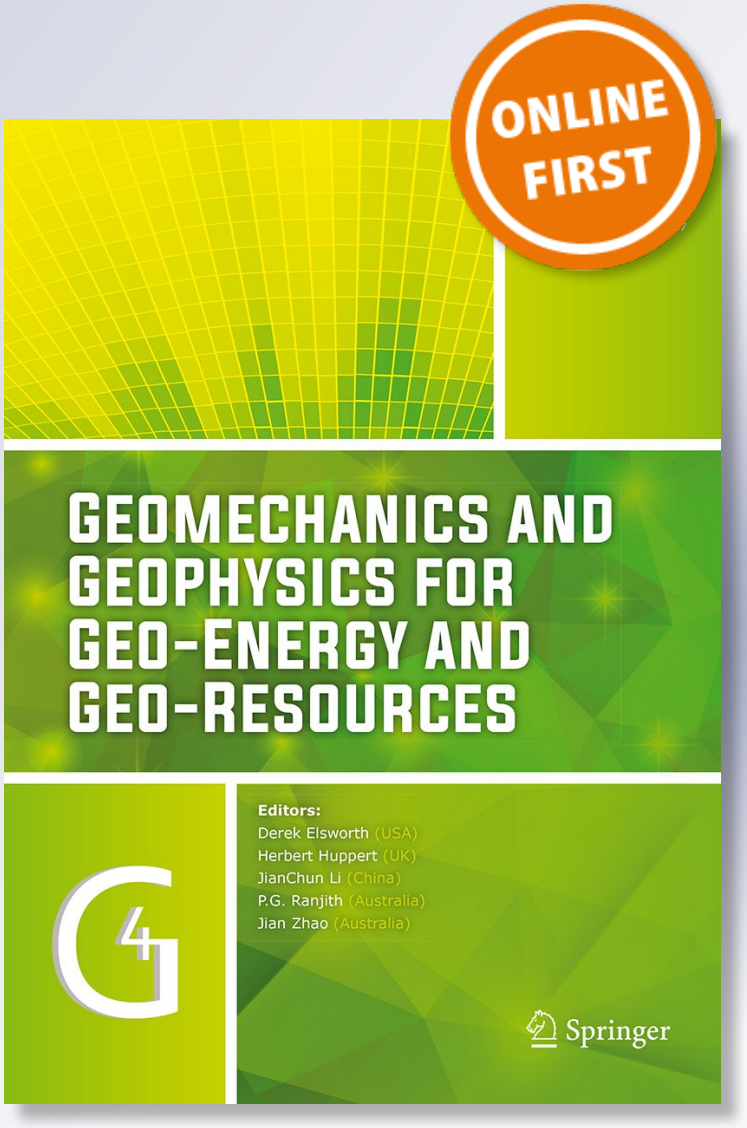
Geophysical inversion of geologic structures of Oyo Metropolis, Southwestern Nigeria from airborne magnetic data

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ORIGINAL ARTICLE

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Abstract High-resolution airborne magnetic data of Oyo Metropolis has been used to map subsurface geological features which in most cases, corresponds to the area of interest for mineral expedition. The airborne magnetic data was first reduced to the magnetic equator (RTE); this is normally done to make the data simpler to interpret. The RTE map was subjected to Fast Fourier Transform to separate the regional and residual magnetic anomalies and estimate their depths. An average depth of 2500 m and 500 m were obtained for the top of regional and residual sources respectively. 3D-Euler deconvolution and tilt derivative interpretation techniques were combined and used on the RTE map, to locate and estimate depths to geologic contacts and pegmatite intrusions attributed to lineaments. The resulting 3D-Euler depth solutions were plotted on the tilt derivative map of the study area. A very good correlation was highlighted, indicating that the methods are good interpretative techniques for mapping magnetic lineaments. The estimated depths obtained from 3D-Euler deconvolution method are in the range of 108.1–544.3 m for structural index 1.0 corresponding to intrusions (dykes), and the result of structural index 0.0 corresponding to geologic contacts are in the range of 5.9–295.2 m. The estimated depth parameters coupled with known geological information, were further used to produce the best image view of the subsurface geological features of the study area, using 2-D profile modeling technique. The result obtained from the 2-D profile model is in good agreement with the results obtained from the 3D-Euler deconvolution and tilt derivative methods, indicating locations and depths of various intrusions (dykes) and geologic contacts. The obtained results from this study will help shed more light into the structural framework of the study area and can help potential explorer target new areas for mineral exploration.

Keywords Oyo Metropolis · 3D-Euler deconvolution · Tilt derivative · Pegmatite intrusion · Depths

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1 Introduction

Magnetic technique is a well-known geophysical method normally applied to locate and have a pictorial

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view of subsurface targets in a wide range of applications from solid mineral exploration to regional scale studies (Ansarin and Alamdar 2009). Airborne magnetic survey is mostly preferred because of its advantage over other magnetic methods e.g. it allows faster and cheaper coverage of large and inaccessible areas. The data obtain from airborne magnetic survey are generally presented in form of gridded maps. This allows quantitative and qualitative interpretation in order to visualize the subsurface geological structures of the Earth. Also, the airborne magnetic data are readily available compared to other magnetic methods, so it is necessary to exploit the potentialities of these data (Salawu 2016; Nwankwo and Salawu 2017). Majority of geophysical data like airborne magnetic data are analyzed to estimate depths and forms of magnetic sources causing the observed magnetic anomalies (Olowofela et al. 2011).

The dipolar nature of magnetic field makes the interpretation of magnetic sources to be somewhat cumbersome. When magnetization occurs in anywhere rather than magnetic poles or the magnetic equator, the observed anomaly will have asymmetric shape. This causes a horizontal displacement between measured anomaly and exact body location. However, the application of reduction to the equator is normally applied to make the measured anomaly symmetric (Ansarin and Alamdar 2009).

The interpretation of gridded high-resolution airborne magnetic data requires the use of relevant geophysical methods to better determine the locations, depths and forms of geological formations which are important targets in mineral expedition. The airborne magnetic maps can be quantitatively interpreted by adopting techniques such as 3D-Euler deconvolution, tilt derivatives, 2-D forward modeling etc.

