International Journal of Research Publication and Reviews, Vol 5, no 10, pp 3424-3433 October 2024

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Investigation of Deep Magnetic Source Rocks in a Part of the Upper Benue Trough, Nigeria Using Pseudo-gravimetric Transformation

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ABSTRACT

A pseudogravity study of a part of the Upper Benue Trough was carried out to investigate the deeper magnetic sources. A grid of the total magnetic intensity map of the area was transformed into a grid of the pseudogravimetric anomaly. The values of the pseudogravimetric anomaly shows that the area is characterized by a positive pseudogravity anomaly that ranges from 0.1mGal to 0.4mGal. The positive pseudogravimetric anomaly can be interpreted in terms of terms of the combined effect of a magnetic basement of variable topography and intrusive igneous bodies existing beneath the trough. The average depth of the undulating magnetic basement is about 4.0 km, varying between a minimum of 2.9 km and a maximum of about 5.2 km.

Introduction

The term Pseudogravimetric transformation was first introduced by Baranov (1957) to simplify the interpretation of magnetic anomalies. Because of the dipolar nature of magnetism and the presence of remanent magnetization in the magnetic sources, the magnetic anomalies have a positive and negative parts and are asymmetrically located over their perturbing sources (Reeves, 2005); (Blakey, 1995). This complicates the interpretation in contrast to gravity anomalies which has a positive and direct relationship with their sources.

Pseudogravimetric transformation is based on Poisson's relations which links the magnetic potential V and the gradient of the gravity potential U due to a common source in a linear relationship (Baranov, 1957). The assumptions made during the transformation is that the magnetization of the source be entirely induced due to the present-day ambient field and the ratio of the magnetization to density in a common source is uniform. The direction of the magnetization of the source is required during the transformation and also the constant ratio of magnetization to density.

Pseudogravimetric transformation has some important advantages when applied to magnetic anomalies. Firstly, it removes the characteristic asymmetry of the magnetic anomaly with respect to the perturbing source. This places the magnetic anomalies directly over their sources (Baranov, 1957). Secondly, it acts like a low pass filter by filtering out the high frequency components of the anomalies from the magnetic grid that are due to shallow sources. This transformation accentuates the amplitude of the low frequency components of the magnetic grid (Pratt & Zhiqun, 2004). Tandrigoda and Ofoegbu (1989) suggested that a pseudogravimetric transformation can be used to determine a common source of gravity and magnetic source when they are compared.

A grid of pseudogravimetric anomalies will therefore be typically characterized by the presence of only the medium to long wavelengths (low frequency) components of the original magnetic grid which will essentially be due to deeper magnetic sources (Ahmed, Chris, Samuel, Derek & Essan, 2013).

Several interpretations of magnetic anomalies over the Upper Benue Trough had been carried out. Ofoegbu (1988) has carried an aeromagnetic study of a part of the Upper Benue tough and interpreted the anomalies in terms of intrusive bodies and the basement topology. Salako and Udensi (2013) carried out a spectral analysis of aeromagnetic data over the Upper Benue Trough. A pseudogravimetric study was carried out in the Upper Benue Trough by Ofoegbu (1986). The author transformed profiles of magnetic anomalies into profiles of pseudogravimetric anomalies to a study part of the Upper Benue Trough, and found a high correlation between the magnetic profiles, the gravity profiles and the Pseudogravimetric profiles.

A source parameter estimation of the magnetic anomaly or pseudogravimetric anomaly will invariably lead to a knowledge of the geology of the region which is the scientific bases for the exploration (Foss, 1989). Depth estimation techniques are commonly used in mineral exploration, geothermal studies, and other geophysical investigations. It helps geoscientists to better understand the subsurface structure and identify potential mineral deposits, geothermal and hydrocarbon resources.

Since the pseudogravimetric transformation effectively acts like a low pass filter, the technique would be an invaluable tool the mapping of deep magnetic sources which will be helpful for the exploration of deep mineral resources, basement studies and deeper magnetic structures which have been mask out by shallow and often high frequency sources in grids. This study aims to transform a 2D grid of aeromagnetic data set into a grid of pseudogravimetric anomalies to investigate deep magnetic structures over a part of the Upper Benue Trough, Nigeria.

