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RESEARCH ARTICLE

COMPREHENSIVE GEOLOGICAL AND STRUCTURAL INTERPRETATION OF THE SOUTHEASTERN NIGER DELTA BASED ON LINEAMENT ANALYSIS

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ABSTRACT

The southeastern Niger Delta, a geologically complex and resource-rich region, was studied using integrated lineament analysis derived from Bouguer anomaly and Total Magnetic Intensity (TMI) maps. The Bouguer anomaly data highlights deep-seated density-driven structures, while the TMI data captures shallow magnetic features such as dikes and sills. Lineament analysis revealed predominant NW-SE and NE-SW orientations, corresponding to deep compressional and shallow extensional features, respectively. The NW-SE trends, observed in the Bouguer anomaly data, align with regional fault systems such as the Nembe and Akata faults, indicating significant compressional stress, while the NE-SW trends in the TMI data reflect shallow extensional deformation linked to recent tectonic activity. Location-specific analysis at key sites, including Ikot Abasi (4.8156°N, 7.0498°E), Onne (4.4500°N, 7.1667°E), and Okirika (4.6167°N, 7.3833°E), identified high-density lineament intersections, suggesting zones of increased structural complexity and potential hydrocarbon accumulation. Hydrogeologically, lineaments highlight aquifer recharge pathways and potential compartmentalization due to fault barriers, emphasizing their role in groundwater management. The integrated analysis enhances the understanding of the tectonic history of the region and provides critical insights for hydrocarbon and groundwater exploration. Recommendations include targeted drilling in areas with intersecting lineaments and further geophysical surveys to validate newly identified shallow magnetic anomalies.

KEYWORDS

Niger Delta, Bouguer anomaly, Total Magnetic Intensity, lineament analysis, NW-SE trend, NE-SW trend, structural interpretation, hydrocarbon exploration, groundwater pathways, tectonic evolution.

1. INTRODUCTION

The southeastern Niger Delta, encompassing parts of Bayelsa, Rivers, Akwa Ibom, and Cross River States, is an area of considerable geological interest due to its complex tectonic setting and significant hydrocarbon potential. This region is a part of the larger Niger Delta Basin, one of the most prolific hydrocarbon provinces globally, characterized by extensive sedimentary sequences and intricate structural formations influenced by regional tectonics (Ekpo et al., 2024a). The basin, situated along the passive margin of the Gulf of Guinea, is primarily extensional, shaped by rifting processes that are linked to the evolution of the Atlantic Ocean (Tuttle et al., 2015; Fatoke, 2010).

The integration of lineament analysis using Bouguer anomaly and Total Magnetic Intensity (TMI) datasets provides a comprehensive approach to understanding the subsurface structures in this region. Bouguer anomaly data capture deep-seated density-driven features, while TMI data highlight shallow magnetic anomalies, such as dikes and sills, which are often indicative of intrusive activities. By combining these datasets, we can gain a multi-scale perspective on the structural framework, enhancing our understanding of both deep and shallow geological features (Ekpo et al., 2024b).

The objectives of this study are to compare the lineament maps derived from Bouguer anomaly and TMI data, analyze structural orientations using Rose diagrams, correlate lineament data with the existing geological map of the Niger Delta, integrate these datasets for a unified interpretation, conduct a detailed location-specific analysis using identified sites such as Ikot Abasi, Bonny, and Okirika, evaluate the tectonic implications of the observed structural features, assess the potential for mineral and hydrocarbon exploration, model potential groundwater flow pathways, and reconstruct the geological history of the southeastern Niger Delta.

1.1 Geology Of The Area Of Study

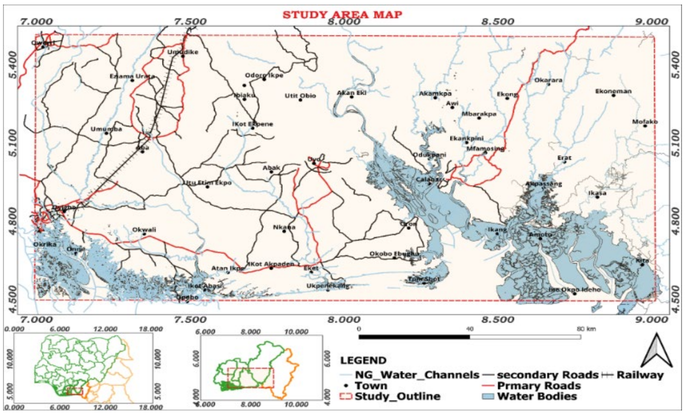

Figure 1: Location map of the study area.

