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Evolution of Gongola Basin Upper Benue Trough Northeastern Nigeria

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Abstract: Nine aeromagnetic maps of $\frac{1}{2}^{\circ} \times \frac{1}{2}^{\circ}$ between longitude $10^{\circ}00'$ and $11^{\circ}30'E$ and latitudes $09^{\circ}30'$ and $11^{\circ}00'N$ representing part of the Gongola Basin, were analysed to determine some characteristics of a prominent aeromagnetic anomaly within the basin. The maps were digitised along flight lines and the data were interpolated on to a regular grid of 0.01° interval. The regional field of the area was approximated to a first order degree polynomial using the robust method. Depths to the first, second and third magnetic levels of the area were determined using the spectral analysis technique. Analysis of the nine blocks of 51×51 residual data points revealed two magnetic levels for some of the blocks while others have three magnetic levels. The first level has an average value of 1.25 km, while the second level has a mean value of 4.03 km, the third magnetic level has an average of 5.39 km. Three profiles covering a prominent anomaly in the area were selected for modeling. The GM-SYS 2½ dimensional modelling programme was used to model the body. The depth to the causative body is between 2.40 and 8.09 km. The causative bodies were interpreted to be basic to ultrabasic rocks. Based on the results obtained, a rift origin was proposed for the basin.

Key words: Gongola basin, upper benue trough, aeromagnetic, spectral analysis, modeling

INTRODUCTION

The Gongola Basin (arm) of the Upper Benue Trough (Fig. 1) is a N-S trending arm of the 1000 km long Benue Trough. The mechanism of the formation of the Trough dominated most of the early studies carried out in the area and, although, still controversial, an unstable RRF (rift-rift fault) triple junction model leading to plate dilation and the opening of the Gulf of Guinea (Benkhelil, 1989; Fairheada and Binks, 1991). Benkhelil (1989) also suggested that the evolution trough could also be as a result of tension resulting in a rift or wrench related fault basin, Mesozoic to Cenezoic magmatism has accompanied the evolution of the tectonic rift as it is scattered all over and throughout in the trough (Coulon *et al.*, 1996), a magmatic old rift was also suggested for the Gongola Basin (Shemang *et al.*, 2001).

However, one thing that is not controversial in the trough is its great potentials for sources of mineral raw materials of economic significance. Deposits of limestone, bricks and fire clay, construction stone, laterite and coal, all of commercial importance exist and some are being worked. Significant occurrences of base metal sulphide (lead with small amounts

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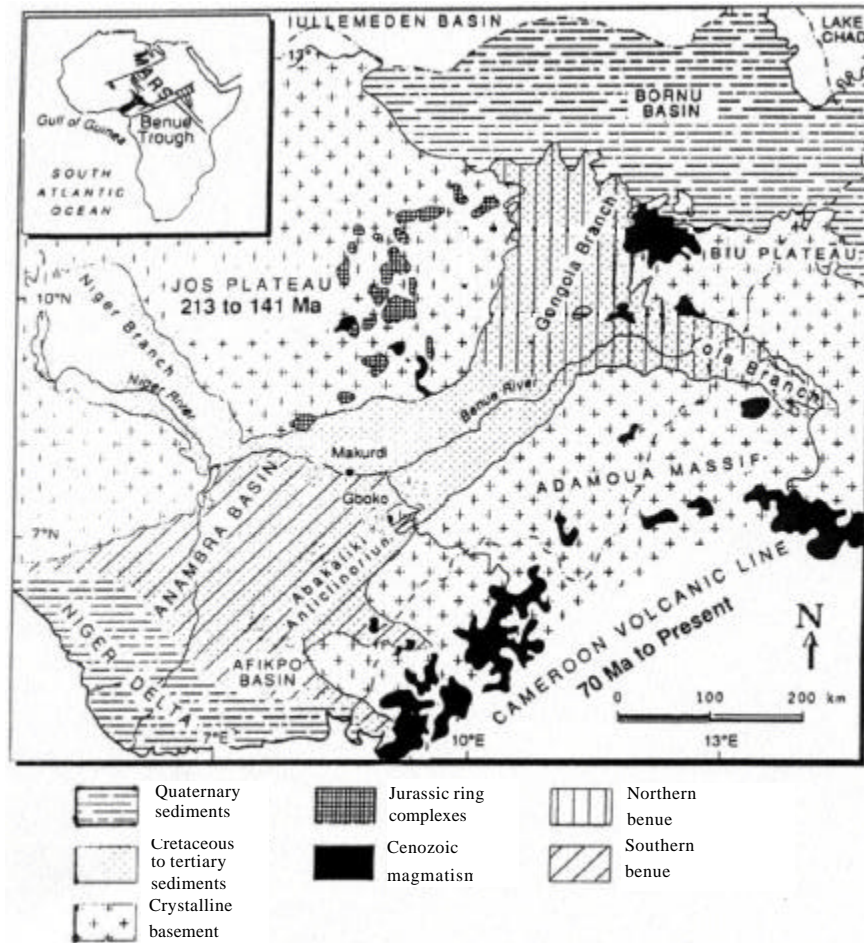


