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Estimation of Magnetic Contact Location and Depth of Magnetic Sources in a Sedimentary Formation

Ocena lokacije magnetnega kontakta in globine magnetnih virov v sedimentni formaciji

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Abstract

The aeromagnetic data of Idogo, Southwestern Nigeria, have been used to study the lithology and to determine the magnetic source parameters within Idogo and its environs. Idogo lies between latitudes 6°30′N and 7°00′N and between longitudes 2°30′E and 3°00′E. The magnetic anomaly map, the regional geology, the analytic signal and the local wavenumber were used to identify the nature and depth of the magnetic sources in the region. Data enhancement was carried out to delineate the residual features relative to the strong regional gradients and intense anomalies due to the basin features. The estimated basement depth using the horizontal gradient method revealed depths ranging between 0.55 km and 2.49 km, while the analytic signal amplitude and local wavenumber methods estimated depth to the magnetic sources to range from 0.57 km to 4.22 km and 0.96 km to 2.43 km, respectively. Depth computations suggested the presence of both shallow and deep sources. The total magnetic intensity values ranged from 3.1 nT to 108.3 nT. The area shows magnetic closures of various sizes in different parts of the area trending West, with prominence at the centre and distributed East–West.

Key words: aeromagnetic, analytic signal amplitude, local wavenumber, total magnetic intensity, reduction to equator

Povzetek

Aeromagnetne podatke iz Idoga v jugozahodni Nigeriji smo uporabili za določitev litološke sestave in ugotovitev parametrov magnetnih virov na območju Idoga in okolice. Območje leži med širinama 6°30′N in 7°00′N in dolžinama 2°30′E in 3°00′E. Za identifikacijo narave in globine magnetnih virov smo uporabili karto magnetnih anomalij, karto regionalne geologije, analitične signale in lokalno valovno število. Ojačanje podatkov smo izvedli z namenom omejitve vpliva rezidualnih vzorcev glede na močne regionalne gradiente in intenzivne anomalije, ki so posledica oblikovanosti kadunje. Ocenjene globine podlage z metodo horizontalnih gradientov so bile med 0,55 in 2,49 km, medtem ko so bile z metodo amplitude analitičnega signala in lokalnega valovnega števila ocenjene globine do magnetnih virov od 0,57 do 4,22 km in od 0,96 do 2,43 km. Izračunane globine nakazujejo navzočnost tako plitvih kot tudi globokih virov. Vrednosti celotne magnetne intenzitete se gibljejo med 3,1 nT in 108,3 nT. Na ozemlju so vidne v različnih delih terena magnetne oblike raznih velikosti s štrlino v sredi in smerjo vzhod-zahod.

Ključne besede: aeromagnetika, amplituda analitskega signala, lokalno valovno število, celotna magnetna intenziteta, redukcija na ekvator

Introduction

An aeromagnetic geophysical survey presents the opportunity of carrying out comparative surveys of very large areas and unreached terrain within a short period of time, which makes it cost-effective. Aeromagnetic survey is a passive [1] geophysical method because it requires no energy source during data acquisition [2]. The investigations are based on the physical properties of the Earth, which can be used for the provision of solutions to various geological problems and for the structural mapping of an area. The Earth's physical properties and the formation of different rock types vary from one area to another due to the composition of the Earth [3]. The purpose of the magnetic survey is to identify the deviations in the geomagnetic field intensity from the local geology. Anomalies are mostly caused by magnetisation contrast of the sub-surface rocks [4], which occurs due to changes in the quantity of magnetite in rocks. In the realm of applied geophysics, anomalous magnetisations might be associated with local mineralisation, which is potentially of commercial interest, or could be due to the sub-surface structures that have a bearing on the location of oil deposits [5]. Regional aeromagnetic study of the anomaly map depicts the regional geological pattern and the structural features that provide the background for explicit interpretation [4]. Mathematical modelling can be used to deduce the shape, depth and characteristics of the rock bodies, which are accountable for the magnetic anomalies [6]. In sedimentary rocks, the magnetic properties are usually insignificant, due to low content of magnetic material, while igneous and metamorphic rocks usually display significant variations in the aforementioned properties, which are helpful in exploring the geological properties of the bedrock. The Earth's magnetic field is generated predominantly in the Earth's core, which is though complex in configuration but can be approached by a dipole field, such as that of a bar magnet. Some materials develop an induced magnetic field in the presence of an applied magnetic field and thus become magnetised, while others have remanent magnetisation or residual magnetism. The interaction of such fields with the Earth's primary field produces the magnetic field at the Earth's surface; thus, magnetic data collected over an area can be used to investigate the magnetic properties of rocks, which reveal the sub-surface structure of the area.

