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Tectonic Architecture and Structural Evolution of the Middle Benue Trough, Nigeria: Implications for Hydrocarbon Exploration

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Abstract: In light of Nigeria's growing energy needs and declining conventional reserves, unlocking unconventional hydrocarbon resources becomes imperative. Previous studies have reported that the Middle Benue Trough (MBT) has good potential for hydrocarbon generation and accumulation. However, the absence of proven conventional hydrocarbon discovery in the basin to date underscores a significant gap in its petroleum prospectivity. This study investigates tectonic controls on syn- and post-depositional deformation between the Keana Anticline and Gboko line aiming to clarify structural influences on unconventional reservoir quality and fluid pathways. Using integrated field mapping, aeromagnetic grid analysis (tilt derivative and source parameter imaging of Total Magnetic Intensity data), and shallow drilling records, researchers identified two deformation phases. An early ductile phase driven by NW-SE compression formed NE-SW anticlines and synclines. Later brittle deformation generated mineralized NW-SE and E-W fractures, including a newly mapped 142 km-long NW-SE Gboko fracture system beneath Lafia's sediments. Aeromagnetic depth estimates revealed five sedimentary depo-centers, with basement depths ranging from 70 m to 4,900m, the deepest at Wuse-Akiri and southwestern Gboko. These structural complexities create natural fracture networks that enhance reservoir permeability, critical for hydraulic fracturing efficiency. Findings from this study, suggest that in order to optimize the recovery of the unconventional resource in the basin, aligning hydraulic fracture propagation with pre-existing fault and fracture orientations while adapting stimulation parameters to local stress regimes will be necessary. By delineating the trough's tectonic evolution and fracture architecture, this research provides a foundational framework for targeted exploitation of unconventional hydrocarbons aligning with Nigeria's goals to expand clean energy amid global transition efforts.

***Keywords**: Middle Benue Trough; Natural Fractures; Hydraulic Fracturing; Santonian Folding; Unconventional Hydrocarbons.*

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I. INTRODUCTION

Following the gas supply shock of 2022/23, natural gas markets have returned to more pronounced growth, with global gas demand expected to reach new all-time highs in both 2024 and 2025. At the same time, the global gas balance remains fragile amid limited LNG supply growth and geopolitical tensions (IEA, 2024).

The Middle Benue Trough is an intra-continental rifted basin with most rocks concealed by thick sediments and vegetation. Geological field mapping is very difficult resulting in high uncertainties. Remote sensing and geophysical techniques can assist in refining lithological boundaries and detecting buried geological features such as intrusive bodies, which can be very useful in interpreting the structural history of a basin (Ajayi and Ajakaiyi, 1981; Yenne *et al*, 2024).

The Middle Benue Trough (MBT) of Nigeria is a structurally complex intracratonic rift basin exhibiting significant potential for unconventional hydrocarbon resources, particularly shale and tight gas. This study integrates aeromagnetic data processing, field mapping, and shallow drilling results to delineate the tectonic framework between the NE-SW Keana Anticline and the NW-SE trending Gboko fracture line, with a focus on understanding how structural features and sediment thickness influence hydrocarbon exploration and development.

