Integrated Analysis of Gravity and Geoidal Anomalies for Understanding Crustal Deformation and Tectonic Processes in the Calabar Flank, Nigeria

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Article Info

ISSN (online): 2582-7138
Volume: 05
Issue: 05
September-October 2024
Received: 12-07-2024
Accepted: 16-08-2024
Page No: 371-377

Abstract

In order to shed light on the subsurface structure and tectonic dynamics of the Calabar Flank, this study presents an integrated analysis of the gravity and geoidal anomalies within the area. Geoidal anomalies varied from extremely low (18.44 to 19.24 m) to extremely high (21.13 to 22.09 m), and gravity anomaly results were classified into five separate ranges, from extremely low (-48.34 to -15.73 mGal) to extremely high (29.82 to 65.55 mGal). Processes like crustal uplift, sedimentary basin formation, and crustal extension can be inferred from the noticeable variations in subsurface density shown by these anomalies. Areas of significant crustal thinning and sedimentary accumulation are highlighted by very low gravity and geoidal anomalies; these features are crucial for hydrocarbon exploration. Transitional zones serve as buffers against tectonic stress, and moderate anomalies indicate these zones. Anomalies in the high to very high range indicate uplift and crustal thickening in certain regions, most likely caused by compressional forces. The results provide important information for hydrocarbon exploration, tectonic monitoring, and risk assessment in the study area, and they help fill gaps in our knowledge about the Calabar Flank's tectonic history.

Keywords: Calabar Flank, Crustal Deformation, Geodynamics, Geoid, Gravity, Tectonic Activity

1. Introduction

Situated in southeastern Nigeria, the Calabar Flank is a geologically noteworthy area marked by intricate crustal deformation and tectonic processes. The Niger Delta Basin, of which this study area is a part, is rich in hydrocarbons and has intricate subsurface structures. Geophysical studies have shown an interest in the Calabar Flank because of the way its geological setting has been affected by rifting, crustal extension, and uplift (Whiteman, 1982; Burke & Whiteman, 1973) [38, 7].

Subsurface density variations and mass distribution can be understood through the use of gravity and geoidal anomalies. These geophysical tools are crucial for understanding underlying tectonic processes (Blakely, 1995; Telford *et al*., 1990) [6, 35]. Geoidal anomalies are surface deviations from an idealised reference ellipsoid caused by mass distribution within the Earth, whereas gravity anomalies are variations in the Earth's gravitational field resulting from differences in subsurface density (Heiskanen & Moritz, 1967; Ekwok *et al*., 2019) [20, 12]. According to Hofmann-Wellenhof and Moritz (2006) [21], these anomalies can be used to learn about a region's crustal structure, lithospheric dynamics, and tectonic evolution.

The tectonic complexity and economic importance of the Calabar Flank, especially in hydrocarbon exploration, have made it the subject of numerous geological and geophysical studies (Doust & Omatsola, 1990) [10]. Tectonic events, such as the opening of the South Atlantic Ocean and the rifting of the African plate that followed, have shaped the study area's sedimentary basins, fault systems, and crustal blocks (Fairhead, 1988; Murat, 1972) [19, 25]. According to Nyblade *et al*. (1996) [26] and Osagie *et al*. (1997) [32], the study area's gravity and geoidal anomalies reflect the substantial crustal deformation caused by these tectonic processes, which includes extension, thinning, and uplift.

Ofoegbu and Onuoha (1991) [28] and Ajakaiye *et al*. (1986) [3] are two studies that have shown how important gravity and geoidal anomaly analysis are for understanding the structural and tectonic evolution of sedimentary basins. Critical for hydrocarbon exploration, subsurface structures like faults, folds, and igneous intrusions have been identified in the Calabar Flank using gravity anomalies (Ekwok *et al*., 2019; Ekwok *et al*., 2020a; Ekwok *et al*., 2020b; Anudu *et al*., 2014; Adepelumi *et al*., 2009) [12, 13, 14, 5, 2]. However, geoidal anomalies help us understand regional tectonics and geodynamics by revealing details about the distribution of mass on a large scale as well as crustal movements (Omosanya *et al*., 2012; Ogagarue & Agumanu, 2012) [31, 29]. A thorough and coordinated investigation of gravity and geoidal anomalies is necessary to fill gaps in our current understanding of crustal deformation and tectonic processes on the Calabar Flank, notwithstanding the wealth of literature on the subject. Understanding the subsurface structures and tectonic evolution of the Calabar Flank is crucial for academic research and resource exploration. An integrated approach would provide a more detailed picture of this (Ojo, 1990; Udinmwen *et al*., 2014; Eldosouky, and Elkhateeb, 2018; Eldosouky *et al*., 2017; Elkhateeb and Eldosouky, 2016) [30, 36. 15, 16, 17].

