



Airborne Geophysical Investigation of the Tectonic Stability of Gereggu North Central Nigeria for Vulnerable Construction

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Abstract

Aeromagnetic data were employed to assess the tectonic stability of Gereggu, one of the proposed sites for Nigeria's nuclear power plant construction. This study utilized High Resolution Aeromagnetic (HRAD) data processed through horizontal gradient magnitude (HGM), analytic signal amplitude (ASA), and 3-D Euler Deconvolution, to generate lineament maps for evaluating regional tectonic stability. The map of the Total Magnetic Intensity indicates values ranging from -106.2 nT to 179.7 nT. Analysis reveals that the northwestern, western, and southwestern regions exhibit short-wavelength anomalies superimposed on longer wavelength features. The analysis identified 161 magnetic lineaments corresponding to deep crustal structures and shallow expressions. The region is characterized by a strong magnetic response with structural trends along the directions of ENE-WSW, NE-SW, E-W, and NNE-SSW. Qualitative interpretation confirms that the most dominant structural trend is ENE-WSW, followed by NE-SW and E-W orientations. Twenty-one magnetic lineaments were classified as faults, with fault F1 traversing the Gereggu site at depths between 500 - 1500 m. Despite this proximity, no evidence of recent tectonic activity was found, indicating the area has remained tectonically stable and poses minimal seismic risk.

Subject Areas

Environmental Sciences

Keywords

Geregu, Tectonic Stability, Aeromagnetic, Remote Sensing, Lineament

1. Introduction

The increasing demand for reliable and sustainable energy sources has prompted many developing nations to explore nuclear power as a viable solution to their electrical supply challenges. Nigeria, facing persistent power shortages that constrain economic development, has identified nuclear energy as a strategic component of its future energy mix. The Nigeria Atomic Energy Commission (NAEC), responsible for overseeing nuclear technology development in the country, has proposed the construction of a 1000 MWe nuclear power plant (NPP) to address the nation's epileptic power supply [1] [2].

Nuclear facility siting requires comprehensive geological assessment to ensure long-term structural stability and public safety. The United States Nuclear Regulatory Commission (NRC) has established stringent criteria for fault assessment, defining potentially hazardous faults as those that have moved at least once within the past 50,000 years or multiple times within the past 500,000 years [3]. These guidelines emphasize the critical importance of detailed tectonic stability analysis before nuclear facility construction.

Tectonic structures, including faults, fractures, and folds, represent manifestations of crustal deformation resulting from geological processes and stress regimes [4] [5]. Faults, defined as fractures or dislocations in the Earth's crust along which relative displacement has occurred [6], constitute zones of structural weakness that can significantly impact infrastructure stability. The surface expression of these subsurface structures often manifests as lineaments linear geomorphic features first recognized by [7] and later refined by [8] as surface expressions of crustal weakness zones or structural displacement.

Lineaments have evolved from simple geomorphological observations to sophisticated indicators of subsurface geological phenomena. Modern definitions characterize lineaments as natural crustal structures representing zones of structural weakness [9], often associated with large fractures and faults whose orientation and distribution patterns provide insights into regional fracture systems [10]. These features serve as critical indicators for assessing subsurface structural stability, particularly for infrastructure development requiring high geological confidence.

Aeromagnetic surveying has proven highly effective for mapping subsurface geological structures, including lithological contacts, faults, dykes, and regional tectonic patterns. The technique has found widespread application in mineral exploration, hydrocarbon prospecting, basement depth estimation, and crustal studies. [11] successfully utilized High-Resolution Aeromagnetic Data (HRAD) to investigate the extension of Nigeria's Ifewara fault zone, revealing NNE-SSW to NE-

SW trending structures extending from southwestern to north-central regions.

NAEC has identified Geregu in Kogi State, North Central Nigeria, as a potential site for nuclear power plant construction. Given the stringent safety requirements for nuclear facilities and the complex geological setting of the Nigerian basement complex, detailed structural characterization is essential. The proposed site's location within the Precambrian basement terrain, characterized by polycyclic metamorphic history and Pan-African tectonic overprinting, necessitates comprehensive fault mapping and stability assessment.

This study conducted aeromagnetic investigation of the Geregu nuclear site to: 1) map subsurface geological structures using advanced magnetic data processing techniques, 2) identify and characterize lineament pattern, and 3) evaluate the tectonic stability of the proposed nuclear facility site based on fault distribution and structural analysis. The research employed horizontal gradient magnitude, analytic signal amplitude, and 3-D Euler deconvolution techniques on aeromagnetic data to provide comprehensive structural framework analysis essential for nuclear facility siting decisions.

