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Aeromagnetic and Radiometric (Thorium) Data Interpretation for Kimberlite pipe(s) occurrence in Malumfashi North-Central Nigeria

S. S. Fadeyi, C. Amos-Uhegbu and A. Adigun

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***Abstracts**: Aeromagnetic and radiometric (thorium Th) data over the Malumfashi area in the Katsina State, North Western Nigeria were analysed to validate the occurrence of suspected volcanic pipes that are associated with kimberlite pipe(s) within the area. The thorium (Th) data were subjected to qualitative interpretation while the magnetic data were qualitatively and quantitatively processed. The volcanic pipes and other linear features were mapped using the Horizontal Gradient Method, and the general trends for the lineaments were determined to be in the Northeast-Southwest (NE-SW) and Northwest-Southeast (NW-SE) direction. The spectral analysis of the magnetic data was used to derive the depth of the magnetic sources. However, the deep magnetic sources were found to range from 0.08 to 0.45 km, while the depth for the shallow magnetic sources ranged from 0.05 to 0.09 km. The circular, semi-circular and elongate structures delineated were deduced to be associated with the kimberlite pipes and/or volcanic intrusions that are possible diamondiferous. The expressions occur as surface and near surface features.*

Keywords: *Aeromagnetic Data, Radiometric, Kimberlite Pipe, Thorium Concentration*

S. S. Fadeyi
Geo-cardinal Engineering Services Limited
Email:
Orcid id

C. Amos-Uhegbu
Michael Okpara University of Agriculture Umudike
Email: fzinoz@gmail.com

A. Adigun
FEMAK Industries Nigeria limited

1.0 Introduction

In the early fifties, , geophysical applications in kimberlite exploration were not widely accepted and utilized because the exploration of diamond was not fully defined by geologists. However, in the last few years, the application of kimberlite exploration for diamond has witnessed several progressive changes. Consequently, several companies are employing the exploration method and are currently undergoing improvements worldwide (McKinlay, 1997).

Since the 1950s, airborne magnetic surveying has been among the most commonly used kimberlite exploration methods (Atkinson, 1989). More rarely, airborne electromagnetic techniques (Urquhart and Hopkins, 1993) have been successfully used in the Northwest Territories (St. Pierre, 1999). The combination of aeromagnetic surveying and radiometric surveying techniques is believed to make it possible to identify more kimberlite pipes than magnetic surveying alone, Kimberlites have generally higher magnetic susceptibility than surrounding gneisses and granites and are additionally prone to retain remnant magnetism. As a consequence, magnetic anomalies are commonly associated with kimberlite intrusions although the association can be subtle. Successful applications of the magnetic method require an in-depth understanding of its basic principles and careful data collection, reduction and interpretation. Interpretation may be limited to qualitative approaches which simply map the spatial location of anomalous subsurface conditions, but under favourable circumstances, the technological status of the method will permit more quantitative interpretations involving specification of the nature of the anomalous sources. No other geophysical methods provide critical input to such a wide variety of problems. Kimberlites (the host rock for diamonds) are explored successfully using high-resolution aeromagnetic surveys (positive or negative anomalies, depending on magnetization contrasts) (Power *et al*., 2004).

A radiometric survey is ideal for geological investigation, this is because it has regional coverage, in appropriate areas, when used as a reconnaissance technique for mapping geology and prospecting, the cost/benefit ratio for airborne radiometric surveying is nearly as good as that for airborne magnetometer surveying.

The application of radioactivity in geoscience is based on knowledge of the physical properties of radiation sources, and the ability to detect these sources through the analysis of remotely sensed data. Radiometric surveys detect and map natural radiometric emanations, call gamma rays, from rocks and soils. At least 20 naturally occurring elements are known to be radioactive (Telford *et al*., 1990). All detectable gamma radiation from earth materials comes from the natural decay products of only three elements, i.e. uranium, thorium, and potassium. While many naturally occurring elements have radioactive isotopes, only potassium, uranium and thorium decay series, have radioisotopes that produce gamma rays of sufficient energy and intensity to be measured by gamma ray spectrometry. This is because they are relatively abundant in the natural environment. Average crustal abundances of these elements quoted in the literature are in the range 2-2.5% of K, 2-3 ppm of U and 8-12 ppm of Th. The basic purpose of radiometric surveys is to determine either the absolute or relative amounts of U, Th., and K in the surface rocks and soils.

1.1 Study location

The study location was the Malumfashi area of Katsina State. It lies in the Northern region of the country Nigeria (Fig. 1). The data area lies between latitudes $11^{o}30^{1}$ and $12^{o}00^{1}$ N and longitudes $7^{o}30^{1}$ and $8^{o}00^{1}$ E.

1.2 The geology of the study area

The study area is the Malumfashi area of Katsina state according to the geologic map of the area (MalumFashi Sheet 79), the Malumfashi area (Fig. 2) is a part of the Nigeria basement complex region and the rocks present there can be grouped to be under this basement categories, these categories are the Older Granites, the Migmatites and the Schists. The volcanic pipe we are analyzing is said to occur as an intrusion within the medium grained slightly foliated pink-grey basement – granite gneiss, the various individual occurring rock types include the different varieties of granites and granite related rocks are such as the porphyroblastic hornblende granite, fine medium grained biotite granite and granodiorite, porphyroblastic biotite granite, fine medium grained biotite granite and granodiorite, and also the metamorphosed sediments or metasediments such as the carbonaceous schist, the semipelitic schist and phyllite, metasiltstone the third main rock types under the older granite present in this region are found in association these are the feldspathoid granite biotite granite gneiss, migmatites and subordinate gneiss.

According to the location of the suspected kimberlite pipe, it is seen that the Kimberlite pipe (Fig. 3) intrudes into the medium grained, slightly foliated, pink-grey basement – granite gneiss in the Malumfashi area of Katsina state, from an exploration point of view, the most important indicator minerals are garnet, chromite, ilmenite, Cr-diopside and olivine. Several of these minerals display diagnostic visual and compositional characteristics, making them ideal pathfinders for kimberlite.

Structural geology is concerned with the study of deformation at a small scale, from submicroscopic (for instance, deformation that occurs in minerals and rocks) to regional (for instance, deformation in small local areas). In the upper part of the lithosphere, close to the surface, or relatively low temperatures and pressures, and at a high intensity of applied forces or a rapidly imposed deformation, rocks break through fracturing (I,e brittle deformation). The existent of fractures implies that the layers of rocks have lost cohesion that enhances the separation of atoms and consequent breakage. A simple fracture is defined when the two sides of the fracture fail to slide with respect to one another but the reverse defines a fault.

Fig.1: Map of the Northern Part of Nigeria Showing the Study Area (Google Images, 2016)

