

Estimation of Sedimentary Thickness of Maiduguri, Northeastern Nigeria, from Fourier Analysis of Aeromagnetic Data

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Abstract

A quantitative interpretation of the aeromagnetic anomalies of Maiduguri (sheet 90) in the north-eastern region of Nigeria has been carried out using Fourier transform method. The study area covers approximately 3,025 square kilometres and forms part of Chad Basin. Regional anomalies were removed from the total magnetic field using 2D least square method and the resulting residual data were used to obtain Fourier spectra of 20 selected profiles. Slopes of high and low frequency portions of each spectrum were utilised to estimate depths to shallow and deeper magnetic sources. The results show that the depths to shallow and deeper magnetic sources vary from 0.20 to 0.84 km with an average of 0.42 km and from 0.85 to 3.27 km with an average of 1.59 km respectively. Depths to deeper magnetic sources are normally inferred as sedimentary thicknesses; therefore the results indicate that the estimated thickness of sedimentary fill in Maiduguri area of Chad basin ranges between 0.85 and 3.27 km.

Keywords: Aeromagnetic, Spectral, Residual, Sedimentary, Maiduguri

Introduction

Airborne geophysical surveying is the process of measuring the regional variation of different physical or geochemical parameters of the earth hidden from direct view such as distribution of magnetic minerals, density, electric conductivity, and radioactive element concentration. The methods used in such measurements are magnetic, gravity, electromagnetic and gamma-ray spectrometry respectively (Mekonnen, 2004).

Aeromagnetic survey measures the variation of the geomagnetic field, which occurs due to the changes in the percentage of magnetite in the underlying rock of an area. It reflects the variations in the distribution and type of magnetic minerals below the earth surface. Magnetic minerals can be mapped from the surface

to greater depth in the rock crust depending on their dimension, shape and the magnetic property of the rock. Sedimentary formations are usually non-magnetic and consequently have little effect whereas igneous and metamorphic rocks exhibit greater variation and become useful in exploring bedrock geology concealed below cover formations (Mekonnen, 2004). Variation in magnetic susceptibility combined with other geophysical data and known geology provide important information about the regional geology especially where rock outcrops are scarce or absent and also helps to develop priorities for follow-up in the most prospective areas. For example, mafic dykes usually give rise to magnetic anomalies that are prominent on the aeromagnetic anomaly maps that now

approach universal coverage for the land areas of the world (Dobrin, 1960; Dobrin and Savit, 1988). In regional mapping, mafic dykes give rise to well-defined topographic features and with respect to granitic and most sedimentary host rocks are dark coloured, covered by denser vegetation and more magnetic. Therefore, they could be easily traced from satellite imagery, aerial photographs and aeromagnetic maps (Chavez, 2000).

Aeromagnetic data allow fast coverage of large and inaccessible areas for subsurface reconnaissance, which makes magnetic data analysis an essential tool of geophysical exploration (Hinze, 1990; Kasidi and Ndatuwong, 2008). In general, magnetic surveying is used in many different studies targeting all kinds of objects from kimberlite pipes to unexploded military ordnances (Lowrie, 2007; Milsom, 2003; Telford *et al*, 1990). Magnetic anomaly studies in Nigeria have mainly been interpreting large scale subsurface structures with high magnetic susceptibility such as volcanic intrusions. As long wavelength anomalies are caused by igneous, iron-rich rocks, they can well be resolved and interpreted in magnetic surveys. Numerous magnetic anomaly interpretations have used this characteristic for location and depth estimation of these mostly intrusive bodies. Another achievement of magnetic anomaly studies is the conformation of the theory of geomagnetic polarity reversals and ocean spreading. The observed lineation of magnetic anomalies parallel to ocean spreading zones is caused by the remanent magnetization of oceanic crust. On the other hand, high resolution magnetic surveys are also applicable for short wavelength analysis, which can reveal fault structures in the sediments, though

they have a significantly lower susceptibility than basement rocks.

In this work, the application of Fourier transform of aeromagnetic anomalies has been used to determine the sedimentary thickness of Maiduguri area of Chad basin, Nigeria.

