters and the direction of magnetization of the magnetic bodies [9]. Therefore, the 3D AS algorithm does not require that the aeromagnetic anomaly data undergo either a reduction-to-pole or equator transformation. Roset et al. [9] showed that the absolute value (amplitude) of the 3D AS can be derived from the square root of the sum of the vertical and horizontal derivatives of the total magnetic field, using the relation:

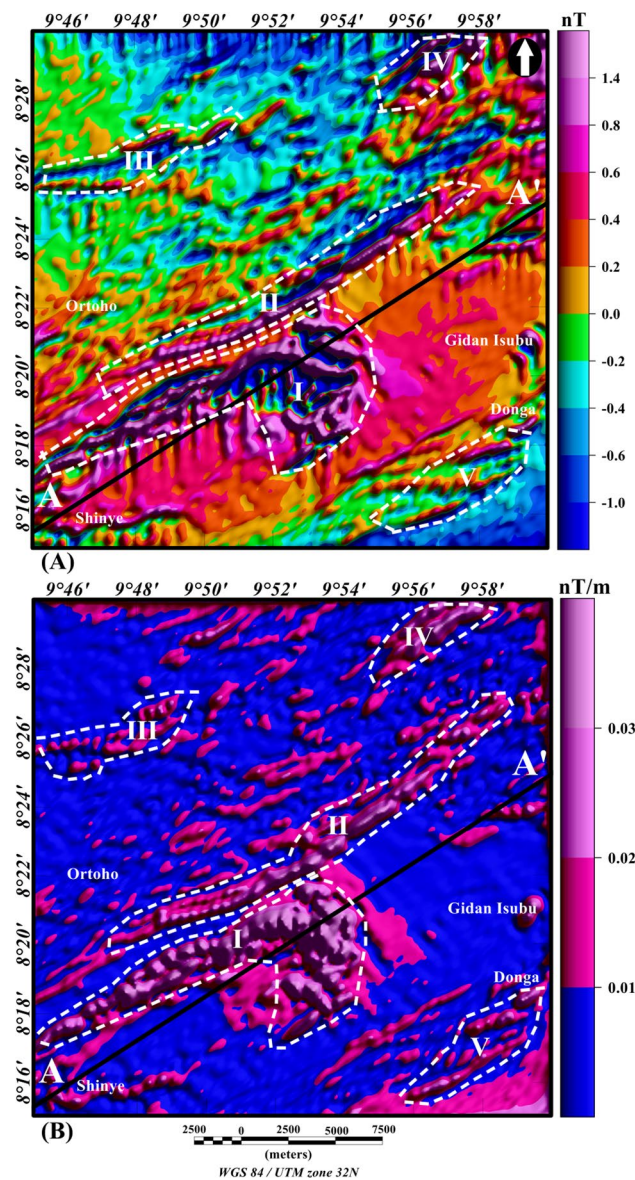
$$|A(x, y)| = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad (3)$$

where  $\frac{\partial T}{\partial x}$ ,  $\frac{\partial T}{\partial y}$ ,  $\frac{\partial T}{\partial z}$  are the first derivatives of the total magnetic anomaly field.

The 3D AS filter was applied to the aeromagnetic anomaly data of Ibi area, in an attempt to map structural features within the study area.

### 3.2.3 3D Euler deconvolution

The 3D Euler deconvolution has proven to be a robust interpretation tool in magnetic data interpretation, because it requires little previous information about the geometry of the magnetic sources. Another advantage of this technique is that it requires no knowledge regarding the magnetization vector [10, 11]. Hence, it can be applied on regions where causative magnetic sources



**Fig. 7** Combined interpretation of structural features within the study area: **a** color-shaded reduced-to-pole residual magnetic anomaly map and **b** color-shaded 3D analytic signal map of the study area

are hidden and where geology of the location is poorly known. Largely, the technique has been used extensively to outline the edges and shapes of sources from potential field image [37]. The 3D Euler deconvolution equation is given as [11]:

$$(x - x_0) \frac{\partial T}{\partial x} + (y - y_0) \frac{\partial T}{\partial y} + (z - z_0) \frac{\partial T}{\partial z} = N(B - T) \quad (4)$$

where B is the regional value of the total magnetic field and  $(x_0, y_0$  and  $z_0)$  are the coordinates of the magnetic

**Table 1** 3D Euler deconvolution magnetic structural indices [38]

S/N	Source type	SI
1	Contact of extensive depth extent	0
2	Edge thin sheet, sill, dike	1
3	Line, thin bed fault, cylinder	2
4	Sphere or compact body at a distance	3

source, which produces the total magnetic field T measured at x, y and z.