Asadi and Hale [7] applied the analytical signal of the total magnetic intensities to delineate intermediate-composition magmatic rocks in the Takab area of Iran. Chandler [8] used the second vertical derivative enhanced-aeromagnetic data, together with gravity data, to interpret the geology of the poorly exposed central part of the Duluth Complex. Experience from Finland showed high degree of correlations between the results from aeromagnetic data and geological structure [9]. Results from the magnetic survey of 1960 by Hunting Survey Limited across the Ashanti Belt – comprising the mineral and rock resources of Ghana – were quite satisfactory [10]. Geological interpretation based mostly on the magnetic maps was effective in segregating lithologies, faults and fracture zones. El-Awady et al. [11] carried out interpretation of the aeromagnetic survey over the Fayum area, Western Desert, Egypt, and obtained information about the crystalline basement structure and local structure in the sedimentary section. The analysis of the constructed magnetic map serves as foundation for studying the structural pattern of the basement complex and the surface structures. The aim of this study was to delineate the sub-surface structure of the area under consideration, hence deducing the lithology of the area and estimate the depth to the basement using horizontal gradient magnitude (HGM) method, local wavenumber (LWN) method and analytic signal amplitude (ASA) method.

Location and Geological Setting of the Study Area

The study area is located between latitudes 6°30′N and 7°00′N and longitudes 2°30′E and 3°00′E, measuring about 3,025 km^2 (Figure 1). It is located in the western part of Ogun State, Southwestern Nigeria.

The study area falls in the Oshosun Formation, which is one of the sedimentary formations of the Dahomey (Benin) Basin. The Dahomey Basin, which covers South-Eastern Ghana,

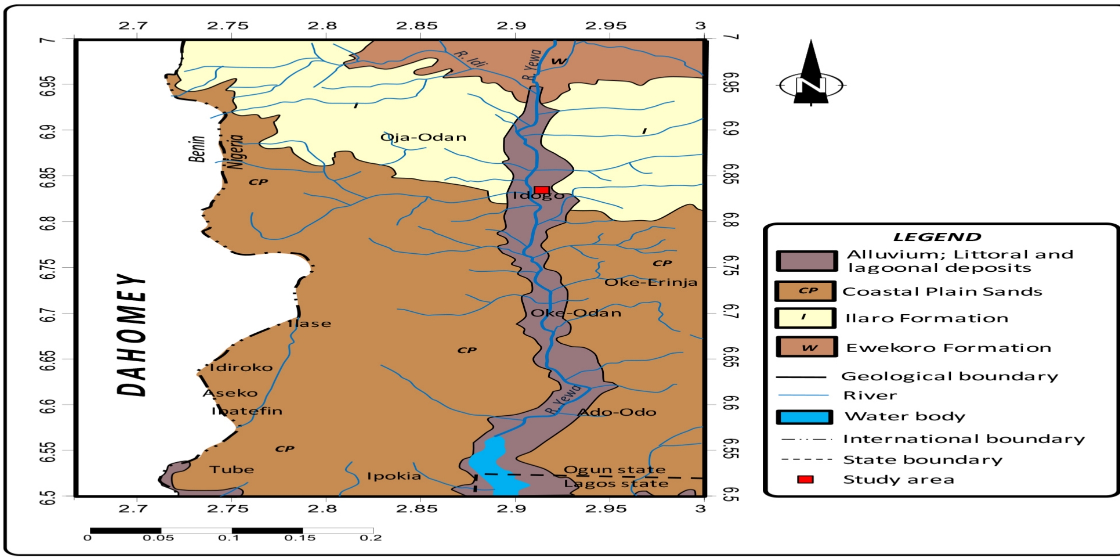

Figure 1: *Geological map of study area.*

Togo, Benin Republic and Western Nigeria, is an extensive sedimentary basin on the continental margin of the Gulf of Guinea [12,13]. The basin is a marginal pull-apart basin [14], which developed in the Mesozoic Era due to the separation of the African and South American lithospheric plates [15]. The basin encloses an extensive wedge of Cretaceous-to-recent sediments, which sets towards the offshore [16]. The sediments of Oshosun Formation in the western part of Dahomey Basin are underlain by lower Cretaceous-to-Palaeocene strata: Ise Formation, Afowo Formation and Araromi Formation, which belong to the old Abeokuta Group, and the Ewekoro Formation [17]. Overlying the Oshosun Formation are the old Ilaro Formation, coastal plain sands and alluvial deposits. All the sedimentary sequences lie on the crystalline Precambrian Basement Complex of Southwestern Nigeria.

Materials and Methods

Data Acquisition

The dataset used in this study includes the contoured aeromagnetic data obtained from the Nigerian Geological Survey Agency. The aeromagnetic data were obtained using a proton precession magnetometer with resolution 0.1 nT, at 80 m altitude, along the flight orientation of NE–SW, with a flight line spacing of 500 m and tie line spacing of 5,000 m. The azimuth of the flight line direction was 135°, while the azimuth of the tie line direction was 45°. The geomagnetic gradient was eliminated from the data using the International Geomagnetic Reference Field (IGRF) of Epoch 2009. The map of the study area was published on a scale of 1:10,000. The topography detail of the map was based on 1:10,000 topography series of the Federal Surveys of Nigeria. The average magnetic inclination, magnetic declination and magnetic field strength across the survey were –13.0364°, –2.3844° and 32,896.0 nT, respectively.

