Estimation of Depth to Magnetic Sources Using Gradient Inversion Method: A Case of Aeromagnetic Field of Binji, North-Western Nigeria

***[1]Nwankwo, L.I., [2]Akinmadeyan, O.C., [2]Lawal, T.O., [2]Ige, S.O. and [3]Saleh, A.**

[1]Department of Geophysics, University of Ilorin, Ilorin, Nigeria
[2]Department of Physics, University of Ilorin, Ilorin, Nigeria
[3]Physics Unit, School of Preliminary Studies, Ibrahim Badamasi Babangida University, Lapai, Nigeria

Received: June 30, 2016; Revised: August 22, 2016; Accepted: September 1, 2016

Abstract

The depth to magnetic sources has been estimated from gradient inversion analysis of the acquired aeromagnetic magnetic data of Binji, north-western Nigeria. The study area is bounded by Longitude 4° 30’ E and 5° E and Latitude 13° N and 13° 30’ N. The total magnetic field was separated into regional and residual fields using least squares polynomial fit, while twenty two (22) profiles of the residual magnetic fields were subsequently used to determine depth to magnetic sources. The depths vary from 0.22 km to 2.19 km with an average of 1.26 km. Since estimation of depth to magnetic sources is also regarded as a proxy for sedimentary thickness; the results showed that the sedimentary layer is not thick enough for hydrocarbon prospect and therefore confirm that petroleum exploration may not be plausible in the study area.

Keywords: Aeromagnetic, basement depth, gradient inversion, residual anomaly

1.0 Introduction

The science of geophysics applies the principles of physics to the study of the earth [1, 2]. Geophysical investigation of the interior of the earth involves taking systematic measurements at or near the earth’s surface that are influenced by the internal distribution of physical properties [3]. Analysis of these measurements can reveal how the physical properties of the earth’s interior vary vertically and laterally [4, 5]. The objective of any geophysical survey is to locate subsurface geological structures or bodies and, where possible, measure their dimensions and relevant physical properties. For example, in hydrocarbon prospecting, sedimentary thickness and structural information are sought because of the association of petroleum with particular features such as anticlines in sedimentary rock; while in solid mineral exploration, the emphasis is on detection and determination of physical properties associated with the sought mineral [3].

Diverse methods of geophysical exploration exist including electrical, seismic, radiometric, gravity and magnetic. However, the magnetic method is utilized in this study. Magnetic data could be acquired from land, marine or airborne. The airborne magnetic surveys (otherwise known as aeromagnetic surveys) play an exceptional role when compared with other methods due to its rapid rate of coverage and low cost per unit area explored [6]. The main purpose of any magnetic survey is to detect rocks (geometry) or minerals possessing unusual magnetic properties that reveal themselves by causing disturbances or anomalies in the intensity of the earth’s magnetic field [7].

***Corresponding Author: Tel: +234(0)8034044244, E-mail: levinwankwo@gmail.com**

Several works had been done by researchers using various magnetic interpretation methods including Fourier Transform for different purposes in the whole of Sokoto basin [8-13]. This work presents estimates of depth to magnetic sources in Binji, near Sokoto, using gradient inversion method for regional petroleum reconnaissance studies. A major significance of depth to magnetic sources is its sufficing as sedimentary thickness of a basin, which is the fundamental piece of information to be sought in petroleum exploration. The present study would therefore contribute significantly in the discussion on the petroleum exploitability of the Binji portion of Sokoto Basin.

2.0 Materials and Methods

2.1 Location and Geology of the Study Area

Binji is the headquarters of Binji Local Government Area of Sokoto State, Nigeria. The town covers an area of about 559 km^2 and has a population of 105,027 as at 2006 census [14]. The area of study, which houses Binji, is bounded by 4° 30’ E and 5° E and Latitude 13° N and 13° 30’ N. The geology of Binji is typical of that of Sokoto Basin of north-western Nigeria (Fig. 1), which lies in the sub-Saharan Sudan belt of West Africa in a zone of savannah type vegetation [15]. The basin is in the dry Sahel, surrounded by sandy savannah and isolated hills. It has an annual average temperature of 28.3^{o}C. However, maximum daytime temperatures are for most of the year generally under 40^{o}C and the dryness makes the heat bearable. The warmest months are February to April when daytime temperatures can exceed 45^{o}C. It is reported that the geological structure of the Sokoto Basin is simple as the beds dip between 2.5^o to 3.8^o per km in a direction 60^o west of North. However, around Sokoto, the direction of dip is about 18^o NW and has the sedimentary deposits lay directly on the crystalline Precambrian basement [16].

