



Source Parameter Imaging (SPI) and Modeling from High- Resolution Aeromagnetic Data Over Upper Benue Trough, Northeastern Nigeria.

Musa; H.¹ Bello, R.¹ and Abe, A. O.¹

¹Department of Physics, Federal University of Kashere Gombe, Gombe state Nigeria.

*Corresponding Author: hayatudeenmusa@fukashere.edu.ng; +2348030919526

Abstract

Source parameter imaging and modelling for sediment thickness, depocentres, basement geometry and morphology (horst and graben) from high resolution aeromagnetic data, over upper Benue trough, northeastern Nigeria were carried out. The data was processed using Oasis Montaj™ software to get the total magnetic intensity (TMI) and the residual maps from where source parameter imaging and modeling were accomplished. The results of the source parameter imaging show that the depth to magnetic sources or sediment thickness ranges between 286.6 meters to 1.65 kilometers for the basement areas and 1.774 kilometers to 4.93 kilometers for the sedimentary areas. The high sediment thickness or depth to magnetic sources were found around (Dukku, Gombe, Yola and Numan areas), while the lowest was found around (Biu, Wade and Jabieb areas). The results of the models are in the range of 1-3 kilometers which agrees with the result of the source parameter imaging of the study area, depocentres, basement geometry and morphology (horst and graben) confirm the rifting nature of the Benue trough.

Keywords: Aeromagnetic data, upper Benue trough, modelling, source parameter imaging and upper Benue trough.

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Introduction

Source parameter imaging and modelling for sediment thickness, depocentres, basement geometry and morphology (horst and graben) from high-resolution aeromagnetic data, over upper Benue trough, northeastern Nigeria were carried out. The total magnetic intensity map was treated employing the Oasis Montaj™ programming software to get the residual map, from where source parameter imaging and modelling were done. The study area is located between longitude 10°:30' - 12°:30' E and Latitude 9°:00' – 11°:00' N, it covers an area of 48,400 km². The upper Benue trough is an important arm of the Benue trough which branches into two virtually perpendicular, the Yola arm trending E-W and Gongola arm trending N-S. It is a linear

Cretaceous sedimentary basin that spreads deep into the African continent and was closely related with the split-up of Africa from the South Atlantic. Several researchers regarded it as an Aulacogen and part of a three-arm rift system involving the South Atlantic Ocean, others believe it to be a true rift and compared it to the Afar region of northeast Africa. However, Benkhelil (1986) and Maurin *et al.*, (1985) interpreted the Cretaceous Benue trough as a set of pull apart sub-basin generated by sinistral displacement along pre-existing NE-SW transcurrent faults. The drainage of this region is realized partly by the Benue and the Gongola rivers. The upper Benue trough is confined by the Hawal massif to the northeast and the

Adamawa Massif to the southeast, both massifs spread into Cameroon Republic. The study area is a Cretaceous sedimentary basin that forms a constricted band of terranes that expanse eastward and splits into small isolated basins into the Cameroon, it is split into Yola arm and Gongola arm. The lithostratigraphic units of the Yola arm comprise the Bima sandstones, the Yolde formation, Dukul, Jessu, Sekule, Numanha, and Lamja sandstone formations in that order Musa (2018), while the Gongola arm include the Bima sandstones, the Pindiga formation, Gombe sandstones and the Kerri – Kerri formation Musa *et al.*, (2018). The basement complex in the area consists of three major groups, Migmatite- gneiss complex, older granite and basic rocks.

Based on the tectonic development of the Benue trough Ofeogbu *et al.*, (1992)

concluded that asthenospheric upwelling crustal thinning and stretching, emplacement of diapiric igneous bodies in the lithosphere, block faulting and subsidence are the main cause of the evolution of the Benue trough. On the analysis of aeromagnetic figures from the upper Benue trough, Nigeria using automated methods Alagbe and Sonmonu (2014) gave a three-depth source of, the deeper sources range from 6.5 to 10.5 km, the intermediate sources ranging from 3.5 to 5.5 km and a shallow source of 0.01 to 2.5 km. Studies on the 2-^{1/2}-dimensional modelling of the major structures underlying Dong and Shelleng of the upper Benue valley, using GM-SYS computer modelling by Omeje *et al.*, (2012), shows that the thickness of the basin varies between 0.9 km to 2.9 Km.

