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Structural Analysis of Malufashi Area and Environs, Northwestern Nigeria, Using Airborne Magnetic Dataset

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Abstract:
Background: *Malufashi Area in Katsina State, northwestern Nigeria, is located in the Western basement Province of the country and the place lacks adequate information on the geological structures underlying it. The place lacks detailed information on the structural analysis and geologic mapping derived from high resolution geophysical data. This study was designed to define the lithology, boundary and the distribution of the rock types and delineate structures with potentials of hosting mineralization within the area.*
Materials and Methods: *High resolution airborne magnetic data were employed in mapping the structures and defining the lithology within the area and its Environs. Magnetic imaging enhancement techniques involving analytical signal, first and second vertical derivatives were used in processing the dataset and these helped in the delineation of the structures and the lithological boundaries within the area.*
Results: *The interpreted results delineated five major fault systems, with dominant trend in the NW-SE direction and with minor NE-SW trend within the study area. The fault systems showed major cross-cut relationships. The dominating series of high angle faults, NE-SW trending fractures and fold structures were defined to have resulted from three major regional series of deformation stages.*
Conclusion: *This study shows that the study area is characterized with very high structural complexity within quartzite schist rocks which are likely zones of mineralization. The delineated lithology and structures aided the design of the structural map of the study area. The study defined and recommended structures for ground geophysical survey as coring as the area is known to host gold mineralization and kimberlite pipes.*
Key Word: *Malufashi Area, Geologic Mapping, High Angle Faults, Structural Deformation, Quartzite Schist Rocks, Gold Mineralization.*

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I. Introduction

The total magnetization of rocks is determined by the quantity and composition of the grain particles of the magnetic minerals and the processes that produced the remnant magnetization carried by the minerals. Structural analysis is one of the objectives of using aeromagnetic survey method in the discovery of spot of magnetic minerals and geological features favourable for mineralization. Airborne magnetic method is a good geophysical tool that is capable of delineating the subsurface geology in terms of its lithology and structures such as fractures, shear zones, folds, veins and faults (Murphy 2007). These parameters are essential in the identification of areas with possible mineralization. The search for gold, for example, is therefore the search for the structures and lithology that are known to favour the mineralization of gold.

About half of the total area of Nigeria landmass is underlain by rocks of the Precambrian age known in the country as the Basement Complex (Haruna 2017). The basement complex is divided into two provinces (Ajibade et al. 1979): the Western Province and the Eastern province. The Western Province is approximately west of longitude 8^0 E, typified by N-S to NNE-SSW trending schist belts separated from one another by migmatites, gneisses and granites. The schist belts are differently interpreted as small ocean basins (Ajibade and Wright 1989), infilled rift structures (Ball 1980) or synclinal remnants of an extensive supracrustal cover (Barley 1989). The Eastern Province lies approximately east of longitude 8^0 E and is more nearly NE-SW; it comprises mainly migmatites, gneisses and large masses of Pan-African granitoids (Older Granites) intruded in Jos plateau, by Jurassic peralkaline granites (Haruna 2017).

The study area, Malufashiand environs in northwestern Nigeria, is located in the Western basement Province of Nigeria and the place lacks adequate information on the geological structures underlying it. At present the area is fast becoming an important study area for geoscientists in view of increased efforts to explore major structural features within it. In recent time, some locations within the study area have attracted the attention of the geoscience’s community in Nigeria owing to the presence of kimberlite (Onugba 1979) in the area. Also the area is known to host gold mineralization.

Gold mining in Nigeria is attracting large number of investors and has contributed significantly to the socio-economic development of the country. Most of the major gold deposits in Nigeria occur in structures (faults, veins, fold, shear zones and fractures) within the Upper Proterozoic Schist Belt (Obaje 2009). The Upper Proterozoic schist rocks have been infolded into the migmatite-gneiss-quartzite complex (Olusegun et al. 1995). The Schist Belts comprise low grade, metasediment-dominated belts trending N–S which are best developed in the western half of Nigeria. The lithological variations of the schist belts include coarse to fine grained clastics, pelitic schists, phyllites, banded iron formation, carbonate rocks (marbles/dolomitic marbles) and mafic metavolcanics (amphibolites) (Obaje 2009). The Early Proterozoic formation bears much similarity with most Archean Greenstone deposits, particularly in terms of its high gold potential.

Most rock-forming minerals are effectively non-magnetic; certain rock types contain sufficient magnetic minerals such as magnetite and pyrrhotite to produce significant magnetic anomalies. Although gold is non-magnetic, the magnetic method has proven to be a valuable tool in the search for gold, because it is closely associated with pyrite which is also nonmagnetic, but pyrite can metamorphose into pyrrhotite at the upper schist-lower amphibolite grades, and pyrrhotite can metamorphose into magnetite (Gunn and Dentith 1997). Minerals that contain pyrrhotite and magnetite are clearly delineated by airborne magnetic surveys. In addition, magnetic surveys can determine the presence of Younger intrusive rocks, and cross-cutting structures that are typically associated with shear hosted Archaean Orogenic gold deposits, as well as differentiate between banded iron formations (BIF), metasediments, metavolcanics and other rock types. The method is effective in geologic mapping.

There is no detailed information on the structural analysis and geologic mapping of the study area in recent time. Information on the regional geology of the area is based on the aero-surveys with low resolution, carried out in Nigeria in 1970s and on ground surveys conducted with low resolution at isolated locations of interest. Hence, in designing the geology map of the area, the lithological boundaries, based on those surveys, were estimated. This Study was designed with the aim of delineating the structures within the study area using aeromagnetic data of high resolution than those of 1970s. The study was meant to define the lithology, boundary and the distribution of the rock types and delineate structures with potentials of hosting mineralization within Malufashi Local Government Area of Katsina State and environs, northwestern Nigeria.