Location and Geology

Maiduguri is situated within the Nigerian sector of Chad basin (Fig. 1). The entire Chad Basin is the largest inland basin in Africa occupying an area of approximately 2,500,000 km² extending over parts of the republic of Niger, Chad, Sudan and the northern portions of Cameroon and Nigeria within latitudes 10°N to 14°N and longitudes 12°E to 15°E. (Nwankwo and Ekine, 2009). The Nigerian sector of the basin constitutes only about 6.5% of the entire basin and extends 152,000 km² of territory in Bornu, Bauchi, Plateau and Kano States. The altitude of the basin ranges from 300 m within the lake to about 530 m at the western margin, along a distance of about 240 km.

The Chad basin is an intra-continental rifted basin. It is believed to be genetically related to the Benue trough, which resulted from a failed arm of a triple junction when South American continent separated from the African continent in Early Cretaceous. These two basins are however, separated by the Zambuk Ridge (Burke, 1969; Genik, 1992).

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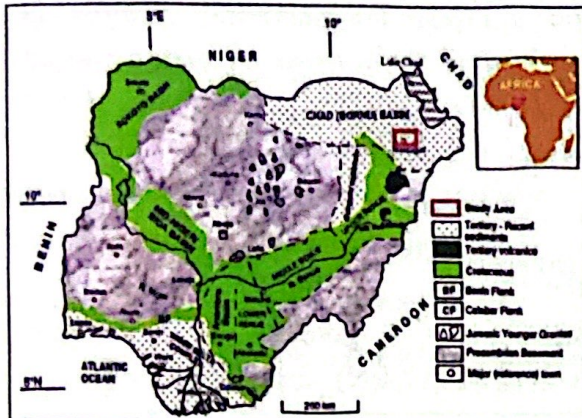


Fig. 1. Geological Sketch of Nigeria showing the study area (After Nwankwo and Shehu, 2015).

Cratchley (1960) delineated the Nigerian sector of Chad basin into three sub-basins prosperous for hydrocarbons explorations. These sub-basins are centred around Gubio to the southwest, Maiduguri to the South and Lake Chad to the North. Since the late 1970s, the Nigerian sector of Chad basin has been an area of interest in terms of hydrocarbon exploration mainly by the Nigerian National Petroleum Corporation (NNPC). Early exploration works were by Shell-D Arcy in 1938; and later Mobil Exploration Nigeria Limited in 1955. At about 1965, all the oil prospecting companies limited their activities to the Southern Nigeria sedimentary basins, especially the Niger Delta, due to non-discovery of oil in the basin (Okpikoro and Olorunniwo, 2010). However, efforts are been made presently by the NNPC to resume petroleum exploration in Chad basin.

Materials and Methods

Airborne magnetic survey contour map 55 x55 km² of total magnetic field intensity published by the Nigerian Geological Survey Agency (NGSA) on a scale of 1:100,000 was used as the basic data for determining the nature of magnetic

anomalies over the area. The survey was carried out in the 1970s along a series of North-South lines with flight spacing of 2 km and an average elevation of 152m above the ground level.

Since one common problem in automated data interpretation is to select digitization spacing and minimum length of data profile in order to minimize aliasing error, selecting a digitization interval of 0.875km is found to solve the problem in this study (Nwankwo *et al.*, 2011). Therefore, the map was carefully digitized using semi-automated method through the following process: the map was scanned, geo-referenced using raster design (AutoCAD) and finally gridded using AutoCAD software at an equal spacing interval of 0.875km to produce a 64x64 data matrix yielding 4,096 data values for the study Area. Although hand digitization is the most elementary and least efficient method of digitization, the use of AutoCAD software in gridding the map, made the digitization easier and more efficient. The re-contoured magnetic map drawn with MATLAB software is shown in Figure 2.