This research intends to address that knowledge vacuum by investigating the Calabar Flank's gravity and geoidal anomalies in great depth. Osazuwa *et al*. (1981) [33] and Adepelumi and Olorunfemi (2000) [1] found that tectonic processes such as crustal extension, thinning, uplift, and compression can be better understood by classifying these anomalies into different ranges and examining their spatial distribution. This research has the potential to apply to hydrocarbon exploration, seismic hazard assessment, and regional tectonic studies (Akaegbobi *et al*., 2000; Offodile, 1976) [4, 27], among other areas that could benefit from a better understanding of the geodynamics of the Calabar Flank.

2. Materials and Methods

2.1. Study Area

The Calabar Flank forms a significant portion of Nigeria's continental margin and is characterized by a complex structural framework dominated by block faulting. This structural configuration is primarily composed of horst and graben systems, which are typical features of extensional tectonics. These structures exhibit a predominant northwest-southeast (NW-SE) orientation, reflecting the tectonic forces that have shaped the region over geological time.

Geographically, the Calabar Flank is situated between latitudes 5°00′ to 5°15′N and longitudes 8°15′E to 8°30′E, (figure 1). This area is strategically located within the southeastern part of Nigeria and forms a crucial link between the Niger Delta Basin to the west and the Cameroon Volcanic Line to the east. The study area's unique tectonic setting has significant implications for its geological history, including the processes of rifting, sedimentation, and hydrocarbon accumulation.

Understanding the structural configuration of the Calabar Flank is essential for interpreting the geodynamic evolution of the region, as well as for exploring its resource potential. The interplay between tectonic forces, sedimentation, and faulting has led to the development of complex subsurface structures, which are crucial for the exploration of natural resources such as oil and gas.

