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Delineation of structural lineaments of Shaki West Southwestern Nigeria using high resolution aeromagnetic data

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Abstract

A minor earthquake, known as earth tremor, often occurs in areas prone to seismic activity. However, there is a notable gap in knowledge about earth tremors, with little documentation conducted before 1987, but a series of notable events between 1990 and 2000 prompted researchers to delve deeper into the study of earth tremors in Nigeria. Therefore, this study is aimed at delineating the structural lineaments of Shaki West Southwestern Nigeria using High Resolution Aeromagnetic Data (HRAD) to identify the underlying basement geology and define the structural framework of the study area. The study area's aeromagnetic data of Shaki (Sheet 199) underwent processing and interpretation using Oasis Montaj software to assess basement configuration and structural integrity. The data were further enhanced using the Total Horizontal Derivative (THDR) in order to determine the orientations of the lineaments in the study area. The orientations of the lineaments obtained from THDR map revealed that the Pan African orogeny constitutes 52%; Kibaran orogeny constitutes 31%, while Liberian orogeny constitutes 17% lineaments in the study area. The upward continuation maps suggest the presence of faults at the depth range of 2.0-2.25 km. The overall depth to magnetic sources of the area is relatively shallow compared to sedimentary basement area. Based on orientation of faults on magnetic fault map obtained from the superposition of the lineaments extracted from THDR map on the geological map of the study area, three distinct set of sinistral /dextral faults were recognized in Shaki west local government area which includes: E-W, NE-SW and NW-SE fault trend. This suggests that NE-SW and NE-SE fault-set could be responsible for the tremor experienced in Shaki west southwestern, Nigeria. It is concluded that the study area is not immune from experiencing occurrences of tremors from time to time.

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1. Introduction

Geologic structures, such as, faults impact the way the ground is shaped, assess the risk of landslides, trap natural gas and petroleum, and move during earthquakes [1]. A fault is

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any general discontinuity or planar fracture that has occurred as a result of considerable displacement caused by movements of the rock mass inside the volume of the rock [2]. Plate tectonic processes cause numerous faults in the Earth's interior and the greatest of which define the borders between the plates which are known as transform faults or subduction zones [1]. The degree of fault activity can be important for determining the risk of seismic shaking and tsunamis to nearby infrastructure and humans. There is change in Earth's magnet whenever rock experiences the changes in stress before the occurrence of earthquake [3].

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 [4–7]. Seismic activities occur worldwide with some regions being more prone to earthquake than others, but the distribution of seismic activity which is closely linked to the location of tectonic plates boundaries [8]. Thus, investigating the Shaki region can provide valuable insight to local faults geometry, seismic hazards, and risk assessment which will provide disaster preparedness and mitigation strategies.

An earthquake is a complicated natural event that occurs when a fault ruptures and releases sudden energy. It is a strong ground motion and it is one of the world's most serious hazards [8]. Seismic intensity describes the effects experienced due to ground shaking, as measured on different intensity scales [8]. Volcanism and earthquakes are examples of orogenic activity that are primarily limited to lithosphere plate borders, according to the theory of plate tectonics [9].

Several authors, such as, Al-Badani and Al-Wathaf [10] and Goki *et al.* [11] have researched earth tremors in the past. Ajakaiye *et al.* [12] reported the 28 July 1984 southwestern Nigeria earthquake and its implication for the understanding of the tectonic structure of Nigeria. A maximum epicentral intensity of six was assigned to this tremor on the basis of the macro seismic effects and was located near Ijebu-Ode. According to the author, three aftershocks were recorded in quick succession within twenty minutes, and they were linked with tectonic activities of Atlantic fractures that extend into the Nigerian landmass. Oladejo *et al.* [13] carried out an investigation of the structural stability of the subsurface of the Ibadan area against Earth tremor using aeromagnetic data. The data were further processed using THDR to obtain the lineament orientations, which revealed the percentage of lineaments Orogenies in the area. The research concluded that the Ibadan area is not immune from experiencing tremor occurrence. Akpan *et al.* [14] carried out an earthquake offshore southwestern Nigeria where it was shown that the fault that triggered the tremor ruptured at about 10 km within the upper crust local magnitude of 4.5 and moment magnitude (Mw) of 4.1. The epicentre of the earthquake lies very close to the fracture zone situated between the Romanche and Chain fracture zones, an extension of the Atlantic fracture zone into the continent. Isogun and Adepelumi [15] researched the seismic occurrence between 1990 and 2009 in the mid-Atlantic fracture zones (between Latin America and West Africa). The structural features of Shaki West south western Nigeria reflects the region's geological complex and cultural history which influences from the pan-African orogeny and the Shaki cultural heritage.

Therefore, this research is aiming at providing a comprehensive understanding of the geological structures underlying Shaki west local government, southwestern, Nigeria and to inform decision-making in seismic hazard assessment, environmental management, and conservation with the use of HRAD interpretation to identify the underlying mechanism driving earthquakes since it has a smaller spatial resolution which allows more precise mapping of geological features. The anomalies contain in magnetic data includes magnetic high, magnetic low, magnetic gradients and magnetic anomalies which consists of fractures and other structural features.

1.1. *Description and geological structure of the study area*

The study area is one of the parts of the Basement Complex of the Southwestern Nigeria. They were thought to have been developed during the Pan-African Orogeny [16]. Part of the regions of the country where Basement Complex rocks are found is south of Nigeria, which includes the larger portions of the state of Kwara, Oyo, Ogun, and Ondo; southwest of Nigeria as shown in Figure 1. Shaki, Oyo State, Southwestern Nigeria located within latitude 8°13'48" – 8°40'12" N and Longitude 3°12' 0" – 3°23'24" E. Figure 1 shows the geologically map of the study area and it is made up of older rock types which had been metamorphosed into various rock types which comprises of Migmatite gneiss, Pegmatite, Hornblende granite, Granite, Szyenite, Porphyritic granite, Porphyroblastic gneiss and Quartz schist also occurring as ridges. These rocks-types exhibits folded structures such as folds, kinks, or crenulations and they have complex interplay of magnetic activity, deformation, metamorphism in the past and the occurrence of these tremors in Nigeria are attributed to the reactivation of ancient's faults and fractures within the granite formation. The major faults such as Shaki-Okemesi fault, Ifewara faults were found in Shaki west south Western Nigeria.

2. Methodology

2.1. *Data acquisition*

The data set consisted of all field aeromagnetic data from Shaki (sheet 199) collected from 2003 to 2009 by Fugro Airborne Survey Limited on behalf of the Nigerian Geological Survey 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 [17].