II. Location and Geology of the Study Area

The study area is located in the Northwestern part of Nigeria. It is bounded by Latitudes 11˚28´00″N and 11˚44´00″N and Longitudes 07˚30´00″E and 08˚00´00″E respectively. It covers Malufashi Local Government Area of Katsina State and its environs, northwestern Nigeria. It is located on a plateau at a height of about 670 m above sea level and more than 640 km away from the sea (Hore 1970). The area is located within the sparsely populated Guinea Savannah. It has a typical savannah climate of distinct wet and dry seasons, with a moderate rainfall of about 1047 mm/a (Garba and Schoeneich 2003). The rainy season in the area usually starts in May and ends in October and the dry season lasts from late October to April.

The study area (Figure 1) falls within the Precambrian Basement Complex of Northern Nigeria which consists of migmatitic gneisses and schist, into which has been an emplacement of granite and, to a lesser extent, more basic materials (Rahaman 1988). Basically, the rocks of Nigerian basement complex have been recognized to belong to three groups; namely the Oldermetasediment groups, the gneiss, migmatite and Older granite groups and the Younger metasediments group. According to Oyawoye (1964), these rocks of the basement complex have undergone at least two major phases of orogenessis. The last of these orogenic cycles was initiated by deposition of sands, muds, greywacke and igneous material on an eroded metamorphic basement formed during the preceding cycle and this extended from the Late Precambrian to Lower Palaeozoic (Jacobson et al. 1964; Grant 1966 and Wright and McCurry 1970). Folding and low–to medium–grade metamorphism of these accumulations also involved extensive remetamorphism and partial mobilization of the underlying basement and according to McCurry (1973) these led to the development of high grade gneisses, migmatite and Older granites. The greater part of the area is covered with thick regolith mainly derived from in-situ weathering of the basement rocks.

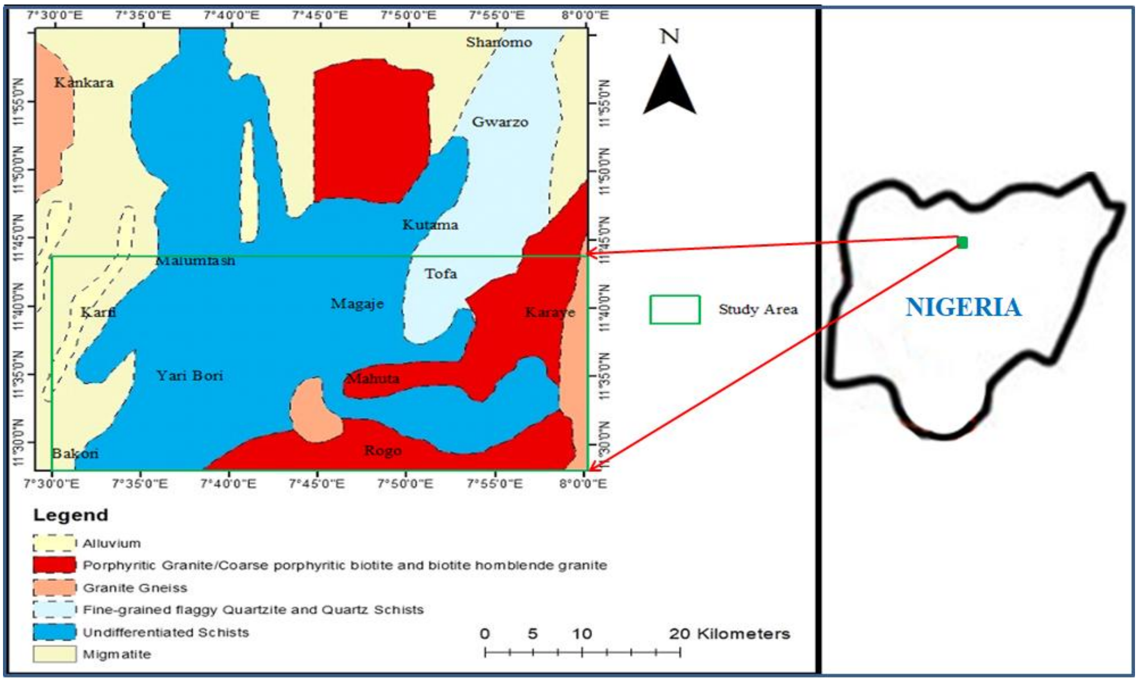

Figure 1. Geology Map of the Study Area.

III. Materials, Methods and Data Processing

The aeromagnetic dataset used for this study is from the high-resolution airborne magnetic survey coverage in Nigeria in 2009 carried out by Fugro Airborne Survey along a series of NW – SE flight lines at 500 m spacing, 20 km tie lines spacing and at 100 m terrain clearance. The data were acquired from the Nigerian Geological Survey Agency (NGSA). The parameter measured was the total magnetic field intensity. This study involved the data from one square block of magnetic map (generated from part of Map Sheet 263) which represents a map on the scale of 1:200000 and covering an area of about 3,015 km^2. The total magnetic intensity grid was generated using a minimum curvature algorithm at a grid cell size of 100 m. The digitized data were filtered using a low pass Fourier domain sub-routine filter to eliminate unwanted wavelengths and to pass longer wavelengths. The separation of the residual and the regional fields was done using trend surface filter. Magnetic imaging enhancement techniques involving analytical signal, first and second vertical derivatives were used in processing the dataset and these helped in the delineation of faults, folds, fractures and lithological boundaries.

The vector nature of magnetic fields at low magnetic latitude places like Nigeria makes the magnetic fields (anomalies) developed by magnetised rocks complex and difficult to interpret (Macleod et al. 1993). This has resulted in the use of data processing technique, Reduction to the Pole, which produces anomalies vertically over the bodies. But reduction to the pole suffers instability during the transformation and also produces artefacts that are not acceptable in the results. A better alternative for positioning anomalies vertically over the bodies is to apply Analytical Signal to the total magnetic field and the Vertical Integral of the magnetic field. With these methods a maximum anomaly was produced over the magnetic body regardless of the direction of magnetization of the body (Macleod et al. 1993).

Analytic signal transformation has an advantage over reduction to the pole and reduction to the equator because it is completely independent of the direction of magnetization and the direction of the Earth's field (Milligan and Gun 1997). This implies that all bodies with the same geometry have the same analytic signal. In addition to this, analytic signal transformations are not subjected to the instability that occurs in reduction to the pole from low magnetic latitudes. The analytic signal maps also define sources positions regardless of any remanence in the sources (Macleod et al. 1993).