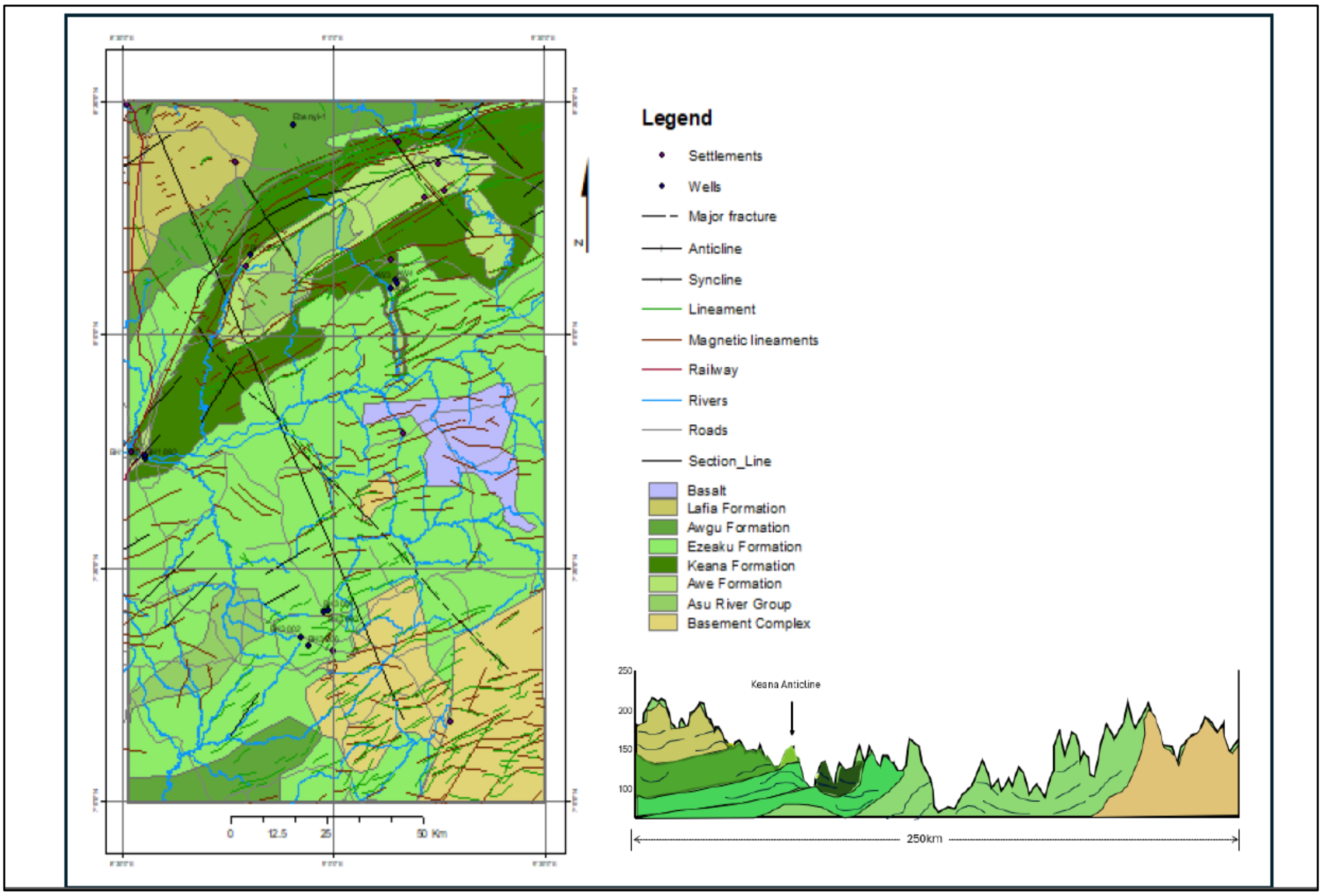

Fig 1: Geological Map with Cross Sections Showing the Various Formations and Structural Elements within the Study Area

II. LITERATURE REVIEW

The architecture and structure of the upper continental crust of Nigeria have been extensively studied using several geophysical and geological techniques. Apart from the deeper structures of the Nigerian crust, the thickness of most sedimentary basins surrounding the basement rocks is also not fully proven.

Abdulsalam *et al.* (2022) aimed to map magnetic lineaments and analyze magnetic signals from different sources in parts of the Middle Benue Trough, Nigeria, using high-resolution aeromagnetic data. Applying Source Parameter Imaging and Spectral Depth analysis, they identified major and minor magnetic lineaments trending NE-SW and NW-SE, respectively. Their results showed sedimentary thickness ranging from about 0.17 km in northern areas like Shendam and Wase to a maximum of approximately 4.55 km around Awe, Aman, and surrounding regions, offering key insights into the subsurface geological structure of the area.

Anudu *et al.*, (2019) used high-resolution aeromagnetic data and advanced depth-estimation methods to characterize the middle Benue Trough as a moderate to deep, fault-bounded rift basin with sediment thickness up to 6300 m. The study identified seven deep sedimentary sub-basins and several shallow basement ridges with dominant NE-SW trends, revealing previously unknown subsurface features and magmatic bodies at shallow depths. Their findings suggest moderate to low oil potential but high prospects for natural gas, providing important insights for hydrocarbon exploration and tectonic evolution of the region.

Osinowo, (2023) utilized a cost-effective and non-intrusive magnetic geophysical method to reduce hydrocarbon exploration uncertainty in Nigeria's Middle Benue Basin. The study revealed a 350 km NE-SW trending sedimentary trough with sediment thickness up to 3.68 km, indicating good potential for hydrocarbon generation. Structural analysis showed active fault systems, and volcanic intrusions were mapped, which may impact hydrocarbon preservation. The north-central part of the basin, with thick sediments and minimal volcanic activity, was identified as the most promising area for further exploration.