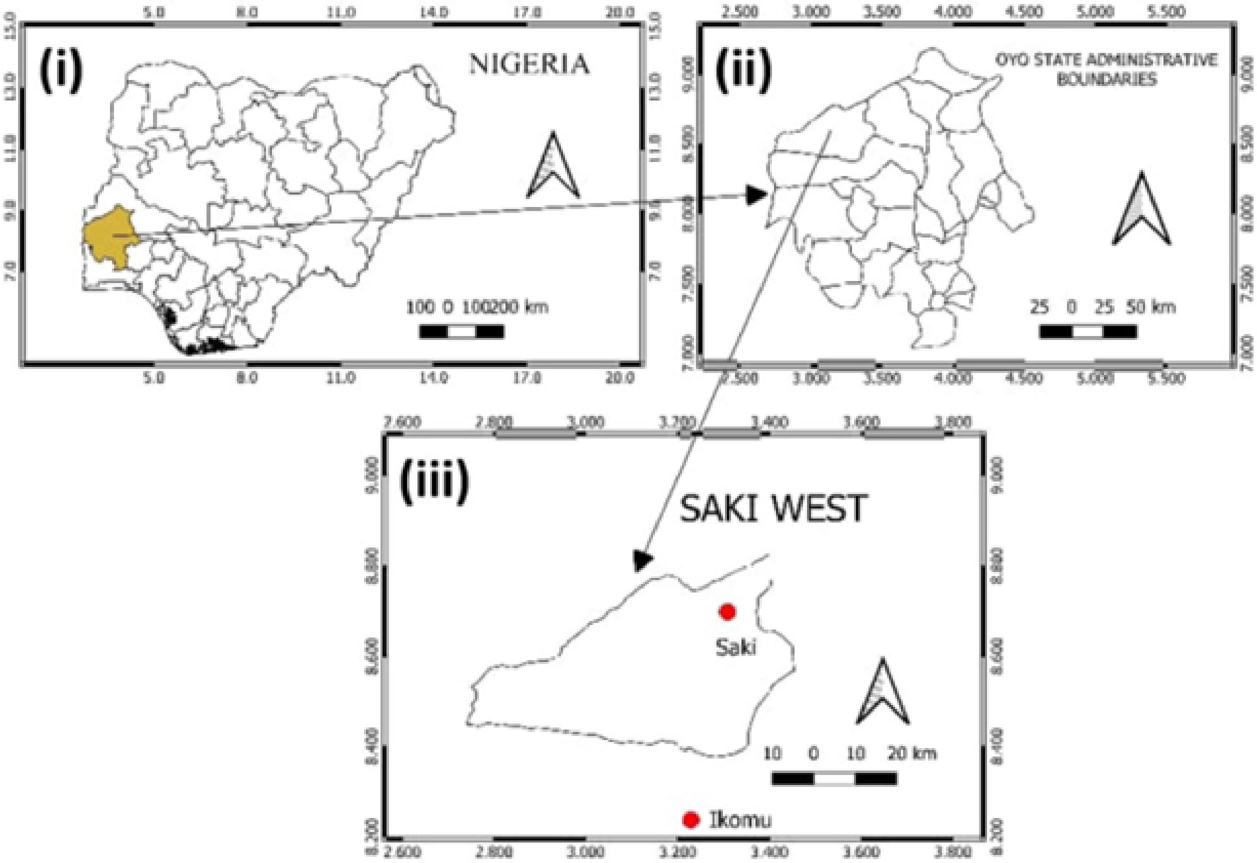

Figure 1. Administrative map of (i) Nigeria, (ii) Oyo State and (iii) study area (Saki).

2.2. *Data processing*

The entire field data set was recorded in profile in Excel format and supplied using Oasis MontajTM. In order to compare the final maps with the region's geological map for interpretive purposes, the constraining geographic coordinates were transformed into degrees using the RockwareTM 15 software.

The HRAD were compiled and gridded at a distance of 100 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. 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.

The RTE residual 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, THDR, Depth estimation, Tilt Derivative, Analytical Signal Amplitude (ASA), 3D Euler Deconvolution at different spectral indices, Source Parameter Imaging together with the Average Power Spectrum.

Figure 3 shows the schematic flowchart of the methods and procedure followed to produce the magnetic anomaly and enhancement map which comprises of the TMI map and the Regional Magnetic Field map of the study area as shown in Figures 4 and 5 respectively.

2.3. *Magnetic derivatives analysis*

X- and Y-horizontal derivatives, vertical derivative, tilt derivative and THDR are examples of magnetic derivatives. These are used in measuring the depth and horizontal placement of magnetic bodies, identify the borders of magnetized structures, and bring out details in magnetic data. However, in this research, The Tilt derivative and THDR were utilized. Using edge detection techniques, the boundaries of faults, intrusive bodies and lateral alterations were marked out with THDR. After the lineaments were taken out of the derivative maps, Rose diagrams were used to show which way they were oriented. Additionally, the azimuthal distribution of the related orogenies and the extracted lineaments was ascertained.

The Tilt derivative is a useful tool for structural mapping, which was used to describe the locations of the magnetic edges in order to identify the side of each edge which is likely to have a higher magnetization and provide a quantitative indication of the dip contact. Tilt derivative was also used in normalization of the signatures present in the images of magnetic data, so that

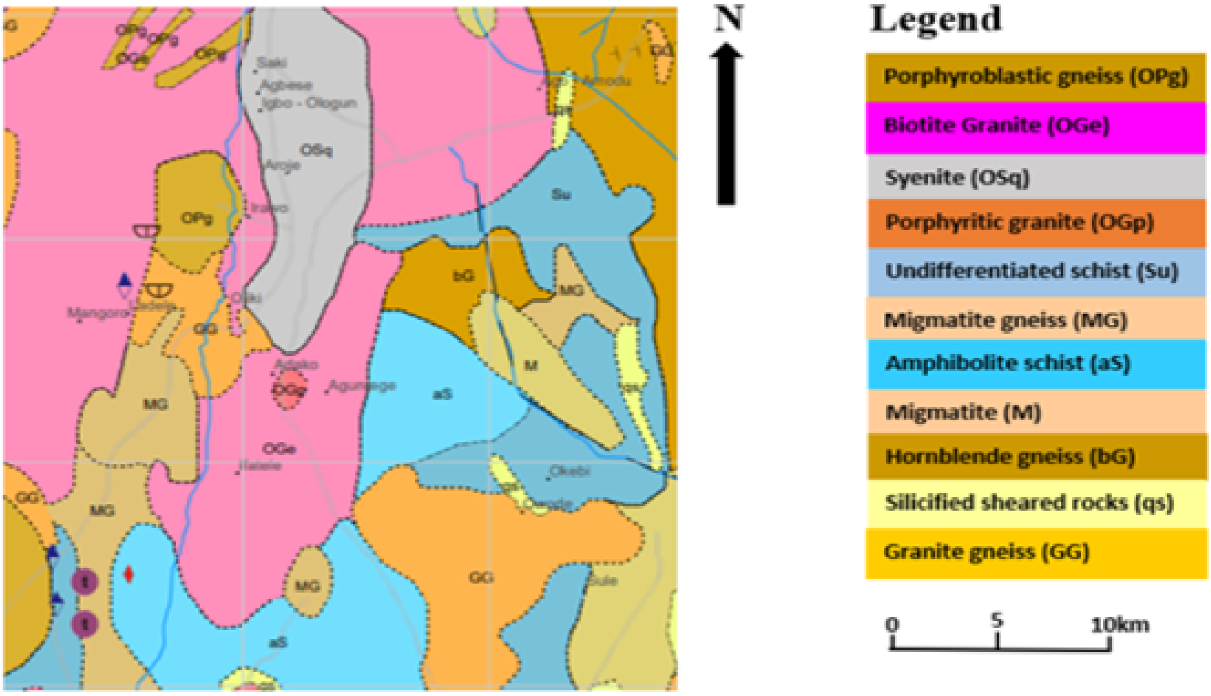

Figure 2. Geological map showing the study area (Shaki).

weak or small amplitude anomalies can be amplified in relations to the stronger ones. Additionally, in this research, ASA was used, which is notable for its independence from magnetization direction, to locate the contacts of magnetic substances that are often characterized by greatest amplitude.