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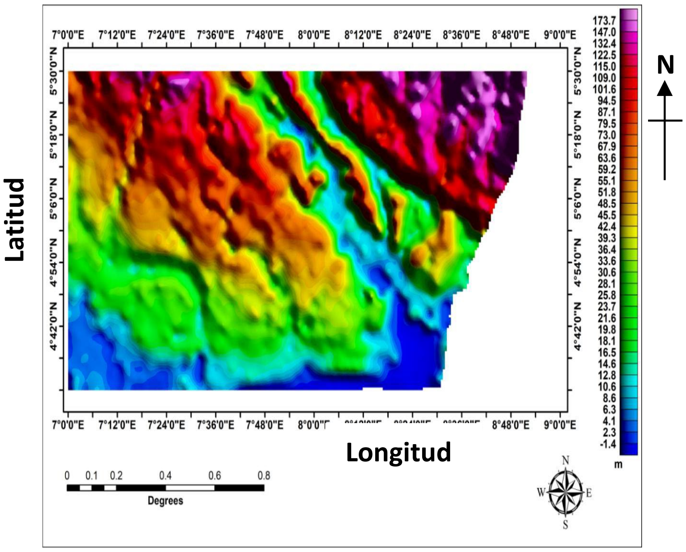

Figure 2: aTopographic map of the study area (USGS).

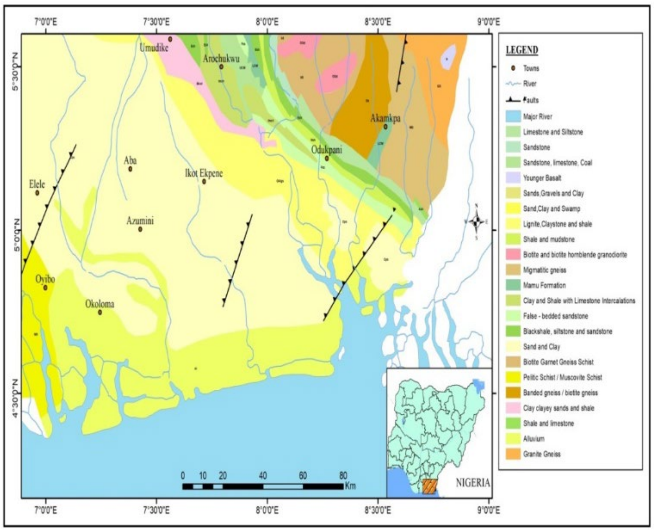

Figure 3: Geologic map of the study area (Ekpo et al., 2024a).

The area of investigation is located in the southeastern onshore part of the Tertiary Niger Delta Basin of Nigeria. It is part of Bayelsa, Imo, Rivers, Abia, Akwa Ibom and Cross River States of southern Nigeria. The area Figure 1lies between latitudes 4° 50' and 5° 50'N and longitudes 7° 00' and 9° 00'E. The study area covers approximately 24,650 km^2. The topographic map of the area is as shown in Figure 2 and the geologic map of the study area is as shown in Figure 3.

The Niger Delta Basin, situated in the Gulf of Guinea along Nigeria's western coast, is an extensional rift basin on a passive continental margin, with geological connections extending toward Cameroon, Equatorial Guinea, and São Tomé and Príncipe (Tuttle et al., 2015). Recognized as one of the largest Tertiary deltas worldwide, it is a highly productive hydrocarbon-rich region (Doust, 1990). The basin spans a subaerial area of approximately 75,000 km^2, covering a total of 300,000 km^2, and contains around 500,000 km^3 of sedimentary deposits (Okiwelu et al., 2013; Tuttle et al., 2015). These sediments reach depths between 9 and 12 kilometers (Merki, 1972; Evamy et al., 1978; Fatoke, 2010; Okiwelu et al., 2013). The basin consists of varied geological formations that reveal its formation history and reflect the regional tectonics at both local and broader scales. As an extensional basin, it is bordered by similarly formed basins in the area.A study describe the Niger Delta Basin as occupying the southwestern edge of the larger Benue Trough tectonic system.(Lehner and De Ruiter.,1977). Its eastern boundary aligns with the Cameroon Volcanic Line and a transform passive margin (Fatoke, 2010). The geological setting of the Southeastern Niger Delta is marked by the presence of faults and fractures that provide pathways for fluid migration, which is essential for geothermal system formation (Reijers, 2011). Additionally, the region's tectonic activity, combined with the emplacement of igneous bodies, creates the necessary heat sources for geothermal reservoirs.