N is identified as the structural index (SI); the values of SI for valid sources are given in Table 1. It is a measure of the decaying rate of the magnetic field with distance from the source. It gives a way to differentiate between various source shapes by signifying the magnetic anomaly attenuation rate at the observation point and relies on the source geometry [10]. In practice, the method is very suitable in characterizing dykes, sills, lineaments or other sharp lateral changes in magnetization [38]. The aeromagnetic anomaly data were subjected to 3D Euler deconvolution analysis in order to map structural features within the study area. The aeromagnetic anomaly data were subjected to 3D Euler deconvolution analysis in order to calculate depth values of subsurface structural features within the study area.

### 3.2.4 Source parameter imaging

The analysis and interpretation of a magnetic anomaly response involves estimating the parameters that characterize the source of the magnetic anomaly. Hence, we utilized the source parameter imaging (SPI) technique to estimate the depths to top of magnetic sources [12]. The technique does not require assumption of structural index to estimate depth of sources [39]. The SPI uses the local wavenumber, denoted  $K(x, y)$ , which is given by the expression:

$$K(x, y) = \frac{\frac{\partial^2 T}{\partial x \partial x} \frac{\partial T}{\partial x} + \frac{\partial^2 T}{\partial x \partial z} \frac{\partial T}{\partial y} + \frac{\partial^2 T}{\partial z^2} \frac{\partial T}{\partial z}}{|A(x, y)|^2} \quad (5)$$

where  $|A(x, y)|$  is given by Eq. 3. For a dipping magnetic contact, peaks of  $K(x, y)$  are positioned directly over the edges of the isolated geologic contacts and are independent of magnetic declination, inclination, strike and dip [40]. Hence, it is not required to reduce the aeromagnetic anomaly data to the magnetic pole/equator. Consequently, the estimations of depth to magnetic sources are obtained from the reciprocal of the local wavenumber as:

$$Depth_{x=0} = \frac{1}{K(x, y)_{\max}} \quad (6)$$

where the maximum value of local wavenumber  $K(x, y)$  over the step magnetic source is given as  $K(x, y)_{\max}$ . Additionally, the SPI technique has two major advantages: It does not depend on selected window size, and it eliminates errors initiated by survey lines [12, 40]. Therefore, we used the SPI to estimate the depths to magnetic basement of the studied region.

## 4 Results and interpretation

The visual inspection of the regional aeromagnetic anomaly map shows good correlation with the reduced-to-pole (RTP) anomaly map in terms of trends and patterns of anomalies. This similarity shows that majority of the causative sources within the studied region are of deeper origin. The RTP and regional aeromagnetic maps reveal circular, semicircular to elongated anomalies with E–W, NW–SE and NE–SW trends. These maps show high- and low-amplitude anomalies between  $-30$  and  $50$  nT. The high-amplitude anomalies which are located at the central and northeastern parts of the study area are attributed to intrusive bodies and/or uplifted basement blocks. The low-amplitude anomalies are probably due to low-frequency contributions associated with deeper crustal portion.

### 4.1 Structural features

The reduced-to-pole (RTP) residual magnetic anomaly map shown in Fig. 7a is typically a structural map [41], highlighting geologic features obscured by strong regional magnetic effect. The RTP residual magnetic anomaly map depicts effects of near-surface structural features but cannot provide information for deep-seated features. In order to overcome this problem, we used the 3D AS map (Fig. 7b) to complement the RTP residual map (Fig. 7a). Visual integration of the RTP residual and 3D AS maps facilitated the division of the study area into five structural zones which provide vital information regarding regional structural features such as faults, folds and intrusions.