Location and Geology of Study Area

The study covers an area which lies between latitudes 10.00º to 11.00º and longitudes 10.49º to 11.50º and forms an important part of the Gongola arm of the Upper Benue Trough, North East Nigeria (Fig. 1), and geologically falls within the KERI-KERI formation and GOMBE sandstone (Figure 2).

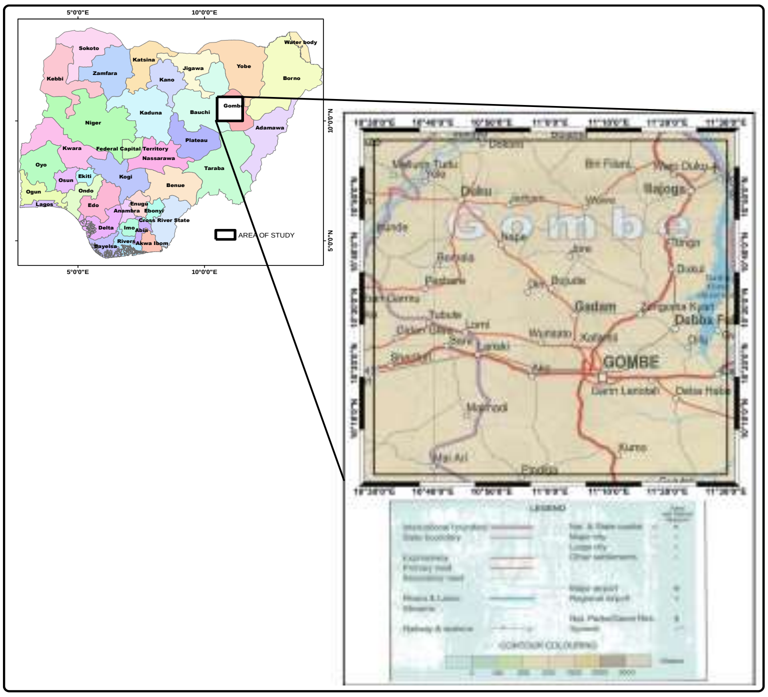


Figure 1: Location of Study Area.

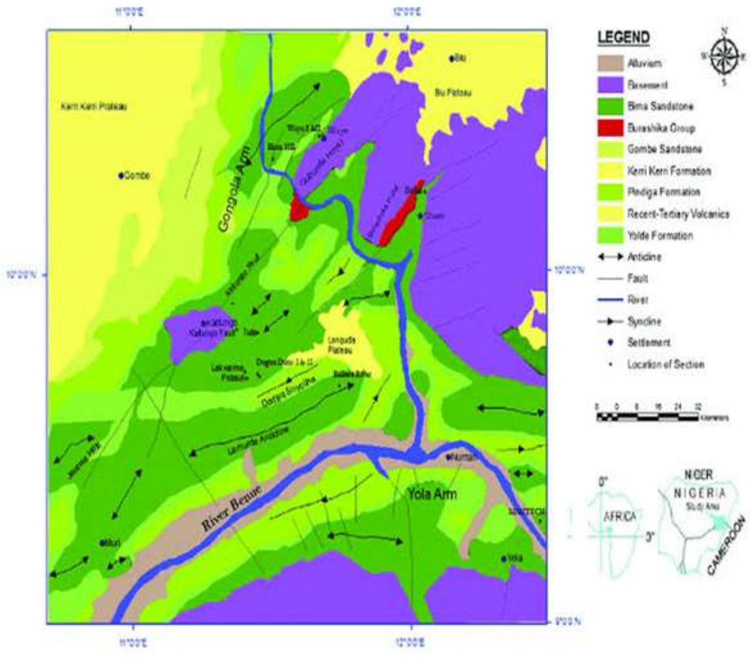


Figure 2: Geology Map of study area.

The opening of the Atlantic which started at the beginning of the Mesozoic triggered the crustal fragmentation of the West Central African Craton into rift systems. The Benue Trough was one of the major rifted basins formed, beginning at the start of the Cretaceous period from the tension generated by the separation of an aulacogen which opened into the Gulf of Guinea through the Niger Delta. As one of the major sedimentary basins in Nigeria, it extends linearly from the northern boundary of the Nigeria Delta to the southern boundary of the Chad Basin for about 800km in length, 50km-150km in width and is estimated to contain 5,000m of cretaceous sediments and volcanic rocks.