2. Geology of the Study Area

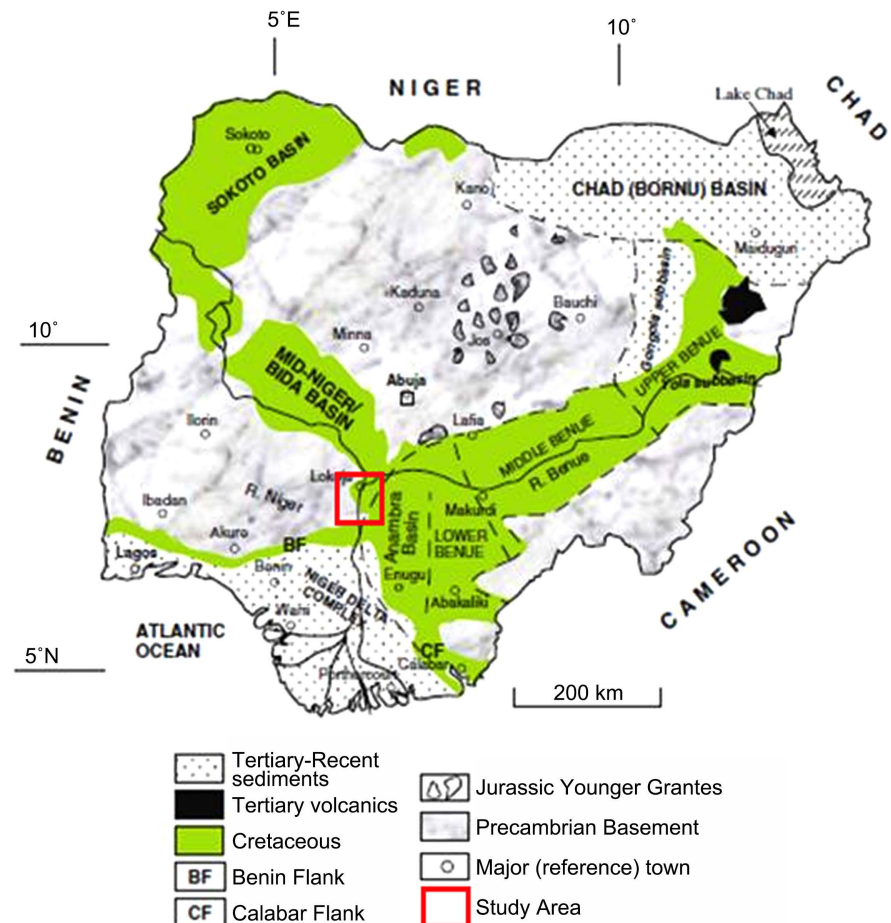


Figure 1. Geological map of Nigeria showing the study area.

Geregu is situated in the Precambrian Basement Complex of north-central Nigeria, underlain by Archean to Proterozoic migmatite-gneiss complexes [12] [13]. The location of the study area is shown in **Figure 1**, covering a total area of 110 km by 110 km. The local geology is composed of medium- to coarse-grained migmatite-gneiss with strong NE-SW foliation intruded by Pan-African granitoids, ca. 600 - 500 Ma age [14]-[17]. These basement rocks are crosscut by pegmatite and quartz veins trending NE-SW and NW-SE, reflecting regional tectonic stress patterns associated with Pan-African orogenic events.

Structural analysis defines brittle deformation features such as minor faults, fractures, and sets of joints corresponding to regional deformation episodes. Despite structural complexity, the area is tectonically stable with no history of seismic events. The polycyclic metamorphism history and proximity to large crustal lineaments make it important to conduct detailed structural characterization for the siting of nuclear facilities.

3. Methodology

The study employed aeromagnetic data to map structural lineaments and assess tectonic stability at Geregu. Data analysis included the application of Geosoft Oasis Montaj v.6.4.2 for aeromagnetic interpretation, ArcGIS 10.3 for spatial analysis, and Rockwork 16.0 for azimuth-frequency modeling of lineaments extracted.

Aeromagnetic data were acquired along NE-SW flight lines spaced at 500 m with NW-SE tie lines at 2 km intervals and a nominal terrain clearance of approximately 80 m. The merged data were interpolated to a 100 m grid cell size using minimum-curvature gridding in Geosoft Oasis Montaj v6.4.2, after which upward continuation was applied at 500 m to suppress shallow cultural noise, while Horizontal Gradient Magnitude (HGM) and Analytical Signal Amplitude (ASA) filters were computed using a 5×5 moving window and Euler Deconvolution was performed with a structural index of 1, a window size of 10, and a tolerance of 15%.

Aeromagnetic Data Processing

Four high-resolution aeromagnetic data covering latitudes 7.00°N to 8.00°N and longitudes 6.30°E to 7.30°E were utilized. The data, which were acquired in Residual Magnetic Intensity format with the International Geomagnetic Reference Field subtracted, were grid-knitted to generate the Total Magnetic Intensity (TMI) map. The TMI data underwent sequential processing steps to enhance structural information. The data were Fourier transformed first to obtain the Reduced-To-Equator (RTE) map, followed by first-order polynomial surface fitting to obtain the Residual Magnetic Intensity (RMI). The RMI was windowed to separate basement and sedimentary regions, then differentially upward continued to enhance deep-seated basement features and attenuate cultural noise.

Advanced filtering methods were then applied to pick fault-related signatures. Horizontal Derivative (HD) processing improved linear structures like fault zones and dykes, whereas Analytical Signal Amplitude (ASA) boosted short wavelength

anomalies for contact definition. Three-dimensional Euler Deconvolution of a structural index of 1 was used to detect fault/contact solutions. Magnetic lineaments were then picked finally by superimposing maxima from Horizontal Gradient Magnitude (HGM), Analytical Signal Amplitude (ASA), and Euler solutions.