Nabighian (1972) suggested the concept of analytic signal (*AS*) and proposed that in the 2-D case, the horizontal and vertical derivatives of magnetic fields satisfy the Hilbert Transform, thus can be regarded as analytic signals. The amplitude of the analytic signal is the same as the total gradient, independent of the direction of magnetization, and represents the envelope of both the vertical and horizontal derivatives over all possible directions of the earth's field and source magnetization (Luo et al. 2011). Therefore the Hilbert Transform is written as:

$$\frac{\partial T}{\partial z} = H\left[\frac{\partial T}{\partial x}\right] \quad (1)$$

where:
T =Magnetic anomaly data.
The analytical signal of a real signal T is defined as

$$AS\left(\frac{\partial T}{\partial x}\right) = \frac{\partial T}{\partial x} - iH\left[\frac{\partial T}{\partial x}\right] \quad (2)$$

where:
$i^2 = -1.$
According to the definition, the analytical signal of the potential field obtained by combining these two quantities into a two-dimensional quantity known as the analytic signal is given as;

$$\text{AS}(\text{x}, \text{z}) = \frac{\partial T}{\partial x} + i\frac{\partial T}{\partial z} \quad (3)$$

where:
$\frac{\partial T}{\partial x}and\frac{\partial T}{\partial z}$ = Horizontal and vertical components of the total field respectively,
$T(x, z)$ = Magnitude of the total magnetic field,
$z$and$x$ = Cartesian coordinates for the vertical direction and the direction perpendicular to strike respectively.
The amplitude of the analytic signal is a symmetric bell-shaped function. By examining its profile across a magnetic source, the analytic signal was used in the interpretation to provide an indication of the edges of the causative body. The maximum value of the analytic signal determines the edges of the magnetic body.
Derivatives (vertical) are based on the principle that the rates of change of magnetic field are sensitive to rock susceptibilities near the ground surface than at depth. The Vertical Derivatives are used to delineate the anomalous source's boundaries. They can be used to delineate the contacts of lithologies of contrasting physical properties such as densities and susceptibilities. These contacts are reflected by inflation point in the potential field which, while difficult to locate on the anomaly map, are accurately traced by the zero contours of the vertical derivative map. First vertical derivative is physically equivalent to measuring the magnetic field simultaneously at two points vertically above each other, subtracting the data and dividing the result by the vertical spatial separation of the measurement points (Nabighian et al. 2005). In accordance with Hendra and Darharta (2017), the First Vertical Derivative (FVD) was used to delineate the anomalous source's boundaries while limiting the high frequency amplification and the Second Vertical Derivative (SVD) was used to enhance high frequency content of the data in this study. The vertical derivatives were obtained from Laplace's equation which is used to describe the magnetic potential field.
The basic equations for first and second vertical derivatives respectively are:

$$\frac{\partial \text{T}}{\partial \text{z}} = -\left(\frac{\partial \text{T}}{\partial \text{x}} + \frac{\partial \text{T}}{\partial \text{y}}\right) \quad (4)$$

and

$$\frac{\partial^2 T}{\partial z^2} = -\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (5)$$

where$T$ = magnetic anomaly field

IV. Results and Interpretation

Figure 2 is the Total Magnetic Intensity (TMI) map of the study area. The figure suggests the presence of linear structures, F1F1'(or F1), F2F2'(or F2), F3F3'(or F3), F4F4'(or F4), F5F5'(or F5), F6F6'(or F6), F7F7'(or F7) and F8F8'(or F8) underlying the study area. The total magnetic intensity map consists of both the regional field and the residual field (from shallow magnetic bodies). The Residual Magnetic Intensity (RMI) map of the area is presented in Figure 3 and it shows high magnetic intensities ranging from 20.13 to > 40.96 nT, intermediate magnetic intensities ranges from -13.87 to < 20.13 nT and low magnetic intensities less than -13.87 nT.

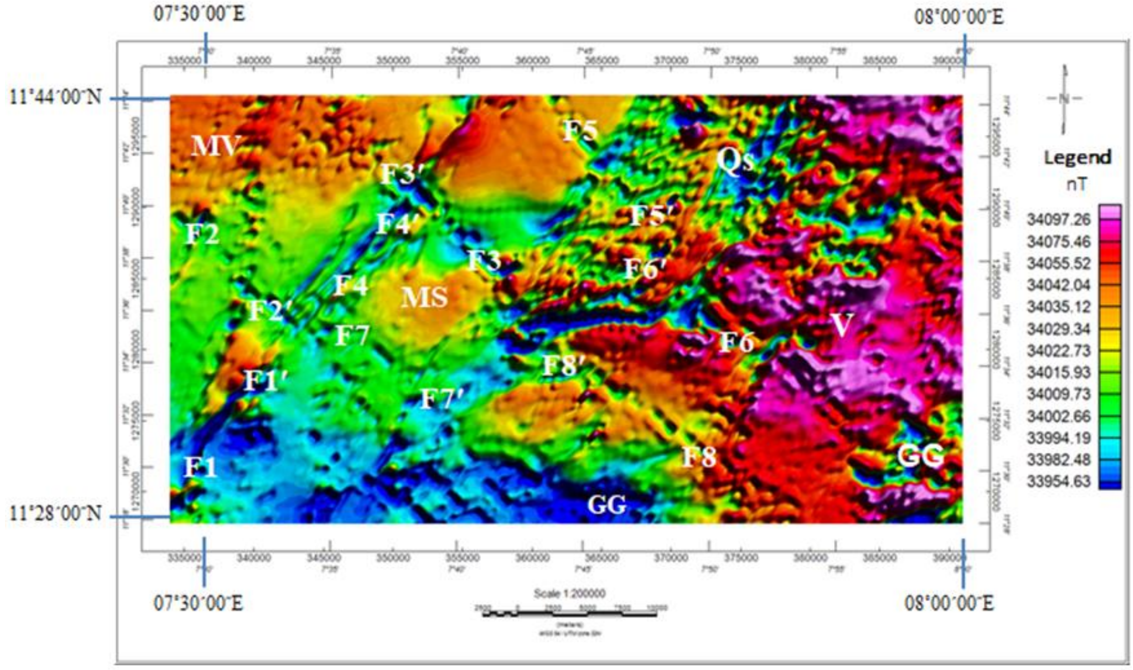

Figure 2. Total Magnetic Intensity Map of the Study Area.