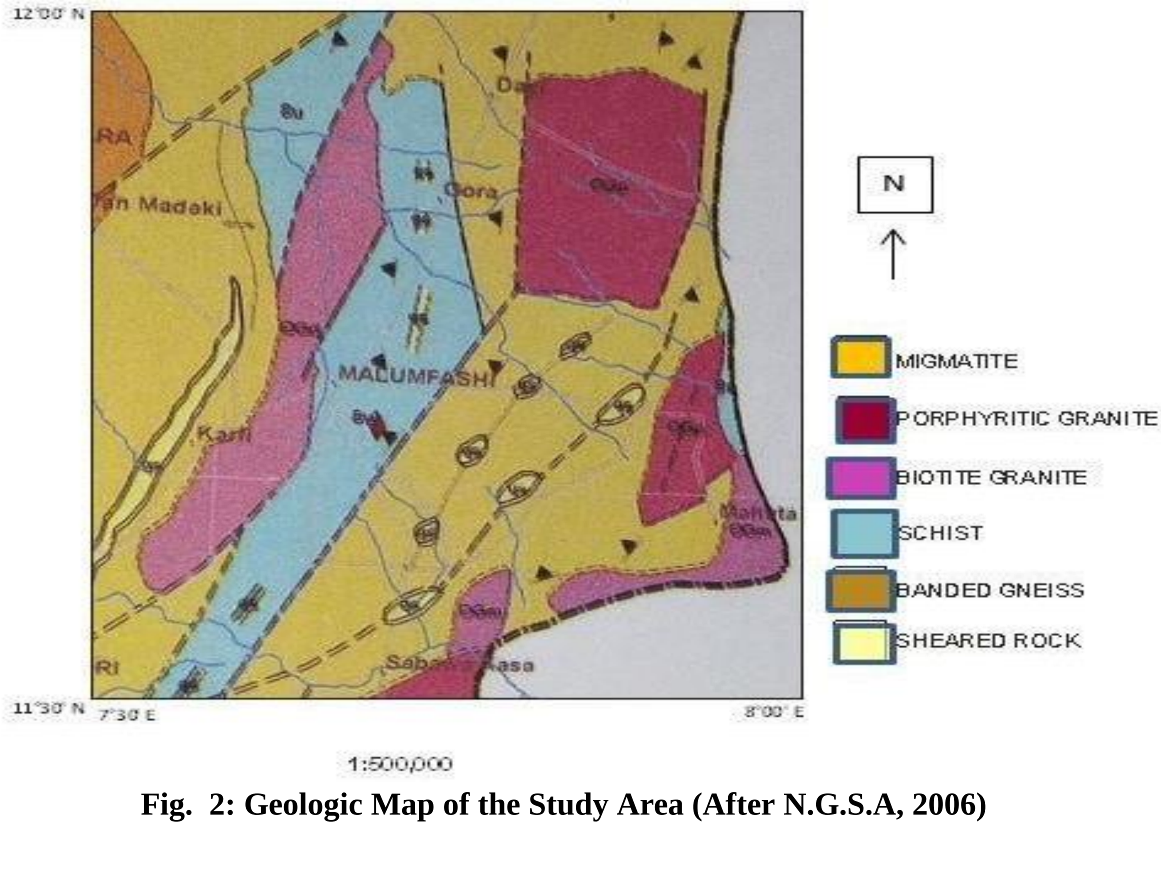

Fig. 2: Geologic Map of the Study Area (After N.G.S.A, 2006)

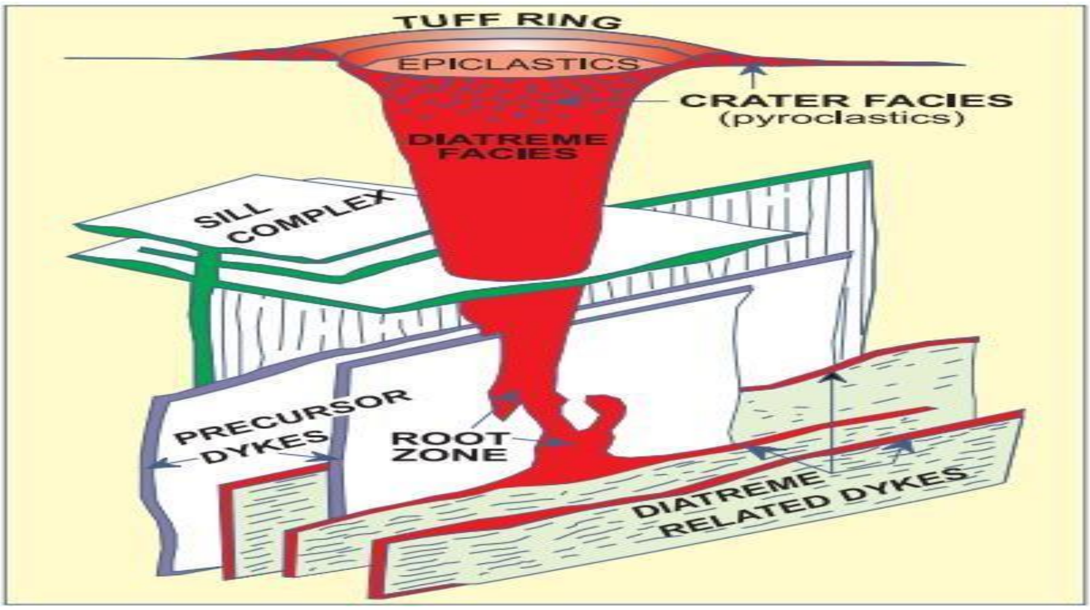

Fig. 3: Schematic Block Diagram Illustrating Principal Intrusive and Extrusive Elements of Kimberlites (after Mitchell, 1986).

2.0 Materials and Methodology

2.1 Basic theory

All substances are magnetic at an atomic scale. The phenomenon in which a material acquires a magnetization when placed within a magnetic field but loses it when it is removed from the field is termed induced magnetization or magnetic polarization. Magnetic polarization is caused by the alignment of the elementary dipoles within the material that is parallel to the direction of the external field but of opposite polarity. The intensity of induced magnetization, ***I*** is proportional to the strength of the external field, **H** (Telford, 1980))

$$\boldsymbol{I} = \chi \mathbf{H} \quad (1)$$

where χ is a dimensionless proportionality constant for the particular magnetic material and is termed susceptibility. Based on materials (and the associated value of magnetic susceptibility) on approach to an external field, three types of magnetic materials can be identified. Diamagnetic materials have low and negative χ, paramagnetic materials have low and positive χ while ferromagnetic materials have high and positive χ. z

2.2 Data acquisition

The aeromagnetic data were obtained as part of a nationwide aeromagnetic survey sponsored by the Nigeria Geologic Survey Agency (NGSA). The survey was carried out along a series of NNW-SSE profiles with a spacing of 500 m and 80 m mean terrain clearance. (Reford *et al* 2010).

2.3 Spectral analysis

Spectral analysis is a quantitative method, based on the properties of the energy spectrum of large and complex aeromagnetic or gravity data sets. It uses the 2-D Fast Fourier Transform and transforms magnetic or gravity data from the space domain to the frequency domain. It makes the consideration of the average depth of the distribution bodies for the anomalies.

This method has been employed by several other researchers (Njandjock *et al*., 2006) for the estimation of average depths of the magnetic or gravimetric sources bodies. Pal *et al*., (1978) evoke that Fourier transformation of the gravimetric and magnetic anomalies from space to the frequential field can lead to the production of a correct method for the estimation of the source depth, especially those sources that have weak components of frequencies of the anomaly.

The transformation of the power spectrum function involves a mathematically the technique that employed Fourier and the logarithm of the power contained in each frequency of the field that is created by the sources at distance h, such that it decreases linearly with increasing frequency within discrete segments of the spectrum (Tadjou *et al*., 2009). Consequently, the depth h of the roof of the body can be estimated using the following equation

$$h = \frac{\Delta \log(E)}{4(f)} \quad (2)$$

where $(f) = e^{-2hf} = |F(f)|^2$ is the energy spectrum (the square of the Fourier amplitude spectrum) and $\Delta \log(E)$ is the variation of the logarithm of the power spectrum in the 5interval of frequency Δ(f).

The energy spectrum generally has two sources. The deeper source is manifested in the smaller wavenumber end of the spectrum, while the shallower ensemble manifests itself in the larger wavenumber end. The tail of the spectrum is a consequence of high wavenumber noise (Tadjou *et al*., 2009).

For this study, depth to the top of magnetic anomaly only was acquired because this study focuses on the depth to the surface estimation of the supposedly volcanic pipe suspected to be in the region. The map was broken into 25 overlapping spectral blocks of 18.5km^2 each to acquire more data points (Fig. 5).

The results obtained from the processing are presented in form of maps, profiles and tabular form Also, the result obtained through the application of filters (such as the RTE, upward continuation and regional-residual separation) isis presented as contour maps; while the HGM isis presented as a lineament map and rose diagram.

The spectral decomposition technique results are shown as a plots of profiles – log (power) against wavenumber (For example, Fig. 6).