Fig. 1: Location map of the study area (Adopted from Coulon *et al.*, 1996)

of copper) cadmium and silver and associated mineral barites are known to occur in the trough. Other economic minerals such as coal and diatomite occur in Gombe and Bularafa, limestone around Ashaka, low-grade base metals, as well as large potential for glass sands and mineral (juvenile water) in the trough. Recently, the petroleum potential of the trough has been of great interest to geologists and geophysicists. Geological and geophysical studies carried out in the Upper Benue Trough have shown the area to have all the qualities possessed by the oil producing area of the trough namely Lower Benue Trough and Middle Benue Trough. The Nigerian government through the Nigerian National Petroleum Cooperation (NNPC) and many oil companies have invested heavily in the NE of the trough prospecting for oil which remains elusive up to today. However, efforts are still on and more money is still being sunk into the area with the hope of finding oil in the near future. This being the case, there is need for more geophysical and geological studies to be carried out in the area to add to the existing data. The research presented in this study is part of this effort and has the following objectives:

- To determine depths to magnetic sources within the study area using spectral analysis
- To modeled a prominent linear aeromagnetic anomaly in the area and its source
- To determine the basement topography
- To infer the possible origin of the Basin from all the above

Spectral analysis of the aeromagnetic field provides a valuable tool for the determination of depths to magnetic sources. In addition, 2½ dimensional computer modeling programme can give a composite model of the surface topography of the basement below the basin and the structure as well as the depth of any intrusions into the basement. Like most of the published procedures of depth determination for magnetic sources, the procedure of spectral analysis used here is based on the method developed by Spector and Grant (1970). On the other hand, the 2½D programme makes use of algorithms described by Won and Bevis (1987). The 2½D calculations are based on Rasmussen and Pedersen (1979).

MATERIALS AND METHODS

The Study Area

The present study was conducted in the Gongola Basin which forms part of the Upper Benue Trough. The project started in June of 2002 and lasted to August 2004 covering an estimated area of 27390.25 km² and lies between longitude 10°00' and 11°30'E and latitude 09°30' and 11°00'N.

The central part of the study area (Fig. 2) is occupied by the Kerri-Kerri formation which extends up to the southwestern corner of the map. The Kerri-Kerri formation is believed to have a thickness of about 320 m. The Pindiga Formation, Bima sandstone, Yolde formation and Gombe sandstone, occupy the Northeastern portion of the map and extend down to the Southeastern part of the area. The Pindiga formation consists mainly of shaly mudstone with intercalation of limestone occurring in some areas. The Pindiga formation is believed to have a thickness of about 240 m. The Yolde formation on the other hand has a thickness of about 200 m. The Yolde formation is indeed a transitional sequence between the continental Bima group and the marine deposits of the lower part of the Pindiga Formation. Gombe sandstone consists mainly of grits and clay and is restricted to the western part of the Basin. The Bima sandstone consists of coarse grain sandstone with an overall thickness of about 3500 m. The crystalline basement rocks which occupy the extreme western portion of the area, consist of scattered remnants of highly metamorphosed sedimentary rocks and diverse, predominantly granitic plutonic masses collectively called older granite (Carter *et al.*, 1963).