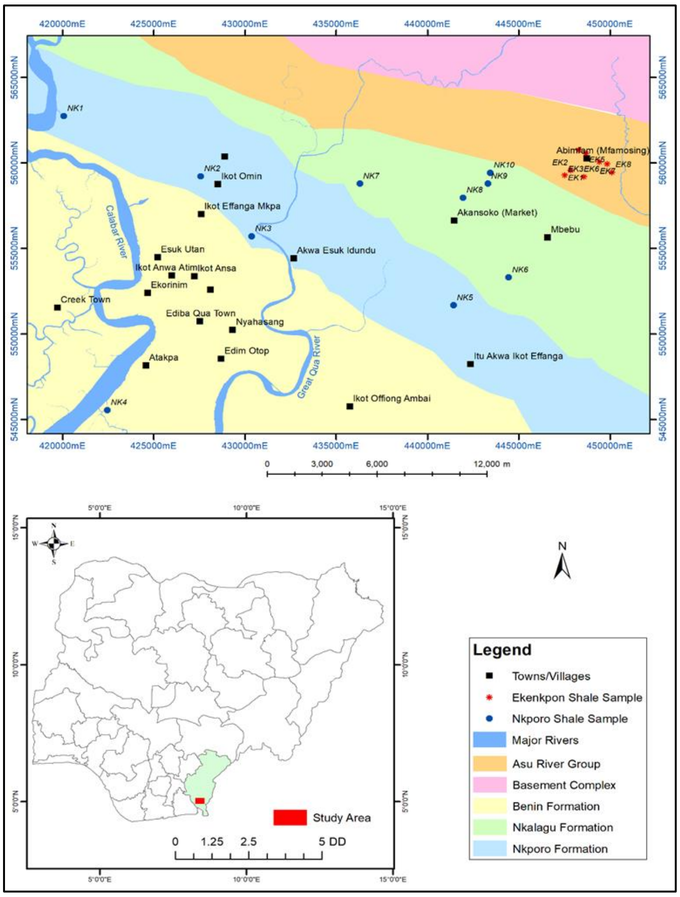

Fig 1: Map of Study Area

2.2. Methods

This study employed a combination of gravity and geoidal anomaly analyses to investigate the subsurface structure and tectonic dynamics of the Calabar Flank. The gravity and geoidal data for the Calabar Flank were obtained from https://podaactools.jpl.nasa.gov. and https://data.nodc.noaa.gov respectively. Before analysis, the raw gravity and geoidal data underwent preprocessing to ensure accuracy and reliability, the gravity data were corrected for latitude (Free-Air correction), elevation (Bouguer correction), and terrain, to isolate the gravity anomalies from the observed gravity field. The geoidal height data were processed to extract undulations by removing the reference ellipsoid component, allowing the calculation of geoidal anomalies. The corrected gravity data were used to compute Bouguer gravity anomalies, reflecting variations in subsurface density. These anomalies were then categorized into five distinct ranges: very low, low, moderate, high, and very high. Spatial analysis was conducted to map the distribution of these anomalies across the study area, using ArcGIS to visualize and analyze the spatial patterns.

Geoidal anomalies were computed to assess the mass distribution within the study area. The geoidal height data were analyzed to calculate geoidal anomalies, which were also categorized into five distinct ranges: very low, low, moderate, high, and very high. The spatial distribution of geoidal anomalies was mapped and visualized, providing insights into the underlying mass distribution.

The gravity and geoidal anomaly data were also used to interpreted to understand the subsurface structure and tectonic processes. The anomalies were correlated with known geological features, including sedimentary basins, fault zones, and tectonic boundaries.

Areas with very low and low gravity and geoidal anomalies were identified as regions of reduced subsurface density, likely due to crustal thinning and sedimentary accumulation. High and very high anomalies indicated regions of increased subsurface density, associated with crustal thickening and uplift.

3. Results

3.1. Gravity Anomaly of Calabar Flank

The gravity anomaly results for the Calabar Flank were classified into five distinct ranges: very low (-48.34 to -15.73 mGal), low (-15.73 to 0.34 mGal), moderate (0.34 to 13.29 mGal), high (13.29 to 29.82 mGal), and very high (29.82 to 65.55 mGal), with a mean gravity anomaly of 4.51 mGal and a standard deviation of 17.53 mGal.

The very low gravity anomalies, which range from -48.34 to -15.73 mGal, indicate regions with significantly lower subsurface density. This density reduction is commonly associated with large sediment-filled basins or highly weathered zones. Such areas are indicative of significant crustal extension, implying that these regions have undergone significant thinning and stretching, possibly due to rifting or tectonic stretching processes.

Low gravity anomalies, ranging from -15.73 to 0.34 mGal, also indicate areas of lower density, albeit less pronounced than very low anomalies. These anomalies could be zones of moderate extension or regions dominated by low-density sedimentary deposits. The lower-density anomalies in these regions indicate that the extension processes have continued, albeit to a lesser extent than in the very low anomaly regions.

Moderate gravity anomalies, ranging from 0.34 to 13.29 mGal, indicate areas with near-average density. These regions are likely to be relatively stable, indicating areas where crustal thickness does not significantly increase or decrease. Such areas could be transitional zones between major structural features or relatively undeformed blocks, acting as buffers against tectonic stresses without causing significant deformation.

High gravity anomalies (13.29 to 29.82 mGal) indicate areas of increased subsurface density, possibly due to the presence of denser igneous or metamorphic rocks. These areas could be associated with crustal uplift or regions where denser materials have been emplaced as a result of tectonic processes. These regions' increased density suggests that they may be subjected to compressional forces, resulting in crustal thickening and uplift.

Very high gravity anomalies, ranging from 29.82 to 65.55 mGal, indicate zones with significantly higher density. This could be due to the presence of mafic or ultramafic rocks, which indicate major tectonic features like uplifted blocks or crustal compression zones. These areas may also indicate the presence of mantle materials closer to the surface, implying high tectonic activity and crustal deformation.

