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Investigation of Magnetic Anomalies and Depth to Magnetic Sources Over Igboho Area Using High Resolution Aeromagnetic Data

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ABSTRACT
The availability of geophysical Information about the presence of magnetic minerals can further showcase the location and depth of suspected minerals, the use of aeromagnetic data over a study area for Investigation of magnetic mineral can provide more information about subsurface geology of the area. Aeromagnetic dataset of Igboho acquired from the Nigeria Geological Survey Agency (NGSA), was processed to map out the geological structures of the area and determine the basement depth to magnetic sources in the study area. Regional correction based on the IGRF value of the study area was carried out on the Total Magnetic Field Intensity (TMFI) values which generates the residual map of the study area. The magnetic enhancement filters including Reduction to Magnetic Equator (RTME), Analytic Signal Amplitude (ASA), and Total Horizontal Derivative (THDR) were further applied to residual total magnetic field intensity data so as to further define the lithological boundaries and magnetic structure locations. This is followed by determination of basement depth to magnetic sources using Euler deconvolution (ED) and Source Parameter Imaging (SPI) techniques. The results of the RTME map generates magnetic anomalies' amplitude ranging from -37.577 nT to 27.398 nT, the northwest, southeast through southern part of the study area are dominated by high magnetic anomaly. However the definite lithological boundaries and geological structures result generated from THDR is similar to the one obtained from ASA technique. The structural trends observed were in NW, NS and SW directions. The SPI results shows 126.383 m as the shallowest depth to basement magnetic anomalous structures and 1834.659 m for the deepest depth to basement magnetic structures with calculated average depth of 981 m. The results of the Euler Deconvolution shows an undulating structural basement with estimated depth between -474.253 m and 1266. 027 m. The results also suggested the basement relief of the location is flat and lying within the basement terrain. Thus the depth to basement at Igboho is relatively deep compared to basement complex terrains of other areas of the state (Ibadan).

Keywords:
Aeromagnetic,
Igboho,
Orelope,
Source Imaging,
Analytic signal,
Horizontal derivative,
Magnetic Equator.

INTRODUCTION

Oyo state is one of the southwestern states in Nigeria endowed with numerous igneous and metamorphic rocks which can be grouped into quartzite schist complex majorly in southern part, undifferentiated basement complex dominant in northern area of the state where the study for this research is cited. Some of the rocks minerals that can be found in Oyo state are schistose quartzite, magmatic gneiss, pegmatite, migmatite among others, they harbor noticeable minerals such as quartz, feldspar, biotite, gold, marble, granite, talc, kaolin, aquamarine, tourmaline and tantalite (Grant et al., 1985). One of the geophysical methods that can investigate the magnetic anomalies is aeromagnetic survey, it detect the ambient magnetic fields generated due to the presence of magnetic minerals in the subsurface.

An aeromagnetic surveying is a geophysical technique, it utilizes airborne geophysical survey in acquiring the magnetic field data of a particular area of study. The data recorded during this survey is further processed in identifying the magnetic signatures in the magnetic field of the earth caused by magnetic properties of the subsurface rocks. This anomaly is a deviation from average magnetic field of the location, its interpretation gives an effective method of studying the basement boundaries, sedimentary basins and crystalline basement rocks (Reeves, 2005). The survey has been extensively discussed by various geoscientists (Ogunkoya et al., 2023; Layade et al., 2016, 2019; Ozebo et al., 2014, 2015 and 2017; Oladejo et. al 2020 among others) to determine its geological structures like fractures/faults, the depth to magnetic sources, lineament and also to identify non-flush geological bodies which may serves as potential hosts for minerals.

The magnetic anomalous may be associated with subsurface magnetic bodies which is potentially area of interest. Therefore, application of aeromagnetic survey in the area would enable us determine geologic structures and also give a wider coverage for providing the magnetization of the earth's magnetic field (Ogunkoya et al., 2023; Olurin, 2017; Reeves 2007). In general the application of aeromagnetic method as proven very useful in the area of petroleum exploration (Kivior and Boyd, 1999); delineation of subsurface structural trends, basement depth estimation (Ikumbur et al., 2019); lineament delineation with relation to faults system trends (Osagie et al., 2021); seismicity interpretation (Khalil et al., 2014); mineral exploration among others.