Using upward continuation, which smoothed the original data through attenuation of the short wavelength or anomalies of high frequency to their low frequency or long wavelength counterparts, the continuation processes allowed data to measure on one surface to be transformed to a higher surface and were used in discriminating the deeper magnetic sources against shallow magnetic sources. Depending on the degree of continuation, the processed output map showed that the remaining high or low frequency anomalies, which corresponded to shallow or deeper origins in the bedrock.

2.3.1. *Reduction to the equator (RTE)*

Reduction to the equator (RTE) is used in low magnetic latitudes because it makes the magnetic field of the Earth and magnetization of the magnetic sources appear horizontal and also centers the peaks of magnetic anomalies over their sources. This can make the data easier to interpret while not losing any geophysical meaning [18–21]. The RTE map was generated using the geomagnetic inclination and declination of -7.8^o and -1.38^o, respectively from IGRF calculation for a position (X – 3.71^o, Y – 8.74^o) for the sheet.

2.3.2. *Regional residual separation*

This is the process of separating the magnetic effects due to deep seated sources known as the regional from the magnetic effects due to shallow sources known as the residual to focus on that of interest. The field continuation method, among other methods (such as graphical residualizing, surface-fitting residualizing methods, empirical gridding methods, and second vertical derivative methods), is used to isolate the regional and residual components from the RTE map [18, 19]. The Fast Fourier transformation is used in this procedure.

3. Results and discussion

3.1. *Total magnet intensity*

The TMI maps (linear and histogram) of Shaki (Figure 4) were processed to generate regional magnetic field anomaly maps (linear and histogram) of Shaki (Figure 5) and the RTE maps, which show a slight shift in the magnetic anomaly positions northeast of the initial positions on the total anomaly. This eliminates the effect of latitude of magnetic bodies on the residual anomalies and enables one to identify the measured. Also, the Residual Magnetic Intensity (RMI) image of Shaki is shown in Figure 6.

It should be noted that the linear component map identifies the faults orientations, faults density and structural complexity of the study area while the histogram components identify the type of magnetic anomaly, anomaly intensity and geological setting of the study area.

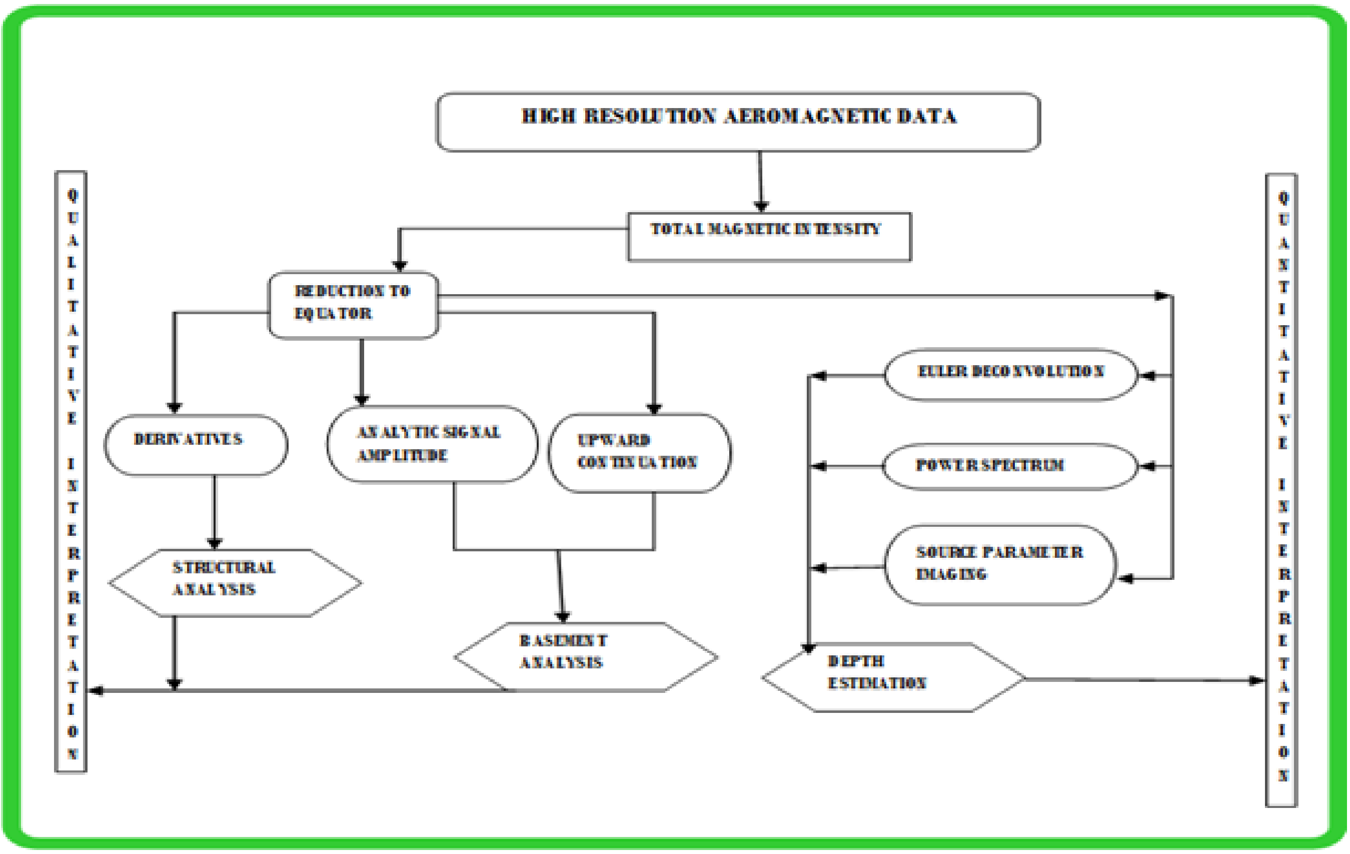

Figure 3. The research workflow procedures was employed as illustrated [18].

The TMI map suggests that Shaki west is characterized by a complex structural setting with multiple generations of faults and fractures. The NE-SW trending lineaments represents reactivated faults which are related to Pan-African orogeny, while the NW-SE trending lineaments represents faults related to Dahomey basin. Profiles taken on the noise-filtered Reduced-to-Equator Total Magnetic Field Intensity (RTE-TMI) anomaly maps, the regional magnetic field anomaly map, and the RMI anomaly map of the study area, Shaki, are displayed in Figure 7.

From the profile, it can be deduced that the regional anomaly curve is smooth and has a large horizontal extent which means that the sources are deeply seated in contrast to the residual anomaly curve which is not smooth.

3.2. The RTE-TMI map

The colour shaded on the RTE-TMI maps (linear and histogram) 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 Figure 8. The high to intermediate magnetic anomalies are interpreted as shallow depth to the magnetic sources while the lowest magnetic anomaly range is interpreted as deep depth to the magnetic sources.

On the map of the study area as shown in Figure 8, the high magnetic anomalies signatures have the magnetic field intensity ranged between 0 and 314 nT which scattered almost all over the study area and are most dominant at southeastern and also dominant at the western region these are area around Okoto, Shaki, Owu, Iganran, Tede, Irawo, Irawo-Owode and so on, these areas have shallow depth to the magnetic sources. The intermediate magnetic anomalies which varies in magnetic susceptibility between 0 and -400 nT. These are the most prevalent in the southwestern area and scattered all around the study area, these are areas around Guremu, Budo-Ige, and Petoko-Titun, these areas are areas of average depth to the magnetic sources. The low magnetic signatures range from -400 to -503 nT.

