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Characterization and Mapping of Calabar Flank Crustal Deformation Using Sentinel -1 Data

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Abstract
This study mapped and characterized crustal deformation within the Calabar Flank, using Sentinel-1 satellite data. The analysis identified three distinct categories of crustal movement: subsidence, normal movement, and uplift, each covering significant areas and exhibiting varying rates of displacement. Subsidence was observed over 7,235.4 km², with rates ranging from 1.7 cm/yr to 2 cm/yr, suggesting active extensional tectonics and the formation of sedimentary basins. Normal movement, covering 22,350 km² with rates of 1.1 cm/yr to 1.4 cm/yr, indicates areas of relative tectonic stability. Uplift, spanning 8,588.8 km², was characterized by movement rates between 1.4 cm/yr and 1.7 cm/yr, pointing to tectonic compression or the influence of buoyant subsurface materials. These findings have significant implications for understanding the tectonic evolution of the Calabar Flank, particularly in relation to hydrocarbon exploration, seismic hazard assessment, and infrastructure development. The results contribute valuable data to the scientific community, enhancing the broader understanding of crustal deformation processes in tectonically active regions.
Keywords: *Calabar Flank, Crustal Deformation, Geodynamics, Sentinel-1, Subsidence, Tectonic Activity*

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I. Introduction

The Calabar Flank, located in southeastern Nigeria, is a significant geological structure on the West African margin with distinct tectonic and sedimentary features. Geoscientists are particularly interested in its complex tectonic history, which is influenced by regional and local geological processes. Understanding the Calabar Flank's crustal deformation is critical for determining the tectonic evolution of the West African margin and assessing the area's geohazard potential.

Crustal deformation is the alteration of the Earth's crust caused by tectonic forces, which can result in the formation of faults, folds, and other structural elements. Plate tectonics is typically responsible for these deformations, which occur when the Earth's lithospheric plates move, accumulating stress and eventually deforming the crust. The Calabar Flank, which is part of the Niger Delta Basin, has undergone significant deformation due to the interaction of various tectonic processes such as rifting, subsidence, and sedimentation (Khan et al., 2007).

The Calabar Flank's tectonic evolution is closely linked to the opening of the South Atlantic Ocean from the Late Jurassic to Early Cretaceous period, which resulted in the separation of the African and South American plates (Reynolds, 2011). This event resulted in the formation of rift basins along the West African margin, including the Calabar Flank, where extensional tectonics predominated (Stich, 2006). Subsequent subsidence and sedimentation during the Cretaceous and Tertiary periods helped to form the study area's thick sedimentary sequences (Watts et al., 1999).

Several studies have been conducted to investigate the structural features and tectonic setting of the Calabar Flank. Early works by Bassey et al., (2020) and Nton and Okoro, (2009) shed light on the regional geology and tectonic framework, emphasising the importance of extensional tectonics in the study area's evolution. These studies were supplemented by more recent research, which used geophysical data to characterise the subsurface structures and deformation patterns in the area (Anudu *et al.*, 2014; Nton and Okoro, 2009). These studies revealed faults, folds, and other structural features that indicate significant crustal deformation.

The characterisation and mapping of crustal deformation in the Calabar Flank is critical for several reasons. To begin, understanding the study area's deformation patterns can shed light on the tectonic processes that have shaped the West African margin (Adepelumi *et al.*, 2012). Second, accurate mapping of these deformations is critical for determining the geohazard potential of the area, as areas of intense deformation are frequently associated with seismic activity and other geological hazards (Asfaw et al., 2020). Third, the study of crustal deformation can help with the exploration of natural resources like hydrocarbons, which are frequently associated with structural traps formed by tectonic processes (Adeniyi and Ojo, 2013).

Geophysical techniques such as seismic reflection, gravity, and magnetic surveys have been extensively used to study crustal deformation in a variety of geological settings, including the Calabar Flank (Khan et al., 2007). These techniques enable the imaging of subsurface structures as well as the detection of fault systems, folds, and other deformation characteristics. Recent advances in geospatial technology, such as remote sensing and Geographic Information Systems (GIS), have improved our ability to map and analyse crustal deformation in complex geological settings (Asfaw *et al.*, 2020).

