Subsurface Basement and Depth Characteristics of Iwo-Osogbo, Southwestern Nigeria from Potential Field Data for Mineral Exploration Appraisal

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ABSTRACT

Mineral resources can be harnessed using Earth's potential field maps. Iwo-Osogbo and its adjoining areas' aeromagnetic data were analyzed to unravel the nature of subsurface structures hosting mineral deposits. This is to establish the structural lithological conditions, trend of distribution of ore deposits, and characterize the depth to basement rocks within the area.

The data passed through improved visual processes indicating -36.4 to 151.9 nT as responses of diverse subsurface rocks with varied mineralogical composition. Reflection of linear structures by derivative maps indicates lineaments, boundaries/lithological contacts, and structural geological setting of the basement terrain. The upward continuation 2000 m and 4000 m maps suppressed small, shallow responses for deep extent subsurface features. Major structural trends identified from derivative maps in NE – SW and ENE – WSW directions indicate major geological structures hosting economic minerals in the area. The recognized fracture/fault patterns give insight to their origin to be from structural deformation (tectonic activities) of the basement rocks. Migmatite and dioritic basement rocks at the southern, central, and northeastern regions are responsible for the high amplitude magnetic analytic signal, while low amplitude signals are due to fractured subsurface rocks, undifferentiated schist, and schist pegmatised in the area.

Power spectrum analysis estimated depth to basement and shallow magnetic sources as 1.3 and 0.5 km, respectively. This signifies depth to magnetized bodies or presence of basement structures controlling the mineral bodies in the area. The geologic model revealed rugose basement geomorphology controlled by tectonic activities forming subsurface structures suitable for mineral accumulation.

(Keywords: mineral exploration, aeromagnetic, subsurface geology, depth characterization, subsurface model)

INTRODUCTION

The geophysical techniques involve the characterization of near-surface structure with the purpose of data collection in relation to Earth's interior for the benefit of mankind. The magnetic geophysical method is a potential field method that gives appreciative information of the subsurface geology. Lateral variations in magnetization of the underlying rocks are caused by Earth's potential field (Hinze, *et al*., 2013). It is a non-invasive method often relevant in mining applications, groundwater reservoirs, buried utilities/foundations mapping, geothermal, and hydrocarbon exploration in spite of its eclipsed by seismic reflection surveying (Reynolds, 1997).

Airborne geophysical surveys, especially aeromagnetic and aerogravity, are regional techniques which are more advantageous than its land/ground and marine borne surveys. This can be attributed to its applicability in inaccessible/remote areas and quick regional coverage. Detailed knowledge of the Earth's composition and structure can be inferred from aero-geophysical surveys. Variation of subsurface rock properties shown as anomalous zones from analyzed data are linked to certain geostructures with some minerals (Lowrie, 2007). Magnetic method depends on degree of material's magnetization to the magnetic field. Sedimentary rocks possess low magnetic susceptibility, metamorphic and acidic igneous rocks are associated with intermediate magnetic susceptibility while, basic igneous rocks have high magnetic susceptibility (Kearey, *et al*., 2002).

Improved visual processes are effective in interpretation of potential field data for structural mapping, engineering, and environmental studies (Nabighian, *et al*., 2005). Aeromagnetic data have been successfully utilized to delineate geologic structures, buried intrusions, differentiate intrusive rocks, and different lithology (Masoud and Koike, 2011; Ademila, 2017; Ademila, 2018), surveying salt domes (Reynolds, *et al*., 1991), delineating rocks and minerals with specific magnetic properties (USGS, 2000), evaluation of ore bodies (Biswas and Sharma, 2016) and mapping depth to the curie isotherm for geothermal resources.

Digging/drilling destroys some materials of interest but applications of high-resolution and high-sensitivity airborne geophysical surveys have become archaeological and mineral investigation standard feature. It is endowed with good depth penetration compared with other geophysical methods and is not influenced by high conductivity range of near-surface clayey soils (Mickus, 2004). This makes its application vast in subsurface exploration with information of subsurface rock magnetization useful in mineral exploration. Airborne potential field data had proved to be the most valuable geophysical tool for exploration of oil before the advent of seismic survey. It offers precise information to better understanding of the geologic features and subsurface lithology.

The quest for detailed information on subsurface geology, structures, and depth of basement rocks prompted this analysis of aeromagnetic data of Iwo-Osogbo area with the goal to locate the subsurface magnetic distributions for geological structures identification. It is also to establish the structural lithological conditions, trend of distribution of ore deposits, and characterize the depth of basement rocks.

DESCRIPTION AND GEOLOGY OF THE STUDY AREA

The area is within latitude 7° 35’ and 7° 53’ N and longitude 4° 07’ E and 4° 40’E of Precambrian Basement Complex of Southwestern Nigeria. It falls within the tropical climatic zone, characterized by alternating dry and rainy seasons, with 20°C - 37°C average temperature. Some notable rivers (Rivers; Awon, Oba, Eyinle, Orufu, Osun, and Aro) control the drainage system of the area in a dendritic pattern. Also, high rainfall distribution per annum majorly recharges the groundwater in the area (Ademila, *et al*., 2020).

Rocks in the area include the Migmatite-Gneiss-Quartzite Complex (Figure 1) with the felsic component consists of granitic rocks, aplite, and pegmatite. Apart from the felsic component of the Migmatite-Gneiss-Quartzite Complex, it also comprised of ultramafic rocks and grey foliated gneiss (Rahaman, 1988). Tectonic activities have influenced the basement rocks from Early Proterozoic (2000 Ma) to Pan-African with the age of 600 ± 200 Ma (Oyinloye, 2011).

The Schist belts in the area are noted with concealed mineral deposits with attendance of pegmatites and tourmaline deposits in parts of the area. Charnockitic rock units (charnockites and bauchite), dioritic, and gabbroic rocks are mapped in the area with older granites (Pan-African granitoids) which composed majorly diorites, granites, and dolerites. They are formed from igneous rock intrusion (metasomatic replacement) into emplaced deep igneous rock (Rahaman, 1988). The rocks of this region have been affected by deformation following series of geotectonic events resulting to different rock types exhibiting different structural features. These structural features control and specify the trend of distribution of ore deposits in the study area.

MATERIALS AND METHODS

Iwo and Ilesha environs’ aeromagnetic data (sheets 242 and 243) acquired from NGSA were used for this work. The aeromagnetic data acquired in 2010 were recorded in Geosoft file (X, Y and Z) format. X and Y signify the coordinates (longitude and latitude) of the study area, while Z denotes the magnetic field intensity (nT) of the area. The purpose of magnetic investigation is to locate and describe geologic structures from the lateral variations in magnetization of the basement rocks. The differences in Earth’s magnetic field are as a result of variations in the subsurface geology. Thus, analyzing the potential field data would provide in-depth information of the subsurface structures and geology. Sheets of Iwo and Ilesha (sheets 242 and 243) served as the materials used for this study. The gridded sheets were knitted digitally into a composite grid forming the study area.