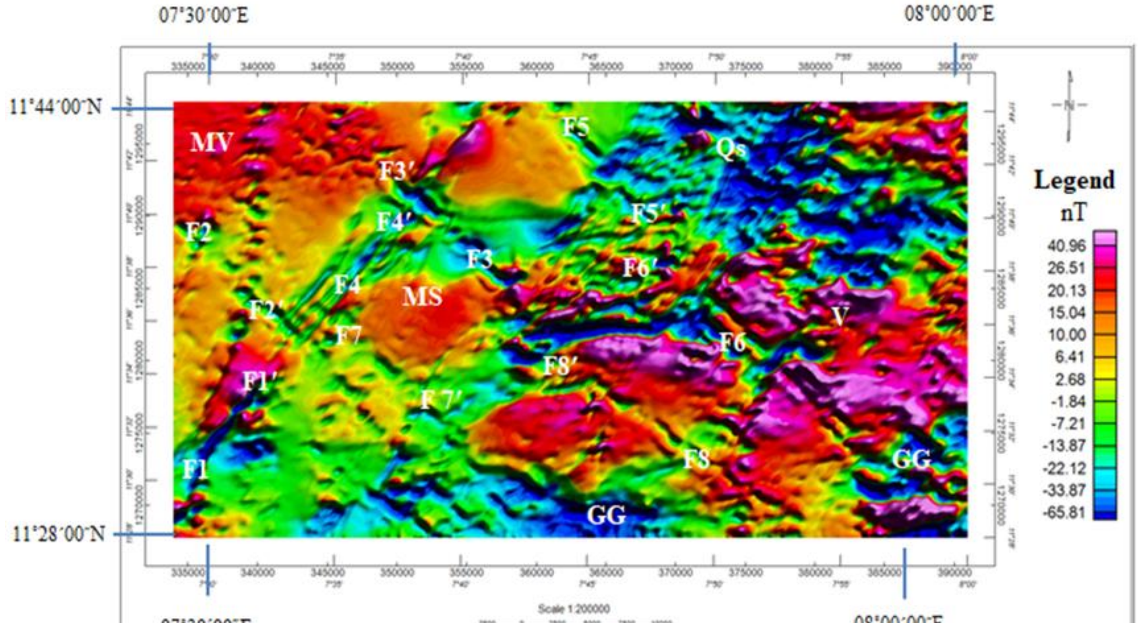

Figure 3. Residual Magnetic Intensity Map of the Study Area.

Figure 4 is the map of the analytical signal of the magnetic data while Figure 5 is the map of the analytical signal of the vertical integral of the magnetic field of the area. The boundaries that exist between the different geological formations in the study area are well demarcated in the analytical signal maps and the high and low magnetic intensity regions respectively were clearly outlined in them than those in the TMI (Figure 2) and the RMI (Figure 3) maps. Also, structures such as F7 are clearly delineated in Figure 5 than in the TMI and RMI maps. Maximum anomalies are correctly positioned over their causative bodies and clearly delineated in the analytical signal maps (Figure 4 and 5) than in the TMI and RMI maps (Figures 3 and 4) because the source positions of the anomalies are defined vertically over the sources regardless of any remanence in and direction of magnetization.

Figure 6 is a contour map of analytic signal superimposed on the Analytic Signal Raster map. The figure has shown areas of contour closure inferred as magnetic mineral accumulation. Figure 7 is the map of the first vertical derivatives of the magnetic data showing major folds within the study area. The first vertical derivative of the analytical signal was also produced that led to the mapping of more structures (minor folds within the study area) in Figure 8. The map of the second vertical derivative of the analytical signal data showing folds and faults within the study area is presented in Figure 9. In this map all the structures delineated in Figures 7 and 8 were enhanced.

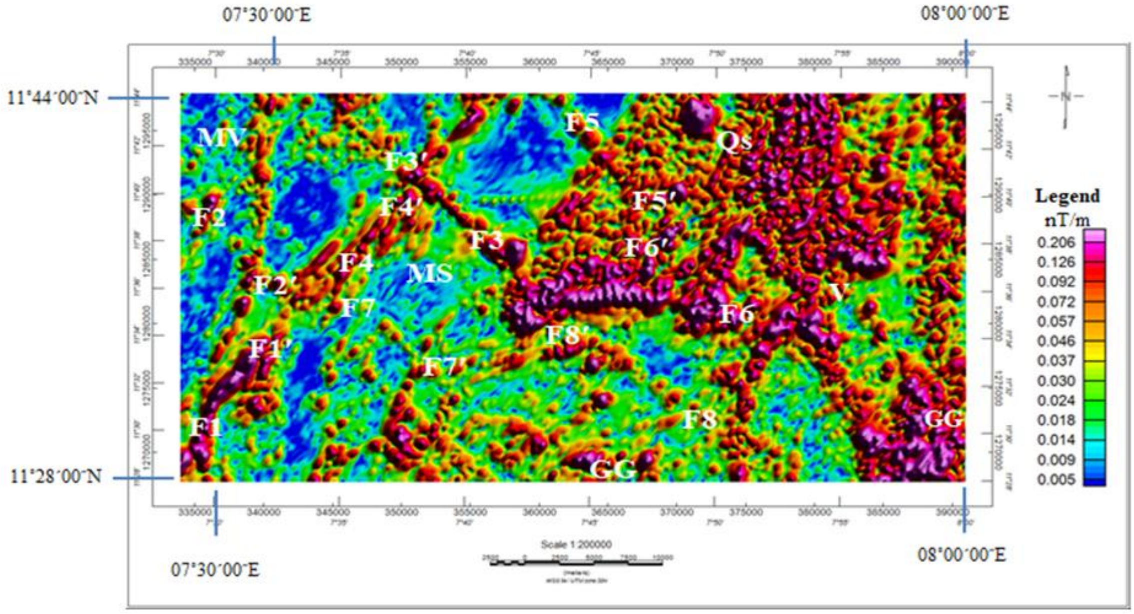

Figure 4. Analytical Signal Applied to TMI of the Study Area.