2. MATERIALS

The aeromagnetic and aerogravity data acquired by Nigerian Geological Survey Agency (NGSA) were used for the study. The materials used for this study include eight (8) each of magnetic and gravity sheets of 321, 322, 323, 324, 329, 330, 331 and 332. Oasis Montaj version 7.0.1, Rockwork16, ArcGIS (version 10.1), Qgis (version 13.6), Microsoft excel and Surfer software (version 13) were employed in analyzing the data.

2.1 Data Acquisition

The airborne data was acquired and assembled by Fugro Airborne Surveys, Canada between 2005 and 2010. These data were collected using Flux-gate proton precession magnetometers and the Flux- Adjusting surface data assimilation system with flight-line space of 0.1 km, tie line space of 0.5 km and terrain clearance ranging from 0.08-0.1 km along 826,000 lines. The observed potential field data were of very high resolution when likened to the 1970 aero-geophysical data. These recent potential field data were noticed to be suited for mineral and petroleum investigations as well as geological mapping.

The International Geomagnetic Reference Field (IGRF) correction was applied to the magnetic data set to remove the regional component of the Earth's magnetic field, while isolating the local magnetic anomalies that are of interest in geophysical exploration. The IGRF is a mathematical model that represents the Earth's main magnetic field, which is largely generated by processes in the Earth's core. The model is updated every five years and provides the expected magnetic field at any location on the Earth's surface. The IGRF correction involves calculating the magnetic field using the IGRF model at the survey locations and subtracting this regional field from the observed data. This leaves the residual magnetic anomalies, which are more directly related to local geological features. The data used for this study were processed to the form of Total magnetic gridded data displayed as imageries in colour raster format (Figure 6).

Reduction to Equator **(**RTE) being a processing technique used to simplify the interpretation of magnetic data by centering magnetic anomalies directly over their causative bodies was applied to the data. Magnetic anomalies can appear skewed or offset due to the inclination and declination of the Earth's magnetic field, particularly at lower latitudes. RTE mathematically transforms the observed magnetic data to simulate what it would look like if the Earth's magnetic field were vertical (as it is at the magnetic poles or equator). This process involves adjusting both the amplitude and the phase of the magnetic field components. The resulting RTE data have anomalies that are centered over their sources, making it easier to correlate magnetic anomalies with subsurface structures.

The regional field in the Bouguer gravity data was subtracted by applying the tenth (10th) International Gravity Standardization Net 1971 (IGSN71) programs, by Fugro Airborne Surveys, Canada. The key benefit of the IGSN71 is the consistency they provide in potential field survey practice beginning from when the IGSN71 became available and generally accepted (Reeves et al., 1997). Fugro Airborne also carried out all other required potential field data treatments and reductions. The data used for this study were processed to the form of Bouguer gravity gridded data displayed as imageries in colour raster format (Fig. 7).