The presence of these solid minerals in Oyo state should showcase the mining opportunities in the state but this potentials are yet to be fully explored due to exclusive geophysical information. So applying geophysical survey to the study area for potential mineral resources would further provide additional geophysical information of the area's subsurface. The purpose of this research is to generate the structural geology of the study area through the investigation of magnetic anomalies, and to also determine the depth to basement structures using high resolution airborne magnetic data. Various methods including Peters' half-slope (developed over five decades), Naudy, Werner deconvolution, Euler deconvolution of analytical signal, Euler deconvolution, Source Parameter Imaging (SPI) or local wavenumber (developed over 2 decades), the continuous wavelength transform among others (Xiong Li 2003) can be adopted for depth estimation. However the techniques used for depth to magnetic body estimation (for quantitative interpretation) in this research are Euler Deconvolution and Source Parameter Imaging (SPI). The correlation between the estimated basement depths of these techniques were also noticed.

Euler deconvolution can be applied to a derivative or combination of derivatives that may require second or higher order derivatives, it allows the identification of magnetic source type automatically. However, SPI method is a complex analytical signal method that requires second order derivatives. Its uses both the phase and magnitude of the analytical signal. The Source Parameter Imaging (SPI) technique is an easy and powerful technique used in determining the depth to magnetic source basement generated from aeromagnetic data (Ogunmola et al., 2016; Adetona et al., 2013; Mono et al. 2018). It is similar to Euler deconvolution in accuracy and has contributed to increase in its global acceptance, the SPI images can easily be interpreted by local geology/geophysics expert Thurston and Smith (*1997)*. Oasis Montal^{TM} software was used to produce the image and depth for interpretation.

Geology of the Study area

The Nigeria Basement belongs to the part of Pan-African mobile belt known as Trans-saharan mobile belt. It is about 1000 Km wide and 3000km long north-south trending belt bounding in the eastern side of the West African craton, it has a boundary with the eastern part of the circum-West Africa belt of gravity heights which marks an eastward dipping suture comprising of unrooted, dense mafic and ultramafic structures. The Nigerian basement is divided into two terrains namely; the Western and Eastern basement. The Eastern zone is characterized with Uranium and its Pegmatite deposites while the Western part of the basement is associated with gold mineralization, banded iron formation and green stone deposits such as gold deposits in Osun state and other part of southwestern region such as Oyo state. The Western basement region is polycyclic which is known to have been affected by three orogenic events. It has shift belt that has only been affected by Pan African orogeny while the Eastern part has Ebonian Protolith that with no cover to the East. It is made up of Protolith that deposited after the Ebonian event and affected by the Pan-African event (Robert 1965). The study area is a wooded savanna area situated in Orelope local governement area of Oyo State. It is between the longitude 8 ^{o} 30' E and 4 ^{o} 00' E while the latitude is from 8^{o} 30' N to 9^{o} 00'N. Igboho is about 405m-445m above sea level, the major town surrounded by Igboho are Igbope, Igbeti, Kishi, Ogbooro, Sepeteri. The area is within the basement geology of southwestern Nigeria which has been described by various researchers such as Ogunkoya et. al., 2023 and Egbeyale et al., 2023 among others. Hence the geology of Igboho falls within the basement complex of southwestern Nigerian terrain characterized by crystalline rocks of Pre-Cambrian age in the form of banded gneiss, migmatites, granites (major rock type) and schist, Amphibolites, Quartzite granite gneiss (minor rock types). The older granite suit such as granitic rocks and banded gneiss forms the large part of the total area of Orelope local government where the study area is cited as shown in Figure 1.

