Research Article

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Journal of Geology, Earth and Marine Sciences

2023

Vol. 1 No. 1: 101

Exploring Hydrocarbon Potential: Insights from Aeromagnetic Data in the Lower Benue Trough

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Citation: Chukwuemeka C, Ehirim CN, Ebeniro JO. (2023) Exploring Hydrocarbon Potential: Insights from Aeromagnetic Data in the Lower Benue Trough. J Geol Earth Mar Sci. Vol 1(1): 101.

Received: February 03, 2023; **Accepted:** February 25, 2023; **Published:** March 02, 2023

Abstract

This study delves into the hydrocarbon prospect of the Lower Benue Trough, employing aeromagnetic data for a detailed examination. The primary objective was to assess the structural, lithological, and sedimentary characteristics influencing hydrocarbon formation. Situated near the hydrocarbon-rich Niger Delta to the south and the recent discoveries in the Chad and Niger Republics, the study area shares similar geological settings. Utilizing Oasis Montaj, Surfer 13, and Arc GIS software, magnetic parameter maps were generated for qualitative and quantitative interpretations. Results unveil distinctive low and high magnetic anomalies corresponding to basement valleys with thick sedimentary cover and uplifted basement areas with thin sedimentary cover, respectively. The delineation of low lineament density and low magnetic anomalies in specific areas suggests optimal conditions for thermal maturation of potential source rocks and hydrocarbon formation, particularly in Akwa, Agwu, Okposi, and Nkalagu areas with 3318.9 m sedimentary thickness. A prevalent NNE-SSW structural trend, believed to be a continental extension of an oceanic fracture system, was identified, influencing sediment deposition, hydrocarbon migration, and trap mechanisms conducive to hydrocarbon plays. The integration of geologic maps with residual magnetic maps highlights that areas of low magnetic anomalies with thick sediments align with sections of the Mamu and Nkporo shale formations and Ajali sandstones—established petroleum systems in the lower trough. Considering the favorable juxtaposition of these geological elements and tectonic structures, the study recommends the Akwa, Agwu, Okposi, and Nkalagu areas for in-depth seismic surveys.

Keywords: Remote sensing; Hydrocarbon; Aeromagnetic; Lower Benue Trough

Introduction

The lower Benue trough has been a focal point of extensive study in recent years, driven by the quest to uncover potential petroleum reserves. Dating back to the early 1930s, petroleum exploration in the trough gained momentum through geochemical and geophysical analyses, surface seep mapping, sediment alterations, and other hydrocarbon indicators [1]. The belief in the presence of substantial hydrocarbon accumulations lies in the deeply buried Cretaceous sediments within the trough, meeting the essential criteria for a comprehensive hydrocarbon system, including source, reservoir, migration, seal, and trap. This belief is further supported by the trough's proximity to the hydrocarbon-rich Niger Delta to the south and the discovery of hydrocarbons in the Kolmani River II well in the Gongola basin, extending to Chad and Niger Republics in the northeast, all sharing similar geological settings.

The genetic relationship between the Niger Delta and the lower Benue trough in the generation and accumulation of hydrocarbons is underscored by their geographical proximity. According to Ekweozor et al. [2], the southern boundary of the Anambra Basin aligns with the northern boundary of the Niger Delta. Petroleum accumulations in the northern part of the Niger Delta primarily consist of light waxy oils sourced from land plant-derived organic matter disseminated throughout the Eocene source rock units. This similarity in scenarios suggests a comparable setting in the adjacent lower Benue trough [2,3].

Various geophysical exploration methods, including gravity, magnetic, and seismic techniques, have been employed in the quest for petroleum in the trough [4]. Among these methods, airborne magnetic studies have proven to be the most utilized for petroleum exploration and reconnaissance studies due to their cost-effectiveness, speed, spatial coverage, and resolution [5-7]. This method effectively maps the thickness, lateral extent, and structural texture of sediments overlying the magnetic basement, providing valuable clues to the potential presence of petroleum.

The magnetic method relies on the magnetic properties of rocks, considering factors such as the type and quantity of magnetic minerals, depth, and geometry of the magnetic source, and the external field. Magnetite, the most magnetic mineral, significantly influences the rock's magnetism. Sedimentary rocks, being the least magnetic among rock types, exhibit uniform magnetic characteristics in contrast to basement areas. High magnetic anomalies in sedimentary terrains are often attributed to intrasedimentary intrusive igneous and metamorphic rocks and shallow underlying magnetic basement.