Thus, the RTE-TMI map suggests that Shaki west is characterized by a complex structural setting with multiple generations of faults and fractures. The NE-SW trending lineaments represents reactivated faults which are related to Pan-African orogeny, while the NW-SE trending lineaments represents faults related to Dahomey basin.

3.3. Magnetic lineament analysis

On the linear maps of the area (Figures 9(a) and (b)), the areas of deep blue in (a) and grey in (b) are of deep depth to the magnetic sources, these areas include: Petoko-Titun, Guremi, Pira, Ago-Are while the portions with others colours are ar-

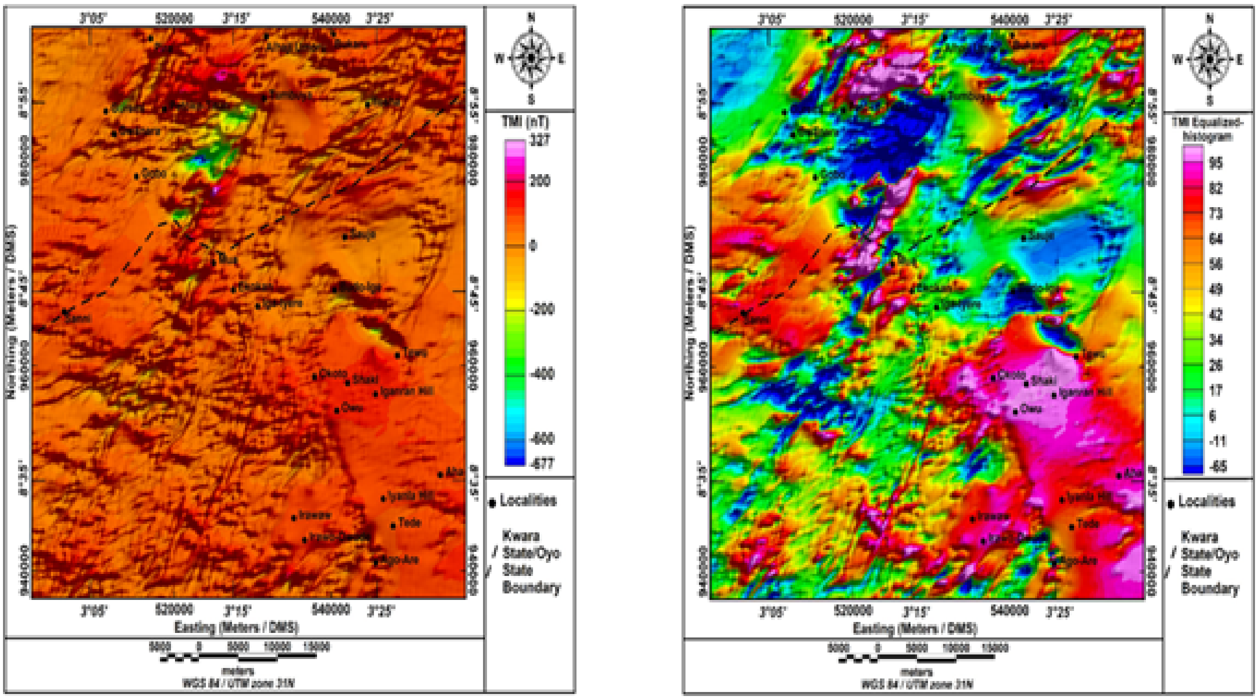

Figure 4. TMI relief image showing both linear and histogram of Shaki.

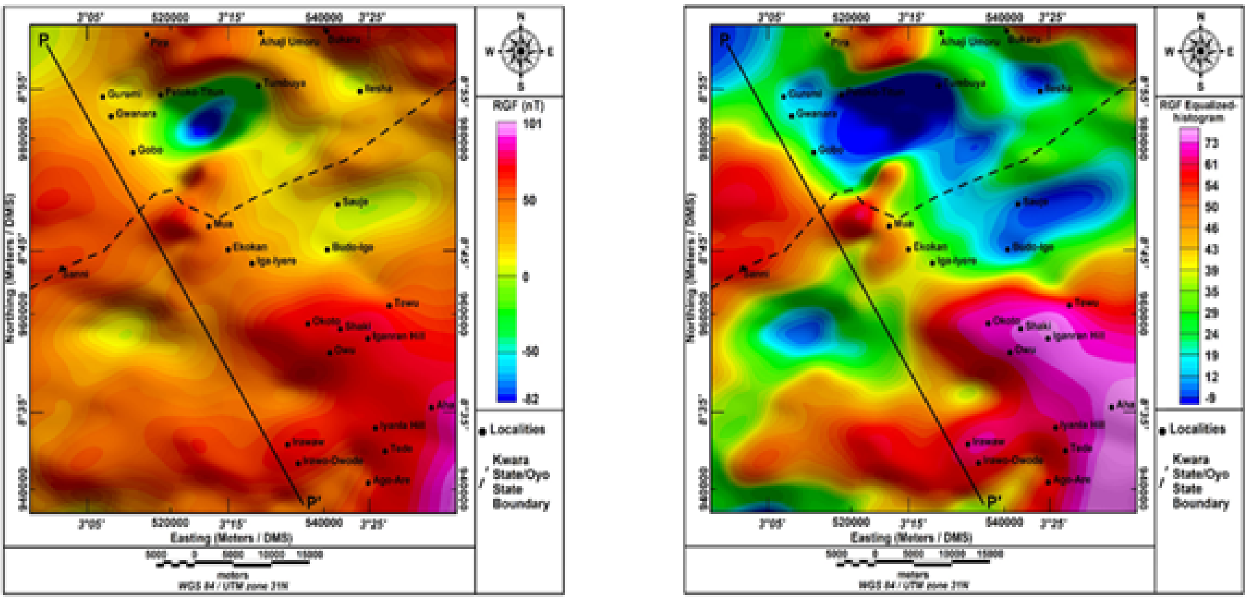

Figure 5. Regional magnetic field showing both linear and histogram of Shaki.

eas of shallow depth to magnetic sources, these areas include: Shaki, Owu, Irawo-Owode, Tede, Ekokan, Iga-Iyere, Sanni.

