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## RESEARCH ARTICLE

**GEOPHYSICAL AND GEOLOGICAL ANALYSIS OF KATSINA AND KADUNA: STRUCTURAL FRAMEWORK, RESOURCE POTENTIAL, AND IMPLICATIONS FOR HYDROGEOLOGY, MINERALIZATION, AND HYDROCARBON EXPLORATION**Uduak J. Idiong<sup>a\*</sup>, Nsikak E. Bassey<sup>b</sup>, Nyakno J George<sup>b</sup>,<sup>a</sup>Department of Geology, Akwa Ibom State University, Mkpato Enin, Akwa Ibom State, Nigeria<sup>b</sup>Department of Physics, Akwa Ibom State University, Mkpato Enin, Akwa Ibom State, Nigeria\*Corresponding Email Author: [uduakidiong3@gmail.com](mailto:uduakidiong3@gmail.com)

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## ABSTRACT

This study presents an integrated geophysical and geological analysis of Katsina and Kaduna to evaluate their structural framework, hydrogeological significance, and resource potential. Utilizing geophysical maps, including Free Air gravity anomalies, regional and residual anomalies, phase symmetry, CET lineament, and rose diagram analyses, the study identifies major subsurface structures influencing groundwater movement, mineralization, and hydrocarbon prospectivity. The dominant NE-SW and NW-SE trending lineaments align with regional tectonic forces, controlling fault-bounded aquifers, mineralized zones, and hydrocarbon traps. Gravity anomalies highlight basement highs and sedimentary basins with implications for petroleum exploration, while the phase symmetry map delineates structural discontinuities essential for fluid migration. The findings underscore the importance of fracture-controlled aquifers for sustainable water resource management, emphasize the role of structurally controlled mineral deposits in guiding exploration strategies, and reinforce the significance of basement structures in hydrocarbon prospectivity. The study recommends targeted hydrogeological surveys, advanced geophysical exploration techniques, and policy-driven resource management initiatives to optimize groundwater utilization, mineral extraction, and hydrocarbon exploration. By integrating geophysical and geological data, this research provides a comprehensive framework for subsurface investigations in Katsina and Kaduna, contributing to informed decision-making in resource development and environmental sustainability.

## KEYWORDS

Structural Framework, Lineament Trends, Hydrogeology, Mineralization, Hydrocarbon Prospectivity, Basement Structures, Fault-Bounded Aquifers.

## 1. INTRODUCTION

The Katsina and Kaduna regions, located in northern Nigeria, exhibit complex geological and structural frameworks primarily influenced by Precambrian basement rocks, tectonic activities, and sedimentary formations (Obaje, 2009; Shettima et al., 2021). The use of geophysical techniques such as aeromagnetic and gravity surveys plays a crucial role in understanding the subsurface characteristics of these regions (Telford et al., 1990; Nabighian et al., 2005). This study provides an integrated interpretation of geophysical and geological maps to analyze structural lineaments, gravity anomalies, and lithological distributions (Reeves, 2005; Kearey et al., 2013). The interpretation is crucial for hydrogeological, mineral, and hydrocarbon exploration, contributing to sustainable resource management and regional development (Hassan et al., 2018; Adepelumi and Falade, 2020). The aim of this study is to analyze the geophysical and geological characteristics of Katsina and Kaduna using various geophysical maps to understand their implications for structural, hydrogeological, and mineral resource assessments. The specific objectives are:

- To delineate major structural lineaments and understand their orientations using CET and rose diagram analyses.

- To analyze gravity anomalies and their correlation with subsurface geological features.
- To evaluate hydrogeological potentials by interpreting fault-controlled groundwater pathways.
- To assess mineralization potential based on identified structural controls and associated anomalies.
- To explore the implications of structural trends for hydrocarbon prospectivity in the region.