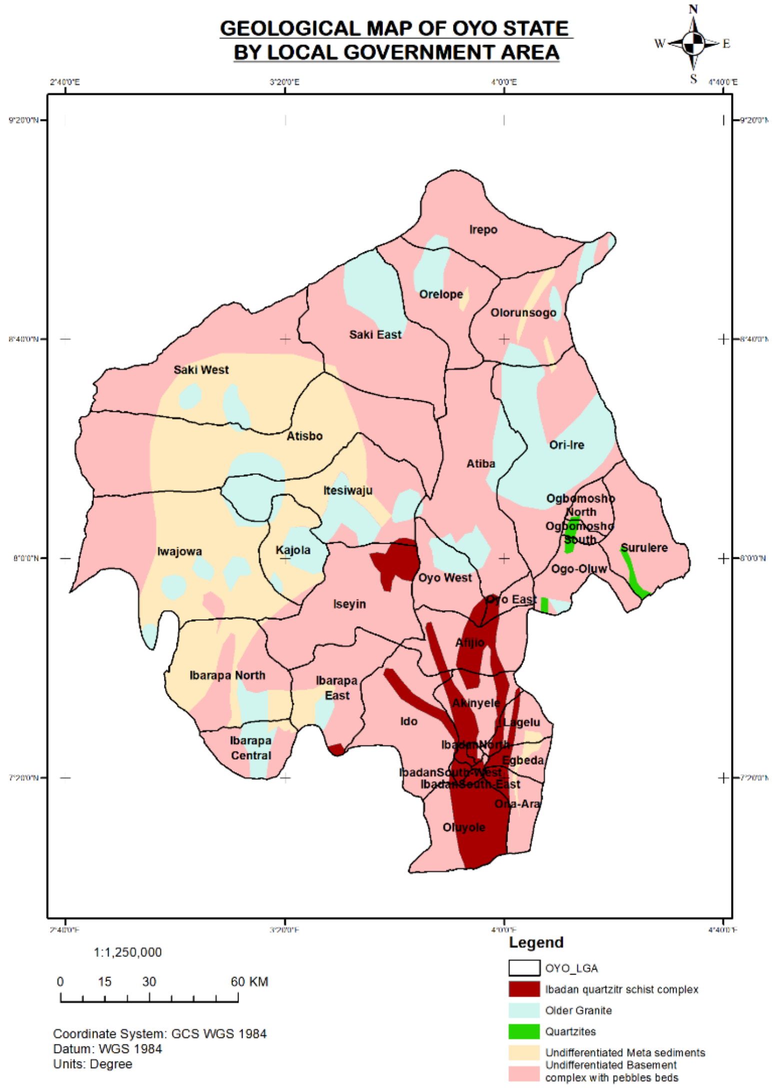


Figure 1: Geological map of Oyo state showing the Local government areas

MATERIALS AND METHODS

The Total Magnetic Field Intensity (TMFI) data of Igboho is an excel format dataset, acquired from Nigeria Geological Survey Agency (NGSA). It was processed using the minimum curvature gridding method at different altitudinal levels to produce TMFI map (Figure 2). Since the study area is within the basement complex of southwestern part of Nigeria, the cultural effect was removed through the filtering process in order to improve the short wavelength signal that originates from shallow geological features. The filtering operations is simply the removal of regional effect (Figure 3) from the acquired TMFI data which will produce Residual Magnetic map (Figure 4). The quality of the signal was further enhanced using Total Horizontal Derivatives (Figure 6) and Analytic Signal Amplitude (Figure 7) technique to ease the interpretation. The residual magnetic data (the filtered aeromagnetic data) were utilized as the starting grid for the ED and Source Parameter Imaging due to the high signal to noise ratio. The Euler deconvolution (ED) map was generated after the structural index, maximum percentage depth of tolerance, window size and maximum distance (processing parameters) were selected to improve the quality of the result.

Reduction to Magnetic Equator (RTME)

The dimension and size of the magnetic body, magnetic inclination and depth of occurrence are some of the factors that determine the shape of any magnetic signature. (Baranov and Naudy, 1964; Salem et al., 2007). The geographical location of Igboho area shows there are effects of latitude on the magnetic signatures, because both angles of declination and inclination are determined by geographical location. The magnetic signature at the pole where the angle of inclination is 90 degree (or 0 degree at the equator) is said to be the peak of the anomaly directly located over the causative body. However, the anomaly become difficult as the peak of the anomaly is situated on their corresponding sources at the middle of the south or north poles. Therefore, reduction to magnetic equator is usually used as one of the interpretation techniques to simplify these anomalies and ensure it lie directly above the causative body. Figure 5 shows the Reduction to Magnetic Equator (RTME) map of the study location.

Analytic Signal Method (ASM)

Analytic signal method (total gradient) is another interpretation technique adopted for this research for enhancement to identify geological features. It unified HG (horizontal gradient) and VG (vertical gradients) of the magnetic anomaly and focus on determining the first derivatives of magnetic anomalies to estimate source characteristics. ASM is designed to clarify that magnetic structures has both positive and negative aimed at simplifying the fact that magnetic bodies is usually associated with a positive and negative peak, even though it is difficult to determine the specific location of the causal structures. The modulus of analytical signal was applied to the total magnetic anomaly. The amplitude of the analytic signal also shows maxima over boundaries/edges as its represented in equation 1 (Ansari and Alamdar, 2009; Ozebo et al., 2017).

$$|A(x,z)| = \left[\left(\frac{dM}{dx}\right)^2 + \left(\frac{dM}{dy}\right)^2 + \left(\frac{dM}{dz}\right)^2\right]^{1/2} \qquad (1)$$

Where $|A(x,z)|$ is the amplitude of the analytic signal at (x, y), M is the magnetic field at $x,y-$direction. $\frac{dM}{dx}$ and $\frac{dM}{dy}$ are the two horizontal and vertical derivatives of magnetic field.