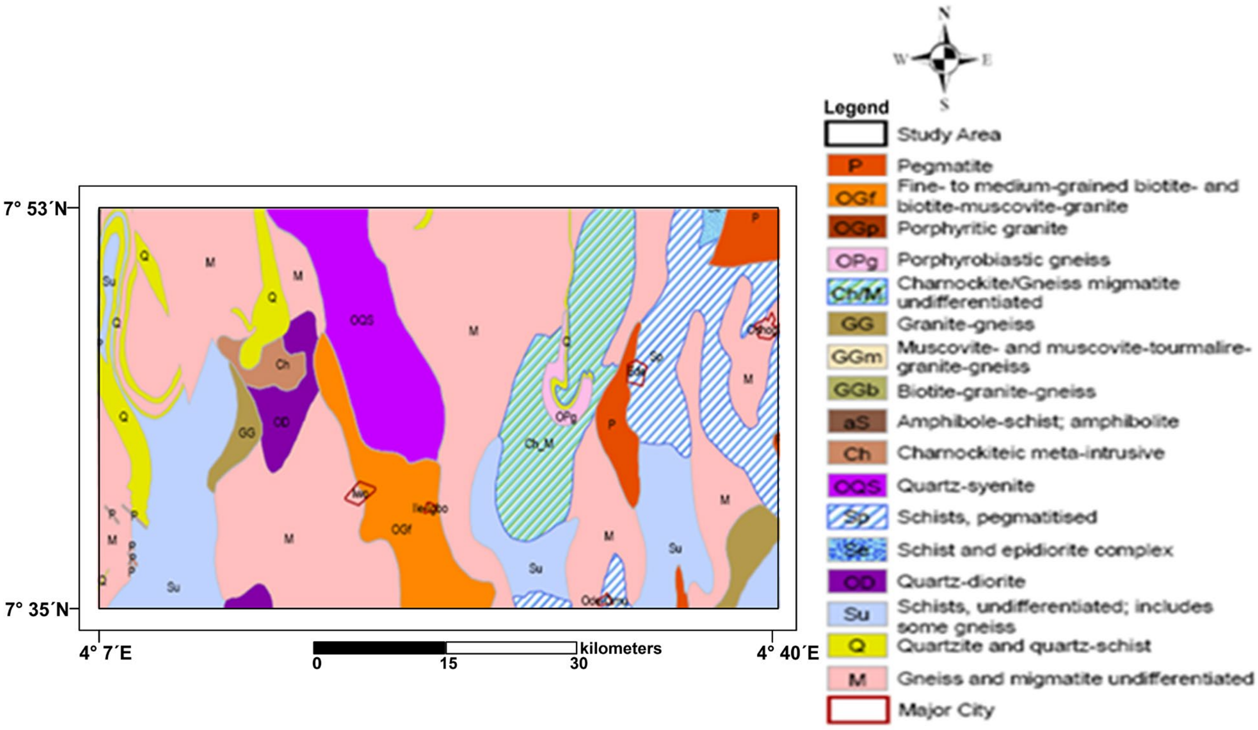


Figure 1: Geological Map of Iwo-Osogbo, Southwestern Nigeria (Nigeria Geological Survey Agency (NGSA) 2009).

Fugro Airborne Survey Limited, Canada acquired the airborne data, pre-processed the data to remove cultural interference from metallic objects, microlevelling, reduce mis-tie and filter noise of no geological interest, supervised by NGSA. 3x scintrex CS3 cesium vapour magnetometer was used for the acquisition of the airborne geophysical data with 100 m, 500 m and 5000 m terrain clearance, flight line spacing and tie line spacing respectively. The flight lines trend at 135° with the tie line direction at 225°. The strength of the local Earth's field is measured as Total magnetic intensity (TMI) data and recorded at resolution 0.001 nT.

Corrected data which highlighted field information of geological importance (TMI data) were interpreted in this work. The International Geomagnetic Reference Field (IGRF) was applied to remove the geomagnetic gradient from the data. The residual field (difference between the measured field and the IGRF) represents the magnetic anomaly. Minimum curvature technique was used to grid the aeromagnetic data to uniformly spaced 100 m cell (Webring, 1981). This technique fits a minimum curvature surface (possible smoothest surface fitting the given data) to required data points by adopting MAGMAP Gx (Oasis Montaj ^{TM} software). The gridding of the data yields the TMI grid and the gridded data resulted to TMI map. The gridded TMI anomaly was reprojected from 32N – 31N (UTM) to ensure that the gridded data correspond to their real coordinates.

The interpretation of magnetic data involves the removal of magnetic effects not relevant to subsurface geology. That is, removal of regional anomalies from the total magnetic intensity resulted to residual anomalies used for qualitative interpretation to highlight local subsurface features masked by broad structures of regional field. The data (TMI anomaly) were further processed for quality result output by means of various data reductions and enhancement techniques. The enhancement commenced with TMI grid reduction to the magnetic equator (RTE) before processing for correction of latitude effect. TMI_RTE map was produced using the RTE filter with the geomagnetic inclination (-11.03°) and declination (-2.56°) such that the magnetic anomalous bodies are realigned, focused, and positioned directly over their causative sources for detailed geological information (Blakely, 1995; Geosoft, 2015).

For the purpose of this work, the gridded RTE_TMI data (Figure 3) served as original processed data for further analysis and improvement from which other maps are produced. The filtering/enhancement techniques, which improve signal to noise ratio were applied to the derived RTE_TMI map. The improved visual processes include residual field, second vertical derivative, tilt-angle derivative, upward continuation, analytic signal, and radially averaged power spectrum. Local field of geological significance from shorter wavelength anomalies were obtained by separating the regional field resulting from gentle trend, characterized by long wavelength anomalies attributed to basement structures from the RTE_TMI anomaly. The effects of near-surface noise (shallow masses) are typically of short wavelength, which can be removed basically by smoothing (filtering out) short wavelength anomalies.

The upward continuation; the principle of continuation is the mathematical projection of potential field data (gravity or magnetic) from one datum vertically upwards or downwards to another datum. This continuation process simulates the residual magnetic intensity at levels below or above sea level as if the magnetic data had been obtained at these levels. Upward continuation is useful in magnetic analysis because it suppresses signals due to small, shallow bodies, while second derivative enhances them.

The RTE data were filtered, thereby soothing signals of short wavelength for deep extent subsurface features (Blakely, 1995; Ademila, 2018). The filtering thereafter shows the effects of depth of continuation as related to crystalline rocks on causative sources (magnetic sources). The upward continuation is used in magnetic analysis to compare measurements recorded at various flight elevations (Telford, *et al.*, 1990). Second vertical derivative (2^{nd}VD) enhances near-surface effects at the expense of deeper anomalies. Second derivatives measure curvature, as large curvatures are related to shallow anomalies by enhancing the resolving power of the gridded data (Gupta and Ramani, 1982). Utilizing this filtering technique in this study completely removes the regional trends, assist in sharpening the anomalies edge for exact description of their positions, extent and depths of existing subsurface geological structures.

Analytic Signal (AS) (total gradient) technique results from the integration of horizontal and vertical gradients of the geological anomalies (magnetic anomalies) and serves as a pattern identification method (Keating and Sailhac, 2004). Its application in depth estimation and generating maximum over the causative source body makes it a vital tool in magnetic interpretation which clearly differentiates geologic boundaries. The maximum identifies the structures accountable for the observed potential field anomalies (magnetic anomalies) over a specific area (Nabighian, 1984; Roest, *et al.*, 1992). Analytic signal amplitude (A) is connected to the amplitude of magnetization with the amplitude of the total magnetic field (T) estimated using Equation (1) (MacLeod, *et al.*, 1993):

$$|A(x,y,z)| = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad \textbf{(1)}$$

Analytic signal amplitude, of the total magnetic field T is derived from the square root of the sum of the squares of the vertical and horizontal derivatives of the magnetic field (its three orthogonal derivatives in the x, y, and z directions). This technique is used in this work to characterize magnetic anomalies, locate depth of the anomaly sources, define the boundaries/edges of magnetic source bodies and visualize their distributions. Tilt-angle derivative (TDR) is an enhancement filter for delineating shallow basement geological features, edges of anomalous source body and positioning anomaly directly above its source (Ademila, 2017; Shahverdi, *et al.*, 2017).

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

First vertical derivative and total horizontal derivative of the potential field are represented as VDR and THDR, respectively.

VDR = $\partial f/\partial z$ (first vertical derivative in z-direction) **(3)**

$$\mathrm{THDR} = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2} \qquad \textbf{(4)}$$

f; magnetic potential field and first derivatives of the field, represented as ∂f/∂x, ∂f/∂y and ∂f/∂z in their respective x, y and z directions.

THDR is the same as the analytic signal but independent of the Earth's geomagnetic field, hence, generates maximum values over magnetic edges sources. It enhances density contrast boundaries, highlights major magnetic sources with respect to their locations.

$$\mathrm{TDR} = \tan^{-1}\left(\frac{\partial f/\partial z}{\sqrt{\left((\partial f/\partial x)^2 + (\partial f/\partial y)^2\right)}}\right) \qquad \textbf{(5)}$$

TDR and THDR are more affected by the reciprocal of depth to source bodies but independent of the amplitude of the total magnetic intensity anomaly (Miller and Singh, 1994; Verduzco, *et al.*, 2004).

In this work, upward continuation filter was applied on the RTE_TMI data (smoothen the data and suppress noise) before the computation of the TDR grid. This filtering technique sharpens the edges of geologic linear features and assists to position anomaly directly above its source (Ademila, 2017). Regional anomalies were suppressed for detailed geological information of the near-surface structures. The method of computing and interpreting the spectrum of potential field data is spectral analysis. It is an efficient 2D technique extensively employed for depth estimation (depth to magnetic sources) and differentiates thickness of sediments in sedimentary terrain from the basement (Spector and Grant, 1970; Blakely, 1995).