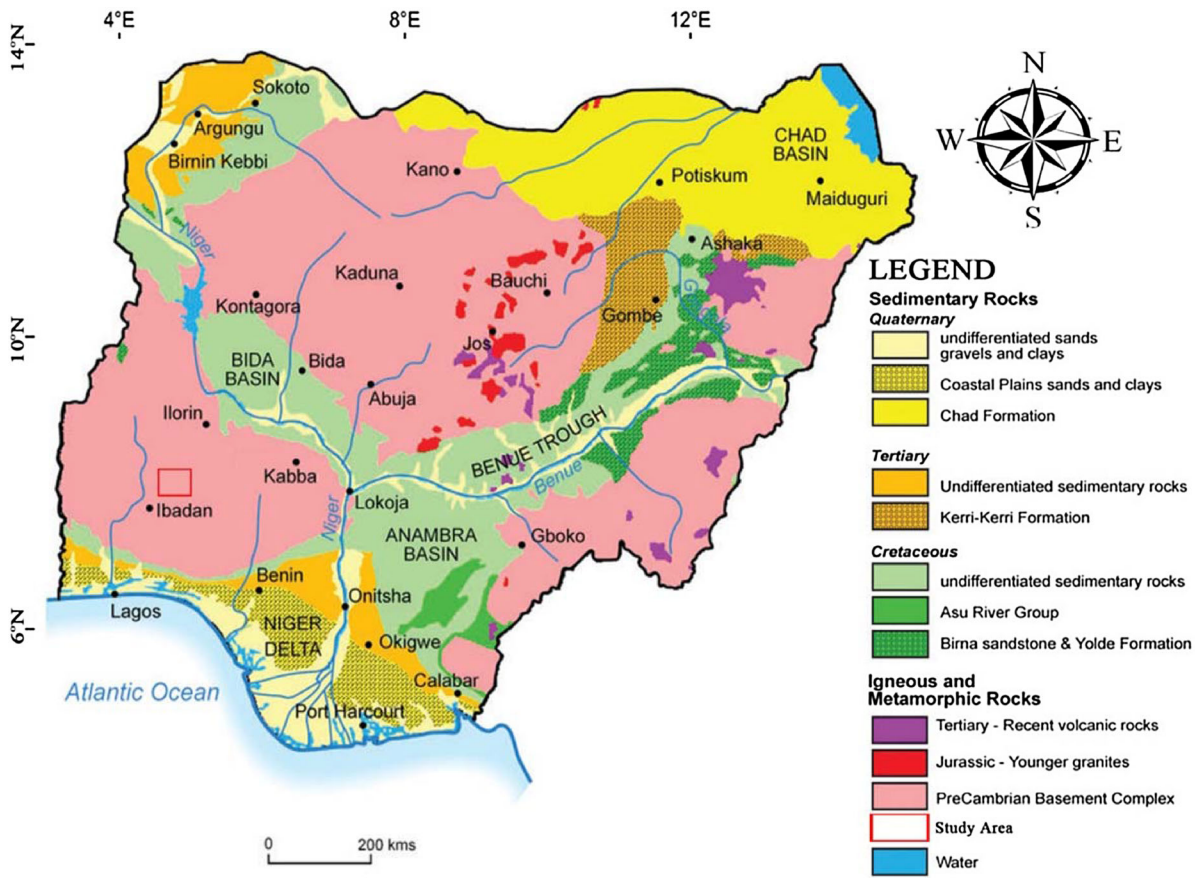


Fig. 1 The geologic map of Nigeria showing the study area (modified after Adelana et al. 2008)

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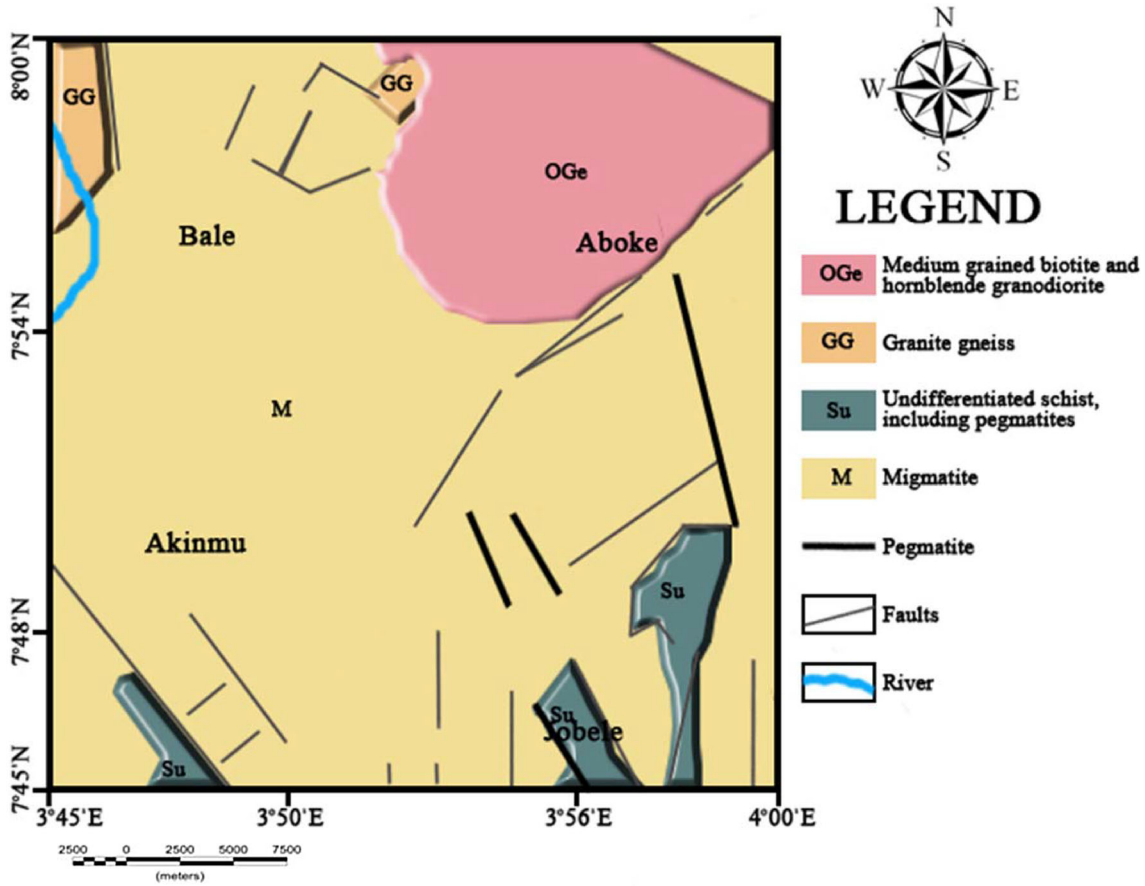


Fig. 2 Geology map of Oyo township (modified after NGSA 1982)

The method known as 3D-Euler deconvolution was first suggested and implemented for the interpretation of magnetic profile data by Thompson (1982). The technique was further developed by Reid et al. (1990) for gridded magnetic data and established the term "Euler deconvolution" which is universally employed to locate and estimate depths of magnetic anomalies. An interpretative method of gridded magnetic data which is based on tilt angle derivatives was developed by Salem et al. (2007). The technique estimates the depth and the horizontal location of magnetic geologic structures. With the advent of computer technology, Talwani and Heirtzler (1964) facilitated the calculation of magnetic sources across 2D structures of polygonal cross sections. This two-dimensional forward-modeling procedure was further improved to include structures of finite strike length (Shuey and Pasquale 1973; Rasmussen and Pedersen 1979; Cady 1980).

This paper presents a quantitative and qualitative interpretation of the high-resolution airborne magnetic data of Oyo metropolis. The data interpretation would be complemented by the consideration of all available previous geological knowledge and all information works in this area.

2 The study area

The area under study is located in Oyo metropolis of south western Nigeria which falls between longitude 3°45′–4°00′E and latitude 7°45′–8°00′N. It lies within the humid together with sub-humid tropical climate of southwest Nigeria (Fig. 1). Oyo township lies on the Basement Complex region of southwestern Nigeria,