The major and minor lineaments of the study area (Figure 10(a)) are of varied lengths between 15000 and 74000 m with a mean length of 54445 ± 445 m and 2000 and 12000 m with a mean length of 5375 ± 549 m, respectively and the structural

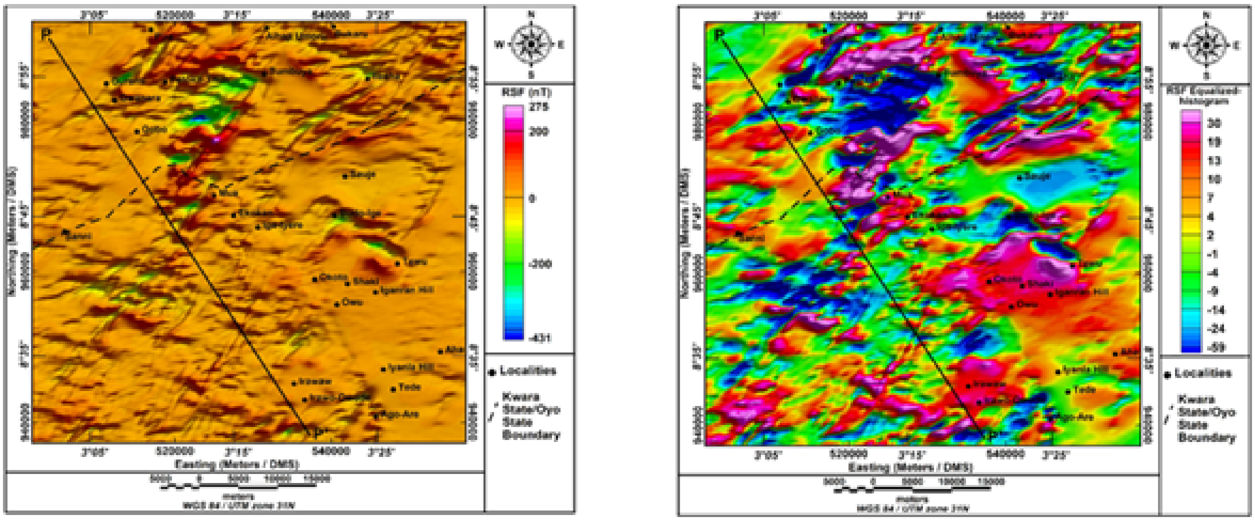

Figure 6. RMI image showing both linear and histogram of Shaki.

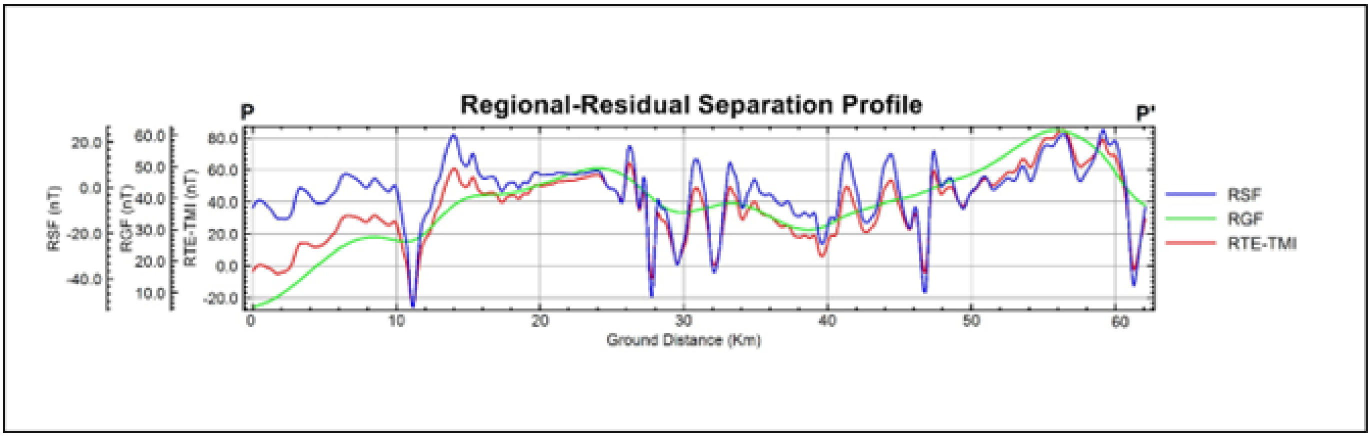

Figure 7. Profile on the RTE-TMI (Total Field), regional field and the RMI of Shaki.

styles as indicated by Rose diagrams are ENE-WSW, E-W, NE-SW and NW-SE (Figure 10(b)) with E-W as most dominant (Table 1) constituting 47% of the 230 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 E-W lineaments (Table 1) or by NE-SW and NW-SE lineaments (D3), which are associated with the Pan African thermo-tectonic event that occurred around 650 ± 150 ma [13].

The contact of magnetic source body was characterized by maximum ASA at their rock-rock contacts as shown in Figure 11, depicted with clusters of pink colours in the study area which is demarcated with white colour. They are found in NW, NE, SW also in the E with maximum amplitude of 1.05 nT/m.

Table 1. Lineaments categories taken from grayscale THDR map and related orogeny.

Lineaments (%)	Trends	Orogenies
47	East-West	Liberian
29	Northeast-Southwest	Pan African
24	Northwest-Southeast	Kiberian

3.4. *Upward continuation*

Upward continuation entails boosting large scale, typically deep features in the survey area; as a result, anomalies resulting from deep sources are often more prominent than those resulting from shallow sources [2, 11].

From the RTE-TMI maps in Figure 8, the regions with red and pink colours depict regions of high magnetic intensity

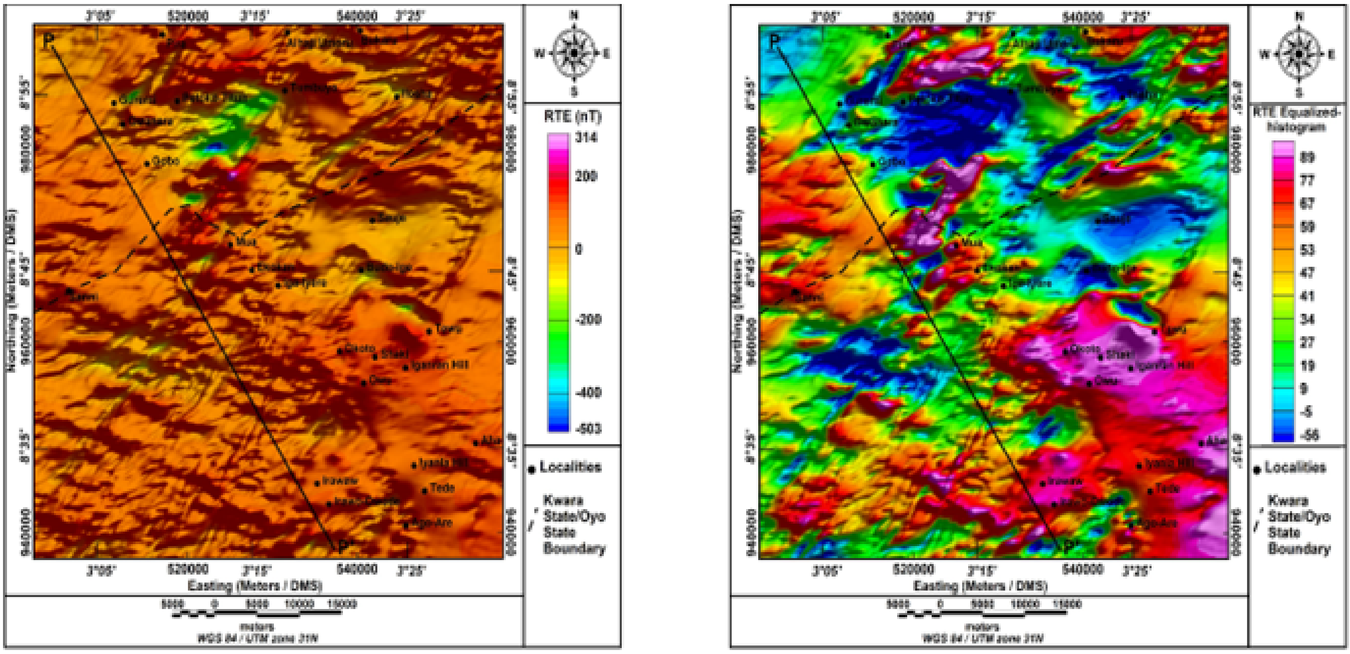

Figure 8. The RTE- TMI map (linear and histogram) of Shaki.