Power spectrum of a potential field is a 2D energy function and wave number usually employed in the identification of average depth of source ensemble. The slope of the logarithmic power spectrum was given as the depth of causative magnetic bodies (Spector and Grant, 1970). The basis of spectral depth technique is that its measured magnetic field at the surface is vital to magnetic influence from all depths. The depth estimated is not dependent on the geomagnetic field of the Earth (Thurston, *et al.*, 2002). The spectral analysis utilizing radially averaged power spectrum (RAPS) was employed to establish the depth of geological basement structures within the study area. The process relates the local wave number (K) of the observed field and potential source depth, which can be estimated from a gridded data for any point using vertical and horizontal gradients (Thurston and Smith, 1997).

RESULTS AND DISCUSSION

Improved visual processes employed on the data have modified high amplitude magnetic signals and enhanced its low/weak responses. Thus, the maps generated assist in better understanding of the trends and dimensions/extent of the subsurface structures and depth to magnetic causative bodies.

Total Magnetic Intensity (TMI)

The TMI map displayed in form of 2D colored map (Figure 2) reveal different magnetic anomalous zones with respect to their intensity range. The TMI values in the range -36.4 to 151.9 nT of the study area signifies variations in magnetic contents of the underlying subsurface rocks. This difference in magnetic intensity shows heterogeneous nature of the area. Based on the TMI range, the area is classified as strong positive magnetic anomalous zones, labelled as A towards the northwestern and northeastern parts (108.7 – 151.9 nT) denoting basement rock of high magnetite content (magnetically susceptible mineral), zones of intermediate magnetite concentration symbolized as B (Figure 2) with magnetic intensity range of 60.2 – 102.8 nT trending the northwestern and southern regions of the area. The zones tagged C showed low magnetic response as shown in Figure 2 at the southwestern and southeastern parts of the area, having magnetic intensity range of -36.4 – 58.1 nT indicate zones of low magnetite concentration.

The variation in magnetic intensity observed in the area is attributed to varied mineralogical composition of the underlying rocks, existence of concealed geological structures and tectonic architecture of the area. Presence of F1 – F1', F2 – F2', and F3 – F3' (fault) orienting south, northwest and northeast indicates deformed subsurface geologic setting of the area resulting from tectonic activities. This could also be due to the coincidence of lithologic units of high susceptibility differences. RTE_TMI map reveals differences in the magnetization of underlying rocks in the area as observed from different magnetic anomaly shapes (ellipsoid, circular, elongated, curvilinear, semi-circular) situated over their causative bodies. The Earth's geomagnetic field has caused insignificantly difference in RTE_TMI and TMI maps (Figure 3). The reduced to equator (RTE_TMI) map shows that the magnetic field of the area towards the southeastern and northwestern parts has a maximum relief of approximately 150 nT and minimum relief of about -27 nT towards the northeastern and north central regions of the area as shown in Figure 3. This is responsible for uneven topographic relief of the area.

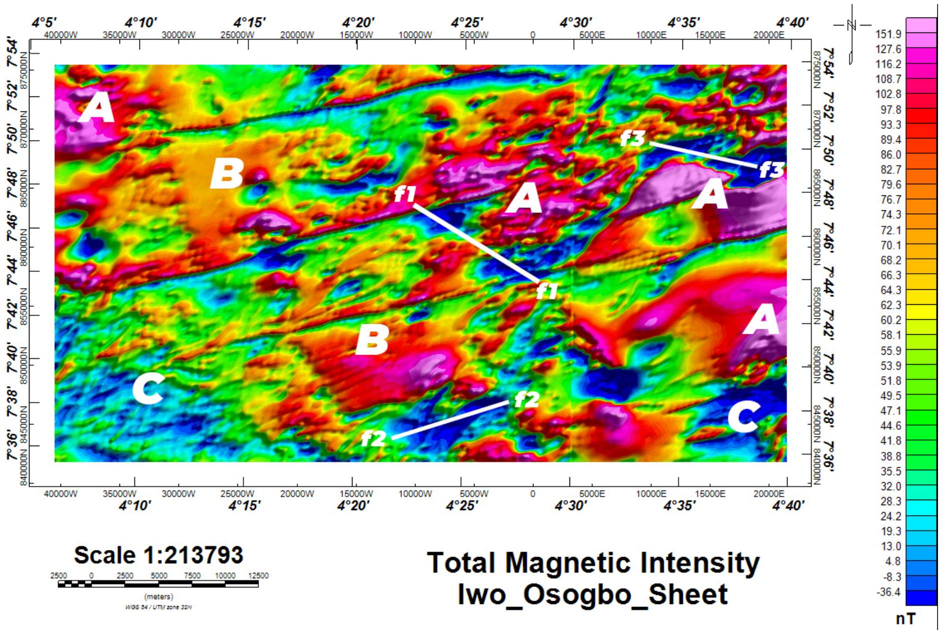


Figure 2: Map of Total Magnetic Intensity of the Area.

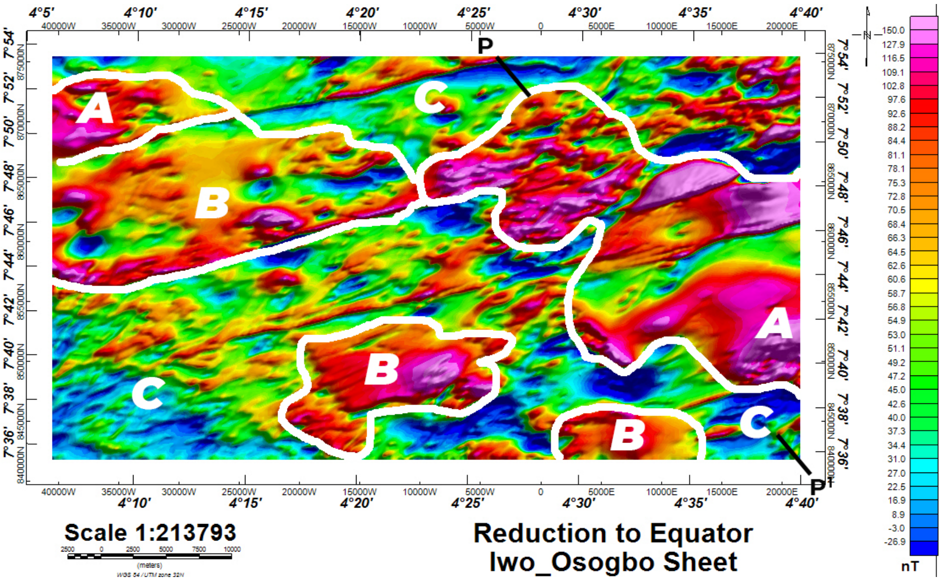


Figure 3: RTE_TMI View of the Area.

Varied amplitude peaks reflect variations in the magnetization, characteristic/attributes of zones of lithological contact of different magnetic susceptibility. The anomalous bodies are distinguished by diverse nature, thus revealing changes in the topography. Majorly, three magnetic zones are delineated; high amplitude magnetic anomaly (109.1 – 150.0 nT) towards northwest and southeast, tagged A. These high magnetic amplitude anomalies suggest the presence of high-rise magnetic basement rocks; which geologically represent migmatite, dioritic, gabbroic, and older granite rocks in the area. These anomalies indicate subsurface geological structures and concealed ores. At the southwestern and western end, intermediate amplitude anomaly (68.7 – 97.6 nT) labeled B is observed, while northcentral and northeastern end showed prominently low to moderate magnetic amplitude (-26.9 – 56.8 nT) anomalies.

This geologically represents weak magnetic felsic medium-grained biotite and porphyritic granite in the area. The anomalies are characteristics of sharp magnetic edge/boundaries, indicative of near vertical/steeply dipping geologic features (fault, fracture or lithological contact). Strong magnetic anomalous structures of varied sizes and amplitudes trending differently in the area contribute to rugose form and nature of the subsurface basement rocks. The negative anomalies reveal faulted/fractured zones within the basement complex with higher magnetic susceptibility.

Residual Anomaly

The residual anomaly images of geological significance (Fig. 4) obtained by separating the regional field from the observed RTE_TMI anomaly highlighted the variation of magnetic susceptibility of subsurface rocks within the area. The residual anomalies were generated by reducing the total magnetic intensity with the regional anomaly. It is employed to view anomalies that are influenced only by definite sources, which clearly shows shallow anomalies that could not be simply delineated in Figure 3. It reveals a pattern that is more composite than the regional anomaly with respect to magnetic susceptibility and concealed lithology.

The residual anomaly showed that the magnetic field intensity of the area is in the range -85.97 nT (anomaly minimum value) to 73.18 nT (anomaly maximum value) as shown in Figure 4. The anomaly pattern associated with a shorter wavelength reveals shallower near-surface effect.