#### 4.1.1 Zone I

This domain is located at the northern edge of the River Benue and extends from the southwestern part of the study area to the central part, with a parallel alignment to the River Benue. There are three structural trends within this domain as shown in Fig. 7a, b: the broad NE–SW-trending structural features which are the dominant trends and the minor N–S and NW–SE trends which occur as associated structures to the former. This domain is suspected to be associated with vein barite mineralization [42]. The minor N–S and NW–SE trends are more visible on the

3D analytic signal map shown in Fig. 7b; this pattern has been documented to be associated with barites mineralization [42, 43]. The NE-trending structural features are almost elliptical in shape, and its magnitude is higher than the associated structural features. As a result of the pattern of formation and the magnitude of the structures, we tentatively interpret the trend pattern as evidence of minor folds that form part of the main asymmetrical synclinorium—Giza synclinorium.

#### 4.1.2 Zone II

The anomaly with elongation along NE–SW trend within the zone originated from southwestern part of the study area extends to the northeastern part (Fig. 7). Due to the pattern and extent covered by this anomaly, we tentatively interpret the anomaly as a major fault zone within the Giza syncline associated with lead–zinc mineralization. The fault is parallel to the axis of the interpreted folds in zone I and is therefore regarded to be a strike-slip fault. The interpreted fault may in fact be attributed to the Giza fault suggested by Ajayi and Ajakaiye [43] around the study area. Additionally, the occurrence of this anomaly is consistent with vein structures which stretch for 5 to 6 km at Bukuyu village in Ibi [42, 44].

#### 4.1.3 Zone III

This zone is more clearly revealed on the residual anomaly map (Fig. 7a) in comparison with the 3D analytic signal map (Fig. 7b). The anomaly within this zone is thin, short with ENE trend and located entirely at the northeastern part of the study area. We interpret this anomaly as an intrusive structural feature in the form of sill (probably dolerite). Our interpretation is consistent with the report of Ofoegbu [45] around the study area, and the researcher revealed the occurrences of intrusive structures in the form of sills (probably dolerite) within the Middle Benue Trough with ENE trends.

#### 4.1.4 Zone IV

This zone is clearly revealed on both the residual magnetic anomaly map (Fig. 7a) and 3D analytic signal map (Fig. 7b). It is located entirely at the northeastern part of the region under study. The anomaly within this zone trend NE–SW with the linear to curvilinear pattern extends beyond the study area at the NE edge of the maps (Fig. 7a, b). Based on the trend and pattern of the anomaly, we interpret the anomaly as a fold which forms a minor syncline within the bigger Giza synclinorium. The anomaly shows similar pattern with the interpreted folds in zone I, although its full extent is not shown in Fig. 7.

