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Depth Estimation from Aeromagnetic Data of Kam

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Abstract: *The Benue basin is a major geological formation underlying a large part of Nigeria, and also 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.*

In this work, the interpretation of the data extracted from the aeromagnetic map of Kam, an area in the upper Benue basin which covers from latitude $08^0 00' \, to \, 08^0 30' \; N$ *and longitude* $11^0 00' \, to \, 11^0 30' \; E$ *in the northeastern part of Nigeria was carried out using automated techniques involving the analytic signal 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 subsurface geology of the area which would in no doubt help in better understanding and characterization of the area investigated. The residual magnetic field data was subjected to two filtering techniques; the analytic signal which was employed to study source parameters which include location, depth and susceptibility contrast of the identified magnetic anomalies in the basement rocks, while the log power spectrum was used to further study the depth estimate to the magnetic basement.*

The results obtained from both profiling curves and depth contour map showed that the study area is magnetically heterogeneous and the basement is segmented by faults. Based on the results obtained from both profiling curves and depth contour maps, it was revealed that the study area is divided into three basinal structures; deep sources ranging between 5km and 8.5km and the area is recommended for further investigation especially for its geothermal energy potentials. The intermediate depths between 2km to 4.5km 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, Kam, Magnetic mineral, Rift valley, Upper Benue basin*

1. INTRODUCTION

The aeromagnetic geophysical method plays a distinguished role when compared with other geophysical methods in its rapid rate of coverage and low cost per unit area explored. The main purpose of magnetic survey is to detect rocks or minerals possessing unusual magnetic properties that reveal themselves by causing disturbances or anomalies in the intensity of the earth's magnetic field [1]. 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 [2, 3]. Aeromagnetic survey maps the variation of the geomagnetic field, which occurs due to the changes in the percentage of magnetite in the rock and reflects the variations in the distribution and type of magnetic minerals below the earth surface and measure variations in basement susceptibility. Local variations occur where the basement complex is close to the surface and where concentration of ferromagnetic minerals exists.

One of the key functions of aeromagnetic survey and interpretation is to quantitatively map the magnetic basement depth beneath sedimentary cover. Depth to source interpretation of magnetic field data provides important information on basin architecture for petroleum exploration and for mapping areas where basement is shallow enough for mineral exploration. All methods used to estimate depth to magnetic source benefit from discrete, isolated source bodies of appropriate shape and moderate to strong magnetization. The process of determining the location and depth of a source from gridded potential field data begins with the construction of a function from the data such that the function peaks over the source. Examples of such functions is the analytic signal amplitude (ASA)

The objective of most magnetic field survey is to produce images for qualitative geological interpretation and gridding is often optimized to reduce noise in the images of Total Magnetic Intensity (TMI) or its enhancement, such as the ASA. Image processing of the grids enhances details and provides maps that facilitate interpretation by even non-specialist. Aeromagnetic method being a faster economical and versatile geophysical tool may help reveal both large and small scale features, including differences in basement type, magnetic intrusion, volcanic rocks, basement surface and fault structures.

This research work wants to evaluate and determining the sedimentary thickness in the study area, depth to different magnetic source layers within the study area and the basement topography displaying the spatial variation in the sedimentary thickness within the study area. A digitized aeromagnetic data of Kam in part of upper Benue basin, as obtained by the Geological Survey of Nigeria Agency, Airborne geophysical series (1974) on a scale 0f 1:1000, 000 covering the study area were employed to determine the locations and depths using the ASA and Log Power Spectrum (LPS).

2. THE STUDY AREA, ITS EXTENT AND GEOLOGICAL SETTING

This study covers an area located in the north-eastern part of Nigeria (Fig.1) between latitude $08^0 00'$ to $08^0 30'$ N and longitude $11^0 00'$ and $11^0 30'$ E. It forms part of what is largely referred to as the Upper Benue basin which is considered to be a failed rift valley [4,5] , and so it is expected that the region should be a major depositional basin and therefore a good site for mineralisation.

The essential geological features in the basin 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 topography is believed to be irregular [6] is exposed in a number of locations in the region. Intruded into the basement are series of basic, intermediate and acid plutonic rocks referred to as the older Granites. Notable outcrops of the older Granites include 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 of the Younger Granites [7]. The cretaceous sediments in the area are believed to be compressionally folded in a non-orogenic shield environment [8] Wright, 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 [9, 10]. These faults show variable trends but the dominant direction lies between north-north-east and east-north-east.