Total Horizontal derivative (THDR)

Total horizontal derivative is an enhancement technique used in locating the boundaries of magnetic sources, delineation the shallow and deeper magnetic sources. Its greatest advantage is the susceptibility to noise in the data, because it requires calculation of two first order derivatives of the magnetic field (Phillips et al., 2000). The amplitude of THDR is given as:

$$|THDR| = \left[\left(\frac{dM}{dx}\right)^2 + \left(\frac{dM}{dy}\right)^2\right]^{1/2} \qquad (2)$$

$\frac{dM}{dx}$ and $\frac{dM}{dy}$ are the horizontal derivatives of the magnetic field in the x- and y- directions.

Source Imaging Parameter (S.P.I)

The S.P.I. method is an extension of Complex Analytical Signal Amplitude (CASA) developed to determine the magnetic source depth. The method was developed by Thurston and Smith in *1997* to determine the depths to magnetic basement. The technique uses the relation between the local wavenumber (k) and magnetic source depth of the observed field calculated for any point within a grid of data through horizontal and vertical derivatives. Interpreting the magnetic anomalies responses involves the determination of parameter identified with the source of the anomaly (AL-Banna and Daham 2019). The Source Parameter Imaging (SPI) method presumes a step type source model in determining the depth using equation 3 below (AL-Banna and Daham 2019).

$$\text{Depth} = \frac{1}{\sqrt{\left(\frac{\partial A}{\partial x}\right)^2 + \left(\frac{\partial A}{\partial y}\right)^2}} \qquad (3)$$

Where A is the tilt derivative (Fairhead, 2011) given as:

$$A = \frac{a\tan\left(\frac{\partial M}{\partial z}\right)}{\sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2}} \qquad (4)$$

Where M is the Total Magnetic Field values

Euler Deconvolution (ED)

Euler deconvolution is a technique used in determining depth, delineate the horizontal boundaries and location of geologic structure producing the magnetic anomaly (Wilsher, 1987; Reid & Thurston, 2014; Thompson 1982; Reid, and Thurston, 2014; Mushayandebvu et al. 2001 and Hsu et al. 2002). It uses the x-, y-, z-derivatives in estimating the location and depth of different magnetic sources like contact, cylinder etc. Each of the source bodies is described by Structural Index (SI) that determines the fall-off rate of the field with distance from the magnetic source. The equation of ED (Thompson 1982) for potential field data is given by equation 2

$$(x - x_o)\frac{\delta M}{\delta x} + (y - y_o)\frac{\delta M}{\delta y} + (z - z_o)\frac{\delta M}{\delta z} = N(B - M) \qquad (5)$$

Where $x, y,$ and z are the field coordinates and assumed to be at origin, $x_o, y_o,$ and z_o are the position of a magnetic sources whose total magnetic field, M is measured field at $x, y,$ and z. B is the total magnetic field of the region, N is the degree of homogeneity or structural index (Whitehead & Musselman, 2008). Hence structural indices 0, 1, 2 and 3 have been assigned to delineate the subsurface structures.

RESULTS AND DISCUSSION

The residual magnetic field anomaly (Figure 4) is determined by extracting the effect of regional magnetic anomaly (Figure 3) from total magnetic field intensity anomaly (Figure 2). The application of techniques such as Total Horizontal Derivative (Figure 6), Analytic Signal Amplitude (Figure 7), Source Parameter Imaging (Figure 8), and Euler deconvolution (Figure 9) in analysis of aeromagnetic data has permitted the enhancement of magnetic anomalies sources and also produce precise locations of the sources of magnetic anomalies with determination of their respective depths.

Total Magnetic Field Intensity (TMFI) anomaly map

The Total magnetic field intensity anomaly map shows lateral change in the magnetic field of the earth with the maximum anomaly value of 99.660 nT dominant in southeastern and southwestern part of the study area, the minimum anomaly value is -4.687 nT majorly in northeastern and partly northwestern part of the study location. High magnetic anomaly is concentrated in southern region of the study area which may be due to the presence of magnetic minerals. Low magnetic anomaly is concentrated in northeastern and northwestern regions.