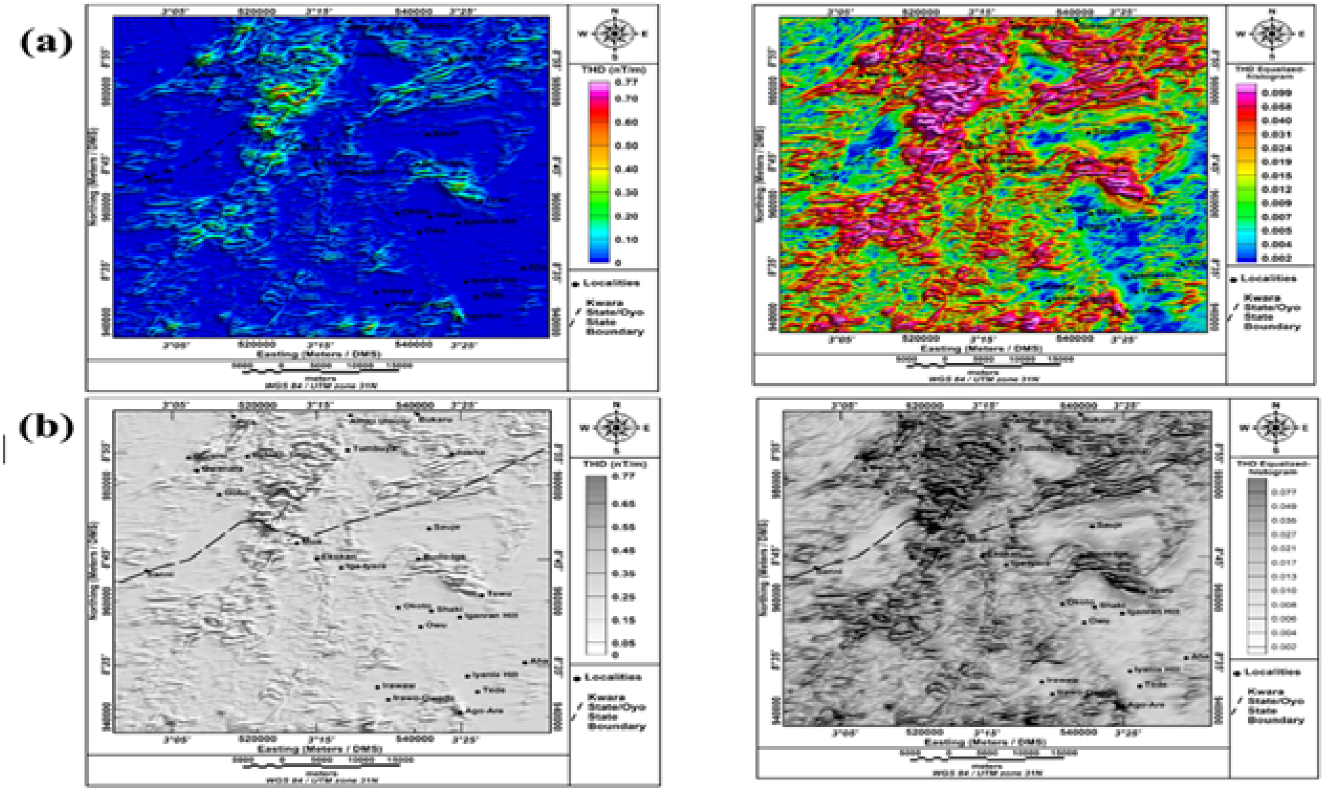

Figure 9. THDR map of Shaki showing both linear and histogram of (a) colour shaded map and (b) Gray shaded map.

sources while the regions with blue colours depict regions with deep depth magnetic intensity sources the regions with green colours depict regions with intermediate magnetic intensity regions it lies between the deep and shallow basement. These are also established by Figures (9(a) and (b)). On the linear maps of the area (Figures 9(a) and (b)), the areas of deep blue in (a) and

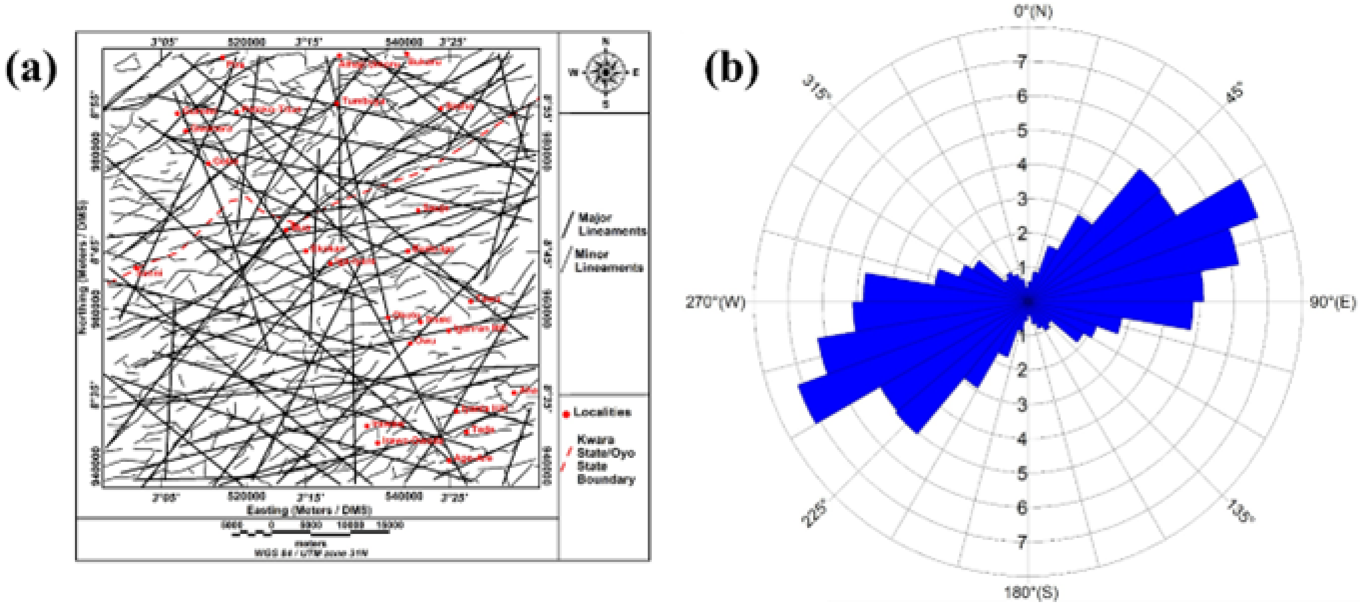

Figure 10. (a) Magnetic lineaments map extracted from the THDR map and (b) Rose diagram displaying the lineaments orientations.