The Benue trough forms an important part of a system of linear sedimentary basins which include rivers Benue, Niger and the Gongola (Ofoegbu, 1984). The basin is characterized by a series of faults and tilted blocks typical of a rift system with depressions which houses a thick succession of shales, sandstone, limestones, coal, evaporates, volcanic and intrusive whose ages ranges from Aptian to Maestrichtian (Ofoegbu, 1988). These sediments were derived from the erosion of older rocks that once covered the area, as well as volcanic ash deposited during volcanic eruptions. Benue Trough is arbitrarily divided into three distinctive basins: Lower Benue, Middle Benue and the Upper Benue Trough.

The Upper Benue Trough is the northern section of the trough, and is made up of two basins: the Gongola basin (Gongola arm) and the Yola basin (Yola arm). The geology consists of crystalline basement, Cretaceous sediments and volcanics. The Precambrian crystalline basement is made up of scattered remains of well metamorphosed sedimentary rocks and diverse, mostly granite, plutonic masses that are collectively called older granites.

The oldest and the most extensive strata in the Upper Benue Trough and which rest unconformably on the uneven surface of the Precambrian basement rocks is the Albiam Bima sandstone. The Bima sandstone consists of a thick series of the continental sandstones, clays and grits and it is possible to differentiate the formation into lower Bima, Middle Bima and the Upper Bima. Lying comfortably on top of the Bima formation is the Yolde formation. It is of Cenomanian age and represents the beginning of marine incursion into this part of the trough. It consists of alternating sandstones and limestone-shale. The base of the Yolde formation is defined by marine shales, and the top by the disappearance of sandstones and the appearance of limestone-shale.

Overlying the Yolde formation are sequences of sedimentary rocks in the Gongola arm and the Yolanda arm. Overlying the Yolde formation in the Gongola arm are the adjacent Pindiga and Gongila formation and the younger Fika shale. In the Yola arm are the Dukku, Jessu, Sekuliye formations together with the Lamja sandstones and Numanha shales. These formations represent marine incursions into the Upper Benue Trough during the Turonian-Santnian period. These were followed by the deposition of the Gombe sandstone and the younger Kerri-Kerri formation in the Gongola arm, and the lamja sandstones and volcanic in the Yola arm. Previous studies had estimated the thickness of the sediments in the Upper Benue Trough to vary from about 1km to about 5km.

Materials and Method

The data sheets used for this survey were TMI sheets 130 (DUKU), 131 (BAJOGA), 151 (AKO) and 152 (GOMBE) obtained from Nigerian Geological Survey Agency (NGSA). The survey which was flown between 2006/12/7 and 2007/05/31 had a flight line spacing of 500m, sensor mean terrain clearance of 80m and tie line spacing of 5000m. The data recording interval was 0.1s or less than 7m. Projection method used in processing the data was the Universal Transverse Mercator (UTM) and WGS 84 as Datum. Since the survey was carried out between 2006 and 2007, an IGRF 2005 model was used for the computation of the declination and inclination which is a requirement for computing the pseudogravimetric anomaly.

Pseudogravimetric Transformation

The pseudogravimetric computation is based on Poisson's relation which shows that the magnetic potential (V) and the gravitational potential (U) for a body with the ratio of density to magnetization constant at each point, and the magnetization vector in a constant direction are related by directional derivatives in three-dimensions (William, Ralph & Afif, 2012).

$$\boldsymbol{V} = \frac{C_m M}{G\rho}(\mathbf{m}.\nabla \boldsymbol{U}), \qquad \frac{M}{\rho} = \boldsymbol{constant} \qquad \mathbf{1}$$

where ρ is the density contrast, M is the intensity of magnetization contrast, **m** is a unit vector in the direction of total magnetization and G is the gravitational constant.