Despite advances in understanding the Calabar Flank's tectonic and structural framework, there is still a need for comprehensive studies that combine geophysical data with modern geospatial techniques to provide a more detailed characterisation and mapping of crustal deformation in the study area (Bassey *et al.*, 2020). These studies are critical for improving our understanding of the tectonic evolution of the West African margin, as well as informing geohazard assessments and resource exploration in the study area.

II. Materials and Methods

2.1 Study Area

The Calabar Flank is a part of the continental margin of Nigeria dominated by block faults with horst and graben trending in the NW–SE direction. The Calabar Flank lies between latitudes 5°00′ to 5°15′N and between longitudes 8°15′E to 8°30′E (Figure 1).

The Calabar Flank sedimentary basin was formerly a part of the Lower Benue Trough, but it was later renamed by its structural orientation. The basin is bounded by the Oban Massif to the north and the Calabar hinge line delineating the Niger Delta basin in the south and is separated from the Ikpe platform to the west by NW – SE trending faults. The East is bounded by the Cameroun volcanic ridge.

The flank is one of the continental margin-sag basins which has similar features with that of Cameroon, Gabon, Congo and Angola and lies along the south Atlantic coastal margin of Africa and the origin is linked with the opening of the South Atlantic.

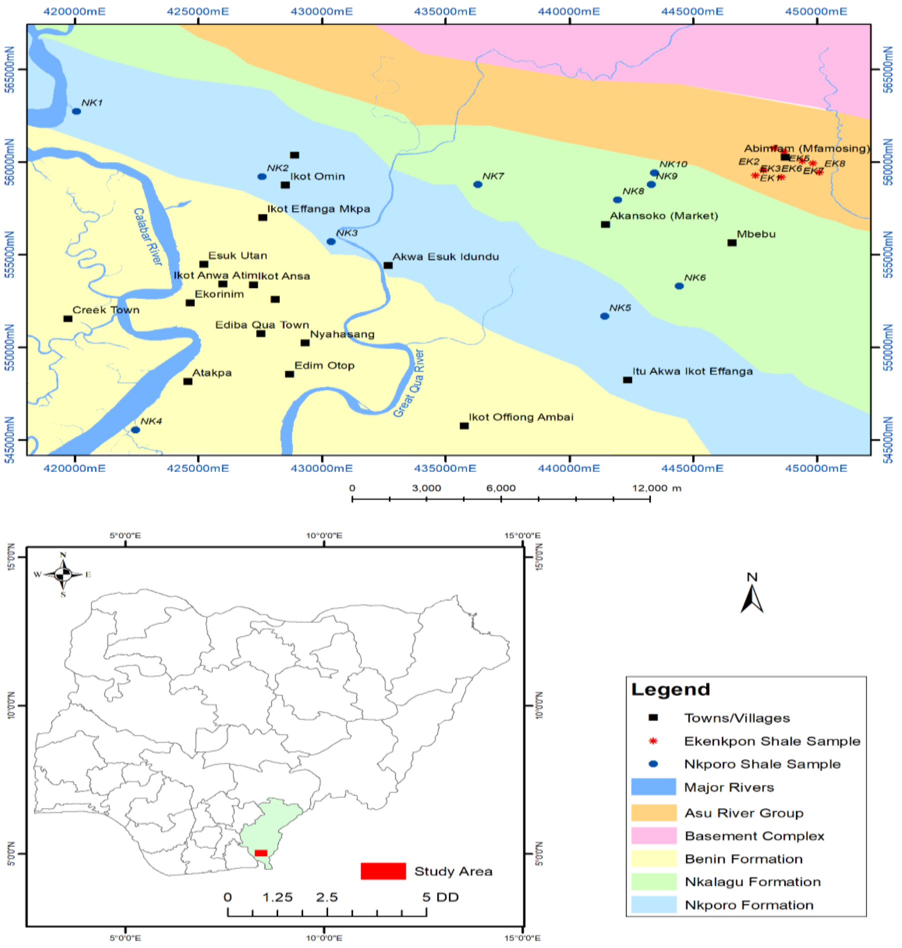

Figure 1: Map of the Study Area

2.2 Methods

In this study, crustal deformation was modelled using a systematic process. First, the TOPSAR Split technique was applied to divide each sub-swath with selected bursts into separate products. Next, the satellite orbit file was acquired to refine the orbit state vectors provided in the SAR product's metadata. Back geocoding was then performed to co-register two S-1 SLC split products from January and June 2024, using their orbits and a Digital Elevation Model (DEM). The Network Enhanced Spectral Diversity (NESD) method was implemented for TOPS co-registration, creating a network of images and estimating range and azimuth offsets. An interferogram was generated, with the flat-earth phase subtracted using orbital and metadata information. The SAR SLC products were de-busted, synchronizing burst images across sub-swaths. Topographic phase was estimated and subtracted from the interferogram using a DEM. Multilook processing was applied to reduce speckle noise and improve image interpretability, followed by Goldstein Phase Filtering and phase unwrapping to enhance accuracy. Finally, displacement was computed by converting the interferometric phase to a displacement map, and Range Doppler Terrain Correction was applied to correct distortions caused by topographical variations and sensor tilt, ensuring that the image's geometric representation closely matched the real world.