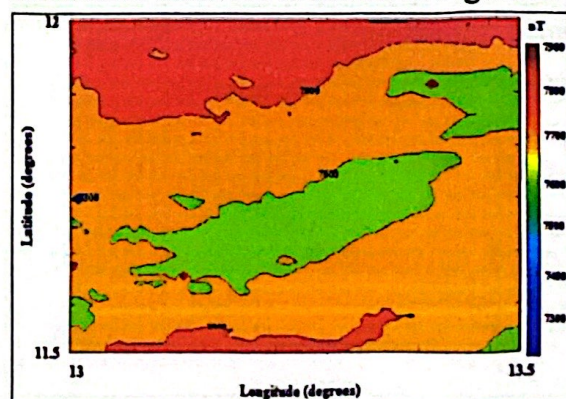


Fig. 2: Re-contoured aeromagnetic of the study area. ($\frac{1}{2} \times \frac{1}{2}$) degree.

Regional fields were then subtracted from the digitised data yielding residual anomaly (Figure 3), which was implemented using a code developed in

MATLAB for least square polynomial fit for potential field data (Nwankwo, 2006). Then, one dimensional Fourier amplitude spectrum of selected 20 residual anomaly profiles (north-south trend) was implemented, with a Low Hanning pass filter incorporated to smoothen the residual profile data.

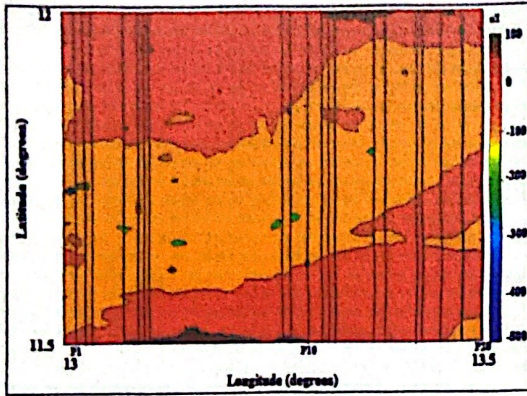


Fig. 3: Derived residual anomaly of the study area showing selected profiles (P1, P2,...P20).

Theoretical Considerations

Fourier analysis is utilized in this work. Fourier theorem explains that a function $f(t)$ having a fundamental period and satisfying Dirichlet's condition can be represented by the following infinite Fourier series:

$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos nt + b_n \sin nt) \quad (1)$$

$$a_0 = \frac{1}{2} \int_{-\pi}^{\pi} f(t) dt \quad (2)$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(t) \cos nt dt \quad (3)$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(t) \sin nt dt \quad (4)$$

where a_0 , a_n and b_n are Fourier coefficients and their estimations is referred to as Fourier analysis. $n = 0, 1, 2, 3, \dots$

$$\Delta T(\omega) = \frac{\pi}{\omega} e^{-h\omega} [(A - A \cos(t\omega \cot d) e^{-i\omega} - B \sin(t\omega \cot d) e^{-i\omega} - j \cos(t\omega \cot d) e^{-i\omega} - A \sin(t\omega \cot d) e^{-i\omega} - B] \quad (7)$$

$$\Delta T(\omega) = \pi e^{-h\omega} [A - A \cos(t\omega \cot d) e^{-i\omega} - B \sin(t\omega \cot d) e^{-i\omega} + j \cos(t\omega \cot d) e^{-i\omega} - A \sin(t\omega \cot d) e^{-i\omega} - B] \quad (8)$$

The analysis is commonly applied in geophysical studies using Discrete Fourier Transforms (Spector and Grant, 1970; Hahn, 1976; Murthy and Mishra, 1980):

$$f(n) = F(n) e^{j\phi(n)} \frac{1}{N} \sum_{u=1}^N f(u) e^{-j(\frac{2m\pi n}{N})u} \quad (5)$$

where the given time series are $f(1), f(2), \dots, f(N)$ for N data points, at equal spacing.