The positive residual anomaly (29.74 – 73.18 nT) towards the northeastern, northwestern and southeastern side of the area tagged H indicates the existence of near-surface/surface outcrops. The anomalies reflect diverse shapes, forms, and polarities trending in different patterns, and directions. High rise migmatite and dioritic basement rocks reflect higher amplitude anomalies having rugose magnetic texture. -0.92 to -85.97 nT (negative residual anomalies) represent minimum residual anomaly in the area.

The trend, size, polarity and nature of the anomalies show that the area is characterized by high and low magnetic signature. Elongated near vertical/linear geological features shown in black lines towards west and northeastern ends (lineaments, contacts, and faults) (Figure 4) are indicative of fractured basement rocks. Major fractures (F1 – F1' and F2 – F2') identified in white lines also traversed the northeastern and southeastern regions of the area constituting distinct setting of the area.

The moderate region is associated with high ferromagnesian rocks of low concentration of felsic minerals of granite-gneiss, while the undifferentiated schist and schist pegmatised in the area are responsible for the low magnetic amplitude. Fractured basement trending NE – SW and ENE – WSW are indicative of geotectonic features. Migmatite rocks at the southern, central and northeastern regions are responsible for the high amplitude magnetic analytic signal. The observed geologic structures (faults, fractures, lithologic contacts and lineaments) serve as fragmented zones hosting potential minerals in the area which could be exploited for economic purposes.

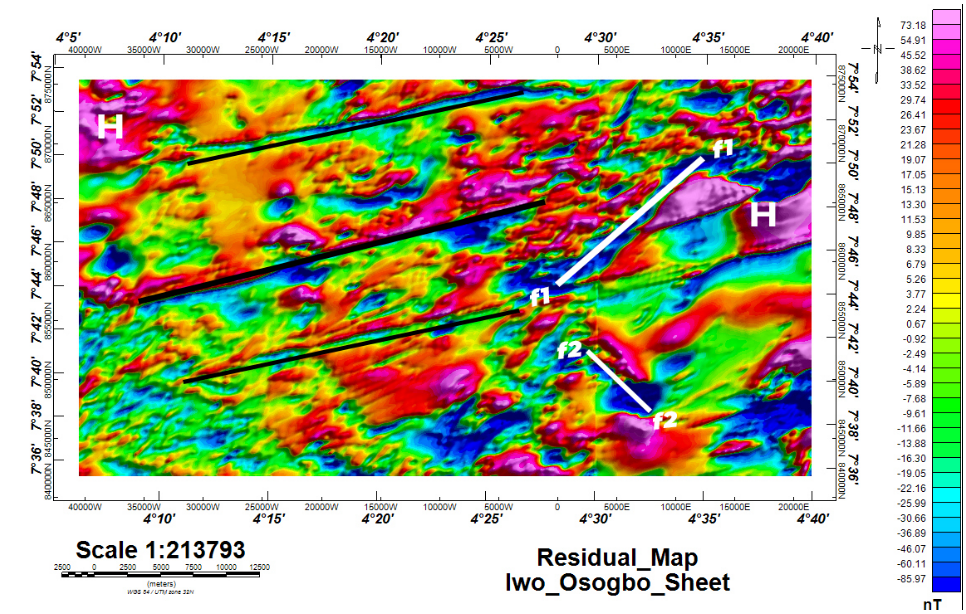


Figure 4: Residual Magnetic Anomaly Map of the Area

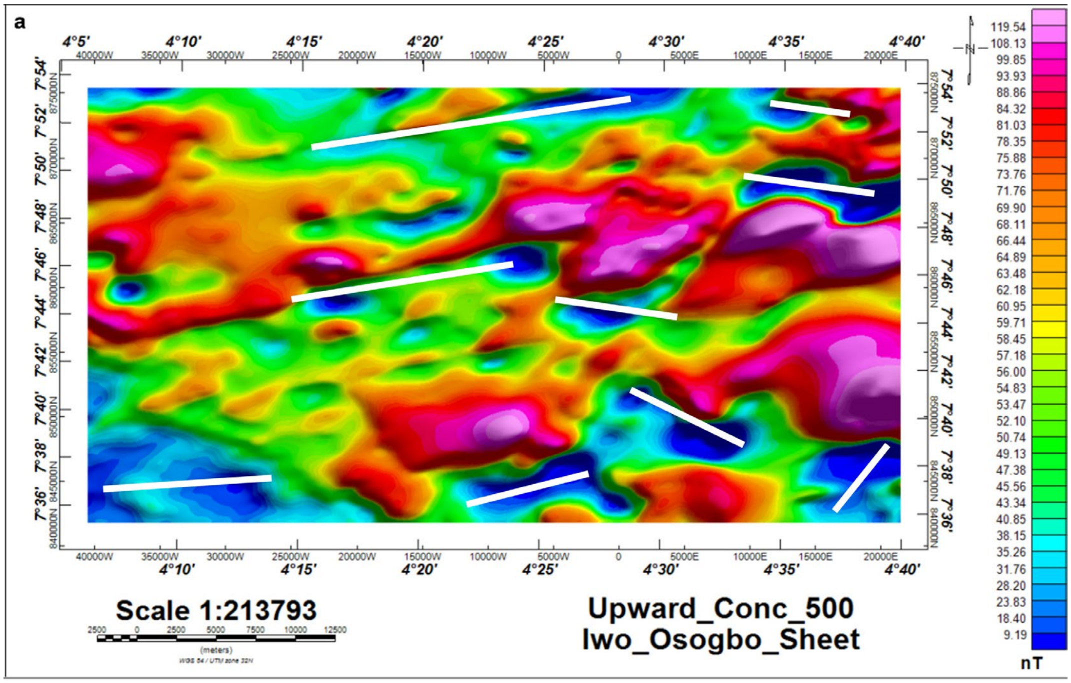
Upward Continuation

Upward continuation filtering technique minimizes near-surface (shallow sources) and noise effects for detailed information on deep-seated (deeper) anomalies. It filters the near-surface features (high wave-number anomalies) and improves relatively the deep-seated anomalous sources by emphasizing response from basement rocks in the area. It's capable of evaluating measurements at different flight elevations (Telford, *et al.*, 1990; Blakely, 1995). Upward continuation smooth-out shorter wavelength anomalies (near-surface effects) having calculated the potential field (magnetic and gravity field) at higher elevation than that of the determined potential field (Hakim, *et al.*, 2006; Ademila, 2018).

It also reduces the amplitudes of the shallow anomalous bodies/features and decreases noise. Gridded data of RTE_TMI anomaly was filtered at 0.5 km, 1 km, 2 km and 4 km. This is carried out to understand the characteristics of basement geological features with depth. Essentially, this improved visual process influences continuation depth on magnetic anomalous bodies by determining trends of deep (regional) features. This filtering technique evidently demonstrates the reduction/ attenuation of shallow anomalies (short wavelength anomalies) with increasing level of source distance. The produced maps reveal varying magnetic source anomalies with depth of continuation. Four upward continuation maps were generated at 500 m, 1000 m, 2000 m and 4000 m from RTE_TMI gridded data. Generally, high to very high magnetic anomalies of > 63.88 nT are seen towards northwestern, northeastern, southern and southeastern parts trending approximately NE – SW and ENE – WSW directions.

Regions of high to very high positive magnetic anomalies characterized by irregular shapes, positive polarity, and anomaly size in the range 63.88 – 119.54 nT (Figures. 5a – 5d) implies the presence of subsurface high magnetic basic intrusion. These high positive anomalous bodies at these parts of the study area clearly show zones of deep lying crystalline basement rocks highly rich in magnetic mineral components (Ademila, 2018).