Yenne *et al.*, (2024) re-processed and interpreted aeromagnetic and multispectral satellite datasets to understand the evolution of the Benue Trough. Igneous with the aim of better constraining the basin evolution in time and space and the study revealed that the extensional and compressional forces from regional and local stress kinematics has played keys roles in the formation of the basin and that the basin evolved through a series of tectonic activities associated with plate movement, magmatic uprising and emplacement within and without the sediments of the basin and more so, the combined activity of rifting and magmatic uprising/emplacement undoubtedly resulted in crustal thinning, basin opening, and the structural styles reflected in its current geometry.

III. MATERIALS/METHOD

- *Data Acquisition and Preprocessing*

High-resolution Total Magnetic Intensity (TMI) aeromagnetic data covering parts of the Middle Benue Trough (Lafia, Akiri, Akwana, Gboko and Katsina Ala sheets respectively) were obtained from the Nigerian Geological Survey Agency.

The workflow consisted of data processing, enhancement and interpretation. The acquired aeromagnetic data was corrected for Diurnal variations and International Geomagnetic Reference Field (IGRF). The corrected data was then gridded to produce a Total Magnetic Intensity (TMI) Map. The pre-processed TMI data were imported into Oasis Montaj (Geosoft Inc.) software for detailed processing and interpretation. The following steps were performed: Reduction to equator (RTE), First Vertical Derivative (FVD), Second Vertical Derivative (SVD), Vertical Tilt Derivative (TDR), Horizontal Tilt Derivative (HTD), Analytical Signal (AS) and Source Parameter Imaging.

- *Geographic Information System (GIS) Integration*

The processed lineament maps and depth estimates generated in Oasis Montaj were exported as georeferenced raster and vector datasets into ArcGIS (Esri Inc.) for spatial analysis and visualization. In ArcGIS, these data were integrated with geological and topographic maps to correlate magnetic lineaments with known geological structures, delineate sedimentary depocenters based on depth estimates and generate composite structural maps illustrating the spatial relationships between faults, folds, and sediment thickness.