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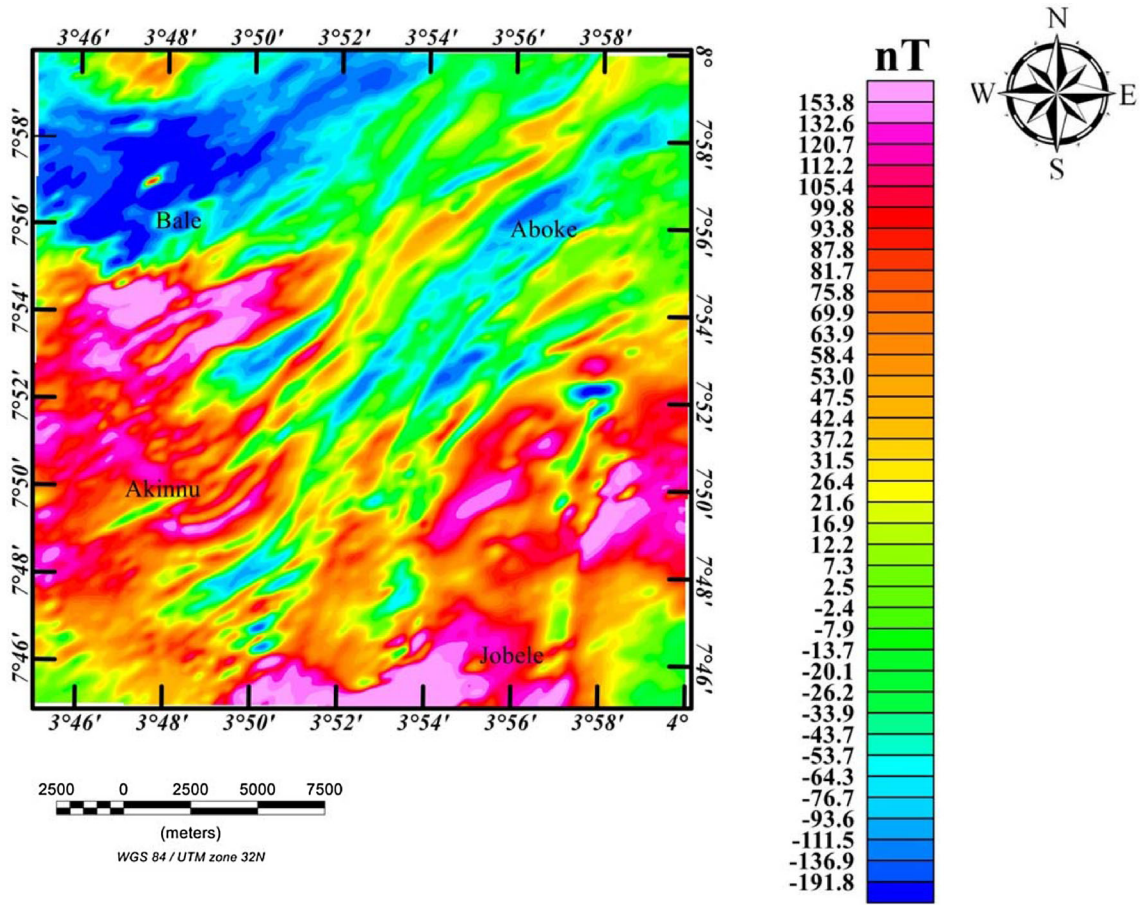


Fig. 3 Total magnetic intensity map of the study area

constituting undifferentiated Gneiss—migmatite complex. Outcrop of rocks in the Oyo metropolis are usually underlain by magmatic gneiss, migmatite, quartzite and undifferentiated schist (Fig. 2). The quartzites occur as extended elongated ridges with NW–SE trending directions and are majorly enormous in nature. The major prevalent rock type in the area are the gneisses, these rocks occur as banded gneisses and granite gneisses with coarse to medium grained texture. Most observed minerals are quartz, feldspar and biotite. Intrusive rocks such as pegmatites are widespread occurring as joints and vein fillings (Adewoye and Adegbola 2017).

3 Methodology

Total magnetic intensity (TMI) map, sheet numbered 243 covering parts of Oyo metropolis, south western Nigeria (Fig. 3) was acquired from the Nigerian Geological Survey Agency (NGSA). The survey was carried out along a sequence of NW–SE flight lines with a spacing interval of 500 m, an altitude of 80 m and tie lines of nearly 2 km interval. The International Geomagnetic Reference Field (IGRF) was used by NGSA to remove the Regional field. In order to delineate and highlight important subsurface magnetic geologic structures, several filtering methods were applied to the TMI grid; these filters were applied using the Oasis Montaj software package. Several range of imaging technique can be applied to airborne magnetic data to visually enhance the effects of important geologic structures using mathematical techniques (Millingan and Gunn 1997). Since the study area is located close to the equator, the TMI map was first reduced to the magnetic equator (RTE), the RTE technique is used to centre the peaks of magnetic anomalies over their sources. This is normally done to

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make the data simpler to interpret. The calculation of inclination and declination were obtained by using the midpoint coordinates of the study area (longitude: 3°52′E and latitude: 7°52′N) and pointed out an inclination of − 9.381 and declination of − 2.910 to a total field of 32, 882 nT.

Table 1 Euler deconvolution magnetic structural indices (Nwankwo and Salawu 2017)

S/N	Source type	SI
1	Contact of considerable depth extent	0
2	Thin sheet edge (sill, dyke, etc.)	1
3	Line source (pipeline, narrow kimberlite pipe, etc.)	2
4	Sphere or compact body at a distance	3

3.1 Regional–residual separation using the fast Fourier transform (FFT)

The energy spectrum for the study area was calculated using RTE airborne magnetic map through the application of the Fast Fourier Transformation (FFT). As a result, a two-dimensional energy spectrum plot was obtained (Fig. 7). Based on the change in the slope of the spectrum plot, the spectrum was divided into two sections; the deep-seated magnetic sources are captured within the low frequency while the shallow sources are obtained within the high frequency region of the region of the spectrum. This technique for separation was applied on the RTE magnetic data using the low-pass and high-pass Butterworth filter to generate the regional and residual maps (Figs. 8 and 9), respectively (Ahmed et al. 2013). The average depth of burial of each source ensemble responsible