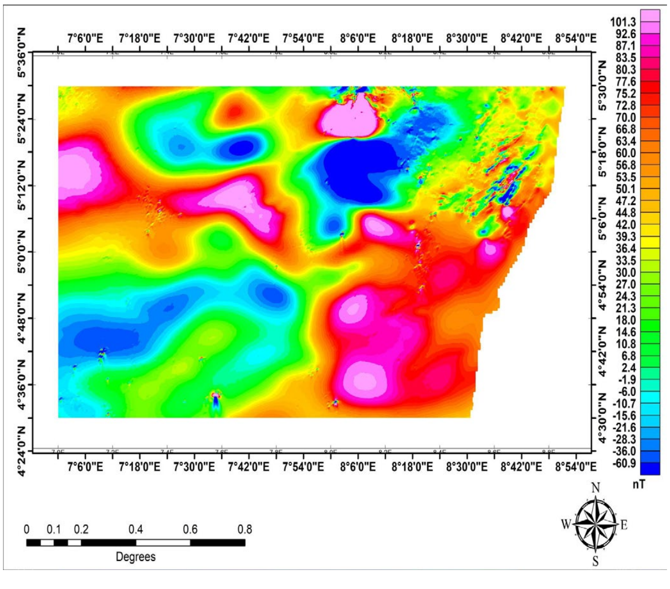

Figure 4: Total magnetic Intensity anomaly map

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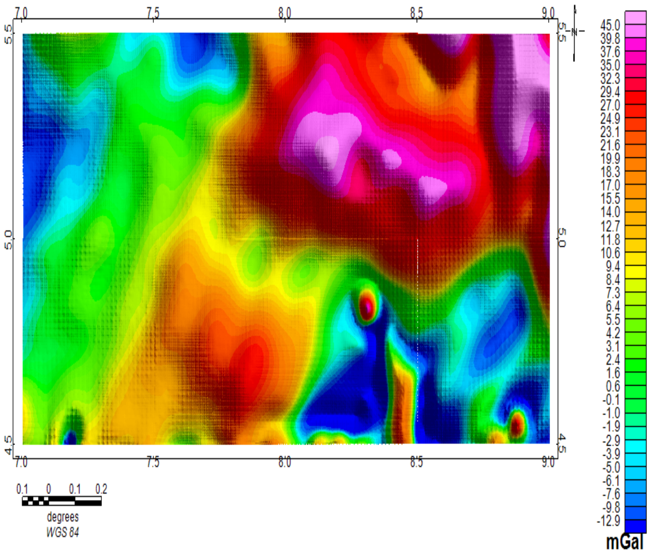

Figure 5: Bouguer anomaly map

3. METHODOLOGY

The section focuses on the Centre of Exploration methods that enhance the detection of linear geological features like faults and fractures in geophysical surveys. It highlights the importance of standard deviation analysis in highlighting local variations within grid data, which is essential for identifying significant anomalies. The technique measures the spread of data values from their mean within a defined window size, helping to detect areas of high variability, often associated with geological structures.

Here is a comprehensive overview of the application of statistical analysis for detecting local variations in geophysical data. The standard deviation technique measures the variability within a local neighborhood of a grid. It calculates the deviation of data values from their mean, helping to identify significant geological features characterized by high variability from the equation below;

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{1}$$

The method uses a filtering window, typically between 3 to 21 cells, allowing for flexible analysis depending on the scale of the features of interest.

A key aspect of the methodology involves choosing an appropriate window size to capture significant anomalies without oversmoothing the data. For instance, a window size of 5 × 5 cells can analyze a local area of approximately 125 m × 125 m, depending on the grid cell scale. By examining the grid data, areas with low standard deviation values indicate uniformity, while high standard deviation values highlight regions with significant structural features like faults or fractures.

The standard deviation analysis is particularly effective in enhancing the detection of lineaments and other geological structures, which often exhibit strong local variability against a more homogeneous background. This statistical approach helps isolate meaningful anomalies, making it a valuable tool for structural mapping and geological interpretation in geophysical surveys.

Phase symmetry analysis which is a method that identifies line-like features based on the symmetry of the data's frequency components was employed. This technique breaks the data into one-dimensional profiles across multiple orientations to detect axes of symmetry, making it useful for finding linear features like faults and lineaments. The symmetry strength is quantified on a scale from 0 to 1, indicating weak to strong symmetry.

Amplitude thresholding and non-maximal suppression which are tools for refining data analysis. These methods help to isolate significant features by reducing noise and enhancing the continuity of line-like structures. Amplitude thresholding categorizes grid values into foreground (features of interest) and background, simplifying the data for clearer interpretation. Non-maximal suppression retains only local maxima, further highlighting linear trends in the data.

Skeletonization, a morphological operation that reduces detected features to their simplest one-pixel-wide form was applied to the amplitude threshing data. This process simplifies the representation of lineaments, making them easier to analyze and vectorize for mapping. The skeletonized data was further processed using the "Skeleton to Vectors" plugin, which converts the linear features into vector segments for use in structural mapping and analysis.