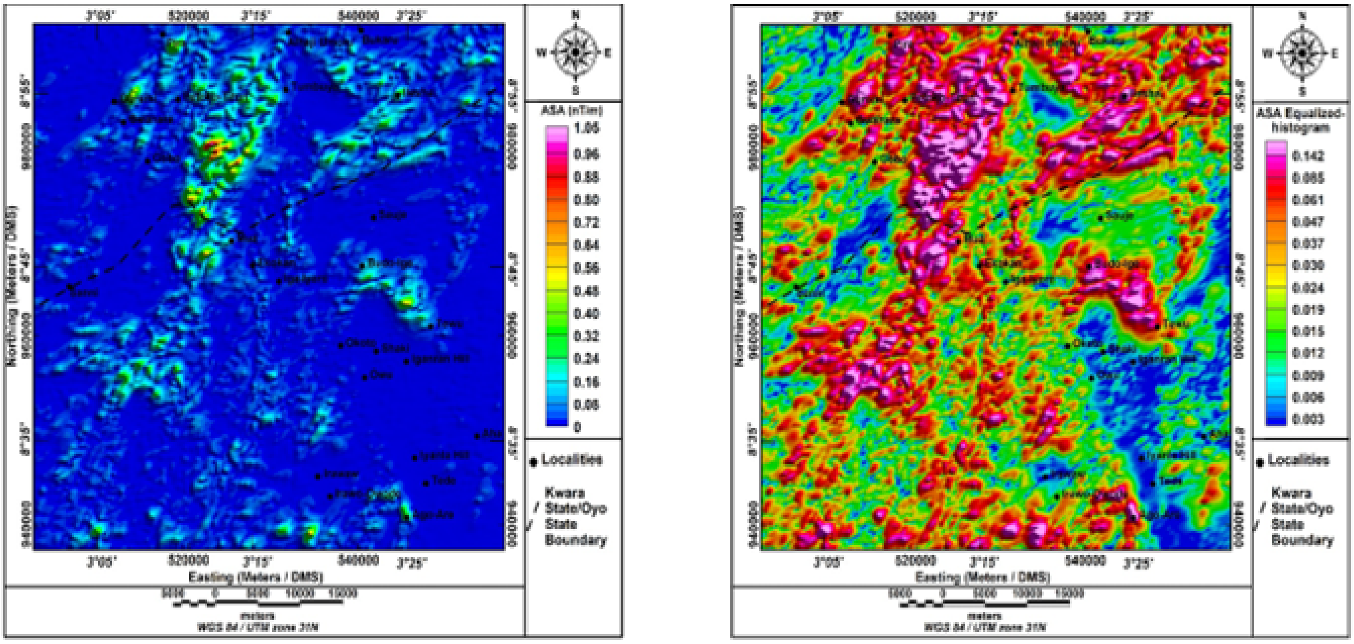

Figure 11. ASA map of the TMI field.

grey in (b) are of deep depth to magnetic sources, these areas include: Petoko-Titun, Guremi, Pira, Ago-Are while the portions with others colours are areas of shallow depth to magnetic sources, the areas include: Shaki, Owu, Irawo-Owode, Tede, Ekokan, Iga-Iyere, Sanni. Several linear features trending NE-SW are observed in the northern part of the study area which represents that faults and fractures were related to the tectonic activities in the study area.

Additionally, as one is traveling away from the anomaly, upward continuation has an effect of smoothing out short wavelength features [11]. On the upward continuation maps of the research areas, however, areas of continuous high amplitude represent areas of deep depth to magnetic sources; similarly, on the map in Figure 12, sharp shifts from high magnetic anomalies to low magnetic anomalies are fault zones areas. Moreover, Figure 12 shows the faults detection zones in the study area and these were identified through the linear features and displacement of the geological units which results in changes in the

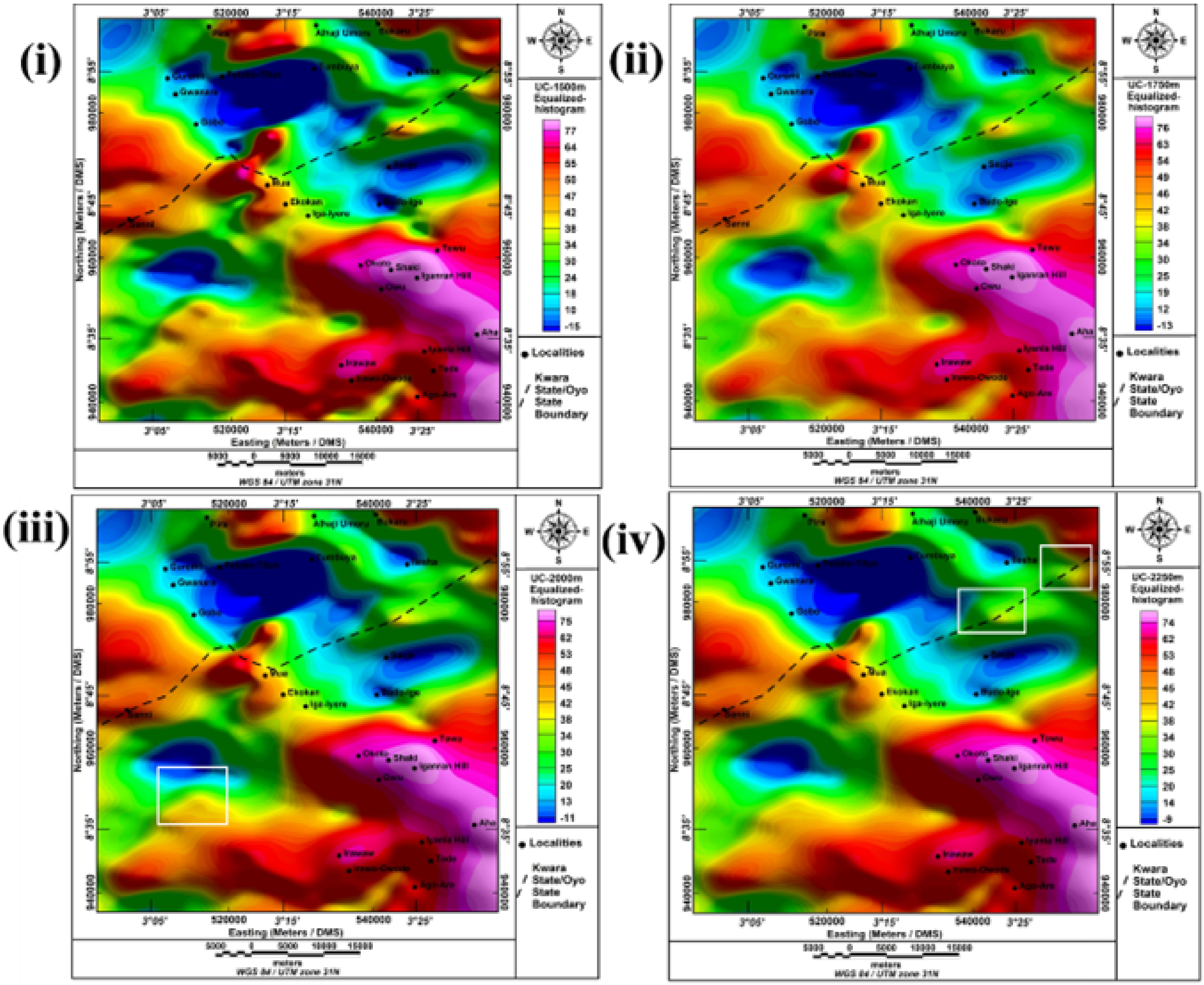

Figure 12. Fault detection at depth: (i) 1500 m; (ii) 1750 m; (iii) 2000 m; (iv) 2250 m; obtained from upward continuation process of RTE-RMI map.

lineaments orientation and positioning of the rocks.