Data Processing and Gridding

The processing of aeromagnetic data for this research involved the application of the enhancement technique, the application of a gridding routine and removal of the Earth's background magnetic field. Some corrections, such as background correction (aircraft, radon and cosmic radiation), stripping, micro-levelling, as well as removal of the diurnal variation of the Earth's magnetic field, aircraft heading, instrument variation, lag error between the aircraft and the sensor, and the inconsistencies between flight lines and tie lines, were done by Fugro Airborne Surveys Ltd., USA. The main software packages used for the processing and enhancement of the airborne geophysical data were the Geosoft® Oasis montaj 6.4, Surfer 13 and the US Geological Survey (USGS) Potential-Field software.

Gridding interpolates the aeromagnetic data from the measurement locations to the nodes of a regular mesh and thereafter creates a new and fundamentally different construct of the data [18]. The data were gridded to a 55 m interval using the minimum curvature technique described by Briggs [19]. Once a grid was produced, it was displayed as an image (Figure 2). The minimum curvature gridding technique was applied to the aeromagnetic data, which takes the randomly distributed survey data and interpolates it onto a regular grid. The images observed were spatially referenced to make it visible in a geographic information system (GIS) setting.

Enhancement of Aeromagnetic Data

Aeromagnetic data were enhanced by a collection of linear and non-linear filtering processes. Mathematical enhancement techniques [20] were applied to a range of imaging routines to visually enhance the properties of the selected magnetic sources represented by geological lithological features.

Significant concentrations of mineral deposits are correlated with high-frequency magnetic responses. High-pass and horizontal gradient filtering were applied to the aeromagnetic data to enhance the high frequencies and define geological body edges. All the enhancement techniques were performed with the Geosoft® (Oasis montaj 6.4) and Surfer13. The *MagMap* extension in Geosoft® was used on the magnetic anomaly grid for the processing and application of filters. The necessary filter was applied, and the magnetic anomaly was displayed as an image by means of the grid and the imaging device.

Reduction to Equator

Reduction to equator (RTE) is a useful and effective operation designed to transform a total magnetic intensity (TMI) anomaly caused by an arbitrary source into the anomaly that this same source would produce if it were located at the pole and magnetised by induction only [21]. Reduction to pole (RTP) converts the magnetic field from the magnetic latitude where the Earth's field is inclined to that field at a magnetic equator where the inducing field is vertical [22]. When the field of the Earth is inclined, magnetic anomalies caused by induction are related to their sources asymmetrically, but when the Earth`s inducing field is vertical, the associated anomalies would be directly over their sources [20]. Fourier transform is applied to transform the RTE from the space domain into the wavenumber domain. The RTE operation in wave number domain is expressed as presented in Eq. (1)

$$A_p(u,v) = \frac{A_c A_p}{(sin\, I + i\, cos\, I\, cos(\, D - \Omega))} \qquad (1)$$

where $A_p(u, v)$ is the Fourier transform of these observed magnetic data; $A_c(u, v)$ is the Fourier transform of the vertical magnetic field; I and D are the inclination and declination of core field, respectively; (u, v) is the wavenumber corresponding to the (x, y) directions, respectively; and $\Omega = \arctan(u/v)$ [22]. The RTE for low geomagnetic latitudes was applied to the magnetic anomaly data. The method utilises an azimuthal filter in the frequency domain to minimise directional noise initiated by the low geomagnetic latitude [23]. The central coordinates of the area were used in calculating inclination and declination. The inclination, declination and average total field of the study area were –13.0364°, –2.3844° and 32,896.9 nT, respectively.

Direct Detection of Structural Trends

Interpretation of the aeromagnetic survey could be performed quantitatively or qualitatively. In this study, the detection of structural trends data aims to map the surface and the sub-surface regional structures such as faults and contact bodies; mineralisation was determined qualitatively. The qualitative interpretation of the shape and trend of magnetic anomalies was conducted by a visual examination of the structural trends and characteristic features. Some of these features [24] are the relative location and amplitudes of the positive and negative contour parts of the anomaly, the elongation and aerial extent of the contour and the sharpness of the anomaly as seen by the contour spacing.

Estimation of Depth

Since magnetisation is primarily a tool for sub-surface mapping, it follows that determination of the depths as well as other physical properties of bodies causing anomalies is important for its application in geological exploration. The depth to basement allows mapping of the sub-surface and indicates the thickness of the sediments. Areas underlain by sediments or other sedimentary deposits may be regarded as profitable depending on the depths.

The LWN Method

The LWN method, which is based on the extension of complex analytical signals, was used for estimation of the magnetic depths. The original LWN, also known as the source parameter imaging (SPI) method [25] works for two models: a 2-D sloping contact or a 2-D dipping thin sheet. For the magnetic field *M*, the LWN is given by Eq. (2) [25]:

$$K = \frac{\frac{\partial^2 M}{\partial x \partial z}\frac{\partial M}{\partial x} - \frac{\partial^2 M}{\partial x^2}\frac{\partial M}{\partial z}}{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \quad (2)$$

For the dipping contact, the maxima of *K* are located directly over the isolated contact edges and are independent of the magnetic inclination, declination, dip, strike and any remanent magnetisation. The depth is estimated at the source edge from the reciprocal of the LWN, as shown in Eq. (3).

$$Depth_{(x=0)} = \frac{1}{k_{max}} \quad (3)$$

where K_{max} is the peak value of the local wave number *K* over the step source. One more advantage of this method is that the interference of anomaly features is reducible, since the method uses the second-order derivatives. In practice, the method is used on gridded data by first estimating the direction of magnetic field at each grid point. The vertical gradient is computed in the frequency domain, and the horizontal derivatives are computed in the direction perpendicular to the strike using the least-squares method.