4. RESULTS

Here is the results from the analysis of Bouguer anomaly and TMI. The paramenters used areaas follows; a filtering window of 9, a window size of 5 × 5 cells can analyze a local area of approximately 125 m × 125 m, and a symmetry strength of 1. Amplitude thresholding and Skeletonization were also applied to the anomaly maps. The results from these analysis are lineament maps from the Bouguer anomaly data (figure 6) and TMI anomaly data (figure 7)

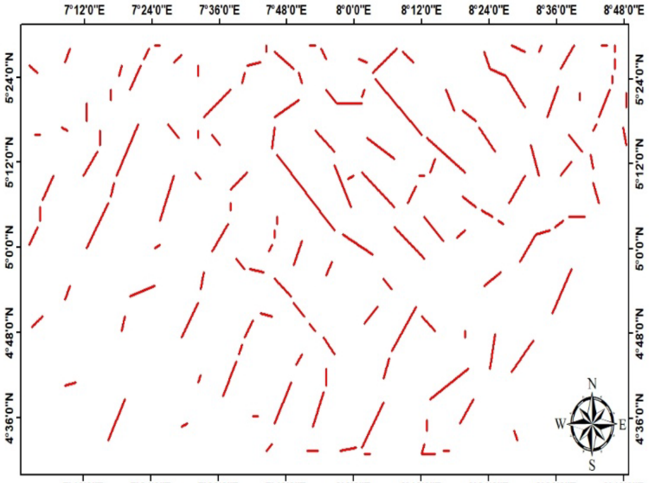

Figure 6: Lineament map extracted from Bouguer anomaly map

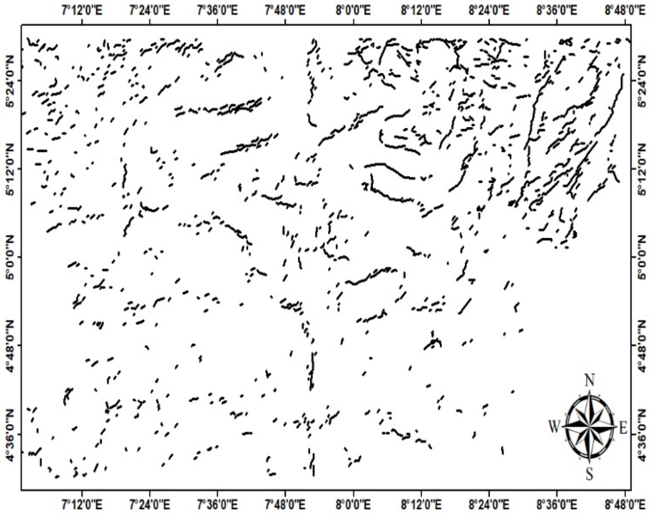

Figure 7: Lineament map extracted from TMI anomaly map

5. DISCUSSION

5.1 Comparative Analysis of Lineament Maps

The lineament maps derived from Bouguer anomaly (Figure 6) and TMI data (Figure 7) offer distinct insights into the subsurface geology of the southeastern Niger Delta. The Bouguer anomaly data primarily reveal deep-seated structures associated with variations in subsurface density. High-density areas, such as those around Ikot Ekpene and Akamkpa, correspond to denser lithologies like granitic and metamorphic intrusions

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(Ekpo et al., 2024b). In contrast, the TMI data highlight shallow magnetic features, capturing dikes, sills, and other intrusive bodies, particularly in areas like Onne and the Calabar Flank, where recent magmatic activities have influenced the near-surface geology (Ekpo et al., 2024a).

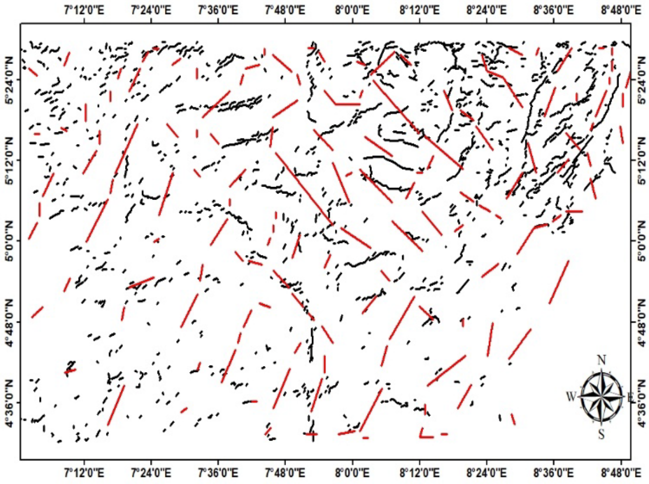

Figure 8: Lineament map showing superimposition of Bouguer and TMI lineament maps