III. Results

The crustal movements within the Calabar Flank identified by Sentinel-1 analysis were divided into three categories based on movement and area covered. They include subsidence, normal and uplift.

The subsidence area spans 7,235.4 km² and moves at rates ranging from 1.7 cm/yr to 2 cm/year. Subsidence in this context refers to the gradual sinking or downward settling of the Earth's surface. This movement is commonly associated with extensional tectonic regimes, in which the crust is pulled apart, causing thinning and the formation of sedimentary basins. The relatively high subsidence rates suggest active tectonic processes, possibly related to rifting or other extensional mechanisms.

The region classified as experiencing normal movements covers 22,350 km² with movement rates ranging from 1.1 to 1.4 cm/yr. These are regions where crustal movement is relatively stable, with neither significant uplift nor significant subsidence. The rates of movement indicate that these areas are not subjected to high tectonic stress, making them relatively stable zones within the Calabar Flank's larger tectonic framework.

The uplifted area, covering 8,588.8 km², exhibits movements ranging from 1.4 cm/yr. to 1.7 cm/yr. Uplift in these areas suggests that the crust is rising, which could be caused by compressional forces, tectonic convergence, or the presence of buoyant materials beneath the crust. The uplift rates indicate active tectonic processes, which could be related to crustal thickening or the intrusion of less dense materials from the mantle.

The Calabar Flank's significant subsidence and associated movement rates suggest that extensional tectonics are still active. This extension thins the crust and creates sedimentary basins, which are critical for understanding the region's tectonic evolution. Subsidence areas are critical for hydrocarbon exploration because they frequently form basins where sediments accumulate and hydrocarbons can become trapped.

The large area classified as normal movements indicates regions with relative tectonic stability. These areas serve as buffers within the larger tectonic regime, allowing for minor adjustments without causing significant deformation. Understanding these stable zones is critical for developing a comprehensive tectonic model of the Calabar Flank because they provide information about the overall stress distribution and tectonic dynamics.

Areas of uplift indicate tectonic compression or the presence of buoyant subsurface materials. The presence of uplift indicates that active tectonic forces are driving the crust upward, which could be related to plate convergence or mantle plume upwelling. These areas are important for understanding tectonic interactions and seismic activity because uplift is frequently associated with increased tectonic stress. Figure 2 depicts crustal movements.