## 1.1 Statement Of Problem

Katsina and Kaduna are regions with significant geological complexity and resource potential. However, limited subsurface investigations have constrained the understanding of their mineral, hydrogeological, and hydrocarbon prospects. Despite the availability of aeromagnetic and gravity data, a comprehensive interpretation of these datasets is necessary to bridge knowledge gaps in structural analysis, resource exploration, and environmental sustainability. The absence of detailed structural evaluations has further limited the effectiveness of groundwater development projects and mineral exploration initiatives. This study aims

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to address these challenges by providing an in-depth interpretation of geophysical data to support exploration and management efforts.

**1.2 Justification**

The integration of geophysical and geological data is essential for regional exploration and resource development. The study's findings will enhance hydrogeological assessments by identifying fracture-controlled aquifers, thereby supporting water resource management in Katsina and Kaduna. Additionally, the identification of structurally controlled mineral deposits will provide insights for targeted mineral exploration. In hydrocarbon exploration, the delineation of fault systems and sedimentary basins will contribute to the evaluation of petroleum prospects. Understanding regional tectonic trends and their influence on resource distribution will also improve exploration efficiency and guide future geological investigations.

**1.3 Geologic Map of Katsina and Kaduna**

The geologic map (Figure 1) of Katsina and Kaduna provides a detailed representation of the rock formations and structural settings of the region (Obaje, 2009; Shettima et al., 2021). Katsina and Kaduna are primarily underlain by Precambrian basement rocks, which include granites, gneisses, and schists, with some sedimentary cover towards the south (Tijani et al., 2012; Olasehinde, 2010). The presence of faults and fractures within these rock formations indicates a tectonically active past that has influenced mineralization, groundwater movement, and hydrocarbon potential (Adepelumi and Falade, 2020; Anudu et al., 2014). The fractured basement rocks serve as secondary aquifers, allowing groundwater storage and movement, while the presence of sedimentary sequences in southern Kaduna suggests the potential for hydrocarbon reservoirs (Hassan et al., 2018; Zarmai et al., 2017). Mineralized zones are likely associated with these structurally controlled features, and the geologic map provides a basis for understanding the fault systems, folds, and lithologic boundaries that are essential for tectonic reconstructions.

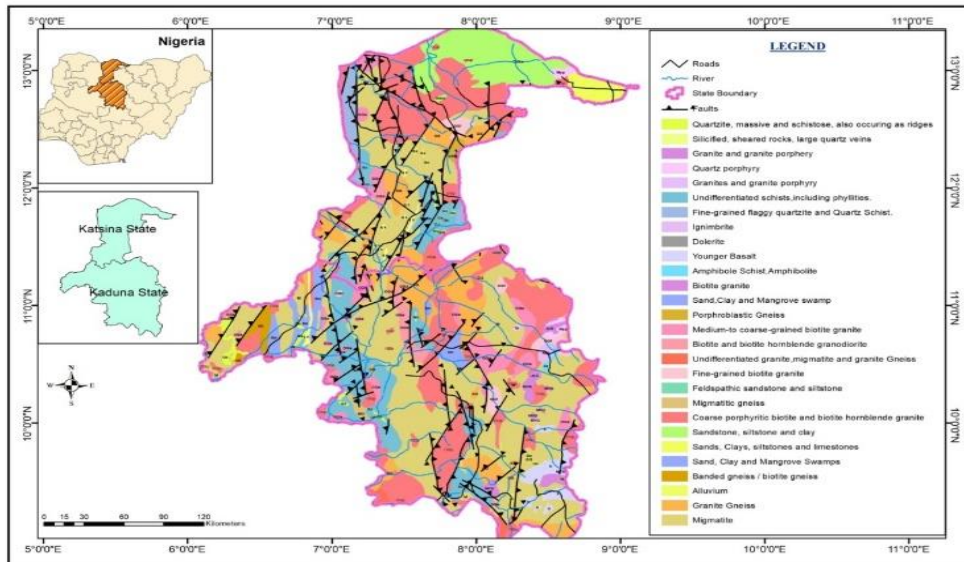


Figure 1: Geologic map of the study area

**2. MATERIALS**

The Free Air gravity data acquired by the Federal Ministry of Petroleum and Mineral Resources using the Lacoste and Romberg Geodetic gravity meter. The data covers part of the Katsina and Kaduna States. The software

programs used for data processing were Oasis Montaj version 7.0.1, Surfer (version 16.6) and ArcGIS (10.5). The data was processed to the form of free air gravity gridded data displayed as imageries in colour raster format (Figure 2).