The comparative analysis reveals that lineaments trending NW-SE and NE-SW dominate both datasets. The NW-SE lineaments, identified in the Bouguer anomaly data, are associated with deep fault systems, including the Nembe and Akata faults, which are prominent structural features extending into the basement. On the other hand, the NE-SW trends observed in the TMI data likely correspond to shallow, extensional features formed during the rifting phases that shaped the delta's evolution (Ekpo et al., 2024b). The integration of these datasets enables a comprehensive understanding of both deep-seated and shallow geological processes, reflecting the complex tectonic evolution of the southeastern Niger Delta.

5.2 Structural Interpretation Using Rose Diagrams

The Rose diagrams constructed from the Bouguer anomaly and TMI data Figure 9 and 10 provide a clear visualization of the predominant lineament orientations. The Rose diagram from Bouguer anomaly data shows a dominant NW-SE trend, consistent with major fault alignments like the Nembe and Akata faults. These orientations suggest a compressional stress regime, likely related to past orogenic events associated with the tectonic activity of the Benue Trough and the Pan-African orogeny.

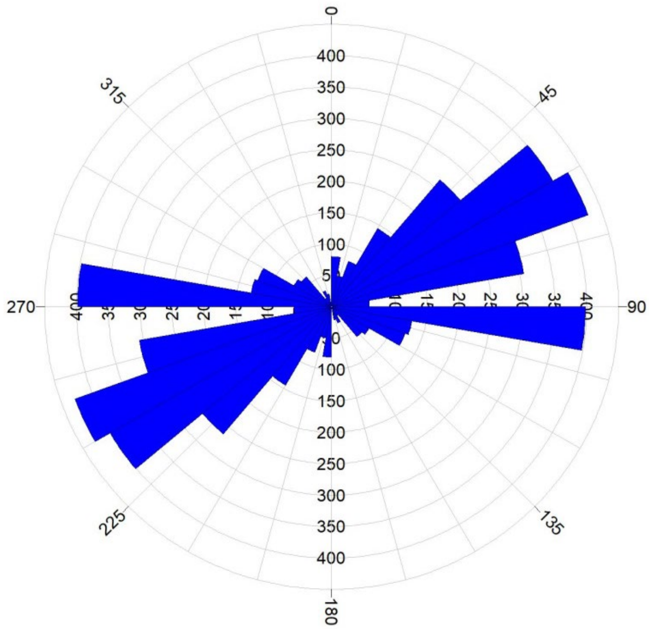

Figure 9: Rose diagram depicting the orientations of the Lineament from the Bouguer anomaly map

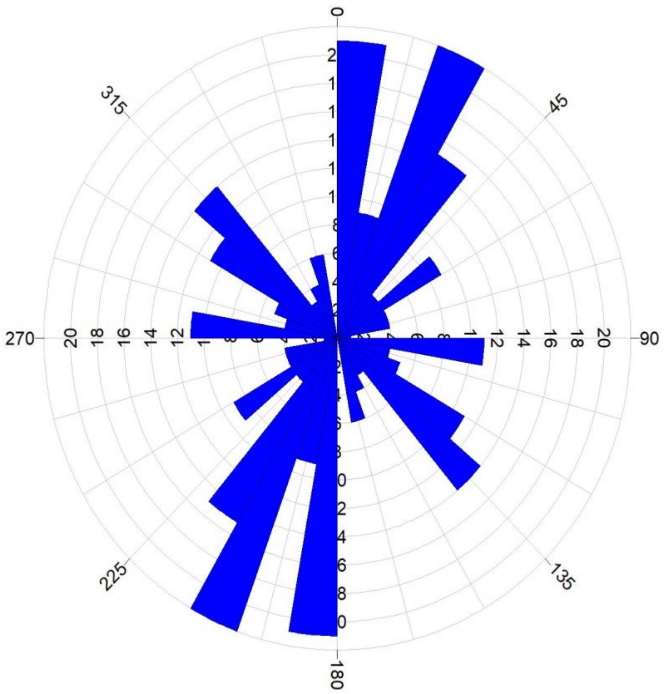

Figure 10: Rose diagram depicting the orientations of the Lineament from the TMI anomaly map

In contrast, the TMI-derived Rose diagram indicates a predominant NE-SW orientation, reflecting shallow, extensional features influenced by rifting processes. This trend is especially pronounced in areas such as Onne (4.5400°N, 7.1667°E), where shallow intrusive activities have been documented. The NE-SW orientation corresponds with recent tectonic adjustments linked to the opening of the Atlantic Ocean and subsequent extensional forces acting along the passive margin (Ekpo et al., 2024b).