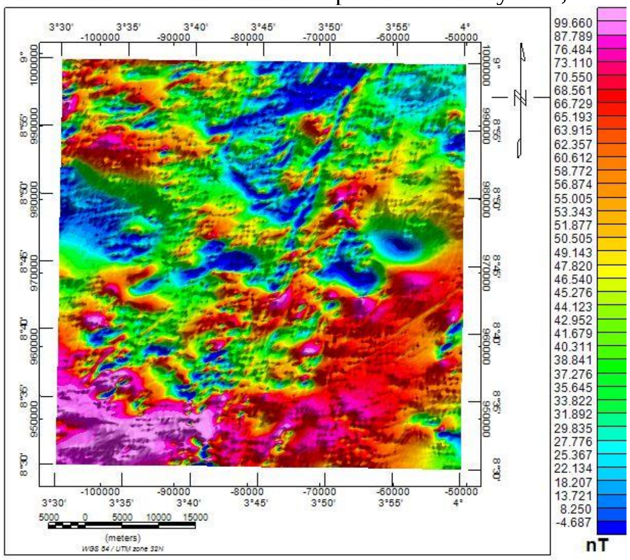


Figure 2: Total Magnetic Field Intensity (TMFI) Anomaly Map of Igboho

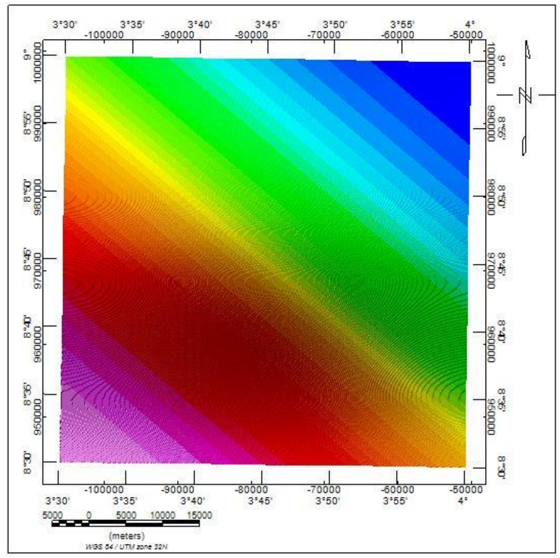


Figure 3: Regional Magnetic Field anomaly of Igboho

Residual Magnetic Field Anomaly

The residual field of the study area composes of low magnetic anomalies reaching a minimum value of -37.577 nT as observed majorly in the western parts and high magnetic anomalies reaching a maximum value of 27.398 nT as observed majorly in the southern part of the study area.

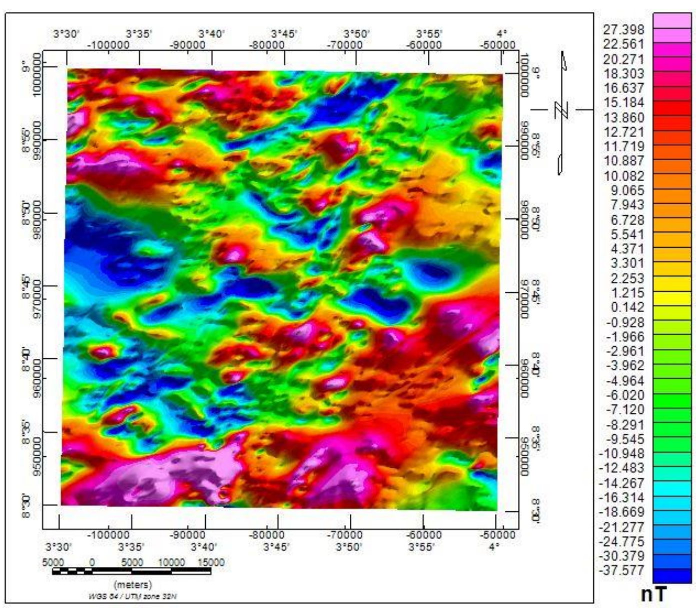


Figure 4: Residual Magnetic Field Anomaly Map of Igboho

Reduction to Magnetic Equator (RTME)
The most common method to accurately display magnetic data especially in the area of low magnetic declination is to generate the Reduction to Magnetic Equator (RTME) of the Total Magnetic Intensity. The aim of the Reduction to Magnetic Equator is to reposition the peak of the anomalies over the magnetic sources with relation to inclination and declination of the magnetizing bodies. The Reduction to Magnetic Equator map (Figure 6) evince the lithological structure of the study area with magnetic intensity values ranging from 1.092 to 94.627 nT. The variance in the magnetic intensity values may be attributed to ferromagnetic materials that often give rise to high intensity and likewise the intense degree of metamorphism and deformation which produce low magnetic intensity values

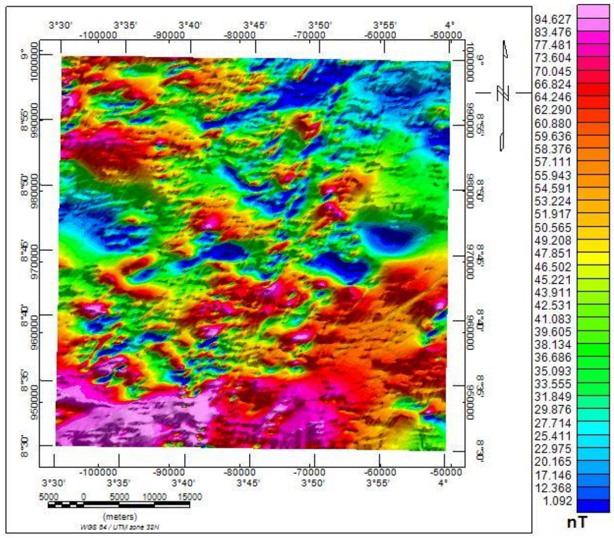


Figure 5: Reduction to Magnetic Equator (RTME) Map of Igboho.