#### 4.1.5 Zone V

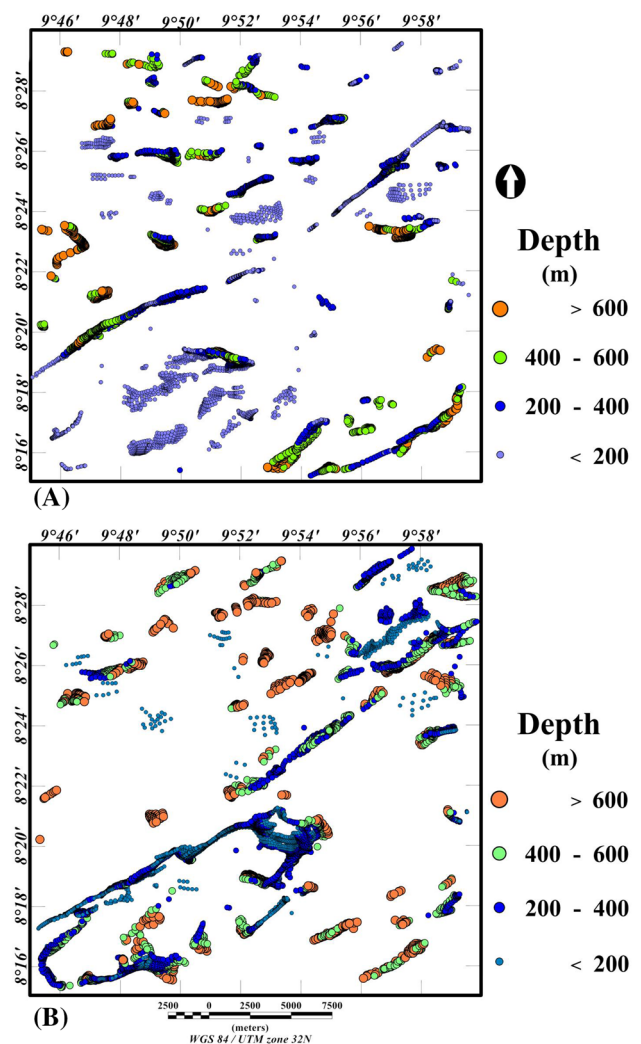
The anomalies within this zone are clearly revealed as a linear pattern on the residual magnetic map (Fig. 7a), but more clearly shown and well distinct on the 3D analytic signal map (Fig. 7b). This zone is situated entirely within the southeastern part of the study area. The anomalies within this zone are thin and trend E–W and NE–SW. As a result of the pattern of formation and magnitude of the anomalies, we interpret these anomalies as buried volcanic intrusions such as dykes and sills within the sedimentary formations. Such intrusions have been confirmed and established by drilling to exist around the region [43]. Also, Chukwu [46, 47] confirmed the existence of such volcanic intrusions through field geologic mapping around the area, while Oden [42] suggested sediment-hosted barite occurrences of hydrothermal origin in Gidanwaya of Ibi area.

#### 4.1.6 Depth estimates of structural features

We applied the 3D Euler deconvolution technique to aeromagnetic anomaly data to estimate possible depths of the mapped structural features shown in the 3D analytic signal and residual anomaly maps (see Fig. 7). The structural indices (SI) shown in Table 1 generate better clustering solutions for different geologic source types, as should be expected. We choose SI of 0 and 1 because of the available geological information of the region under study, and they are the best-fit indices based on the scope of this study. The following conditions were used to actualize the 3D Euler depth solution maps of Ibi area.

- The locations and depth estimations of intrusive structural features such as dykes, sills and veins are realized using SI of 1.0, depth tolerance error of 12% and window size of 2000 m square grids.
- The estimation of depths and locations of geological contacts was achieved, using window size of 2000 m, SI of 0.0 and maximum depth tolerance of 10%.

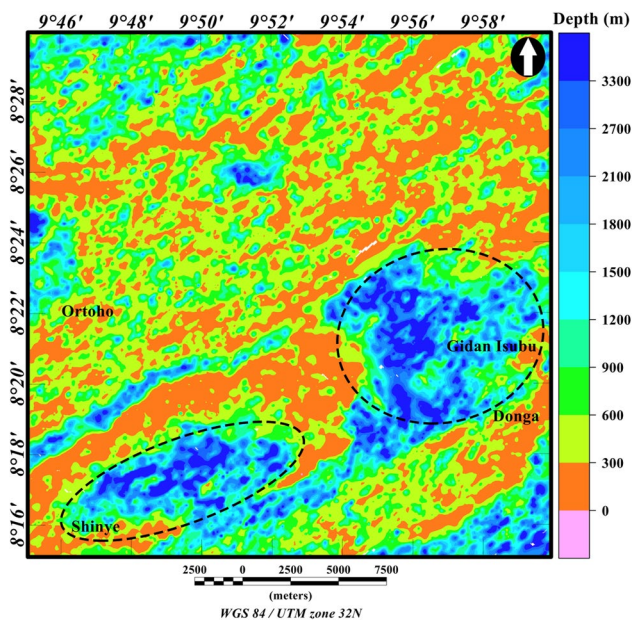
Utilizing these relations, we produced the 3D Euler depth solution maps of Ibi area shown in Fig. 8a, b. The maps depict clearly locations, trends and depth information of different structural features within the study area. The interesting observations on the maps are the trends and locations of structural features which correlate perfectly with those depicted on the residual magnetic map (Fig. 7a) and 3D analytic signal map (Fig. 7b). Furthermore, the 3D Euler depth solution maps revealed solutions for depth values between 200 m and 600 m within the study area. The first obvious pattern on the 3D Euler depth solution map for SI = 1.0 (Fig. 8b) is the interpreted zone I on the residual magnetic map (Fig. 7a) and 3D analytic signal



