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Detection of Subsurface Structures at Ganmo–Amoyo–Ojoku Nigeria Using High-Resolution Aeromagnetic Data

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ABSTRACT
Subsurface structures have their economic importance and play very important role in mineralization such as conduits and loci of deposition. This study is aimed at detecting the structural lineaments that play very important roles in mineralization of Ganmo–Amoyo–Ojoku areas, Southwestern Nigeria. High Resolution Aeromagnetic Data (HRAD) of Ilorin (Sheet 223) was acquired from the Nigerian Geological Survey Agency (NGSA), processed and interpreted using Oasis Montaj software to assess basement configuration and structural disposition of the area. The data were further enhanced using magnetic techniques such as analytic signal (AS), first vertical derivative (FVD) and tilt angular derivative (TDR). Analytic Signal map locates the magnetic source and boundaries of the magnetic bodies ranging from 0.0884 – 0.2249 nT/m around Agun, Ereje, Orogun, Alaya and Apala which could be targets for mineral prospecting. The Tilt Angular Derivative (TDR) determine the orientations of the lineaments in the study area. The extracted lineament map from FVD and TDR suggested the dominance of Pan African and Liberian orogeny with the orientation in NE-SW and NW-SE. This suggests that NE-SW and NW-SE regional fault could be responsible for the mineralization of the area. It is concluded mineral exploration needs to be conducted in the area for further investigation.

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INTRODUCTION

The detection of geological structures, mineral deposits and any feature of interest in the subsurface depends on the physical characteristics of geophysical method that differentiate them from the surrounding media or host rock (Folorunso *et al*., 2024; Hung *et al*., 2005; Javhar *et al*., 2019). The faults, structural lineaments, hydrothermal alteration, and mineral potential of the subsurface can be studied at the regional scale using a variety of geophysical techniques including the seismic, gravimetric, electric/electromagnetic, radiometric, and magnetic approaches (Adepoju *et al.,* 2021; Hubbard *et al.*, 2012; Liu *et al.,* 2000; Saheed & Magaji, 2022). Magnetic method is a geophysical technique that exploits the variation in magnetic properties of the subsurface, with the ultimate objective of characterizing it. Magnetic field variations are usually diagnostic of the mineral structures as well as regional structures, making it the most versatile of all the geophysical methods (Telford *et al*., 1990). In this method, measurements can be made on the ground (i.e. ground magnetic survey), on the sea/water using ships (i.e. shipborne magnetic survey), and in the air using aeroplane (i.e. airborne magnetic survey or aeromagnetic survey).

Aeromagnetic surveys are usually done as reconnaissance surveys to obtain regional features. Some geological structures have been defined to be the most favourable structural conditions in control of various mineral deposits (Magaji *et al.,* 2025a; Abdelouhed *et al.,* 2022; Megwara and Udensi, 2013). They include the traces of major regional lineaments, the intersection of major lineaments or both major (regional) and local lineaments, lineaments of tensional nature, local highest concentration (or density) of lineament, between echelon lineaments, and lineaments associated with circular features (Mwaniki *et al.,* 2015; Ramli *et al*., 2010; Magaji and Sanusi, 2021). Linear features are clearly discernible on aeromagnetic maps and often indicate the form and position of individual folds, faults, joints, veins, lithologic contacts, and other geologic features that may lead to the location of individual mineral deposits. They often indicate the general geometry of subsurface structures of an area thereby providing a regional structural pattern (Ismaeel *et al.,* 2025; Magaji *et al*., 2025b; Onyewuchi *et al.*, 2012). The geological ingredients that can be interpreted from magnetic surveys are those that influence the spatial distribution, volume and concentration of magnetically significant minerals. Therefore, this research aims at identifying geological structures that play a very important role in mineralization in Ganmo–Amoyo–Ojoku areas, Southwestern Nigeria.