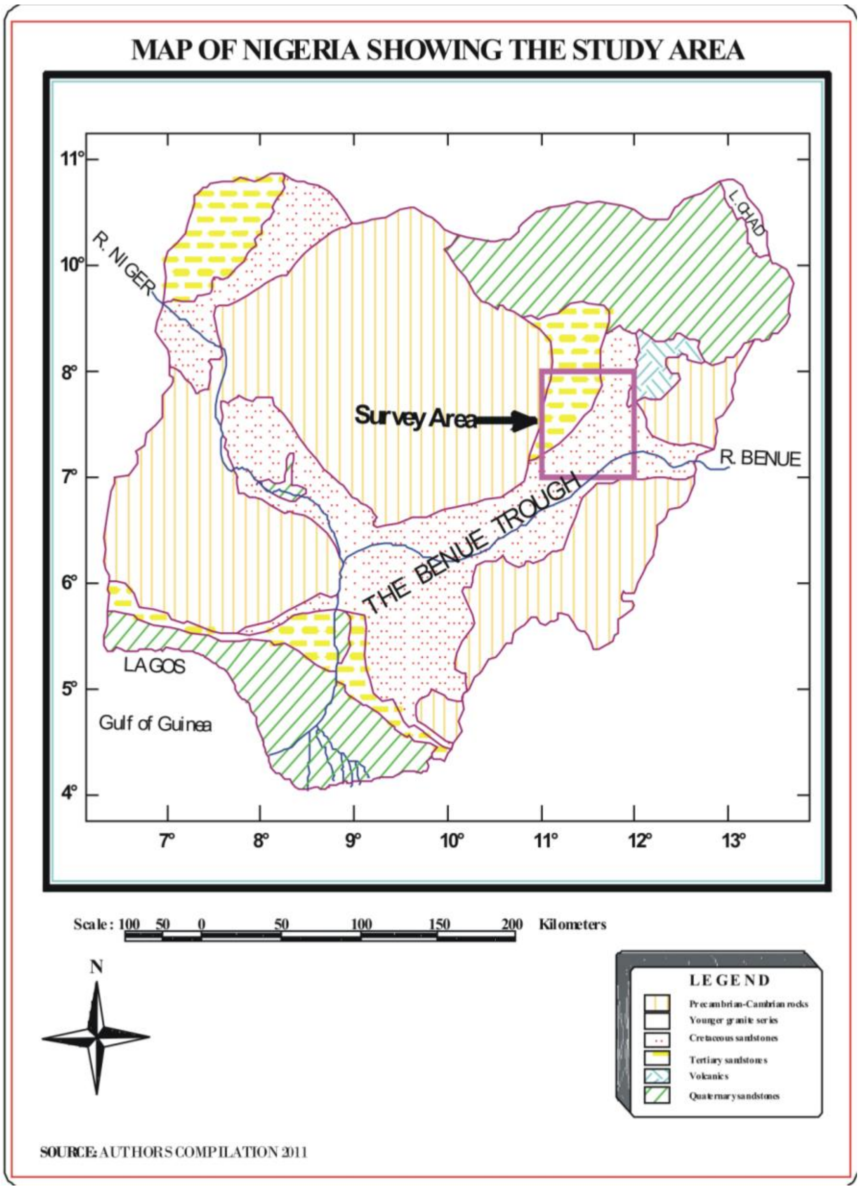

Fig1. *Geological map of Nigeria showing the study area*

3. MATERIALS AND METHODS

The primary data used for this analysis is the aeromagnetic map of Kam (sheet numbers 236), from part of the upper Benue basin, published by the Geological Survey of Nigeria Agency, Airborne geophysical series (1974) on a scale of 1:1000, 000.

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 map used is 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 map was based on International Geomagnetic Reference Field (I.G.R.F).

The map was carefully hand digitized into a 2km by 2km square matrix cell, given rise to a 27 by 27 square matrix, so 729 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 magnetic anomalies that are less than 4km in width may not be resolved with this digitizing interval. However,[5], consider this digitizing interval suitable for the portrayal and interpretation of magnetic anomalies arising from regional crustal structures. [7] 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 map were used in generating the total magnetic intensity map for (Kam) the study area using Surfer 8 computer software. 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 data for the study area. The residual anomaly data was later subjected to analytic signal and log power spectrum which are, filtering and enhancement techniques using Synproc (Signal Processing) software, these 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, and from which depth to magnetic basement were calculated using half-width of the amplitude method for ASA method while for the LPS, the depths were automatically generated for the quantitative interpretation.

3.1. Processing Methods

3.1.1. Analytic Signal Method

The analytic signal is formed through a combination of the horizontal and vertical gradients of a magnetic component. Analytic signal (AS) 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 [11].

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 [12] Nabighian, for 2D case, primarily as a tool to estimate depth and position of sources. More recently the method has been expanded to 3D problems [13] as a mapping and depth-to-source technique and as a way to learn about the nature of the causative magnetization.