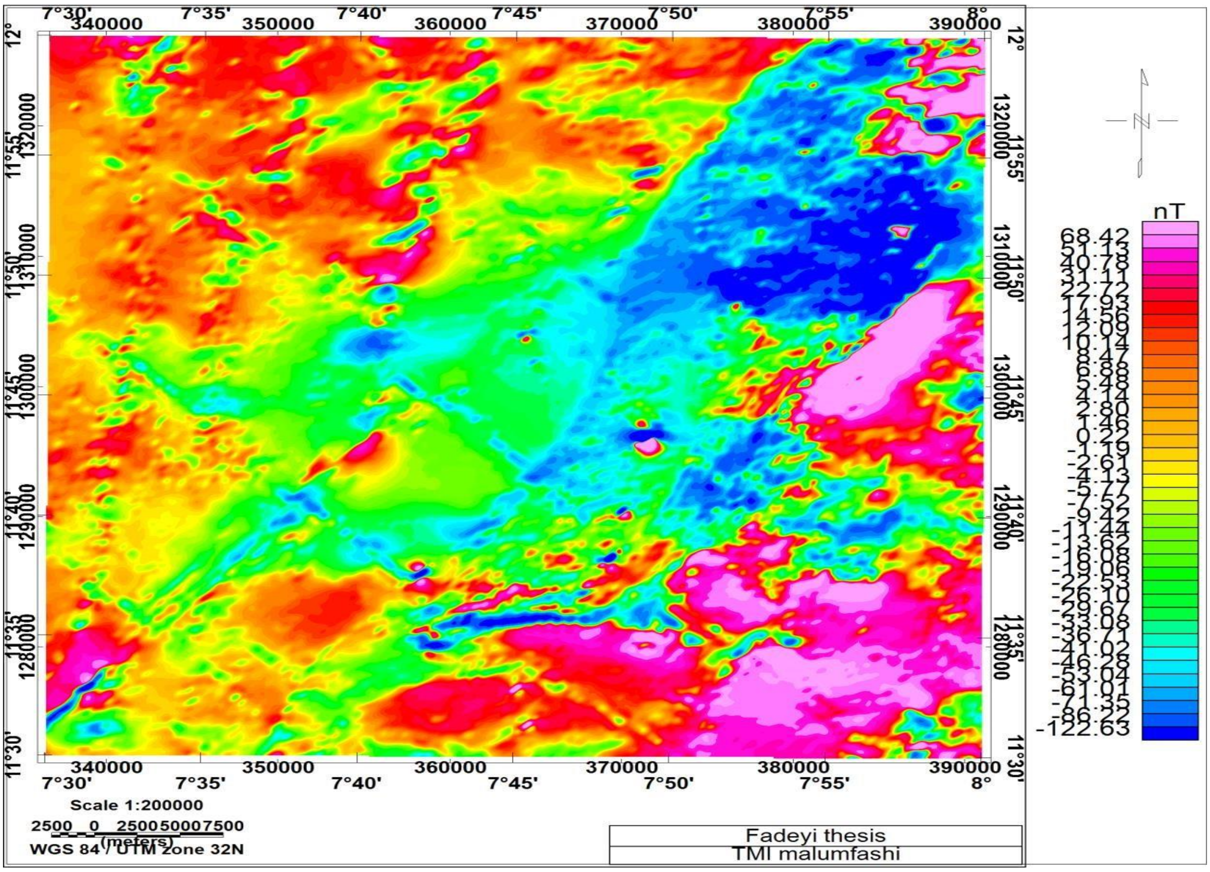

Fig. 4: The Raw Aeromagnetic Total Magnetic Intensity (TMI) Map of the Study Area. Reduction to Magnetic Equator (RTE), Upward Continuation, and Horizontal Gradient Method is qualitative analysis methods used in this research.