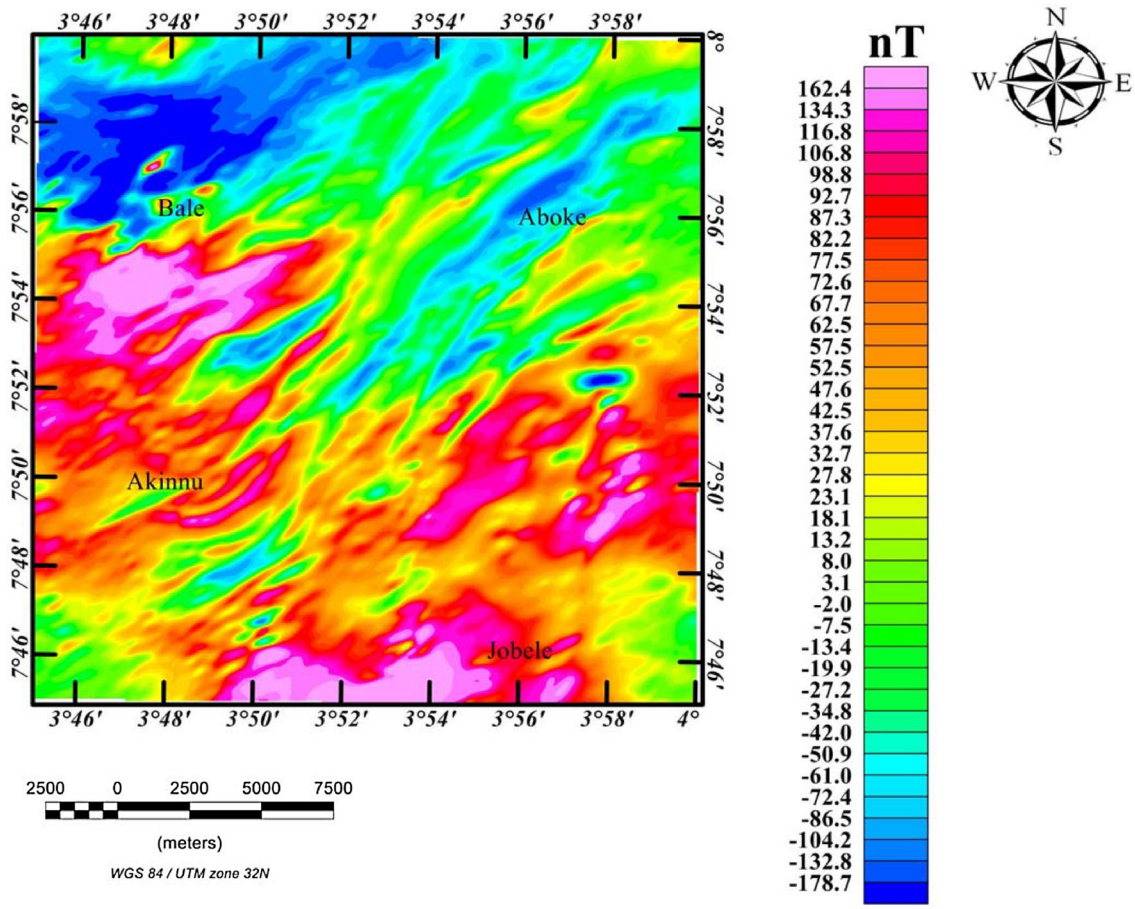


Fig. 4 Reduced to the magnetic equator anomaly map of study area

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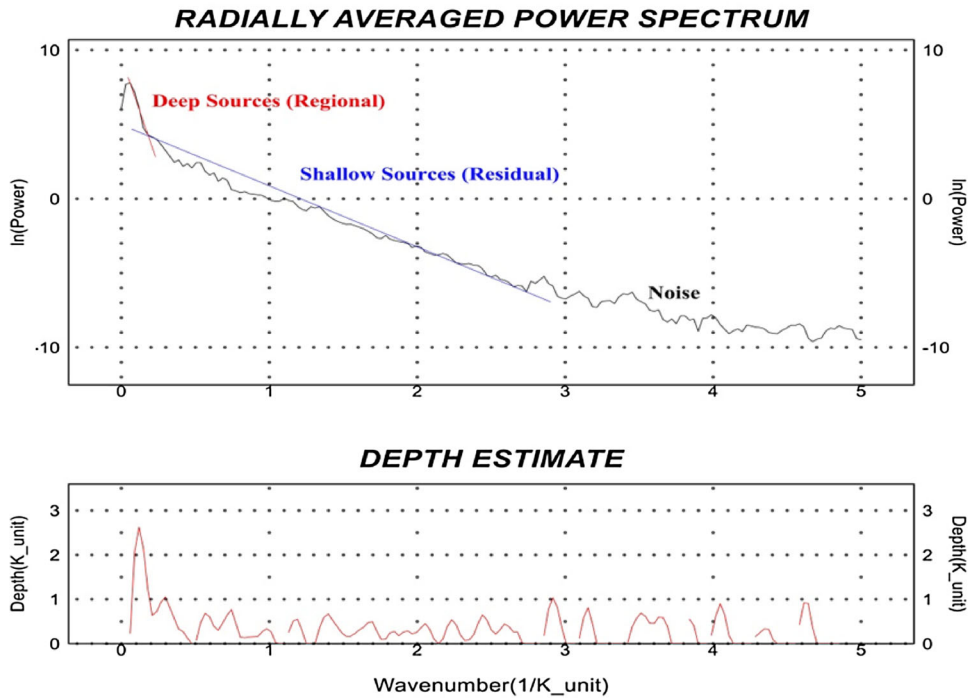


Fig. 5 Power Spectrum of the RTE airborne magnetic data of the study area

for magnetization in each segment was calculated by introducing the slope of this segment in the formula:

$$H(depth) = \frac{-slope}{4\pi} \quad (1)$$

According to the power spectrum plot a low and high-pass filter maps with a cut-off wavelength of 5000 m (wavenumber 0.2 Rad/km) were generated.

3.2 Tilt angle derivative (TDR) method

TDR is a technique routinely applied for mapping subsurface solid minerals exploration target (Saada 2015). It is utilized for enhancing features and the edge of causative magnetic sources normally clarified as lineaments in potential field data (Marwan and Yahia 2017). The tilt angle filter is defined as:

$$TDR = \tan^{-1}\left(\frac{VDR}{THDR}\right) \quad (2)$$

where VDR is the vertical derivative and THDR is the total horizontal derivatives.

The amplitudes of TDR range between − 90° and + 90° irrespective of the amplitude of the vertical derivative or the absolute value of the total horizontal gradient (Salem et al. 2008). The TDR gives a zero value close to the edges of the magnetic geologic source and, therefore, could be used to highlight lineaments which are attributed to the edges of the sources (Miller and Singh 1994). Positive values of the TDR are directly above the magnetic sources and negative are found away from them. Additionally, the horizontal distance between the 45° and 0° position of the tilt angle gives the depth to the top of the contact (Miller and Singh 1994) or the half distances between − 45° to + 45° (Salem et al. 2007).

3.3 2-D Forward modeling

The two-dimensional forward modeling inversion algorithm employs a 2-D flat layered-earth model for geomagnetic response calculations. Each one of the several structural blocks within the model could be extended to plus and minus infinity in the x/y-direction to avoid any artificial lateral magnetic effects, if present. With an iterative procedure done manually, magnetic susceptibility variation and reshaping could be done on each structural block within the model. Furthermore, the geomagnetic response of the modeled layer structure is compared

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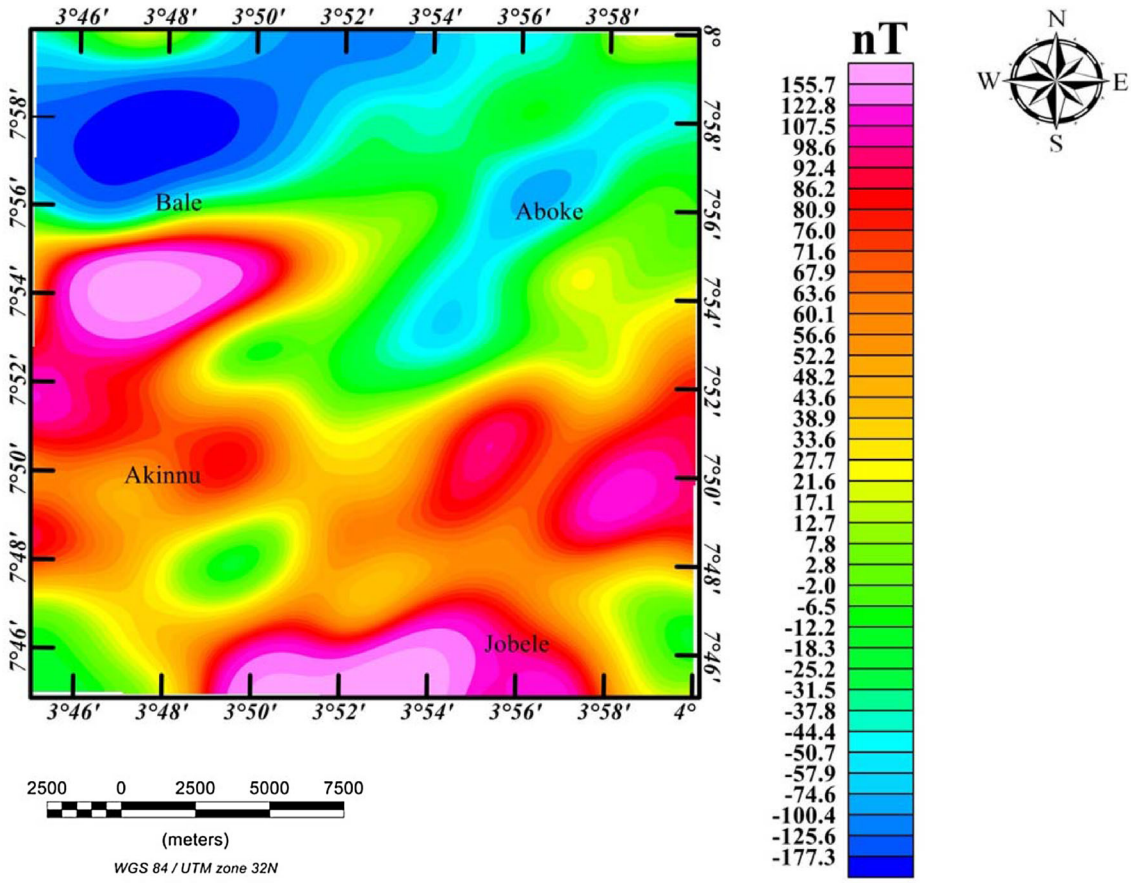


Fig. 6 Regional magnetic map of the study area

to the observed magnetic response until a good fit is noticed and the RMS error is reduced. Hence, it should be noted that prior information are needed for all starting models.