Analytic Signal Method

The absolute analytic signal magnitude is defined as the square root of the squared sum of the vertical and horizontal derivatives of the magnetic field, as presented in Eq. (4).

$$ASM(x,y) = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \quad (4)$$

The advantage of this method of magnetic data enhancement is that its amplitude function is always positive and does not need any assumption of the direction of body magnetisation [26]. In a manner identical to that used in the HGM, peaks in the ASA are located. The maxima of the analytic signal are used to detect the structures responsible for the observed magnetic anomalies over the studied area.

Spectral Analysis

Spectral analysis provides an opportunity for calculating and interpreting the spectrum of geophysical data. The spectrum analysis, is a transformation of data from the time or space domain to the frequency or wavenumber domain, respectively. The spectral depth method is based on the principle that a magnetic field measured at the surface can be considered as the integral of the magnetic signature from all depths [27]. The power spectrum of a surface field can be used to identify the average depths of the source ensembles [28]. The spectral analysis method provides the average depth value to the top of the statistical ensemble of blocks of anomalies. The discrete Fourier transform, presented in Eq. (5), is a mathematical tool for spectral analysis and is applicable to aeromagnetic data [29].

$$f(x) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\frac{n\pi x}{L} + b_n \sin\frac{n\pi x}{L}\right) \quad (5)$$

The aeromagnetic data were divided into grids, and the graph of the logarithm of spectrum energy against the frequency were obtained for each block. Previous studies [30–32] have proposed a two-step technique that can evaluate the bottom depth (Z_b) of the deepest magnetic sources with the aid of the spectral analysis designed by

Spector and Grant [28]. The first step of the 2-D analysis is the determination of the depth to the centre of the magnetic body (Z_o), while the second step is the calculation of the depth to the top (Z_t) of the magnetised body. These depth values of the magnetic sources are determined from the slope of the log power spectrum fit. The bottom depth, Z_b, is then obtained from these two depths by using Eq. (6) [32].

$$Z_b = 2Z_o - Z_t \qquad (6)$$

Results and Discussion

TMI Map Interpretation

The TMI variation of the aeromagnetic map of Idogo and its environs ranges between 3.1 nT and 108.3 nT, with a group of long-wavelength anomalies in the NE–SW direction. The TMI field of the area under consideration is presented in Figure 2. The map reveals the existence of a thick sediment cover that tends towards the south-east. The TMI field variation reveals two distinct magnetic structural trends of high and low reliefs. The high side runs from the north-western part to the south-eastern part, while the low side runs from the south-western part to the south-eastern part, having distinct and different magnetic intensities. Presence of long-wavelength anomaly in the TMI map (Figure 2) reveals that the study area is a sedimentary basin, and a blanket of sedimentary rocks covers the region.

RTE Approach

The effect of the application of reduction–to-the-magnetic-equator filter is shown in Figure 3. The filtering process attempts to reduce the low-latitude effect of the horizontal elongated anomalies. It has been applied to produce the RTE map (Figure 3), which shows that the correction in the asymmetries of the observed anomalies had been minimised and the anomalies are centred directly over the causative elongated bodies. The reduced-to-equator magnetic intensity values range from 32.90 nT to 72.2 nT. The reduced-to-equator map is characterised by high frequency, small size, weak intensity, sharp boundary and nearly irregular-shaped anomalies, which are the effect of near-surface sources, such as shallow geologic units and cultural features within the area under consideration.