Location and Geology of the Study Area

The area lies between 08˚14′00″ to 08˚28′00″N and 004˚34′00″ to 004˚46′00″E with an area of 562.62 km^2. It covers part of an adjacent half degree sheet of Ilorin (i.e. sheet 223NW) and forms part of the Nigerian Basement Complex, a segment of the Pan-African mobile belt. This basement terrain is composed predominantly of high-grade metamorphic rocks and granitoids that have undergone multiple phases of deformation, metamorphism, and magmatism during the Pan-African orogeny (Rahaman, 1989). Regionally, the Nigerian Basement Complex is subdivided into the migmatite–gneiss complex, the schist belts and the Pan-African granitoids. The migmatite–gneiss

complex constitutes the oldest component and comprises banded gneisses, migmatites, and associated granitoid intrusions (Ajibade *et al.,* 1987; Dada, 1998; Turner, 1983; Rahaman, 1988).
The geology of the crystalline basement rocks of the Ilorin constitutes a component of the West African Craton which is similar to that of the other basement rocks of southwest Nigeria (Dada, 1998; Rahaman, 1989; Turner, 1983). They consist of an Eburnean (2000-200 Ma) migmatite complex. The region's extensive magmatic activity caused the Older Granite series of Pan African age to be deposited. Basement rocks with crystals that range in age from fresh to weathered make up the lithologies beneath. Gneiss, augen gneiss, charnockitic rocks, porphyritic diorites, and granitoids, with pegmatite and aplite occurring as cross-cutting bodies are the main crystalline rocks of the area. The geological setting reflects a structurally complex basement terrain in which lithological diversity and deformation patterns are closely linked (Rahaman, 1988).

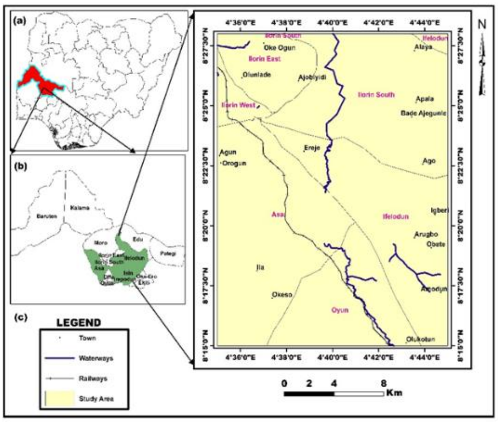

Figure 1: Location Map of the Study Area

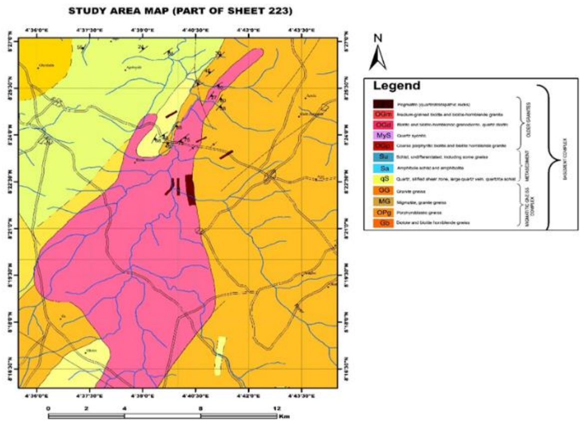

Figure 2: Geological Map of the Study Area

MATERIAL AND METHODS

Data Acquisition

The data set consisted of all field aeromagnetic data from Ilorin (Sheet 223) collected from 2003 to 2009 by Fugro Air borne Survey Limited on behalf of the Nigerian Geological Sur vey Agency during the high-resolution aerial aeromagnetic surveys of Nigeria, real- time differential Global Positioning System (GPS) in drape mode and a sensor mean terrain of 75 m was used as clearance, the survey was used to carry out the operation. The tie line and flight directions were NW–SE and NE–SW, respectively, the tie line and traversed separation was 200 and 500 m, respectively. This is done to improve anomaly information and minimize potential noise and latitude effects, the data were corrected, de-cultured, leveled, adjusted for the International Geomagnetic Reference Field (IGRF), and gridded to the appropriate cell size (Paterson and Reeves,1985).

Data Processing

The entire field data set was recorded in grid format (grd) and then imported into Oasis Montaj (R) software. The High-Resolution Aeromagnetic Data (HRAD) were compiled and gridded at a distance of 125 m in other to produce the Total Magnetic Intensity (TMI) map of the study area. The map was reduced to the equator and was analyzed for correct positioning of the anomalies (i.e. a RTE to correction of 4.132° declination, 9.5342° inclination). The Reduced to the Equator (RTE) operates in areas of low latitude which helps to simplify the interpretation through transformation of the recorded magnetic data at different magnetic field inclinations to what they would be at zero inducing field inclination (Hinze *et al.,* 2013; Phillips, 2007; Lawal and Nwankwo, 2017). The RTE aeromagnetic intensity maps of the study area were then processed using Geosoft Oasis Montaj 6.4.2 software to perform a range of processing operations and data filtering which includes Analytical Signal Amplitude (ASA), First Vertical Derivative (FVD) and Tilt Derivative (TDR). Fig 3 shows the schematic flowchart of the methods and procedure followed to produce the magnetic anomaly and enhancement map which comprises of the ASA, FVD and TDR Field map of the study area.