IV. RESULTS

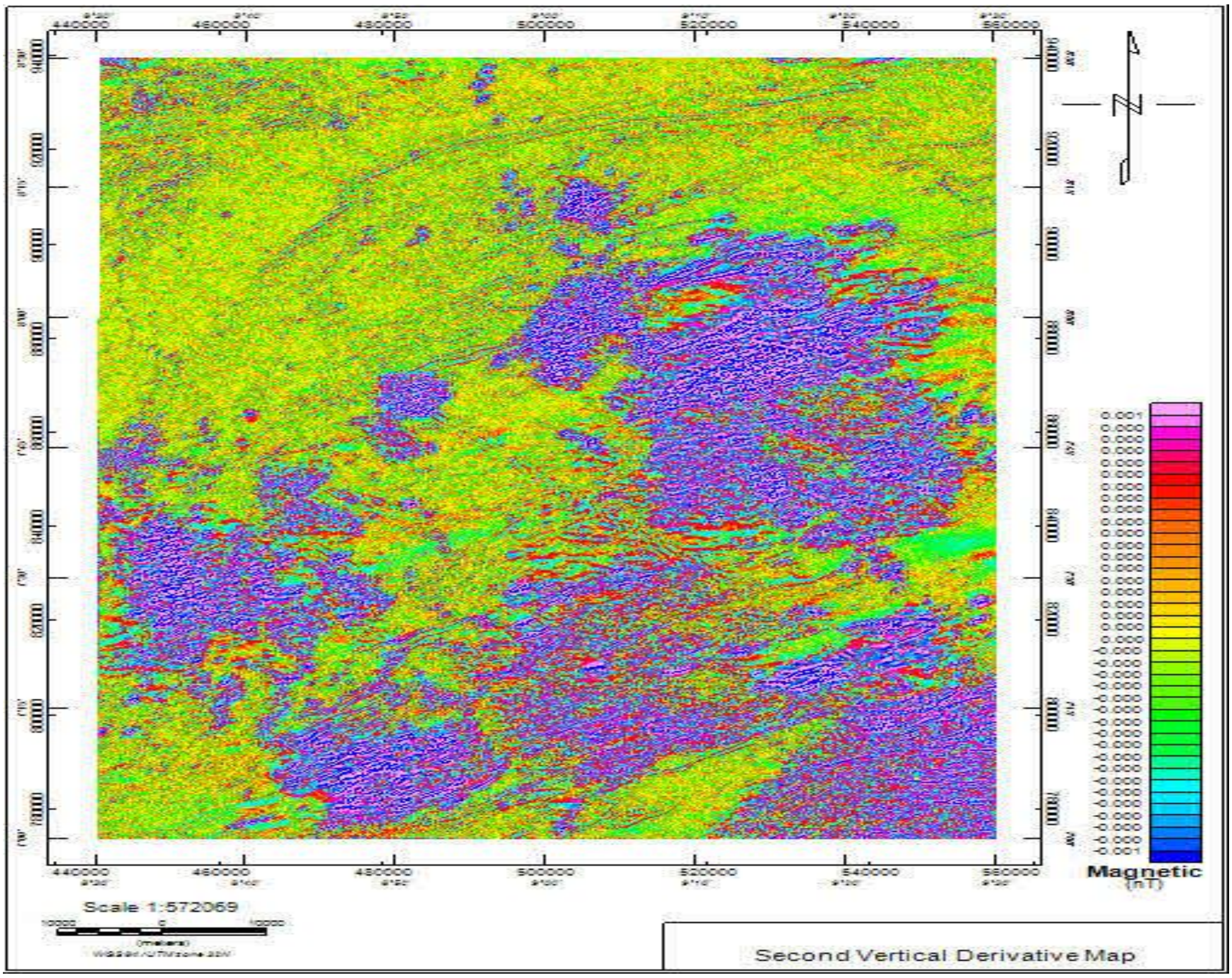

Fig 2: Processed Aeromagnetic Lineament Map of the Middle Benue Trough Derived from Total Magnetic Intensity (TMI) Data, Highlighting Major Structural Trends Including the Continuous NW-SE Oriented Gboko Fracture Line and Associated Fault Systems Beneath Sediment Cover.

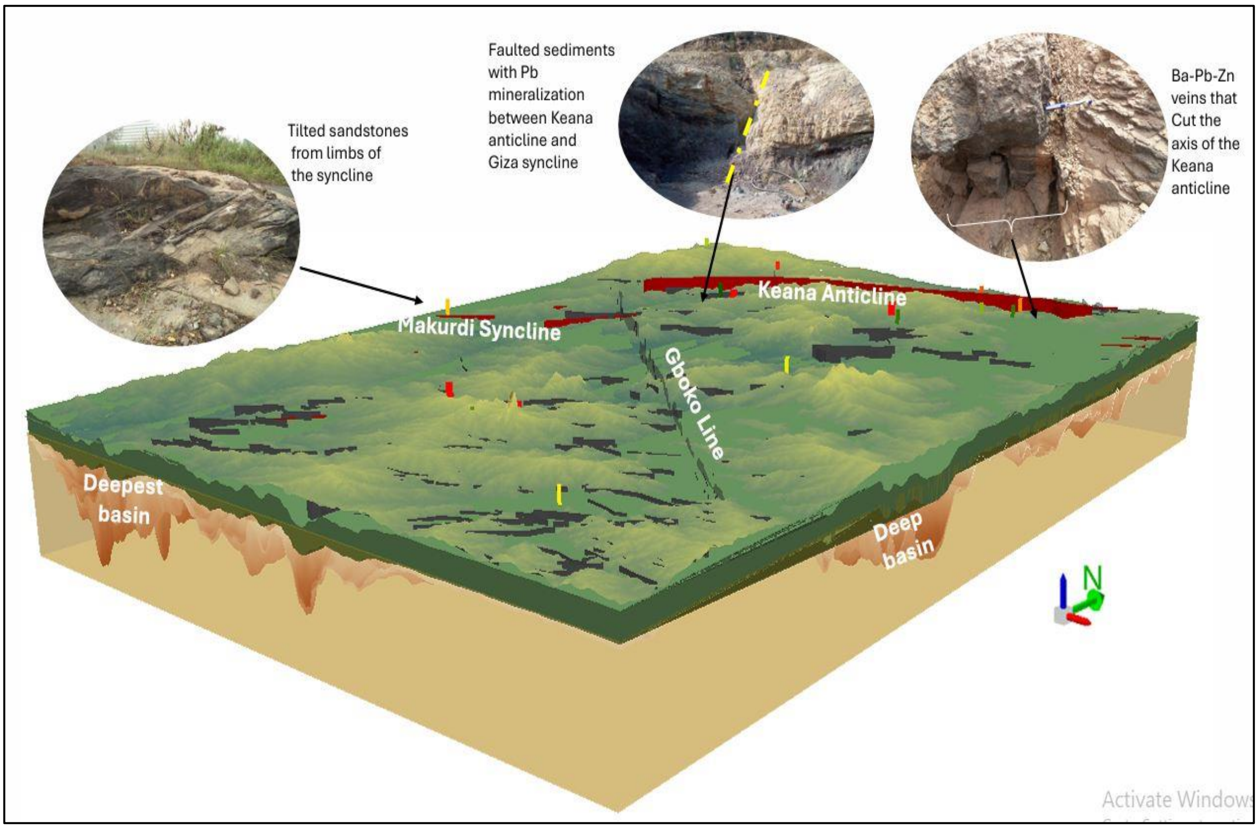

Fig 3: Three-Dimensional Structural Model of the Middle Benue Trough Showing Spatial Relationship Between the Keana Anticline, the NW-SE Trending Gboko Line and Depocenters.