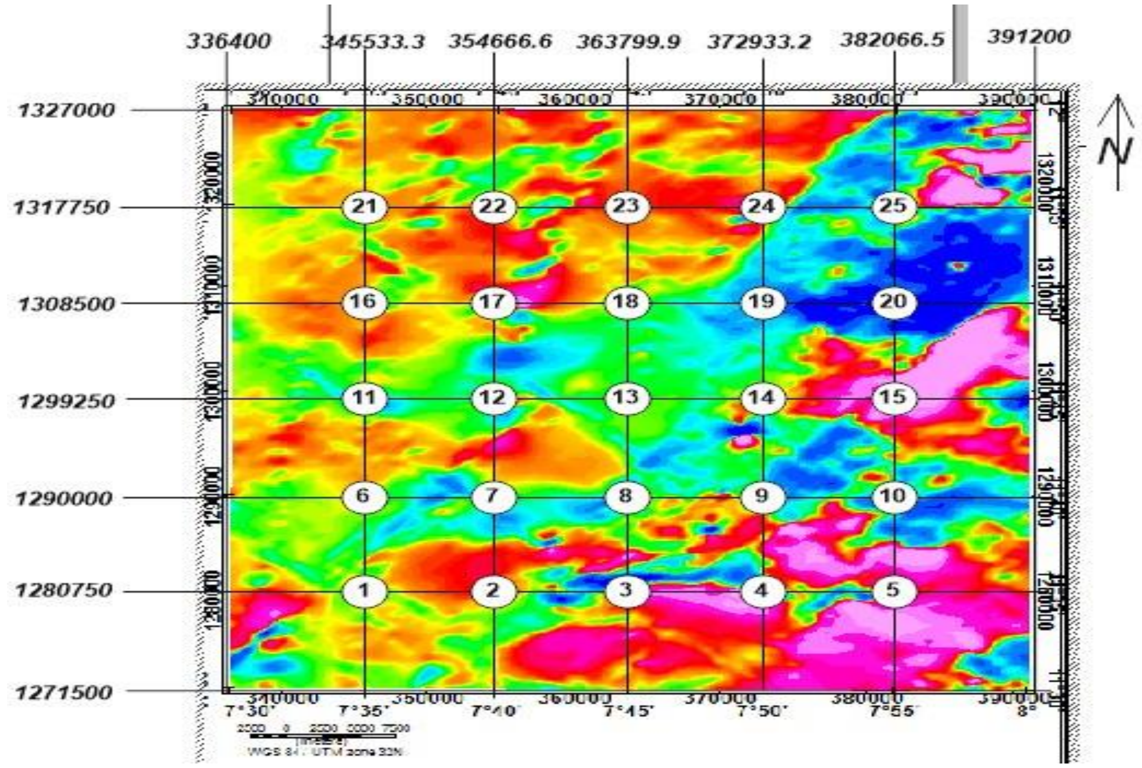

Fig. 5: Spectral Blocks over the Study Area

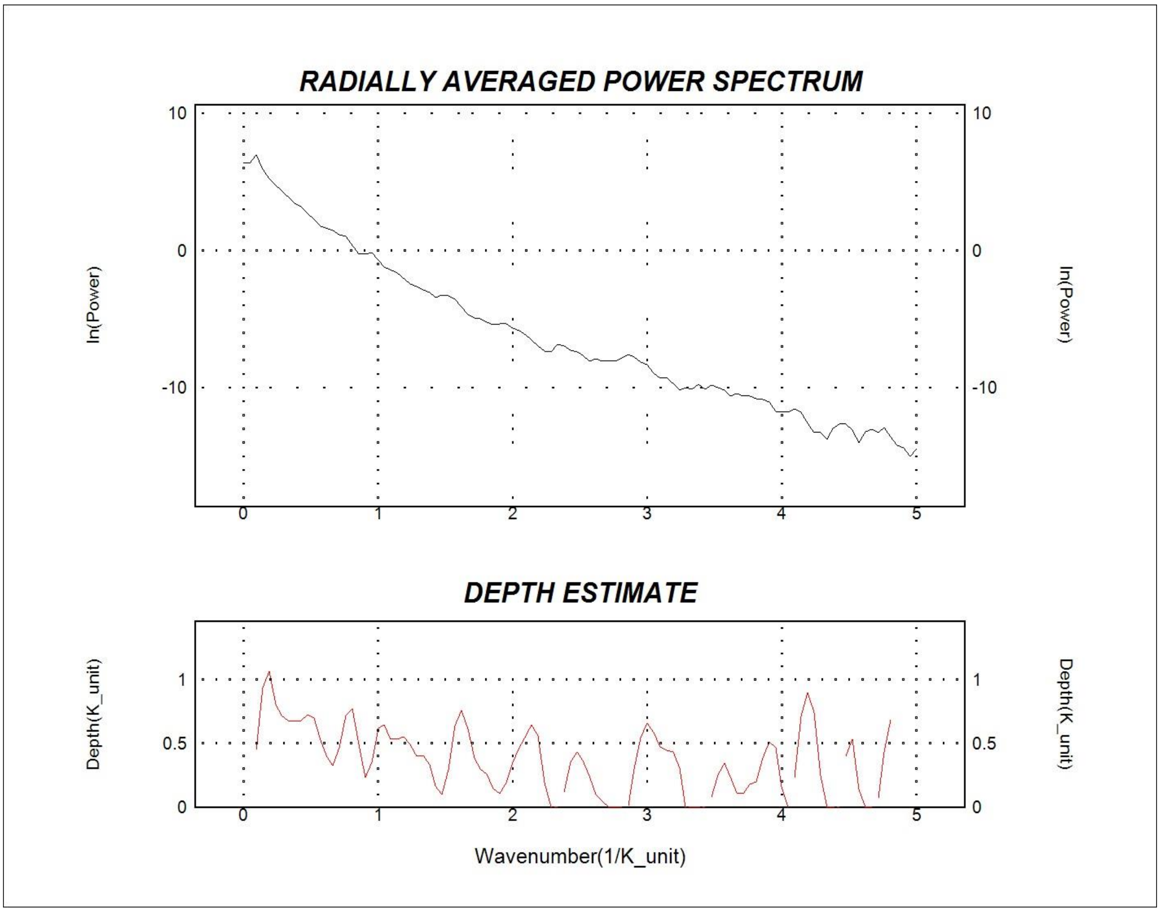

Fig. 6: Spectral Plot (Power Spectrum) For Block 7.

3.0 Results and Discussion

3.1 Magnetics

The Total Magnetic Intensity (TMI) image shows high magnetic susceptible areas in low magnetic values (blue) while less magnetic susceptible areas are depicted as high magnetic values (pink colour). The total magnetic intensity level in the studied area ranges from -122.63 to 68.42 nT, but the residual map was upward and continued by 200 meters resulting in the anomaly range between -66.5 to 49.6nT, the positively peaked region are the pinkish region and are having a magnetic intensity value ranging from 29.2 to 49.6 nT , the negatively peaked (blue) region have the magnetic intensity that ranged from – 22.3 to -66.4 nT, which indicates a sharp variation from positively peaked anomaly to negatively peaked anomaly at the southeastern (more positive than negative) East and the Northeastern (more positive than negative) part of the map, But of special interest to this particular work is the prominent anomaly around the central region of the map (Fig. 8) which consisted of the center red anomaly enclosed within a rectangular-like southwestern trending blue anomaly which in turn is surrounded by the positive anomaly, and also some variation around this region which is characterised by a very low anomaly (blue) surrounded by very high zone (pink). The consequence maybe as a result of an intrusion of high magnetic susceptibility characterised by the shape and wavelength that reflects a prominent composite body, characterized by that which would be produced by a volcanic pipe (kimberlite pipe). Also, an intrusion within the basement in the region may be enclosed within a circle as seen in Fig. 8.

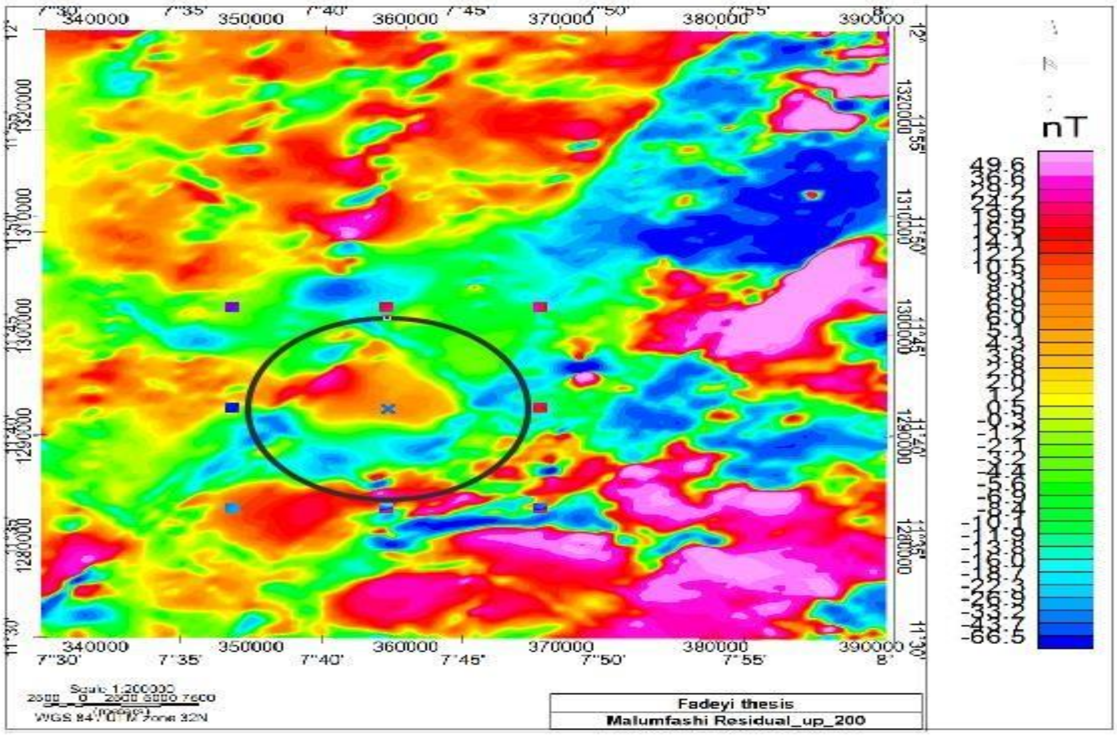

Fig. 8: **First Order Residual Total Magnetic Intensity map of the Study Area Upward Continued by 200 m.**

3.2 Reduction to Equator (RTE)

This is the first filtering process applied to the aeromagnetic data that is done because the data were obtained from an area close to the equator, , hence the transformation of the magnetic anomaly to that which is observed at the equator. Anomalies in different regions are useful in the interpretation of the earth mean field.

. A major factor influencing the shapes of the anomaly formed is the geomagnetic field element which is the angle of inclination and angle of declination. In this transformation, the values use dare viz; angle of inclination (I=1.188) and the angle of declination (D= -1.553).

3.3 Upward Continuation

In this work, the RTE map was upward and continued in the first order until a stable anomaly at the height of about 5 km (5000 meters) was obtained. Consequently, the regional gradient map of the area was developed. The first order regional trend is shown in Fig. 9.