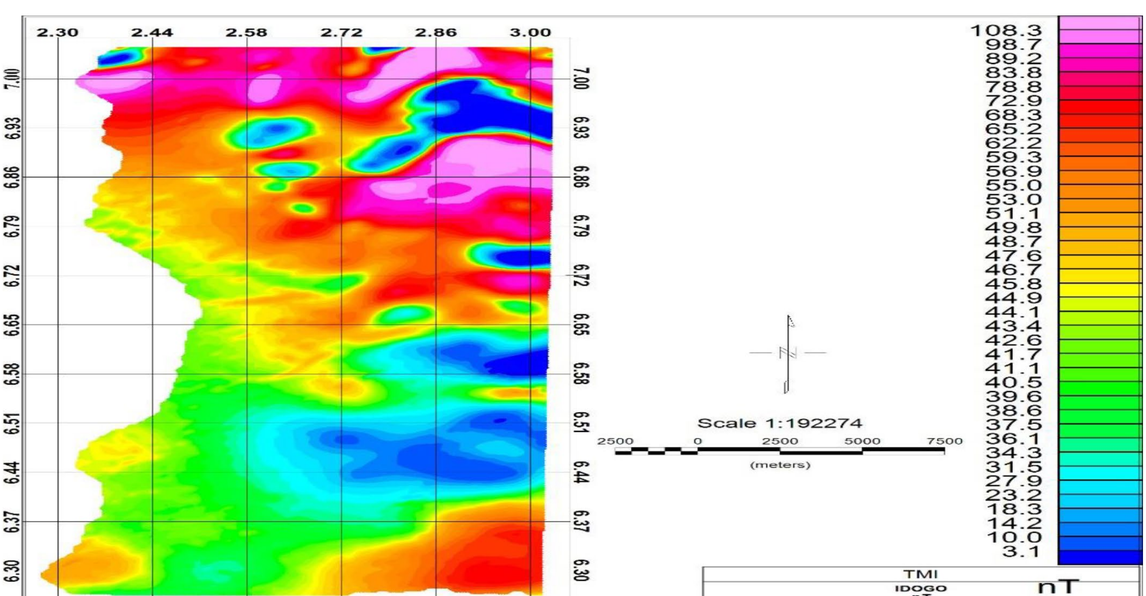

Figure 2: *TMI map of the study area.*

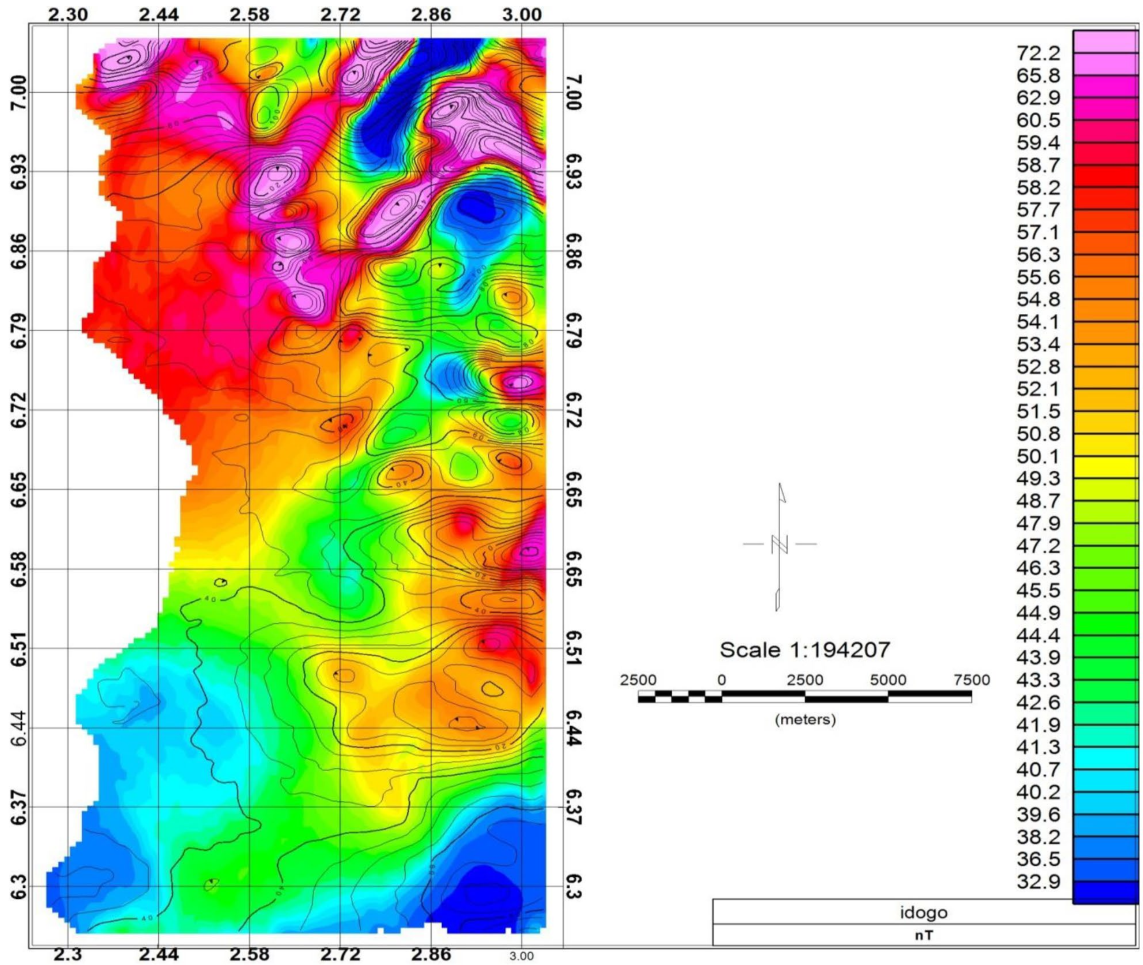

Figure 3: *RTE map of the study area.*

Magnetic Source Location and Depth Estimation

The magnetic sources location and magnetic contact depth solutions were computed by the HGM of the reduced-to-pole grid, the ASA of the TMI grid, and the LWN of the TMI grid, with a maximum standard error of 15%. Depths on Sheet No. 278 (Idogo) are shown in Figures 4, 5 and 6, respectively. The results obtained indicate that HGM records the highest number of contacts, with 113 solutions at comparatively deeper depths than do the other methods. The solutions from the HGM and ASA functions are comparable and better than the solutions from the LWN method because the LWN uses second derivatives, which makes it susceptible to noise in the data. In each diagram, the centre of each circle coincides with the location of the maximum for that function and the diameter of the circle is proportional to the depth estimate for the magnetic source point. A close examination of the maps obtained by HGM, ASA and LWN reveal the differences in the diagnostic attributes of the gradient functions.