The analytic signal of potential field data in 2- D could be written as,

$$A(x) = \varphi_x + i\varphi_z \tag{1}$$

where the 2-D analytic signal amplitude (ASA) of potential field is

$$|A(x)| = \sqrt{\varphi_x^2 + \varphi_z^2} \tag{2}$$

Roest et al. (1992) write the analytic signal in 3D as a vector encompassing the horizontal derivatives and their Hilbert transform and the 3D analytical amplitude of the potential field $\phi(x, y)$ measured on a horizontal plane as

$$|A(x, y)| = \sqrt{\varphi_x^2 + \varphi_y^2 + \varphi_z^2} \tag{3}$$

For the 3 D case, the analytic signal is written as

$$A(x, y, z) = \frac{\partial \Delta T}{\partial x} i + \frac{\partial \Delta T}{\partial y} j + i \frac{\partial \Delta T}{\partial z} k \tag{4}$$

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

$$|A(x, z)| = \sqrt{\left(\frac{\partial \Delta T}{\partial x}\right)^2 + \left(\frac{\partial \Delta T}{\partial y}\right)^2 + \left(\frac{\partial \Delta T}{\partial z}\right)^2} \tag{5}$$

The real and imaginary parts of the Fourier transform of equation (4) are the horizontal and vertical derivatives for ΔT, respectively.

The amplitudes of the analytic signal is simply related to amplitudes of magnetization which could be easily derived from the three orthogonal gradients of the total magnetic field using expression in equation (5). An important property of a 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 latitudes.

The analytic signal 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.

The analytical signal method is more sensitive to noise and aliasing in the data and the Peaks of the analytic signal amplitude are generally less enlongated and more circular. Depth information is limited to minimum and maximum values [14].

3.1.2. 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 [2]. In direct interpretation, the information such as the maximum depth at which the body could lie and depth estimates of the centre of the body is obtained directly from magnetic anomaly map. It is clear that infinite number of different configurations can result in identical magnetic anomalies at the surface and in general, magnetic modeling is ambiguous.

In indirect interpretation the simulation of the causative body of the magnetic anomaly is computed by simulation. The variables defining the shape, location, and magnetization etc. of the body are altered until the computed anomaly closely matches the observed anomaly. As it is well-known, potential fields obey Laplace’s equation which allows for the manipulation of the magnetic in the wavenumber domain. Many scientists have used the calculation of the power spectrum from Fourier coefficients to obtain the average depth to the disturbing surface or equivalently the average depth to the top of the disturbing body.

Here, 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;

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

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

$$A_k = \sum_{j=0}^{n-1} M(x_{j,} z)\, e^{-i2\pi k x_j} e^{\pm 2\pi k z} \tag{7}$$

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

$$(A_k)_0 = \sum_{j=0}^{n-1} M(x_j, 0)\, e^{-i2\pi k x_j} \tag{8}$$

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

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

Then the power spectrum P_k is defined as,

$$P_k = (A_k)^2 = (P_k)_0 \, e^{\pm 4\pi k z} \tag{10}$$

Taking logarithm of both sides,

$$\log_e P_k = \log_e (P_k)_0 \pm 4\pi k z \tag{11}$$

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 (3.31) as,

$$d = -\frac{\Delta P}{4\pi \Delta k} \tag{12}$$

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 $-\dfrac{\Delta P}{4\pi \Delta k}$ is the slope S of the plot, it then follows that;

$$d = -S \tag{13}$$

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, this is an important piece of information in the early phases of petroleum exploration. 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 [12].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.

[15], 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 [16, 2, 17, 18, 19].

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 [20]. A single power spectrum may yield up to five depth values [21], 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. [22] shows that this equivalent layer causes a magnetic field with the slope of its log power spectrum being proportional to the depth of the layer.

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. This implies that long-wavelength anomalies necessarily originate from deep-seated sources. However, a magnetic anomaly of large areal extent may also be due to a large, weakly magnetized shallow structure [23].

In within the profile, we find the same depth, but embedded in gneiss with rather high and variable susceptibilities. Thus two geological sections can be classified as, weak sources and strong sources in a variable magnetic matrix.

4. Result and Discussion

4.1. The Total Magnetic Intensity Map (TMI)

The 2D TMI map is as shown in Fig. 2. The analysis of the map shows the general magnetic susceptibility of basement rocks and the inherent variation in the basin under study. The map is presented as colour map for easy interpretation. The coloured maps aided the visibility of a wide range of anomalies in the magnetic maps and the ranges of their intensities were also shown. Areas of strong positive anomalies likely indicate a 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.

The magnetic anomaly of magnitude between 7800nT and 7900nT appears to be very dominant (Yellow colour). It is observed to be conspicuous in the west, northwest, southwest, south and northeastern parts of the study area. Closely followed by these in spread are those anomalies ranging between 7700nT and 7800nT in magnitude (green colour). These are only prominent at 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 7900nT and 8000nT (Deep blue 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 7600nT and 7700nT (Neon red colour) noticed in the southeast and northeast of the area.