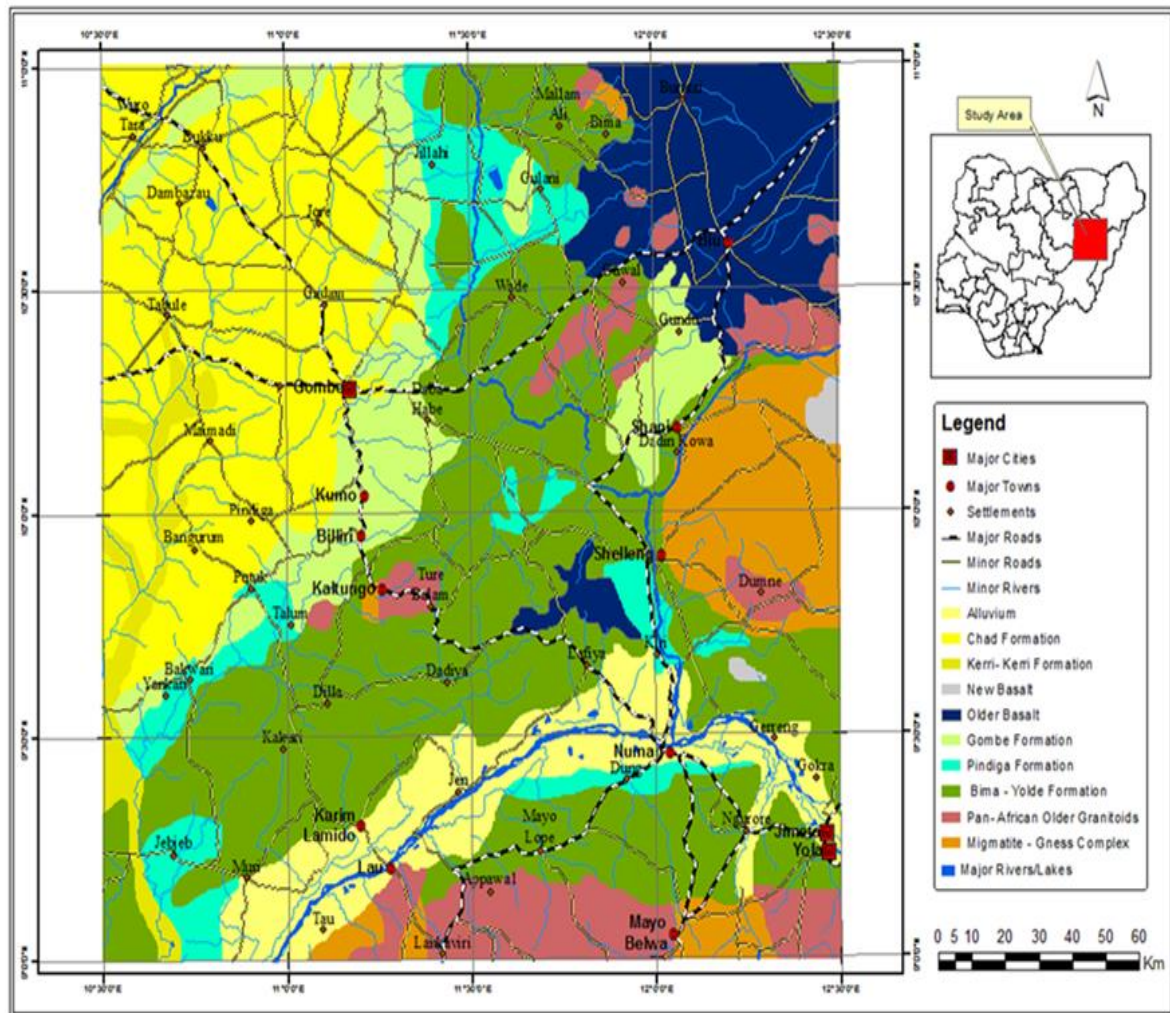


Figure 1: Geologic map of the study area (modified from NGSA 2006).

Working on the depth to basement determination using source parameter imaging (SPI), of aeromagnetic data: an application to upper Benue trough and Borno basin Salako (2014), got sediment thickness of 5.0 kilometers in the area. Analysis of the high-resolution aeromagnetic figures (HRAM), for source parameter imaging (SPI) to define the magnetic basement depth over parts of middle Benue trough Nwosu (2014) displays that the highest sediment thickness in the region is 6.29 kilometers. The aim and objective of this research work is to interpret the high resolution aeromagnetic data over the study area so as to determine the Source parameter imaging and modelling for sediment thickness, depocentres, basement geometry and morphology (horst and graben).

Materials and Methods

The high-resolution aeromagnetic figures utilized in this analysis were procured for Nigeria Geological Survey Agency (NGSA) in 2010 as part of a countrywide geological survey with the following information, terrain clearance of 80 m, flight line spacing of 500 m and a tie line spacing of 5000 m, sixteen (16) sheets were utilized for this research work. The data were treated via the Oasis MontajTM software to get the total magnetic intensity (TMI) as well as the residual maps from where source parameter imaging and modelling were done to get the sediment thickness, depocentres, as well as basement geometry and morphology (horst and graben). The source parameter imaging was carried on the residual data to investigate the sedimentary thickness beneath the subsurface. The depth of the magnetic source was determined through mathematical processing from the grids. The pre-processes grids from the residual grid as input grid are dx , dy and dz , whose output grids were later served as input grids for SPI processing. The source parameter imaging (SPITM) function is a fast, easy, and influential technique for computing the depth of magnetic sources. With an accuracy of $\pm 20\%$ in tests on actual data sets with drill hole control. This precision is comparable to that of Euler

deconvolution, conversely SPI has the advantage of producing a more comprehensive set of coherent result and it is easier to use, Salako (2014) used the SPI method to estimate the depth from the local wavenumber of the analytical signal. The analytical (investigative) signal $A_1(x, z)$ as defined by Nabigian *et al.*, (2005) as:

$$A_1(x, z) = \frac{\partial M(x, z)}{\partial x} - j \frac{\partial M(x, z)}{\partial z} \quad 1$$

where $M(x, z)$ remains the size of the strange total magnetic field, j is the invented number, z and x are Cartesian coordinates for the perpendicular and the horizontal directions correspondingly, Nabigian *et al.*, (2005) displays that the horizontal and perpendicular derivatives involving the actual and invented portions of the 2D analytical signal are related as follows:

$$\frac{\partial M(x, z)}{\partial x} \Leftrightarrow - \frac{\partial M(x, z)}{\partial z} \quad 2$$

Where $\Leftrightarrow$ denotes a Hilbert transformation pair. The local wavenumber k_1 is defined by Salako (2014) to be

$$K_1 = \frac{\partial}{\partial x} \tan^{-1} \left[\frac{\frac{\partial M}{\partial z}}{\frac{\partial M}{\partial x}} \right] \quad 3$$

The idea of an analytic (investigative) signal comprising second-order derivatives of the total field if used similarly to that used by Salako (2014), the Hilbert transform (convert) and the vertical-derivative operators are rectilinear, consequently the perpendicular derivative of (2) will provide the Hilbert transform (convert) pair off,

$$\frac{\partial^2 M(x, z)}{\partial z \partial x} \Leftrightarrow - \frac{\partial^2 M(x, z)}{\partial^2 z} \quad 4$$