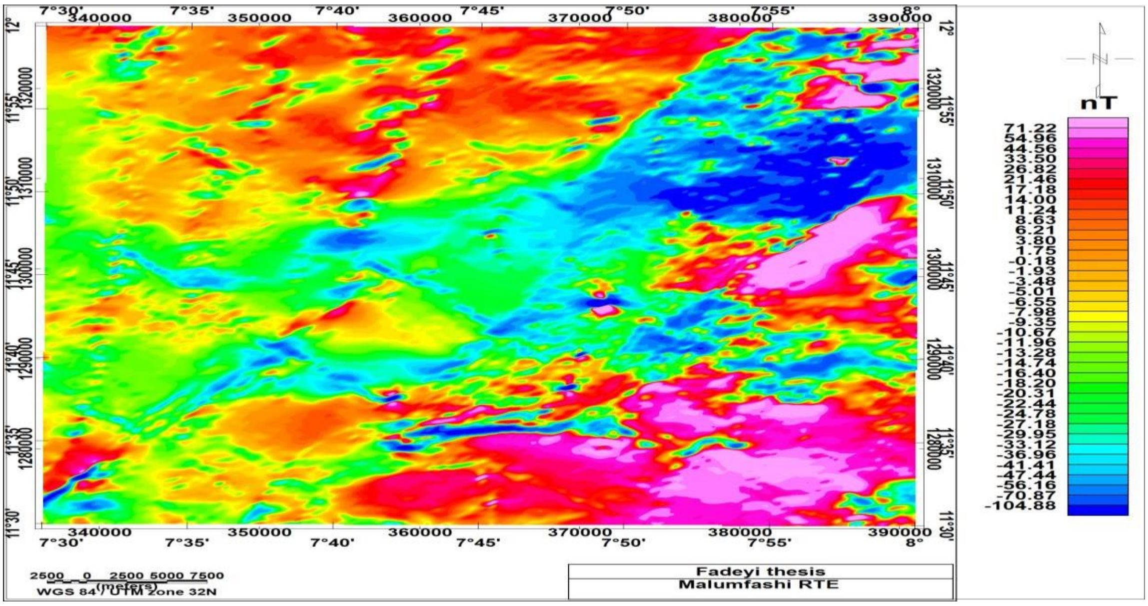

Fig 9: Total Magnetic Intensity (TMI) Map of the Study Area Reduced to Magnetic Equator.

3.4 Regional-Residual Separation

This is a process whereby the I subtracted the first order regional trend from the RTE map to get the residual map of the area, after this the residual map was upward continued to the height of 200 m (Figure 8) to further filter the noise from it. The residual map is depicted in Fig. 11.

3.5 Thorium

Anomalies in the thorium data in Fig. 12 enhance the mapping of the lithology and lithological boundaries of the area. The thorium, Th map shows three distinct regions of thorium concentration in the area. These concentration zones are represented by pink colour, relatively high concentration of the Th concentration represented by green colour and low Th concentration represented by blue colour.

The radiometric data can be interpreted qualitatively using the color variation of the different areas on the map (Fig. 12), the radiometric anomaly for this work is categorised into three, the first are those with high radiometric values characterised by the reddish to pinkish coloration with values ranging from 18.1 to 27.4 ppm this area are marked by the black polygon (figure 4.5) correspond to the granite and the migmatite because granite are rock with high thorium content due to the presence of minerals like monazite [ThO_2 + rare-earth phosphate], thorianite [$(Th,U)O_2$] and thorite, uranothorite [$ThSiO_4$ + U] this minerals occurred highly in granites and pegmatite (Telford *et al*. 1990.), the second are the intermediate radiometric value ranging from 16.0 to 17.0 ppm and the third with the very low radiometric values from 12.9 to 10.8 ppm are marked by white polygon correspond to the undifferentiated schists including the flaggy quartzite which are metasedimentary/metavolcanic series.

Kimberlite pipes are known to usually have a high thorium concentration, therefore the likelihood of occurrence of this volcanic pipe that I am prospecting for in the region is likely to be in the area with high thorium concentration enclosed within the black polygon (Ford *et al*, 2007).