The southwestern, parts of the southern section and northern parts are characterized by low to intermediate magnetic anomalies (< 63.88 nT) in dome-like, circular, elongated curvilinear and ellipsoidal shapes. Low to moderately low anomalous zones at specific stations have pronounced features seen above 500 m (0.5 km) and 1000 m (1.0 km) (Figures. 5a and 5b respectively). These features diminish as the upward continuation depth increases to 2000 m (2 km) (Figure 5c) and finally disappear as the depth of continuation goes beyond 2 km (Figure 5d).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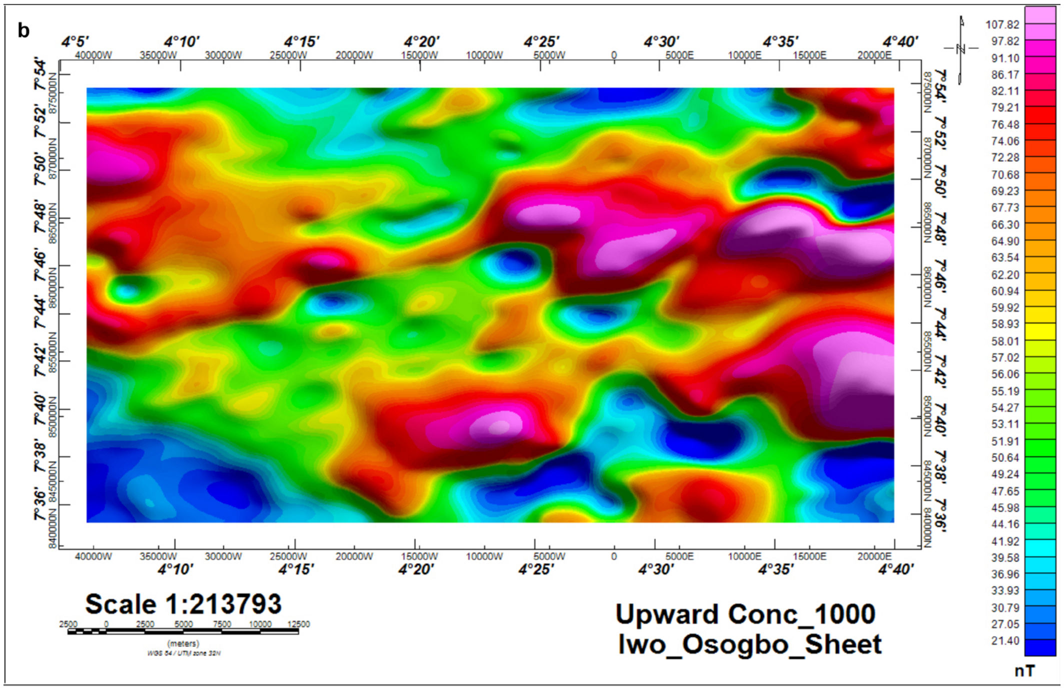
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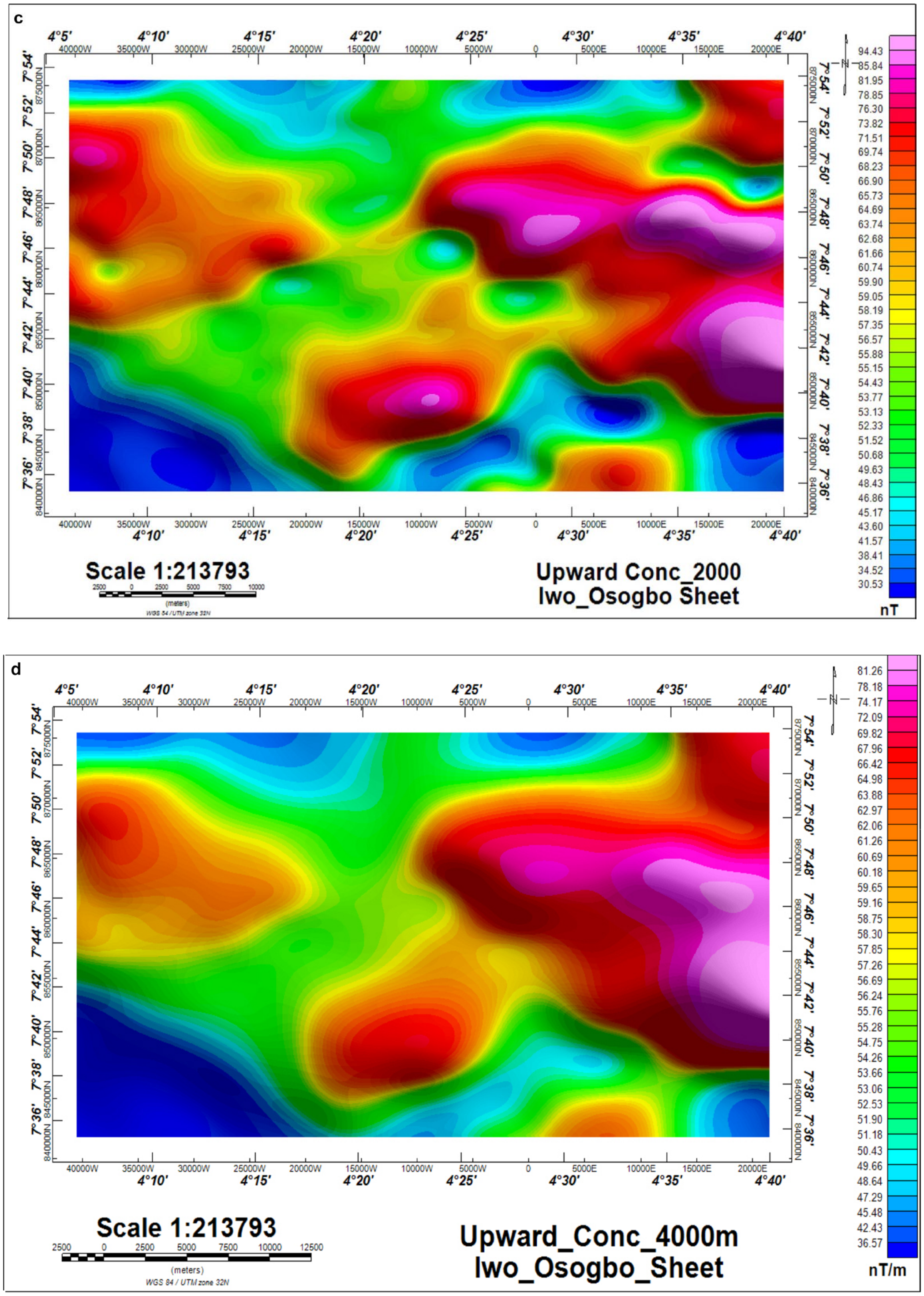

Figure 5: Upward continuation maps at 0.5 km (a), 1 km (b), 2 km (c) and 4 km (d).

Basement rocks in the area trend towards NE – SW and ENE – WSW directions as shown in Figure 5d. Observation of the upward continuation maps to 500 m (Figure 5a) and 1000 m (Figure 5b) show most features similar to the RTE_TMI map, while the upward continuation 2000 m and 4000 m maps suppressed small, shallow responses for deep extent subsurface features (Figures 5c and 5d). Consequently, observation of the upward continuation 4000 m map (Figure 5d) shows the major high magnetic anomalies at the northeastern, southern and northwestern parts of the area.

The high amplitude magnetic regions are majorly in Osogbo area. The upward continuation map (Figure 5a) reveals deep magnetic bodies and lineaments which correlate with the lineaments from the second vertical derivative (2ndVD). This implies the continuity of magnetic bodies from shallow to deep level. This forms the conduit/pathway for the migration of the hydrothermal mineralizing fluid from the deepest part of the Earth to shallow structures, through which the auxiliary fractures were mineralized. The lineament mapped from 2ndVD which correlates with lineament from upward continued map are associated with hydrothermal alteration zones, while lineaments delineated from upward continuation map but not shown on 2ndVD is related to deep magnetic bodies.

Second Vertical Derivative (2ndVD)

Derivatives of the potential field data improve the component of the field related to shallow/near-surface geologic structures and deemphasize field component of deeper causative sources. The 2ndVD map (Figure 6) highlights the shallow magnetic signal without attenuating the deeper/basement magnetic anomalies. It sharpens the response of shallow sources and aids in the determination of edge/boundary of anomalous body. The filter also improves the resolution of weak shallow features. Subsurface linear elongated signatures on the map (Fig. 6) are due to the existence of geological structures (fault, fracture, and lineament) dislocating the basement rocks in the area.