V. INTERPRETATION AND DISCUSSIONS

Magmatic Bodies and Structural Controls

The magmatic bodies are inferred from their pronounced magnetic signatures, which stand out against the weaker responses of surrounding sedimentary rocks and outline distinct circular, semi-circular, and linear features (Figure 2). Following the interpretations of Anudu *et al.*, (2014) and Yenne *et al.*, (2024), these anomalies are associated with intrusive and extrusive igneous rocks emplaced within and above the sedimentary sequence. They are characterized by high-amplitude, short-wavelength magnetic anomalies, which are readily distinguishable in the mapped data (Figure 2). Shallow-magnetic data indicate that the more prominent semi-circular features likely represent sub-horizontal sills or near-circular plutons. The igneous bodies are largely confined to the southeastern half of the survey area and define a broad NE-SW structural trend, consistent with a locus of magmatic activity probably controlled by NE-SW-trending faults, as also suggested by Anudu *et al.* (2014) and Yenne *et al.* (2024).

The timing of magmatic emplacement appears to coincide with the Late Cretaceous, either post-dating the main rifting phase or forming an integral part of it, with most intrusions likely emplaced during the Albian-Turonian interval (Ofoegbu *et al.*, 1985). The spatial distribution of the igneous rocks suggests a half-graben geometry for the basin, with major basin-bounding normal faults initially localized along the southeastern margin. Within this framework, magmatic bodies are generally oriented NE-SW, and their concentration towards the eastern part of the trough parallels the pattern of uplift of the Moho interface reported by Ofoegbu (1984). This spatial relationship supports the view that the magmas originated from mantle-derived basaltic melts and that the restricted zone of magmatism reflects extensional tectonism coupled with crustal thinning and magmatic intrusion (Ajayi and Ajakaiye, 1991).

NE-SW-trending dykes appear to post-date the formation of the NE-SW-striking normal faults, given the documented interval of magmatic activity from the Late Aptian to the Eocene. For the NW–SE-trending dykes, the inferred paleostress regime corresponds to extensional tectonics, with the maximum extensional principal stress axis acting perpendicular to the dyke strikes, such that NE–SW extension produced structural dilation conducive to magma injection (Yenne *et al.*, 2024). Overall, these observations imply two major episodes of extensional deformation that shaped the present-day basin configuration.

Magmatic emplacements in the area are broadly inferred to span the Early to Middle Cretaceous (147-106 Ma), Late Cretaceous (97-81 Ma), and Palaeocene-Eocene (68-49 Ma), although direct age constraints are limited. The emplacement ages generally young from north to south, though the available data are sparse and show some local variability. By comparing the interpreted intrusions with the ages of surrounding sedimentary units (Figure 2), it is further suggested that the intrusions become progressively younger away from inferred intrusive centres located within the oldest exposed Aptian-Albian strata.

The mapped intrusions provide insight into the basin's evolution. NE-SW-trending dykes concentrated in the northeastern part of the survey area are interpreted as the earliest (Aptian) phase of igneous activity, associated with initial basin opening under NW-SE-directed extension (Figure 2). Similar dykes along the present southeastern margin help define the probable original rift axis. Variations in basement morphology suggest that the western portion of the study area is structurally less complex and therefore more prospective for unconventional hydrocarbon exploration (shale gas and tight gas), as this region may host deeper, deeper-seated grabens and horsts with relatively limited magmatic intrusion.

- *Sediment Thickness and Basement Configuration*

The depth to basement (sediment thickness) varies from about 70 m to 4,900 m across the study area (Figure 3), in broad agreement with previous estimates by Yenne *et al.*, (2024), who reported average basement depths between 1,800 m and 8,400 m for the Middle and Lower Benue Trough. Shallow source depths occur along the northern and southeastern flanks, which correspond to the Nigerian Northern and Eastern Basement Complexes and are underlain by crystalline basement overlain by thin regolith and recent sediments. Comparable shallow depths are also observed around Akwana-Arufu and Igbor-Kegh within the Trough itself, where recent magnetic data processed with edge-enhancement techniques have revealed widespread magmatic bodies (Anudu *et al.,* 2019). These features are interpreted as uplifted basement blocks and magmatic intrusions such as stocks, bosses, feeder systems, pipes, plugs, and dykes (Anudu, 2017).