Thus the analytic signal could be defined based on second-order derivatives, $A_2(x, z)$, where

$$A_2(x, z) = \frac{\partial^2 M(x, z)}{\partial z \partial x} - j \frac{\partial^2 M(x, z)}{\partial^2 z} \quad 5$$

This gives rise to a second-order local wavenumber k_2 , where

$$k_2 = \frac{\partial}{\partial x} \tan^{-1} \left[\frac{\frac{\partial^2 M}{\partial^2 z}}{\frac{\partial^2 M}{\partial z \partial x}} \right] \quad 6$$

The first- and second-order local wave figures are used to regulate the most suitable model and a depth approximation independent of any expectations about a model, Nabighian *et al.*, (2005) provides the expression for the perpendicular and horizontal gradient of an inclined contact model as:

$$\frac{\partial M}{\partial X} = \frac{2KFc \sin d}{h_c \cos(2l-d-90) + x \sin(2l-d-90)} \quad 7$$

$$\frac{\partial M}{\partial X} = \frac{2KFc \sin d}{x \cos(2l-d-90) + h_c \sin(2l-d-90)} \quad 8$$

where K is the susceptibility contrast at the contact, F is the magnitude of the earth's magnetic field (the inducing field), $c = 1 - \cos^2 i \sin^2 \alpha$, α is the angle between the positive x -axis and magnetic north, i is the ambient-field inclination, $\tan I = \sin i / \cos \alpha$, d is the dip (measured from the positive x -axis), h_c is the depth to the top of the contact and all trigonometric arguments are in degrees. The coordinate system has been defined by the origin of the profile line ($x = 0$) is directly over the edge.

The display by the magnetic-field anomaly owing to a dipping thin sheet is

$$M(x, z) = 2KFc w \frac{h_l \sin(2l-d) - x \cos(2l-d)}{h_c^2 + x^2} \quad 9$$

where w is the thickness and h_l is the penetration to the top of the thin sheet. The display by the magnetic-field anomaly owing to a long horizontal cylinder is

$$M(x, z) = 2KFS \frac{\sin i (h_h^2 - x^2) \cos(2l-180) + 2x h_h \sin(2l-180)}{(h_c^2 + x^2)^2} \quad 10$$

S is the cross-sectional area and h_h is the depth to the centre of the horizontal cylinder, Salako (2014) and Nwosu (2014). Substituting equations (7), (8), (9) and (10) into the expression for the first- and second-order i.e. (3) and (6) respectively local wavenumbers, we obtained after some simplification, a remarkable result as:

$$k_1 = \frac{(n_k + 1)h_k}{h_k^2 + x^2} \quad 11$$

And

$$k_2 = \frac{(n_k + 2)h_k}{h_k^2 + x^2} \quad 12$$

Where n_k is the SPI structural index (subscript $k = c, t$ or h), and $n_c = 0$, $n_t = 1$ and $n_h = 2$ for the contact, thin sheet and horizontal cylinder models, respectively. From (11) and (12) above, it remains apparent that the first- and second-order local wave numbers are independent of the susceptibility contrast, the dip of the source, the inclination, declination, and the strength of the earth's magnetic field. The contact, thin sheet and horizontal cylinder are all two-dimensional models (infinite strike extent), consequently it is an inherent postulation of the SPI technique that the geology is two dimensional. If the body is two-dimensional and there is no intrusion from nearby bodies, the depth evaluation will be reasonable and the structural index should be constant for the whole region for which the response is anomalous. This filter was applied in determining the sediments thickness and depth to magnetic sources. Whereas the general aim of modelling magnetic data is to estimate the geometry and physical character of the cause to an investigated anomaly. GM-SYS module of the Oasis Montaj remained used for this exercise. The program compares a theoretical anomaly with successive fits improvement until the best possible fit is obtained. The computational bases for the GM-SYS model response make use of the algorithms described by Won and Bevis (1987). GM-SYS use' a two-dimensional flat earth model for a potential field that is based on geological constraints. The difference between the observed magnetic data and calculated magnetic response to this model is minimized by reshaping the model or by altering the susceptibilities of the structural unit block contained within the model until a fit is obtained Fairhead (2007). Since the computation of earth models is established on the observed field data and the starting model, a poor starting model will result in an unreasonable solution. In this work the initial model parameter used is the contact/basement boundary blocks and the lower part of the magnetic source as

estimated from source parameter imaging and available geologic information. Each separate portion of the model (basement/sedimentary) was assigned a susceptibility value. The anomaly along the entire profile was the addition of the contributions of each separate block, the model involved four pieces of information, top surface, bottom surface, susceptibility and magnitude, Musa *et al.*, (2020), if any

three of the above is known or assumed the fourth item can be calculated. In this study seven (7) profiles were drawn across prominent anomalies for investigation as shown in fig 5. All the magnetic field responses computed from the models used total field strength of 34132 nT, declination of -0.065 degrees and inclination of -3.5 degrees.