Summarily, the 2D TMI map of Kam revealed that the area is magnetically heterogeneous. Areas of very strong magnetic values (7800nT to 8000nT) may likely contain outcrops of crystalline igneous or metamorphic rocks, deep seated volcanic rocks or even crustal boundaries. The areas between7600nT to 7700nT are suspected to contain near surface magnetic minerals like sandstones, ironstones, near-surface river channels and other near-surface intrusives.

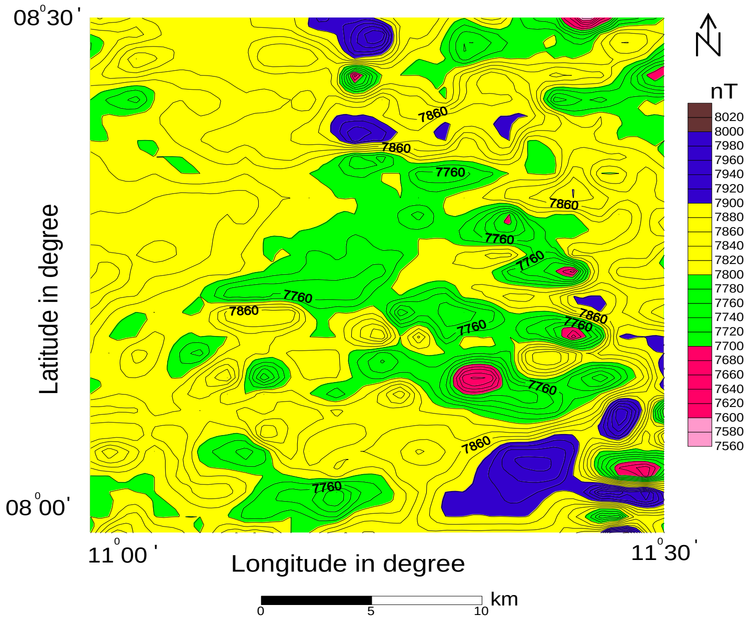

Fig2. *Total Magnetic Intensity map of Kam*

4.2. Discussion of 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 magnetic responses from 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 residual field produced by the target sources. Residual map have been used extensively to bring into focus local features which tend to be obscured by the broad features of the field. Discussed below are the features observed from the extracted residual map from the total intensity map generated.

The 2D residual map of kam (Fig. 3) revealed that local magnetic field variation whose magnitude varies between 0nT to 20nT (green colour) and those ranges between -30nT to 0nT (neon red) are very dominant in the study area and appeared to be well distributed almost in equal proportion throughout the entire study area. Residual anomalies with magnetic intensity ranging between -55nT to -30nT (pink colour) are observed at two places at the east and southeastern parts of the study area even though in small proportion. Equally, anomalies between 20nT to 35nT (yellow) are also observed in small proportions at north, northeast, east, and southeastern parts.

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 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 . These could also be associated with volcanic and ophiolitic rocks. Negative anomalies are associated with 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).