Intermediate to deep source depths (1,500-4,900 m) correspond to deep-seated crustal basement structures within the Trough and coincide with depocentres filled by thick Cretaceous sedimentary sequences. Maps of the mean depth to basement (Figure 3) show that depths along faulted basement–sediment contacts are heterogeneous, with shallow values near Precambrian crystalline basement areas and greater depths toward the Cretaceous sedimentary domain. This pattern indicates that the rifted, faulted and downwarped crystalline basement along the northern margin dips southward to southeastward, whereas that along the southeastern margin dips northward to northwestward. The resulting configuration reflects subsurface tectonic elements such as sub-basins, basement ridges and other basement structures, which are largely controlled by the dominant NE-SW to ENE-WSW tectonic fabric of the Benue Trough region.

- *Depocentres and Basin Architecture*

The model reveals basement depths reaching up to 4,900 m, consistent with aeromagnetic and drilling data, and highlights several major depocentres as key zones for hydrocarbon generation and accumulation. These depocentres are influenced by the complex fault network, which governs reservoir quality and fluid-flow pathways. The present study identifies seven deep sedimentary sub-basins within the Middle Benue Trough, characterized by sub-rounded to lozenge-shaped geometries and flanked by numerous shallow, elongated basement highs (horsts) (Figure 3). The central axial region of the Trough is dominated by uplifted basement ridges and magmatic structures occurring at surface to shallow depths of 0–c. 1,800 ± 270 m, with widths ranging from about 5 to 45 km (Anudu *et al.*, 2019).

The sub-basins, typically >20 km wide and elongated NE–SW, are arranged in an en echelon pattern and contain Cretaceous sedimentary strata whose thicknesses commonly exceed 2,500 ± 375 m. Their en echelon arrangement implies that they formed as pull-apart sub-basins, bounded by elongated basement highs that likewise developed as pull-apart ridges, under tensional deformation with a significant sinistral component along shallow- to deep-seated NE–SW-trending regional strike-slip faults during the Early to Middle Cretaceous. This interpretation aligns with studies from other segments of the Benue Trough and the wider West and Central African Rift System (Benkhelil *et al.*, 1989). The presence of seven sub-basins suggests that the area experienced rapid subsidence associated with both extensional and wrench-type tectonics in the Early to Middle Cretaceous.

Thicker basin fills occur in sub-basins adjacent to basement–trough margins, indicating that sediment depocentres migrated parallel to the basin-bounding faults and ultimately buried the original rift-margin fault scarps. This configuration also implies that syn-rift sediments deposited during the Early Cretaceous rifting phase are likely to attain maximum thickness across the trough's boundary faults. The elongated basement highs influenced the geometry of structures in the overlying sedimentary succession, producing local variations in bed strike and dip. Furthermore, these highs likely affected facies distribution, as evidenced by the Campanian–Maastrichtian Lafia Formation, the only known post-Santonian succession in this segment of the Middle Benue Trough (Figure 3), being restricted to the Lafia-Amaku Sub-basin in the northwestern part of the Trough. The overall NE–SW orientation of the mapped sub-basins and basement highs corresponds to the dominant structural trend recognized across the Benue Trough and its adjoining basement complexes (Benkhelil *et al.*, 1988, 1989; Guiraud *et al.*, 1989; Anudu *et al.*, 2014).

Aeromagnetic and drilling data indicate that sediment thickness within fault-bounded depocentres such as Wuse-Akiri and southwestern Gboko ranges from a few hundred metres to over 4,900 m (Osinowo *et al.*, 2023). These depocentres are interpreted as zones of optimal organic-matter preservation and thermal maturity, which are critical for gas generation in shale and tight reservoirs. The distribution of sediment thickness is primarily controlled by extensional faulting and later inversion, producing structural lows that favour both thick organic-rich shale accumulation and hydrocarbon retention.

- *Structural Style and Tectonic Framework*

The mapped lineaments provide critical constraints on the tectonic framework governing sedimentation, structural deformation, and fluid-flow pathways, which are essential for planning unconventional hydrocarbon exploration and hydraulic fracturing strategies. The refined lineament map integrates enhanced aeromagnetic processing and additional interpretation to delineate more detailed fracture systems and fault orientations. This improved resolution clarifies the continuity and subsurface extent of key structural features, such as the NW-SE Gboko fracture line, beneath the sedimentary cover.