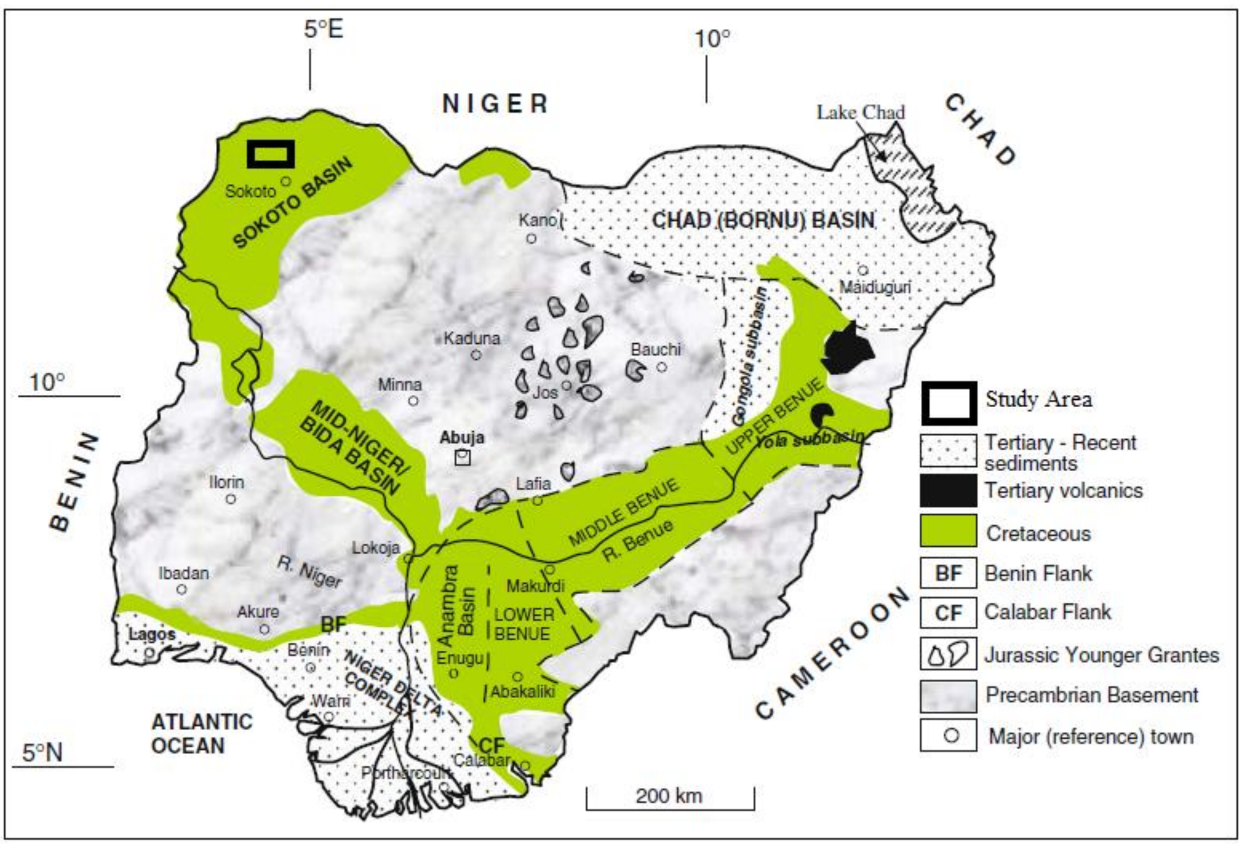

Fig.1. Geological map of Nigeria showing the study area

2.2 Theoretical Considerations

There are different methods of quantitative magnetic data interpretation, which include: gradient inversion, spectral analysis, Euler deconvolution, Peter's half slope, among others [17-19]. Nevertheless, the gradient inversion method is applied in this work. The technique was chosen because no priori information of structural geology is needed for proper processing and quantitative interpretation of magnetic data.