The total magnetic field over the study area was obtained by digitizing nine aeromagnetic maps of the Geological Survey of Nigeria (GSN) airborne geophysical series sheets 129 (Ganjuwa), 130 (Dukku), 131 (Bajoga), 150 (Alkaleri), 151 (Akko), 152 (Gombe), 171 (Yuli), 172 (Futuk) and 173 (Kaltungo). The maps were digitized along flight lines. The data obtained by the digitization of the various maps are unequally spaced, while that is good in minimizing aliasing effecting in sampled data (Bath, 1974), the data is not suitable for most methods of quantitative interpretation. The method for interpolation of these data in the present study is a method that combines Laplace interpolation and that of quadratic weighting. A grid interval of 0.01 degree of latitude and longitude were used to obtain a 51×51 data points. The gridded data were then integrated and the data obtained is used to plot the composite map of the study area. From the total magnetic field obtained, the residual magnetic field over the area was calculated by removing a first-degree regional field derived

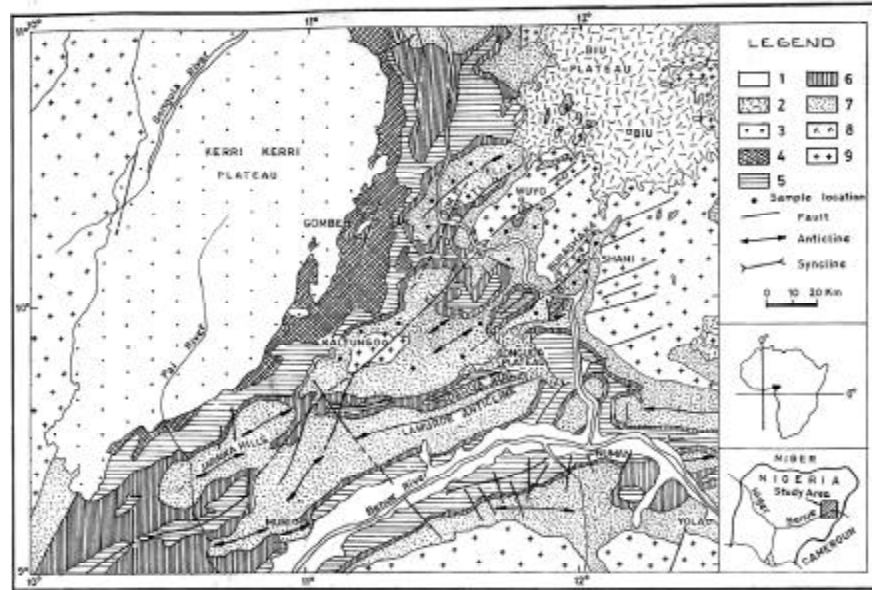


Fig. 2: Geologic map of the study area (after Benkhelil, 1989). Simplified geological map of the Upper Benue Trough showing sample locations. 1: Quaternary alluvium; 2: Tertiary volcanics; 3: Kerri-kerri Formation; 4: Gombe Sandstone; 5: Pindiga Formation; 6: Yolde Formation; 7: Bima Sandstone; 8: Burashika Complex (Mesozoic volcanism); 9: Undifferentiated Basement Complex. Main Fault zones; BL: Burashika Fault; KL: Kaltungo Fault; TL: Teli Fault (After Benkhelil, 1989)

by using a method of robust statistics described by Ojo and Kangkolo (1997). The residual maps of the study area is shown in Fig. 3.

Spectral Analysis

The 2-dimensional Fourier Transform pair may be written as (Bhattacharyya, 1966; Bath, 1974):

$$G(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y) e^{-i(ux+vy)} dx dy \dots \dots \dots (1)$$

$$g(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(u, v) e^{i(ux+vy)} du dv \dots \dots \dots (2)$$

where, u and v are the angular frequencies in the x and y directions, respectively.

G (u, v), when broken up into its real and imaginary parts is given by:

$$G(u, v) = P(u, v) + iQ(u, v)$$

The energy density spectrum or simply the energy spectrum is given by:

$$E(u, v) = |G(u, v)|^2 = (P^2 + Q^2)$$

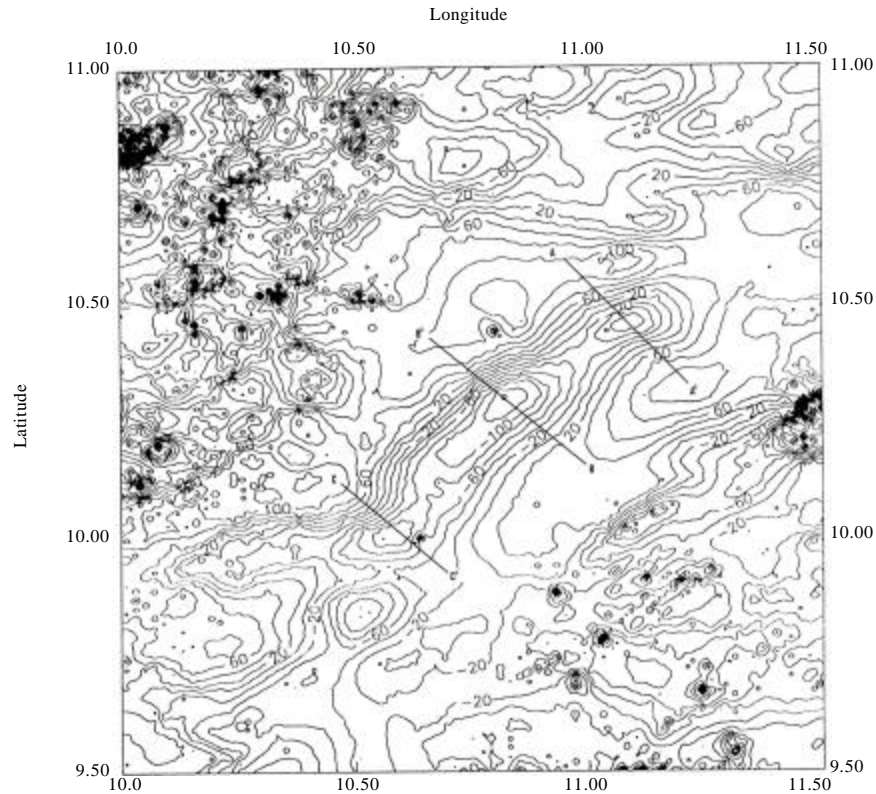


Fig. 3: Residual magnetic field intensity map of the study area (contour interval 20 nT).
 Inserted are profiles taken for the modeling exercise

Residual total magnetic field intensity values are used to obtain the two-dimensional Fourier transform from which the spectrum is to be extracted. The frequency intervals are then further divided into sub-intervals, which lie within one frequency range. The average spectrum of all the values falling within this frequency range is calculated and the resulting value together constitute the radial spectrum of the anomalous field.

A logarithmic plot of the power spectrum versus frequency on a linear scale shows a series of points, that may well be represented by bodies occurring within a particular depth range, which fall on one or more straight line segments whose slopes provide a measure of the mean depth to the ensemble of anomalous bodies (Spector and Grant, 1970). If z is the mean depth of a layer, the depth factor for this ensemble of anomalies is $e^{-2\pi}$. Thus, the logarithmic plot of the radial average power spectrum would give a straight line whose slope is $-2z$. The mean depth of burial of the ensemble is thus given by:

$$\bar{z} = -\frac{m}{2}$$

where, m is the slope of best fitting straight line. The above equation is used directly if frequency units are in radians km^{-1} , but for those in cycles km^{-1} is used:

Table 1: Depth in kilometers to the first, second, and third magnetic levels for nine (9) blocks of 51 x 51 grid size

Block No.	X1	X2	Y1	Y2	D1	D2	D3
	----- (degree) -----				----- (km) -----		
01	10.00	10.50	10.50	11.00	1.03	2.68	4.02
02	10.50	11.00	10.50	11.00	1.11	4.06	-
03	11.00	11.50	10.50	11.00	1.05	2.61	3.51
04	10.00	10.00	10.00	10.50	1.00	2.75	4.21
05	10.50	11.00	10.00	10.50	1.80	3.51	8.03
06	11.00	11.50	10.00	10.50	1.15	3.70	-
07	10.00	10.50	09.50	10.00	1.04	3.51	7.20
08	10.00	11.00	09.55	10.00	1.54	3.50	-
09	11.00	11.50	09.50	10.00	1.65	6.20	-