From the upward continuation map; the identified faults are demarcated with white rectangles at depth 2000 m at SSW and NNE and at 2250 m at NNE of the area (Figure 12). The map of THDR shows the TMI along the x (horizontal) and y (vertical) directions (Figure 9) 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. [15]. The THDR map (Figure 12) and applied on the RTE-RMI 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 [22–26]. And base on this, the magnetic lineaments which is extracted from THDR map (Figure 9) has been overlain on their corresponding RTE-TMI maps (Figure 8) using Arc-GIS 10.3 software in other to obtain the lineaments map in Figure 13 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 [22, 23, 25].

The ductile deformations were identified and delineated by white circles at NNE around Ilesha, SSE around Ago-Are, central around Okoto and SSW around Sanni while brittle deformations were found and demarcated by white rectangle at North around Pira, NNE around Bukaru, Central around Mua, West around Guremi, and east around Tewu of Shaki.

The structural framework was further investigated using magnetic fault map which was obtained from the superposition of the lineaments extracted from the THDR maps on the respective geological maps of the study areas (Figure 13). By applying the techniques such as THDR and ASA maps with other geological and geological data to the context of the study area helps to gain a better understanding of the subsurface geol-

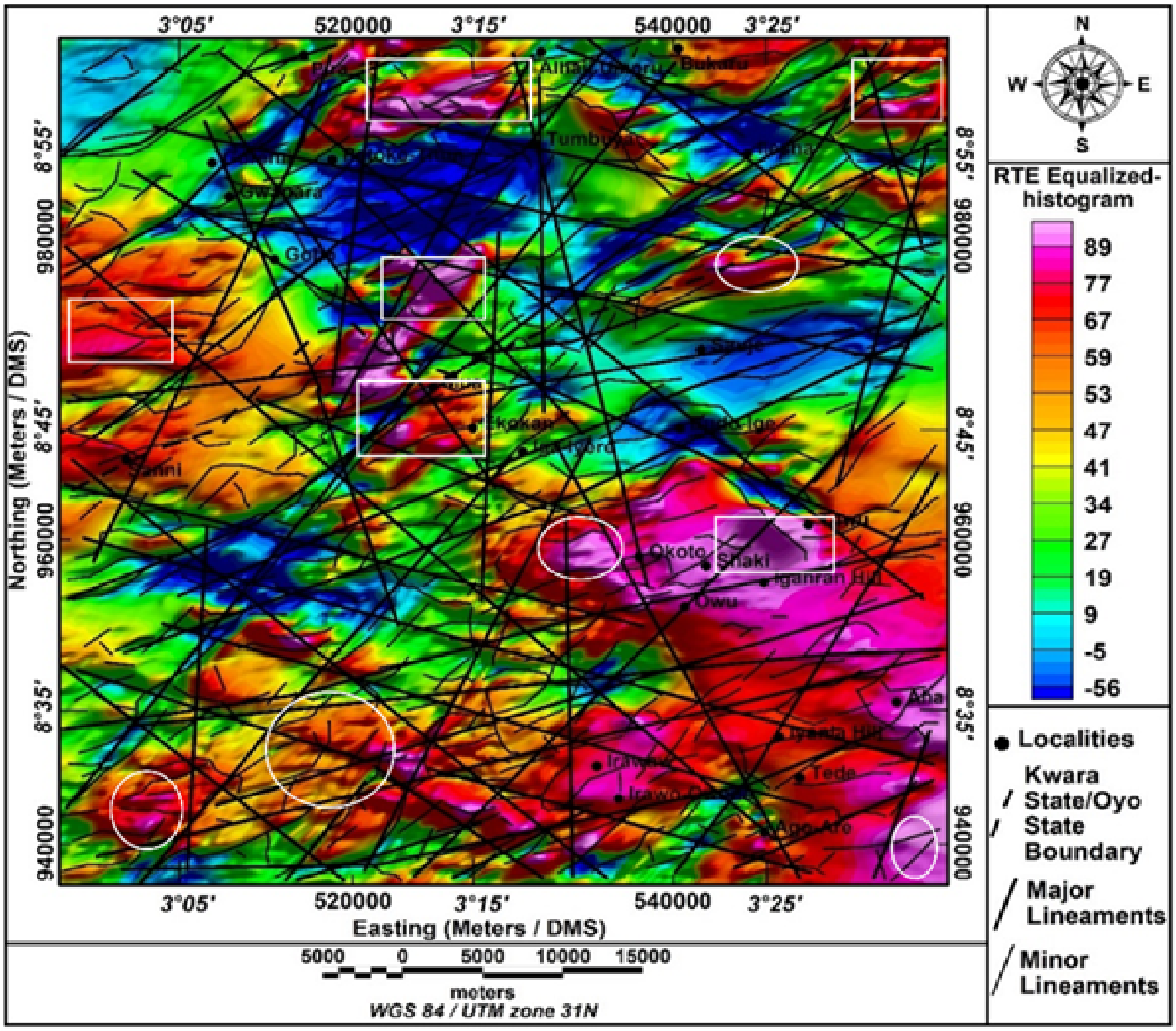

Figure 13. Combine lineaments map and its RTE-RMI map.

ogy and make more informed decisions. Moreover, techniques such as THDR, ASA, 3D Euler Deconvolution reveals the orientation and trend of structural features such as faults, fold, and lineament of the study area.

4. Conclusion

In this study, HRAD of Shaki (sheet 199) was processed, corrected, recorded, enhanced, and interpreted with the use of Geosoft Oasis Montaj, ArcGIS and Rockwares analysis and data processing software was used to study the lithology and structural disposition of the study area to determining the stability of the area. The lithological setting of the study area as shown from the anomaly maps revealed three distinct (low, intermediate, and high) magnetic signatures about -400 to -503 nT; 0 to -400 nT; 0 to314 nT. The extracted lineament from THDR maps suggested the dominance of Pan African and Liberian orogeny and the structural styles by rose diagram revealed the orientation in ENE-WSW, NE-SW, E-W and NW-SE with E-W as most dominant. The study area has either or both of these features: the oldest orogeny known for the Precambrian basement complex of Nigeria and it is Liberian >2500 ma, and it is characterized by E-W lineaments, or by NW-SE and NE-SW lineaments, which is associated with the Pan African thermo-tectonic event that occurred around 650 ± 150 ma (D3). The superposition of these lineaments on their corresponding residual reduced to the equator map of the study area indicated ductile deformations around Shaki, Ilesha, Ago-Are, Okoto and Sanni. The depth continued maps obtained from upward continuation process of RTE-TMI magnetic intensity maps of the study area suggested that there is presence of faults at the depth range of 2000 – 2250 m. Based on the spatial magnetic field intensity of the study area which has more values of high and intermediate magnetic anomalies. The basement depth of the magnetic sources in the study area is relatively shallow, even around the zones that are of low magnetic values. The tremor experienced around Shaki in August 2021 could be as a result of faults identified in the area. Thus, the area could be further probed using seismic method of geophysical investigation. In other to improve the body of knowledge on the study of lineament and structural lineament in Shaki west, south western Nigeria, future research could focus on integration of multidisciplinary data such as remote sensing data, seismic data by applying advanced analytical techniques such as machine learning algorithms, fractal analysis and geospatial analysis to investigate the relationship between lineaments and other geological features.

Data Availability

The data used for this paper will be made available on request.

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