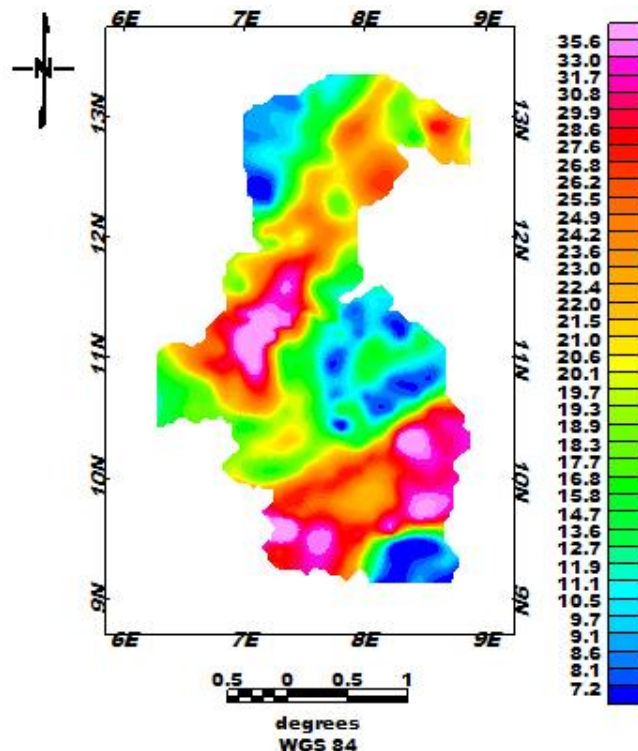


Figure 2: Free Air anomaly map over Katsina and Kaduna

A combination of qualitative and quantitative data analysis methods was applied to the Free Air gravity data. Initially, qualitative analysis was conducted using the Oasis Montaj software, where the Free Air gravity data was digitized into Geosoft grid file format with X, Y, and Z channels (Ekpo et al., 2024a). This was facilitated through the utility module of the gridding tools within the software's grid and map functions. The digitized data was subsequently stored in a pre-created database, which had been prepared before data importation.

Filtering processes were employed to enhance data accuracy and

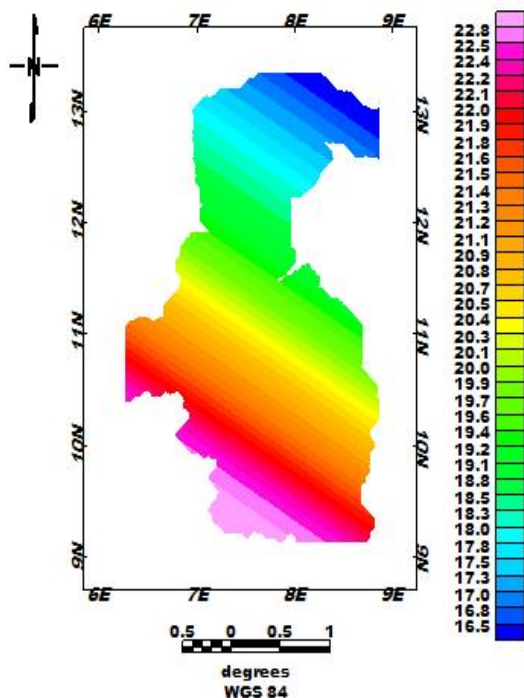


Figure 3: Regional anomaly map over the study area

resolution. Pre-spectrum analysis, utilizing the Fast Fourier Transform (FFT), was applied to each data component before the regional-residual separation process (Ekpo et al., 2024b). The regional and residual separation was carried out using the X utility module on the principal Z channel. The polynomial filtering technique of degree one (1) was applied to generate distinct regional and residual anomaly channels. This process ensured effective differentiation between large-scale geological trends and localized anomalies, providing enhanced insights into the subsurface (Ekpo et al., 2024c) structures of the study area as presented in figures 3 and respectively.