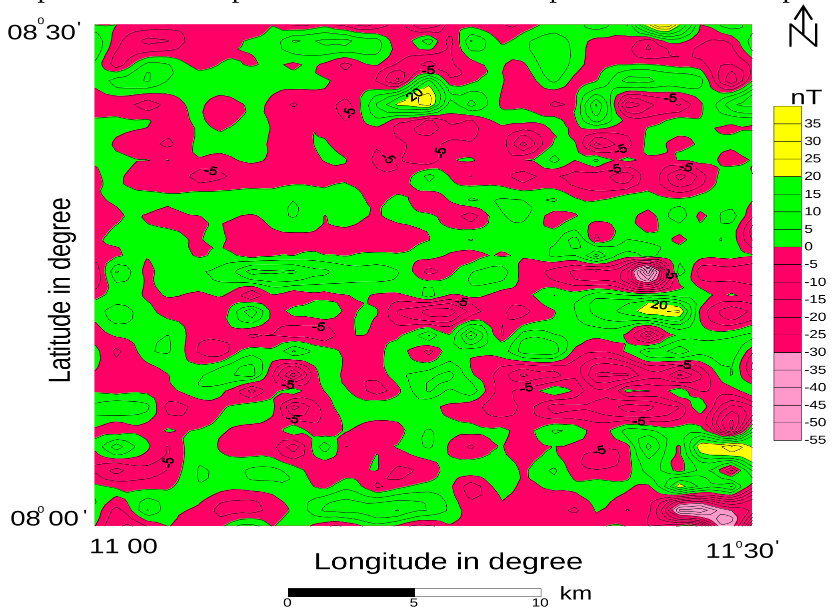

Fig3. *Residual map of Kam*

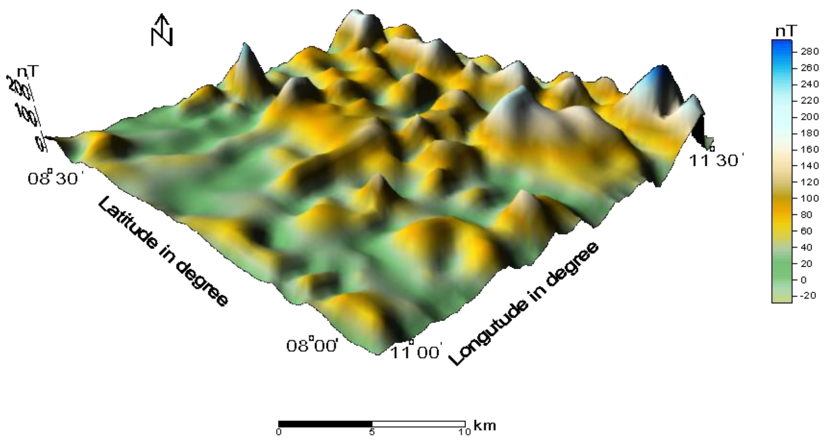

Fig4. *Surface plot of residual map of Kam*

4.3. Analytic Signal Contour 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 and such simplification is to derive or generate a map on which the amplitude of displayed function would be directly and simply related to a physical property of the underlying rocks [16]. An example of such map is the analytic signal map. With analytic signal method, it is now possible to isolate weak anomalies resulting from the subdued magnetic sources occurring within sedimentary strata. The analytic signal contour map (Fig. 5) allows us to identify and map near-surface magnetic minerals somewhat more readily.

The 2D analytic signal Map of Kam (Fig. 5) revealed near-surface anomalies whose magnitude ranges between 0nT and 80nT (neon red) being dominant in the area in terms of distribution. Those anomalies whose magnetization varies between 80nT and 140nT (green) are observed in the northwest, and north and southwest in scanty manner, but occupying a reasonable parts of the study area around northeast, southeast, and central parts. Another major observed anomalies ranging between 140nT and 220nT (yellow) are observed in the north, northeast and southeastern parts of the area. Observed at three different locations within the study area are anomalously high value magnetic anomalies that ranges between 220nT and 300nT (deep blue). The suspicion around these areas to be an outcrop is very high. Also in the south, and northern parts are observed low magnetic field variation – 40nT to 0nT (pink). These areas are suspected to be occupied by a deep-seated magnetic body, weak magnetic bodies or a magnetic body or large area of extent.

Generally, observed anomalies on the analytic signal maps are not entirely different from what was obtained from the residual map 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 study area which is part of Upper Benue and which affirmed the region to be a rifted zone coupled with the results of the analysis of data of the studied area 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.

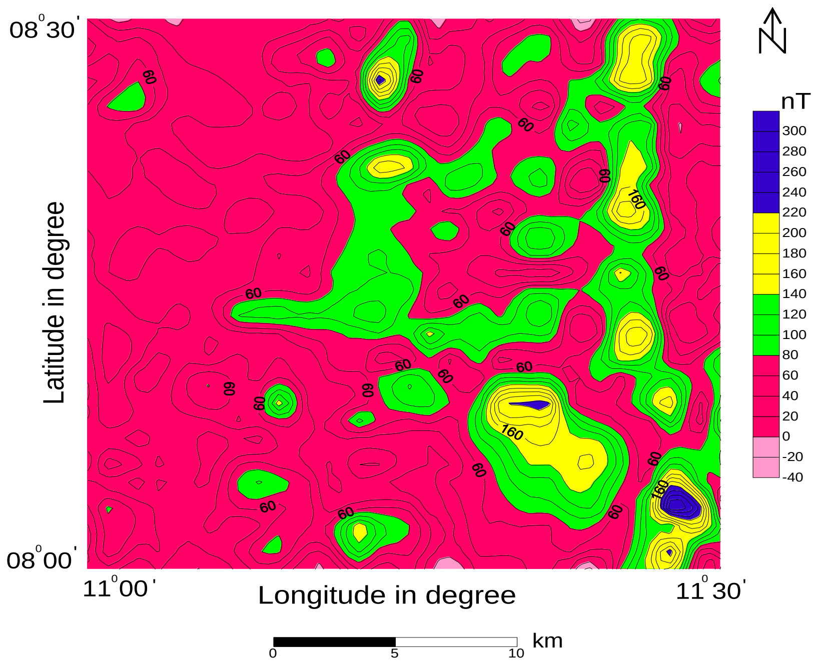

Fig5. *Analytic Signal map of Kam*

4.4. Depth Estimation from the Profilings of Analytic Signal (Quantitative Interpretation)

The analytic signal profiling shapes are used to determine the depth to the magnetic sources. The magnitude/ amplitude of the peak of the analytic signal signatures are believed to be proportional to the magnetization and that their maxima occur directly over faults and contacts. The 2-D profile analysis of the aeromagnetic data along the transverses suggests that the study area is composed of magnetic minerals in varying quantities and occurring at different depths along each profile as shown by the series of highs and lows. Depth estimates to tops of anomalous magnetic bodies are also generated from analytic signal method. 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.