The gravity anomaly data indicate a pattern of crustal deformation in the Calabar Flank. The very low and low gravity anomalies suggest extensive crustal extension and the formation of sedimentary basins, which are critical for hydrocarbon exploration. These regions may have undergone significant rifting, resulting in crustal thinning and sediment deposition.

Moderate gravity anomalies indicate relatively stable crustal regions or transitional zones that serve as buffers between more deformed regions, allowing tectonic stresses to be accommodated without causing significant deformation. High to very high gravity anomalies indicate crustal uplift and compression, which may be related to tectonic convergence and the presence of denser subsurface materials. These areas are most likely subject to significant tectonic forces, resulting in crustal thickening and uplift. The gravity anomaly is depicted in Figure 2.

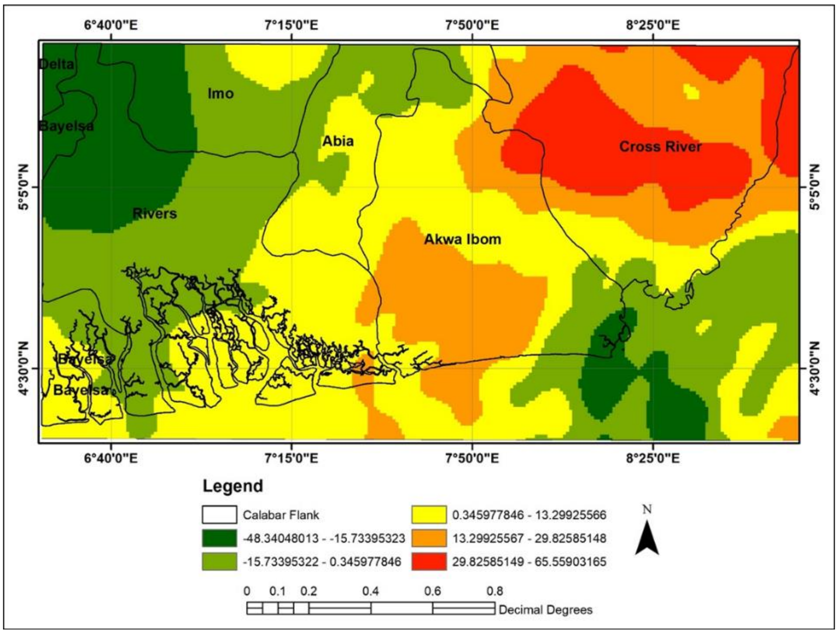

Fig 2: Gravity Anomaly of Calabar Flank

3.2. Geoidal Anomaly of Calabar Flank

The geoidal anomaly data for the Calabar Flank is divided into five categories: very low (18.44 to 19.24 m), low (19.24 to 19.83 m), moderate (19.83 to 20.43 m), high (20.43 to 21.13 m), and very high (21.13 to 22.09 m), with a mean geoidal anomaly of 19.92 m and a standard deviation of 0.79 m.

The extremely low geoidal anomalies, which range from 18.44 to 19.24 m, indicate areas where geoid height is significantly lower than average. These anomalies indicate lower mass density, which could be attributed to extended crustal thinning and the presence of large sedimentary basins. This could indicate significant tectonic stretching and rifting processes, which contributed to the observed lower mass distribution.

Low geoidal anomalies, ranging from 19.24 to 19.83 m, also indicate areas with lower-than-average geoid height, albeit less pronounced than very low anomalies. These areas may be associated with moderate crustal thinning or the presence of lower-density sedimentary deposits. Such anomalies indicate ongoing tectonic extension, albeit to a lesser extent than regions with extremely low geoidal anomalies.

Moderate geoidal anomalies, ranging from 19.83 to 20.43 m, correspond to regions of near-average geoid height. These regions are expected to be relatively stable in terms of mass distribution and crustal deformation. They could be transitional zones between more deformed regions or relatively undeformed blocks that maintain a balance of extension and compression forces.

High geoidal anomalies (ranging from 20.43 to 21.13 m) indicate that the geoid height is higher than average. These anomalies indicate areas with higher mass density, which could be due to crustal thickening, denser subsurface materials, or uplifted crustal blocks. These regions may be subjected to compressional forces, resulting in crustal thickening and uplift.