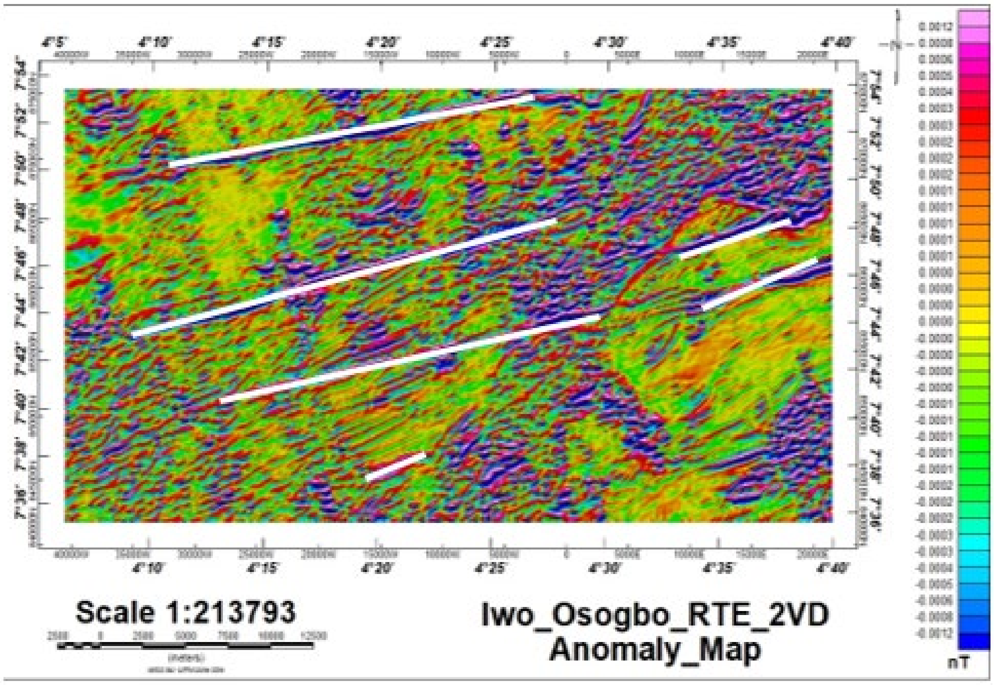

Figure 6: Second Vertical Derivative Geomagnetic Map of the Area.

The 2ndVD map shows shallow/near surface sources mainly lineaments/faults trending approximately NE – SW and ENE – WSW directions (Figure 6). The mapped faults and lineaments in the area suggest their origin from intense structural deformation (tectonic activities) of the basement rocks. The map shows the precise positions of the lineaments and location of the lithological contacts in the study area. The anomalies are emphasized and repositioned with the aid of a second vertical derivative filter and show related structures as that of the residual magnetic anomaly map (Figure 4). The 2ndVD geomagnetic anomaly map (Figure 6) shows improved edges/boundaries of elongated linear structures and location of near-surface magnetic features in the area. Transversely distributed low and high magnetic signals in the area are associated with fractured/faulted granitic and migmatitic basement rocks.

Tilt-angle derivative (TDR)

The tilt derivative (TDR) techniques are efficient in providing information related to geologic anomalous source features with depth. It is capable of delineating shallow structures, identifies edges of lineaments and contact locations of linear and continuous geological structures at depth. It has been successfully utilized to enhance weak anomalous structures obscured by strong features and disclose zones of anomalous structures that are minimally affected by noise within reliable repeated depth estimates (Salem, *et al.*, 2007). The tilt angle derivative filtering technique positions anomaly directly above its causative source and subtle anomalies not pronounced on other maps are resolved on the tilt angle derivative map (Ademila, 2017). The filter offers an alternative means of improving shallow anomalous sources and preserving geologic information on deep-seated sources.

The magnetic TDR (Figure 7) map reveals the enhanced edges of linear structures and structural geological setting of near-surface of the subsurface terrain. These geological structures could be related to shallow and deep-seated basement structures (Miller and Singh, 1994). The TDR map was grey shaded to enhance shallow structures in the area, thus represents the lineament/fault map of the study area. Major structural trends are identified from the map in NE – SW and ENE – WSW directions (Figure 7).

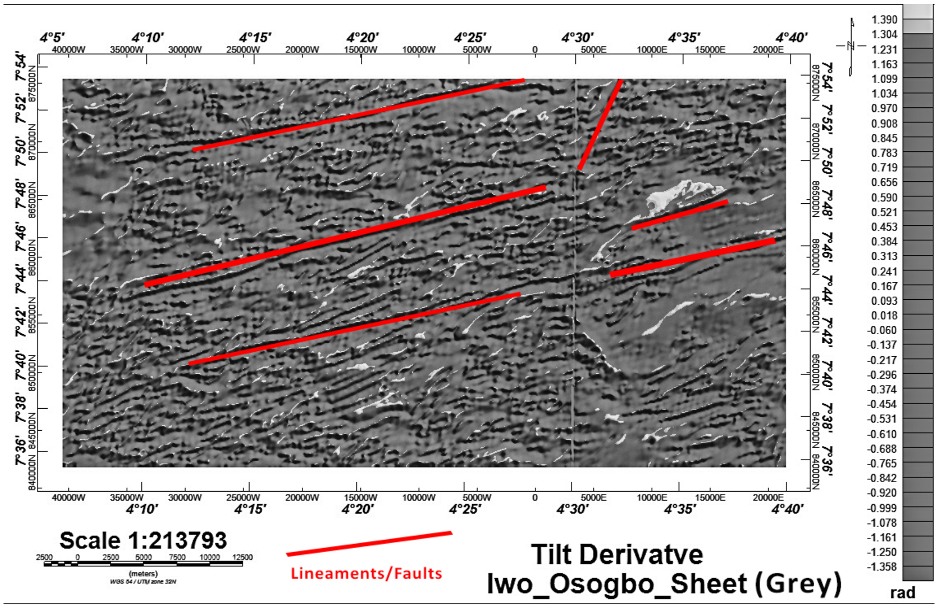

Figure 7: Tilt Derivative Grey Colored Magnetic Map of the Area.

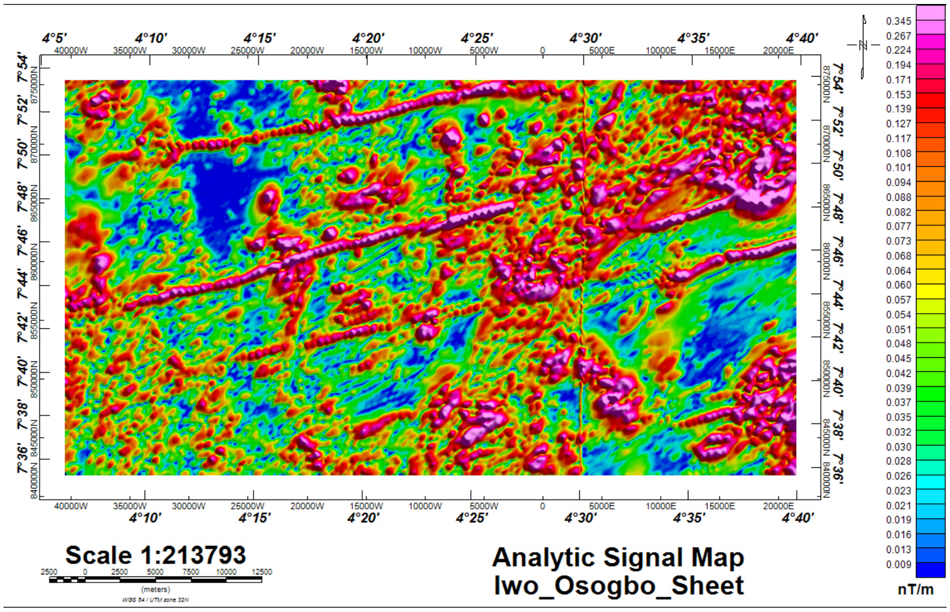

Figure 8: Distribution of Magnetic Anomaly Analytic Signal of the Area.

The recognized fault patterns give insight to their origin resulting from structural deformation (tectonic activities) of the basement rocks. Observed alternation of high and low magnetic signatures in the area are responsible for variation in lineaments orientation. These varying trends of geologic features specified in this study signify the fractured nature of the basement terrain.

Analytic Signal (Total Gradient Method)

The map of the analytic signal shows the distribution of compact magnetic signatures (Figure 8). The maximum amplitude (amplitude peaks) of analytic signal is appropriate in distinguishing geologic boundaries (Roest, *et al.*, 1992). This is employed to identify edges (boundaries) of anomalous magnetic susceptibility distributions in subsurface rocks. The response of analytic magnetic signal is classified into three groups; high magnetic, intermediate magnetic and low magnetic signature. The amplitude peaks in the area indicate differences in magnetization relating to lithologic contact zone of varying magnetic susceptibility.

High amplitude anomalies in the northeastern, central and southern parts correspond to high magnetic signatures in the range 0.101 – 0.345 nT/m (Figure 8). Moderate analytic signal zones (0.030 – 0.094 nT/m) as shown in Fiure 8 are connected to the presence of granite-gneiss (highly rich ferromagnesian rock of low content of felsic minerals). 0.009 – 0.030 nT/m at the southeastern and northwestern characterizes low amplitude signal which are of substantial magnetic susceptibility due to presence of schist, biotite granite, metasediments and gneissic rocks rich in felsic minerals.

