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Interpretation of Aromagnetic Data from Upper Benue Basin, Nigeria Using Automated Techniques

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Abstract: *The Benue basin is a major geological formation underlying a large part of Nigeria. It is a part of the broader Central African rift system. The Upper Benue basin being part of Benue basin is believed to be rift valley and is expected to be a major depositional basin, because rifting structures are often good sites for mineralization. The strategic economic importance and the availability of data from the study area arose the interest of many researchers including this present work to focus their attention on the area in search of geological features that are favourable to mineral deposition in the basin. The area investigated covers from* $07^0 00'$ *-* 08^0 *30'N and from* 11^0 *00' -* 12^0 *00'E.*

In this work, the interpretation of the data extracted from the aeromagnetic maps of the basin was carried out using automated techniques involving the analytic signal, horizontal gradient magnitude and the log power spectrum techniques to delineate linear geologic structures such as faults, contacts, joints and fractures within the study area in a bid to unravel the gross sub surface geology of the area which would in no doubt help in better understanding and characterization of the area investigated. The residual magnetic field was subjected to three filtering techniques, the analytic signal, horizontal gradient method and the log power spectrum. A grid of analytic signal technique was employed to study source parameters which include location, depth and susceptibility contrast of identified magnetic anomalies in the basement rocks. The horizontal gradient method was used to study the fault and contact pattern in the study area while Power spectrum technique was also used to further study the depth estimates to the magnetic basement.

Results from analytic signal technique showed that the basement in the study area is segmented by faults whose depth ranges between 0.5km and 10.5km with an overall average depth ranging between 1.13km to 5.88km. The estimated depths were contoured to portray the basement isobaths for the study area. The horizontal gradient method revealed a minimum depth or sedimentary cover ranging between 0.01km to 2km and faults pattern trending northeast- southwest (NE- SE), Eastnortheast- westsouthwest (ENE- WSW) and westnorthwest- eastsoutheast (WNW- ESE). Depth estimates from the log power spectrum revealed two major grabens or sub-basins with depth ranging between 1.22km and 3.45km for depth to magnetic basement while those ranging between 0.01km and 1.49km are identified with shallow sources which are due to near surface intrusives.

Based on the result obtained it was revealed that the study area is divided into three basinal structures; the deep sources ranging between 6.5km and 10.5km are associated with some layers of intra-crustal discontinuities; an indicator to feature volcanic eruption in the area. The intermediate depths between 3.5km and 5.5km correspond generally to the top of intrusive masses occurring within the basement, a depth deep enough for possible hydrocarbon deposit. Shallow depths between 0.01km and 2.5km are attributed to shallow intrusive bodies or near surface basement rocks probably isolated bodies of ironstones formation concealed within the sedimentary pile.

Keywords: *Aeromagnetic map, Analytic signal, Log power spectrum, Magnetic mineral, Rift valley, Upper Benue basin*

I. Introduction

Airborne geophysical surveys are an extremely important aspect of modern geophysics and compared with ground surveys it allow faster, and usually cheaper coverage, of large areas.

Over the last decade there has been increase in the use of airborne magnetic and more recently, gravity in the petroleum exploration industry. The early use of potential field methods in petroleum was to map sedimentary basin thickness while high resolution surveys are used to investigate basement trends and intra-formational structures [1], [2].

In many countries of the world including Nigeria, government agencies and private interests have employed aeromagnetic method to survey most of their countries in search for oil and gas and for mapping strongly magnetic basements at regional scale and for delineating weakly magnetic sedimentary contacts at local scale [3]. With the use of aeromagnetic data, it has been possible to locate intrasedimentary faults and subtle lithological contacts.Airborne geophysical surveying is the process of measuring the variation of different physical or geochemical parameters of the earth such as distribution of magnetic minerals, density, electric conductivity and radioactive element concentration [4]. Aeromagnetic survey maps the variation of the geomagnetic field, which occurs due to the changes in the percentage of magnetite in the rock. It reflects the variations in the distribution and type of magnetic minerals below the earth surface. 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 and over formations [5].

Therefore, for this study, data obtained from aeromagnetic map of some part of upper Benue shall be subjected to three automated techniques of analysis; the analytic signal, horizontal gradient magnitude and Log power spectrum techniques and the results so obtained shall be analyzed, interpreted and used in the study of structural and geophysical mapping of the study area.

II. The Study Area, Its Extent and Geological Setting

This study covers an area of approximately 18150 km^2 in the north-eastern part of Nigeria between latitudes $07^{0}00'$ and 8^{0} 30'N, and longitudes $11^{0}00'$ and $12^{0}00'$E and covering some part what is known as Upper Benue Region (Fig. 1) .These areas include Kam, Kiri, Serti, Dau, Gashaka and Filinga. The Upper Benue is largely referred to as failed rift valley [6], [7], and so it is expected that the region should be a major depositional basin and therefore a good site for mineralisation. Upper Benue basin belongs to the genetically and physically related systems of faults and rifts termed the West and Central African Rift System (WCARS). The system's origin is attributed to the breakup of Gondwanaland and the opening of South Atlantic and Indian Ocean. The Upper Benue – Chad axial trough is believe to be the third and failed arm of a triple junction rift system that preceded the opening of the South Atlantic during the early Crretaceou and subsequent separation of African and South American continent [8].The essential geological features in the basin (Fig. 1) consist of sedimentary rocks ranging in age from upper Cretaceous to Quarternary, overlying an ancient crystalline basement made up mainly of Precambrian granites and gneisis.

The Cretaceous sediments and the underlying basement complex, as in most other parts of Nigeria, are invaded by numerous minor and major intrusions of intermediate to basic composition. The older intrusives are largely granites and granodiorites while the younger intrusives are mainly granitic and pegmatitic types, although diorites and some synetites also occur. There were also occurrences of igneous and volcanic activities within the region extending from cretaceous to recent times. Prominent among the Tertiary and Recent volcanics in the region are the basic lavas of Biu and Longuda.

The crystalline basement whose topograph is believed to be irregular [9], is exposed in a number of locations in the region. Intruded into the basement is a series of basic, intermediate and acid plutonic rocks referred to as the older Granites. Notable outcrops of the older Granites include the small inliers of biotite granites which are found around Kaltungo, Gombe, Kokuwa, and in the Bauchi area. The uplifted basement rocks in the North-westen part of the area were also intruded by orogenic acid ring complexes, the Younger Granites [10]. The cretaceous sediments in the area are thought to be compressionally folded in a non-orogenic shield environment [11], and the folding took place mainly along ENE-WSW axes, particularly in Dadiya, Kaltungo, Lamurde, and Longuda areas. Numerous faults have also been reported in the region [12], [13]. These faults show variable trends but the dominant direction lies between north-north-east and east-north-east.

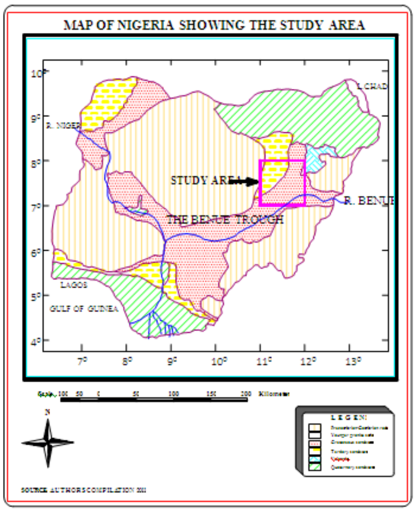


Fig. 1: General Geological map of Nigeria showing the study area

III. Materials And Method

3.1 Materials

The primary data used in this analysis is the aeromagnetic maps from part of upper Benue basin. Six aeromagnetic maps published by the Geological Survey of Nigeria Agency, Airborne geophysical series (1974) on a scale 0f 1:1000, 000 covering the study area were used. The maps used were from sheet numbers 236, 237, 256, 257, 276, and 277 (i.e.,Kam, Kiri, Serti, Dau, Gashaka,and Filinga respectively) .

The survey was carried out along a series of NE- SW lines with a spacing of 2km and an average flight of constant elevation terrain of 152m above ground level. Other flying parameters given on the maps used are as follows; Nominal tie line spacing: 20km, Average magnetic inclination across survey area; from $I=7^0$ in the north to $I= 4^0$ to the south. The regional correction on the maps was based on I.G.R.F (epoch date 1st of January, 1974, using IGRF 1975 model).

The maps were carefully hand digitized into a 2km by 2km square matrix cell, given rise to a 27 by 27 square matrix, each with a total of 729 data points per map sheet. So for the six maps, a total of 4,374 data points were processed and the digitization was carried out along flight lines. An interval of 2km directly imposes a Nyquist frequency of 1/4 km^{-1}. This implies that the magnetic anomalies less than 4km in width may not be resolved with this digitizing interval. However, [7], consider this digitizing interval suitable for the portrayal and interpretation of magnetic anomalies arising from regional crustal structures. [10], also indicated that, crustal anomalies are much larger than 4km and therefore lie in a frequency range for which computational errors arising from aliasing do not occur with a 2km digitizing grid.