4. Results

The Total Magnetic Intensity (TMI) map shows magnetic anomaly values ranging from -106.2 nT to 179.7 nT in the study area (**Figure 2(a)**). Reduced-to-Equator (RTE) map shows spatial variation of magnetic anomalies after pole reduction transformation (**Figure 2(b)**). Both the maps show short and long wavelength anomalies, with definite short wavelength features present predominantly in the northwestern, western, and southwestern parts, superimposed over broad long wavelength anomalies.

First-order polynomial surface fitting to the data of RTE produced the regional magnetic anomaly map (**Figure 3(a)**) and the Residual Magnetic Intensity (RMI) map (**Figure 3(b)**). The RMI map effectively distinguishes between shallow magnet sources and deeper regional trends, allowing for lineament analysis of the local structure.

The Horizontal Gradient Magnitude (HGM) technique applied to RMI data produced a 2D color-shaded relief map delineating thin, continuous, and linear contact positions (**Figure 4(a)**). The computed HGM maxima were selected and overlayed onto the HGM map to determine linear contacts corresponding to structural lineaments (**Figure 4(b)**).

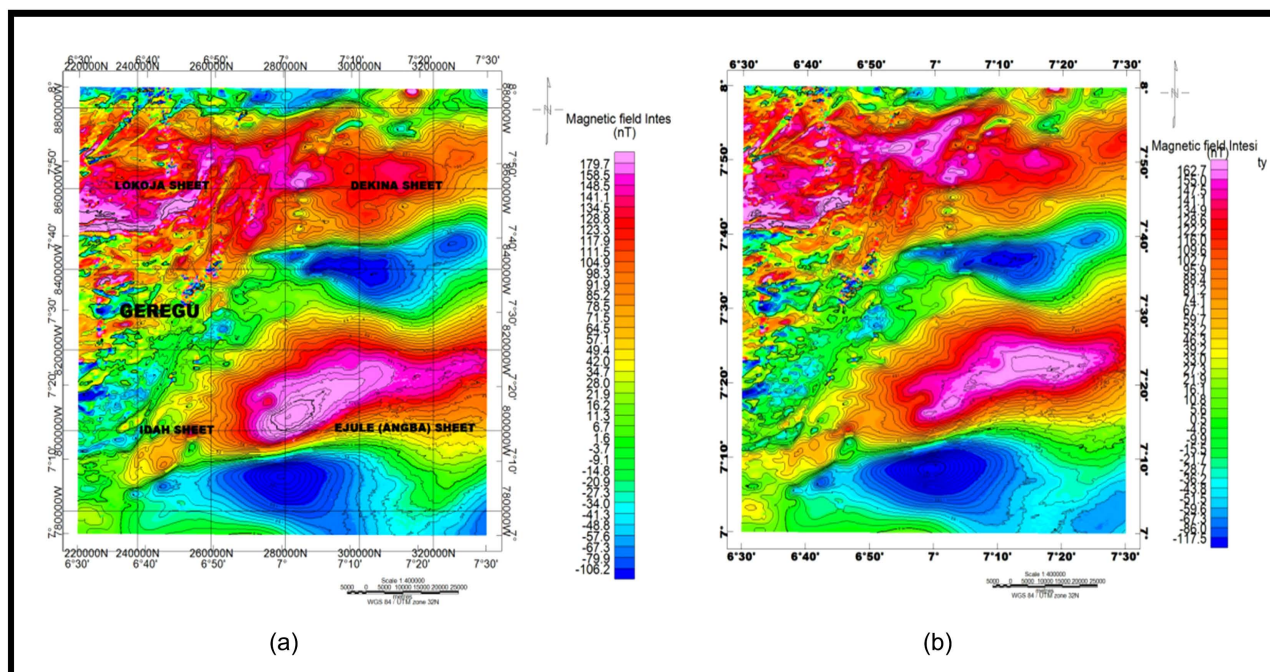


Figure 2. (a) illustrates the aeromagnetic contour map of the study area, (b) illustrates the reduced to equator map of the study area.