The magnetic field anomaly $T_{x,y,z}$ at an external point due to a body is related to the magnetic potential (V) as;

$$\boldsymbol{T_{x,y,z}} = \boldsymbol{f}.\nabla \boldsymbol{V} \qquad \mathbf{2}$$

where **f** represents a unit vector in the direction of Earth's total field. Substituting equation into equation we obtain:

$$T_{x,y,z} = \frac{C_m M}{G\rho} f.\nabla(m.\nabla U) \qquad 3$$

It is possible therefore to compute a theoretical gravity potential U from any given measured magnetic anomaly T(x,y,z) and from this gravitational potential, a pseudogravity anomaly ∇U can be computed. This pseudogravity anomaly is not the true gravity anomaly due to the body, but a fictitious anomaly completely derived from a true magnetic anomaly assuming the ratio $\frac{M}{\rho}$ to be constant throughout the source body (Blakely, 1995). From equation the pseudogravimetric potential is obtained:

$$U = \frac{G\rho}{C_m M} \iint_{-\infty}^{\infty} T_{x,y,z}\, dfdm \qquad \mathbf{4}$$

Taking the fictitious density contrast to be equal to:

$$\rho = \frac{C_m M}{G}, \qquad 5$$

The pseudogravimetric anomaly is then given by:

$$g_{x,y,z} = \frac{dU}{dz} = \frac{d}{dz}\int\int_{-\infty}^{\infty} T_{x,y,z} df dm. \qquad 6$$

Taking Fourier transform of both sides, we obtained:

$$\boldsymbol{F}(\boldsymbol{g_{x,y,z}}) = \boldsymbol{F}(\boldsymbol{H_f}) * \boldsymbol{F}(\boldsymbol{T_{x,y,z}}) \qquad 7$$

H_f = Filter that transforms the total-field anomaly $\boldsymbol{T_{x,y,z}}$ measured on the horizontal surface into the Pseudogravity anomaly $\boldsymbol{g_{x,y,z}}$.

The Fourier transform of the pseudogravimetric transform filter is given by (Blakely, 1995):

$$F(H_f) = \frac{|k|}{(|k| f_z + i k_x f_x + i k_y f_y)(|k| m_z + i k_x m_x + i k_y m_y)} \qquad 8$$

k_x, k_y are wavenumbers in the direction of x and y axis respectively, ($\boldsymbol{m} = m_x, m_y, m_z$) and $\boldsymbol{f} = f_x + f_y + f_z$ are unit vectors of ambient magnetic field and magnetization field with respect to x, y, z axis.

The process consists of three steps; Fast Fourier transformed the magnetic field anomaly $\mathcal{F}(T_{x,y,z})$, multiplied by the Fourier transformed filter $\mathcal{F}(H_f)$ and then inversed Fourier transformed the product. The process requires a 2D gridded magnetic data set.

Pseudogravity transform can also be carried out by the vertical integration of the reduction to the pole aeromagnetic data (Blakely, 1995).

Spectral Analysis

The magnetic field measured at the surface is considered to be a summation of the magnetic signatures from all depths. This is the principle upon on which the spectral depth method is based upon. The application of the Fourier transform of the measured surface field was proposed by Bhattacharyya (1965), and the power spectrum of the surface field can be used to identify average depths of source ensembles (Spector & Grant, 1970). In its complex form, the two-dimensional Fourier transform pair may be written as:

$$G(u,v) = \iint_{-\infty}^{\infty} g(x,y) e^{i(ux-vy)} dxdy \qquad 9$$

$$g(x,y) = \frac{1}{4\pi^2}\iint_{\infty}^{\infty} G(u,v) e^{-i(ux-vy)} dudv \qquad 10$$

g (x, y) represents the signal in space domain, G(u,v) represents the signal in wavenumber domain, u and v are the angular frequencies in x and y directions respectively. G(u,v) is generally complex and can be expressed into its real and imaginary parts given as:

$$G(u,v) = P(u,v) + iQ(u,v) \qquad 11$$

It can also be written as:

$$G(u,v) = |G(u,v)| e^{i\theta(u,v)} \qquad 12$$

Were,

$$|G(u,v)| = \left[\left(ReG(u,v)\right)^2 + \left(ImG(u,v)\right)^2\right]^{\frac{1}{2}} \qquad 13$$

$$\theta(u,v) = arctan\left[\frac{ImG(u,v)}{ReG(u,v)}\right]$$

|G(u,v)| and $\theta(u,v)$ are called the amplitude spectrum and the phase spectrum respectively. The power spectrum $|G(u,v)|^2$ and its total energy spectrum is given by:

$$E_T = \frac{1}{4\pi^2}\iint_{\infty}^{\infty} |G(u,v)|^2 dudv \qquad 14$$

For depth estimation for magnetic sources, this is expressed as:

$$E(u,v) = e^{-4\pi hr}$$

Replacing h with Z and t with f we obtain:

$$\text{Log}\, E = -4\pi Z f$$

A linear graph of log E vs f gives slope:

$$s = -4\pi Z$$

The depth to a statistical ensemble of sources can is determined by the following expressions:

$$Z = \frac{s}{4\pi} \qquad 15$$

Where, Z is depth to a statistical ensemble, s is the slope of the log (energy) spectrum.