The results obtained using HGM (Table 1) showed that the estimated depth ranges from 0.55 km to 2.49 km, which implied that the limit to shallow magnetic source depth is 0.72 km and the limit to deep magnetic source depth is 2.94 km (Figure 4).

The results obtained using analytic signal method (Table 2) showed that the estimated depth ranges from 0.57 km to 4.22 km, which implied that the limit to shallow magnetic source depth is 0.57 km and the limit to deep magnetic source depth is 4.22 km (Figure 5). The lines in the circles (Figures 4, 5 and 6) indicate the direction of strike, which suggest possible fault trend.

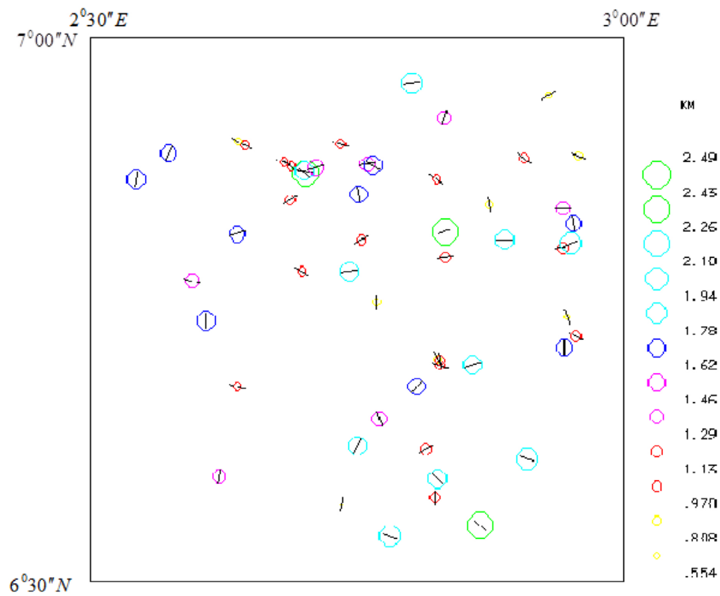

Figure 4: *Magnetic source depth estimated using the HGM (USGS Potential-Field software).*

Table 1: *Magnetic source depth parameters as Estimated by the HGM.*

Serial no.	Depth (km)	Percentage error in depth	Strike of contact
1	2.14	10.57	55.36
2	0.55	14.24	92.00
3	0.74	13.77	87.17
4	2.49	14.00	–83.30
5	1.20	9.96	88.90
6	1.32	8.57	83.20
7	1.70	3.29	101.78
8	1.23	6.66	93.88
9	1.22	12.09	87.40
10	1.00	9.91	91.32

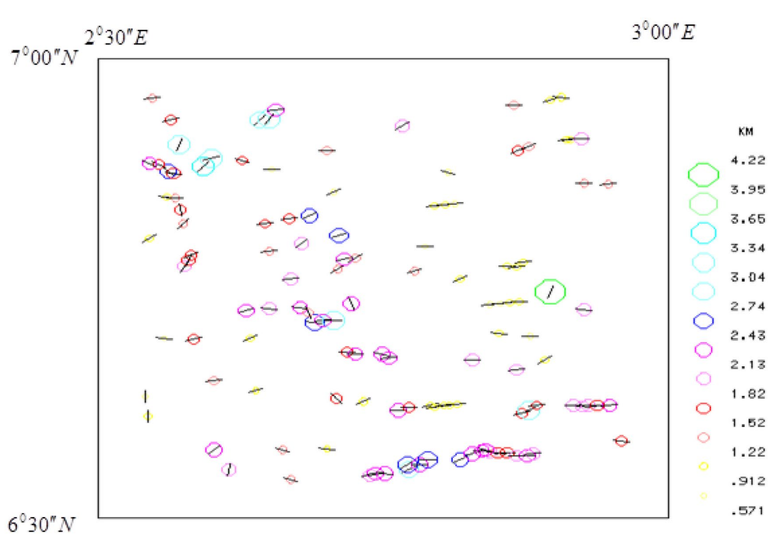

Figure 5: *Magnetic source depth estimated using the analytic signal method (USGS Potential-Field software).*

Table 2: *Magnetic source depth parameters as estimated by the analytic signal method.*

Serial no.	Depth (km)	Percentage error in depth	Strike of contact
1	3.49	10.19	−67.08
2	4.22	5.47	−60.25
3	2.17	8.22	80.96
4	1.76	4.55	99.52
5	1.17	6.82	114.50
6	0.57	14.65	95.98
7	4.04	8.72	−51.62
8	2.47	2.98	5.06
9	2.67	10.98	5.68
10	0.99	12.60	59.84