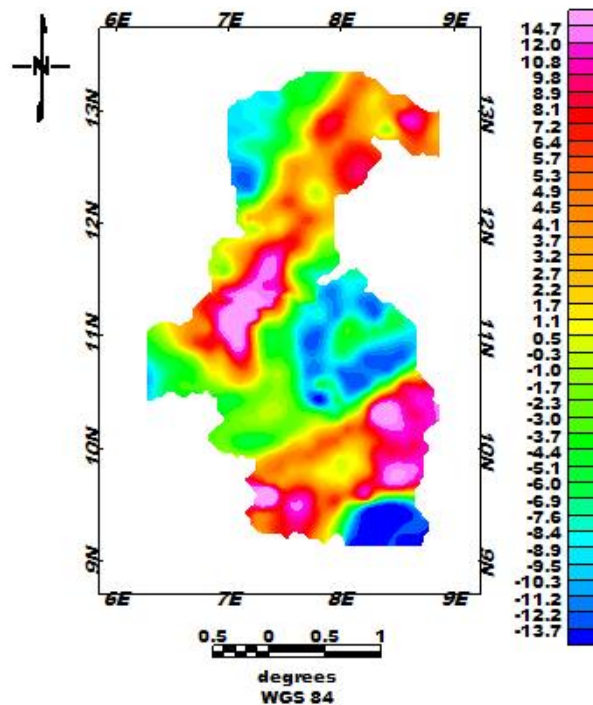


Figure 4: Residual anomaly map over the study area

2.1 Methodology

The section focuses on the Centre of Exploration Technology (CET) methods that enhance the detection of linear geological features like faults and fractures in geophysical surveys. The work flow for this method is presented in figure 5;

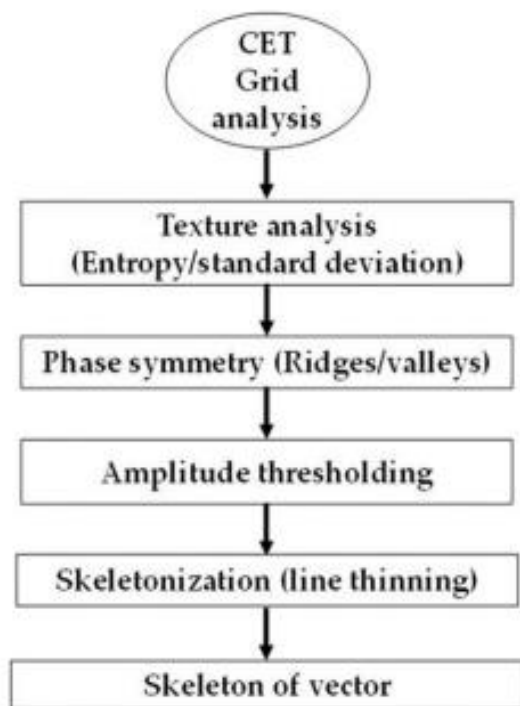


Figure 5: Work flow for this CET method

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.