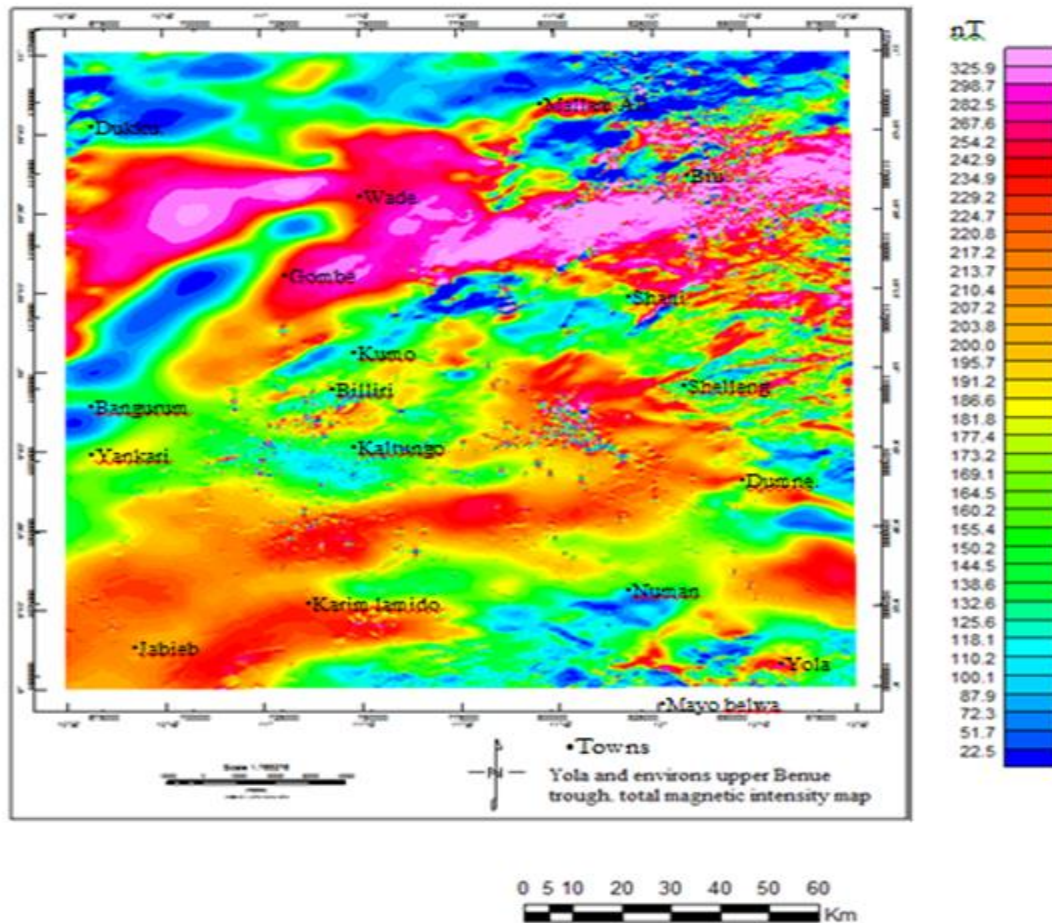


Figure 2. Total magnetic intensity map of the upper Benue trough. N. E. Nigeria.

Results

The total magnetic intensity map of the study area figure 2 displays anomalies of high and low magnetic intensity, with values ranging from 22.5- 325.9 nT. The map displays that the area is composed of the different magnetic regions. The regions are distinguished base on the disparity of the intensity of magnetic response. Visual inspection of the aeromagnetic map discloses that the most dominant feature in the study

area is the NE-SW direction. The residual aeromagnetic map figure 3 illustrates magnetic anomalies similar to that of the TMI map in figure 2. The dominant trend is in the NE-SW direction, which is related to the Pan Africa trend. The anomalies of 100.6 to -129.8 nT exist as a sequence of areas of magnetic highs and lows. These areas are not continuous but seem as numerous elongated lobes extending over varying distances before being interrupted by the occasional

occurrence of short wavelength anomalies which may be due to near surface intrusives, volcanic plugs, basement rocks or thin basaltic flows. The depth to the magnetic source of the (SPI) figure 4, was processed from the residual data using several mathematical processing from various grids. The pre-processed grids for the residual data are dx, dy and dz. These output grids were to serve as input grids for SPI processing. The first order derivative was adhered to as the SPI is much more sensitive to noise at higher levels. Careful filtering of the data was ensured to have good estimates of the depth. The depth to magnetic sources ranges between 286.6 meters to 1.65 kilometers for the basement areas and 1.774 kilometers to 4.93 kilometers for the sedimentary areas. The results of the source parameter imaging utilize the effect of near surface anomaly source and calculate depth to magnetic basement and basement-sediment interface. The high sediment thickness values are found in the northerly part and the tip end of the southeastern part. (Dukku, Gombe, Yola and Numan areas), as marked by blue colours, this high sediment thickness is usually from sedimentary rocks or altered basement rocks. While the lowest sediment thickness values

are found in the northerly part, the central area and at the tip ends of the southwestern and the southeastern part. (Biu, Wade, Mayo-Belwa and Jabieb areas). These are caused by near surface intrusive bodies of high magnetic susceptibility values and these areas have shallow sediment deposit and are closer to the surface they are represented by pinkish colours. The procedure of source parameter imaging technique to determine the depth to magnetic sources or sediment thickness has been used by several authors (Salako 2014, Omeje *et al.*, 2012, Nwosu *et al.*, 2015 and Oha *et al.*, 2016). It is a profile or grid-based technique for appraising magnetic source complexities and for certain geometric sources, the inclination and the susceptibility contrast. The technique exploits the correlation between source depth and local wavenumber k of the perceived field, which can be considered for some point within a grid of data via horizontal and perpendicular gradients. At peaks in the confined wavenumber grid, the source depth is identical to n/k where n depends on the assume source geometry (equivalent to the structural index of the Euler deconvolution) for example $n=1$ for contact, $n=2$ for dyke.