Gradient inversion method has been extensively discussed [19]. The magnetic anomaly ΔF at any point on the profile across a buried magnetic source can be written as:

$$\Delta F = C_f\,[(\phi_A - \phi_B)\cos\theta_F + \sin\theta_F \ln(r_A/r_B)] \tag{1}$$

where: ΔF is ΔZ, ΔH *or* ΔT, which is the vertical, horizontal or total field anomaly respectively, depending upon what is measured. The coefficients C_f and θ_F depend on whether ΔF is ΔZ, ΔH *or* ΔT. ϕ_A, ϕ_B, r_A and r_B are functions of the depth of burial of magnetic source h, semiapical width b, and x (distance of the field point on the profile relative to the epicentral position X_o). These parameters are related by: $\phi_A = \tan^{-1}[(x + b)/h]$, $\phi_B = \tan^{-1}[(x - b)/h]$, $r_A = h^2 + (x + b)^2$, and $r_B = h^2 + (x - b)^2$.

Practically, ΔF is the measured magnetic anomaly versus x, the distance of observation on the profile, which has the following features:

(i) ΔF profile has maxima ($M : x_M$) and minima ($m : x_m$) points. The coordinates of these maxima and minima are determined by deriving the analytical expression for the horizontal gradient of ΔF_x profile since $\Delta F_x = 0$ at $x = x_M$ or $x = x_m$.

Differentiating the two sides of Equation (1) with respect to x, the expression for ΔF_x is obtained as:

$$\Delta F_x = (2bC_f / r_A^2/r_B^2)[(h^2+b^2-x^2)\sin\theta_F - 2xh\cos\theta_F] \tag{2}$$

If $\Delta F_x = 0$ in Equation (2),

$$x = x_M = -(h\cot\theta_F + R), \text{ and} \tag{3}$$

$$x = x_m = -(h\cot\theta_F - R) \tag{4}$$

where $R = (b^2 + h^2\,\mathrm{cosec}^2\,\theta_F)^{1/2}$.

Since $M = \Delta F(x = x_M)$ *and* $m = \Delta F(x = x_m)$, Equation (1), (3), and (4) yield:

$$M = C_f[\cos\theta_F \tan^{-1} A_1 + ½\sin\theta_F \ln\{(R-b)/(R+b)\}], \text{ and} \tag{5}$$

$$m = C_f[\cos\theta_F \tan^{-1} A_2 + ½\sin\theta_F \ln\{(R-b)/(R+b)\}], \tag{6}$$

where $A_1 = b/(h\,\mathrm{cosec}^2\,\theta_F + R\cot\theta_F)$ *and* $A_2 = b/(h\,\mathrm{cosec}^2\,\theta_F - R\cot\theta_F)$

Similarly, the following expression for $\Delta F(0)$ is obtained by setting x = 0 in Equation (1),

$$\Delta F(0) = 2C_f\cos\theta_F \tan^{-1}(b/h)] \tag{7}$$

and by comparing Equations (5), (6) and (7),

$$\Delta F(0) = M + m \tag{8}$$

(ii) The epicentral position $X = X_0$ or $x = 0$ is therefore the coordinate on the distance axis at which the anomaly has the same value as the algebraic sum of its maximum and minimum value.

(iii) The relation between the values of x_M and x_m are:

$$\tfrac{1}{2}(x_M + x_m) = -h \cot \theta_F \qquad (9)$$

$$\tfrac{1}{2}(x_M - x_m) = R = (b^2 + h^2 cosec^2\, \theta_F)^{1/2}, \text{ and} \qquad (10)$$

$$-x_M x_m = (b^2 + h^2) = U^2 \qquad (11)$$

(iv) Finally, since the positions $x = 0$ and $x = U = (-x_m x_M)^{1/2}$ could be obtained, Equation (2) gives the values of $\Delta F_x(0)$ and $\Delta F_x(U)$ as

$$\Delta F_x(0) = (2b/U^2)\, C_f \sin \theta_F, \text{ and} \qquad (12)$$

$$\Delta F_x(U) = (-2b/Uh)\, C_f \cos \theta_F \qquad (13)$$

Equations (9), (11), (12) and (13) then shows that the ratio $[\Delta F_x(0) / \Delta F_x(U)]$ bears the following relation with θ_F:

$$[\Delta F_x(0) / \Delta F_x(U)] = [(x_M + x_m)/U] \tan^2 \theta_F = B^2. \qquad (14)$$

$$\text{Thus, } \theta_F = \pm \tan^{-1} B[U/(x_M + x_m)]^{1/2} \qquad (15)$$

These features of the observed magnetic profile ΔF and of its horizontal gradient ΔF_x can consequently be used to estimate the values of the depth h to magnetic sources in the subsurface.