Analytic Signal (AS)

Analytic signal is an enhanced technique which is related to potential fields (e.g., magnetic field data) by obtaining their derivatives. The expression is given as follows (Nabighian 1972; Miller and Singh, 1994):

$$\mathrm{AS}\,(\mathrm{x,y,z}) = \sqrt{(\partial M/\partial x)^2{}_{\hat{x}} + (\partial M/\partial y)^2{}_{\hat{y}} + (\partial M/\partial z)^2{}_{\hat{z}}} \quad (1)$$

Where$\hat{x}$, $\hat{y}$, and $\hat{z}$ are the unit vectors in *x, y,* and *z* directions.

First Vertical Derivative (FVD)

The FVD is used to enhance shallow features with their boundaries and associated lineaments (Eldosouky *et al.,* 2017). This technique has the ability of amplifying high–wave number anomalous features at the expense of the lower ones (Ibraheem *et al.,* 2019). As a result, shallow features can be properly identified and mapped (Nabighian 1972). Evjen (1936) was the first to delineate edges of gravity and magnetic bodies using the first vertical derivative. If M is the magnetic field, the expression for the FVD is given as (Ibraheem *et al.,* 2019).

$$\mathrm{FVD} = \frac{\partial \mathrm{M}}{\partial \mathrm{x}} \quad (2)$$

Tilt Angle Derivative (TDR)

The tilt derivative filter has been demonstrated by Verduzco *et al.,* (2004) to carry out an automatic gain-control (AGC) function, which attempts to balance the response from both strong and weak anomalies. As a result, the filter offers a useful method for locating notable anomalies within the study region. The TDR was performed on the Reduction to the Magnetic Equator (RTE) map. According to Miller and Singh (1994), the tilt angle is defined as:

$$\Theta = \mathrm{TDR} = \tan^{-1}\frac{(\mathrm{FVD}_{(z)})}{(\mathrm{HGM}_{(x,y)})} \quad (3)$$

where $FVD_{(z)} = \text{First Vertical Derivative}$ and $HGM_{(x,y)} = \text{Total Horizontal Gradient}$

Although the tilt angle gradient is a dimensionless ratio, it responds well to both deep and shallow sources, as well as sources at the same level with a wide dynamic range of amplitudes (Cooper, 2006). The TDR values are much easier to grasp because they are limited to values between - ð/2 and +ῦ/2 (Cooper, 2006).

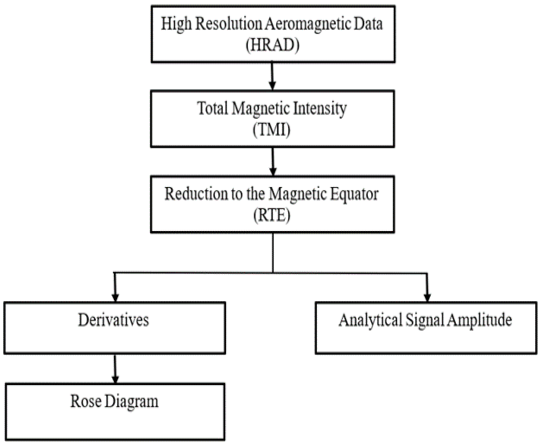

Figure 3: The Research Workflow Procedures

RESULTS AND DISCUSSION

Reduction to the Magnetic Equator Map

The colour shaded on the RTE-TMI map of the study area show three distinct magnetic signatures described by high which is depicted by red and pink colours, intermediate which is depicted by green and yellow colours and the low magnetic anomalies map is depicted by blue colour on the map magnitude is as shown in Fig 4. The high to intermediate magnetic anomalies are interpreted as deeper depth to the magnetic sources while the lowest magnetic anomaly range is interpreted as shallow depth to the magnetic sources. On the map, the high magnetic anomalies signatures have the magnetic field intensity ranged between 56.9329 and 101.345 nT which scattered almost all over the study area and are most dominant at northwestern and also dominant at the southern region these are area around Oke Ogun, Olunlade, Ajobiyidi, Okeso and Amodun, these areas have deeper depth to the magnetic sources. The intermediate magnetic anomalies which vary in magnetic susceptibility between 40.456 - 56.9329 nT. These are the most prevalent in the southwestern area and scattered all around the study area, these are areas around Ila, Amodun and Agun, these areas are areas of average depth to the magnetic sources. The low magnetic signatures range from -93.8619 – 39.4993 nT. Thus, the RTE-TMI map suggests that Ganmo–Amoyo–Ojoku areas are characterized by a complex structural setting with multiple generations of geological structures such as folds, faults and fractures. The NE-SW trending lineaments represents reactivated faults which are related to Pan African orogeny.