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;

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

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. The Phase symmetry map over the study area is presented in figure 6;

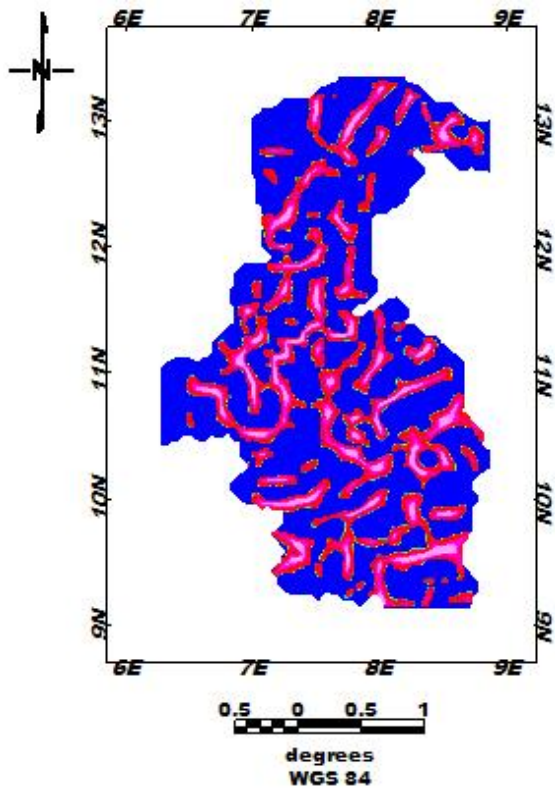


Figure 6: Phase symmetry map over the study area

### 3. DISCUSSION

The Free Air gravity anomaly map over Katsina and Kaduna highlights variations in gravity that result from surface and subsurface density changes. These variations are indicative of underlying geological structures, allowing for the identification of regional tectonic trends and subsurface features. High gravity anomalies typically correspond to denser rock formations, which may influence groundwater storage and flow, while low gravity anomalies often indicate sedimentary basins that have potential for hydrocarbon accumulation. In mineral exploration, areas with high-density anomalies may correspond to metallic ore bodies. The Free Air gravity anomaly map thus plays a significant role in revealing fault zones and possible buried structures that define the geological framework of the study area.

#### 3.1 Regional Anomaly Map

The regional anomaly map focuses on broad-scale geological trends by filtering out local variations. This allows for the identification of large lithological and structural features that have significant implications for various geological processes. The understanding of regional groundwater flow systems is enhanced by this map, as it delineates large-scale aquifer structures. In hydrocarbon exploration, it helps in identifying major sedimentary basins with thick sequences that are favorable for petroleum systems. The regional anomaly map also indicates broad mineralization zones that may contain valuable mineral resources. Additionally, it provides insights into large-scale tectonic deformations that have shaped the geological evolution of Katsina and Kaduna.

#### 3.2 Residual Anomaly Map

The residual anomaly map isolates smaller, localized geological features by removing regional trends. This allows for the identification of specific structures that are not apparent in the regional anomaly map. Local aquifers or fractured zones that serve as potential groundwater reservoirs can be delineated with greater precision. In hydrocarbon exploration, the residual anomaly map helps pinpoint smaller traps and potential reservoirs that may have been overlooked in broader studies. For mineral exploration, it enhances the detection of mineralized veins and ore deposits, while also revealing localized faulting and folding patterns that contribute to a more detailed structural framework of the study area.

#### 3.3 Phase Symmetry Map

The phase symmetry map is a crucial tool for identifying structural discontinuities such as faults and fractures by analyzing symmetric patterns in geophysical data. This is particularly useful in understanding how these discontinuities influence groundwater movement, as faults and fractures often serve as conduits for groundwater flow. In hydrocarbon

exploration, phase symmetry analysis can help identify faulted traps and migration pathways that may contain accumulations of hydrocarbons. Many mineral deposits are associated with shear zones and fault-controlled mineralization, making this map an essential resource for mineral exploration. The understanding of fault kinematics and deformation history provided by the phase symmetry map also contributes to refining the structural framework of the region.