2.3 Data Acquisition and Analysis

The aeromagnetic data map of Binji (sheet number 9) made available by the Nigerian Geological Survey Agency (NGSA) on a scale of 1:100000 was used as the primary data in this study. The survey was carried out in 1976 along N-S flight lines with a spacing of 2 km, tie-lines of 5 km and flight height of 152 m above the ground level. Regional correction based on the International Geomagnetic Reference Field (IGRF) was carried out including a constant subtraction of 25000 nT by the NGSA before the publication of the map. The map was digitized using a constant spacing of 2 km giving a 27 x 27 data matrix, thus producing a total of 729 values. The re-contoured map of Binji is shown in Fig. 2.

Regional anomaly was removed from the total magnetic field intensity data to obtain the residual anomalies using the Least Square Analysis of plane surface polynomial fitting [20]. The derived trend equation is given as:

$$g(x,y) = 24.205 - 0.0072x + 0.6434y \qquad (16)$$

where x and y are grids coordinate which describes the position of the data points with respect to the origin of the two axes.

Twenty two (22) horizontal residual profiles and their corresponding horizontal gradients were then ploted and each of the profile plots was subsequently analysed to obtain an estimate of the depth to magnetic source within the profile axis.

3.0 Results

The resulting regional and residual magnetic values, which were computed using Equation 16, are presented in Figs. 3 and 4 respectively. The residual magnetic data (Fig. 4) was subsequently used to obtain the depths to the magnetic basement while adopting Gradient Inversion Method [19].

Twenty two (22) profiles of the residual magnetic anomaly were strategically selected, while making sure that the profiles cut across different geologic structures in the study area. Examples of the magnetic profiles and their corresponding computed horizontal gradients are shown in Fig. 5. Within each profile, anomalies with good magnetic inversions were chosen for magnetic depth estimations and the resulting depth estimates are as presented in Table 1.