The data obtained from the digitized maps were digitally merged and was used in generating the total magnetic intensity map of the study area. The geomagnetic gradient was removed from the data using International Geomagnetic Reference Field, IGRF (epoch 1 January 1974, using IGRF 1975 model) and this was used in producing the resultant residual anomaly map for the study area. The residual anomaly map was later subjected to analytic signal, horizontal gradient and Log power spectrum filtering and enhancement techniques, which were later used for the interpretation.

Magnetic profiles of the area were also generated which shows various degrees of variation in the magnetic susceptibilities in the basement rock of the area.

3.2 Processing methods

The basic problem in the analysis of magnetic data is the isolation of weak magnetic anomalies caused by low concentrations of magnetic minerals. These weak anomalies are often masked by much stronger magnetic anomalies caused by underlying magnetic rock/or by rocks in the sedimentary basin.

The weak anomalies can efficiently be isolated by applying various transformation and enhancement techniques to the magnetic data. Such techniques include; reduction to pole, upward and downward continuation, derivatives-based filters, analytic signal, Log power spectrum, horizontal gradient method. But for the purpose of this research work, three automated processing techniques to determine the structural and depth to magnetic source from the filtered and processed aeromagnetic data were employed. The three automated processing techniques are (i) analytic signal, horizontal gradient and (ii) Log Power spectrum methods. The processing techniques are basically imaging techniques. One advantage that would be derived from these techniques is that, by looking at many different types of presentation, the features that are not visible in some images will be more apparent in other images.

3.2.1 Analytic Signal Method

The analytic signal is formed through a combination of the horizontal and vertical gradients of a magnetic component. It requires first-order horizontal and vertical derivatives of the magnetic field or of the first vertical integral of the magnetic field.

The horizontal derivative of magnetic field is a measure of the difference in magnetic value at a point relative to its neighbouring point whereas the vertical derivative is a measure of change of magnetic field with depth or height. These derivatives are based on the concept that the rates of change of magnetic field are sensitive to rock susceptibilities near the ground surface than at depth. Subsequently, the amplitude of the analytical signal [14], which ensures precise location of structures and boundaries of causative sources were also computed.

The first vertical derivative is an enhancement technique that sharpens up anomalies over bodies and tends to reduce anomaly complexity, thereby allowing a clear imaging of the causative structures. The transformation can be noisy since it will amplify short wavelength noise i.e. clearly delineate areas of different data resolution in the magnetic grid.

The application of analytic signals to magnetic interpretation was pioneered by [14], for 2D case, primarily as a tool to estimate depth and position of sources. More recently the method has been expanded to 3D problems, [15], [16], as a mapping and depth-to-source technique and as a way to learn about the nature of the causative magnetization.

The 3D analytical amplitude of the potential field $\phi(x, y)$ measured on a horizontal plane is given as

$$|A(x,y)| = \sqrt{\phi_x^2 + \phi_y^2 + \phi_z^2} \qquad (1)$$

For the 3 D case, the analytic signal is given by

$$A(x,y,z) = \frac{\partial \Delta T}{\partial x} i + \frac{\partial \Delta T}{\partial y} j + i\frac{\partial \Delta T}{\partial z} k \qquad (2)$$

The amplitude of the analytic signal (AAS) of magnetic can be defined as the square root of the sum of the vertical and two orthogonal horizontal derivatives of magnetic field.

$$|A(x,z)| = \sqrt{\left(\frac{\partial \Delta T}{\partial x}\right)^2 + \left(\frac{\partial \Delta T}{\partial y}\right)^2 + \left(\frac{\partial \Delta T}{\partial z}\right)^2} \qquad (3)$$

The amplitude is simply related to amplitude of magnetization which can be easily derived from the three orthogonal gradients of the total magnetic field using expression in equation (3). An important property of the 2 D analytic signal is that its amplitude is the envelope of its underlying signal.

Analytic signal method generally produces good horizontal locations for contacts and sheet sources regardless of their geologic dip or the geomagnetic latitude, therefore very useful at low magnetic latitude, also its amplitude peaks over magnetic contacts, but if more than one source is present, then the shallow sources are well resolved but the deeper sources may not be well resolved. Depth information is limited to minimum and maximum values [17].

3.2.1.1 Analytic Signal Profilings and Depth Estimation

The analytic signal profiling shapes can be used to determine the depth to the magnetic sources. The magnitude/ amplitude of the peak of the analytic signal signature are proportional to the magnetization and the maxima occurs directly over faults and contacts [18]. The 2-D profile analysis of the aeromagnetic data along the transverses suggest that the study area is composed of magnetic minerals in varying quantities along each profiles as shown by the series of highs and lows (Fig. L1to L8). Major faults may also be recognized by pronounced lows on magnetic profiles.

Sharp peaks are indicators of outcrops while broad peaks indicate deep seated or magnetic minerals of very large areal extent. Depth estimates to tops of anomalous magnetic bodies are also generated from analytic signal methods.

To determine the depths to magnetic sources observed on 2D profiling curves, the anomaly width (model) at half the amplitude was used to derive the depths.

Eight profilings were drawn across the maps (Fig. L1to L8) and these show the variations of magnetic minerals along each profile.

3.2.2 Horizontal Gradient Method

Horizontal gradient method requires first-order horizontal derivatives and a Reduction-to-pole or pseudogravity transformation. The method is least susceptible to noise, but results are accurate only where the magnetization is induced and the sources are of very specific types. The use of the HGM for depth estimation was first proposed by [16], and it has been shown to be very easy to use and also very stable in the presence of noise.

The horizontal Gradient Magnitude Method requires a transform of the magnetic anomaly map to a map with data reduced to the pole or to a pseudogravity anomaly map.

i.e. $$HGM(x,y) = \sqrt{\left(\frac{2\Delta T}{2x}\right)^2 + \left(\frac{2\Delta T}{2y}\right)^2} \qquad (4)$$

where Δ T is the total field reduced to the pole.

According to [2], this function peak over magnetic contacts under certain assumptions;

(i) the magnetic field and source magnetization are vertical

(ii) the contact is vertical and (iii) the sources are thick.

Violation of the first two assumption leads to shift of peaks away from the contact location. Violation of the third assumption leads to secondary peaks parallel to the contacts.

When these assumptions are satisfied, the method is effective in detecting lineaments that may correspond to basement faults and contacts. It has the advantage that it is not very susceptible to noise.

HGM is primarily useful for the approximate horizontal location of edges and for estimating minimum and maximum source depths. The disadvantages are that the depth information is limited to minimum and maximum values and that it requires reduduction-to-pole and pseudogravity transformations and this can present problems at low magnetic latitudes and in areas of high remanent magnetization.

3.2.3 Log Power Spectrum

One of the main researches on magnetic anomaly maps is to estimate depth of the buried objects resulting the anomaly. In interpretation of magnetic anomalies by means of local power spectra, there are three main parameters to be considered. These are depth, thickness and magnetization of the disturbing bodies [4].

It is necessary to define the power spectrum of a magnetic anomaly in relation to the average depth of the disturbing interface. It is also important to point out that the final equations are dependent on the definition of the wavenumber in the Fourier transform. For an anomaly with n data points the solution of Laplace equation in 2D is given as;

$$M(x_j, z) = \sum_{j=0}^{n-1} A_k e^{i2\pi k x_j} \; e^{\pm 2\pi k z} \tag{5}$$

Where wavenumber k is defined as $k = \frac{1}{\lambda}$ and A_k are therefore the amplitude coefficients of the spectrum,

$$A_k = \sum_{j=0}^{n-1} M(x_{j,} z) e^{-i2\pi k x_j} \; e^{\pm 2\pi k z} \tag{6}$$

For $z = 0$, equation 3.27 can be written as,

$$(A_k)_0 = \sum_{j=0}^{n-1} M(x_j, 0) e^{-i2\pi k x_j} \tag{7}$$

Then equation (2.27) can be rewritten in terms of (3.28) as,

$$A_k = (A_k)_0 \, e^{\pm 2\pi k z} \tag{8}$$

Then the power spectrum P_k is defined as,

$$P_k = (A_k)^2 = (P_k)_0 \, e^{\pm 4\pi k z} \tag{9}$$

Taking logarithm of both sides,

$$\log_e P_k = \log_e (P_k)_0 \pm 4\pi k z \tag{10}$$

One can plot wavenumber, k, against $\log_e P_k$ to attain the average depth to the disturbing interface.

The interpretation of the $\log_e P_k$ against wavenumber k requires the best fit line through the lowest wavenumbers of the spectrum. The wavenumbers included in this procedure are those smaller than the wavenumber where a change in gradient is observed. The average depth can be estimated from plotting equation (10) as,

$$d = -\frac{\Delta P}{4\pi \Delta k} \tag{11}$$

Where d is the average depth, ΔP and Δk are derivative of P and k respectively.