3.4 3D-Euler deconvolution (ED) method

One of the most used geophysical techniques is the 3D-Euler deconvolution method because of its ability to determine the location and shape of magnetic sources from potential field image. It has emerged as a powerful magnetic interpretation method in recent time for the direct estimation of probable source geometry in magnetic data interpretations. The technique can highlight causative bodies such as geological contacts and dykes with observable precision. It has been extensively used for direct interpretation, since it needs no prior information of the source direction and presumes no specific interpretation model. Normally the structural index (N) is fixed and the locations and depths (x_0, y_0, z_0) of causative geologic sources are discovered using the following equation:

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = N(B - T) \tag{3}$$

where T is the observed field at location (x, y, and z) and B is the regional value at the point (x, y, z) and N is the structural index or degree of homogeneity (Reid et al. 1990). Equation (3) is solved for the source position by least-squares inversion of a moving window of data points. In order to acquire a precise estimate of the causative location, the acquired data must properly sample any anomalies present in the data. The window size must be selected big enough to

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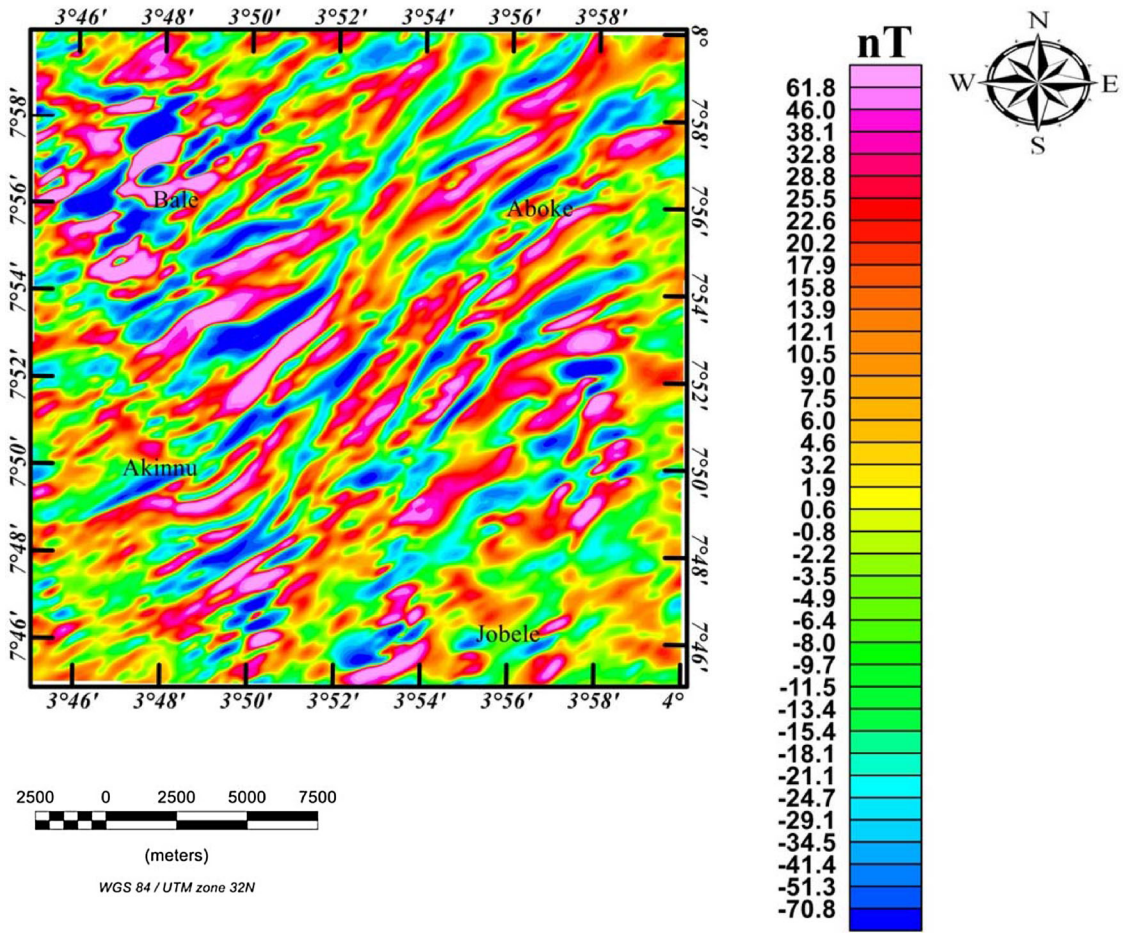


Fig. 7 Residual magnetic map of the study area

contain abundant variation of the field gradient, but small enough not to embrace significant effects from different sources. To obtain a good depth estimate the choice of the structural index must be correctly selected and the data should be adequately sampled (Reid et al. 2013). Table 1, summarizes the structural indices which usually assumes values that range between 0 and 3. While different structural index generate improved cluster solutions for various geologic source types, as expected. The preferred indices are 0 and 1, since geologic contacts and intrusions are prominent within the study area. The RTE grid was subjected to Euler deconvolution analysis using Structural index 0 and 1. The deduced 3D-Euler deconvolution results were later used to produce maps that show the locations and depth of geologic sources of magnetic anomalies of the study area.

4 Result and discussions

4.1 Discussion of the results of TMI and RTE maps

The TMI map in Fig. 3 reflects high amplitude magnetic values along W and SE part of the area. Also, large amplitude magnetic anomalies values are more prominent in the western part of the area ranging from 83 to 154 nT reflecting high level of mineralization. The high amplitude magnetic sources located in these area are mostly felsic intrusive igneous rocks due to their elevated magnetite content and they may have occur due to major several tectonic events which resulted in the basement complex formation. While low amplitude magnetic anomalies are prominent in the N and NE part and few of them were also noticed in

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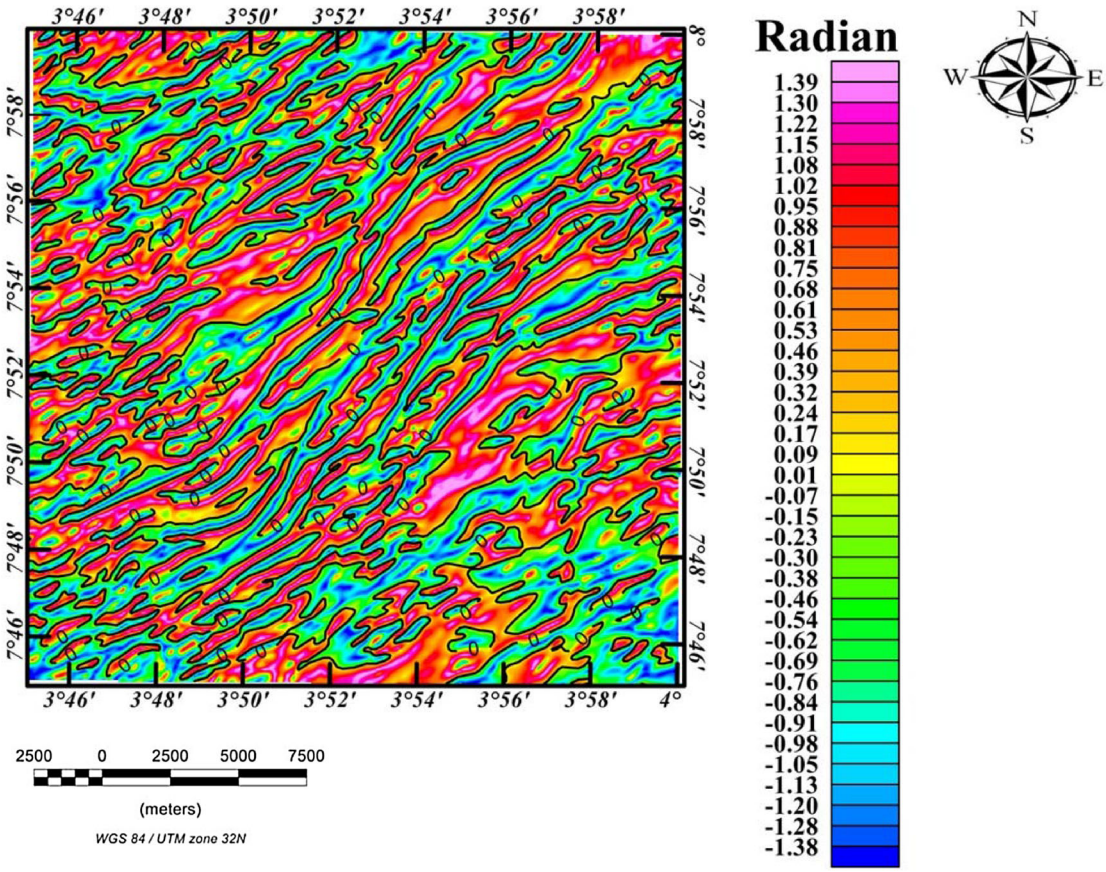


Fig. 8 TDR map of the study area with black lines indicating the 0 rad contour of the tilt angle

the central part of the study area and majority of these anomalies trends in SE–NE directions, ranging from − 191 to 22 nT. The low amplitude magnetic values observed in the study area may be mafic sediments due to their low magnetite content.