The results have been corrected for flight height

$$\bar{z} = -\frac{m}{4\pi}$$

Spector and Grant method consistently overestimates depths over the range of 0 to 15 km (Fedi *et al.*, 1997), while the use of discrete Fourier transform introduces the problem of aliasing and the truncation effect. Hence, the corrected power spectrum of Fedi *et al.* (1997), was used in the present study to correct for depth overestimation. While, digitizing the magnetic field data can reduce the aliasing effect, truncation effect is reduced by applying a cosine taper to the observed data before Fourier transformation (Bath, 1974). For the determination of depths to magnetic layers using the spectral method, the study area was divided into nine sections consisting of 51x51 grid size (or data points). Table 1 gives the locations of these sections with X₁ and X₂ representing the limiting longitude values while Y₁ and Y₂ give the limiting latitude values. Each of these sections covers an estimated area of about 54x54 km². The main aim of this part of the analysis was to provide some guides in the starting depths to be used later in the modeling exercise. The radial spectrum for each section was then evaluated in the manner described above. Some of these graphs present two linear segments while others present three segments. From the gradient of these segments the average depths to the causative layers were determined and designated D₁, D₂ and D₃ as the case may be.

Modeling

Several methods for modeling anomalous bodies have been developed over the years. These methods include the two-dimensional modeling (2-D), the three-dimensional (3-D) e.g., Talwani *et al.* (1959) and the 2½ dimensional modeling developed by Gemperle *et al.* (1991). The two-dimensional modeling techniques are often used or applied in modeling elongated bodies with length to width ratio greater than 10, as in the case of dykes, thus, the length is assumed to be infinite. In the 3-D techniques, many geometric forms have been used to model magnetic bodies. Some of these forms, such as the vertical and inclined prism, have been particularly successful, especially in near surface exploration work. The 2½-D modeling technique is an improvement of the 2-D methods and an approximation to the 3-D model. In this method, the length is made finite though considerably longer than the width of the body. The modeling technique applied to any survey depends on the structure intended to be modeled and the purpose of the survey. Two-dimensional techniques may readily be used to model dyke-like bodies, since, their length to width ratio is usually greater than 10. 3-D modeling techniques are easily used in modeling batholiths, while moderately elongated slabs can be modeled using the 2½-D method (Gemperle *et al.*, 1991).

In the present study, the aim was to model the shape and depth of the Gongola Basin, along with structures of the basement and intrusions overlaid by the basin. The GM-SYS

two-and-half-dimensional modeling technique satisfies the need enumerated above for the present work. The GM-SYS modeling programme, is a programme used for the easy interactive modeling of a 2-D and optionally 2½-D geologic cross-section with the ability to quickly calculate and display the gravity and magnetic response from the cross-section. In this study, the 2½-D option was used. The method used in calculating the magnetic response and model is based on the methods of Talwani *et al.* (1959) and Talwani and Heirtzler (1964). The programme makes use of algorithms described in Won and Bevis (1987). The 2½-D calculations are based on Rasmussen and Pedersen (1979). Three profiles were selected for modeling covering the anomaly as shown in Fig. 3. All the profiles were taken perpendicular (i.e., NW-SE) to the strike direction of the most prominent anomaly (i.e., NE-SW) in order to obtain the best estimate of the parameters of the body from the profiles taken. In modeling the profiles, the depth factor was initially estimated by the results obtained from spectral analysis. Furthermore, the basin was assumed to be underlain by granite-gneiss, which is the dominant rock type of the basement complex of Nigeria (McCurry, 1971). The choice of susceptibility values used in this modeling was based on reported susceptibility ranges of 0.009-0.0097 SI units (Ajakaiye, 1981), which have been obtained for the Benue Trough (of which the present study area is part). The GM-SYS uses the Gaussian (CGS) system of units for magnetic quantities hence, all values were converted to Gaussian units before input into the programme.

RESULTS

Spectral Analysis

The results of the Spectral analysis carried out is displayed in Table 1. The first layer depth (D_1) varies from 1.00 to 1.80 km with an average value of 1.19 km, while that of the second layer depth (D_2) varies from 2.61 to 6.20 km with an average value of 3.16 km, the third layer depth (D_3) varies from 3.51 to 8.03 km with an average value of 5.39 km.

2½-D Modeling

Profile AA¹

A susceptibility of 0.012 SI units that represents an overall average for the basement rocks as reported by previous workers, was used for the host rock as a trial value. A susceptibility value of 0.364 SI units was needed for the magnetic body to obtain a good fit. This value falls within the range of values for basic rocks and basalt (Dobrin and Savit, 1988; Telford *et al.*, 1976).