Summarily, if d is the estimated depth to the anomalous body and $-\frac{\Delta P}{4\pi \Delta k}$ is the slope S of the plot, it then follows that;

$$d = -S \tag{12}$$

As stated earlier one of the most useful pieces of information to be obtained from aeromagnetic data is the depth of magnetic source or rock body. Since the source is usually located in the so-called 'magnetic basement' (i.e.the igneous and metamorphic rocks lying below the- assumed non-magnetic-sediments), this depth is also an estimate of the thickness of the overlying sediments. The wavelengths of anomalies are primarily related to their depth of burial; shallow bodies give sharp, short wavelength anomalies, deep bodies give broad and long wavelength anomalies.

[19] quoted to have attributed to the slope of the logarithmic (log) power spectrum of aeromagnetic data to the depth of magnetic bodies/interfaces in the crust. This interpretation of the power spectrum is very convenient and enjoys continuing popularity as can be seen from a number of recent publications [4], [20] and [21].

The cut-off wavenumber was selected based on the changeover of the short-wavenumber and long-wavenumber segments of the azimuthally averaged power spectra of the entire profile lengths [22]. A single power spectrum may yield up to five depth values [23], which seems to indicate the existence of various horizontal magnetic interfaces in the crust.

If the slope of the log power spectrum indicates the depth to source, then a section with constant slope defines a spectral band of the potential field originating from sources of equal depth.

These depth values were then utilized to separate the effects caused by shallow and deep-seated sources, assuming that long- and short – wavelength anomalies originate from deep-seated and shallow sources respectively.

IV. Result And Discussion

4.1 Interpretation Of Aeromagnetic Maps

Air borne magnetic surveys provide a quick means of geological mapping. The magnetic data give information about geological patterns at depth about the metamorphic basement on which younger sediment rock lie, and throw light on the presence of major structures which may have influenced its development [2].

Generally, there would always be a magnetic susceptibility contrast across a fracture zone due to oxidation of magnetic to hematite, and/or infilling of fracture planes by dyke likebodies, whose magnetic susceptibilities are different from those of their host rocks. Such geological features may appear as thin elliptical closures or nosing on an aeromagnetic map. These features represent geological lineaments. The presentation of geophysical data which used to be mostly in profile or contour maps benefited from the advances in technology wherein user friendly presentation systems were developed. One of such presentation is transformation of contour maps as colour shades. It is realized that display of geophysical data in colour shades form enhances the visual perception by several order of magnitude when compared to contour maps.

Magnetic anomalies can generally be interpreted qualitatively or quantitatively. The qualitative technique has been practiced for many years and it involves the description of the anomaly in terms of, width amplitude, trend e.t.c. The quantitative interpretation could be done graphically by hand choosing special points on the anomalies, such as maxima, inflection points, half-width, e.t.c. Most important parameter in quantitative interpretation is the depth of the anomalous body.

4.2 Qualitative Interpretation Of Aeromagnetic Maps Of The Study Area

This involves the visual inspection of magnetic maps and making of geologic deductions from the observed features. Areas of magnetic high are likely indicate of higher concentration of magnetically susceptible minerals (principally magnetite). Similarly, areas with broad magnetic lows are likely areas of low magnetic concentration, and therefore lower susceptibility.

An aeromagnetic survey measures variations in basement susceptibility. Interpretation is how the variation in this susceptibility affects the overlying sedimentary section. Local variations occur where the basement complex is close to the surface and where concentration of ferromagnetic minerals exists. Thus, the primary applications of the magnetic method are in mapping the basement and locating ferromagnetic ore deposits.

4.3 Total Magnetic Intensity (Tmi) Map

The analysis of the total magnetic intensity (TMI) of the map shows the general magnetic susceptibility of the basement rocks and the inherent variation in the basin under study. The maps are presented as colour shades for easy interpretation. The coloured shades aided the visibility of a wide range of anomalies in the magnetic maps and the ranges of their intensities were also shown.

The 2D TMI map of the study area is as shown in Fig. 2, located on latitude $07^0 00^' \text{to} 08^0 30^' N$ and longitude $11^0 00^' \text{and} 12^0 00^' E$, shows values ranging between 32620nT and 33000nT. The magnetic anomaly of magnitude between 32800nT and 32840nT appears to be very dominant (Yellow colour). It is observed to be conspicuous in the west, northwest, southwest and southern parts of the study area. Closely followed by these in spread are those anomalies ranging between 32840nT and 32900nT in magnitude (green colour) and those between 32740nT and 32800nT (blue colour). These are only prominent in the central part of the study area with little traces of it the northeast, southwest and northwest.

Found almost in small quantity are anomalies of very high magnetic intensity value between 32960nT and 33000nT (faded pink colour) which are observed the north and southeastern parts of the study area. Also found in small quantity in the area are the anomalies between 32900nT and 32960nT (red colour) noticed in the southeast and northeast of the area. Anomalies ranging between 32680nT and 32740nT (dark brown) were observed in southeastern and Northeastern part of the study area.

Summarily, the 2D TMI map of the study area revealed that the area is magnetically heterogeneous. Areas of very strong magnetic values (32800nT to 33000nT) may likely contain outcrops of crystalline igneous or metamorphic rocks, deep seated volcanic rocks or even crustal boundaries. The areas between 32620nT to 32780nT are suspected to contain near surface magnetic minerals like sandstones, ironstones, near-surface river channels and other near-surface intrusive. Equally several contour closures on the map indicates shallow basement and thus may be due to the fact that Niger- Benue River confluence is an uplifted area, very similar to a model proposed by [11].

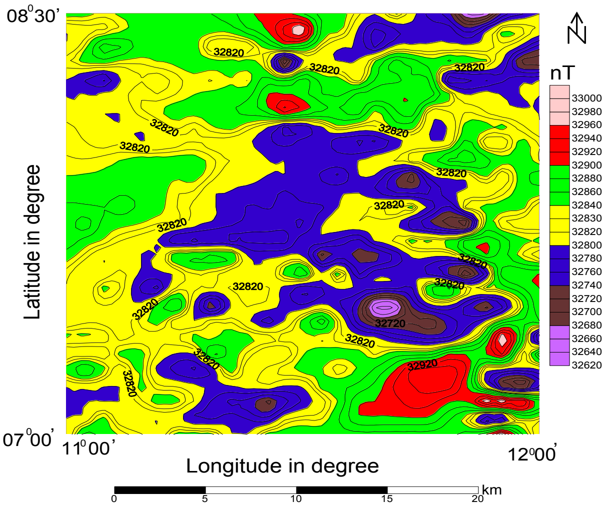


Fig. 2: Total magnetic intensity map of the study area

4.4 The Residual Map

Large scale structural elements caused very long wavelength anomalies referrered to as regional, superimposed on these are smaller localized perturbations, the residual caused by smaller scale structures or bodies. Magnetic data observed in geophysical surveys are the sum of magnetic fields produced by all underground sources. The target for specific surveys are often small-scale structures buried at shallow depths, and the magnetic responses of these targets are embedded in a regional field that arises from magnetic sources that are usually larger or deeper than the targets or are located farther away. Correct estimation and removal of the regional field from the initial field observations yields the residual field produced by the target sources [15]. The extracted residual anomalies are often useful for structural mapping or qualitative interpretation based on visual inspection of the data. The resulting residual map might be a clear enough image of the anomaly so that qualitative interpretation may be carried out. Residual maps are used extensively to bring into focus local features which tend to be obscured by the broad features of the regional field.

The 2D residual map of the study area (Fig. 3) revealed that local magnetic field variation whose magnitude varies between 20nT to 25nT (red colour) appearing in the North and southeastern part of the map and those ranges between 5nT to 20nT (yellow colour) are observed scantly across the area. Very dominant in the study area and appeared to be well distributed almost in equal proportion throughout the entire study area is the anomalies ranging between -10nT and 5nT (blue colour). Residual anomalies with magnetic intensity ranging between -40nT to -25nT (faded purple) are observed at two places in the east and southeastern parts of the study area even though in small proportion. The residual aeromagnetic anomalies appear to be sufficiently isolated from regional field. At some places on the residual map (Fig. 3) there are anomalies that are not present on the total magnetic map (Fig. 2). These anomalies are due to magnetic source of shallow origin.

Local positive residual anomalies observed in the parts of the study area are interpreted or suspected to be some outcrops of cretaceous rocks and perhaps concentrations of sand stones within the study area [24]. These could also be associated with volcanic and ophiolitic rocks. Negative anomalies are ascribed to greater thickness of cretaceous rocks contained within the fault-bounded edges and depicting isolated basinal structuring and these are well distributed across the study area.

Major faults may be recognized as a series of closed lows on the contour maps. Volcanic rocks with reverse polarity could also produce distinctive, high – amplitude negative aeromagnetic anomalies. The distribution of magnetic highs and lows (i.e. positive and negative anomalies) are as shown by the peaks and the depressions in the surface map of the residual map of kam (Fig. 4).