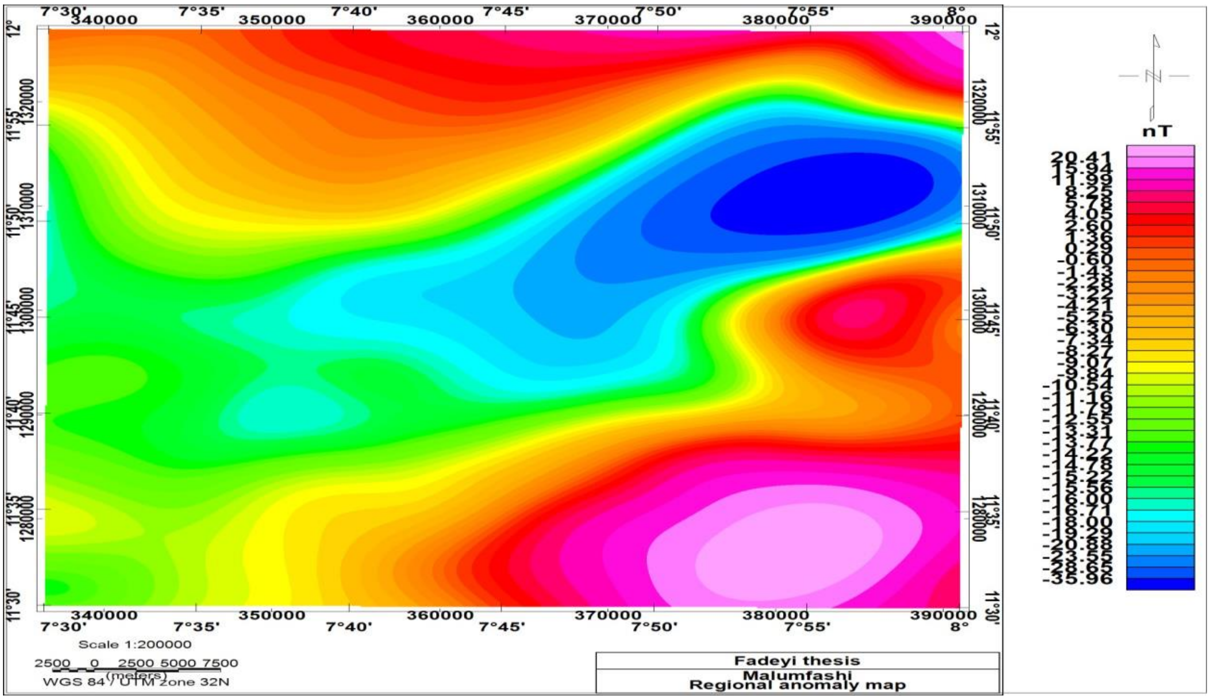

Fig. 10: First Order Regional Trend Map of the Study Area

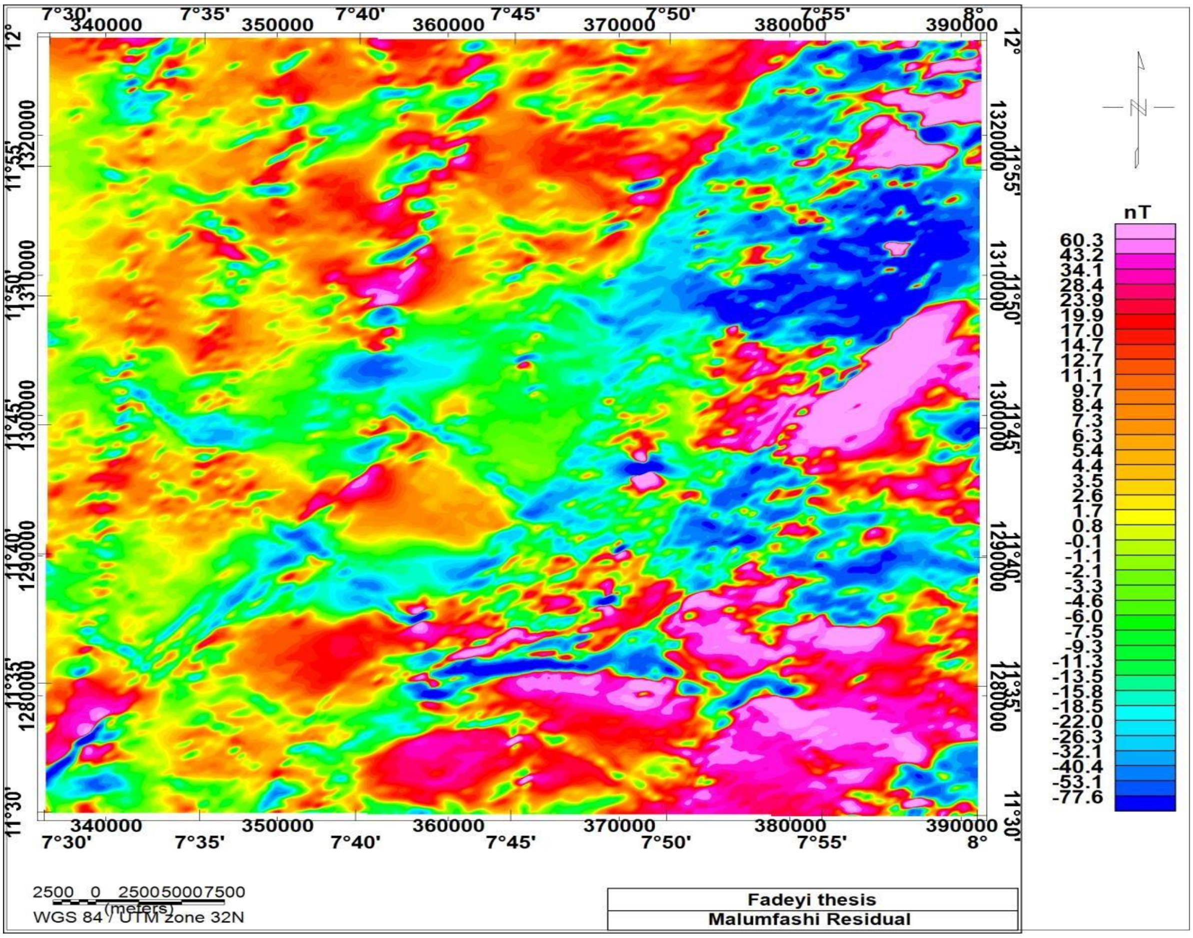

Fig. 11: First Order Residual Total Magnetic Intensity Map of the Study Area.

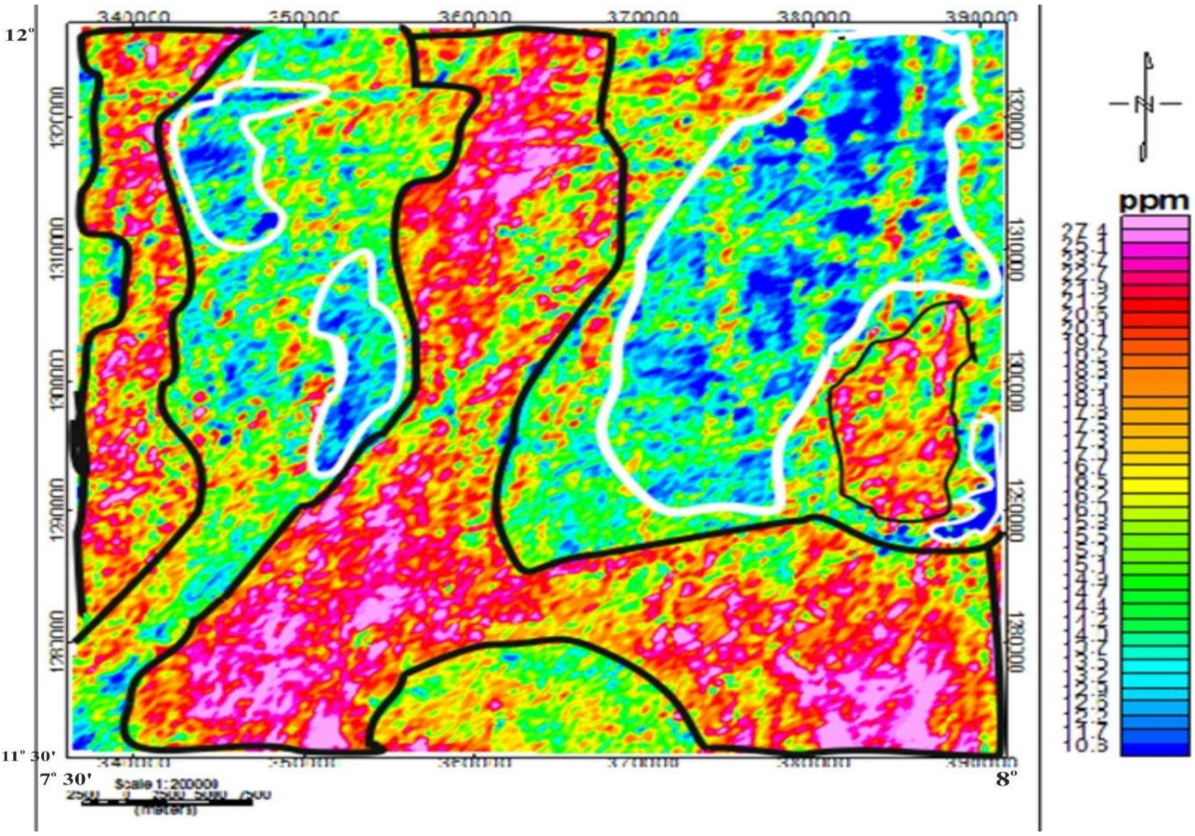

Fig. 12: Gamma spectrometric image for thorium (eTh) Concentration

3.6 The Horizontal Gradient Magnitude map (HGM)

The horizontal gradient magnitude map (HGM) was obtained after the analysis of the residual map upward continued by 200 meters, upward continuation was applied to the residual map to eliminate the presence of short wavelength noise.

The resulting HGM map reveals some interesting geological features/ structures (supposedly faults and contacts) in the area, lineaments were analysed to extract further information on the distribution and nature of the lineaments and for this purpose, a conventional technique called rose diagram was applied. A Rose Diagram was used to display graphically different tendencies for structures like joints or fault planes representing the angular relationships of the geologic map data. The purpose of this study is to analyse the spatial distribution of lineaments extracted from aeromagnetic images according to their length and orientation to contribute to the understanding of the faults of the study area. Fig. 13 is a Rose diagram representation for the regional strike of the delineated lineament from aeromagnetic data by using a polar plot where the distance from the centre of the plot is proportional to the sum of the line lengths in that orientation. Structural lineament orientation or azimuth direction on the structural lineament map (Fig. 14) were measured manually and plotted as a Rose Diagram using GeoRose software.

The horizontal gradient lineament map of the area shows a tabular body extending and aligning in the Southwest to Northeast (SW-NE) direction this is enclosed in the red circle in Fig. 15, since the HGM maps the edge of the underlying structure, this tabular shaped structure revealed and enhanced by the lineament map is said to be the edges of the supposed kimberlite pipe (volcanic pipe) present in the area this is consistent with the work of Verheijen and Ajakaiye (1979) on Kafur kimberlite, other suspected area with kimberlite occurrence is also circled close to the main tabular body. The Rose Diagram (azimuth frequency) depicted most (major) lineament extracted trends in the Northeast – southwest (NE-SW) and the Northwest-Southeast (NW-SE).