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 0.75km to 6.25km, with an overall average depth of 2.19km for the entire study area which are in agreement with the results of similar previous works in and around the study area [24,5,25,26,17,2 and 10],

The summary of the depths distribution of magnetic minerals in the study area is as shown in Table 1 below

Table1. *Depth Estimates From Analytic Signal Profiles on Map Sheet 236 (Kam), Using Half-Width of the Amplitude Method*

Profile Number	Anomaly Depth Estimates (km)								Average Depth
0	2	1.25	6.25	3.5	2				3
1	3.25	1	6.25	1	1				2.5
2	2.25	1	2	3	3.25				2.3
3	4	3	4	3	3				3.4
4	1.25	2.5	2	3	2.5				2.25
5	2.5	2.75	2	2.5	3				2.55
6	1.25	3	4	1.5	1.75	2.25			2.29
7	1	2.5	1.75	1.5	2	1			1.63
8	1.75	1.25	1.75	1.25	1.5	1	1.25		1.39
9	3.25	2	2.25	1.5	2				2.2
10	2	1.75	5.75	1.75	1	2			2.38
11	2.25	1	1	1.5	1.5	2			1.58
12	2.5	1.25	3	2.25	1.75	2.5			2.21
13	2.25	2.25	1	1.5	1	2	2.25		1.75
14	2	1.5	1.25	1	1.25	1.5	2.5		1.57
15	1.75	2	2	1.25	2.25	2.75			2
16	1.75	3	3.25	4	1.25				2.65
17	3.75	2	2	1.25	1.75				2.15
18	5.5	2.5	1.75	2	2.75				2.9
19	5.5	2.5	1.75	2	2.75				2.9
20	5.75	1	1	2.5	3.75				2.8
21	5.25	2	1.75	1.25	2	1.25			2.25
22	2.75	2.25	1	4.75	3				2.46
23	1	1	1.75	1.75	0.75	0.75	0.75	1	1.09
24	1	2	2.5	1	1	1			1.42
25	2	2	1	1.75	3.5				2.05
26	1.5	1.5	1	1	1.5	3			1.58

Overall average= 59.25/27 = 2.19km

The depth contour map (Fig. 6) 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 (Deep blue), dark brown colour (6.5km to 8.0km) and those from 8km and above (ice 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 potentials.

The intermediate depths between 3.5km and 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 three locations of the study area, the west, southeast, and east-central parts. Depths between 2km to 3.5km (green) 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 and 2km (neon red) are probably attributed to shallow intrusive bodies or some near- surface basement rocks. These could also be due to shallow buried river channels. Lastly, a negative depth value of -1km to 0km (pink) is observed in the southwest and southeastern parts of the study area and this is most likely to be due to plume uprising during the volcanic activities in the region.

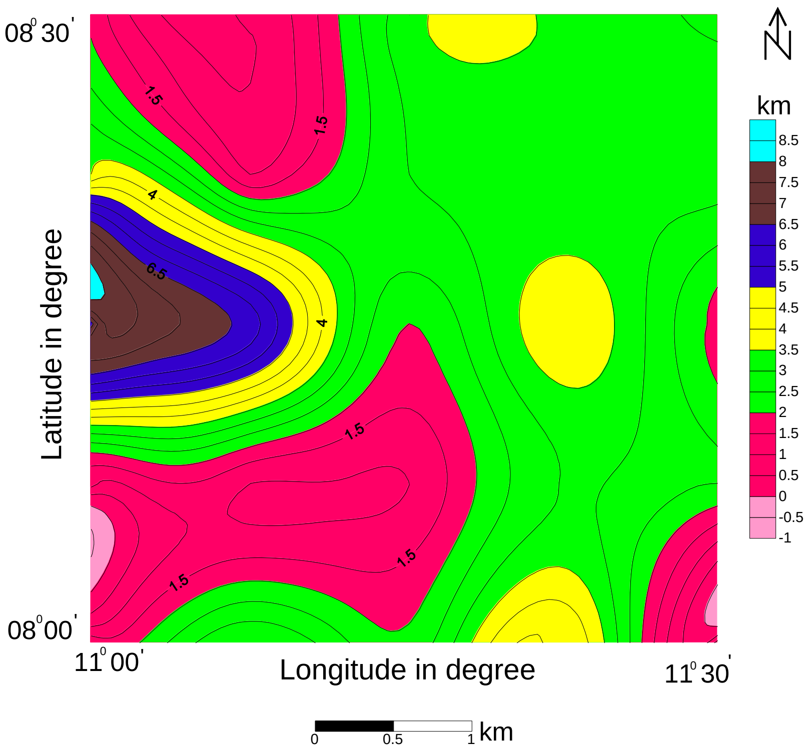

Fig6. *Contour map of the depth estimate of Kam*

4.5. Depth Estimation from the Profilings of Log Power Spectrum (Quantitative Interpretation)

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, this is an important piece of information in the early phases of petroleum exploration. 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 [12,28 and 2].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.