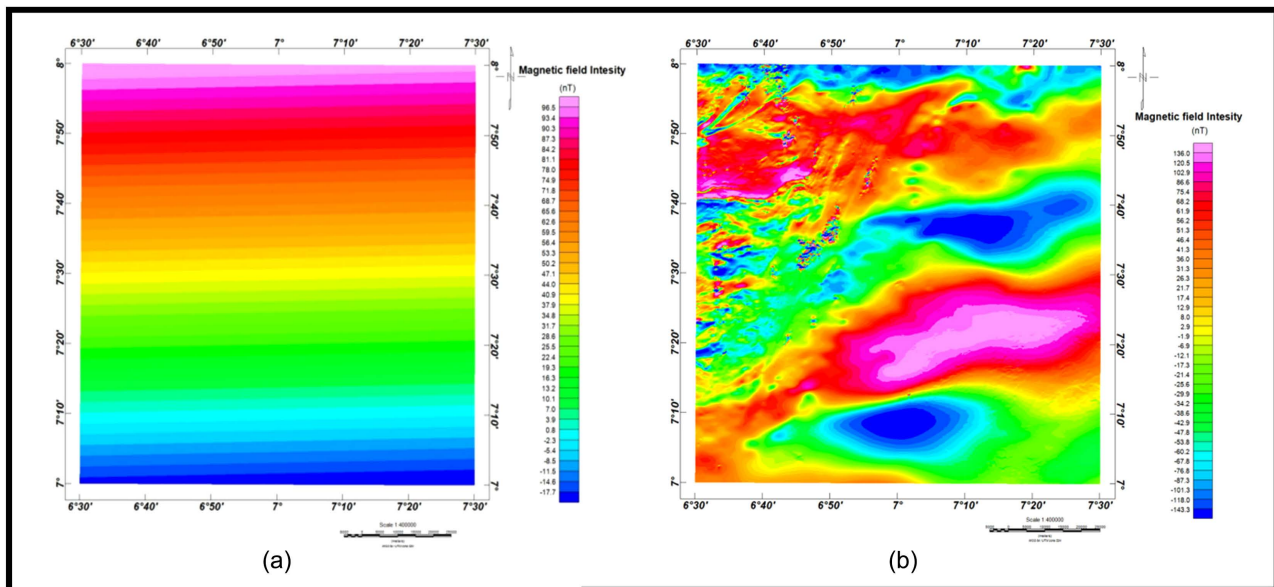


Figure 3. (a) Regional map of the study area (obtained from RTE Map using first order polynomial surface fitting) and (b) Residual Magnetic Intensity (RMI) Map.

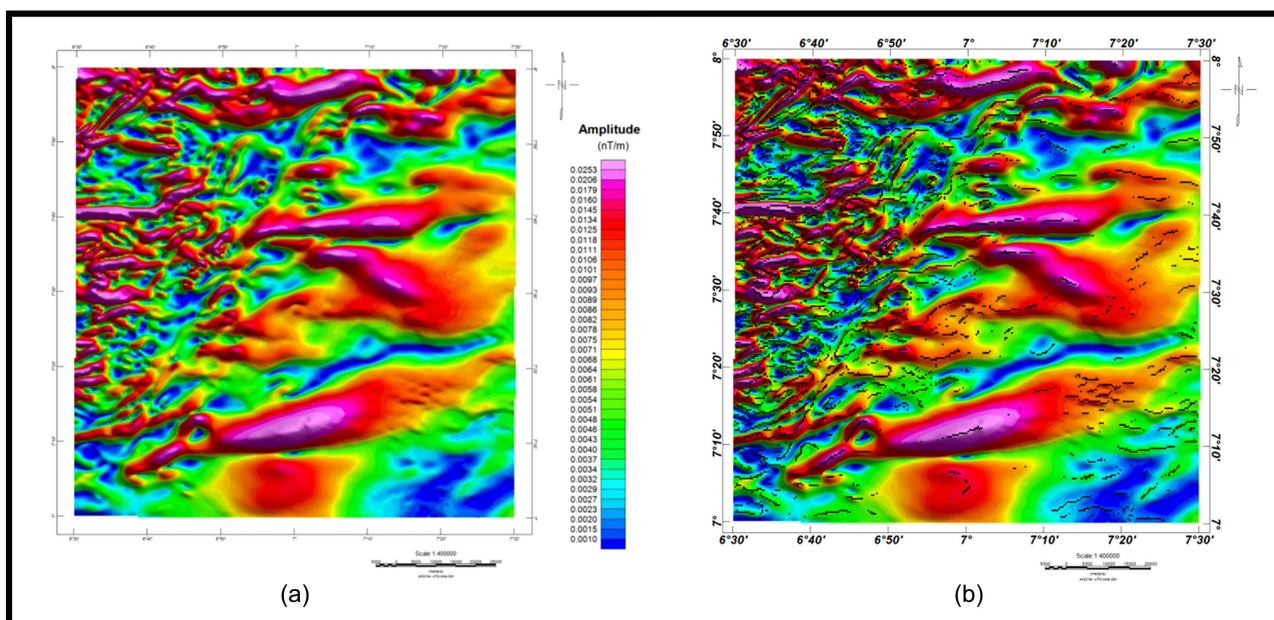


Figure 4. (a) illustrates the Horizontal Gradient Magnitude (HGM) map and (b) illustrates the HGM peaks overlain on the HGM Map.

The Analytic Signal Amplitude (ASA) analysis yielded maxima at magnetic edges, shown as a color-shaded relief map 2D (**Figure 5(a)**). Picked ASA peaks overlaid on the original ASA map to identify structures responsible for detected magnetic anomalies as shown in **Figure 5(b)**. ASA maxima are plotted separately in **Figure 6(a)**, while locations of integrated contacts from both HGM (red lines) and ASA (green lines) techniques are shown in **Figure 6(b)**.

Three-dimensional Euler Deconvolution with a structural index $N = 1.0$ (for

faults) produced clustered solutions representing linear structural trends (**Figure 7(a)**). The same orientations are obtained in the Euler solutions as are deduced by HGM and ASA methods. A composite map combining HGM maxima (red lines), ASA maxima (green lines), and Euler solutions (blue points) as shown in **Figure 7(b)**, provides integrated lineament identification.