In magnetic analysis, it is useful to have proposed models, such as sphere, cylinders, fault, etc. which cause the anomaly at the surface. For this reason, the total magnetic field anomaly ΔT , measured in the direction of geomagnetic field is given by (Spector and Grant, 1970; Hahn, 1976; Murthy and Mishra, 1980):

$$T = \frac{1}{2} A \left[\ln \frac{(x-t \cot d)^2 + (h+t)^2}{x^2 + h^2} + B \left[\tan^{-1} \left(\frac{(x-t \cot d)}{(h+t)} \right) - \tan^{-1} \left(\frac{x}{h} \right) \right] \right] \quad (6)$$

where

$$A = 2kH_0 (1 - \cos^2 i \cos^2 h\lambda) \sin d \cos(d - 2\beta)$$

and

$$B = 2kH_0 (1 - \cos^2 i \cos^2 h\lambda) \sin d \sin(d - 2\beta)$$

, I = magnetic inclination, d = dip of the step, t = thickness of the step, k = susceptibility constant, H_0 = geomagnetic field and the angle I and h are combined into a single variable defined by $\tan \beta = \tan i / \sin \lambda$.

The Fourier transform and modified transform of equation (8) is given respectively as:

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The modified Amplitude Spectrum is consequently given by

$$A(\omega) = Ce^{-h\omega} (1 + e^{-2i\omega} - 2 \cos(t \omega \cot d) e^{-i\omega}) \frac{1}{2} \quad (9)$$

where $C = 2\pi KH_o (1 - \cos^2 i \cos^2 \lambda) \sin d$

Taking the logarithm of equation (9):

$$\ln A(\omega) = \ln C - m\omega + \frac{1}{2} \ln [1 + e^{-2i\omega} - 2 \cos(t \omega \cot d) e^{-i\omega}] \quad (10)$$

For sufficiently larger value of ω , equation (10) reduces to:

$$\ln A(\omega) = \ln C - m\omega \quad (11)$$

where $\ln A(\omega)$ is modified amplitude and ω is frequency (cycle/km).

The depth h to the causative bodies can subsequently be calculated using the relation (Spector and Grant, 1970):

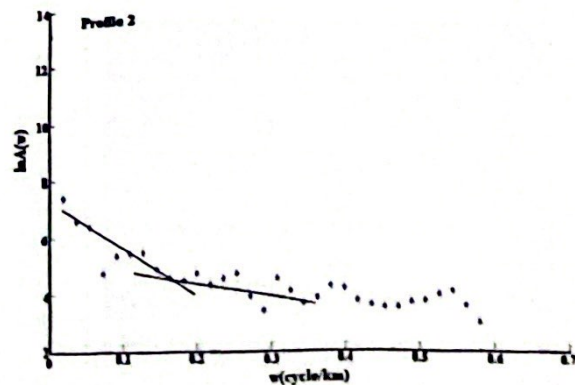
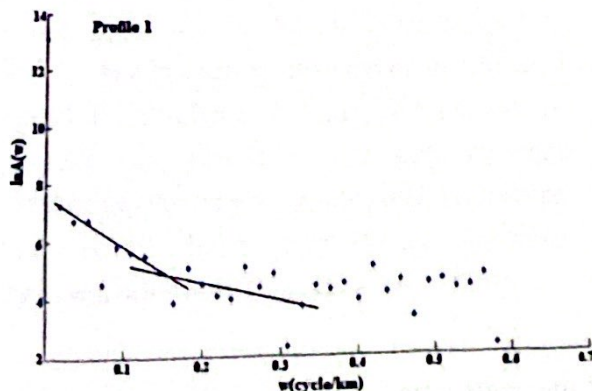
$$h = -\frac{m}{4\pi} \quad (12)$$

In this work, the graph of $\ln A(\omega)$ against frequency (ω) was plotted and the gradient (m_1) for the deeper source and gradient (m_2) for shallow source were deduced. The depths h_1 and h_2 are therefore given by the respective slopes of straight line segments of low and high frequency portions (Spector and Grant, 1970; Hahn, 1976; Murthy and Mishra, 1980):