The subsurface structural map (Figure 3) reveals that the Middle Benue Trough is dissected by numerous regional basement-involved sedimentary faults, which predominantly strike NE-SW, with subordinate NW-SE trends. These faults bound the imaged sub-basins and basement ridges, with those close to the basement–trough margins mainly controlled by NE-SW-striking faults. The three-dimensional structural model highlights the NE-SW-trending Keana Anticline and the NW–SE-oriented Gboko fracture system as major structural elements, as well as the deepest basement area coinciding with one of the principal depocentres where sediment thickness reaches up to 4,900 m (as inferred from integrated aeromagnetic and drilling data). These features define the basin's compartmentalization, influence reservoir quality, and create preferential pathways for fluid migration, information critical for unconventional hydrocarbon exploration.

The dominant structural trends identified in this study, NE-SW, NNE-SSW, and ENE-WSW, with minor N–S and E–W components (Figure 3), closely resemble the strike of major faults and shear zones of Pan-African age widely recognized across Nigeria and Cameroon (Benkhelil *et al.*, 1989; Obaje, 2022). These "Pan-African trends" are interpreted as shallow-level expressions of reactivated ancient crustal weaknesses of Late Pan-African age (600 ± 200 Ma), which likely controlled the orientation of the Benue Trough and its internal structures, including faults and fold axes, and promoted the alternation of pull-apart basins and basement ridges during rift development.

The Middle Benue Trough initiated as an aulacogen, an aborted arm of a triple rift system, during the Early Cretaceous, undergoing initial extension and subsidence that led to the deposition of up to about 5,000 m of lacustrine, fluvial, and marine sediments (Akande *et al.*, 1988). The sedimentary succession includes organic-rich shales such as the Awgu and Awe Formations, which are primary source and reservoir rocks for shale and tight gas. Mesozoic to early Cenozoic magmatism, involving alkaline and tholeiitic basalts as well as intrusive rocks, accompanied extensional tectonics and significantly influenced the basin's thermal history and structural architecture (Coloun *et al*., 1996).

From the mid-Santonian (~84 Ma), the MBT underwent a compressional tectonic phase that folded the earlier extensional basin fill, generating more than 100 anticlines and synclines, most commonly trending NE-SW. This inversion episode reactivated pre-existing faults and created complex fracture networks. The Trough is crosscut by a system of deep-seated, basement-rooted normal faults with dominant NE-SW, NW-SE, and ENE-WSW orientations. These faults produced horst and graben structures that controlled sediment thickness and overall basin architecture. Subsequent compressional events reactivated many of these features as strike-slip and reverse faults, giving rise to flower structures and fault-related folds.

Faults act as barriers that compartmentalize reservoirs, affecting pressure regimes and fluid flow, while fault-proximal damage zones enhance permeability in otherwise tight rocks and facilitate both natural gas migration and hydraulic fracture propagation. However, fault reactivation during stimulation can elevate the risk of induced seismicity and wellbore instability. Large-scale anticlines such as the Keana and Makurdi anticlines, formed during compressional inversion, serve as structural traps for hydrocarbons (Petters and Ekweozor, 1982). Folding induces brittle deformation, producing fracture networks along fold limbs and hinges, which increase reservoir permeability and connectivity and make these structures particularly attractive targets for unconventional gas development.

The interplay of faults, anticlines, and variable sediment thickness has important implications for shale and tight-gas exploitation in the MBT. Fault-related damage zones and fold-generated fractures provide natural permeability pathways that can enhance hydraulic fracture propagation and increase the stimulated reservoir volume. Aligning hydraulic fractures with the dominant natural fracture orientations (primarily NW-SE and NE-SW) and the regional in-situ stress field is expected to maximize connectivity and gas recovery (Yenne, 2022). Thick sediment packages and marked structural compartmentalization justify the use of horizontal wells with multistage fracturing to improve reservoir contact and production efficiency. Careful control of injection pressures is necessary to minimize the risk of fault reactivation and induced seismicity while ensuring effective fracture growth.

- *Implications for Tight Gas and Shale Gas*

The MBT is characterized by a complex intracratonic rift basin architecture, shaped by combined extensional and compressional tectonics that have controlled the distribution, quality, and connectivity of unconventional gas reservoirs.

Aeromagnetic data analysis reveals five major sedimentary depocenters with sediment thicknesses ranging from 70 m to nearly 4,900 m, consistent with previous observations by Anudu *et al.* (2019) and Yenne *et al.* (2024). These deep depocenters provide substantial thicknesses of organic-rich shales, such as the Awgu and Gboko Formations, which are known source and reservoir rocks for shale gas (Petters and Ekweozor, 1982; Akande *et al.*, 1988). The accumulation of thick sediment packages under fault-bound compartments enhances hydrocarbon generation and preservation due to increased burial depth and thermal maturity (Osinowo *et al.*, 2023).