2D radially averaged power spectrum (RAPS)

Spectral analysis is a method used in estimating and analyzing spectrum of potential field data, effective in transforming functions from one domain (time or space) to another (frequency or wavenumber). It is used to transform the magnetic data into two-dimensional radial energy spectrum. Thus, its usefulness in diverse functions of convoluting, data filtering, and frequency content analysis of geophysical data. The 2D power spectrum was estimated and presented in form of logarithmic plot of energy against wavenumber (Figure 9). It is used to determine the average depth of source ensembles, that is depth to subsurface geological structures (Spector and Grant, 1970; Ademila, 2018).

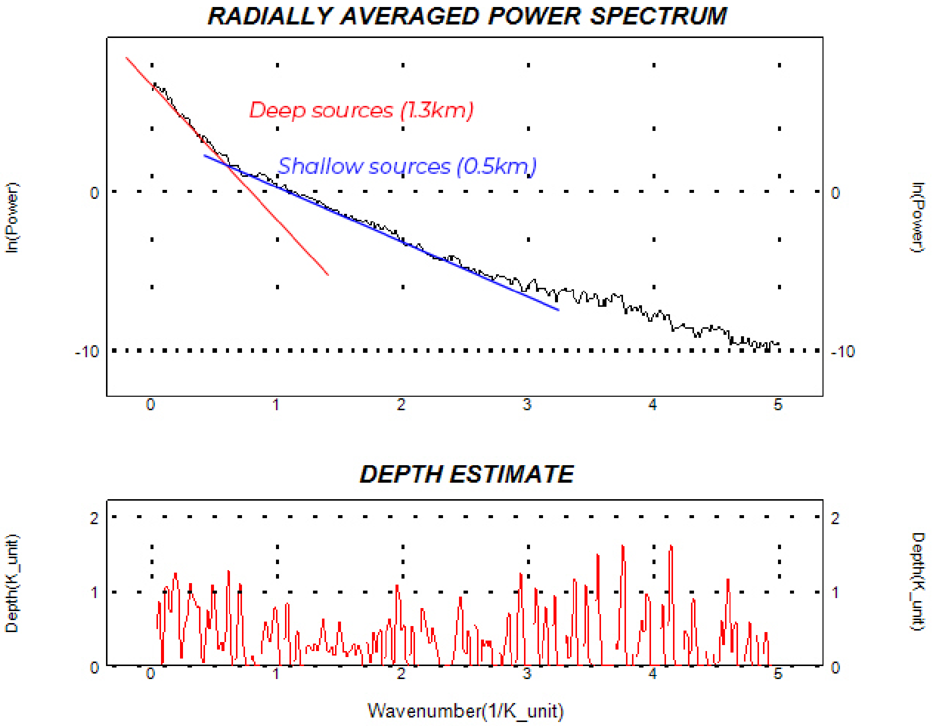

Figure 9: Radially Averaged Power Spectrum (RAPS)/Spectral Plot of RTE_TMI Data.

The regional, residual and noise effects can be evaluated from the power spectra curve (Ross, *et al.*, 2006) with the section parallel to the wavenumber axis on the RAPS curve denoting the presence of near surface/shallow sources, used for estimating depth to top of causative anomalous sources.

The section of the RAPS curve parallel to the spectral energy axis implies deeper sources useful for determining basement depth. The depths evaluated are used to identify the top of the anomalous source bodies in the area. Geological information of depth of causative bodies were obtained from the slopes on the spectral plot (Figure 9) with the segment of low wavenumber associated with deep seated anomalous sources while the section of high wavenumber is related to shallow anomalous sources. The 2D power spectrum of the airborne magnetic data (Figure 9) gives information on depth of basement surface. Thus, indicate that the mean depth estimated to the top of deep seated and shallow magnetic sources are 1.3 and 0.5 km respectively. This represents depths to Precambrian basement rocks and its related geologic structures (Ademila, 2017). It could also signifies depth to magnetized bodies or presence of intra-basement structures (faults and fractures) controlling the mineral bodies in the area.

2D Geological Model

2D geological model was constructed from profile P – P´ (Figure 3) to image the structural geological settings of the area. The 2D subsurface model produced (Figure 10) revealed the basement geomorphology of the area. The 2D geomagnetic model highlights irregular geological rock setting associated with major geotectonic features hosting mineral deposits.

The modeled structure (Figure 10) shows different characteristics of magnetic anomaly dipping across the area. The geological model reveals moderately gentle topography and thick overburden of the area. The observed magnetic anomalies are attributed to the topographic variation of basement relief with the expression of structural magnetic highs and lows across the area.

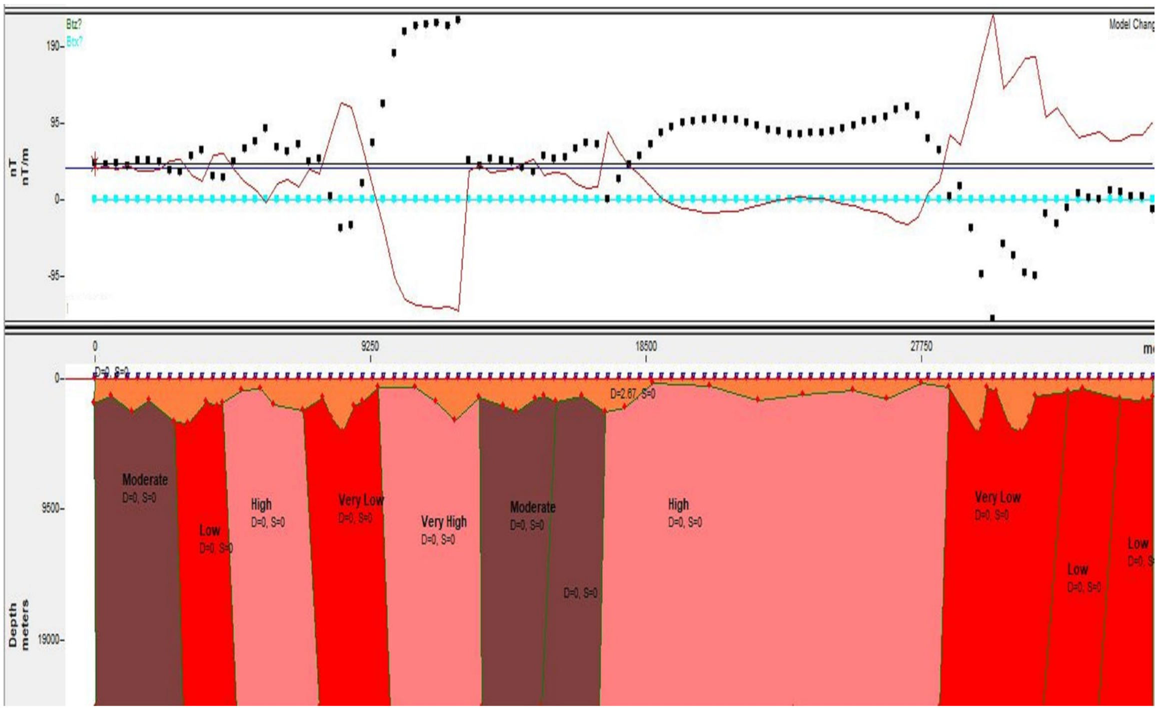

Figure 10: 2D Subsurface Magnetic Setting of the Area.

CONCLUSIONS

High resolution airborne magnetic data were processed using series of enhancement techniques and interpreted for appreciable information of the subsurface geology for exploration of endowed natural mineral resources of the study area. Geological features of the area revealed by the anomalous geophysical signatures are associated with hydrothermal alteration zones. High magnetic anomalies suggest the presence of magnetic basement rocks with mineral ores. Low to moderate magnetic intensity (-26.9 – 56.8 nT) at the northcentral and northeastern parts could be ascribed to weak magnetic felsic biotite and coarse-grained granite in the area. These anomalies are characteristics of sharp magnetic boundaries, indicative of near vertical/steeply dipping geologic features (fault, fracture, or lithological contact).

The residual anomaly reveals a pattern that is more composite than the regional anomaly with respect to magnetization and concealed lithology. Map of 4000 m upward continuation attenuates features by suppressing near-surface source bodies at the northwestern region to enhance deep-lying anomalous features orienting NE – SW and ENE – WSW. Major structural trends are identified from the derivative maps in NE – SW and ENE – WSW directions controlling mineral deposits. The recognized fault patterns give insight to their origin resulting from structural deformation (tectonic activities) of the basement rocks. The analytic signal maps identify the geologic boundaries of the subsurface rocks. The regions of high amplitude signals mostly in the northeastern, central and southern parts confirm the maximum peaks over the boundaries (edges) of the causative sources.