$$h_1 = \frac{m_1}{4\pi} \text{ and } h_2 = \frac{m_2}{4\pi} \quad (13)$$

Results and Discussions

Spectral plots of the analysed profiles are shown in Figure 4, while the ensuing quantitative results are shown in Table 1. The table shows that the deeper magnetic sources vary from vary from 0.85 to 3.27 km with an average of 1.59 km, while the shallow sources vary from 0.2 to 0.84 km with an average of 0.43 km. This is found to be fairly consistent with previous results revealing that the depth to deeper magnetic sources in the Maiduguri area of Chad basin ranges between 0.5 and 3 km (Okonkwo *et al.*, 2012) and from 1.5 to 4 km (Lawal *et al.*, 2015). The estimated depth to shallow magnetic sources obtained in this study is also fairly consistent 0.1 – 0.46 km reported by Lawa *et al.*, (2015). Table 1 further show that, while considering the deeper magnetic sources, the central part of the study area is statistically the deepest while both the western and eastern parts are the lowest as elucidated in Fig. 5.



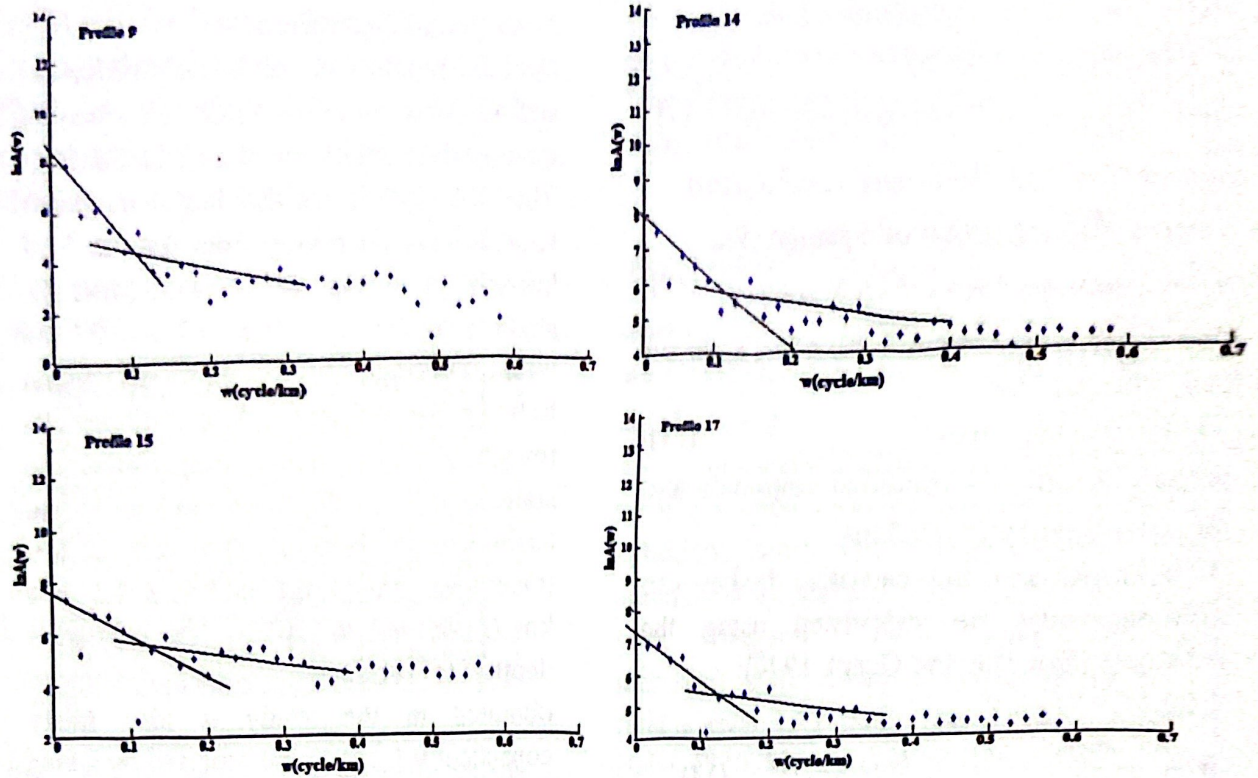


Fig. 4: Amplitude spectrum of selected profiles.