The energy spectrum generally has two sources. The deeper source is manifested in the smaller wavenumber end of the spectrum, while the shallower ensemble manifests itself in the larger wavenumber

For the purpose of easier handling of the large data involved, the four residual blocks of the study area were subdivided into 25 spectral cells, labelled 1-25 (figure 3) of 37 km by 37 km overlapping blocks in order to accommodate longer wavelength depth could be investigated.

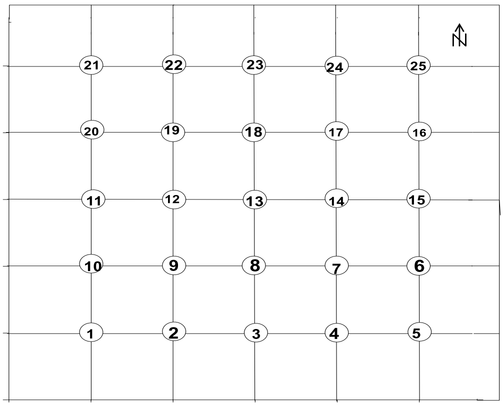
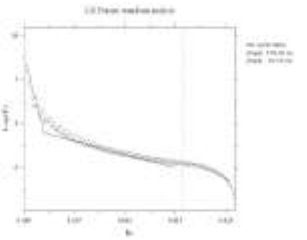


Figure 3: Spectral Cells

Digital signal processing software (OASIS MONTAJ), employing the fast Fourier transform technique was used to transform the residual magnetic data into the radial energy spectrum for each block. The average radial power spectrum was calculated and displayed in a semi-log figure of amplitude versus frequency.

Spector and Grant (1970) have shown that the Log-power spectrum of the source have a linear gradient whose magnitude is dependent upon the depth of the source. Graphs of logarithm of the spectral energy against frequencies for the 25 spectral cells was plotted and shown in figure (4).

BLOCK 1



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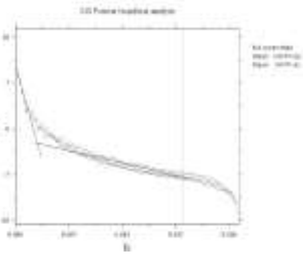

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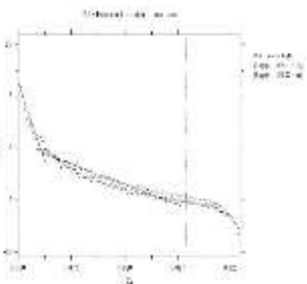

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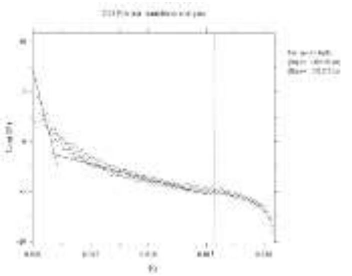

Figure 4: Typical plots of log of energy spectrum versus frequency

Results

The total magnetic intensity (TMI) map (Figure 1.3) shows areas of high magnetization indicated by positive magnetic anomalies ranging from 4.2 nT – 214.4 nt. The magnetic anomalies are of different trend, shape and wavelength that suggest different sources. The magnetic anomalies will characteristically be skewed from their perturbing sources typical of magnetic anomalies at low latitudes.

The reduced to the pole (RTP) magnetic anomaly is shown in Figure 1.4. As can be seen, the RTP anomaly is different from the magnetic anomaly in (Figure 1.3). This is to be expected because the skewness has been removed and the anomalies are now centered on their sources. From the map, about four prominent anomalies can be discerned: top left (Dashi, Baluro within DUKKU TMI), bottom left (Mai Ari, Shakala within AKO TMI), bottom right (Wudil, Zango within GOMBE TMI) and top right (Gadi, Galgaidu within BAJOGA TMI).