5.3 Structural Significance

The intersection of the red and black lineaments indicates areas where tectonic reactivation has led to structural complexity. These zones often act as conduits for the migration of fluids, both hydrothermal and hydrocarbon-rich, and are critical in the formation of economic deposits. Fault zones in these areas are also known to influence the movement of groundwater, playing a key role in hydrogeological processes

5.4 Implications for Mineralization

The northeastern part of the study area, identified as having high Bouguer anomaly values, is particularly significant in the context of mineral exploration. These areas are typically associated with dense rock masses, which may indicate the presence of mineral deposits. High Bouguer anomalies are often linked to the presence of metallic ores such as iron, copper, and gold, which are concentrated in fault zones where hydrothermal fluid circulation has occurred.

Fault-controlled zones, particularly those intersecting with lineaments from the TMI map, are prime candidates for mineralization. The movement of hydrothermal fluids along these fault lines can result in the deposition of ore minerals in fractures and cavities within the rock mass. In addition, these zones may host significant reserves of non-metallic minerals, such as limestone, which are important for local construction industries

In the southeastern Niger Delta, similar tectonic and structural settings have been linked to the presence of hydrocarbon accumulations. The region's complex fault systems create traps where hydrocarbons can accumulate, particularly in structures such as rollover anticlines or fault closures. This structural framework is crucial for the exploration of both oil and natural gas, and the insights gained from aeromagnetic and aerogravity data can significantly enhance exploration strategies

5.5 Hydrogeological Insights from Lineament Data

The interpretation of lineaments is not only valuable for mineral and hydrocarbon exploration but also for understanding the hydrogeology of the region. Faults and fractures in the subsurface, as revealed by the lineaments on the Bouguer and TMI maps, play a critical role in the movement and storage of groundwater.

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5.5.1 Groundwater Flow

The orientation and distribution of faults indicated by the red and black lineaments suggest that certain regions of the southeastern Niger Delta may have preferential flow paths for groundwater. Faults and fractures create spaces where water can infiltrate and move through the rock layers, facilitating the recharge of aquifers. In particular, regions where the black TMI lineaments intersect with the red Bouguer lineaments are likely to serve as critical conduits for groundwater movement.

5.5.2 Compartmentalization of Aquifers

Conversely, faults oriented perpendicular to the groundwater flow may act as barriers, restricting the movement of water between different sections of an aquifer. This can lead to compartmentalized groundwater systems, where water resources are isolated in different parts of the delta, affecting both water availability and the sustainability of groundwater resources

5.6 Geographic Context and Specific Locations

The study area is located within the southeastern part of the Niger Delta, which is geographically positioned along the Gulf of Guinea in southern Nigeria. Key towns and cities in proximity to the study area, such as Port Harcourt, Okrika, and Bonny Island, are major hubs for both hydrocarbon extraction and mineral processing. The precise coordinates of the study area, as marked on the geological map, correspond to regions with significant structural features, including fault zones and sedimentary basins. These features are crucial for understanding the distribution of resources within the region.

For example, the area near the Okrika Fault Zone, is a major structural feature that has influenced both the tectonic evolution of the area and the distribution of resources. The intersection of these faults with the surrounding sedimentary layers makes it a prime target for both hydrocarbon exploration and mineral resource management

5.7 Correlation of Lineament Data with Geological Map Features

The geological map of the southeastern Niger Delta (**Figure 3**) was used to validate the lineament interpretations from the Bouguer anomaly and TMI datasets. The lineaments identified from the Bouguer anomaly data align well with major mapped fault systems, such as the Oloibiri and Afam faults, which control subsidence and sedimentation patterns in the delta. The alignment of these features with deep-seated faults confirms that the Bouguer anomaly data effectively capture basement structures that extend into the sedimentary cover.