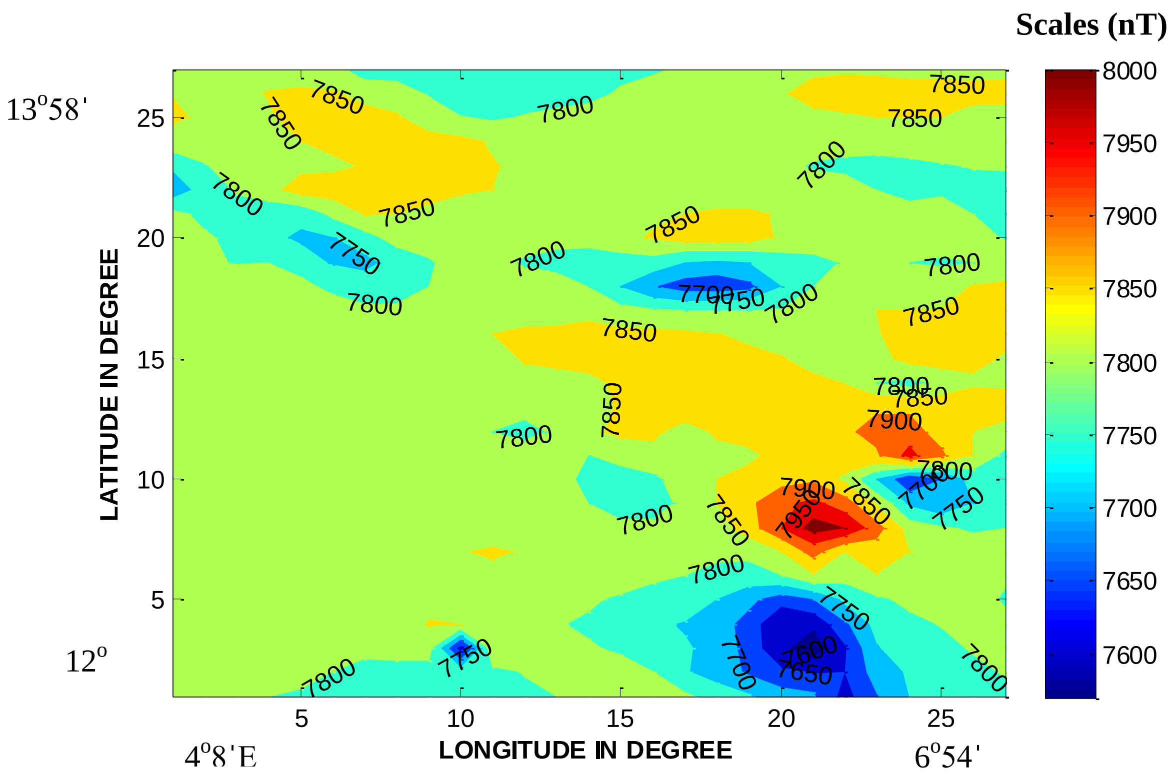

Fig. 2: Re-contoured map of Binji

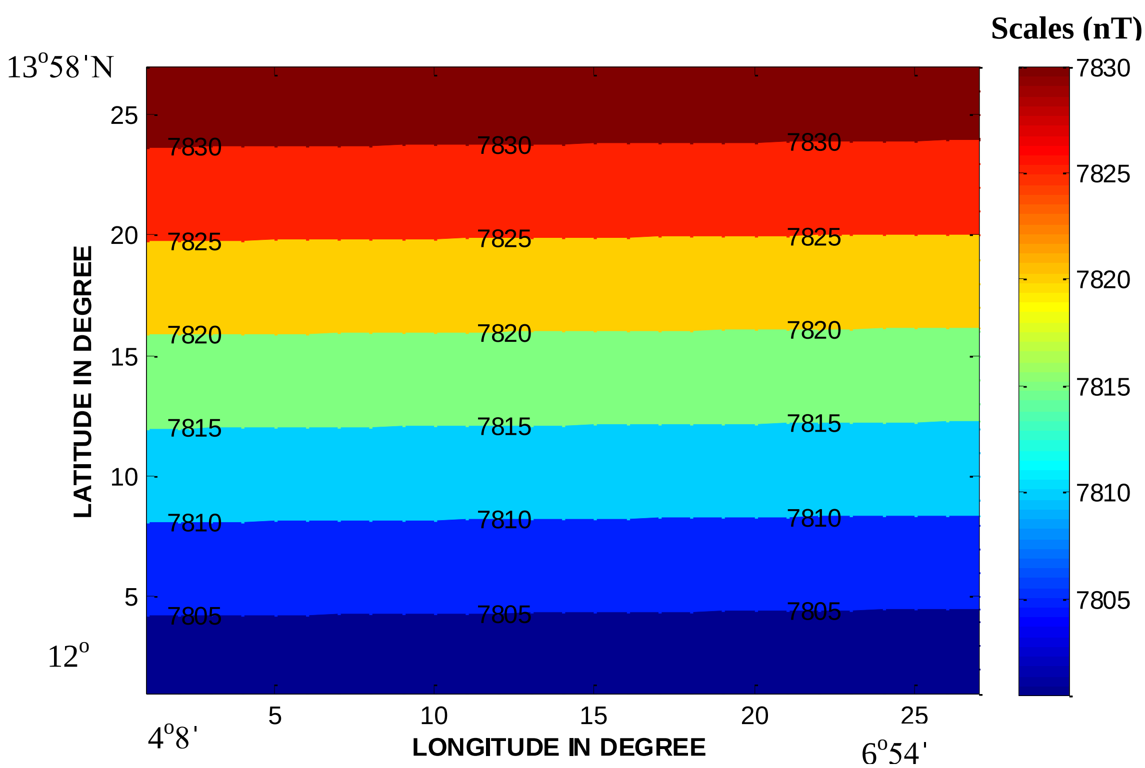

Fig. 3: Regional magnetic anomaly map of Binji

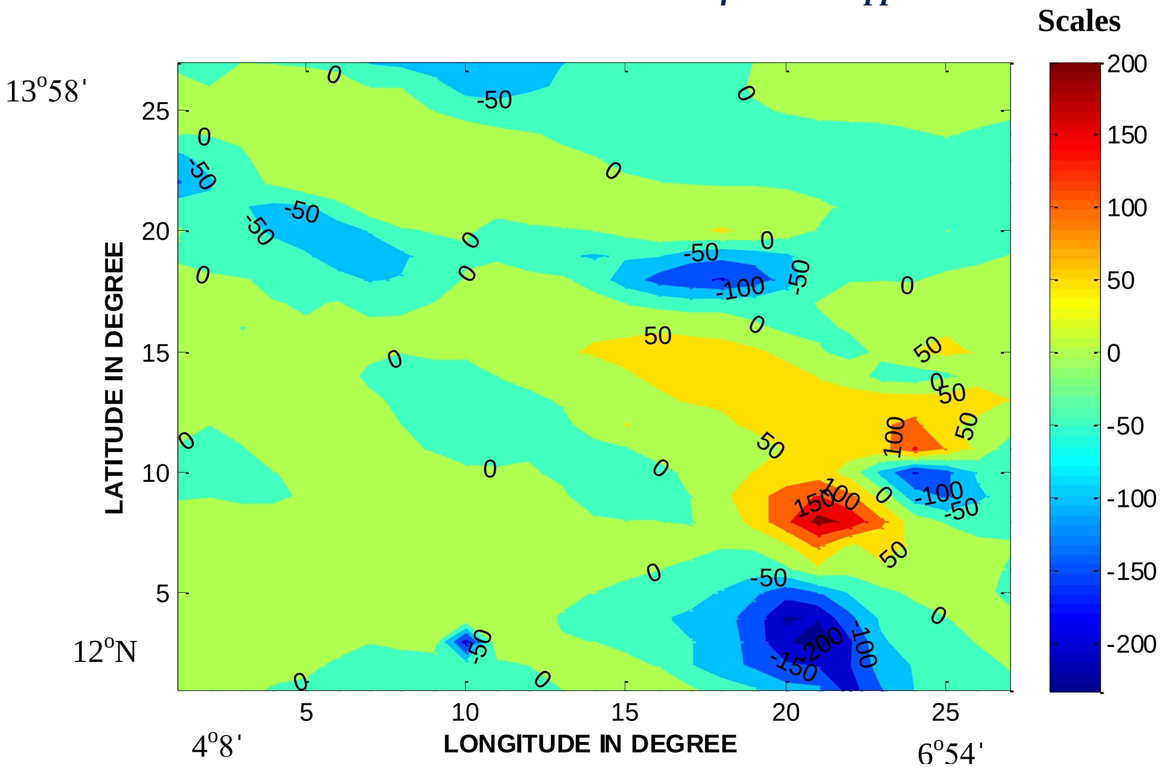

Fig. 4. Residual magnetic intensity map of Binji

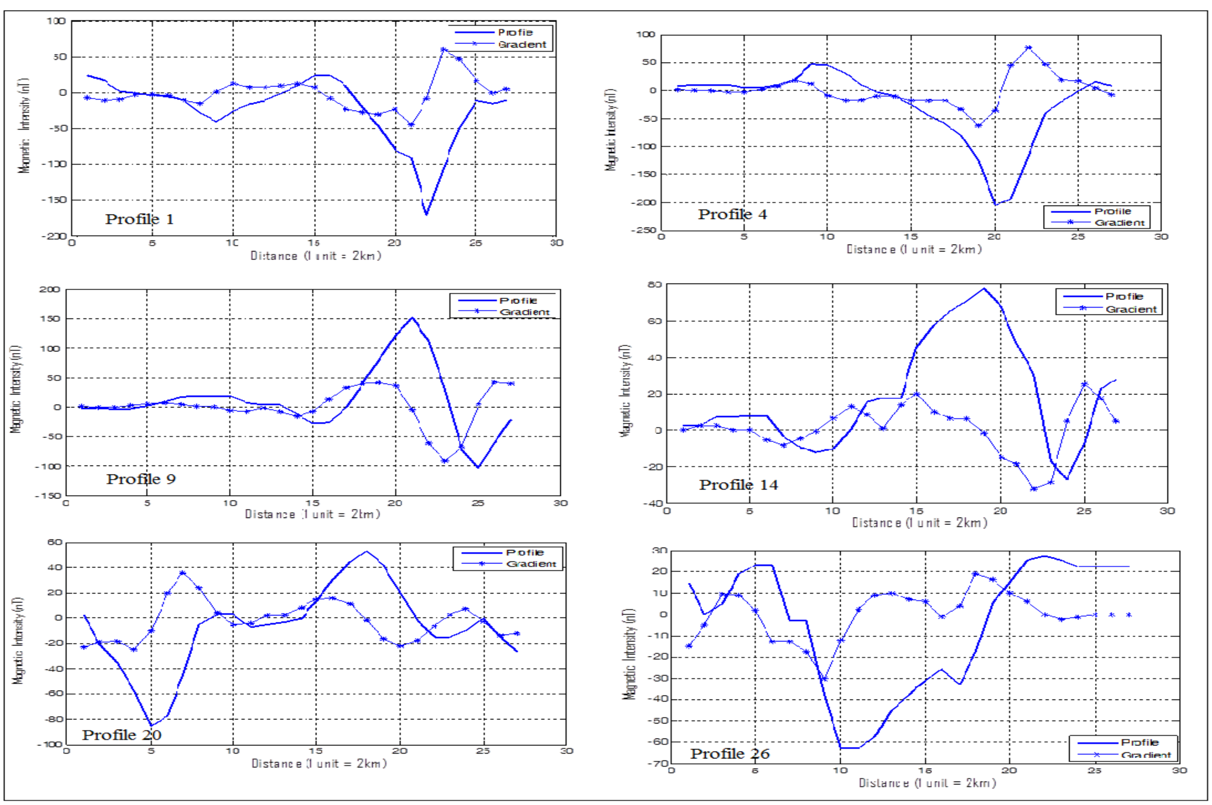

Fig. 5: Residual magnetic anomaly and horizontal gradient of selected profiles

Table 1: Calculated depth to magnetic sources in the study area

Profiles	Estimated Depth (km)	*Estimated Depth (km)
1	0.87	0.72
2	1.51	1.36
3	0.37	0.22
4	2.34	2.19
5	0.40	0.25
6	1.06	0.91
7	2.15	2.00
8	2.20	2.05
9	1.23	1.08
10	1.63	1.48
11	1.17	1.02
12	1.65	1.50
13	1.97	1.82
14	1.87	1.72
15	0.98	0.83
16	0.92	0.77
17	0.41	0.26
18	1.28	1.13
19	1.80	1.65
20	2.06	1.91
21	0.81	0.66
22	0.45	1.44
Average	1.32	1.26

* Flight height of 152 m subtracted

4.0 Discussion

The depths to magnetic sources obtained in the subsurface of the study area varied between 0.22 and 2.19 km with an average of 1.26 km. These results are in agreement with those estimated by other researchers using different methods in the Sokoto Basin: 0.6 km -1.83 km [21], 0.36 km – 2.28 km [11], 0.46 km - 1.96km [10], 0.80 km to 1.72 km [22], 0.4 km-2.0 km [9].