Total Horizontal Derivative (THDR)
Total Horizontal Derivatives (THDR) is a technique used to detect the boundaries of magnetic structures resulting from magnetic susceptibility contrast, thereby extracting information about the shallow magnetic anomalies or near surface magnetic signatures from THDR map generated from the aeromagnetic map. The structural trends are more pronounced in the direction of northwest through the central to southwestern direction. The visibility of the magnetic sources especially the high magnetic structures in N-W, N-S and S-W region increases compared with Figure 6. The maximum values of THDR are dominantly located majorly in the southwestern part through the southeastern region representing the geological magnetic sources within the area.

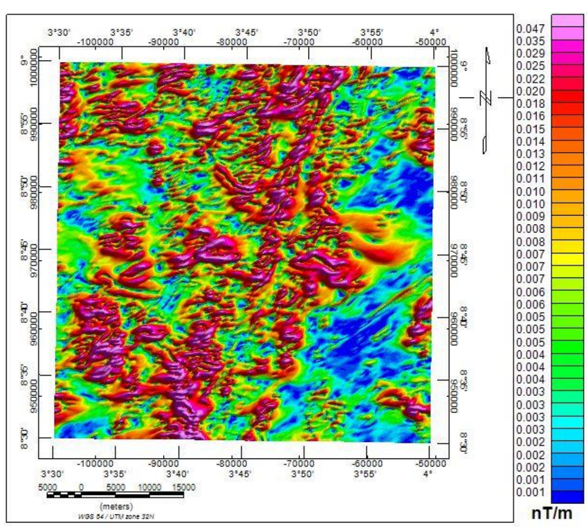


Figure 6: Total Horizontal Derivative (THDR) Map of Igboho showing

Analytic Signal Amplitude (ASA)

Analytical Signal Amplitude (ASA) is an enhancement techniques applied on the aeromagnetic data to delineate boundaries of lithological units. It combines both the vertical and horizontal derivatives over all possible directions of the magnetic field of the earth. The analytic signal amplitude obtained from the study area are as shown in Figure 7. By comparing ASA with the Reduction to Magnetic Equator (Figure 5), the visibility of high magnetic contact locations are obviously pronounced in the central part of the region in Figure 7 but similar to Figure 6 because they both aligned on the top of the magnetic source boundaries. The high analytical signal amplitude are prominent in northwestern through the central to the southwestern region of the study area. However low ASA are seen mainly in the eastern region of the map. These low values are attributed to anomaly structures of lower magnetic structures.

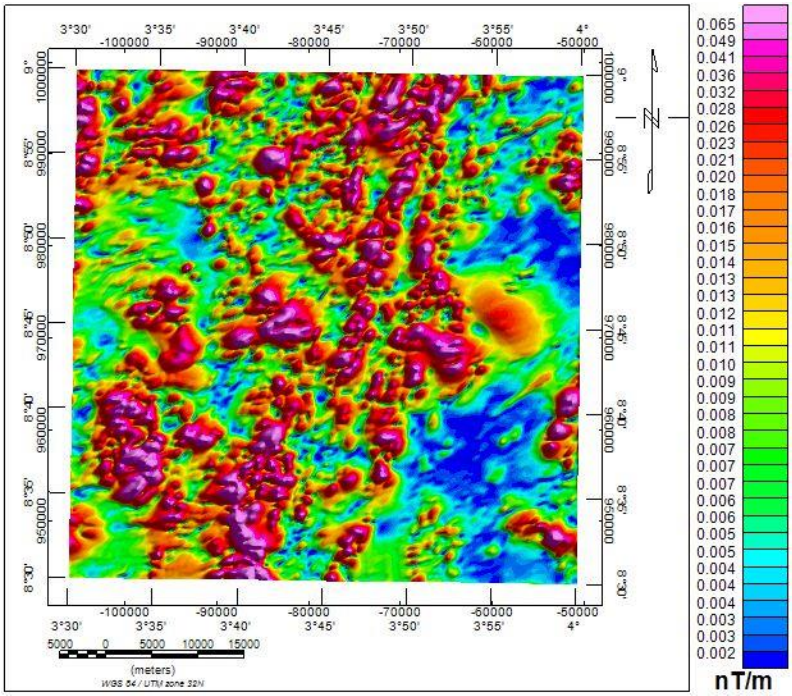


Figure 7: Analytic Signal Amplitude Map of the TMI field of Igboho.