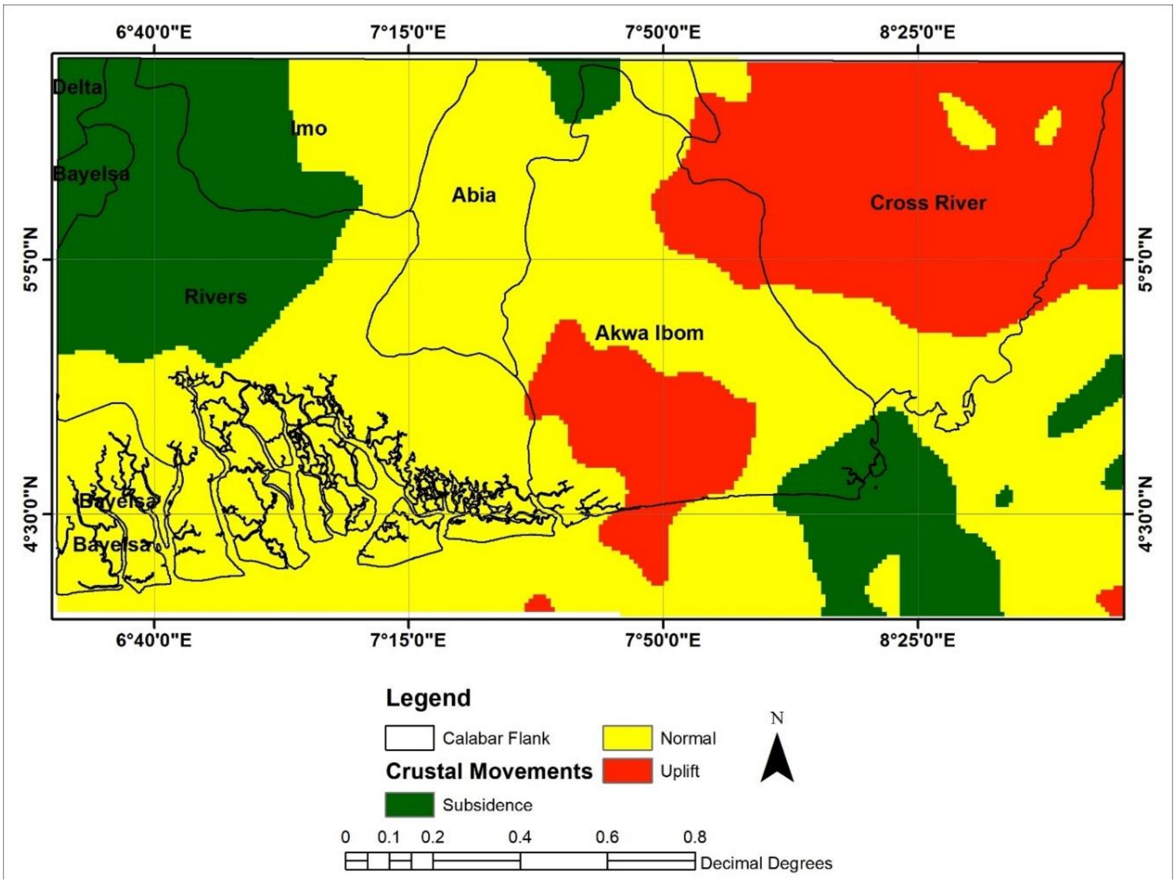

Figure 2: Map of Crustal Movements in Calabar Flank

IV. Discussion of Results

The analysis of crustal movements in the Calabar Flank using Sentinel-1 data provides vital insights into the region's tectonic dynamics. The Calabar Flank is classified into subsidence, normal, and uplifted areas, highlighting the various tectonic regimes that influence it. These findings are consistent with previous research, but they also provide novel observations that improve our understanding of the area's geodynamics.

The Calabar Flank exhibits significant extensional tectonics, as evidenced by subsidence ranging from 1.7 cm/yr to 2 cm/yr across 7,235.4 km². This type of movement is consistent with the thinning of the Earth's crust, which is commonly associated with rifting and the formation of sedimentary basins, according to research on other rifted margins such as the East African Rift System (Ebinger and Casey, 2001). The relatively high rates of subsidence in the Calabar Flank indicate that the region is actively undergoing similar extensional processes, which may be linked to the larger tectonic framework of the West African margin (Khan et al., 2007).

Normal movement areas cover 22,350 km² at rates ranging from 1.1 cm/yr to 1.4 cm/yr, indicating relative tectonic stability. These findings are consistent with stable zones found in other tectonically active regions, such as the Iberian Peninsula, where similar low-magnitude crustal movements have been documented (Stich *et al.*, 2006). The presence of these stable zones within the Calabar Flank is critical for understanding the overall stress distribution because they likely act as buffers, accommodating minor changes without causing significant deformation (Nton and Okoro, 2009).