Generally, the entire study area revealed both positive and negative residual anomalies, indicating series of magnetic highs and lows. The positive residual anomalies were obtained in areas where they could be related to the surface rocks (outcrops) and/ or with measured magnetic values. The positive anomalies could also be interpreted in terms of combined effect of zones of mafic/intermediate intrusions occurring in the basement or within the sedimentary basin [24], [25] and [21]. Similarly, negative residual anomalies were obtained where the observed field produced definite magnetic lows that could be partially correlated with measured magnetic fields of granitoid and felsic volcanic rocks or major fault zones [25].

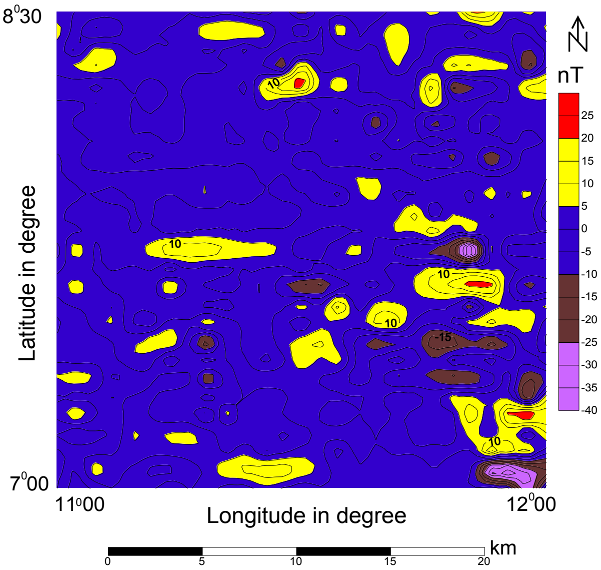


Fig. 3: Residual field map of the study area

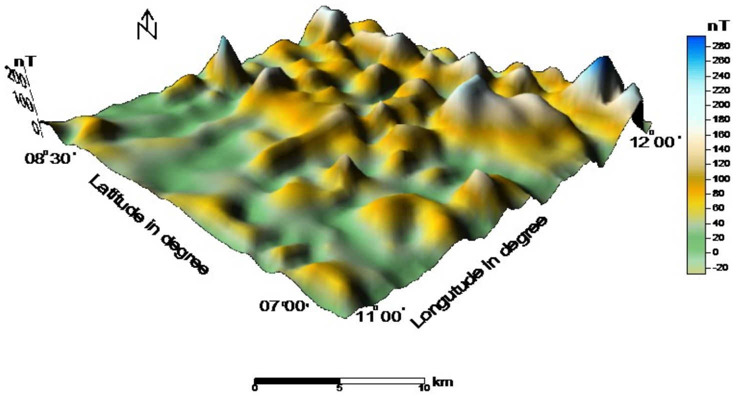


Fig. 4: Surface plot of residual map of the study area

4.5 Analytic Signal Map

Analytic function is extremely interesting in the context of interpretation, in that it is completely independent of the direction of magnetization and direction of the earth's magnetic field. This means that all bodies with the same geometry have the same analytic signal.

An important goal of data processing is to simplify the complex information provided in the original data. One of such simplification is to derive a map on which the amplitude of displayed function is directly and simply related to a physical property of the underlying rocks [18]. An example of such map is the analytic signal map. If more than one source is present, then the shallow sources are well resolved but the deeper sources may not be well resolved. With analytic signal method, it is possible to isolate weak anomalies resulting from the subdued magnetic sources occurring within sedimentary strata. The analytic signal contour map allows us to identify and map near-surface magnetic minerals somewhat more readily.

The 2D analytic signal map of the study area (Fig. 5) revealed near-surface anomalies whose magnitude ranges between 0nT and 40nT (dark brown red), mostly trending in the norh-west direction and being dominant in the area in terms of distribution. Those anomalies whose magnetization varies between 40nT and

80nT (red) are observed to be well distributed in the study area area. Another major observed anomalies ranging between 120nT and 1600nT (blue colour) are observed in the north, northeast and southeastern parts of the area. Observed at the central, eastern and southeastern part of the area are anomalies ranging between 80nT and 120nT (yellow colour). Around northeast and southeast are anomalies between 160nT and 200nT, other anomaly values ranges between 200nT and 280nT and the suspicion around these areas to be an outcrop is very high. The closely spaced linear sub-parallel orientation of contours from the map suggests the possibility of faults or local fracture zones passing through these areas. There would always be a magnetic susceptibility contrast across a fracture zone due to oxidation of magnetite to hematite, and/or infilling of fracture planes by dyke-like bodies whose susceptibilities are different from those of their host rocks. Such geological features may appear as thin elliptical closures or nosing on an aeromagnetic map. These features represent geologic lineament.

Generally, observed anomalies on the analytic signal maps are not entirely different from what was obtained from the residual maps but the anomalies in the analytic signals are clearer and sharpened because many of the obscured anomalies are now brought to focus.

Now going by the geology of the Upper Benue which affirmed the region to be a rifted zone coupled with the results of the analysis of data of some parts of the basin investigated in this research work, the region is actually fragmented by features such as outcrops, cracks, fractures, faults and joints all which serves as reservoir for the suspected minerals in the region. From the investigation, some likely and common minerals in region are; lead, zinc, tin, columbite, limestone, gypsi-ferrous shales, sandstones, marble, tin ore, graphite,barite coal. Older and younger granites, quartzites and magmatites are common in outcrops in the area [26].

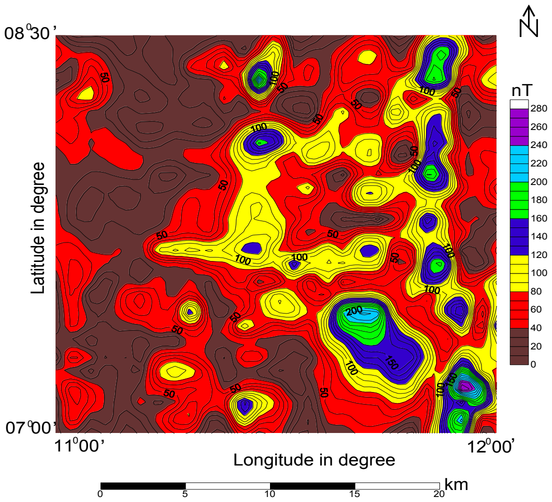


Fig. 5: Analytic Signal map of the study area

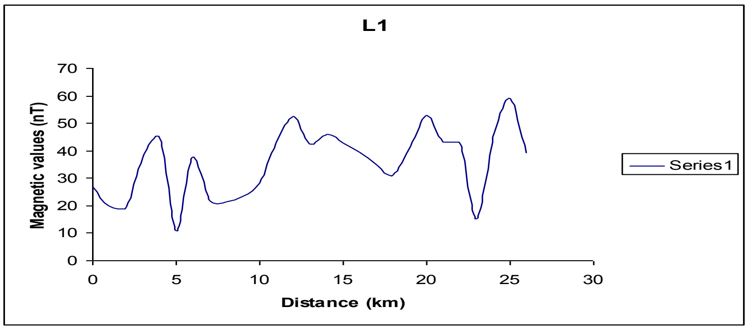
4.6 Quatitative Interpretation Of Aeromagnetic Maps Of The Study Area

Several methods have evolved in the early days of magnetic interpretation simply to estimate the depth of sources from their anomalies without reference to any specific source models. Depth estimates to tops of anomalous magnetic bodies are generated by a number of means including; slope measurement methods and analytic signal methods.

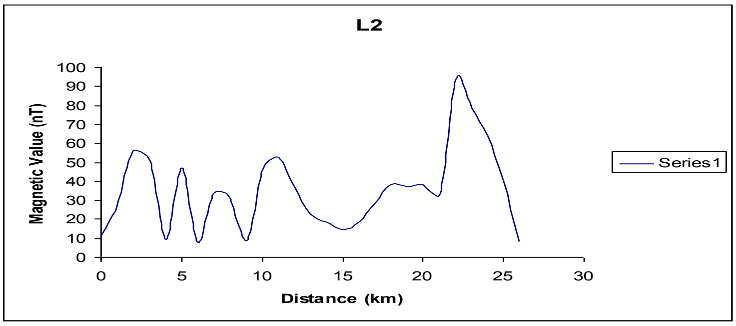
4.6.1 Analysis of Analytic Profiling Map

The 2D Analytic Profiling curve of maps of the study area (Fig. 6: Analytic Signal Profile L1 – L8) has further revealed some interesting geological features in the area. Eight profiling curves were drawn on the map of the study area at, 07^0 00'; 07^0 15'; 07^0 30'; 07^0 45'; 08^0 00'; 08^0 15' and 08^0 30'. This profiling was believed to serve as the representative of the whole area covered under this study. Deep seated and or magnetic minerals of large areal extent are observed along profiles, L3, L4, L5 and, L7. These could also be associated deep faults, deep seated volcanic rock or igneous rock. It could also be a consequence of intensive weathering and erosion of the iron formation from plateaus, this may have yielded a local concentration of limonite or magnetite in the area.