Table 1: Estimates of depth to magnetic sources

Profiles	Latitude (°N)*	Longitude (°E)*	Depth to the shallow source (Km)	Depth to the deeper source (Km)
1	11.75	13.016	0.61	1.31
2	11.75	13.023	0.56	1.23
3	11.75	13.031	0.57	1.89
4	11.75	13.070	0.31	2.05
5	11.75	13.086	0.42	1.13
6	11.75	13.094	0.24	0.85
7	11.75	13.101	0.30	1.68
8	11.75	13.257	0.52	2.12
9	11.75	13.265	0.40	2.63
10	11.75	13.289	0.84	3.27
11	11.75	13.304	0.58	1.76
12	11.75	13.312	0.60	1.15
13	11.75	13.320	0.40	1.60
14	11.75	13.367	0.36	1.42
15	11.75	13.382	0.20	1.41
16	11.75	13.421	0.27	1.36
17	11.75	13.429	0.44	1.19
18	11.75	13.452	0.31	1.67
19	11.75	13.476	0.24	0.91
20	11.75	13.500	0.27	1.20
Average			0.42	1.59

* Centre of Profile

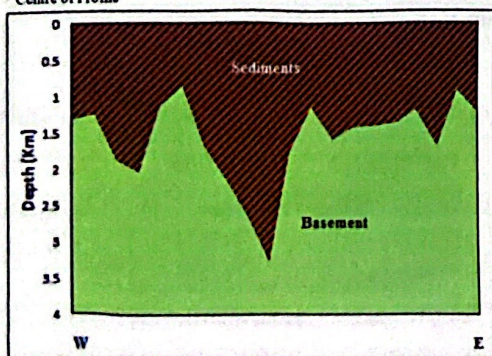


Fig. 5: Estimated sedimentary thickness section of the study area.

Deeper magnetic source is generally regarded as a proxy for sedimentary thickness; consequently, Table 1 also reveals that about 80% of the analysed profiles have sedimentary thickness less than 2 km, while only 5% have sedimentary thickness up to 3 km. Such thickness of sedimentary extent may unlikely favour hydrocarbon formation in the Maiduguri area of Chad basin.

The residual aeromagnetic anomaly map (Fig. 3) shows that the study area is dominantly made up of high magnetic anomalies. The rock types associated with positive magnetic anomaly values are usually made up of basic intrusive or rocks rich in ferromagnesian minerals e.g. gabbros, norites, anorthosites, trocolites, dolerites the main minerals in basic rocks are calcicplagioclase, pyroxenes (augite and hypersthene), olivine etc. It can also be observed that basic rocks are under saturated and therefore do not usually contain free silica (quartz). This is because both remanent and induced magnetism can contribute to the magnetic field produced by basic rocks, and for every old basic intrusive, the remanent magnetization can be a dominant factor contributing to magnetic anomalies. More so basic rocks generally have high iron content and are more magnetic than others, so magnetic methods can be used to map them efficiently. It is also believed that area has some presence of basalt (Onuba *et al.*, 2008). Hydrocarbon prospects in the area could be doubtful because of the likely presence of basalt whose emplacement may have destroyed geological structures that could have served as possible hydrocarbon traps (Onuba *et al.*, 2008).

Conclusions

Depth estimates from Fourier transform analysis of aeromagnetic data of Maiduguri area of Chad basin indicated a two-depth source model. The depth to deeper sources ranges from 0.85 to 3.27 km with an average of 1.59 km, while the shallow source ranges from 0.20 to 0.84 km with an average of 0.42 km. The results of the deeper magnetic source estimation show that the thickness of sedimentary fill in the study area is in the neighbourhood of 0.85 - 3.27 km. However, only 5% of the analysed profiles have sedimentary thickness up to 3 km. Therefore, such thickness of sedimentary extent is unlikely to favour hydrocarbon formation. More so, hydrocarbon prospects are largely doubtful because of the likely presence of basalt in the area whose emplacement may have destroyed geological structures that could have served as hydrocarbon traps (Onuba *et al.*, 2008).

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