Analytical Signal (AS) Map

The AS map (Fig. 5) reveals magnetic anomalies ranging from 0.0065 to 0.2249 nT/km. The map was interpreted for magnetic lineaments by delineating the anomaly maxima mostly observed in the southern and eastern portions of the study area extending from Orogun to Apala and Alaya with continuous linear contour patterns. The lineaments range in lengths from 50 m to 1000 m while the orientations range from NE-SW to NW-SE. In the first magnetic domain, the majority of maxima are trending in the NE–SW direction, while minor maxima are observed to be trending in the NW–SE direction. The contact of magnetic source body was characterized by maximum ASA at their rock contacts depicted with clusters of pink colours in the study area. They are found in SW, NE, SE also in the W with maximum amplitude of 0.225 nT/m.

Magnetic Lineament Analysis

First Vertical Derivative Map

The results obtained after applying the FVD filtering method (Fig. 6) give a good representation of features closer to the subsurface, e.g. faults. In this case, the filtration of data enhanced high-frequency anomalies so that shallower sources could be mapped at the expense of the low-frequency ones. Almost all the entire area is occupied by these high-frequency anomalies, indicating shallow depth to causative sources in comparison with some other parts such as southwest, northeast, northwest and part of north central with deeper sources which have the presence of sedimentary covers (Salem *et al.,* 2007). Also, on the map are long and short linear features distinguishing the edges of magnetic source bodies with zero contour lines representing the locations of the contacts or faults. These two groups of maxima can be associated with intruded granite bodies (e.g. biotite granite, granite gneiss) rich in ferromagnesian-bearing rocks with amount of felsic minerals (Telford *et al*., 1990; Balogun, 2019; Folorunso *et al*., 2024; Magaji *et al.,* 2025). In contrast, the low– and intermediate–magnetic intensity zones might be reflections of downfaulted blocks of the basement complex filled with sediments or possibly a set of tectonic trends controlling the overlying sediments which can be observed at Oke Ogun and Olunlade areas.

The Tilt Derivative (TDR)

The map of TDR shows the RTE-TMI along the x (horizontal) and y (vertical) directions (Fig. 7) to represent the rate of change in the magnetic field and there by highlighting the magnetic anomalies which give clearer contrast between the geologic units and the lineaments/faults e.t.c. (Benabbas, 2006). The map was applied on the RTE-TMI gridded data enhanced shallow wavelength features, resulting to near surface structures, giving rise to a better and clearer picture of the subsurface. The structural framework depends on the normalized magnetic derivatives of its suitability for structural mapping (Oladejo *et al.,* 1999; Gunn and Dentith, 1997). And base on this, the magnetic lineaments which is extracted from TDR map (Fig. 7) has been overlain on their corresponding map in other to obtain the lineaments map in Fig 8 and for the interpretation. Geologically, areas where the magnetic lineaments are in agreement with the anomalies are called ductile deformation zones; on the other hand, areas where they are not in agreement with the anomalies are called brittle deformation zones (Oladejo *et al.,* 1999; Arogundade *et al*., 1999; Barbosa *et al.*, 1999). The ductile deformations were identified and delineated at NNE around Ago, Ajobiyidi, Ila, Igbeti, North of Okeso and central part of the map while brittle deformations were found at the North around Pira, Agun, Alaya and Oke Ogun.