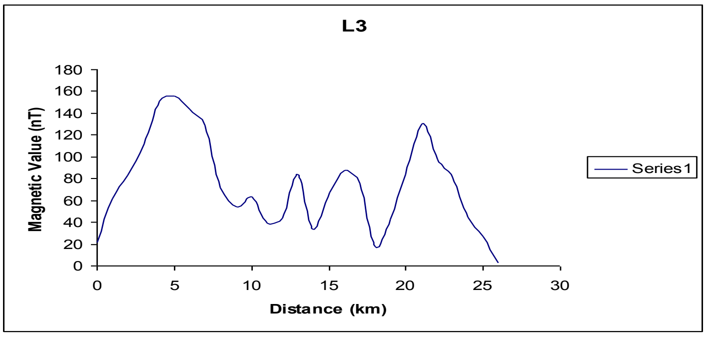
The very sharp anomaly peaks observed along profiles L1, L2, L6 and L8 could be attributed to the outcrops of crystalline igneous and/or metamorphic rock or even exposed volcanic rocks. The sharp inflections at about 27km on profiles L2, L4, L5, L7 and L8 are indicative of rock contacts [3]. Other anomalies observed as revealed on the profilings are probably due to the presence of sandstones, ironstones, shales, graphites, limestones, intrusives and other near-surface magnetic minerals. The magnetization levels for the entire study area are observed to range between 0nT to 550nT showing varying degree of magnetic susceptibility across the area.



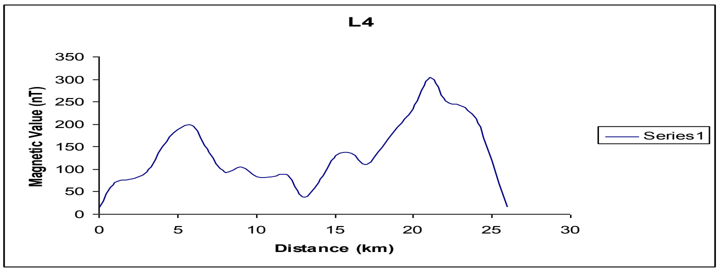
Analytic Signal Profile L1



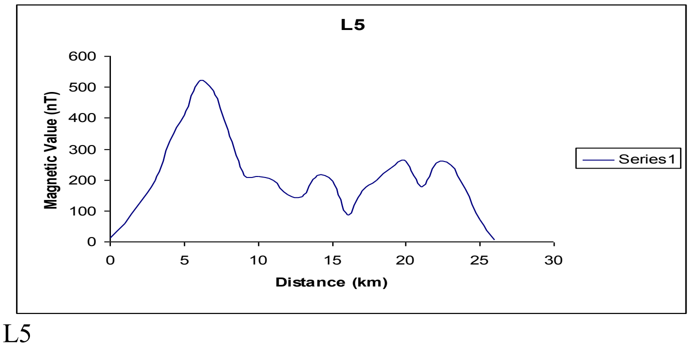
Analytic Signal Profile L2



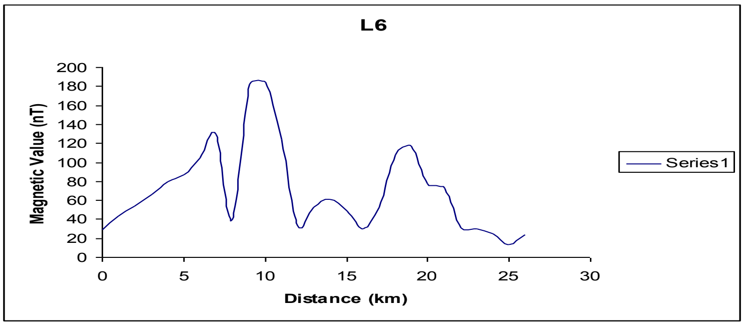
Analytic Signal Profile L3



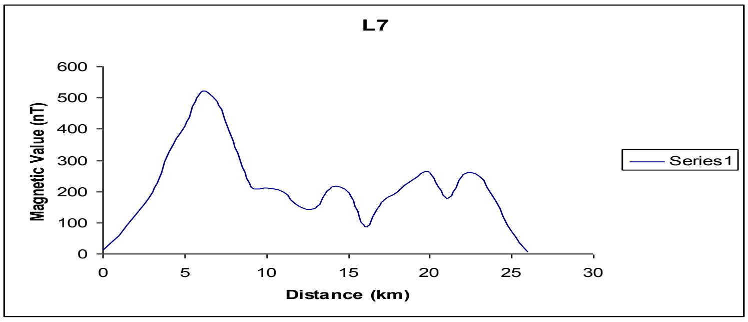
Analytic Signal Profile L4



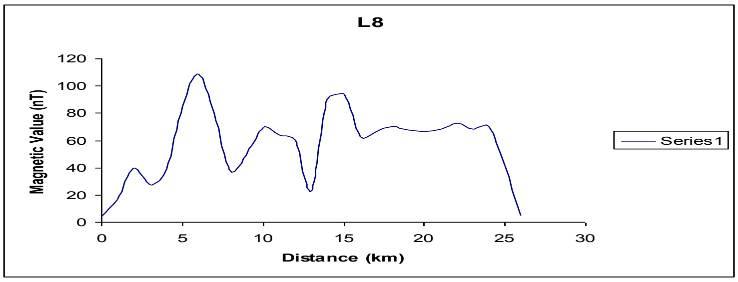
Analytic Signal Profile L5



Analytic Signal Profile L6



Analytic Signal Profile L7



Analytic Signal Profile L8

Fig. 6: Analytic Signal Profile L1 – L8

4.6.1.2 Depth Estimation

The depths for each anomaly on each profile were calculated and averaged to obtain a representative depth estimate for the profile. These representative depth estimates was again averaged to obtain a representative depth estimate for the study area.

The depth to the magnetic source(s) along the profiles in the study area was found to range between 0.50km to 10.50km, with an average depth of 2.67km for the entire study area which are in agreement with the results of similar previous works in and around the study area [24], [7], [27], [28], [29], [4 and [21].

The depth contour map (Fig. 7) showed that the depth is increasing towards the Western part of the map and decreases outwardly. Deep sources magnetic anomalies observed at the Western part of the study area ranges between 5km to 6.5km (blue colour). These zones could probably be related to the presence of a deep fault or an intra-crustal discontinuity in the area. These regions are recommended for further investigation especially for its geothermal and hydrocarbon potentials.

The intermediate depths between 3km and 4.5km (yellow) correspond generally to the top of intrusive masses occurring within the basement. A depth of this magnitude should also be investigated for possible hydrocarbon deposit, and these zones are observed in the north and trending towards the southern part the study area, it is also observed in the western part of the area. Depths between 1.5km to 3.0km (red) represent depths to the true basement surface. It appears to be the dominant depths in terms of spread in the study area, covering the entire northeast, southeast and east. These depths indicate clearly the magnitude of variations in depth of both the basement topograph and other intrusive in the area. These areas could also be investigated further for the major magnetic minerals like ironstone, sandstones, granite gneiss, magmatite, lead and so on. Additionally, the zone appears to be the store house for the concealed magnetic minerals.

The shallow depths between 0km to 1.5km (Pink) observed in the northwest trending to west and from northeast to east and the southwestern parts are probably attributed to shallow intrusive bodies or some near-surface basement rocks or shallow buried river channels.

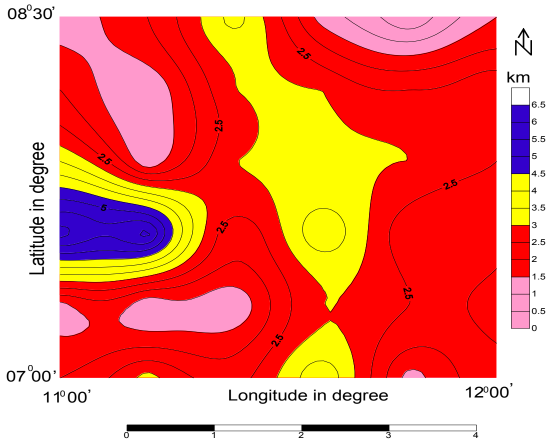


Fig. 7: Depth contour map showing basement topography of the study area

4.6.2 Horizontal Gradient Method Map

The horizontal Gradient Magnitude Method requires a transform of the magnetic anomaly map to a map with data reduced to the pole. Maxima in mapped enhancement indicate source edges. HG maxima were used to reveal the horizontal boundaries of the sources. Horizontal gradient method is a simple approach to locate linear structures such as contacts and faults from potential field data. The method is effective in detecting lineaments that may correspond to basement faults and contacts.