The pseudogravimetric anomaly map (Figure 1.4) was transformed using a density contrast of 1.0 g/cm^3 and magnetization of 1.5 A/m. The pseudogravity anomaly clearly shows a simpler map compares to the total magnetic intensity (TMI) map (figure 1.2) and the reduced to the pole anomaly (Figure 1.3). The Pseudogravimetric anomalies are broader and longer indicating that they are from deeper sources

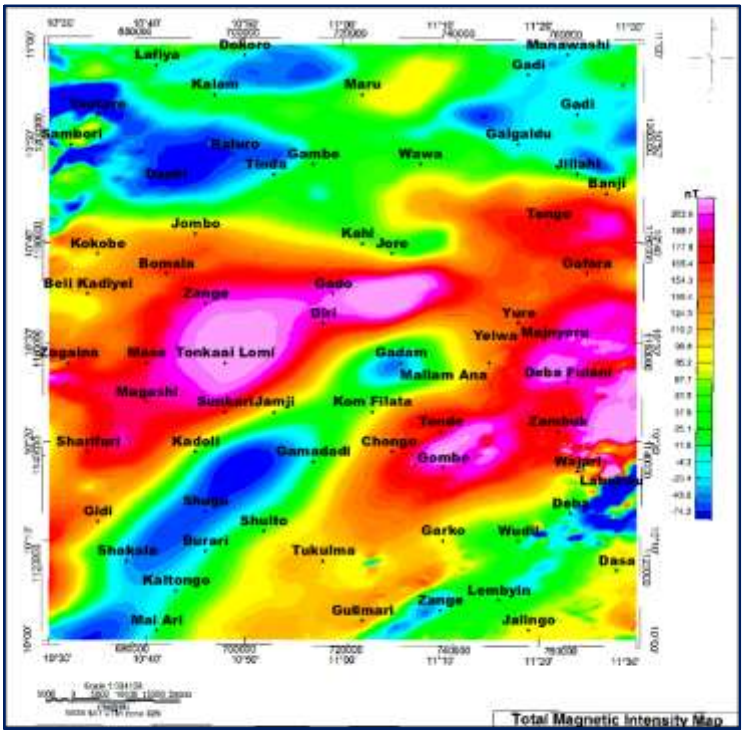

Figure 5: Total Magnetic Intensity (TMI) anomaly map of study area produced by Oasis Montaj