Very high geoidal anomalies, ranging from 21.13 to 22.09 m, indicate zones with significantly higher geoid height, implying much higher mass density. This could be due to the presence of dense igneous or metamorphic rocks, significant tectonic features such as uplifted blocks, or areas where mantle materials are closer to the surface. These anomalies point to significant tectonic activity and crustal deformation.

The geoidal anomaly represents a pattern of crustal deformation within the Calabar Flank. Very low to low geoidal anomalies indicate significant crustal extension and thinning, most likely caused by rifting processes. These areas correspond to massive sedimentary basins that are critical for hydrocarbon exploration.

Moderate geoidal anomalies indicate relatively stable crustal regions or transitional zones that regulate tectonic stresses. Geoidal anomalies ranging from high to very high indicate crustal uplift and thickening, which may be caused by compressional tectonic forces and the presence of denser subsurface materials. Figure 3 depicts how these areas are experiencing significant tectonic convergence, which is causing crustal thickening and uplift.

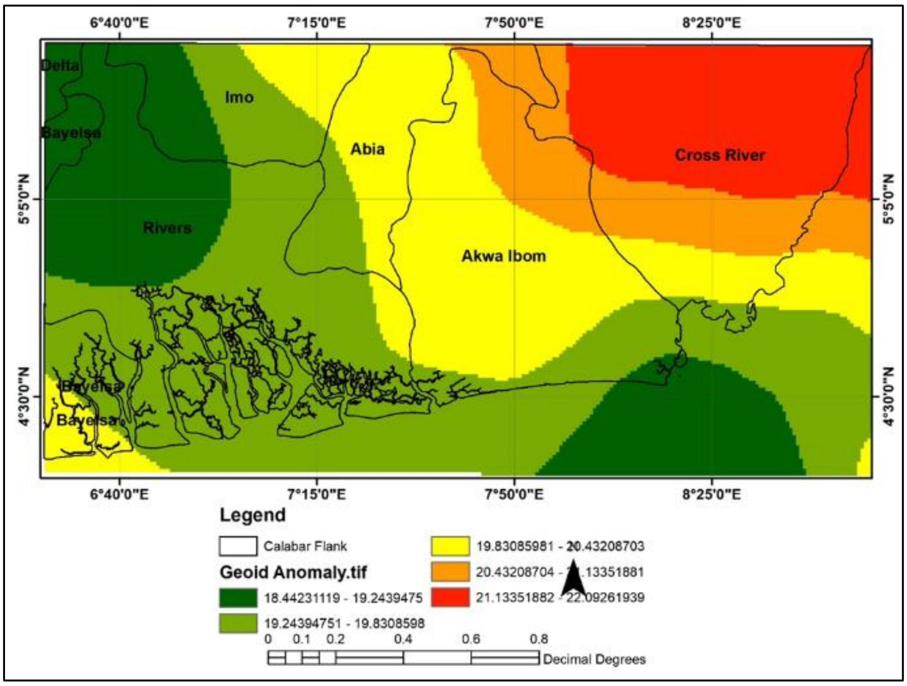

Fig 3: Geoidal Anomaly of Calabar Flank

3.3. Discussion of Results

The results from the analysis of gravity and geoidal anomalies within the Calabar Flank provide significant insights into the study area's crustal deformation patterns. The categorization of gravity anomalies into very low, low, moderate, high, and very high ranges reflects a diverse subsurface structure that is influenced by tectonic forces, crustal thinning, and the presence of various rock densities. The geoidal anomalies further support these findings, indicating variations in mass distribution and crustal deformation.

The findings of this study align with previous research conducted in similar tectonic settings. For instance, gravity anomaly studies in rift zones have often identified very low anomalies associated with extensive sedimentary basins and crustal thinning, consistent with the results observed in the Calabar Flank (Ebinger & Casey, 2001; Fairhead, 1988) [11, 19]. The low to very low gravity anomalies in this study, which suggest regions of reduced subsurface density and significant crustal extension, are comparable to those found in other rift-related basins such as the East African Rift System (Chorowicz, 2005) [8].