Fig. 8, show the contour map of the horizontal gradient magnitude ,the linear structures are indicative of faults and contacts and that the major trends of the faults are northeast- southwest (NE- SE), Eastnortheasr-westsouthwest (ENE- WSW) and wetnorthwest- eastsoutheast (WNW- ESE). Because HGM reduced to pole measures minimum depth, the near-surface structures are well revealed and that the suspicion of an outcrop or a concentration of nearsurface magnetic minerals in the eastern part of the study area almost certain with magnetic value ranging between 2000nT to 4500nT (green colour) . Just beside this is another observed deep fault or a fault of large area of extent whose value ranges between - 4500nT to -2000nT (dark brown colour). All these features are confirming the uplifted and the fracture nature of the study area.

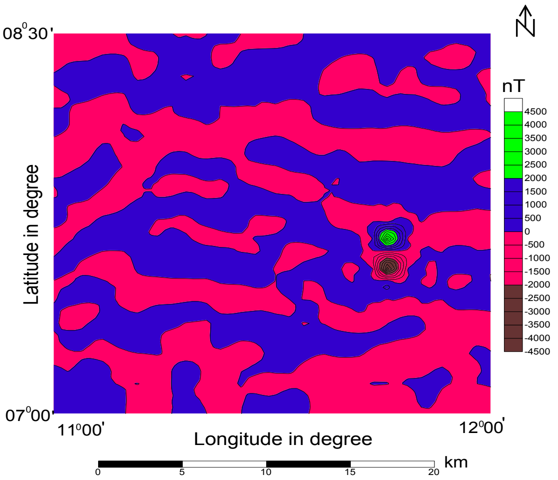
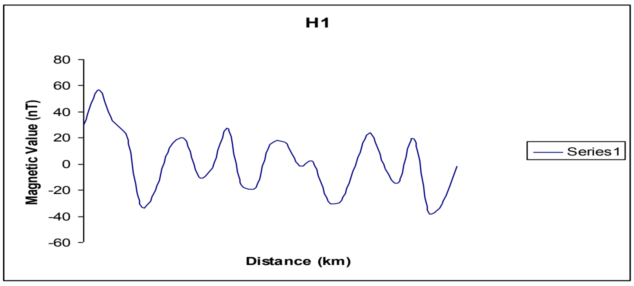


Fig. 8: Horizontal Gradient map of the study area

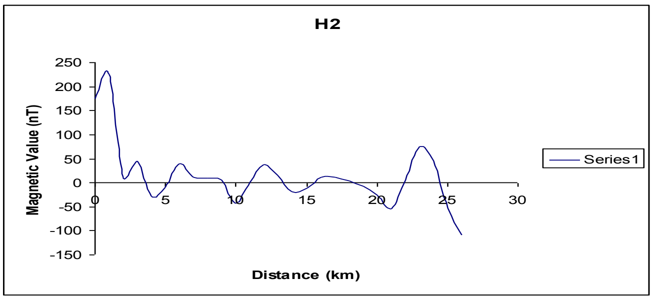
4.6.2.1Analysis of Horizontal Gradient Method (HGM) Profiling Map

Eight selected profiles believed to serve as the representative of the area were drawn across the study area. Maxima in mapped enhancement indicate source edges and this could be used to reveal the horizontal boundaries of the sources. Maximum values of the horizontal gradient are located near the vertical sides of a contact and it represents linear structures such as contacts and faults from potential field data [29].

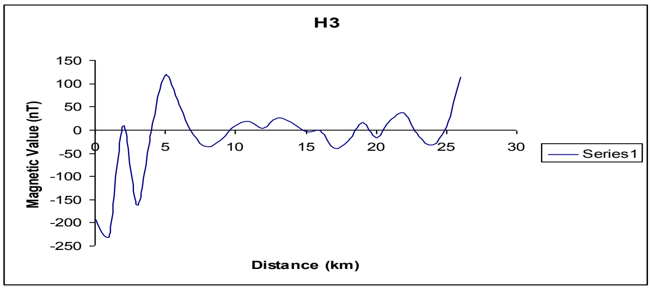
The distribution of maxima or maximum values along the horizontal profiling curves (Fig. 9: Horizontal Gradient Method Profile H1 – H8) reveals the distribution of suspected faults and contacts across the study area. The inflection points on H2 , H3 , H5 , H7 and H8 are clear evidence of presence of contacts within the area. The Peter's Half Slope method was again applied to determine the depth to the anomalous bodies. Depth values ranging between 0.01km to 2km were recorded. The depth estimates were used to generate depth contour map (Fig. 10), showing the basement topography for the horizontal gradient method. The method show a maximum depth in two locations in the north and the north central part of the study area, and a minimum depth in the south trending towards the west and the northeastern part of the study area



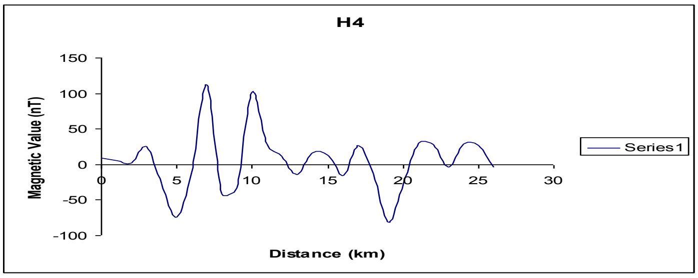
Horizontal Gradient Method Profile H1



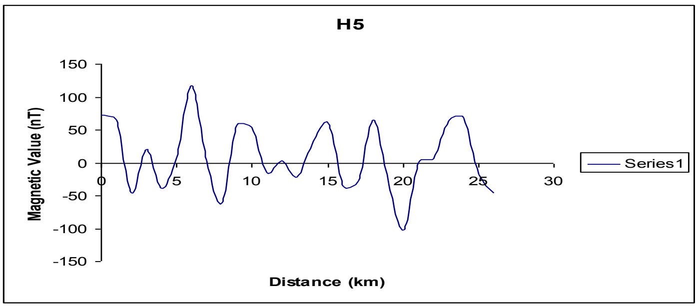
Horizontal Gradient Method Profile H2



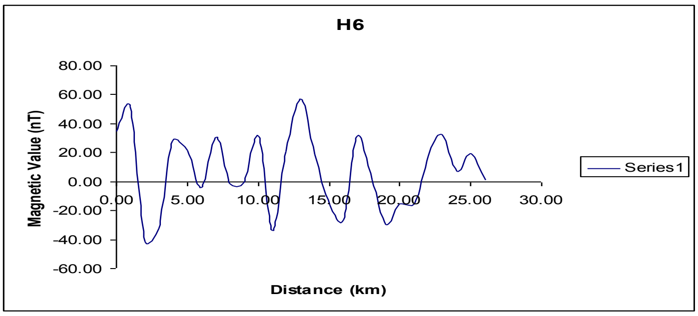
Horizontal Gradient Method Profile H3



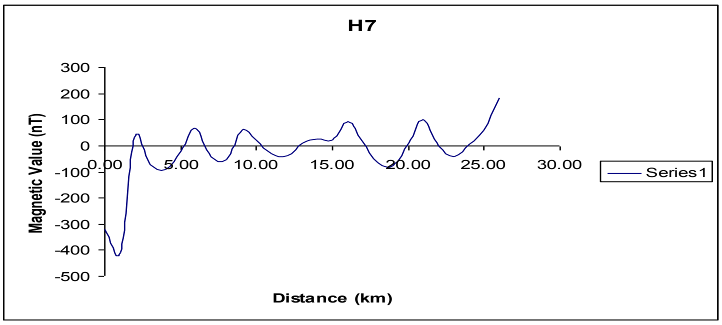
Horizontal Gradient Method Profile H4



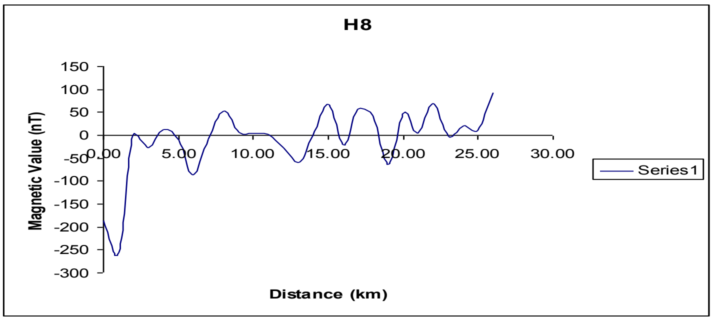
Horizontal Gradient Method Profile H5



Horizontal Gradient Method Profile H6



Horizontal Gradient Method Profile H7



Horizontal Gradient Method Profile H

Fig. 9: Horizontal Gradient Method Profile H1 – H8

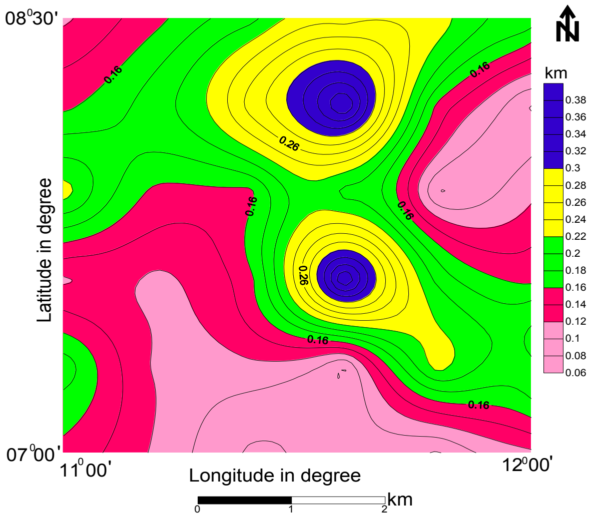


Fig. 10: Horizontal Gradient Depth contour map showing basement topography of the study area