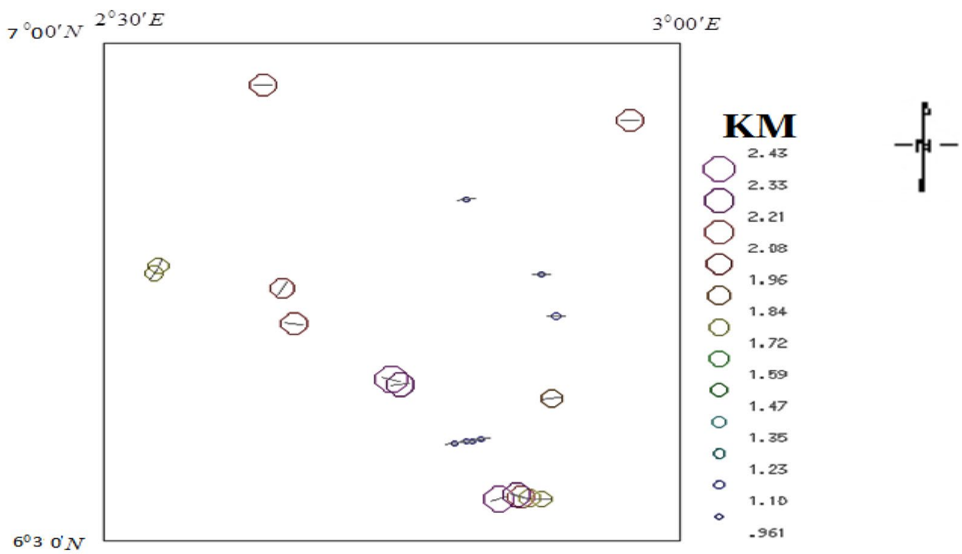

Figure 6: *Magnetic source depth estimated using the LWN method (USGS Potential–Field software).*

Table 3: *Magnetic source depth parameters as estimated by the LWN method .*

Serial no.	Depth (km)	% Error in depth	Strike of contact	Dip angle	Dip azimuth	Susceptibility contrasts
1	0.96	8.20	82.86	−7.14	485.25	0.00
2	1.91	13.23	79.04	−10.96	360.33	−0.003
3	0.99	13.66	81.43	−8.57	476.36	0
4	2.19	12.67	85.72	175.72	46.43	0
5	2.43	13.40	105.56	−164.44	160.93	0
6	2.14	13.99	100.67	−169.33	150.60	0
7	1.00	8.69	88.76	178.76	101.94	0
8	1.15	13.04	87.00	−3.00	394.13	0
9	2.26	5.16	83.83	173.83	158.71	0
10	1.15	13.04	87.00	−3.00	394.13	0

LWN was applied on the gridded data of the area under consideration. The results (Table 3) show that the estimated depth ranges from 0.96 km to 2.43 km, which implied that the limit to shallow source depth is 0.96 km and the limit to deep source depth is 2.43 km (Figure 6), and the susceptibility contrasts ranges from –0.001 to 0.001.

Conclusion

The study was carried out using the digitised aeromagnetic data of the entire Idogo area and its environs to map both the locations and the depths of the magnetic source edges as an aid to magnetic source interpretation. The data were analysed using advanced and suitable magnetic gradient interpretation techniques. These techniques were applied to gridded digitised data from aeromagnetic sheets that cover the study area in order to demonstrate their efficiency and accuracy in mapping the magnetic source edges.

These magnetic interpretation techniques include the RTP, ASA, HGM and LWN methods. The phase-shift effect in the total magnetic anomalies resulting from a non-vertical geomagnetic field vector was removed using RTP filtering, in which the intended effect is to move the anomaly peaks and gradients directly over their magnetic sources to aid in the interpretation.

The automated magnetic gradient interpretation methods were also used to estimate the locations and depths of magnetic sources. Since each automated method makes different assumptions about the magnetic sources, the use of several interpretational techniques was adopted to provide a reality check for the results. HGM, ASA and LWN methods were adopted for automatic estimation of the location and depth of magnetic sources. The estimated basement depth for Sheet No. 278 using HGM revealed a depth range of 0.55–2.49 km, while the ASA gave an estimated depth to the magnetic sources between the range of 0.57 km and 4.22 km. The LWN method revealed an estimated depth within the range of 0.96–2.47 km.

The location and depth to magnetic contacts were estimated from the maxima of the HGM, LWN and ASA functions of the total intensity magnetic data. The results of this study showed that the estimates of the depth limit to shallow magnetic contact obtained by the HGM and LWN methods are relatively close and comparable.

References

[1] Henry, L. (2010): Magnetic and Gravity Methods in Mineral Exploration: the Value of Well-Rounded Geophysical Skills. CSEG recorder, 27(2), pp. 31–35.

[2] Jose, R. (2009): Gravity and magnetic methods: Presented at "Short Course on Surface Exploration for Geothermal Resources", organized by UNU-GTP and LaGeo, in Ahuachapan and Santa Tecla, El Salvador, pp. 1–13.

[3] Roy, A. (1966): The method of continuation in mining geophysics. Geoexploration, 4, pp. 65–83.

[4] Mariita, N.O. (2007): The magnetic method. Presented at Short Course II on Surface Exploration for Geothermal Resources, organized by UNU-GTP and kenGen, at Lake Naivasha, Kenya, pp. 1–8.

[5] Lowrie W. (2004): Fundamentals of Geophysics. Swiss Federal institute of technology.