The TMI map was further subjected to the Reduce to the magnetic equator; this is normally done to make the data simpler to interpret. The reduced to the magnetic equator (RTE) map produced an enhanced view of the inherited TMI map. Positive anomalies with amplitude (> 60 nT) with elongated shapes were observed mostly trending along WSW and SSE directions. While negative anomalies response with amplitude (> − 178 nT) were also observed in the NNW, NNE and along the central part of the study area. Also, the shapes of the anomalies are centered over their various causative sources which are clearly visible on the map; the RTE technique also highlights the geologic contacts between the areas of high and low magnetic regions which are clearly visible on the map (Fig. 4).

4.2 Discussion of power spectrum, low-pass (regional) and high-pass (residual) maps

The Fast Fourier Transform (FFT) was applied on the RTE map of the area under study, the result is shown in Fig. 5. This spectrum comprises of essentially three components, signifying the regional, residual and the noise signals. The depth estimate chart was used to calculate the average depths to the top of regional (deep) sources which is approximately 2500 m and residual (shallow) sources with a depth of approximately 500 m. According to the spectrum plot, the sources can be separated using low and high passes of the Butterworth filter.

The low-pass (regional) magnetic map (Fig. 6) indicates deep seated magnetic sources with high

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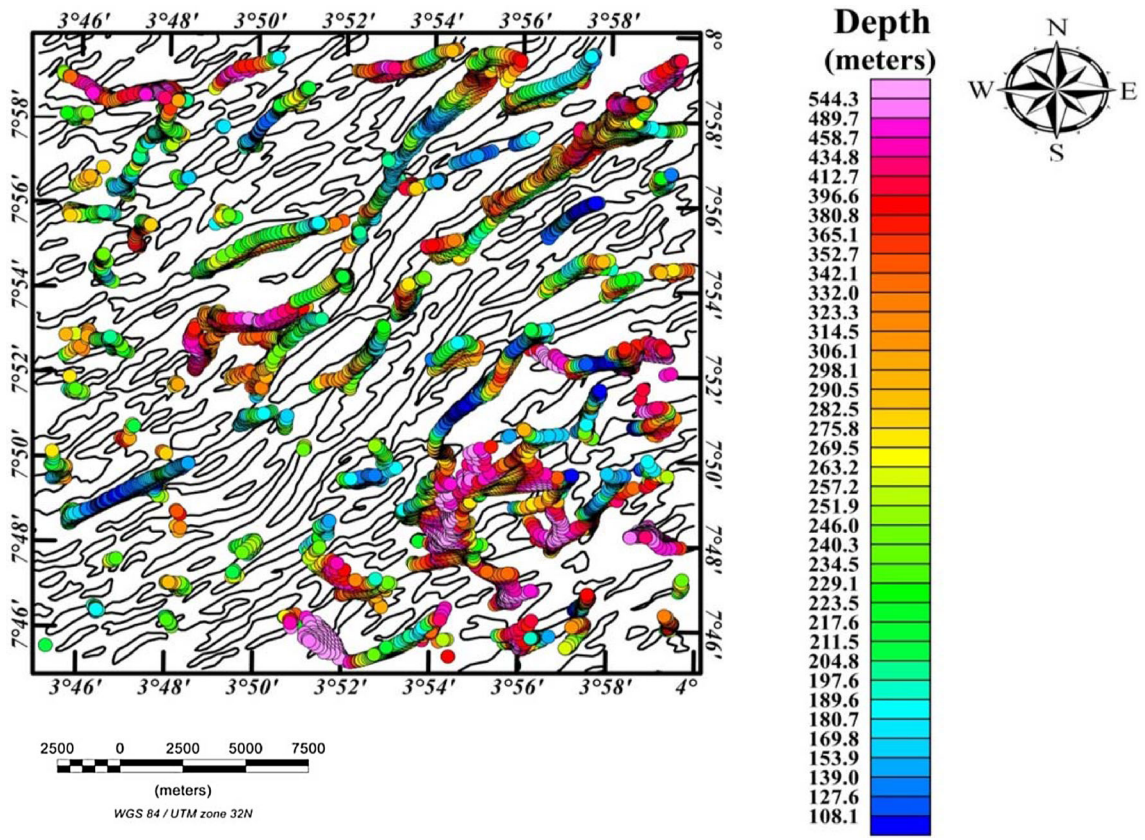


Fig. 9 The Euler solutions superimposed on TDR map of the Study Area for S.I = 1.0

positive and negative amplitudes. Careful investigation of the regional map shows that, many magnetic sources from original RTE map (Fig. 4) continue to appear on the regional map but with slightly low intensity. The regional map highlights the major anomalies affecting the deeper geologic structures of the area. These structures are mainly in the WSW-SSW and SSE-ESE trending directions, with amplitude ranging between 71 and 155.7 nT, these sources may have arisen due to ultrabasic intrusions.

The residual map (Fig. 7) highlights shallow structures which are essential in structural mapping of features like, dykes, geologic contacts, tectonic inferences, etc. We focused on the investigation of the residual magnetic map which shows that, it is characterized by presence of broad and elongated positive magnetic sources, widely distributed across the map mainly in the NE–SW trending directions; some of the magnetic anomalies are of large areal extent. These shallow magnetic anomalies suggests that, the magnetic bodies responsible for the magnetization are extended at depth which could be attributed to pegmatite intrusions and geologic contacts. The variation in anomaly intensity varies from high to low indicating variations in varieties of mineral content of the intrusions. The sources of the high magnetic content could be attributed to micas and tourmaline. The map also assisted to draw and deduce geological intrusion in the study area, these intrusions where fractured and faulted by different tectonic regimes. Taking into account the geological setting of the study area characterized by the presence of faults, this could aid the general abundance of pegmatite intrusion observed in the study area.