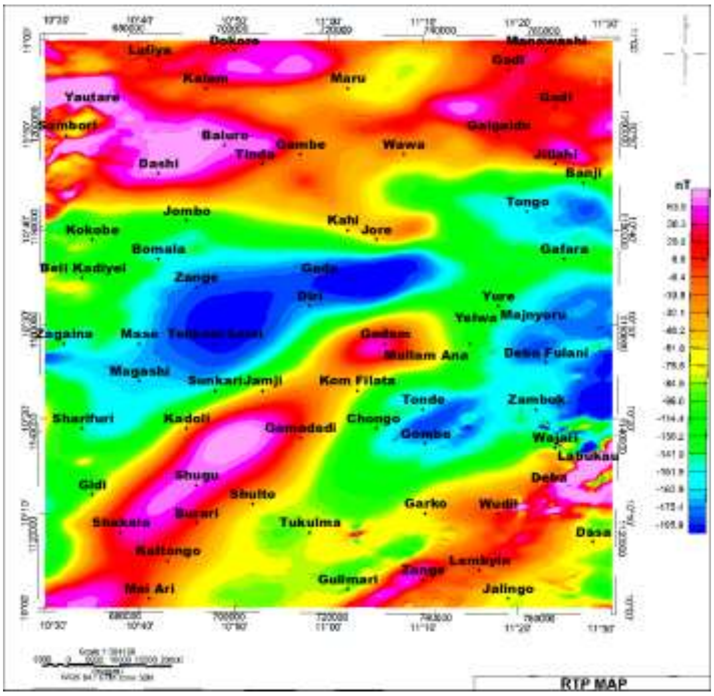

Figure 6: Reduction to the Pole (RTP) of the Magnetic Anomaly in Figure 5

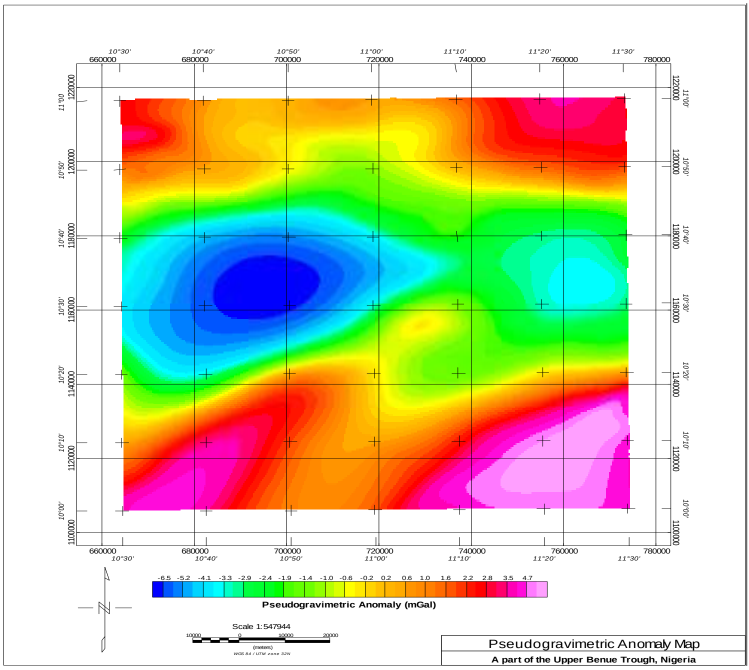

Figure 7: Pseudogravimetric anomaly map transformed from the Magnetic Anomaly of Figure 5.

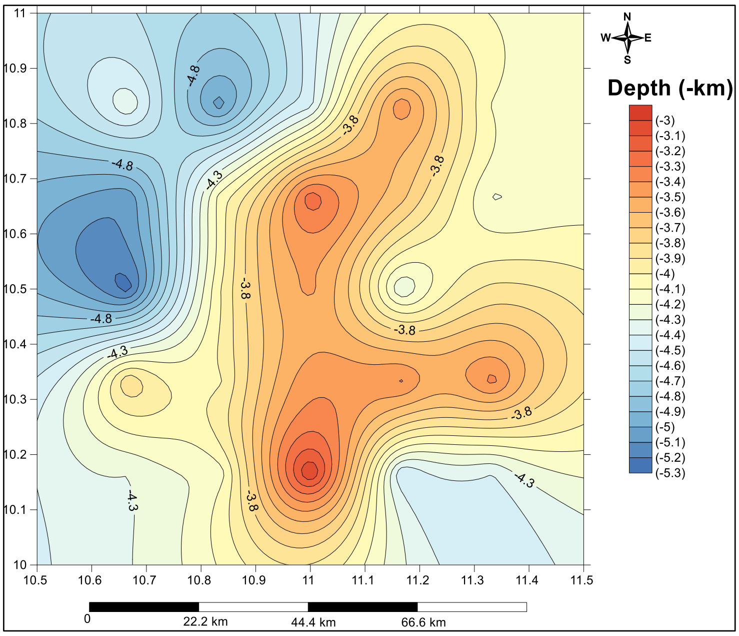

Figure 8: 2-D Contour Plot of the Magnetic Basement Surface Z_1 (Deep Source), Contour interval 0.05.

SPECTRAL BLOCKS	LONG	LAT	Shallow Magnetic Source depth (Z_2) meters	Deep magnetic source depth (Z_1) (Km)
1	10.6666	10.1666	-301.73	-4.29664
2	10.8333	10.1666	-269.983	-4.16046
3	11	10.1666	-390.27	-2.98912
4	11.1666	10.1666	-302.273	-4.48948
5	11.3333	10.1666	-327.953	-4.39665
6	10.6666	10.3333	-264.051	-3.81372
7	10.8333	10.3333	-256.256	-4.01825
8	11	10.3333	-304.232	-3.43715
9	11.1666	10.3333	-289.438	-3.39121
10	11.3333	10.3333	-257.055	-3.36479
11	10.6666	10.5	-287.056	-5.24639
12	10.8333	10.5	-340.579	-4.013
13	11	10.5	-376.048	-3.48061
14	11.1666	10.5	-343.444	-4.30418
15	11.3333	10.5	-260.102	-3.87248
16	10.6666	10.6666	-269.099	-5.0604
17	10.8333	10.6666	-381.002	-4.06902
18	11	10.6666	-323.715	-3.23755
19	11.1666	10.6666	-525.819	-3.67015
20	11.3333	10.6666	-349.599	-4.20926
21	10.6666	10.8333	-277.303	-4.31628