#### 3.4 Centre for Exploration Targeting (CET) Map

The Centre for Exploration Targeting (CET) map (figure 7) delineates lineaments, which are linear structural features that play a crucial role in geological processes. These lineaments often coincide with groundwater flow paths and recharge zones, making them important for hydrogeological studies. In hydrocarbon exploration, structural lineaments indicate potential migration pathways and traps that can host hydrocarbon reserves. Many mineral deposits are structurally controlled, meaning they are often associated with major lineaments. By analyzing the CET map, researchers can gain valuable insights into regional structural analysis and tectonic evolution. The dominant lineament trends in the study area primarily follow NE-SW and NW-SE directions, which align with the major faulting systems and regional tectonic stress fields. These trends suggest a prolonged history of deformation and structural evolution that directly influences groundwater recharge, mineralization processes, and hydrocarbon trapping mechanisms.

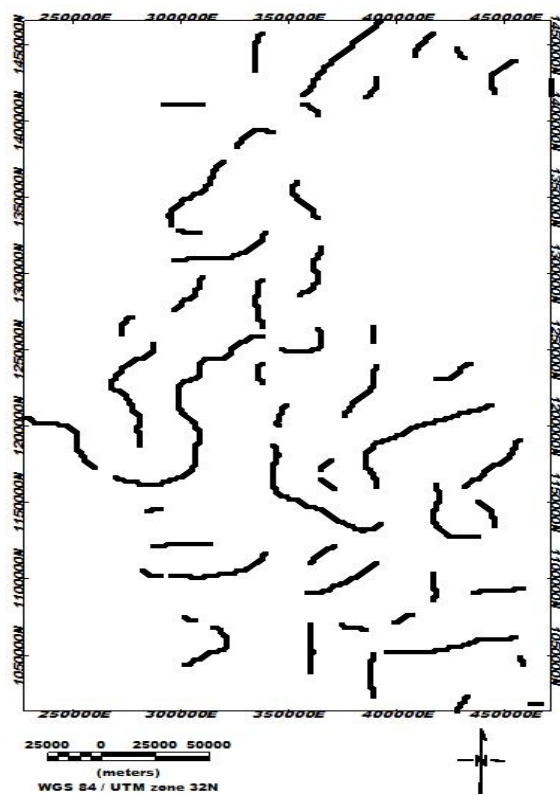
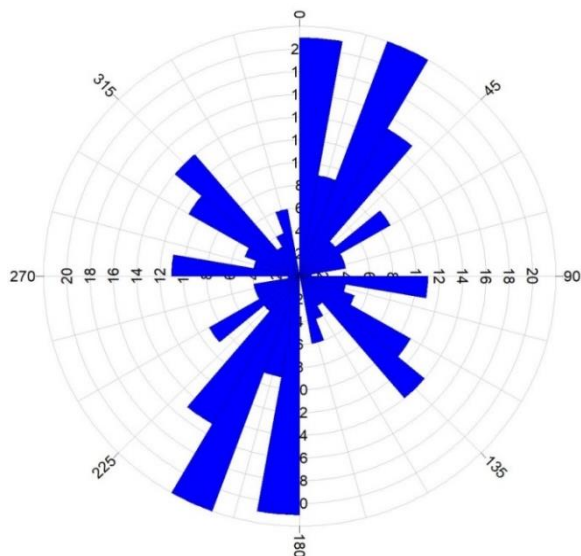


Figure 7: Centre for Exploration Targeting (CET) map, showing the lineament in the study area

#### 3.5 Rose Diagram of Lineament Orientations

The rose diagram (8) presents the dominant orientations of the lineaments extracted from Free Air gravity data, providing a visual representation of regional stress fields and tectonic forces. The dominant trends observed in the study area are primarily in the NE-SW and NW-SE directions, which align with major tectonic forces that have influenced the region's structural evolution. The orientation of these lineaments is crucial for understanding fracture-controlled aquifers, as they indicate the preferred direction of groundwater flow within fractured rock formations. In hydrocarbon exploration, these orientations align with stress directions that influence fault-sealed hydrocarbon reservoirs. In mineral exploration, the rose diagram can help identify mineralized shear zones, which are often aligned with regional stress fields. The data obtained from the rose diagram also provides crucial information on regional tectonic regimes and deformation patterns, which enhances the overall understanding of the geological setting of Katsina and Kaduna. The alignment of the lineaments with known fault systems suggests that these structural features serve as pathways for fluid migration, which is vital for both hydrogeological studies and resource exploration.