With the first aeromagnetic surveys came the recognition that the largest magnetic anomalies were produced by sources near the top of the crystalline basement, and that the wavelengths of these anomalies increased as the basement rocks became deeper [6]. Techniques were then devised to estimate the depths to the magnetic sources and, thus, the thickness of the overlying sedimentary basins. Mapping basement structure subsequently became an important application of the aeromagnetic method. For example in petroleum exploration, pieces of information regarding depths to basement structures and thickness of the sedimentary fill in a basin are sought for initial reconnaissance surveys in order to avoid loss of millions of United States Dollars in unproductive surveys. The minimum average thickness of sediment required to achieve a threshold temperature for the commencement of hydrocarbon formation is 2.3 km [23].

In order to attract the attention of geoscientists, there are several unscientific claims that there exists occurrence of commercial hydrocarbon deposit in the Sokoto Basin. However, researchers including industry experts and technocrats doubted the validity of the statement, premising on the lack of substantial prospect data on the basin [24]. Furthermore, an average sedimentary thickness of 1.26 km inferred in the study area confirms that hydrocarbon exploration may not be plausible in the study area.

5.0 Conclusion

In this study, the depth to magnetic sources has been estimated from gradient inversion analysis of the acquired aeromagnetic magnetic data of Binji, north-western Nigeria. The results showed that the depths to magnetic sources, which are considered as proxies for sedimentary thickness, vary from 0.22 to 2.19 km with an average of 1.26 km. However, the minimum average thickness of sediment required to achieve a threshold temperature for the commencement of hydrocarbon formation is 2.3 km. This study has therefore established that considering the revealed sedimentary depth extend, petroleum exploration may not be plausible in the study area.

Acknowledgement

The Nigerian Geological Survey Agency is acknowledged for releasing the aeromagnetic data at a subsidised rate.