**Fig. 8** 3D Euler deconvolution maps for structural index (SI) of 0 and 1, produced from the aeromagnetic anomaly data of the study area: **a** 3D Euler solution map for SI=0.0 and **b** 3D Euler solution map for SI=1.0

map (Fig. 7b). Also, the 3D Euler depth solution map SI = 1.0 (Fig. 8b) confirms the interpreted structural features within zones II, III and IV on the residual magnetic map (Fig. 7a) and analytic signal map (Fig. 7b). The southeastern part of the 3D Euler depth solution map for SI=0.0 is marked by a major alignment with NE–SW trend which correlates perfectly with similar pattern and trend observed on the SE part of residual magnetic map (Fig. 7a) and 3D analytic signed map (Fig. 7b).



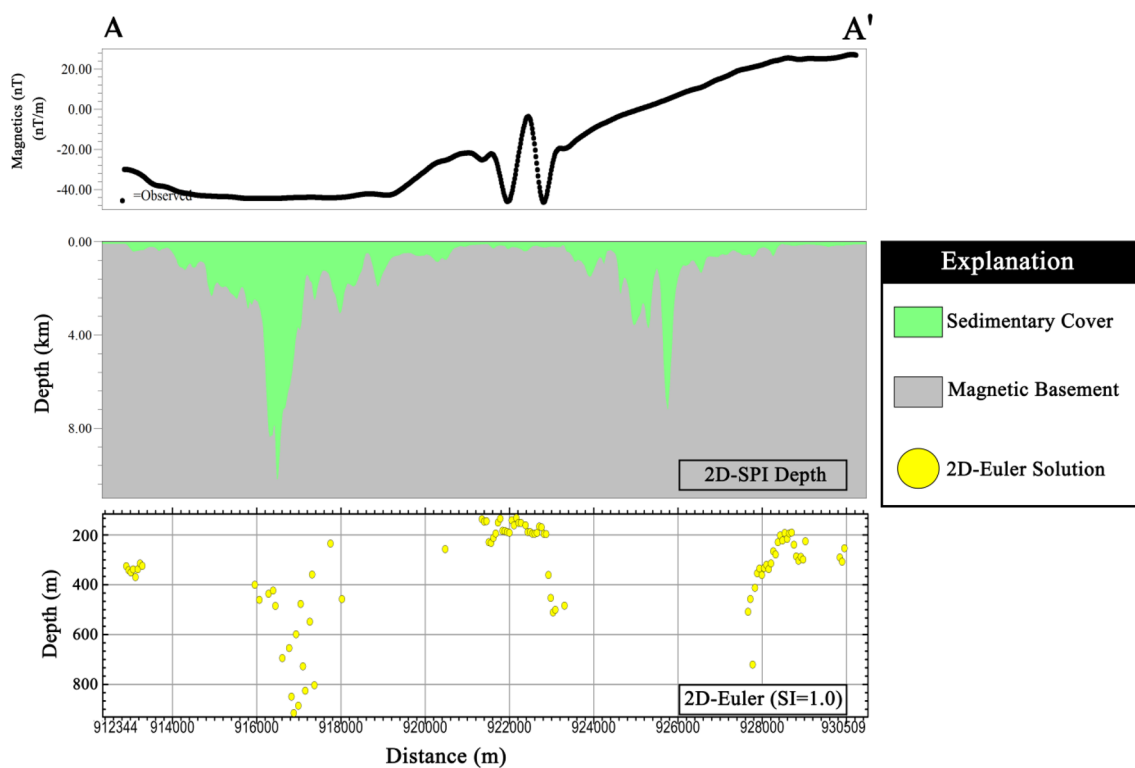


**Fig. 9** Magnetic basement depth map estimated utilizing source parameter imaging method. The dashed black lines indicate two deep zones which are probably the hydrocarbon provinces of the study area