**Figure 8:** Rose diagram depicting the orientations of the Lineament from the Free Air gravity data over the study area.

### 3.6 Integrated Discussion and Implications

The integration of these geophysical and geological maps provides a comprehensive understanding of the subsurface conditions of Katsina and Kaduna, which has significant implications for various geological applications. The geological map establishes the fundamental lithological and structural framework, highlighting major rock formations and fault systems. The Free Air gravity anomaly map reveals subsurface density variations that are essential for identifying buried structures and tectonic trends. The regional and residual anomaly maps refine this understanding by distinguishing large-scale geological trends from localized features, helping to pinpoint areas of interest for hydrogeology, hydrocarbon exploration, and mineral exploration. The phase symmetry map further refines structural interpretations by identifying fault networks and deformation zones, which are crucial for understanding groundwater movement, hydrocarbon migration pathways, and mineralized structures. The CET map delineates lineaments that control various geological processes, while the rose diagram provides a statistical analysis of their orientations, offering insights into regional stress regimes and structural controls.

The dominant structural trends observed, particularly in the NE-SW and NW-SE directions, suggest a strong influence of regional tectonic forces in the geological evolution of Katsina and Kaduna. These trends have implications for hydrogeology by indicating preferential groundwater flow paths, for hydrocarbon exploration by aligning with fault-controlled traps, and for mineral exploration by highlighting structurally controlled mineralization zones. The presence of these dominant lineaments indicates active structural deformation, which enhances the potential for hydrocarbon accumulation in structurally controlled traps. Furthermore, mineralization processes are often guided by fault intersections along these lineaments, making them crucial targets for exploration. Collectively, these maps contribute to a deeper understanding of the geological framework of the study area, enabling informed decision-making in resource exploration and environmental management. Through this integrated approach, the study area's hydrogeological, hydrocarbon, and mineral potential can be systematically evaluated, providing a solid foundation for future exploration and development initiatives.

## 4. CONCLUSION

The interpretation of geophysical maps over Katsina and Kaduna has provided critical insights into the structural framework, lithological variations, and resource potentials of the region. The analysis of lineament orientations using the CET map and rose diagram has revealed dominant NE-SW and NW-SE trends, which are significant for fluid migration and mineralization. The Free Air gravity anomaly map has highlighted subsurface density variations, identifying basement highs and sedimentary basins suitable for hydrocarbon exploration. Regional and residual anomaly maps have further refined these interpretations by differentiating large-scale geological structures from localized anomalies. The phase symmetry map has effectively delineated structural discontinuities that control groundwater flow and mineral deposition. Overall, the findings have demonstrated that structural geology plays a vital role in resource distribution and regional tectonic evolution.

## 4.1 Recommendations

Based on the findings, the following recommendations are proposed:

- **Hydrogeological Development:** Further hydrogeological surveys should be conducted in areas where faulted and fractured zones have been identified to enhance groundwater exploitation and sustainable water resource management.
- **Mineral Exploration:** Detailed geochemical and geophysical investigations should be carried out in areas with significant structural anomalies to assess their mineral potential more effectively.
- **Hydrocarbon Exploration:** More extensive seismic and well-log studies should be integrated with the current gravity and magnetic data to better evaluate hydrocarbon potential in sedimentary-covered areas of Kaduna.
- **Structural and Tectonic Studies:** Continued geophysical surveys and geological mapping should be encouraged to refine the structural framework and understand regional tectonic evolution further.
- **Policy and Resource Management:** The findings should be utilized to guide policymakers in planning sustainable resource exploration, groundwater development, and environmental conservation efforts in the region.

Through the integration of geophysical and geological analyses, this study provides a comprehensive approach to understanding the subsurface complexities of Katsina and Kaduna, thereby supporting regional development and resource management initiatives.

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