4.3 Discussion of Tilt derivative map

The TDR map shown in Fig. 8, highlights subsurface geologic features such as fractures and dykes, which are characterize as lineaments. The locations where

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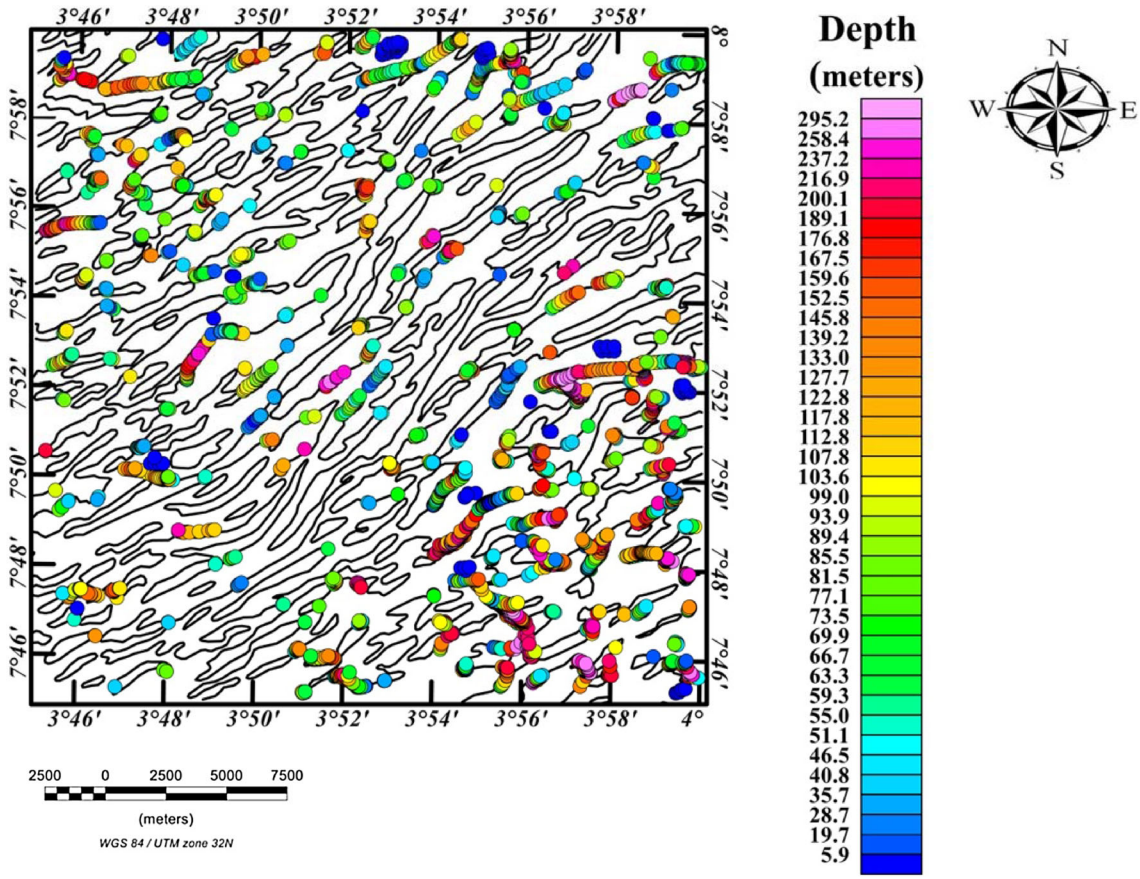


Fig. 10 The Euler solutions plotted on TDR map of the study area for S.I = 0

there are sharp transitions in susceptibilities between the positive and negative sources are suggested as the zero contour lines clearly indicated on the TDR map as black lines. Hence, the lines present the boundary of magnetic geologic anomalies in the study area. The TDR map indicate lineament in the NE–SW trending directions.

4.4 Discussion of 3D-Euler deconvolution results

Depth estimation by 3D-Euler deconvolution technique was applied on the RTE data to delineate geologic intrusion and contacts. The estimation of depths and locations of intrusions are realized with a window size of 2000 m square grids, depth tolerance error of 8%, and a structural index value of 1.0. Figure 9, shows the distribution of Euler solutions for structural index 1.0 superimposed on TDR map of the study area to know the extent of similarity between the methods. The cluster solutions for structural index (S.I) 1.0 give an excellent location and depth estimates for sills or dykes. The results from the depths estimate for S.I = 1.0 which are attributed to pegmatite intrusions are in the range 108.1–544.3 m. Buried pegmatite dikes in the study area are clearly depicted on the Euler map (Fig. 9). The map shows that the pegmatite dykes are widely spread out across the area, these dykes trend in the NE–SW directions, the 3D-Euler deconvolution result for S.I = 1.0, is in good agreement with the geology of the area when correlated with the geologic setting and information of the study area. Abuja leather mining district located in a neighboring local government is one of the productive pegmatite field with lot of mining activates in Nigeria and is known to bear valuable economic minerals such as rare metals and gemstones and associated with

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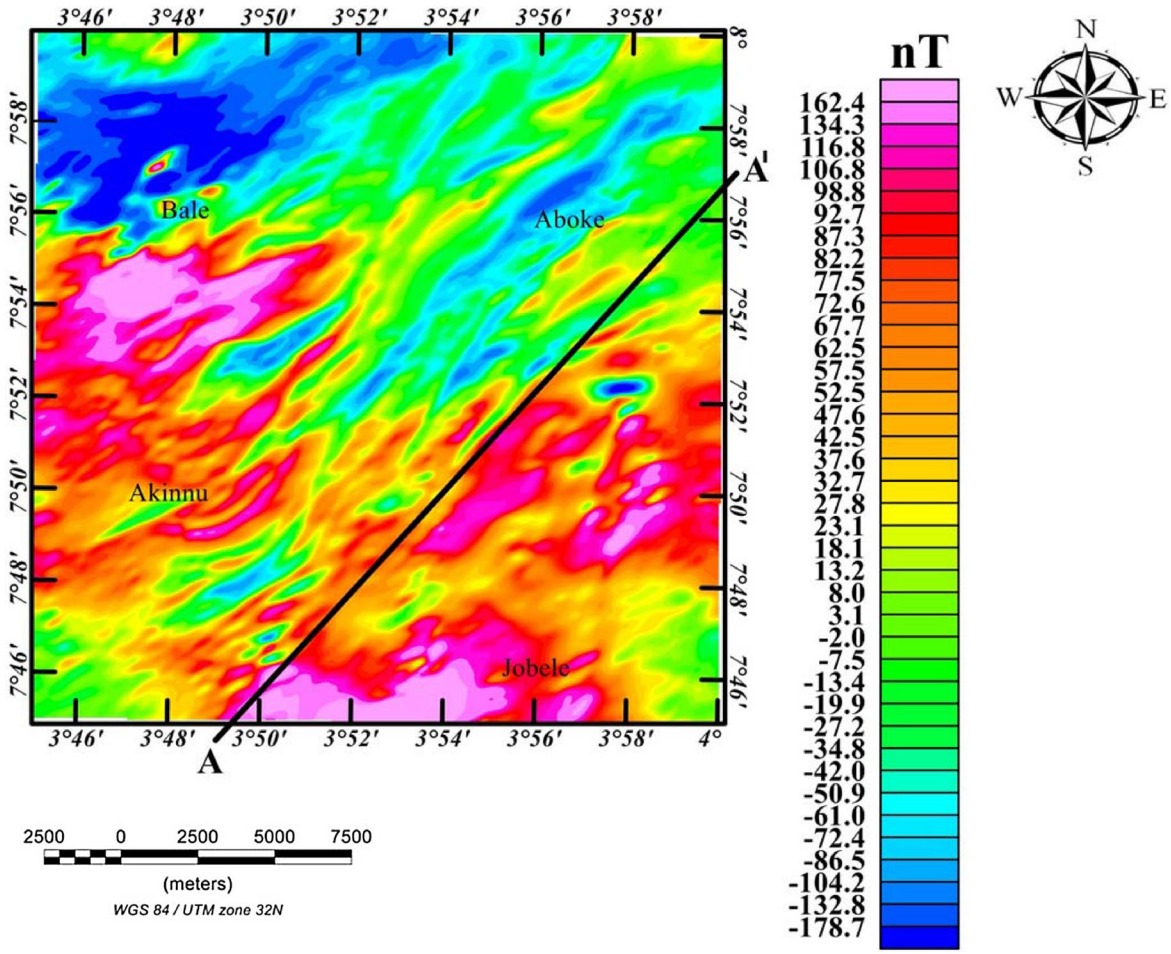


Fig. 11 Reduced to the magnetic equator anomaly map of study area with profile A–A′

Table 2 Maximum volume magnetic susceptibility (Hunt et al. 1995)

S/N	Rock types	Susceptibility (SI units)
1	Quartzite	0.004
2	Schist	0.003
3	Gneiss	0.025
4	Granite	0.05
5	Avg. Acidic igneous rock (pegmatite)	0.082

granite gneiss and the area is not located within the established zone. This indicates the occurrence economic important rare metal pegmatite is not only restricted to the belt alone as described by Wright (1970).