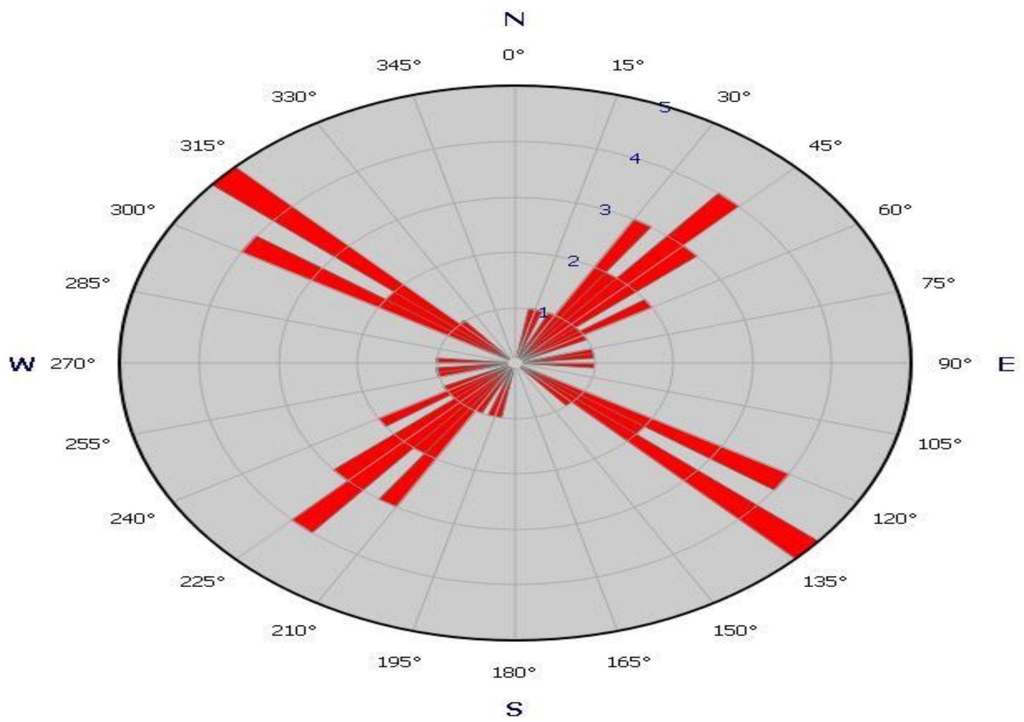

Fig. 13: Rose diagram showing the lineaments orientation of the study area

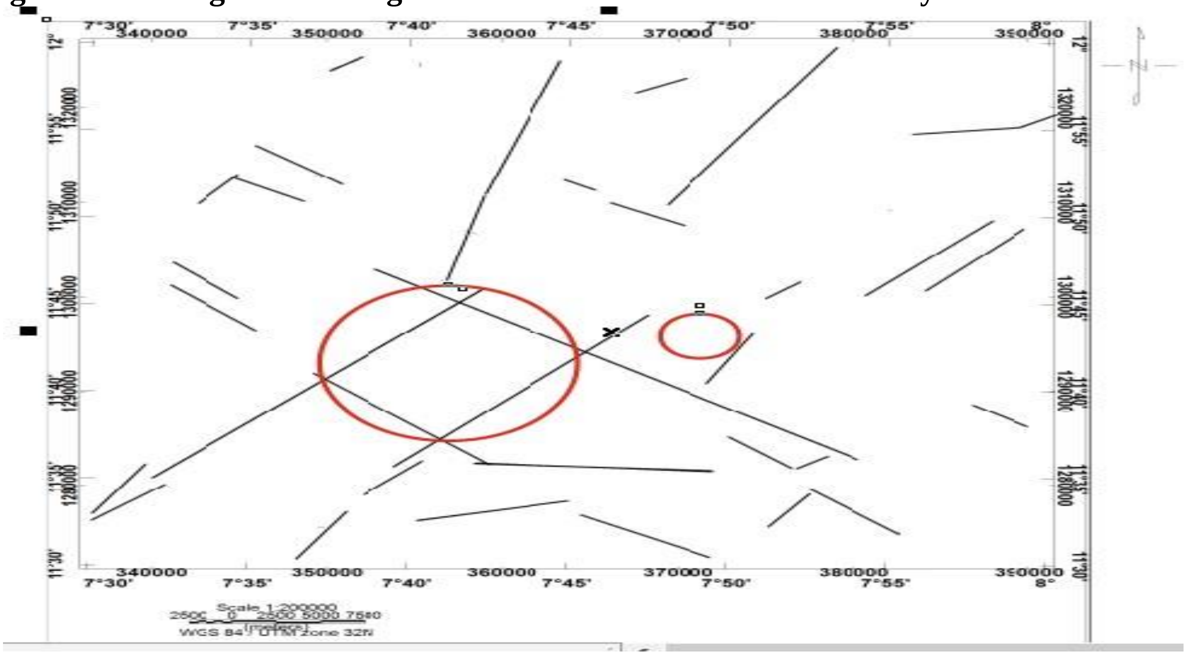

Fig. 14: Lineament map of the study area.

3.7 Depth to the basement from spectrum power

The power spectrum of the aeromagnetic gives an idea of the distribution of magnetic sources at different depth levels.

The result was grouped into two intervals (or two main sources depth), including the deeper sources and the shallow sources, the deeper sources are the first segment of the spectrum plot and this reflects the Precambrian basement.

The shallow magnetic horizons represented by the second segments are assumed to reflect sources that are shallower than the

Precambrian. These shallower horizons may be unreliable sources therefore for this work our focus goes into the deep sources mainly.

The computed depth to the basement for the deep sources from the spectral ranges from 0.08 to 0.48 km. These values are low and are peculiar to the basement environment, this is in agreement with the Rahaman (1988) which classified the area as a basement complex terrain.

From the deep source map (shown in Figs. 16 and 17), the depth solution or the depth to the magnetic source at the points labelled A and B around the center of the map ranges in value from 0.04 to .1 km, this source depth is suspected to have resulted from a near surface or volcanic vertical intrusion supposedly kimberlite pipe, which usually occurs at or near the surface. (Table 1)

This result corresponds with those obtained from the qualitative interpretation of the thorium (eTh) concentration shown in Fig. 12, and the HGM map (Fig. 15). The interpreted result suggests a possible occurrence of volcanic pipe (Kimberlite pipe) in the investigated area.