References

[1] Telford, W.M., Geldart, L. P. and Sheriff, R. E. (1990). Applied Geophysics, Cambridge, Cambridge, University Press.
[2] Lowrie, W. (2007). Fundamentals of Geophysics, Cambridge, Cambridge University Press.
[3] Griffiths, D.H. and King, R.F. (1981). Applied Geophysics for Geologists and Engineers, Cambridge, Cambridge University Press.
[4] Kearey, P., Brooks, M. and Hill, I. (2002). An Introduction to Geophysical Exploration, Oxford, Blackwell Science.
[5] Ahmed, K., Mostafa, T., Awad, H. and Khamil, M. (2014). Electrical and Magnetic methods. Earth Sciences Research Journal, Vol. 18, No. 1, pp. 7–13.
[6] Nabighian, M.N., Grauch, V.J.S., Hansen, R.O., Lafehr, T.R., Peirce, J.W., Phyllips, J.D. et al. (2005), The historical development of the magnetic method in exploration. Geophysics, Vol. 70, No. 60, pp. 33-61.
[7] Alagbe, O.A. (2015). Depth estimation from Aeromagnetic data of Kam. International Journal of Advanced Research in Physical Science, Vol. 2, pp. 37–52.
[8] Bonde, D.S., Udensi, E.E. and Momoh, M. (2014). Delineating of magnetic zones of Sokoto Basin in North-Western Nigeria using Aeromagnetic Data. International Journal of Engineering and Science, Vol. 4, pp. 37-45.
[9] Shehu, A.T., Udensi, E.E., Adeniyi, J.O. and Jonah, S.A. (2004). Spectral Analysis of the Magnetic Residual Anomalies over the Upper Sokoto Basin, Nigeria. Zuma Journal of Pure and Applied Science, Vol. 6, No. 2, pp. 37–49.
[10] Adetona, A.A., Udensi, E.E., Agelaga, A.G. (2007). Determination of depth to buried magnetic rocks under the lower Sokoto Basin, Nigeria, using aeromagnetic data. Nigerian Journal of Physics, Vol. 19, No. 2, pp. 275-284.
[11] Bonde, D.S., Udensi, E.E. and Rail, J.K. (2014). Spectral Depth Analysis of Sokoto Basin. IOSR Journal of Applied Physics, Vol. 6, pp. 15-21.
[12] Nwankwo, L. I. (2015). Estimation of depth to the bottom of magnetic sources and ensuring geothermal parameters from aeromagnetic data of upper Sokoto Basin, Nigeria. Geothermics, Vol. 54, pp. 76-81.
[13] Kurowska, E. and Schoeneich, K. (2010). Geothermal exploration in Nigeria, In: Proceedings World Geothermal Congress. Bali, Indonesia, pp. 25-29.
[14] Balogun, O.Y. (2003). Senior Secondary Atlas, Lagos, Longman Inc.
[15] Anderson, H. R. and Ogilbee, W. (1973). Aquifers in the Sokoto basin, north western Nigeria, with a description of the general hydrogeology of the region water supply, In: Proceedings of Nigerian Geological Conference, Lagos, pp. 175
[16] Obaje, N.G. (2009). Geology and Mineral Resources of Nigeria, Lecture Notes in Earth Sciences, Berlin, Springer.

[17] Spector, A. and Grant, F.S. (1970). Statistical Models for interpreting aeromagnetic data. Geophysics, Vol. 335, pp. 293-302.

[18] Hahn, A., Kind, E.G., Mishra, D.C. (1976). Depth estimation of magnetic sources by means of Fourier amplitude spectra. Geophysics, Vol. 24, pp. 287-308.

[19] Pal, P.C. (1985). A gradient analysis based Simplified inversion Strategy for the Magnetic anomaly of an inclined and infinite thick dike. Geophysics, Vol. 50, pp. 1179–1182.

[20] Nwankwo, L.I. (2006). A least square plane surface polynomial fit of two dimensional potential field geophysical data using Matlab^{TM}. Nigerian Journal of Pure and Applied Sciences, Vol. 21, pp. 2006–2012.

[21] Chikwelu, E.E. and Ogbuagu, F.U. (2014). Determination of Depth of the Buried Magnetic Rocks Under Upper Sokoto Basin in the North-Western Part of Nigeria Using Aeromagnetic Data. International Journal of Emerging Technology and Advanced Engineering, Vol. 4, No. 5, pp. 10–15.

[22] Taufiq, S., Udensi, E.E. and Muhammed, S.B. (2014). Analysis of Aeromagnetic Data across Kebbi State, Nigeria. International Journal of Marine, Atmospheric & Earth Sciences, Vol. 2, No. 1, pp. 41-51.

[23] Wright, J.B., Hastings, D., Jones, W.B. and Williams, H.R. (1985), Geology and Mineral Resources of West Africa, London, George Allen and Urwin Inc.

[24] Obaje, N.G., Aduku, M. and Yusuf, I. (2013). The Sokoto Basin of Northwestern Nigeria: A Preliminary Assessment of the Hydrocarbon Prospectivity. Petroleum Technology Development Journal, Vol. 3, No. 2, pp. 66–80.