[15] attributed the slope of the logarithmic (log) power spectrum of aeromagnetic data to the depth of magnetic bodies/interfaces in the crust. This interpretation method of the log power spectrum is very convenient and enjoys continuing popularity as can be seen from a number of recent research works [19, 29].

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 region [20]. A single power spectrum may yield up to five depth values [21], which seems to indicate the existence of various horizontal magnetic interfaces in the crust. [22] shows that equivalent layer causes a magnetic field with the slope of its log power spectrum being proportional to the depth of the layer.

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. This implies that long-wavelength anomalies necessarily originate from deep-seated sources. However, a magnetic anomaly of large areal extent may also be due to a large, weakly magnetized shallow structure [23].

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.

The data obtained from the hand digitized aeromagnetic map of Kam in the Upper Benue was subjected to Log Power Spectrum a filtering technique using Synproc (computer software) 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 12 and 13).

For the aeromagnetic map analyzed (Kam), depth estimates from Log power spectrum indicate a two depth model of shallow and deep sources.

From the log power spectrum analysis, the depth to the magnetically deep sources ranges from 1.22km to 3.45km with an overall average depth of 1.62km whilst the depth to the shallow sources ranges from 0.01km to1.49km, with overall average depth of 0.57km. The positive slopes observed on local portions of profiles numbers 3, 7, 8, 17- 20 and 26 are attributed to plume uprising.

The summary of the depths distribution of magnetic minerals in the study area using log power spectrum is as shown in Table 2 below.

Table2. *Depth Estimates From the Slopes of Log Power Spectrum on Map Sheet 236 (Kam)*

Profile Number	Depth Estimate (km)	
	Regional	Local
0	-1.60	-1.42
1	-1.64	-0.22
2	-1.47	-0.02
3	-1.65	0.20
4	-1.52	-0.12
5	-1.64	-0.23
6	-3.45	-1.58
7	-1.25	0.02
8	-1.40	0.21
9	-1.22	-0.02
10	-1.45	-1.38
11	-1.72	-0.38
12	-1.63	-0.02
13	-1.50	-1.49
14	-1.63	-0.06
15	-1.71	-0.38
16	-2.32	-0.73

17	-1.62	0.57
18	-1.63	0.08
19	-1.75	0.75
20	-1.63	1.34
21	-1.48	-0.81
22	-1.16	-0.74
23	-1.22	-0.60
24	-1.85	-0.47
25	-0.97	-0.56
26	-1.59	0.05

Average depth = 43.81/27 Average depth=15.42/27

=1.62km =0.57km

The depths computed were used to construct the contour map showing the basement topography of the study area (Fig. 7 and 8). The map shows a gradual increase in the sedimentary thickness towards the north, 1.4km to 2.15km for the regional and 0 km to 1.7km for the local anomaly depth. For the deep sources (Regional, Fig. 7), 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) (Fig. 8) 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.