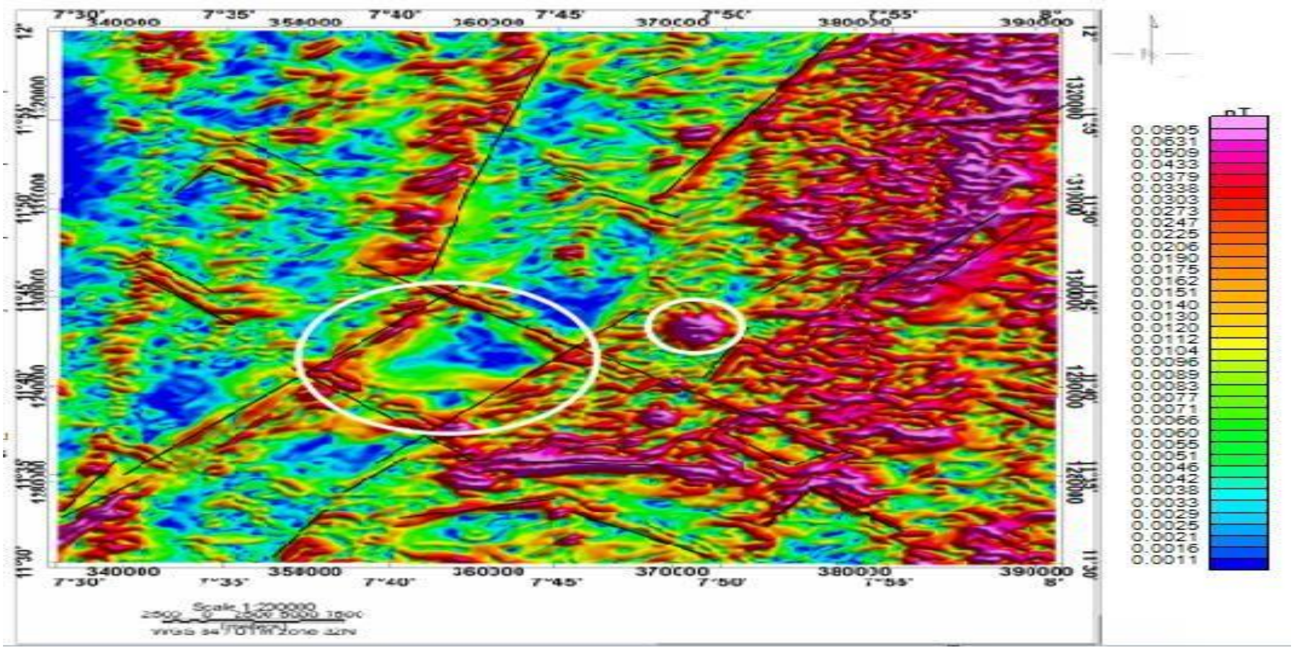

Fig. 15: Total Horizontal Gradient Map of the area

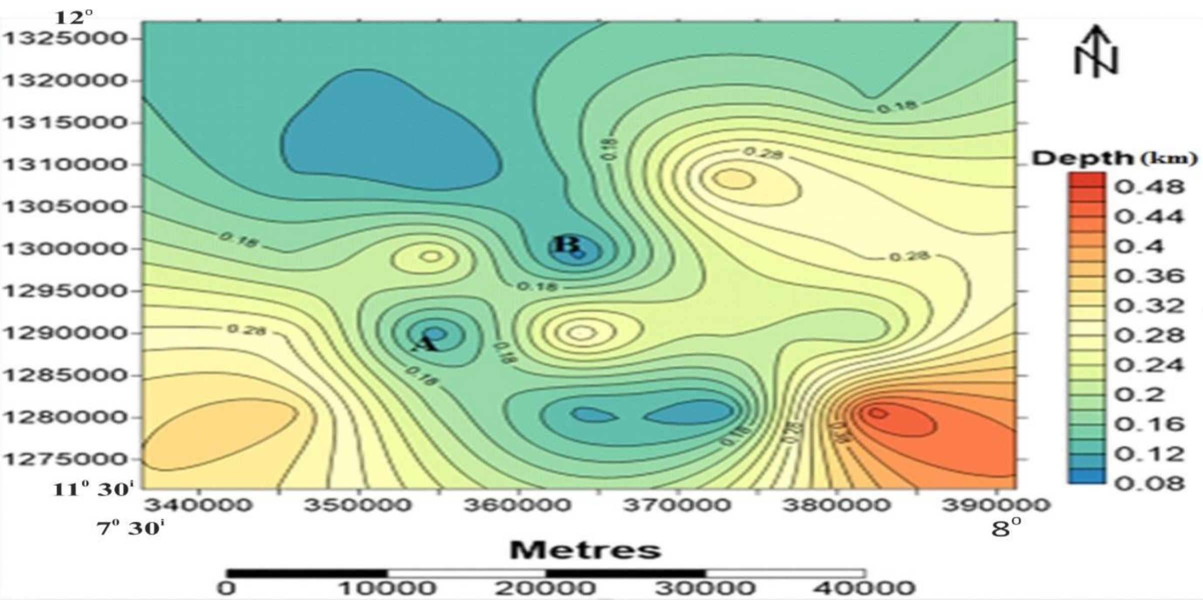

Fig. 16: Relief of the deep magnetic source estimated from the 2D-spectral analysis.

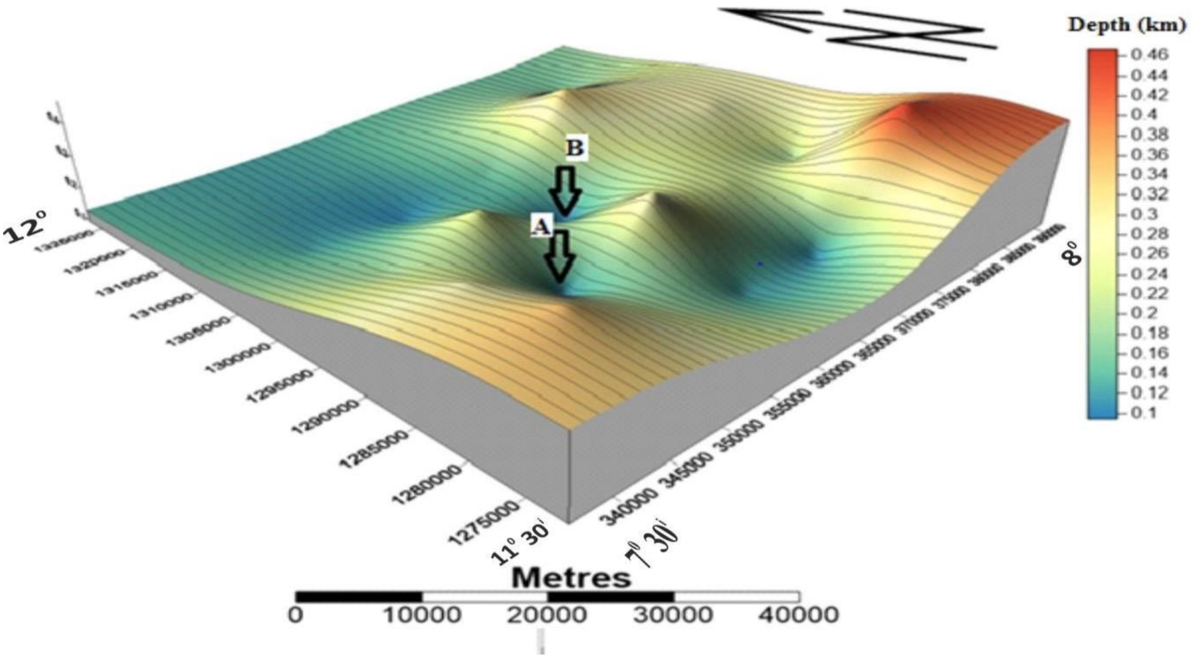

Fig. 17: 3D relief map of the deep magnetic source estimated from the 2D-spectral analysis.

Table 1: Spectral depth estimates to the top of the magnetic sources over each block in the studied area

Spectral Blocks	Source Depth (kilometres)	
	Deep	shallow
1	0.35	0.0787
2	0.1986	0.0602
3	0.1143	0.0551
4	0.101	0.0518
5	0.4707	0.1011
6	0.2783	0.0876
7	0.1048	0.0566
8	0.3003	0.047
9	0.2224	0.0644
10	0.1973	0.0694
11	0.1813	0.0613
12	0.2513	0.0759
13	0.0907	0.0395
14	0.2367	0.055
15	0.284	0.0944
16	0.1216	0.0597
17	0.1017	0.057
18	0.1457	0.0643
19	0.338	0.1154
20	0.2735	0.0765
21	0.1229	0.0533

22	0.1205	0.0523
23	0.1561	0.0694
24	0.1936	0.0718
25	0.1589	0.0682

4.0 Conclusion

The total magnetic intensity aeromagnetic (TMI) and radiometric data over the Malumfashi area of Katsina State in the Northern part of Nigeria were analysed, and interpreted to validate the occurrence of possible volcanic pipes (kimberlite pipes) in the region. Qualitative interpretations were carried out on the radiometric data, while the magnetic intensity map was subjected to both qualitatively and quantitatively data interpretation.

From the processed radiometric map, areas with the potential for the occurrence of kimberlite were mapped. The magnetics map is characterized by distinct elongated circular anomalies which are interpreted as possible kimberlite pipes.

The HGM edge of the anomaly map leads to the detection of the rectangular-like structure from the lineament plot which is interpreted as the edges of the volcanic intrusive bodies which are deduced to be associated with kimberlite pipes in the area investigated. From the 2D spectral analysis carried out on the 25 overlapping blocks of 18.5km^2 each, the radially averaged power spectrum and the corresponding depth to the top of the deep magnetic source in each block revealed the deep sources to vary from 0.08 km to 0.48 km, while the depth to the top of the shallow magnetic sources varies from 0.04 and 0.09 km. These shallow sources within the study area are interpreted to be associated with the delineated kimberlite pipes.

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Conflict of Interest

The authors declared no conflict of interest