The model (Fig. 4a, b) consists of a layer of sedimentary rock with an assumed susceptibility of 0. The sediment thickness on this profile reaches a depth of 3.38 km. Basement rocks underlie this sedimentary layer with susceptibility of 0.012 SI units. The most prominent feature along this profile is a high susceptibility body (of susceptibility 0.364 SI units), which has a depth to the top of 3.08 and 8.05 km to the bottom. This is modeled to be the cause of the prominent magnetic anomaly occurring at the central part of the profile AA¹. The susceptibility also suggested that the source of the body is a basic intrusion at depth within the crust, probably emplaced during the rifting of the Benue Trough.

Profile BB¹

The model for profile BB¹ is shown in Fig. 5a and b. The susceptibility value of the host rock was kept at i.e., 0.012 SI units while, a susceptibility value of 0.354 SI was required for the intrusive rock to obtain a good fit. The sediment thickness in this model reaches a

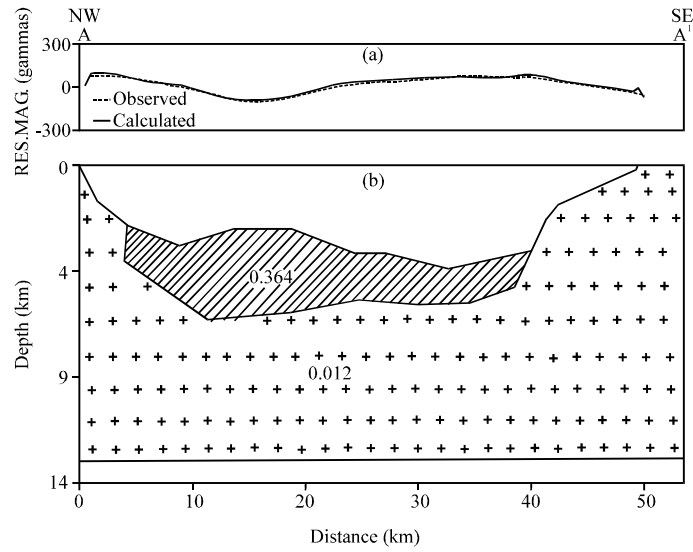


Fig. 4: (a) Calculated and observed residual magnetic field along profile AA¹ and (b) model for profile AA¹

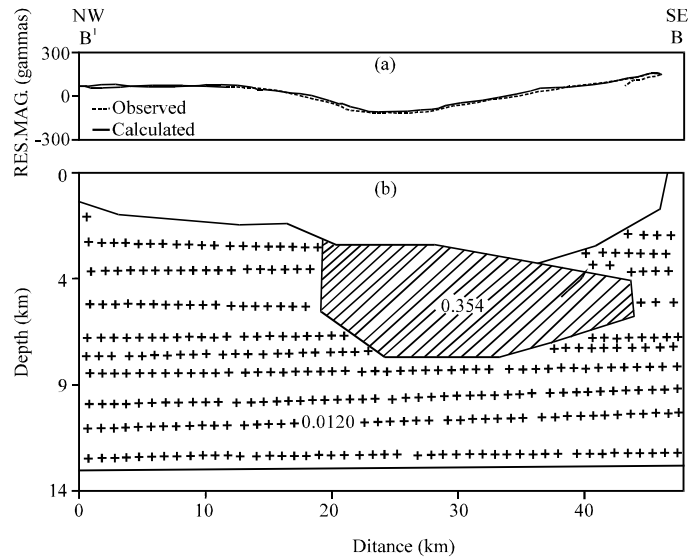


Fig. 5: (a) Calculated and observed residual magnetic field along profile BB¹ and (b) model for profile BB¹

maximum value of 4.50 km along this profile, with depth to the top and bottom of the high susceptibility body reaching 2.75 and 6.76 km, respectively.