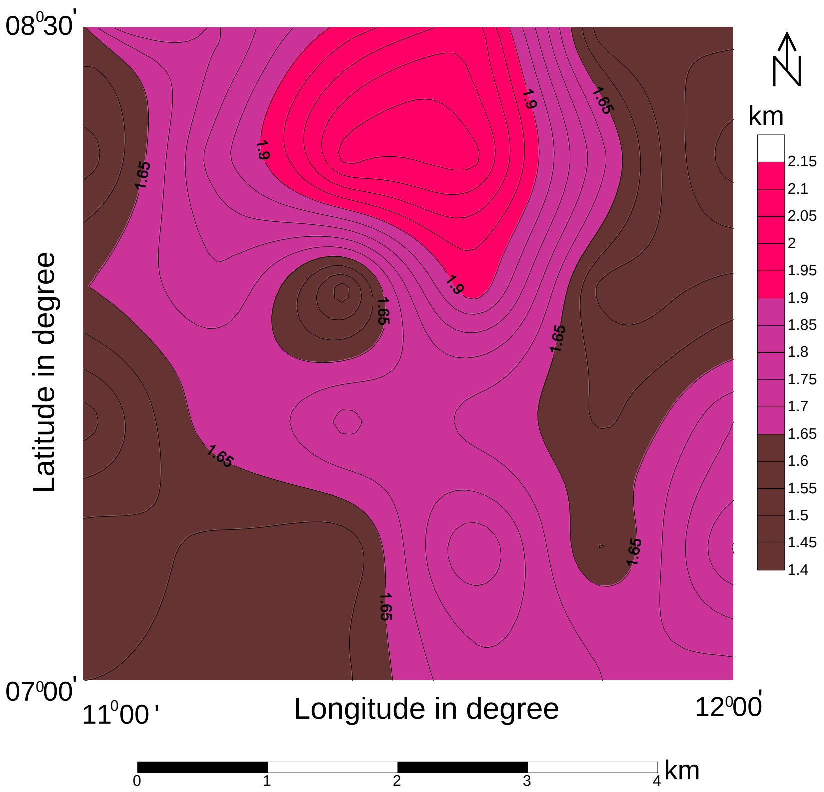

Fig7. *Depth contour map from regional anomaly showing basement topography of the study area*

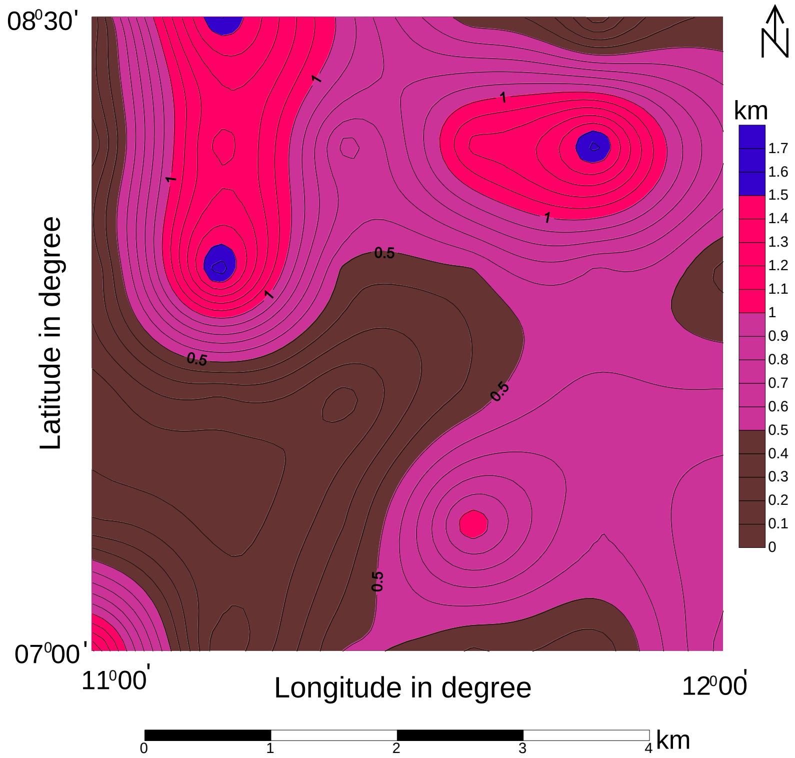

Fig8. *Depth contour map from local anomaly showing basement topography of the Study area*

Going by the results obtained so far from the two interpretation techniques employed, it is discovered that the analytic signal method is by far superior to the Log Power Spectrum. The analytic signal method is able to define very clearly and in a simple manner all the source parameters needed to properly analyze and interprete an aeromagnetic data. The technique is able to define the magnetization level(s), the area of extent and the depth to the anomalous bodies. The technique is also able to estimate deeper depths when compared with Log power Spectrum.

The only source parameter that is well-defined by Log Power Spectrum is the depth estimation. The analytic signal technique (profiling) is able to estimate magnetic variations point-by-point along a profile. It is also possible to observe anomalous bodies that are at the same depth levels but at different location along the same profile. The Log Power Spectrum takes average of all the depths along a profile and so does not give room for observation of distribution of depths at different points along a profile. But despite all these shortcomings, the technique is an excellent means in depth estimation in magnetic interpretation.

5. Conclusion

Airborne geophysical study is utilized to delineate the subsurface structure(s) which controls the anomalous mineralization zones of the study area. In this research work, aeromagnetic data is considered as the main source of information.

Two analysis techniques were applied to airborne magnetic data to map the location and depth of the magnetic sources as an aid to structural interpretation. These techniques are analytic signal and Log power spectrum techniques. The two techniques showed similar efficiency in depth determination. But the analytic signal techniques showed superior efficiency and accuracy over the Log power spectrum technique in that, it has proved to be an excellent and versatile tool in its ability to reveal the magnetization levels of various concealed magnetic bodies, the source locations, their estimated depths and other complex geological structures. Another advantage of analytic signal technique over power spectrum technique is that it allows a rapid evaluation without any assumption as to the geometry or magnetization of the structures.

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. Depth estimates from the Log power spectrum revealed two major grabbers or sub-basins with depth ranging between 1.22 and 4.45km for depth to magnetic basement while those ranging between 0.01km and 1.49km 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.

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