The structural framework was further investigated using magnetic fault map which was obtained from the superposition of the lineaments extracted from TDR and FVD maps (Fig 8). By relating the techniques such as TDR and ASA maps with the geology of the study area helps to gain a better understanding of the subsurface geology and make more informed decisions. The major and minor lineaments of the study area (Fig 8) are of varied lengths between 1950 and 4000 m with a mean length of 2155 ± 535 m and 100 and 900 m with a mean length of 750 ± 305 m, respectively and the structural styles as indicated by Rose diagrams are ENE-WSW, E-W, NE SW and NW-SE (Fig 9) with NE-SW as most dominant constituting 45% of the 136 extracted lineaments. The area under study has either or both; the oldest orogeny known for the basement complex of Nigeria is Liberian >2500 ma, and it is characterized by NE-SW lineaments or by E-W and NW-SE lineaments (D3), which are associated with the Pan African thermo-tectonic event that occurred around 650 ± 150 ma (Oladejo *et al.,* 2019).

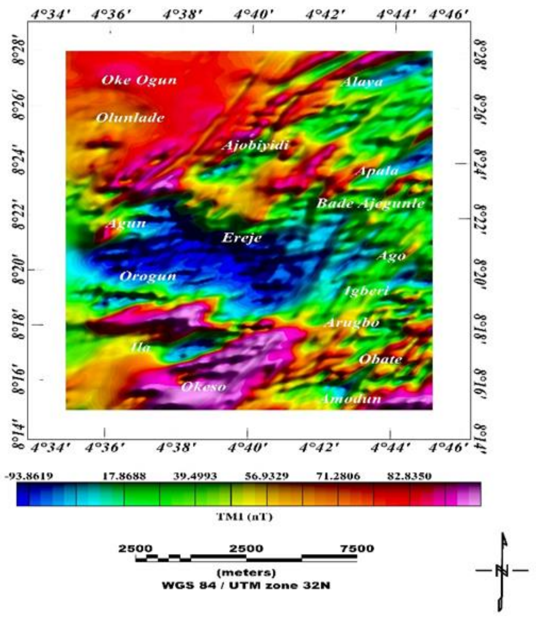

Figure 4: RTE-TMI Map of the Study Area

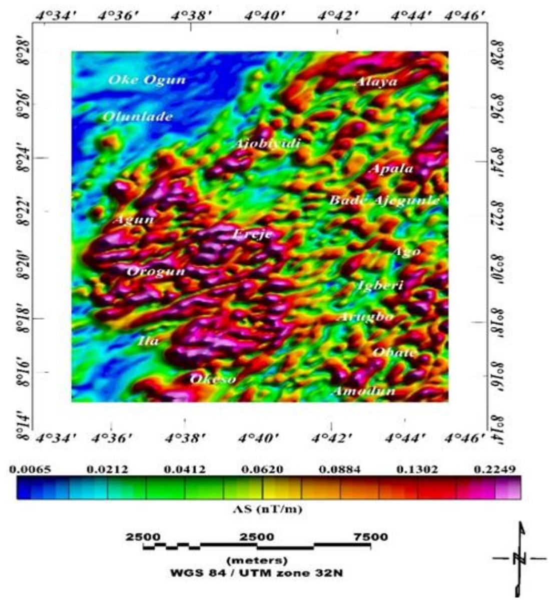

Figure 5 Analytic Signal Map of the Study Area