4.6.3 Profiling and Depth Estimate of the Log Power Spectrum of the Study Area

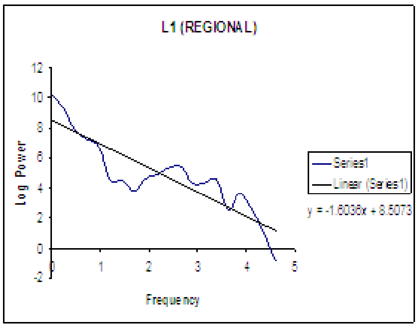
The data obtained from the digitized six aeromagnetic maps in the Upper Benue was again subjected to another filtering technique called Log Power Spectrum in an effort to separate the anomaly components into shallow and deep sources.

Depths to magnetic sources are associated with the negative slope of the plot of Log power against the frequency of the 2D anomaly curves (equations 11 and 12).

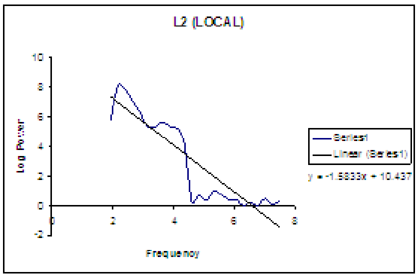
For each of the six aeromagnetic maps analyzed, depth estimates from Log power spectrum analysis of magnetic data of the study area indicate a two depth model.

For the eight selected profilings of the Log Power Spectrum for the study area (Fig. 11: Log Power Spectrum Profile L1-L8 (REGIONAL and LOCAL)), the depth to the magnetically deep sources ranges from 1.50km to 3.45km with an overall average depth of 1.62km whilst the depth to the shallow sources ranges from 0.21km to1.58km ,with overall average depth of 0.57km. The positive slopes observed on local portions of profiles L1, L2, and L7 are attributed to plume uprising still confirming the uplifted and rifted nature of the study area.

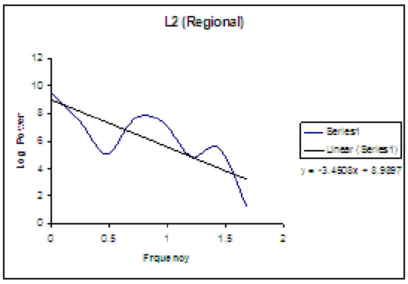
The deep (herein called the regional) sources depth estimates could be identified with basement, while the shallow (herein called the local) sources are attributed to near-surface intrusive and low – laying river valleys. Depth estimates with negative values are ascribed to plume uprisings in the area. The depth estimates so obtained are in agreement with those of previous researches over the upper Benue basin [24], [30]and[4].



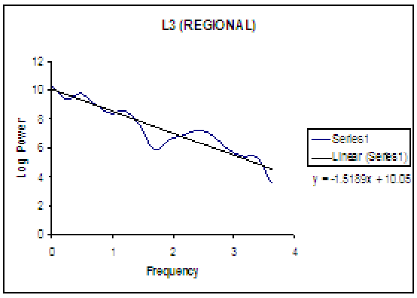
Log Power Spectrum Profile L1 (REGIONAL)



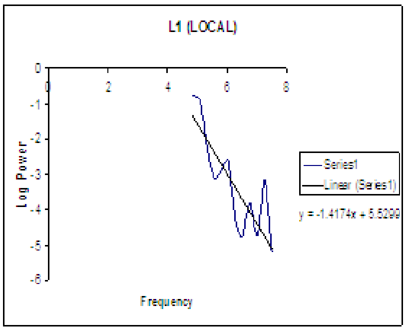
Log Power Spectrum Profile L2 (LOCAL)



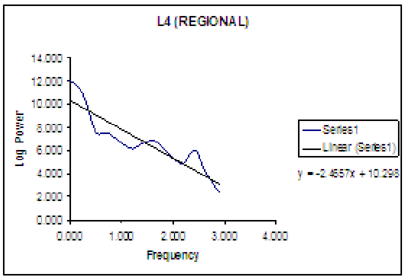
Log Power Spectrum Profile L2 (REGIONAL)



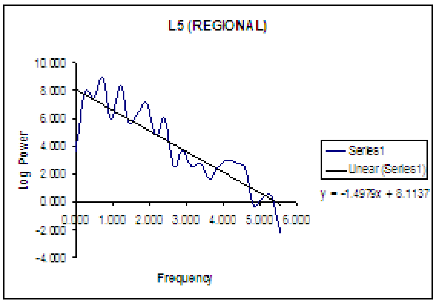
Log Power Spectrum Profile L3 (REGIONAL)



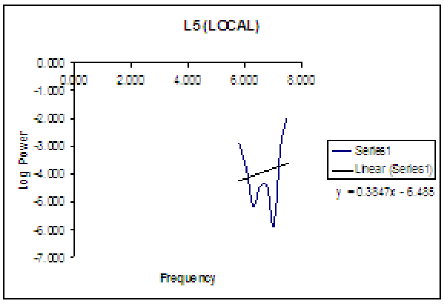
Log Power Spectrum Profile L1 (LOCAL)



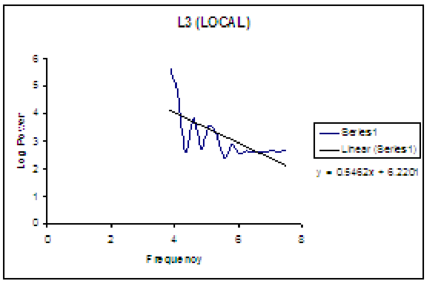
Log Power Spectrum Profile L4 (REGIONAL)



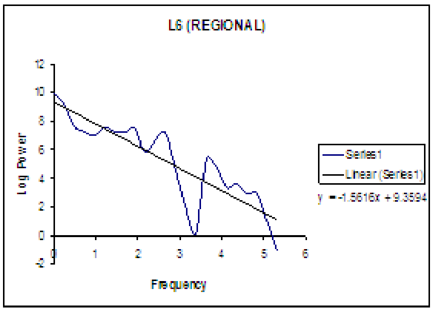
Log Power Spectrum Profile L5 (REGIONAL)



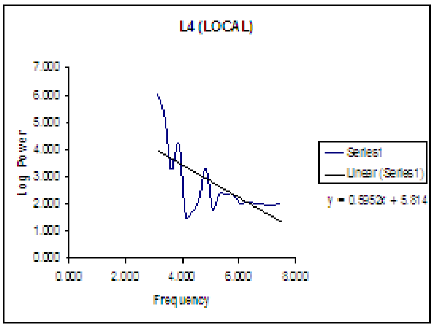
Log Power Spectrum Profile L5 (LOCAL)



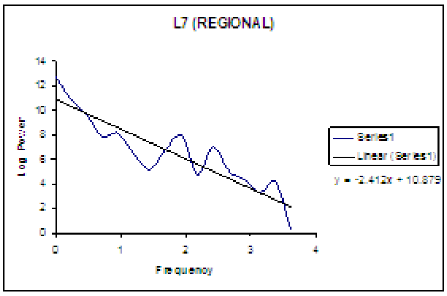
Log Power Spectrum Profile L3 (LOCAL)



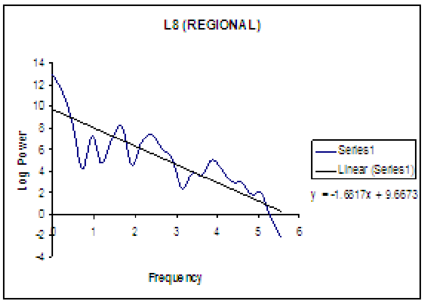
Log Power Spectrum Profile L6 (REGIONAL)



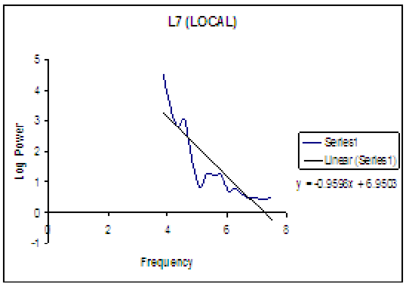
Log Power Spectrum Profile L4 (LOCAL)