The TMI data, however, reveal additional shallow structures not depicted on the geological map. For example, the lineaments detected near Onne and Okirika (4.6167°N, 7.3833°E) coincide with magnetic anomalies, suggesting the presence of uncharted dike intrusions. These findings underscore the utility of integrating TMI data for identifying near-surface geological features, enhancing the overall structural interpretation (Ekpo et al., 2024b).

5.8 Location-Specific Structural Analysis

Detailed structural analysis of key sites such as Ikot Abasi, Onne, and Okirika reveals significant variations in subsurface features. In Ikot Abasi (4.8156°N, 7.0498°E), the high density of intersecting lineaments suggests intense tectonic activity, likely influenced by the Afam fault system. These intersecting lineaments indicate zones of structural weakness, which may enhance fluid migration, making this area a prime target for hydrocarbon exploration (Ekpo et al., 2024b).

Akamkpa and its environs exhibits prominent NE-SW trending lineaments in the TMI data, indicating the presence of shallow magnetic anomalies. These features, interpreted as dike intrusions, suggest recent magmatic activities that could have influenced local hydrothermal systems. Similarly, the Okirika region shows a mix of NW-SE and NE-SW trends, reflecting a complex interplay of compressional and extensional tectonics (Ekpo et al., 2024a).

6. CONCLUSION

The integrated analysis of lineament data from Bouguer anomaly and TMI datasets provides a comprehensive understanding of the structural framework of the southeastern Niger Delta. The predominant NW-SE and NE-SW orientations reflect the multi-phase tectonic evolution of the region, characterized by deep-seated compressional features and shallow extensional structures. The identification of intersecting lineaments and uncharted magnetic anomalies offers valuable insights for hydrocarbon exploration, particularly in areas such as Ikot Abasi, Onne, and Okirika.

This study highlights the importance of multi-dataset integration in geophysical exploration, allowing for a detailed and accurate interpretation of subsurface features. The findings support the potential for resource exploration, including hydrocarbons and groundwater, in structurally complex zones identified by the lineament analysis.

RECOMMENDATIONS BASED ON FINDINGS:

HYDROCARBON EXPLORATION

- **Target Fault Intersection Zones**: The regions where Bouguer anomaly and TMI lineaments intersect are likely to host structural traps, making them prime targets for hydrocarbon exploration. These areas should be prioritized for seismic surveys to validate subsurface structures.

- **Focus on the Northeastern Zone**: With significant Bouguer anomalies suggesting dense rock masses, this zone should be investigated for potential hydrocarbon accumulations, particularly in fault-controlled rollover anticlines or stratigraphic traps.

MINERAL RESOURCE POTENTIAL

- **Geophysical Surveys in High-Anomaly Regions**: Conduct detailed geophysical and geochemical surveys in areas of high Bouguer anomalies, as these are likely to host economically significant mineral deposits such as iron sulfides, quartz, or metallic ores.

- **Hydrothermal Alteration Mapping**: Deploy satellite imagery or hyperspectral analysis to identify surface alterations indicative of mineralized zones, particularly near fault intersections revealed by the maps.

GROUNDWATER RESOURCE MANAGEMENT

- **Exploration of Aquifers in Lineament Zones**: Faults and fractures identified in the southeastern Niger Delta should be investigated for their potential to serve as conduits or barriers to groundwater flow. Detailed hydrogeological surveys can confirm aquifer recharge and discharge patterns.

- **Groundwater Sustainability Measures**: In areas where lineaments act as barriers, aquifers may be compartmentalized. Monitoring and regulation of groundwater extraction in such zones are recommended to prevent overexploitation and maintain sustainability.

GEOTECHNICAL STUDIES FOR DEVELOPMENT

- **Stability Assessments in Fault Zones**: Engineering projects, such as infrastructure development, should consider the fault zones identified in the lineament maps. Faults can influence soil stability, requiring geotechnical assessments before construction.

- **Hazard Mitigation**: Active or reactivated faults pose risks such as subsidence or localized earthquakes. Regular monitoring is advised, especially in regions with significant human or industrial activities.

FURTHER RESEARCH AND DATA INTEGRATION

- **Integrated Multi-Disciplinary Approach**: Combine aeromagnetic and aerogravity data with seismic, resistivity, and other geophysical methods for a holistic understanding of subsurface geology.

- **Refinement of Geological Models**: Update geological models for the southeastern Niger Delta based on the findings, incorporating new data to improve the accuracy of structural interpretations and resource estimations.

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