The moderate gravity anomalies identified in this study, representing near-average density and relative crustal stability, correspond with transitional zones observed in other geological settings. These areas are often interpreted as regions that act as buffers, accommodating tectonic stresses without significant deformation (Cowie *et al*., 2000) [9]. The stability indicated by these moderate anomalies is crucial for understanding the distribution of tectonic forces within the study area.

High to very high gravity anomalies, which suggest regions of increased subsurface density due to the presence of denser igneous or metamorphic rocks, align with studies in tectonically active regions where crustal uplift and thickening are prevalent (Wang *et al*., 2012; Kaban *et al*., 2016) [37, 23]. Similar findings have been reported in regions with significant compressional forces, where mantle materials or denser crustal blocks are closer to the surface, leading to high gravity anomalies (Jordan & Schott, 2001) [22].

The geoidal anomalies reported in this study, particularly the very low to low anomalies indicating significant crustal thinning and rifting, are consistent with studies in other extensional tectonic settings (Sandwell & Smith, 2009; McKenzie, 1978) [34, 24]. The observed pattern of geoidal anomalies suggests a dynamic tectonic environment where crustal extension and compressional forces are actively shaping the subsurface structure.

The results of this study contribute to the broader understanding of crustal deformation processes within rift and tectonic settings. The detailed categorization of gravity and geoidal anomalies offers valuable insights into the subsurface structure and tectonic activity of the Calabar Flank, a region that has been relatively under-explored in previous studies. These findings are particularly relevant for hydrocarbon exploration, as the identification of sedimentary basins and fault structures can guide exploration efforts in this study area.

Moreover, the study's integration of gravity and geoidal anomaly data provides a comprehensive view of the study area's tectonic evolution, highlighting areas of potential seismic activity and crustal instability. This information is crucial for earthquake risk assessment and mitigation efforts in the Calabar Flank and similar regions.

The identification of distinct gravity and geoidal anomaly ranges provides a framework for monitoring crustal deformation in the Calabar Flank. The ability to categorize and map these anomalies allows for the ongoing assessment of tectonic processes, offering a valuable tool for predicting future deformation patterns and potential hazards. The study's findings can be used to refine models of tectonic activity in the study area, improving our understanding of the forces shaping the Earth's crust in this area.

4. Conclusions

The gravity and geoidal anomaly analysis of the Calabar Flank provides crucial insights into the study area's subsurface structure and tectonic dynamics. The very low to low gravity and geoidal anomalies indicate extensive regions of crustal extension and significant sedimentary basin formation. These areas are characterized by reduced subsurface density, likely resulting from tectonic stretching and rifting processes. These findings are crucial for understanding the geodynamic history of the Calabar Flank and have direct implications for hydrocarbon exploration, as such basins are often prime locations for oil and gas reservoirs.

Moderate gravity and geoidal anomalies correspond to regions of near-average density and stability. These areas likely represent transitional zones between more deformed regions and relatively undeformed blocks. These zones act as buffers, accommodating tectonic stresses without significant deformation, thereby playing a vital role in the study area's overall tectonic stability.

The high to very high gravity and geoidal anomalies highlight regions of increased subsurface density, possibly due to the presence of denser igneous or metamorphic rocks. These areas are indicative of crustal uplift and thickening, potentially related to compressional tectonic forces. The presence of such anomalies suggests ongoing tectonic convergence and the potential for significant crustal deformation in these areas.

The detailed categorization of gravity and geoidal anomalies across the Calabar Flank provides a framework for monitoring tectonic activity in the study area. The identification of regions with different degrees of crustal deformation allows for targeted monitoring and assessment of potential seismic risks, making this study highly relevant for disaster preparedness and risk management.

The findings enhance the understanding of the Calabar Flank's tectonic evolution and contribute to the broader geological and geophysical knowledge of similar rift-related regions. By identifying areas of crustal thinning, thickening, and uplift, the study provides valuable data for refining existing tectonic models and supporting future research efforts.

The identification of extensive sedimentary basins, as indicated by low gravity and geoidal anomalies, is particularly relevant for hydrocarbon exploration. These findings provide essential data for locating potential hydrocarbon reservoirs within the Calabar Flank, supporting exploration efforts and economic development in the study area.

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