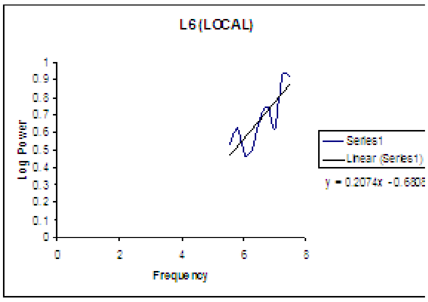
Log Power Spectrum Profile L7 (REGIONAL)



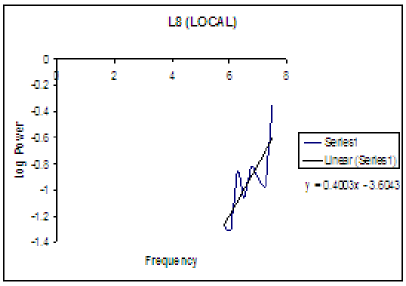
Log Power Spectrum Profile L8 (REGIONAL)



Log Power Spectrum Profile L7 (LOCAL)



Log Power Spectrum Profile L6 (LOCAL)



Log Power Spectrum profile L8 (LOCAL)

Fig. 11: Log Power Spectrum Profile L1-L8 (REGIONAL and LOCAL)

The depths computed were used to construct the contour map showing the basement topography of the study area (Figures 12 and 13). The map shows a gradual increase in the sedimentary thickness towards the north, 1.4km to 2.15km for the regional and okm to 1.7km for the local anomaly depth. For the deep sources (Regional, Figure 12), the results obtained indicate three depth sources. Those sediments whose depth ranges between 1.9km to 2.5km (red colour) are observed towards the northern part of the study area. The intermediate depth of values ranging between 1.65km to 1.9km (pink colour) are observed in the north and trending south and southeast. Sedimements whose depth ranges between 1.4km to 1.65km (dark brown) are observed in the northeast and running towards south and northeast trending towards the south.

The contour map for the local (shallow) (Figure 13) generally indicate depth sources with sediment thickness increase towards the north and a decrease towards the south. The increase in the sediment thickness towards the north of the study area should not be seen as a surprise as this is a region towards the Yola arm of Upper Benue and also towards the Chad Basin which has a reasonable sedimentary cover and thereby raising the hope of discovering hydrocarbon deposit in the area.

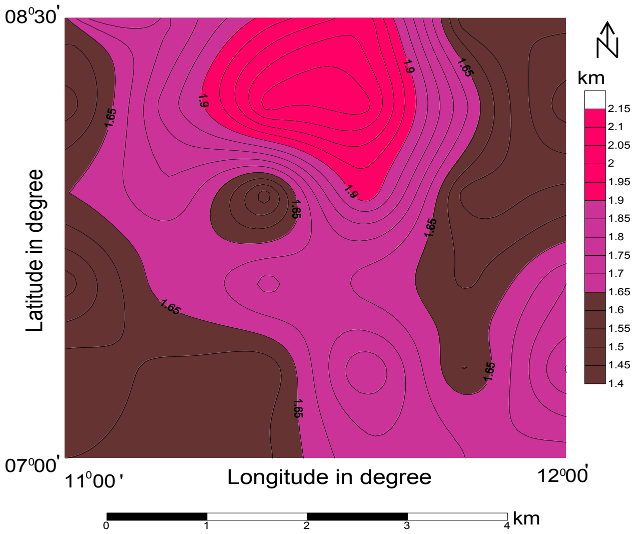


Fig. 12: Depth contour map from regional anomaly showing basement topography of the study area

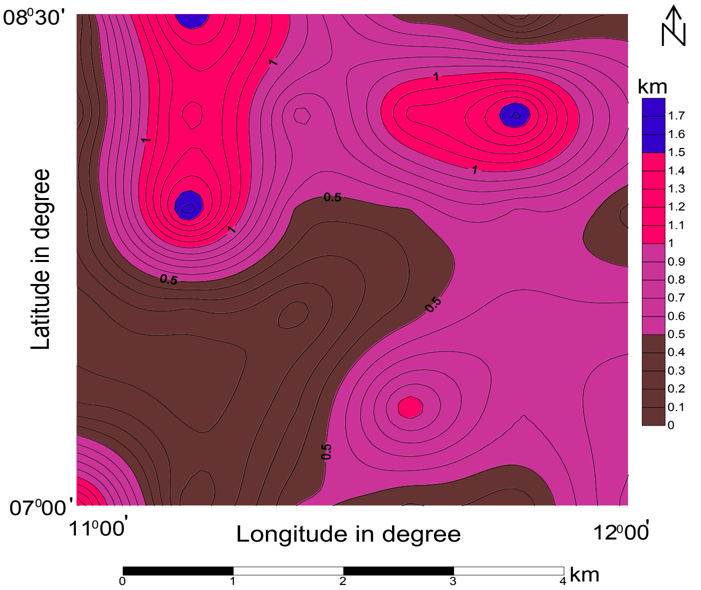


Fig. 13: Depth contour map from local anomaly showing basement topography of the Study area

V. Conclusion

Three analysis techniques were applied to airborne magnetic data from Upper Benue Basin to map the location and depth of the magnetic sources as an aid to structural interpretation.

Results from analytic signal technique showed that the basement in the study area is segmented by faults whose depth ranges between 0.5km and 10.5km with an overall average depth ranging between 1.13km to 5.88km, which represent the sedimentary cover within the study area. Horizontal gradient method showed network of faults and contact trending in the northeast- southwest (NE- SE), Eastnortheasr- westsouthwest (ENE- WSW) and westnorthwest- eastsoutheast (WNW- ESE), and depth values ranging between 0.01km to 2km were recorded. The estimated depths were contoured to portray the basement isobaths for the study area. Depth estimates from the Log power spectrum revealed two major grabbers or sub-basins with depth ranging between 1.22 and 3.45km for depth to magnetic basement while those ranging between 0.01km and 1.58km are identified with shallow sources which are suspected to be due to near-surface intrusive.

When the result of analytic signal was combined with that of power spectrum, one addition depth horizons is obtained at 6.5km and 10.5km. These depth sources have been ascribed to some deep intracrustal magnetic discontnuties which could be seen as an indicator to feature volcanic eruption in some part of the study area.

So, based on the results obtained, it was revealed that the study area is divided into three basinal structures; deep sources ranging between 6.5km and 10.5km. The intermediate depths between 3.5km to 5.5km correspond generally to the top of intrusive masses occurring within the basement, a depth deep enough for possible hydrocarbon deposit. Shallow depths between 0.01km and 2.5km are attributed to shallow intrusive bodies or near-surface basement rocks probably isolated bodies of ironstones formation concealed within the sedimentary pile.

The interpretation of the aeromagnetic data of the study area has equally revealed a complete architect of the basement rocks in the area. The study showed the area to be a fractured or rifted zone and rifting structures is often good sites for mineralization. The basin also revealed, great potentials for mineral deposit, which could serve as raw material(s) for many factories and industries and this has necessitated the siting of many factories and industries in and around the region. The presence of ironstones, sandstones, manganese, clay, bentonite, dolomite, iron ore, tin e.t.c. perhaps informed the siting of the Ajaokuta steel industry in Kogi state. The Uranium mineralization in the basin also prompt the Federal government to be proposing siting a nuclear power station in Borno state, to assist in improving and increasing electricity power generation. The presence of limestone and marble will definitely provide raw materials for building industry, mainly for cement purposes and for ornamental stones. Some resources like gravel, calcrete, laterite, grainedsandstones have also been tested for road stabilization purposes [26].

The detaic sandstone, coal and reasonable sedimentary thickness (3.5km-5.5km) across the study area called for further and comprehensive investigation for possible hydrocarbon deposit in the basin. These features that are considered favourable to hydrocarbon deposit has prompted the Federal Government of Nigeria to have committed heavy amount of money to oil prospecting in the basin, especially in the Yola arm of the basin [4], and this has started yielding positive results in many parts of Upper Benue and with the recent discovery of oil in Niger and Kwara states.

All the areas or zones whose estimated depths are as deep as 6km and above could be investigated for their geothermal potentials for possible establishment of geothermal power station(s) to boost our electricity generation and supply in the country. This is possible because magmatic heat could be used to derive hydrothermal system [20].

Also there are observed mantle plume uprisings as revealed by the three techniques of analysis employed, so there is the possibility of volcanic eruption in the area under investigation. The rise of mantle plume may lead to abnormal heat, resulting in melting of the upper mantle, thining and stretching the crust, followed by rifting of weakened crust [31]. This may have been repeated several times, with the Benue basin deformed between rifting episodes. When a magnetic intrusion is present in stable rock the difference in geophysical properties can cause localized stress concentrations particularly when the intrusion is weaker than the surrounding rock.

[31] also showed that inhomogeneities (magnetic) in the continental crust by this rock association can cause local stress in concentrations. Rock intrusions also in parts of the basin may have created enough local stress concentration to initiate volcanic eruption. The possibility of volcanic eruption in the region confirms the occurrence of volcanic eruption in Benue state on November 5th, 2010 and landslide that occurred in Anambra on July 19th, 2011.

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