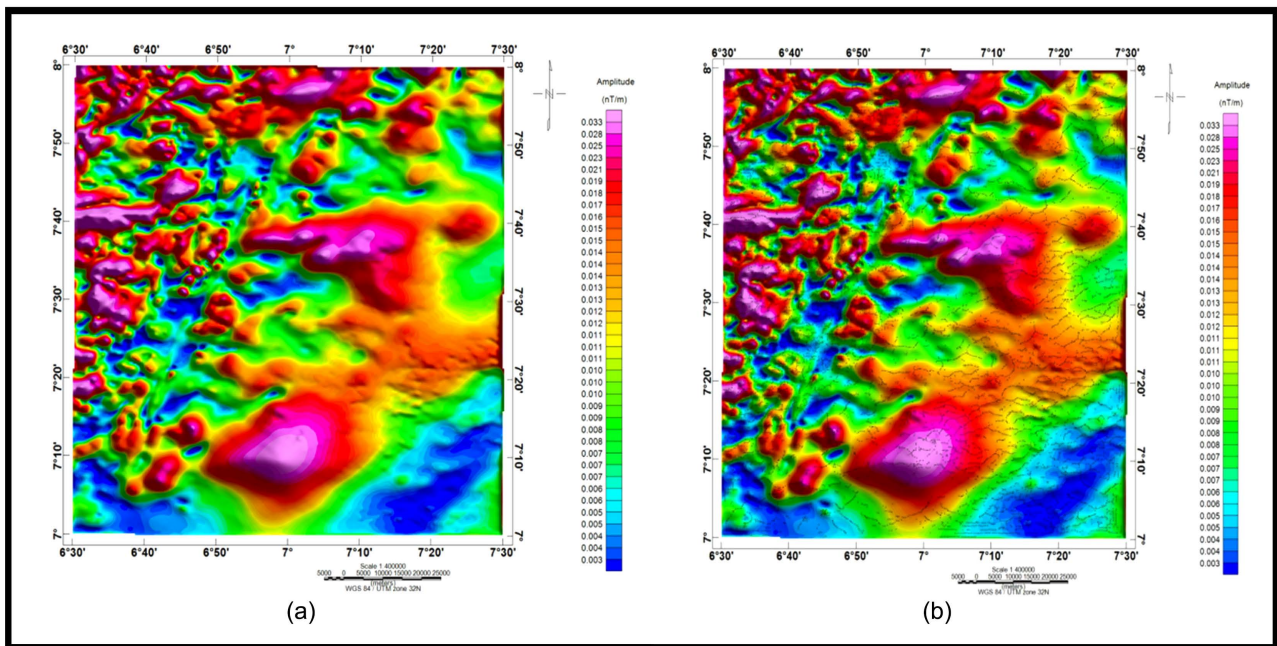


Figure 5. (a) Analytic Signal Amplitude (ASA) Map and (b) illustrates the ASA peaks overlain on the ASA map.

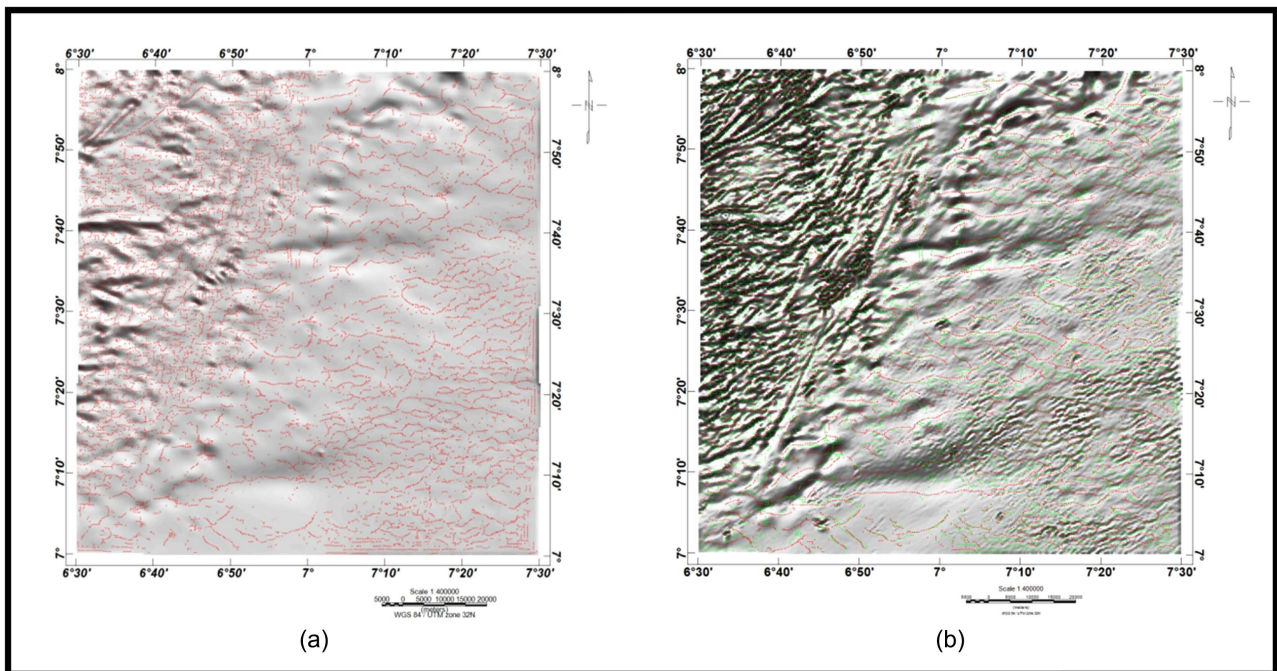


Figure 6. (a) Maxima of Analytic Signal Amplitude and (b) illustrates the estimated locations of contacts according to Horizontal Gradient Method (red) and Analytic Signal Amplitude (green).