22	10.8333	10.8333	-337.911	-5.04623
23	11	10.8333	-284.625	-4.42897
24	11.1666	10.8333	-287.418	-3.43237
25	11.3333	10.8333	-256.76	-4.11325

Table 1. Estimation of the depth to magnetic sources.

Discussion

Pseudogravity anomalies have been used to investigate the deep magnetic source rocks of a part of the Upper Benue Trough, Nigeria of the Benue rift system. In computing the pseudogravimetric anomalies from the total magnetic intensity map of the trough, a density contrast of 1 gcm^{-3} and magnetization of 1.5 A/m were used. This is in accordance with previous studies in the Trough, (Ofoegbu, 1988; Shemang, Jacoby & Ajayi 2004).

The results show the pseudogravimetric anomalies (Figure 7) would be best accounted for in terms of the combined effect of a magnetic basement of variable topography and intrusive igneous bodies flanking on either side a sedimentary basin also of variable thickness (figure 7 & 8). The average depth of the undulating magnetic basement is about 4.0 km, varying between a minimum of 2.9 km and a maximum of about 5.2 km.

The pseudogravity anomalies are positive in some areas peaking at 4.7 mGal around Mai Ari and Deba and minimum with the lowest at -6.5 mGal between Duku and Gombe. The area between DUKKU and Gombe is a graben filled with sediments. Comparing the two maps: reduced to the pole anomaly map (Figure 6) and Pseudogravity anomalies (Figure 7), it would be noticed that there is a high level of correlation between the them. The areas where they correlate are probable areas with deep magnetic rocks, and the areas are found within the top northern and bottom southern sections of the study area. The only apparent difference is the absence of short wavelength anomalies in the pseudogravimetric anomalies that are present in the other two. From afore mentioned analysis, it is highly probable that the pseudogravimetric anomaly would correlate well with the gravity anomaly of the same area considering the fact that the magnetization is proportional to the density of the same source.

Ofoegbu, (1988), through an analysis of the aeromagnetic data over a part of the Upper Benue Trough, estimate the thickness of the sediments in the trough to vary between 0.5 km and about 4.7 km and the intrusives to be basic to intermediate in composition appears in close agreement with the results obtained in this research.

Conclusion

The pseudogravimetric anomaly has some special mathematical characteristics that allows it to amplify the amplitude of the long wavelength (low wave number) anomalies that are due to deeper sources at the expense of the short wavelength (high wave number) anomalies that are due to shallow sources (Figures 6 & 8). This affirms the capacity of the pseudogravimetric transformation to act as low pass filter and an effective tool for mapping the magnetic basement and illuminate the deeper magnetic sources. It is also highly probable that the gravity anomaly would correlate with the pseudogravimetric and magnetic anomaly giving the nature of the magnetic sources. The areas where there is a high level of correlation between Figures 6, 7 & 8 are probable areas with deep magnetic source rocks. Pseudogravimetric transformation has received little attention from researchers as a tool for enhancing magnetic anomalies. This may probably be attributed to the amplification of the long wavelength anomalies that are due to deeper sources at the expense of the short wavelengths that are due to shallow sources. Also, the assumptions made during the transformation may be a factor: that the remanent magnetization is negligible and that the ratio of the magnetization to density be constant throughout the source. But in spite of those impracticable assumptions and limitations, it is still a useful tool for exploring deep magnetic sources.

Acknowledgement

The completion of this research was made possible through the support of Tedfund. Their financial assistance not only facilitated the acquisition of the essential data, software and other logistics, but also enabled the successful execution of the study. I would also like to express my deepest appreciation to Prof. Charles Ofoegbu, Director, the Institute of Geosciences and Earth Resources, Nasarawa State University, Keffi and Prof Etim Uko of Nasarawa State University, Keffi for their scholarly contribution.

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