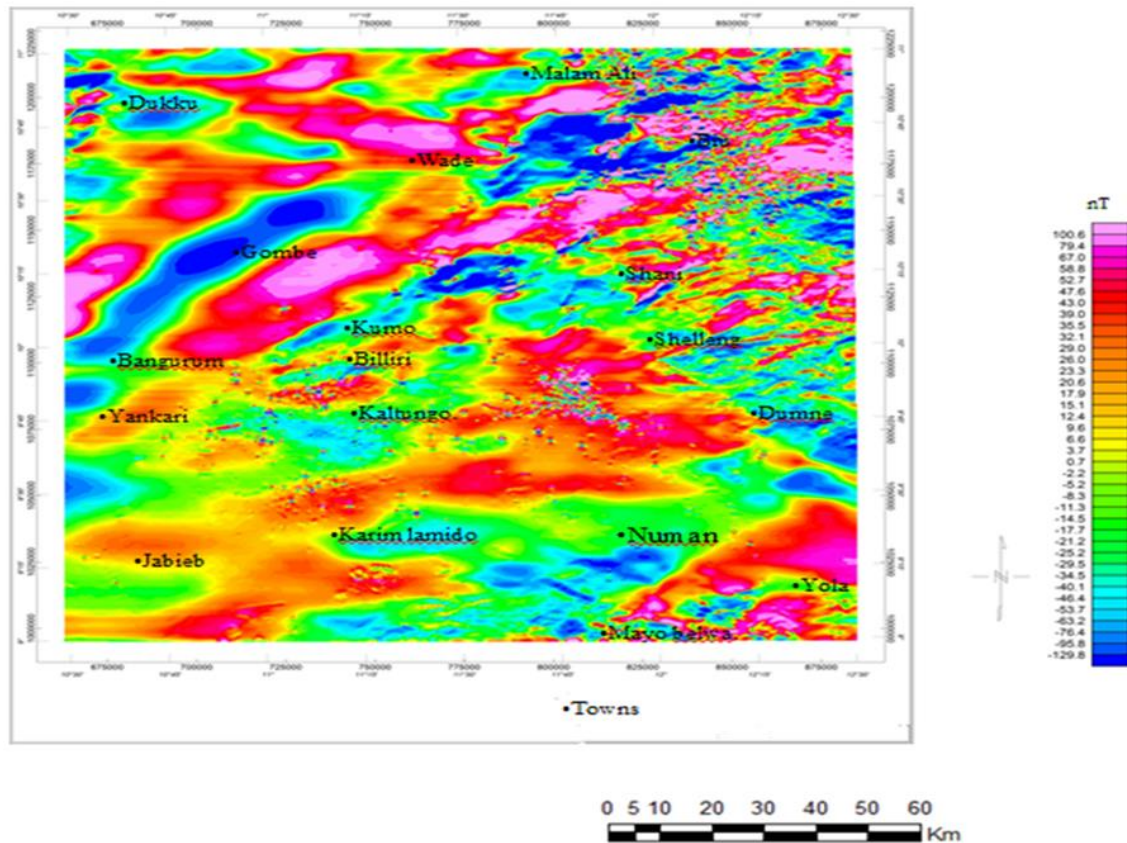


Figure 3. Residual aeromagnetic map of the upper Benue trough. N. E. Nigeria.

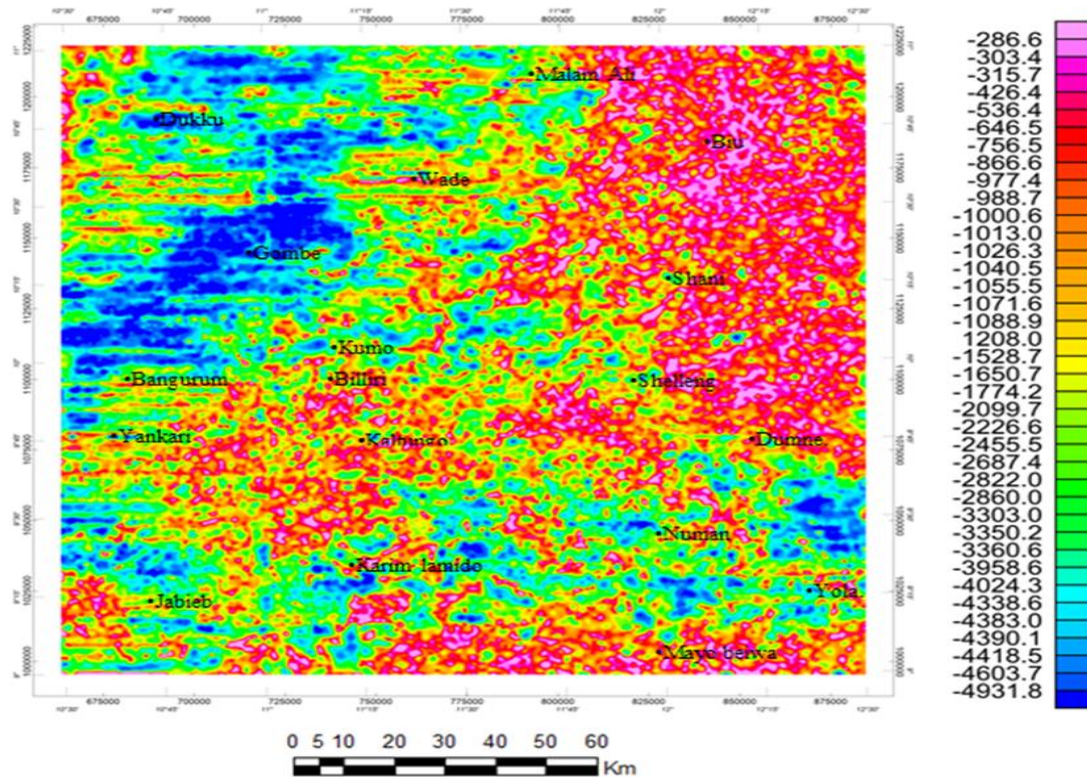


Figure 4. Source parameter imaging (SPI) map of the upper Benue trough. N. E. Nigeria.