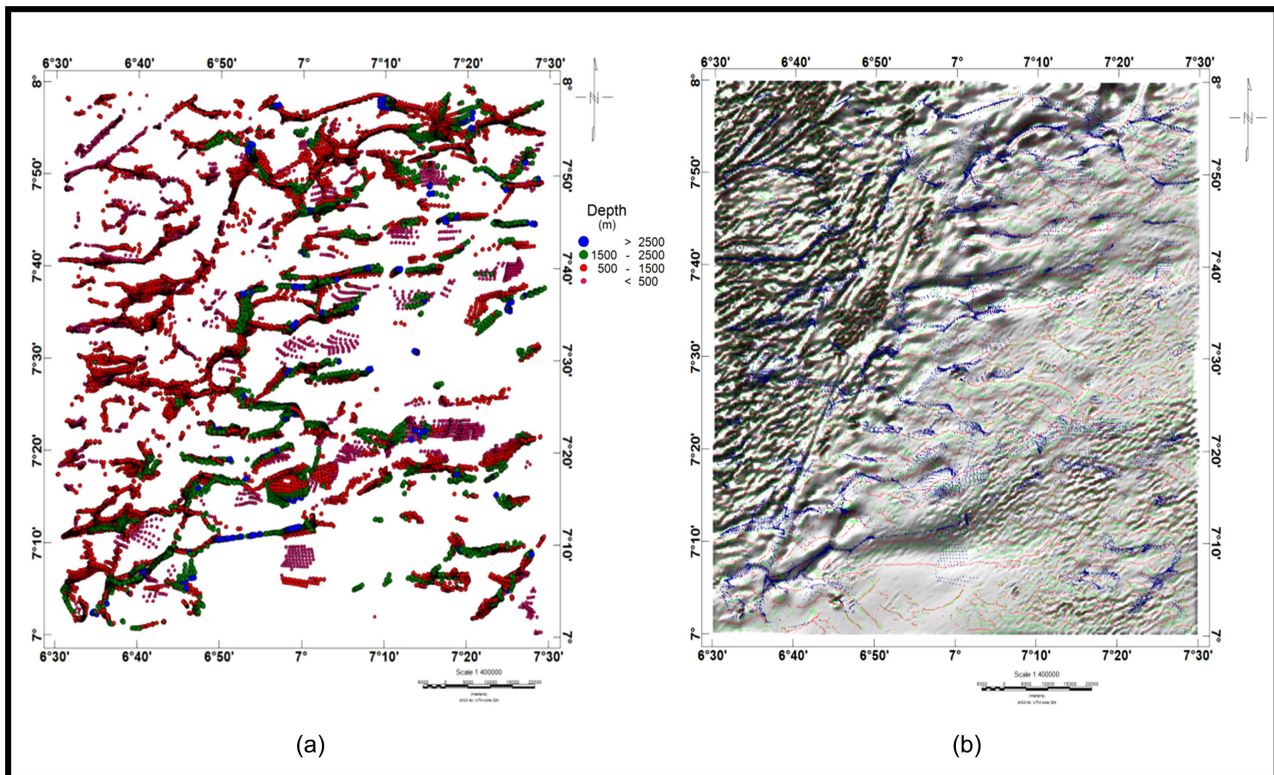


Figure 7. (a) Euler Solutions Map for a Structural index $N = 1$, 1515 km window and maximum relative error 15 and (b) Map showing the inferred contacts/ fracture locations in the study area with the maxima of ASA in green and other contacts from correlation with HGM in red and euler solution in blue.

Collective structural studies resulted in a merged magnetic lineament map with 161 total lineaments (**Figure 8**). 21 major lineaments were recognized as faults (F1 - F21) with lengths varying from 5.9 km (F20) to 27.6 km (F1). The source parameter imaging (SPI) method was employed to estimate depth to the magnetic sources. The SPI map in **Figure 9** shows the variation depths to the magnetic sources in the study area and the basement morphology. The magenta color at the uppermost part of the SPI legend represents areas with shallow depth whereas the deep blue color at the lowest part of the legend represents areas with high thickness and depth. The low sedimentary thicknesses (<90 m) at the North-western, Western and Southeastern parts suggest that these areas are basement complex areas. In the northern and Southeastern region, the SPI method revealed sedimentary thicknesses of over 1400 m. Rose diagram analysis shows three large-scale structural trends: ENE-WSW (most prominent), NE-SW, and E-W, with minor orientations of ESE-WNW, SE-NW, and NNE-SSW. Notably, fault F1 transversing at the Geregu site, with estimated depths varying from 500 - 1500 m.