Source Parameter Imaging (SPI)

The image representation of the Source Parameter Imaging (SPI) of the study area was generated using the Oasis montaj^{TM} software to determine the depth variation to magnetic bodies and the result is presented in Figure 8. The negative depth values evinces the depth of deep seated subsurface magnetic structures. The results of the imaging shows 126.383 m as the shallowest depth to basement magnetic anomalous structures and 1834.659 m for the deepest depth to basement magnetic anomalous structures, the approximate average depth is calculated as 981 m. The SPI map of this study area is also characterized with deep seated magnetic anomalous bodies having depth range from 451.855 m to 1834.697 m; and shallow magnetic structures at depth ranges from 126.383 m to 432.090 m. The highest depth (the blue color) depicts sediment suitable for magnetic minerals.

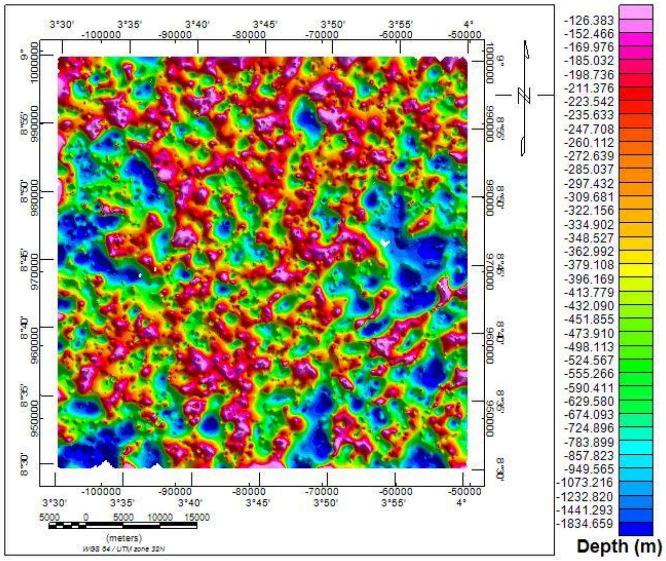


Figure 8: Source Parameter Imaging (SPI) of the study area

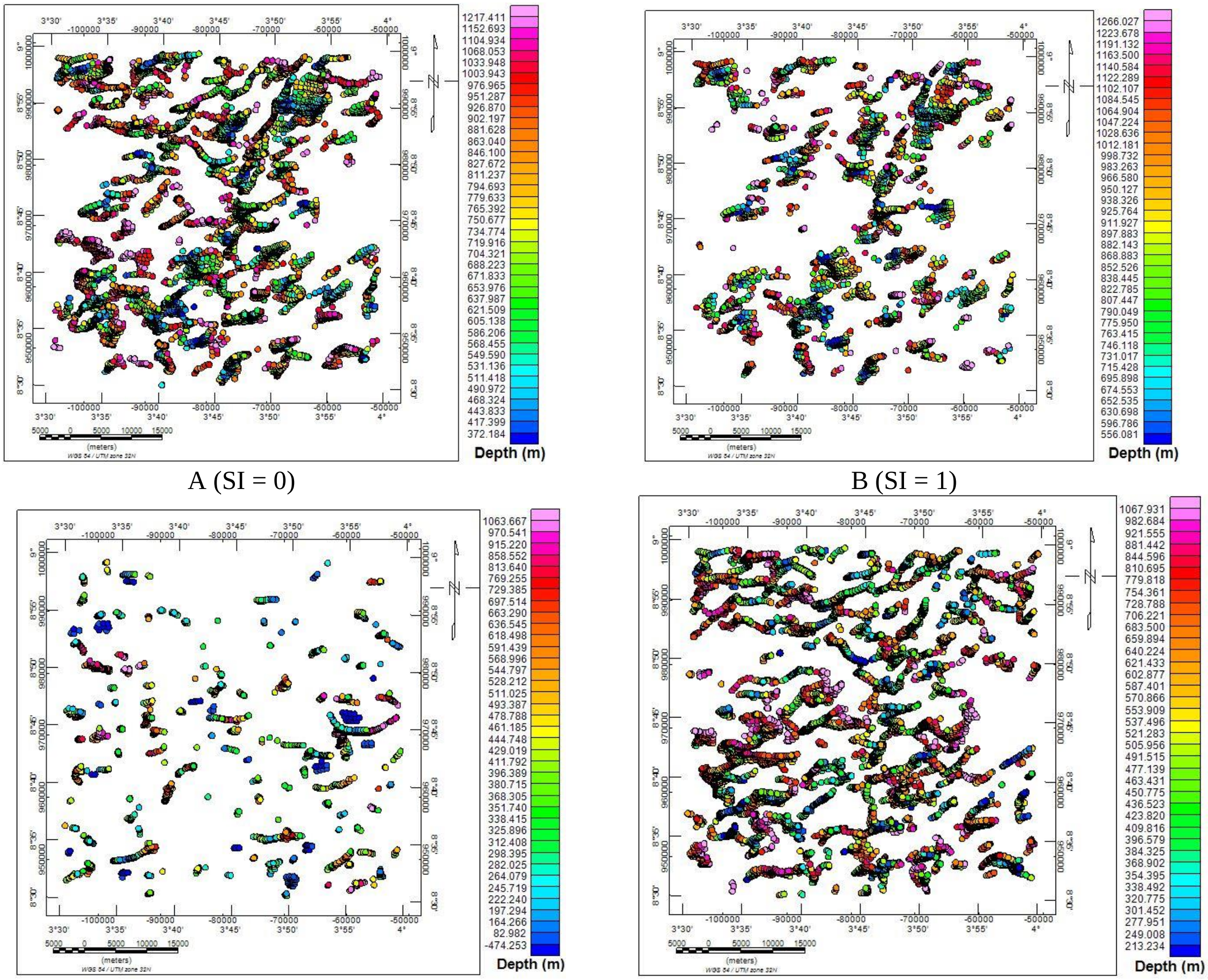
Euler deconvolution

The Euler deconvolution on Oasis Montaj software was used in estimating the basement depth to the magnetic sources using the appropriate structural index setting, this depth provides meaningful information about basement complex of the study area. The structural indices used were 0, 1.0, 2.0, and 3.0 as represented in Figure 9a-d.The location of magnetic sources in this study area are represented by the center of the circles in the Euler maps while the diameter of each colored circle is directly proportional to basement depth. The size represent the depth variation ranging from -474. 253 m to 1266 m. The Euler result were windowed with respect to their structural index to determine the best solution in relation to the geological formation, hence the results in Figure 9a is suspected to be the best accepted result because it shows the a well clustered solution around the magnetic sources and also reflect the stability of the structural index. The summary of the Euler result presented in table 1 were generated by varying values of structural indices from 0 to 3.0 with tolerance of 10%. It was observed that the shape of the causative body based for structural indices 0, 1.0, 2.0, and 3.0, with the geological models contacts, dyke/sill, dyke/horizontal cylinder and sphere models were best fits with the basement complex of the area. The windowed Euler solution with structural index 0 is also similar to the areas of high analytic signal amplitude and are suspected to represent areas with dominant magnetic anomaly contacts.