Profile CC¹

The model for this profile is shown in Fig. 6a and b. The susceptibility of the host rock was also maintained at 0.012 SI while a susceptibility value of 0.312 SI units was required here

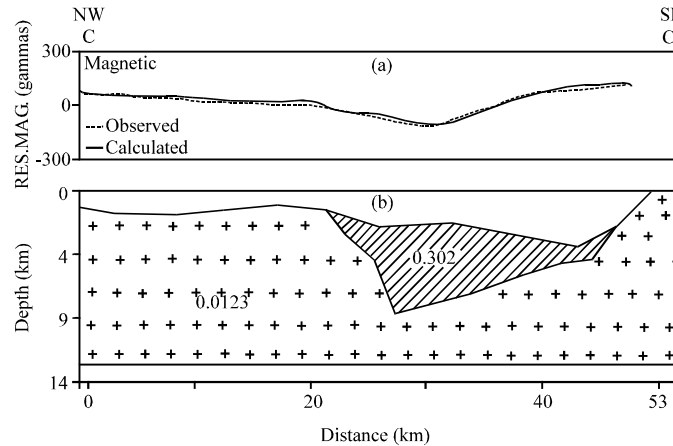


Fig. 6: (a) Calculated and observed residual magnetic field along profile CC¹ and (b) model for profile CC¹

for the intrusive magnetic body to obtain a good fit. As can be seen, all the values fall within the range of values for basic rocks. The model also shows the sedimentary layer attaining a depth of up to 4.05 km. A depth of 1.37 and 8.09 km were obtained for the top and bottom of the intrusion or the magnetic body, respectively.

DISCUSSION

Previous geophysical studies carried out in the area have suggested the existence of near-surface intrusion, volcanic plugs, basement rocks and/or basalt flow which could be deeply rooted (Ofoegbu, 1984, 1988; Ajakaiye *et al.*, 1986; Ajayia and Ajakaiye, 1981; Ofoegbu, 1986). Shemang *et al.* (2001) concluded after a 2-dimensional modeling of magnetic data, that there is the existence of basic intrusive at depths of 1-7 km at different points in the trough and also the existence of marginal intrusion at depths of 1-2 km from the surface. Hence, the depth values obtained in this study of 1-1.80 km for the marginal intrusions appear to be quite logical. The slight differences observed in the results could be attributed to the different methods used in estimating these depths, for instance while, Shemang *et al.* (2001) used Werner deconvolution to estimates these depths spectral analysis was used in the present study.

Shemang *et al.* (2001) concluded after a 2-dimensional modeling of some magnetic anomaly in the Gongola Basin to be an old magmatic rift, the 2½-dimensional modeling used in the present study is an improvement over the 2-dimensional and also a short cut to the 3 dimensional methods. The method did not only suggest the existence of basic intrusions at different depth in the basin but also mapped out the basement topography which was seen to have a graben like structure. The models suggests the existence of basic rocks of large extent at depths between 1.37-8.09 km. The source of the basic rocks could not be seen from the models as they are completely embedded within the basement. This, however, suggest that the source could be at a greater depth thereby suggesting the area to be an old rift. According to Benkhelil (1989), magmatic activity in the upper Benue trough occurred in two major episodes. The first episode took place in the Mesozoic and this includes the Burashika complex of Jurassic age and the basaltic veins of Cretaceous age, restricted to faults trending

N55° (Carter *et al.*, 1963). The second phase occurred during the Tertiary, corresponding to the intense alkaline magmatic activity in relation to the Cameroon volcanic line. This tertiary phase of magmatic activity is seen to occur in form of Biu basalt (Fig. 1). The magnetic susceptibility for the intrusions from the present study suggest a value ranging from 0.312 to 0.364 SI units, suggesting that they are basic to ultrabasic in composition thus, indicating that they are mantle derived (probably volcanic). The existence of these two major episodes of magmatism in areas adjacent to the study area (Burashika complex and Biu plateau) and especially the Tertiary episode which outcrops in the area in the form of basalts (Biu basalts) strongly suggest that the basic rocks observed at depth in the area of study are a product of volcanism at depth in the area.

CONCLUSION

From the results obtained, it can be said that the Gongola Basin evolved through a combination of different processes, first there was mantle upwelling or rise of a mantle plume which resulted Crustal stretching and thinning as observed by the linear nature of the modeled anomaly. There was block faulting in the area as the basin tends to show a graben like structure. The emplacement of basic igneous material in the crust then follow with some not reaching the surface but, were trap within the basement rocks as seen from the model and also within the sediments and consequently rifting.

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