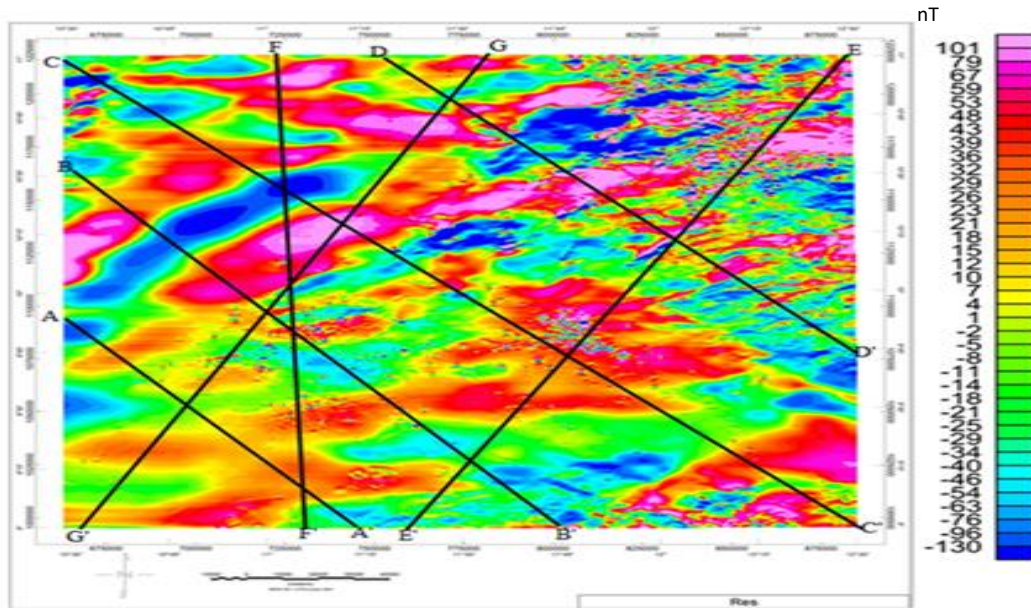


Figure 5. Profiles 1-7 were drawn on the residual map across the study area.

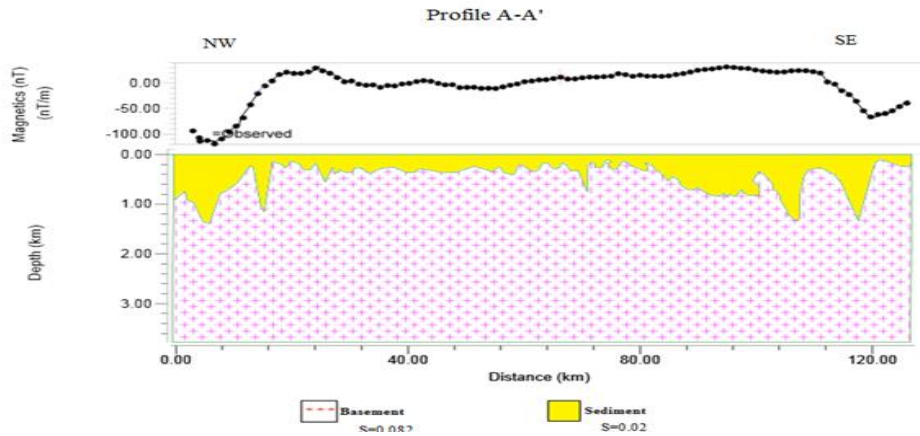


Figure 6. Modeled magnetic profile cross-section A-A'.

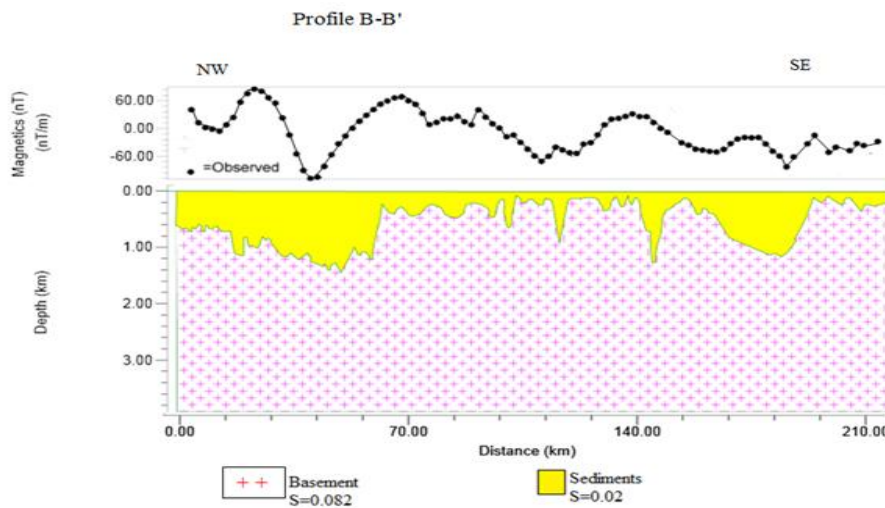


Figure 7. Modeled magnetic profile cross-section B-B'.

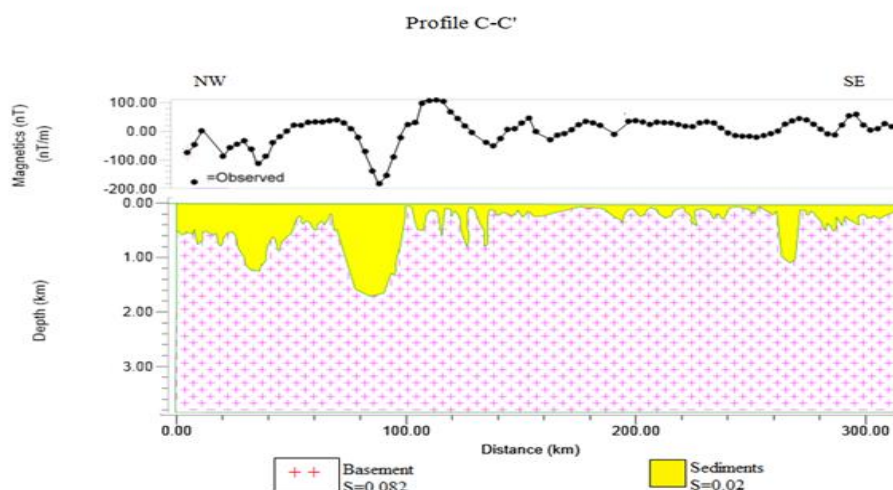


Figure 8. Modeled magnetic profile cross-section C-C'.