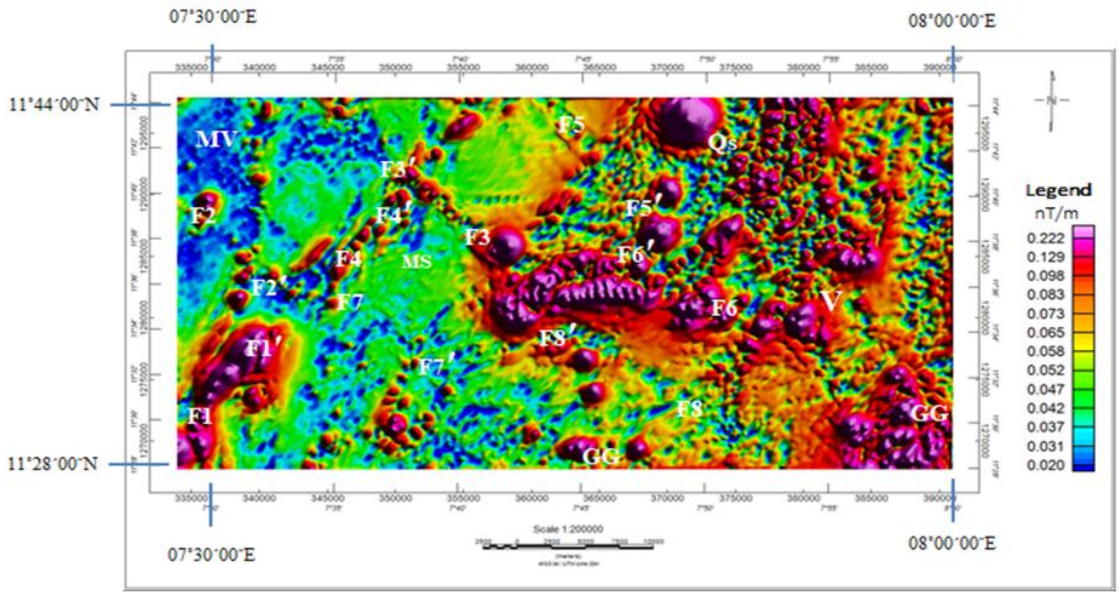

Figure 5. Map of Analytical Signal Applied to Vertical Integral of the Magnetic Data of the Study Area.

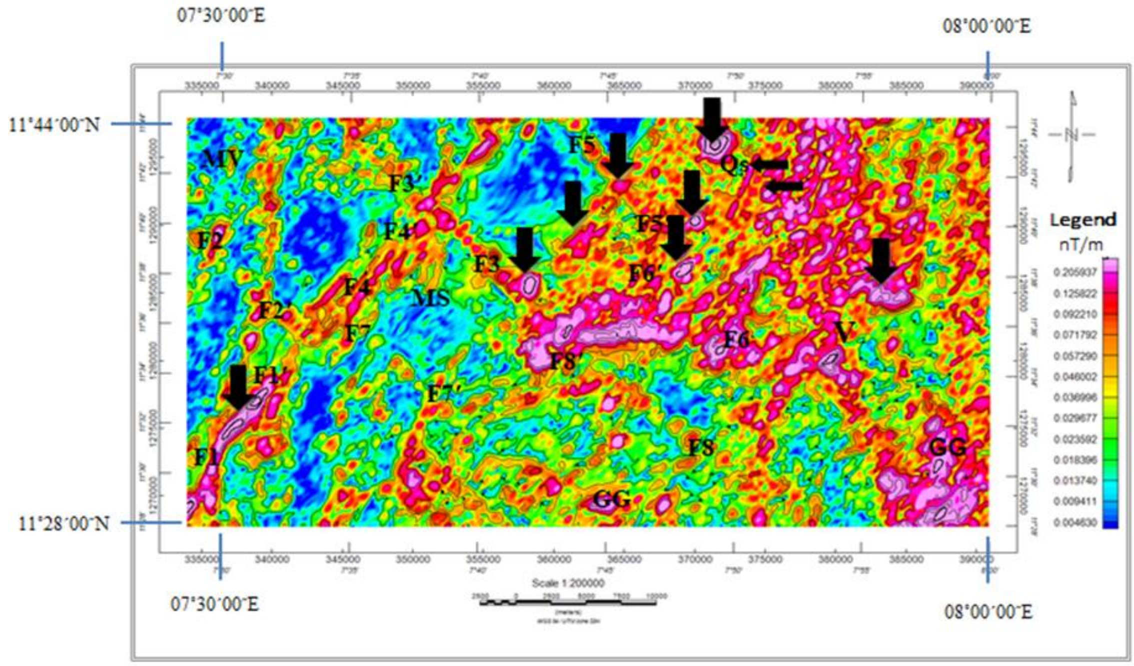

Figure 6. Contour Map Superimposed on Analytic Signal of the Magnetic Data of the Study Area.