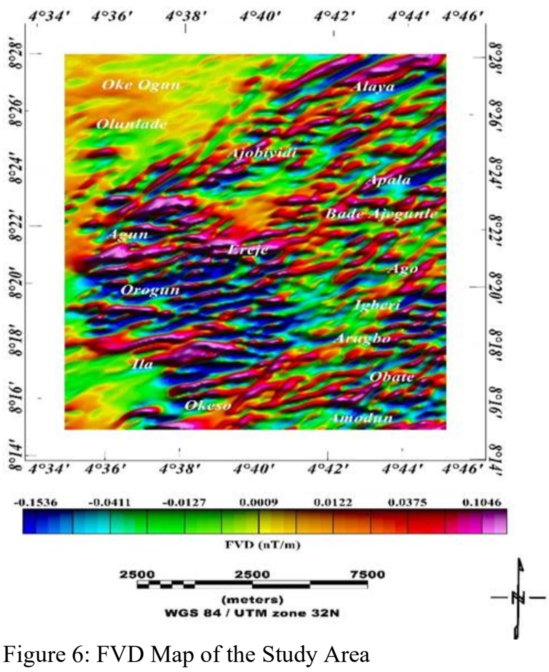

Figure 6: FVD Map of the Study Area

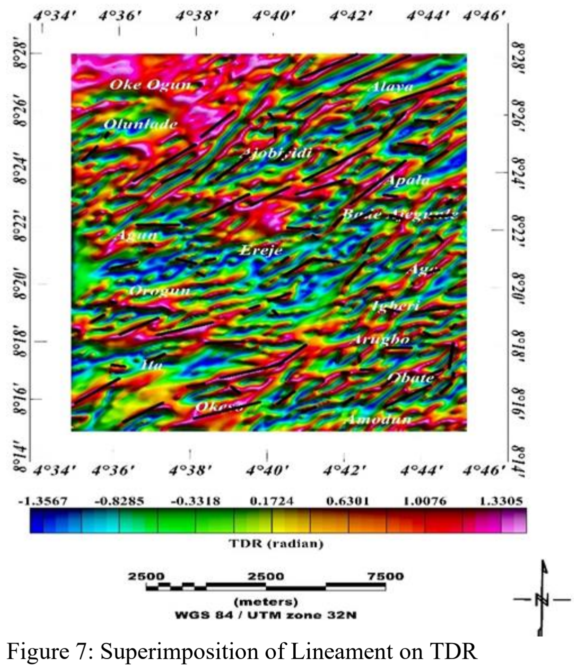

Figure 7: Superimposition of Lineament on TDR

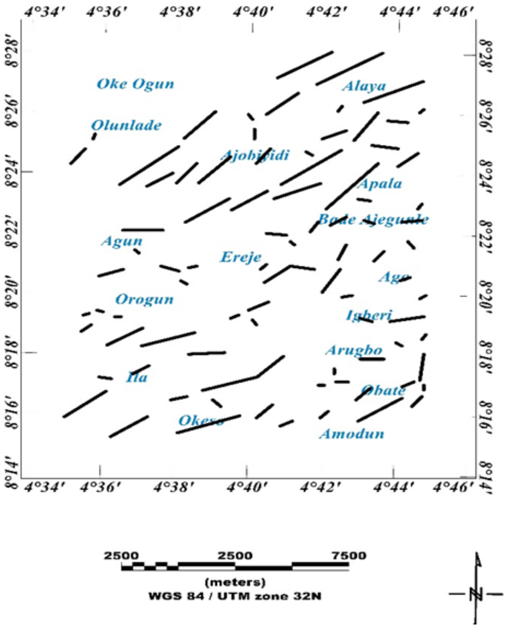

Figure 8: Subsurface Lineaments of the Study Area

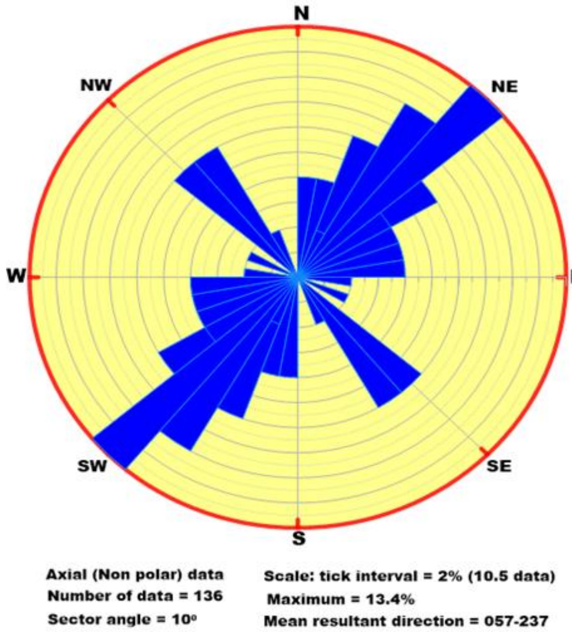

Figure 9: Rossette Diagram of the Study Area

CONCLUSION

This study identified the lithology and structural disposition of Ganmo–Amoyo–Ojoku areas, Southwestern Nigeria using HRAD of Ilorin (Sheet 223). The lithological setting of the study area as shown from the anomaly maps revealed three distinct (low, intermediate, and high) magnetic signatures of about -93.86 and 82.835 nT. The Analytic Signal map locates the magnetic source and boundaries of the magnetic bodies ranging from 0.0884 – 0.2249 nT/m around Agun, Ereje, Orogun, Alaya and Apala which could be targets for mineral prospecting. The extracted lineament map suggested the dominance of Pan African and Liberian orogeny with the orientation in ENE-WSW, NE-SW, E-W and NW-SE. The superposition of these lineaments on their corresponding TDR indicated ductile deformations around Ago, Ajobiyidi, Ila, Igbeti, North of Okeso and central part of the study area.

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