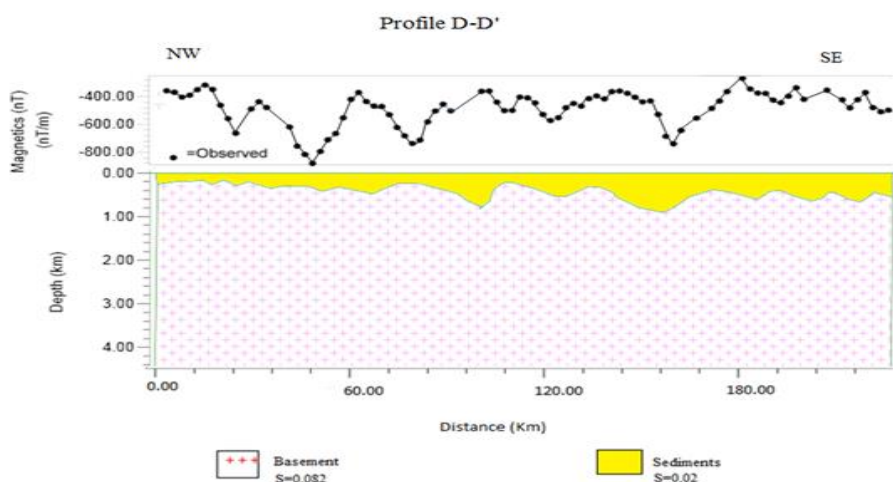


Figure 9. Modeled magnetic profile cross-section D-D'.

Modeled magnetic profile A-A'

Fig. 6 is the magnetic model which passes across the study area in the NW-SE direction, and comprises both the basement and the sedimentary sections. The model has a length of 120 kilometers. The profile was modeled as two (2) blocks i.e. basement and sedimentary. The entire model has a depth of 3.8 kilometers with a sediment thickness of fewer than 1.5 kilometers. Three small graben blocks were observed both in the left- and right-hand sides of the model which is saving as depocentres, and are interpreted to be lithologic contact or joints or faults which have slightly moved relative to the

neighbouring blocks, contributing to the irregular topography of the area.

Modeled magnetic profile B-B'

Fig. 7, is the magnetic model which passes across the study area in the NW-SE direction, and comprises both the basement and the sedimentary sections. The model has a length of 210 kilometers, with a depth of 3.8 kilometers and sediment thickness of fewer than 1.5 kilometers. Two broad graben blocks were observed both in the left- and right-hand sides, which serve as a depocentres.

Modeled magnetic profile C-C'

Fig. 8, is the magnetic model which passes across the study area in the NW-SE direction,

and comprises both the basement and the sedimentary sections. The model has a length of 300 kilometers, with a depth of 3.8 kilometers and sediment thickness of fewer than 1.8 kilometers. A graben block was observed in the left-hand side of the model, which serves as a depocentre.

Modeled magnetic profile D-D'

Fig. 9, is the magnetic model which passes across the study area in the NW-SE direction, and comprises both the basement and the sedimentary sections. The model has a length of 200 kilometers, with a depth of 4.5 kilometers and sediment thickness of 1 kilometer on average. A small graben block was observed on the right-hand side of the model, which serves as a depocentre.

Modeled magnetic profile E-E'

Figure 10, is the magnetic model which passes across the study area in the NE-SW direction, and comprises both the basement and the sedimentary sections. The model has a length of 240 kilometers, with a depth of 2.5 kilometers and sediment thickness of less than 1 kilometer. Three small graben blocks were observed on the right-hand side of the model, which serve as depocentres.

Modeled magnetic profile F-F'

Figure 11, is the magnetic model which passes across the study area in the N-S direction, and comprises both the basement and the sedimentary sections. The model has a length of 220 kilometers, with a depth of 4 kilometers and sediment thickness of fewer

than 1.5 kilometers. A graben block was observed in the left-hand side of the model, which serves as a depocentre.

Modeled magnetic profile G-G'

Figure 12, is the magnetic model which passes across the study area in the NE-SW direction, and comprises both the basement and the sedimentary sections. The model has a length of 220 kilometers, with a depth of 3.5 kilometers and sediment thickness of fewer than 2.8 kilometers. A graben block was observed in the left-hand side of the model, which serves as a depocentre.

Discussion

The result of the source parameter imaging which is between 286.6 m to 1.65 kilometers for the basement areas and 1.77 kilometers to 4.93 kilometers for the sedimentary areas, shows that the high sediment thickness values are found in the northwestern part, and the tip end of the southeastern part. Dukku, Gombe, Yola and Numan areas, they should be targeted for further studies, this high sediment thickness is usually from sedimentary rocks or altered basement rocks. While the lowest sediment thickness values are found in the northeastern part, the central part and at the tip ends of the southwestern and southeastern parts (Biu, Wade, Mayo-Belwa and Jabieb areas). These are caused by near surface intrusive bodies of high magnetic susceptibility values and these areas have shallow sediment thickness and are closer to the surface.