[6] Koulomzine, T., Lamontagne, Y., Nadeau, A. (1970): New methods for the direct interpretation of magnetic anomalies caused by inclined dykes of infinite length. Geophysics, 35, pp. 812–830.

[7] Asadi, H., Hale, M. (1999): Integrated analysis of aeromagnetic, Landsat TM and mineral occurrence data for epithermal gold exploration in northwest Iran.13th International Conference on Applied Geologic Remote Sensing, Vancouver. British Columbia.

[8] Chandler, V. (1990): Geological interpretation of gravity and magnetic data over the central part of the Duluth Complex northeastern Minnesota. Economic Geology, 85, pp. 861–829.

[9] Airo, M., Loukola-Ruskeeniemi, K. (2003): Characterization of sulfide deposits by airborne magnetic and gamma-ray responses in eastern Finland. Ore Geology Reviews, 24, pp.67–84.

[10] Kesse, G. (1985): The mineral and rock resources of Ghana. United States: A.A. Balkema Publishers, 610 p.

[11] El-Awady, M., El-etr, H., Bakrah, A. (1984): Aeromagnetic geophysical investigation in El-Faiyum district, western desert, Egypt. Qatar University Science Journal, 5, pp. 335–357.

[12] Slansky, M. (1962): Contribution a prelude geologique du basin sedimentaire cotier au Dahomey at du Togo.

Bulletin de la Société Géologique de France, 12, pp.18–31.

[13] Antolini, P. (1968): Eocene phosphate in the Dahomey Basin. Journal of Mining Geology, 17, pp. 17–23.

[14] Klemme, H.D. (1975): Geothermal Gradient Heat flow and hydrocarbon Recovery In: Fischer, A.G., Judson, S. (Eds.). Petroleum and Global Tectonics. Princeton University Press, pp. 251–304

[15] Burke, K.G, Dessauvagie, T.F.J, Whiteman, A.J. (1972): Geological history of the Benue Valley and adjacent areas. In: Burke, K.G., Whiteman, A.J. (Eds.). African Geology. Geology Dept., Univ. of Ibadan, Nigeria, pp. 188–205.

[16] Whiteman, A. (1982): Nigeria: Its Petroleum Geology, Resources and Potentials. 1 and 2, Graham and Trotham Limited: London, UK.

[17] Omatsola, M.E., Adegoke, O.S. (1981): Tectonic Evolution and Cretaceous Stratigraphy of Dahomey Basin. Journal of Mining and Geology, 18, pp. 130–137.

[18] Foss, C. (2011): Magnetic data Enhancement and Depth Estimation. Encyclopedia of Earth Sciences Series, pp. 736–746.

[19] Briggs, I. (1974): Machine contouring using minimum curvature. Geophysics, 39(1), pp. 39–48.

[20] Gunn, P., Maidment, D., Milligan, P. (1997): Interpreting aeromagnetic data in areas of limited outcrop. AGSO Journal of Australian Geology and Geophysics, 17(2), pp. 175–185.

[21] Li, X. (2008): Magnetic reduction-to-the-pole at low latitudes. Fugro Gravity and Magnetic Services. Houston, USA. Fugro.

[22] Luo, Y., Xue, D.J., Wang, M. (2010): Reduction to the Pole at the Geomagnetic Equator. Chinese Journal of Geophysics, 53(6), pp. 1082–1089.

[23] Philips, J. (1997): Potential-Field Geophysical Software for the PC, U.S.G.S. Open File Report, pp. 97–725.

[24] Sharma, P.V. (1976): Geophysical Methods in Geology, Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York, 428 p.

[25] Thurston, J.B., Smith, R.S. (1997): Automatic conversion of magnetic data to depth, dip, and susceptibility contrast using the SPIÔ method. Geophysics, 62 (3), pp. 807–813.

[26] Jeng, Y., Lee, Y.L., Chen, C.Y., Lin, M.J. (2003): Integrated signal enhancements in magnetic investigation in archaeology. Journal of Applied Geophysics, 53, pp. 31–48.

[27] Taha R. (2009): Prospecting for the ferromagnetic mineral accumulations using the magnetic method at eastern desert. Egypt Geophysics Engineering, 6, pp. 401–411.

[28] Spector, A., Grant F.S. (1970): Statistical model for interpreting aeromagnetic data. Geophysics, 35, pp. 364–383.

[29] Onwuemesi, A. (1997): One-dimensional spectral analysis of aeromagnetic anomalies and Curie depth isotherm in the Anambra Basin of Nigeria. Journal of Geodynamics, 23(2), pp. 95–107.

[30] Bhattacharyya, B.K., Leu L.K. (1975): Spectral analysis of gravity and magnetic anomalies due to two dimensional structures. Geophysics, 40, pp. 993–1013.

[31] Bhattacharya, B.K., Leu, L.K. (1977): Spectral analysis of gravity and magnetic anomalies due to rectangular prismatic bodies, Geophysics, 42, pp. 41–50.

[32] Tanaka, A., Okubo, Y., Matsubayashi, O. (1999): Curie point depth based on spectrum analysis of the magnetic anomaly data in East and Southeast Asia. Tectonophysics, 306, pp. 461–470.