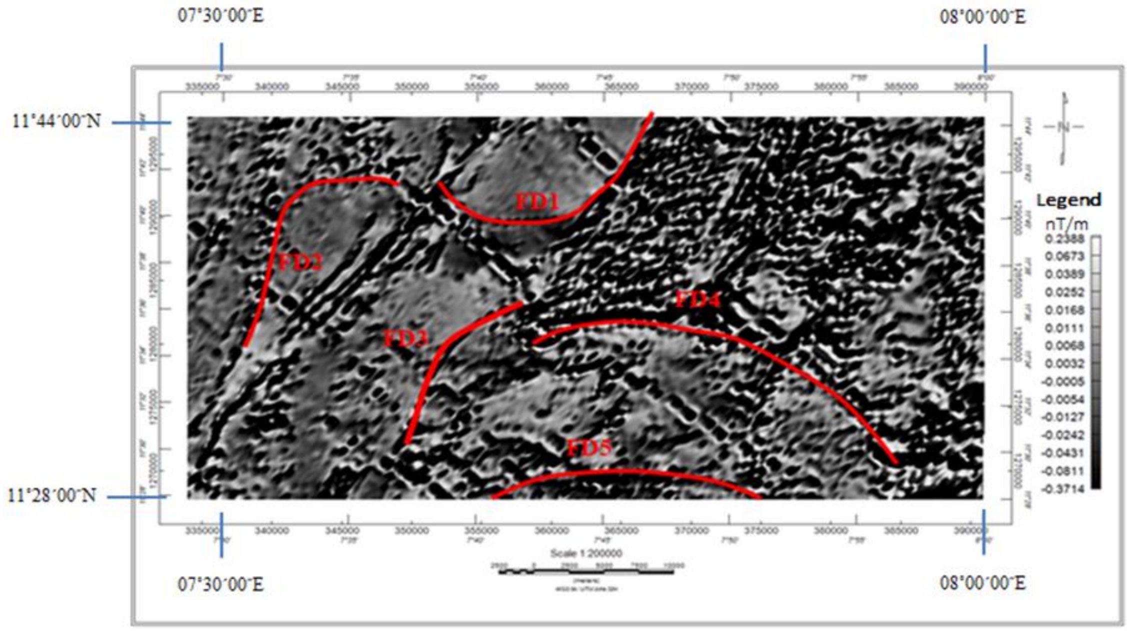

Figure 7. Map of First Vertical Derivative of RMI Data Showing Major Folds within the Study Area.

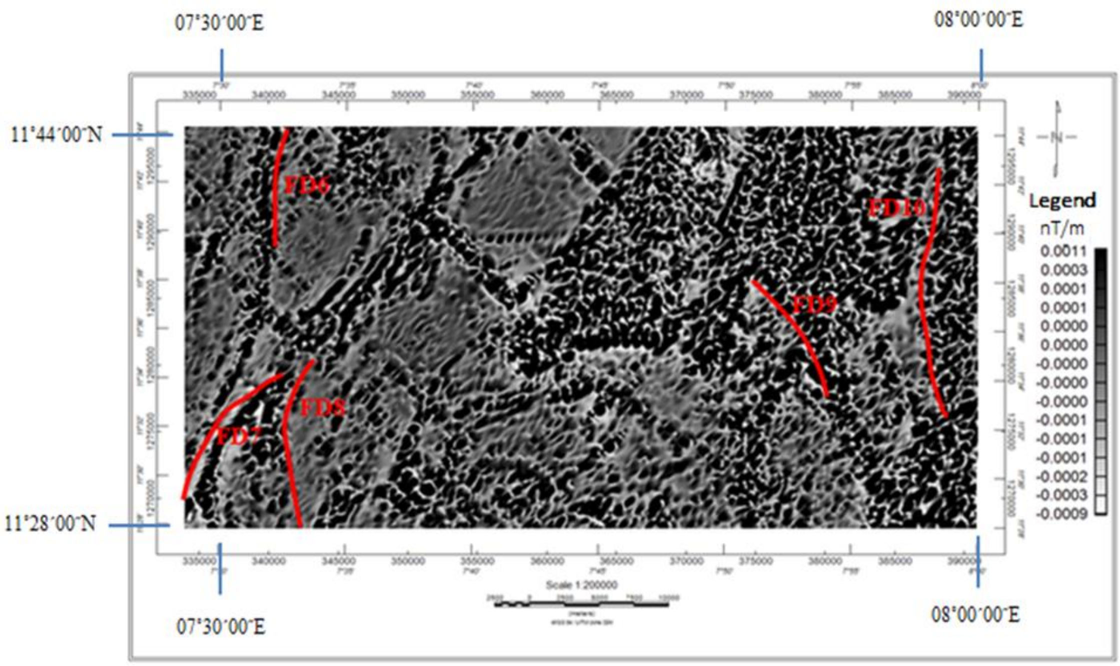

Figure 8. Map of First Vertical Derivative of the Analytical Signal Data showing Folds within the Study Area.

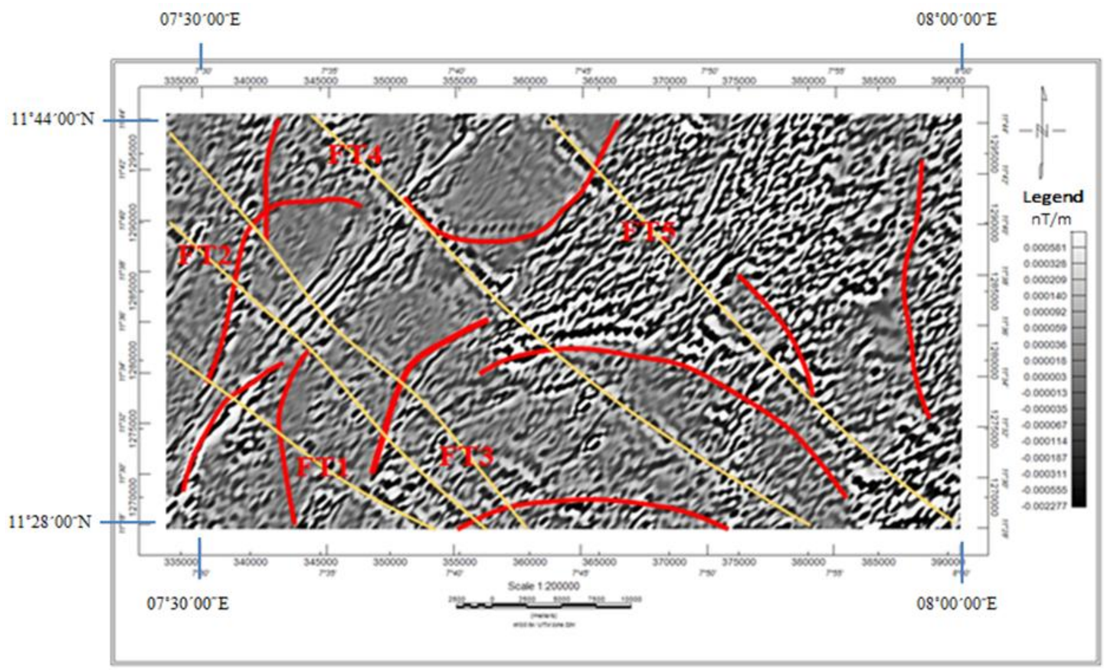

Figure 9. Map of Second Vertical Derivative of the Analytical Signal Data showing Folds and Faults within the Study Area.