The rose diagram for the deduced lineaments from HRAD shows the directional frequency of the mapped lineaments over the study area. The rose diagram identified five peaks of preferential direction: the ENE-WSW, NE-SW, E-W, ESE-WNW and NNE-SSW are the magnetic trends.

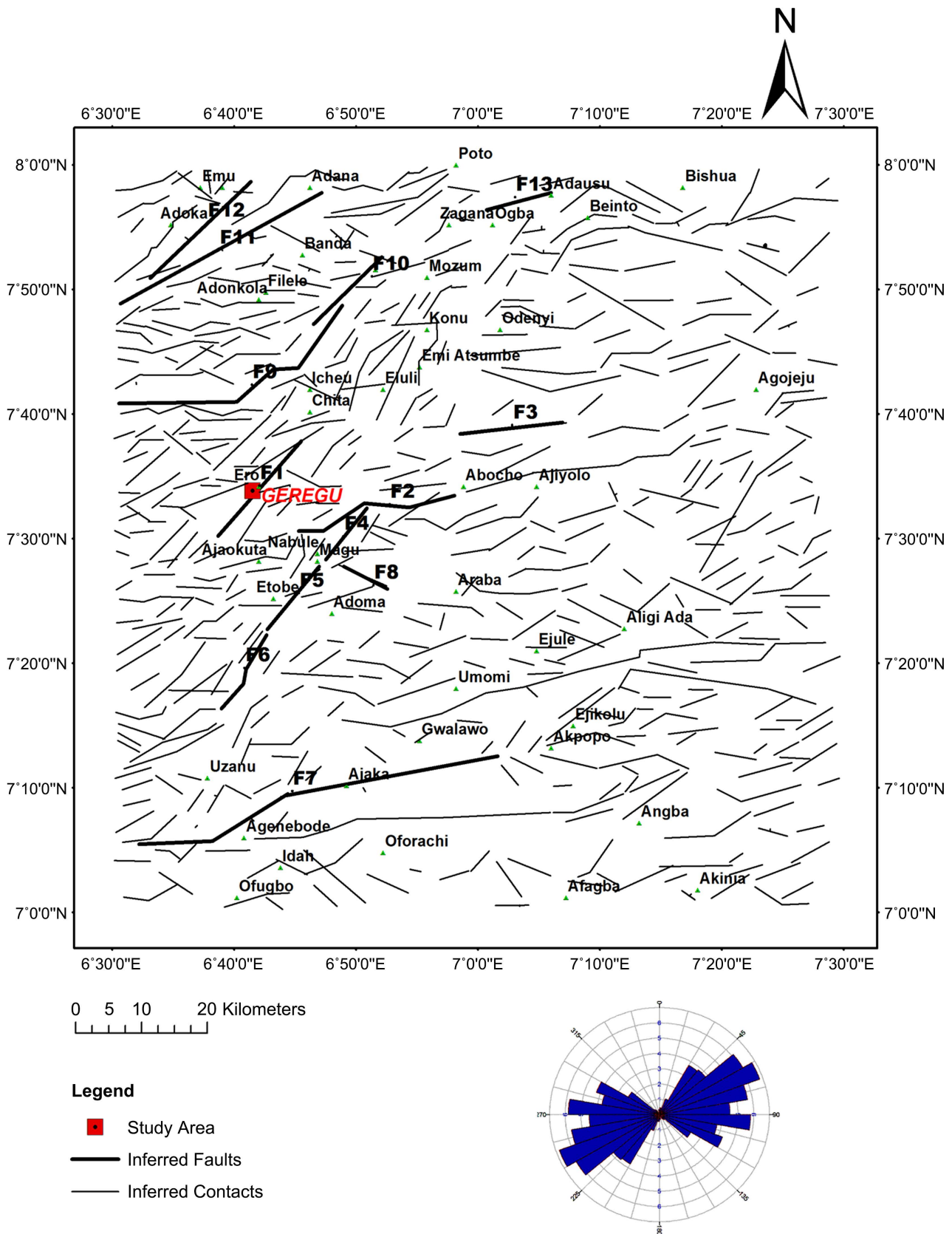


Figure 8. Inferred mapped fault/discontinuity zones in the study area.