Structurally, the MBT underwent two principal deformation phases: an early ductile NW-SE compressive phase creating NE-SW trending folds (Keana and Makurdi anticlines), followed by a brittle phase responsible for developing mineralized NW-SE and E-W fracture systems, notably the newly delineated 142 km continuous Gboko fracture line beneath the sedimentary cover. Such structural elements play critical roles in unconventional reservoirs by providing natural fracture networks that enhance permeability within tight and shale formations.

These fracture corridors facilitate the propagation of hydraulic fractures during stimulation treatments, thus increasing stimulated reservoir volumes and improving hydrocarbon recovery efficiencies (Yenne, 2022).

The interaction of faults, folds, and basement morphology creates structurally compartmentalized reservoirs requiring advanced drilling and stimulation strategies. Fault damage zones and fracture networks act as preferential fluid migration pathways, which is vital for methane migration in tight and shale gas reservoirs as well as CBM reservoirs where fracture permeability is inherently low (Anudu *et al.*, 2020). Furthermore, folding induces brittle deformation and fracture development along fold limbs and hinges, which can act as both traps and conduits, optimizing reservoir connectivity and gas accumulation.

Hydraulic fracturing design in the MBT must consider natural fracture orientations primarily NW-SE and NE-SW and local in-situ stress regimes to optimize fracture complexity and connectivity, avoiding fault reactivation that poses risks of induced seismicity and wellbore instability (Yenne, 2022). The thick sediment packages necessitate horizontal drilling with multistage fracturing to maximize reservoir contact in structurally compartmentalized settings. The extensive magmatic activity documented, especially intrusive and extrusive igneous bodies emplaced along structurally controlled zones, impacts thermal history and basin evolution, influencing hydrocarbon maturation and altering local stress fields (Jourdan *et al.*, 1995). The magmatic intrusions, dated from the Early Cretaceous to Paleocene-Eocene, coincide spatially with regions of structural complexity and basement highs, affecting reservoir heterogeneity and possibly reducing reservoir quality in highly intruded zones.

Comparatively, the MBT's structural setting shares analogies with prolific unconventional hydrocarbon basins globally, such as the Permian Basin (USA), Barnett Shale (USA), and Bowland Shale (UK), where complex fault-fracture systems and thick organic-rich sediments similarly govern reservoir development and production strategies (Benkhelil, 1987). These analogs emphasize the necessity of detailed structural and geomechanical studies in maximizing unconventional resource recovery.

Therefore, we can say that the Middle Benue Trough's fault-bounded sedimentary depocenters, large-scale folding, and pervasive natural fractures establish favorable conditions for unconventional gas accumulations. The study's comprehensive structural characterization underpins the importance of integrated geophysical and geological approaches in reducing exploration risks and guiding reservoir development. Tailored hydraulic fracturing designs aligned with structural frameworks will be critical to unlocking the MBT's shale gas, tight gas, and CBM potential, supporting Nigeria's energy diversification and cleaner energy goals.

VI. CONCLUSION

This study provides insights into the tectonic evolution and structural architecture of the Middle Benue Trough through an integrated analysis of field mapping, aeromagnetic data, and shallow drilling records. Two distinct deformation phases were identified: an early ductile compressional regime responsible for NE-SW trending folds such as the Keana and Makurdi anticlines, and a later brittle phase generating NW-SE and E-W fracture systems, including the newly delineated 142 km-long Gboko lineament. Aeromagnetic depth estimations revealed significant basement relief, with depocenters reaching up to 4,900 m at Wuse-Akiri and southwestern Gboko, underscoring the basin's heterogeneous sediment distribution.

These structural complexities, particularly natural fracture networks and fault systems, play a pivotal role in governing reservoir permeability and fluid migration pathways. Aligning hydraulic fracturing operations with pre-existing fracture orientations and stress regimes offers a strategic pathway to optimize recovery in low-permeability unconventional reservoirs. This work establishes a robust tectonic framework essential for mitigating exploration risks and guiding targeted resource exploitation in the Middle Benue Trough. By bridging geological characterization with engineering applications, the findings advance Nigeria's capacity to harness gas reserves sustainably, aligning with national energy security objectives and global decarbonization goals. Future studies should focus on dynamic stress modeling and microseismic monitoring to refine stimulation strategies in fractured reservoirs.

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