V. Discussion of Results

The qualitative interpretation involving the correlation of the TMI map (Figure 2) with the geology map of the study area suggests that:

(1) the high magnetic intensity regions are most likely volcanic rock (V) defined as porphyritic granite,

(2) the intermediate magnetic intensity zones are most likely metasedimentary rocks (MS) defined as schist,

(3) the high frequency, intermediate magnetic intensity zones are most likely quartzite schist (Qs).

(4) the intermediate magnetic intensity zones (MV) are most likely migmatite and
(5) the low magnetic intensity regions (GG) are most likely granite gneiss.

The metavolcanics (MV) and quartzite schist (Qs) rocks are seen to be more extensive in the residual magnetic intensity map (Figure 3), with the quartzite rock showing low magnetic intensity anomaly with high frequency bodies; this most likely has resulted from alteration by hydrothermal activities that led to the formation of quartzite within the schist rock. The granite gneiss (GG) is interpreted to show low magnetic intensity; this is accredited to its thermal history and not to hydrothermal activities.

From the analytic signal maps shown in Figures 4 and 5, the formation (MV) recorded the lowest magnetic intensity. Analytic signal enhances the anomaly of a body with high magnetic contrast and shows weak responses for moderate to low magnetic bodies. Hence, MV associated with moderate magnetic anomalies in Figures 2 and 3 recorded low magnetic intensities in Figures 4 and 5 and low magnetic intensity is generally associated with migmatite gneiss. The average magnetic signatures registered at MS are most likely responses from metasedimentary rock (schist) while the high magnitude and frequency anomalies at Qs suggest that, the formation is most likely quartzite schist rock. The high magnetic intensities observed in the quartzite schist regions are granulite facies of mafic rock, since it is very magnetic and is located within the schist belt; its strong magnetism arises because of the great production of secondary magnetite related to amphibole and pyroxene growth during prograde reactions. The high magnetic intensity within the schist also suggests that the unit is rich in iron. The high magnetic intensities observed within the granite units in Figures 2 and 3 suggest that, the formations are made of igneous rocks with high amount of magnetic minerals.

The boundaries that exist between the different geological formations in the study area are well demarcated by the application of the analytical signal (Figures 4 and 5); the blue areas depict the metasediments (MS) and metavolcanic rocks, the pink-magenta areas depict volcanic rocks. In Figure 6 the smooth contours seen at the areas labelled MS with the deep blue colour reflect areas covered with low magnetic metamorphic rocks (schist). The complex contour lines observed in the remaining areas with high magnetic intensities are indicative of igneous and metamorphic terrains (metamorphic rock intruded by high magnetic rock).

The rock types delineated in this study for the study area agree with the results of some earlier geophysical studies that cover the study area and its environs. For example, Rahaman (1988) observed that the major rock types within the study area and its environs include Migmatitic gneiss, granite and schist, into which has been an emplacement of granite. Ibe (2016) delineated similar rock types in a site in Zaria Area (the study area is part of Zaria Area).

The high horizontal anomaly gradients in Figure 6, seen between the deep blue and the pink areas are indicative of contacts between rocks with different susceptibility values. The sharp contrasts in the colours (Figure 6) are indicative of lithological boundaries and/or faults. This implies that there are different basement rock blocks which have contacts within the area. Such contacts of different rock blocks have been reported in the past in Zaria Area, which includes the study area. For example, McCurry (1973) reported that there are gneisses and granites mostly in the central and eastern (including the study area) parts of Zaria Area and the contacts between them are gradational. Shemang (1990) confirmed the contacts between different rock blocks in Zaria Area but suggested that the boundary between the Zaria granitic batholith and gneiss unit is sharp and not gradational. Ibe et al. (2012) and Ibe (2016) observed that the bedrocks in the study area are made up of rocks of different lithology, separated by elongated rock contact and fault zones. Ibe (2016) discovered a contact between porphyritic granite and gneiss which has recently been exposed at the floor of a valley in Zaria Area by the erosive power of the seasonal stream that flows through the valley.

The lineaments observed on the TMI map (Figure 2) suggest the presence of faults within the study area. These faults trend majorly in the NW-SE direction with minor NE-SW trends. The analytic signal maps (Figures 4 and 5) have also delineated the structures, F1, F3 and F4 as dykes and F2, F5, F6, F7 and F8 as major faults within the study area. Figure 6 shows that F1, F3 and F4 are characterised with long narrow anomalies which suggests that they are elongated. A number of NE-SW trending structures, most likely minor faults, were delineated in areas with high magnetic intensities. The circular contours in Figure 6 are indicative of circular features.

A grey scale applied to the first vertical derivative of the residual field data (Figure 7) and the first and second vertical derivatives of the analytical signal (Figures 8 and 9) delineated structures, FD1, FD2, FD3, FD4 and FD5 (Figure 7) which are most likely major folds within the study area. Similar structures (minor folds), FD6, FD7, FD8, FD9 and FD10 which were not clearly enhanced in Figure 7 were delineated in the first vertical derivative of the analytical signal (Figure 8). The map of the second vertical derivative of the analytical signal presented in Figure 9 shows that all the structures delineated in Figures 7 and 8 were enhanced; some features such as the cross-cut relationships of the faults and fractures within the area were delineated. The extents of the fractures delineated in Figure 9 are also clearer than those in Figures 7 and 8. Also the structures, FD1 – FD10, that were delineated in the first vertical derivative map (Figure 7) and first vertical derivative of the analytical signal map (Figure 8) were also enhanced in the second vertical derivative of the analytical signal map (Figure

9).The fault systems within the area were also enhanced and redefined as FT1, FT2, FT3, FT4 and FT5 in Figure 9. They are the major fault systems within the area trending NW-SE.