Table 1: Summary of Basement Depth Estimated from Euler deconvolution

Structural Index	Geological model	Estimated depth
0	Contact	372.184-1217.411 m
1.0	Dyke/Sill	556.081-1266.027 m
2.0	Dyke/Horizontal cylinder	-474.253-1063.667 m
3.0	Sphere	213.234-1067.931 m

Depth range from 372.184 m to 1217.411 m (795 on average) for structural index 0; 556.081 m – 1266.027 m was obtained from structural index 1 with approximate average of 911 m; -474.253 m – 1063.667 m (295 m average) for structural index 2; and structural index 3 has average depth of 641 m ranging between 213.234 m and 1067.931 m. The structural indices of 0, 1, and 3 evinces the maximum numbers of magnetic structures compared with structural index 2 image. Furthermore the positive (high magnetic values) and negative (low magnetic values) anomaly observed in the study area depicts the regions with magnetic sources located above and below the reference datum of the study area respectively.



A (SI = 0) B (SI = 1)

C (SI = 2) D (SI = 3)

Figure 9a-d: Euler deconvolution depth plot at different Structural Index (SI) obtained from RTP residual aeromagnetic intensity map of the study area at (a) SI = 0, (b) SI = 1, (c) SI = 2, (d) SI = 3

CONCLUSION

High resolution aeromagnetic data of Igoho has been processed and qualitatively and quantitatively interpreted to delineate the subsurface magnetic structures in the study area. The qualitative interpretation provides the variation in the magnetic intensities of the magnetic bodies which is suspected to be among the older granitic rock minerals. However, the quantitative interpretation gives information about the physical properties including the depth, dimension and location of sources of geologic interest. It was observed that magnetic structures in the study area are majorly concentrated in center through the southwest and southeastern part of the study area. The maximum depth range of magnetic structures obtained from Euler deconvolution method and SPI techniques corresponds to the depth of older granitic mineral rocks like granite rocks and banded gneiss prevalent in the area.

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