However, the occurrence of fault noticed on the geologic map could affect the orientation of the dykes. Information obtained from borehole drillers in a neighboring community indicates a high availability of Gemstones which occur with pegmatite intrusion, in most case quartz are also found to be in association with pegmatite. The location and depth information depicted on the Euler map gives a potential mineral explorer, target areas for mining expedition. Highly important gemstones are found in association with pegmatite and quartz veins in Basement Complex rocks and Younger Granites. Like the precious metals, gemstones are also important source of Government revenue for a country like Nigeria (Obaje 2009).

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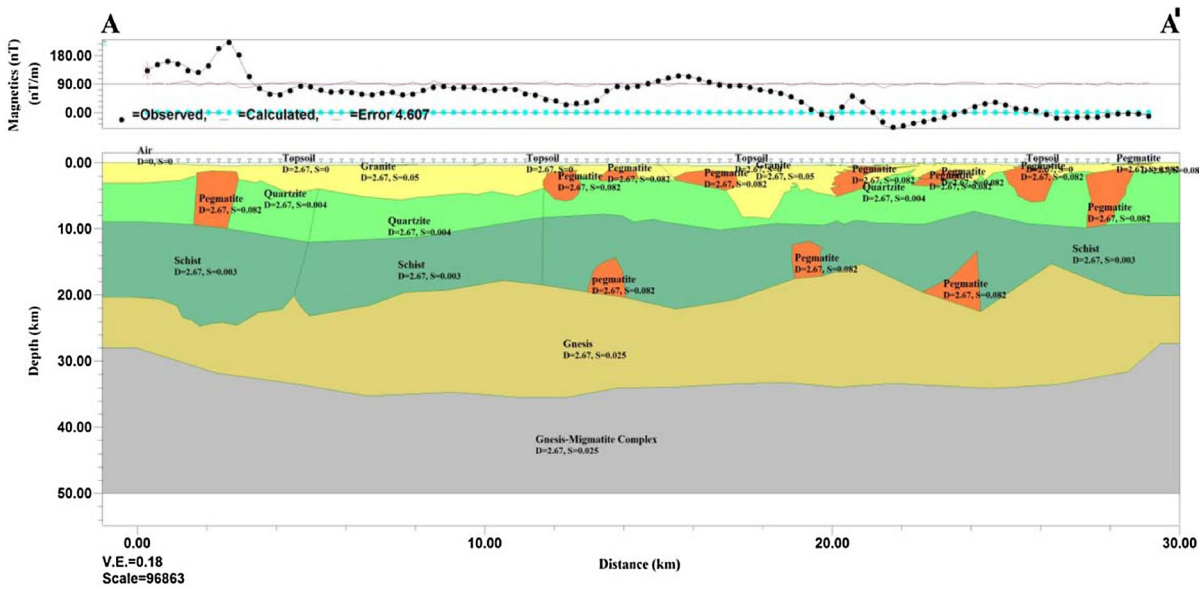


Fig. 12 Magnetic model response of profile A–A′

To emphasize the effects of geological contacts, the window size of 1000 m, with SI = 0.0 and maximum depth tolerance of 14% was chosen and applied on the RTE map. The resulting cluster solutions are plotted on the TDR map to also measure the extent of similarity between the TDR map and the location depth solutions for contacts; this is shown in Fig. 10. These magnetic contacts might represent faults, fractures or geologic boundaries. Therefore, Euler deconvolution technique is said to be a boundary locator. However, the mapped geologic contact could host fluid migration and mineralization. Several unmapped fault within the study area, which appears to be widely dispersed across Oyo Township, and there are clearly shown in Fig. 10, with depths ranging from 5.9 to 295.2 m. Contacts at the top of the concealed intrusive pegmatite are likely areas where concealed associated important mineral deposits may be found.

The 3D-Euler maps (Figs. 9, 10) shows that the subsurface of the study area have great imprints of several intrusions and fracturing widely spread across the study area. In order to have a pictorial view the subsurface of the study area, 2D forward modeling was carried on the RTE map of the area (Fig. 11), various known geological information were incorporated to achieve the best geophysical modeling.

The magnetic profile A–A′ was taken from south direction on the RTE map of the study area (Fig. 11) to visualize the subsurface. Next, several geologic bodies, intrusive rocks were fitted and moved using the maximum volume magnetic susceptibility values from the updated collation of magnetic parameters of rocks standard charts (Table 2) compiled by Hunt et al. (1995) until a good fit was obtained between the calculated and observed magnetic field in order to achieved a reasonable geologic model with error reach of 4.607.

The results of 2-D forward modeling shows similar results to the previously discussed tilt derivative and Euler deconvolution results, The magnetic model (Fig. 12) has shed more light on the existence of fractures and pegmatite intrusions attributed to lineaments in the study area which is in good agreement with the geology of the study area shown in Fig. 2.

4.5 Comparison of TDR with ED and 2D modeled maps

In order to improve the interpretation of the results related to pegmatite intrusions within Oyo metropolis, the deduced results from ED with TDR and 2D forward modeling maps were compared. The presentations of the maps are similar, containing the effects of magnetic geologic anomalies. The tilt derivative map (Fig. 8) clearly depicts both intrusions and fractures within the study area; this shows the

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technique can provide information for both fractures and intrusions. The 3D-Euler deconvolution has the advantage of interpreting known and limited range of established magnetic geologic structures (Table 1). However, these structures have their integer structural index that must be selected when utilizing the ED technique. The ED map (Fig. 9) clearly shows depth solutions attributed to intrusions which are achieved by manually selecting an appropriate integer S.I = 1.0 (Table 1). The modeled profile map (Fig. 12) shows an enhance view of the subsurface of the study area. However, information regarding the subsurface are realized along traverses.

5 Conclusion

This study presents an interpretation of the subsurface magnetic anomalies over Oyo Metropolis, caused by the uneven distribution of the magnetic properties in the subsurface formation. The application of 2-D modeling, 3D-Euler deconvolution and tilt derivative techniques for analysis of the airborne magnetic data, provide the maps that gives useful information of the subsurface structure of the study area, which could be attributed to geologic contacts and pegmatite intrusions.

The RTE map of the study area was first subjected to regional–residual separation, through the application of the Fast Fourier Transformation, in order to separate the deeper sources from shallow sources. Analysis of the resulting spectrum plot indicates the depths to the top of regional (deep) sources is approximately 2500 m and residual (shallow) sources is almost 500 m. The zero contour lines (black lines) of the TDR map was used to highlights subsurface geologic features such as fractures and dykes, which are characterize as lineaments.

3D-Euler depth estimates with a structural index of 0.0 clearly depict locations and depth estimates for geologic contact. The resulted cluster solutions were superimposed on the TDR map with depths ranging from 5.9 to 295.2 m and the map also shows how cluster solutions are widely spread across the study area, it also help delineate several unmapped fault in the area. Also, 3D-Euler deconvolution depth estimates with a structural index of 1.0 located many potential intrusive bodies in the range of 108.1 – 544.3 m across the study area, which may be associated with pegmatite intrusion and undiscovered mineralization. A good correlation was noticed between the TDR and Euler deconvolution methods.

The 2-D modeling was done by incorporating different know geological information to produce the best image view of the subsurface of the study area. The produced model has major implications for mapping concealed mineral resources in the study area. The depth information obtained from the model is in good agreement with results obtained from the 3D-Euler deconvolution technique.

The results, obtained from this study bring new information allowing improvements of our knowledge on the distribution subsurface geological structures of the study area. Recognizable patterns of magnetic sources correspond to geological targets for mineral potential, such as geologic contact and pegmatite intrusion. Analysis on the main features provides new insights into structural framework of the study area and can help geologists target new areas for mineral exploration.

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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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