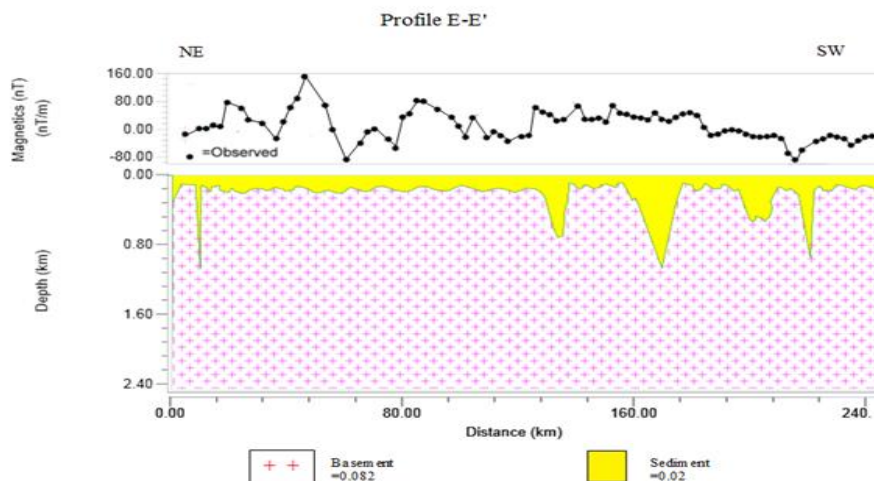


Fig. 10. Modelled magnetic profile cross-section E-E'.

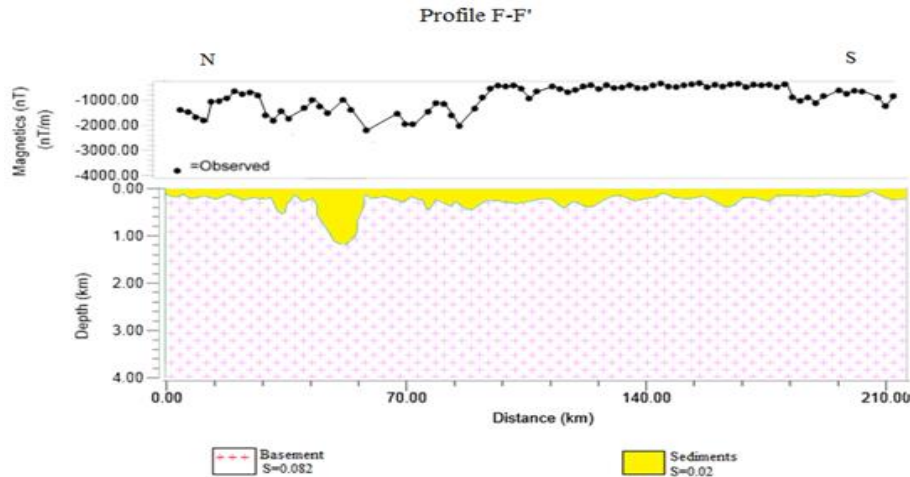


Fig. 11. Modeled magnetic profile cross-section F-F'.

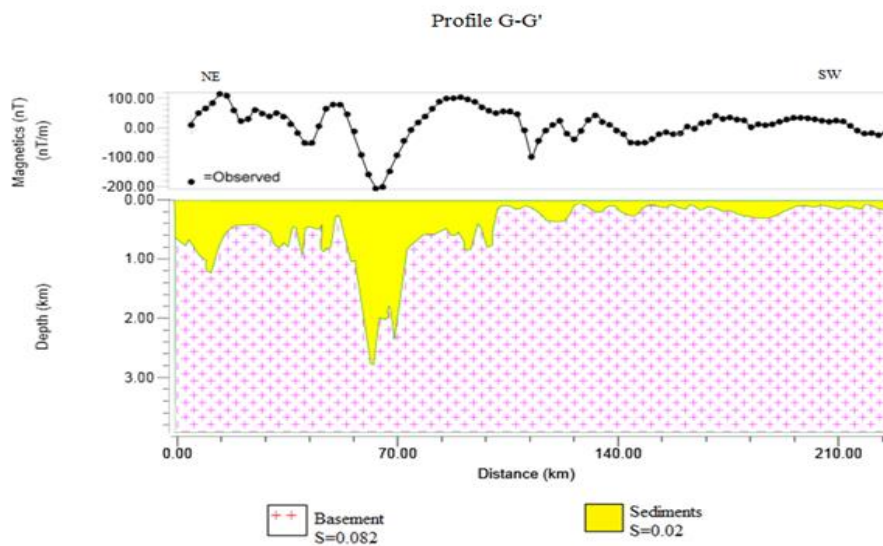


Fig. 12. Modeled magnetic profile cross-section G-G'.

The result of the source parameter imaging of the study area agrees with the work of Salako (2014), working in the upper Benue trough and Borno basin N.E. Nigeria using source parameter imaging got sediment thickness of 5.0 kilometres in the area.

Nwosu *et al.*, (2015) while working in the middle Benue got 2-6.29 kilometers from source parameter imaging of the area. Modeling of aeromagnetic data was carried out to delineate depocentres, basement geometry and morphology (horst and graben) as well as estimate the physical characteristic of the cause to an investigated anomaly. This involves making numerical estimates of the depth and dimensions of the source of

anomalies, conceptual models of the surfaces are created and their anomalies calculated to see whether the earth model is consistent with what has been observed, the theoretical anomaly of the model is calculated (forward modeling) and compared with the observed anomaly. The end product of this work shows that most of the models are in the range of 1-3 kilometers which agrees with the outcome of the source parameter imaging of the study area and also with the work of Omeje *et al.* (2012), that studied 2-^{1/2}-Dimensional modeling of the major structures underlying Dong and Shelleng of the upper Benue valley, using GM-SYS computer modeling. Their result shows that the sediment

thickness around these areas varies between 0.9 km to 2.9 Km. Horst and graben were identified in the models which confirm the rifting style of the Benue trough.

Conclusion

Source parameter imaging remained an important filter to reveal the depth to magnetic sources or sediment thickness of the areas. (Dukku, Gombe, Yola and Numan areas), have high sediment thickness or depth to magnetic sources while the lowest were found around (Biu, Wade Mayo Belwa and Jabieb) areas. The results displayed by the models are in the range of 1-3 kilometers which agrees with the outcome of the source parameter imaging of the study area, depocentres, basement geometry and morphology (horst and graben) confirm the rifting style of the Benue trough.

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