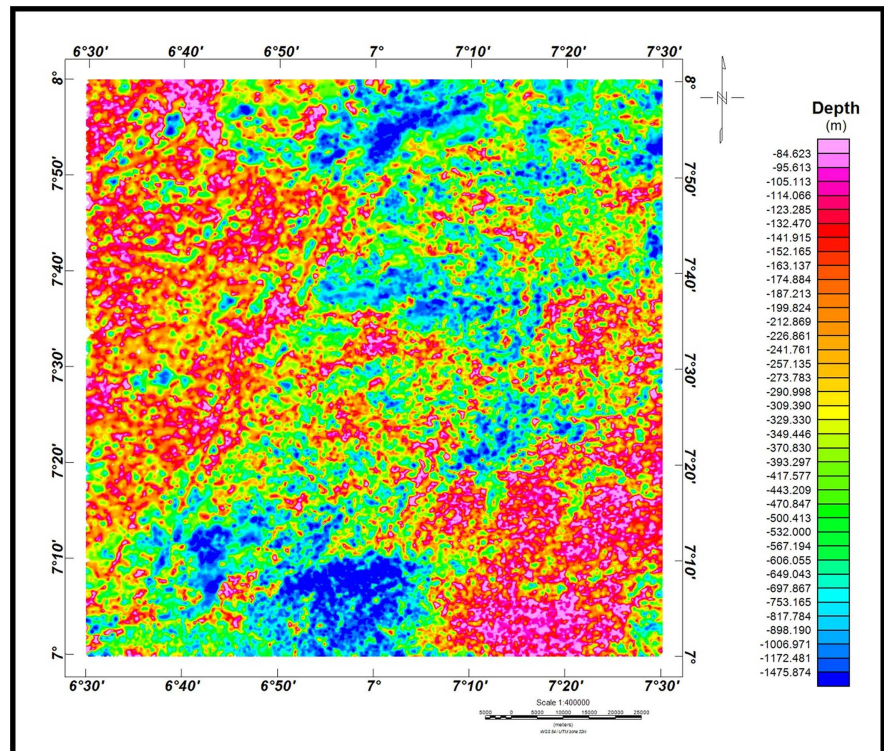


Figure 9. Depth determinations from source parameter imaging.

5. Discussion

The map of TMI displays tremendous variations in magnetic intensity reflecting lithological unit and basement topography heterogeneity in the investigated area. These amplitude changes are linearly correlated with rock magnetization. The spatial distribution pattern of magnetic anomaly implies a complex geological setting of varying metamorphism and extent of intrusivity. The prevalence of short wavelength anomalies in the northwestern, western, and southwestern regions is indicative of near-surface magnetic bodies corresponding to the basement complex. The anomalies are likely the result of outcropping or shallow crystalline rocks consistent with the migmatite-gneissic terrain of the Nigerian basement complex. The long wavelength anomalies, by contrast, are indicative of deeper-seated magnetic sources, which could be a result of regional basement geometry or gigantic-scale intrusive bodies.

Integration of HGM, ASA, and Euler Deconvolution techniques efficiently picked up 161 magnetic lineaments, 21 of which were significant faults. The dominant ENE-WSW structural trend, augmented by NE-SW and E-W directions, is consistent with widely reported Pan-African tectonic regimes (Ajibade et al., 1987; Rahaman, 1988). The directions point towards regional stress regime in the Pan-African orogeny (ca. 600 - 500 Ma), implying that local structures are controlled by continent-scale deformation processes.

The complex nature structural intricacy deformations suggest polyphase deformation history. The ENE-WSW trend is the primary Pan-African fabric, and sec-

ondary NE-SW and E-W trends may reflect later reactivation stages or conjugate fracture sets. Minor ESE-WNW, SE-NW, and NNE-SSW trends record local perturbations of stress due to possible regional basement heterogeneities or post-orogenic restructuring.

The in-line fault F1 at the site of the Geregu nuclear facility site poses major siting concerns. These faults, 500 - 1500 m deep, are active structural discontinuities that have the potential to influence ground stability and seismic hazard potential. However, their relatively shallow depths and lack of connection with major regional fault systems suggest minimal seismic risk.

The dominance by Pan-African orientations suggests that structural patterns present are reflective of old orogenic processes rather than active tectonism. The fact that there is no evidence of recent seismic activity in the region, combined with polycyclic metamorphic development, supports regional tectonic stability. However, the fault systems presently identified require intense ground-truthing and engineering geological assessment. Detailed site-specific studies should be aimed at defining the fault displacement history, fracture density, and fluid migration potential in structural directions.

The study has provided essential baseline data for nuclear facility siting at Geregu. While tectonic stability within the area is comparatively good, the presence of proximal fault systems (F8, F13) necessitates detailed investigations like paleoseismic analysis, detailed structural mapping, and geotechnical characterization.

6. Conclusions

The study successfully applied aeromagnetic data to establish Geregu's tectonic stability for nuclear power plant construction. Horizontal gradient magnitude (HGM), analytic signal amplitude (ASA), and 3-D Euler Deconvolution of residual magnetic intensity data provided large-scale structural characterization of the target area.

The analysis identified 161 magnetic lineaments corresponding to deep crustal structures and shallow expressions. The dominant ENE-WSW structural trend, followed by NE-SW and E-W indicates regional conformity to Pan-African tectonic trends, in support of mature crustal fabric developed by Precambrian orogenic processes.

Twenty-one of the greater magnetic lineaments were classified as faults, some of which F1 traverse the Geregu nuclear site at depths between 500 - 1500 m. In spite of this close fault proximity, the structural study reveals no sign of active faults, which would mean the area has remained in a condition of tectonic stability with no displacement during the last 50,000 years. However, the presence of cutting fault systems F1 in the Geregu site necessitates site-specific paleoseismic and geotechnical/engineering geology investigations to ascertain local ground conditions and potential infrastructure impacts. These additional studies will provide the engineering parameters necessary for safe nuclear facility design and regulatory approval.

Conflicts of Interest

The authors declare no conflicts of interest.

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