The uplifted areas of 8,588.8 km², with movements ranging from 1.4 cm/yr to 1.7 cm/yr, suggest active tectonic compression or the influence of buoyant materials beneath the crust. Such uplift is frequently associated with compressional forces or tectonic convergence, similar to the processes seen during the Andean orogeny. The Calabar Flank's uplift rates suggest that crustal thickening is ongoing, which could be caused by tectonic plate convergence or mantle plume upwelling. This uplift is significant for understanding the region's tectonic interactions and seismic activity because uplift is frequently associated with increased tectonic stress (Turcotte and Schubert, 2002).

The findings of this study are consistent with previous studies on crustal deformation in similar tectonic settings. For example, the observed subsidence is consistent with extensional tectonics documented in the East African Rift, which has seen similar rates of crustal thinning and basin formation (Ebinger and Casey, 2001). The stable areas identified in this study are similar to tectonic stability zones on the Iberian Peninsula, where similar low-magnitude movements have been observed (Stich *et al.*, 2006). The observed uplift in the Calabar Flank is consistent with findings from orogenic zones such as the Andes, where tectonic compression causes significant crustal uplift.

These findings are extremely important to the scientific community, particularly in the areas of tectonics and geodynamics. The identification of active subsidence, stability, and uplift zones in the Calabar Flank provides critical data for modelling the region's tectonic evolution. Furthermore, this research contributes to a broader understanding of crustal deformation processes, providing insights that can be applied to similar tectonic settings around the world.

These findings are especially important for understanding the Calabar Flank's hydrocarbon exploration potential, as subsidence areas frequently form sedimentary basins in which hydrocarbons can be trapped. Stable zones are less likely to experience significant tectonic stress, so identifying them is useful for infrastructural development. The uplifted regions highlight the possibility of seismic activity, which is critical for assessing earthquake risks in the region.

V. Conclusions

The Calabar Flank is experiencing active tectonic processes, as indicated by the significant regions of subsidence, normal movement, and uplift, as determined from the analysis of the crustal movements computed from Sentinel-1. The observed rates of these movements indicate continuous crustal deformation induced by both extensional and compressional forces.

The extensive subsidence area of 7,235.4 km², characterised by movements ranging from 1.7 cm/yr to 2 cm/yr, suggests ongoing extensional tectonics, resulting in the thinning of the Earth's crust and the creation of sedimentary basins. The significance of these basins lies in their role in comprehending the tectonic development of the area and their implications for hydrocarbon exploration, as they represent possible locations for the buildup of sediments and energy resources.

The vast expanse of typical movements (22,350 km²), characterised by movement rates ranging from 1.1 cm/yr to 1.4 cm/yr, delineates areas of relative tectonic stability. These stable zones serve as elastic zones within the larger tectonic structure, allowing for small modifications without substantial distortion. A thorough comprehension of these domains is essential for the development of a comprehensive tectonic model of the region.

The 8,588.8 km² uplifted regions, characterised by movements ranging from 1.4 cm/yr to 1.7 cm/yr, indicate areas experiencing tectonic compression or the impact of buoyant materials beneath the Earth's crust. Uplift signifies the existence of dynamic tectonic forces that propel the Earth's crust upwards, perhaps associated with tectonic convergence or mantle upwelling. An analysis of these elevated regions is crucial for assessing the likelihood of seismic events in the area.

The delineation of elevated areas also increases the likelihood of seismic events occurring within the Calabar Flank. Significant uplift is frequently linked to heightened tectonic stress, rendering these regions crucial for seismic hazard evaluations and the formulation of mitigation measures.

These findings provide significant data to enhance the overall scientific knowledge of crustal deformation processes. This study confirms the results obtained from other tectonically active areas and offers fresh perspectives on the geodynamics of the Calabar Flank. These findings have practical implications in several areas including hydrocarbon exploration, infrastructure development, and seismic hazard assessment.

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