## 4.2 Magnetic basement depth estimates

### 4.2.1 Source parameter imaging

The source parameter imaging (SPI) technique was used for automatic estimate of magnetic source depths from the aeromagnetic anomaly data, which could provide significant information regarding the hydrocarbon potential of the region. Previous assessment of the hydrocarbon potential of succession in the Benue Trough showed a number of rich organic intervals capable of yielding large quantities of hydrocarbon within the Cretaceous section [48]. The resulting SPI map is presented in Fig. 9, indicating spatial locations of numerous magnetic sources at various depths within the study area. The map shows two deep zones characterized by blue color with depths values between 2700 and 3300 m which are suspected to be the hydrocarbon provinces of the study area, because of substantial sedimentary thickness, in addition to the mapped structural features and established stratigraphic information of the region. We interpret these deep zones as the locations of the depocenters within the study area, which are indicated as dashed black lines. These zones are



**Fig. 10** 2D Euler and 2D SPI depth model for profile A–A', across zone I (located in Fig. 7). The observed magnetic curve was extracted from the aeromagnetic anomaly grid (Fig. 4)

surrounded by folds and numerous intrusive bodies which are capable of providing the required minimum temperature for hydrocarbon maturation in addition to their trapping qualities. Wright et al. [49] described that the lowest sedimentary thickness essential to realize the threshold temperature of 115 °C for the initiation of hydrocarbon would be 2300 m thick when all other conditions for fossil maturation are favorable. The indicated deep zones on the SPI map have shown good potential hydrocarbon provinces within the study area, which shares obvious and common stratigraphic continuity with the Gongola Basin where three exploratory wells have been drilled: Kuzari-1, Nasara-1 and Kolmani River-1 [48]. The interpreted folds in zone I in Fig. 6 are also visible on the SPI map which can act as hydrocarbon traps. The interpreted model shown in Fig. 9 runs approximately from southwestern to eastern part of the study area which traverses the interpreted depocenter on the SPI map, in addition to the anomalies in zone I on the residual anomaly map (Fig. 7a) and 3D analytic signal map (Fig. 7b). The 2D Euler deconvolution contributed to obtaining the depth values of suspected edges of folds interpreted in zone I is shown in Fig. 7. This technique, coupled with the 2D SPI depth model, revealed high hydrocarbon potential of adequate sedimentary pile within the delineated deep zones (shown in Fig. 9). This is corroborated by the recent discovery of hydrocarbon in Kolmani River-II within Gongola Basin-Upper Benue Trough [50], which shares common stratigraphic characteristics with Ibi area. Additionally, the depth values of the structural features on the SPI map show compelling alignment of results with the structural features shown in the 3D Euler depth solution map for structural index 1.0 (Fig. 8b).

## 5 Conclusion

The analysis and interpretation of high-resolution aeromagnetic anomaly data of Ibi area allows the delineation of locations, trends and extent of regional structural features, in addition to detailed depth information regarding the underneath basement. The interpretation of the residual magnetic and 3D analytic signal maps reveals five structural zones within the study area (Fig. 7). The interpreted structural features within these zones are linear to curvilinear with N–S, NE–SW, NW–SE and ENE–WSW trends. The structural features represent faults, folds and intrusions. The 3D Euler deconvolution depth maps provide additional information regarding various aspects of these structural features, such as the size, depth, extension and trends. Also, the source parameter imaging map indicates the depths to magnetic basement of the region

which ranges from 0 to 3300 m with an average depth value of 1650 m. This map shows two deep zones with estimated depth values between 2700 m and 3300 m which are likely to be the hydrocarbon provinces of the study area. Additionally, the shallow depth values on the source parameter imaging map show compelling alignment of depth results with structure features shown in the 3D Euler depth solution map for structural index 1.0. These results reveal information of subsurface configuration of the study area which is essential for hydrocarbon and mineral exploration projects within the region.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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