The delineation of structures like faults, fractures and folds in this study is in agreement with the results of some earlier geophysical and geological studies in the study area. According to Grant (1969) and Ike (1988), the intense regional tectonism that preceded and accompanied emplacement of the older granite during the Pan African Orogeny produced a well-defined and extensive north – south trend in north central Nigeria, including the study area. McCurry (1975) suggested that the basement complex in this area, together with its supracrustal Younger Metasediments, suffered two phases of tight isoclinal folding during the Pan African Orogeny and the later deformation episode produced steeply dipping structures. Joints – sets and fractures formed here are frequently filled with aplite – pegmatite veins in granites or vein quartz (Adanu 1987). Circular contours in Figure 6 suggest circular features and some earlier geophysical surveys in the study area have inferred the presence of such structures which were referred to as kimberlite pipes (Onugba 1979). Also the areas with the closed contours and with successive contour values increasing towards the centre, and those areas with circular and oval magnetic anomalies indicated by arrows in Figure 6 may be due to accumulations of magnetite and/or pyrrhotite. The accumulation of magnetite and pyrrhotite may be associated with deposit of gold, silver, zinc, lead or copper (Boddington 1990). The areas with very high magnetic intensities (Figure 6) could be due to magnetite and remnant magnetised massive pyrrhotite, while the average magnetic intensities indicated by green colour adjacent to the high magnetic intensities could be due to the destruction of the pyrrhotite by thermal processes. The narrow linear magnetic features seen in F1, F3 and F4 in the contour map (Figure 6) may be due to accumulations of magnetic minerals in fault planes or differences in magnetic properties.

Proposed Structural Map

The results obtained in this study and the interpretations prompted the design of the Structural map (Figure 10) of the study area. The map suggests that the study area has a lot of structural complex features such as dykes, major faults that trend NW-SE, minor faults and fractures trending NE-SW with minor NW-SE, shear zones and folds.Areas that have complex structures are known to correlate with mineralization, especially, where found within the quartzite schist rocks; therefore areas with higher structural complexity are likely zones of mineralization (Zlotnikov 2012).

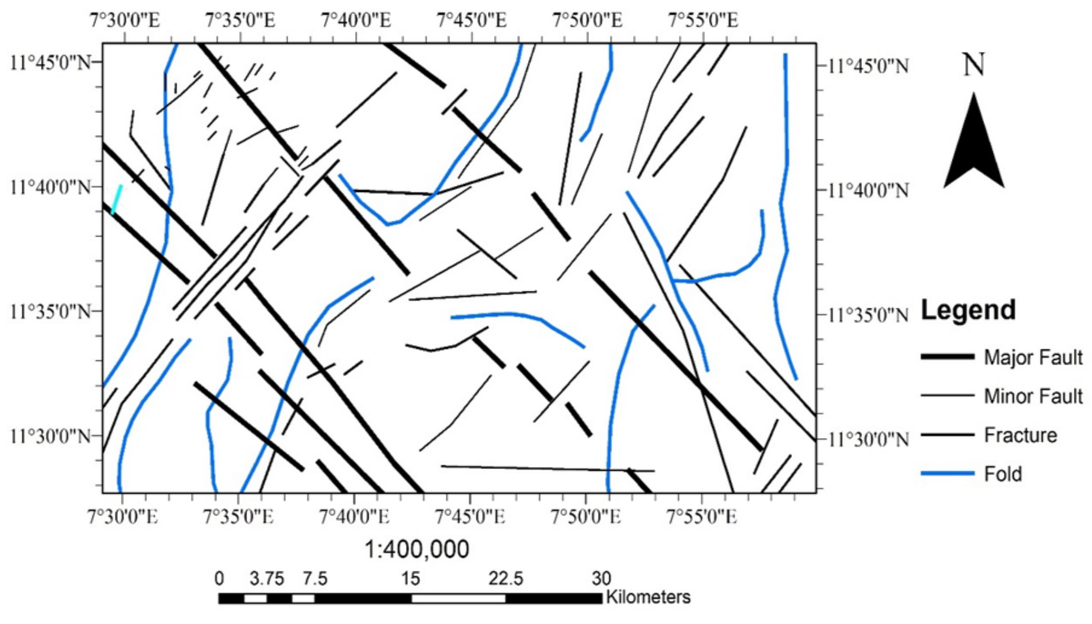

Figure 10. Interpreted Structural Map of the Study Area.

Three deformation events were proposed based on the interpreted structures as deduced from the magnetic dataset. The earliest deformation event (D1) is defined to be a ductile deformation producing folds whose axial planes trend N and NE-SW directions. The second deformation event (D2) resulted in the reactivation of the D1 structures, particularly, the folds, in the N-S and NW-SE directions and the formation of the major fault systems within the area. The third deformation event (D3) produced a transgressive deformation, starting with ductile deformation, resulting in the development of NE-SW to E-W oriented structures observed at the boundary and within the schist rocks at the central and northeastern parts of the area; brittle deformation occurring at later stages of the D3 event producing fractures oriented in the NE-SW and E-W directions. These interpreted deformation events are in agreement with the work of obaje (2009).

VI. Conclusion

This study delineated migmatite gneiss and granite gneiss, schist, porphyritic granite and quartzite schist with granulite facies of mafic rock, as the principal rock types constituting the lithology of the study area. The study also delineated five major fault systems, with dominant trend in the NW-SE direction, minor faults and fractures trending NE-SW with minor NW-SE, shear zones and folds, within the study area. The fault systems show major cross-cut relationships. The delineated lithology and structures aided the design of the structural map of the study area. The delineated structural complexity within quartzite schist rocks suggested zones of mineralization and hence recommended ground geophysical survey as coring as the area is known to host gold mineralizationand kimberlite pipes.

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