Power spectrum analysis estimated depth to basement and shallow magnetic sources as 1.3 and 0.5 km respectively. This also signifies depth to magnetized bodies or presence of basement structures (faults and fractures) controlling the mineral bodies in the area. The 2D subsurface model showed that the basement geomorphology is structurally influenced by tectonic activities which enhance development of varied geologic structures (faults, lineaments, fractures, and sheared zones) suitable for mineral deposits.

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REFERENCES

1. Ademila, O. 2017. "Aeromagnetic Characterization of Parts of Ondo and Ekiti States, Southwestern Nigeria". *Environmental and Earth Sciences Research Journal*. 4(3):66-75. https://doi.org/10.18280/eesrj.040303

2. Ademila, O. 2018. "Integrated Geophysical Methods for Subsurface Characterization and Health Hazard Assessment in Parts of Southwestern Basement Nigeria". IOP Conference Series: Earth and Environmental Science. 173:1-17 (2018) 012024. https://doi.org/10.1088/1755-1315/173/1/012024

3. Ademila, O., A.I. Olayinka, and M.A. Oladunjoye. 2020. "Land Satellite Imagery and Integrated Geophysical Investigations of Highway Pavement Instability in Southwestern Nigeria". *Geology, Geophysics and Environment*. 46(2):135-157. https://doi.org/10.7494/geol.2020.46.2.135

4. Biswas, A. and S.P. Sharma. 2016. "Integrated Geophysical Studies to Elicit the Structure Associated with Uranium Mineralization around South Purulia Shear Zone, India: A Review". *Ore Geological Review*. 72:1307-1326.

5. Blakely, R.J. 1995. *Potential Theory in Gravity and Magnetic Applications*. Cambridge University Press: New York, NY. 441p.

6. Geosoft. 2015. *Magmap Filtering How To Guide: Defining and Applying Filters and Inverse Fast Fourier Transform in Magmap. Oasis Montaj User Guide,* www.geosoft.com. 1-23.

7. Gupta, V.K. and N. Ramani. 1982. "Optimum Second Vertical Derivatives in Geologic Mapping and Mineral Exploration". *Geophysics*. 47:1706-1715.

8. Hakim, S., N. Jun, E. Sachio, and A. Essam. 2006. "Integrated Gradient Interpretation Techniques for 2D and 3D Gravity Data Interpretation". *Earth Planets Space*. 58:815-821.

9. Hinze, W.J., R.R.B. VonFrese, and A.H. Saad. 2013. *Gravity and Magnetic Exploration: Principles, Practices, and Applications"*. Cambridge University Press: New York, NY. 512p.

10. Kearey, P., M. Brooks, and I. Hill. 2002. *An Introduction to Geophysical Exploration, 3rd ed.* Blackwell Scientific Publications: Oxford, UK. 262p.

11. Keating, P. and P. Sailhac. 2004. "Use of the Analytic Signal to Identify Magnetic Anomalies due to Kimberlite Pipes". *Geophysics*. 69(1):180-190. https://doi.org/10.1190/1.1649386

12. Lowrie, W. 2007. *Fundamentals of Geophysics, 2nd ed*. Cambridge University Press: New York, NY. 381p.

13. Macleod, I.N., K. Jones, and T.F. Dai. 1993. "3-D Analytic Signal in the Interpretation of Total Magnetic Field Data at Low Magnetic Latitudes". *Exploration Geophysics*. 24:679-688.

14. Masoud, A.A. and K. Koike. 2011. "Auto-Detection and Integration of Tectonically Significant Lineaments from SRTM DEM and Remotely-Sensed Geophysical Data". *ISPRS Journal of Photogrammetry and Remote Sensing*. 66:818-832. https://doi.org/10.1016/jisprsjprs.2011.08.003

15. Mickus, K. 2004. "The Gravity Method in Engineering and Environmental Applications". In: *Geophysics 2003*. Federal Highway Administration and Florida Department Transportation Special Publication.

16. Miller, H.G. and V. Singh. 1994. "Potential Field Tilt - A New Concept for Location of Potential Field Sources". *Journal of Applied Geophysics*. 32(2-3): 213-217. https://doi.org/10.1016/0926-9851(94) 90022-1

17. Nabighian, M.N. 1984. "Toward a Three-Dimensional Automatic Interpretation of Potential Field Data via Generalized Hilbert Transforms: Fundamental Relations". *Geophysics*. 49(6):782-785.

18. Nabighian, M.N., V.J.S. Grauch, R.O. Hansen, T.R. LaFehr, Y. Li, J.W. Peirce, J.D. Phillips, and M.E. Ruder. 2005. "The Historical Development of the Magnetic Method in Exploration". *Geophysics*. 70(6):33-61. https://doi.org/10.1190/1.2133784

19. Nigeria Geological Survey Agency. 2009. *Geological Map of Iwo and Osogbo Areas*. Geological Survey of Nigeria: Abuja, Nigeria.

20. Oyinloye, A.O. 2011. "Geology and Geotectonic Setting of the Basement Complex Rocks in Southwestern Nigeria: Implications on Provenance and Evolution". *Earth and Environmental Sciences*. 98–117.

21. Rahaman, M.A. 1988. "Recent Advances in the Study of the Basement Complex of Nigeria. *First*

Symposium on the Precambrian Geology of Nigeria proceedings, Kaduna, Special Publication of Geological Survey of Nigeria. 11-41.

22. Reynolds, J.M. 1997. *An Introduction to Applied and Environmental Geophysics*. John Wiley and Sons: New York, NY 10158-0012, USA. 796p.

23. Reynolds, R.L., N.S. Fishman, and M.R. Hudson. 1991. “Sources of Aeromagnetic Anomalies over Cement Oilfield (Oklahoma), Simpson Oilfield (Alaska), and the Wyoming-Idaho-Utah Thrust Belt”. *Geophysics*. 56(5): 606-617.

24. Roest, W.R., J. Verhoef, and M. Pilkington. 1992. “Magnetic Interpretation using the 3-D Analytic Signal”. *Geophysics*. 57:116-125. https://doi.org/10.1190/1.1443174

25. Ross, H.E., R.J. Blakely, and M.D. Zoback. 2006. “Testing the Use of Aeromagnetic Data for the Determination of Curie Depth in California”. *Geophysics*. 71:151-159.

26. Salem, A., S. Williams, J. D.E. Fairhead, D. Ravat, and R. Smith. 2007. “Tilt-Depth Method: A Simple Depth Estimation using First-Order Magnetic Derivatives”. *The Leading Edge*. 26(12):1502-1505. https://doi.org/10.1190/1.2821934

27. Shahverdi, M., L. Namaki, M. Montahaei, F. Mesbahi, and M. Basavand. 2017. “Interpretation of Magnetic Data Based on Tilt Derivative Methods and Enhancement of Total Horizontal Gradient, A Case Study: Zanjan Depression”. *Journal of Earth Space Physics*. 43(1):101-113.

28. Spector, A. and F.S. Grant. 1970. “Statistical Models for Interpreting Aeromagnetic Data”. *Geophysics*. 35(2):293-302. https://doi.org/10.1190/1.1440092

29. Telford, W.M., L.P. Geldart, R.E. Sheriff, and D.A. Keys. 1990. *Applied Geophysics. 2nd ed.* Cambridge University Press: New York, NY. 770p.

30. Thurston, J.B. and R.S. Smith. 1997. “Automatic Conversion of Magnetic Data to Depth, Dip, and Susceptibility Contrast using the SPI (TM) Method”. *Geophysics*. 62(3):807-813. https://doi.org/10.1190/1.1444190

31. Thurston, J.B., R.S. Smith, and J.C. Guillon. 2002. “A Multimodel Method for Depth Estimation from Magnetic Data”. *Geophysics*. 67:555-561.

32. U.S. Geological Survey 2000. “Three Aeromagnetic Surveys in South Central Arizona – A Web Site for Distribution of Data”. Online edition: U.S. Geological Survey Open-File-Report 00-155. http://pubs.usgs.gov/of/2000/ofr-00-0155/

33. Verduzco, B., J.D.E. Fairhead, C.M. Green, and C. Mackenzie. 2004. “New Insights into Magnetic Derivatives for Structural Mapping”. *The Leading Edge*. 23(2):89-95.

34. Webring, M. 1981. MINC: “A Gridding Program based on Minimum Curvature”. US Geological Survey: Raton, FL.. 81 – 1224: 43.

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