While the magnetic method does not directly map hydrocarbons in the subsurface, it provides crucial insights into potential traps associated with hydrocarbon accumulation through the analysis of magnetic anomalies. Biochemical processes in hydrocarbon-bearing sediments lead to alterations and the accumulation of magnetic minerals, creating weak magnetic anomalies or aureoles above the hydrocarbon zone. These anomalies, when isolated from the stronger regional field, serve as direct indicators of hydrocarbons (DIH) [8-13].

The study area, situated in the southeastern part of Nigeria within the lower Benue trough geologic zone, encompasses Nsukka, Igumale, Udi, and Nkalagu areas. Covering an area of 12,000 square kilometers, the region is characterized by undulating landforms and diverse biomes. The study aims to map and delineate structural and lithological features while estimating the depth to the magnetic basement (thickness of sedimentary pile) using aeromagnetic data. This comprehensive analysis seeks to uncover potential indications of petroleum accumulations within the lower Benue trough.

Material and Methods

Geology of the Study Area

The study area is situated within the Abakaliki and Anambra basins in the lower Benue trough (refer to Figures 1 and 2). The lower Benue trough is characterized by a substantial thickness of sedimentary rocks, including intrasedimentary igneous intrusions, resting on the Precambrian basement. The Precambrian Basement Complex comprises predominantly granitic and magmatic rocks, prominently visible in the eastern part of the study area [14]. Stratigraphically, the lower Benue trough encompasses rocks from the Aptian to mid-Eocene periods, forming a sequence that includes the Asu River Group, Eze-Aku, Awgu, Nkporo Group, Mamu, Ajali, Nsukka, Imo, and Bende-Ameki Formations.

Noteworthy petroleum systems in the region include Nkporo-Mamu and Mamu-Ajali, with the Nsukka and Imo shale Formations serving as regional seals [15,16]. The Nkporo-Enugu and Mamu shale Formations exhibit characteristics indicative of potential hydrocarbon source rocks, contributing to oil/gas and condensate shows within Ajali reservoir sandstones [17,18].

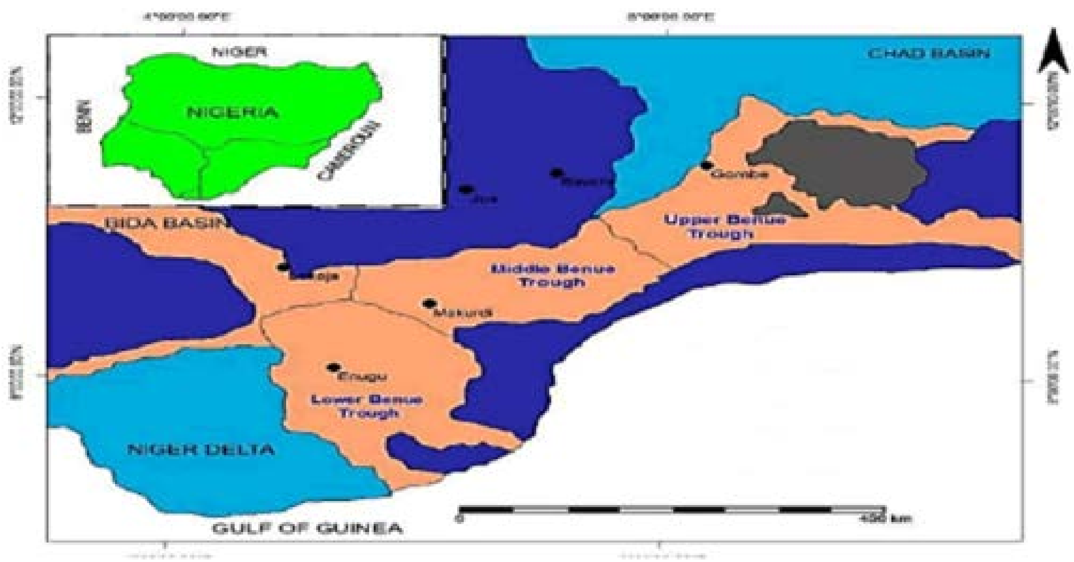

Figure 1: Location map of the study area.

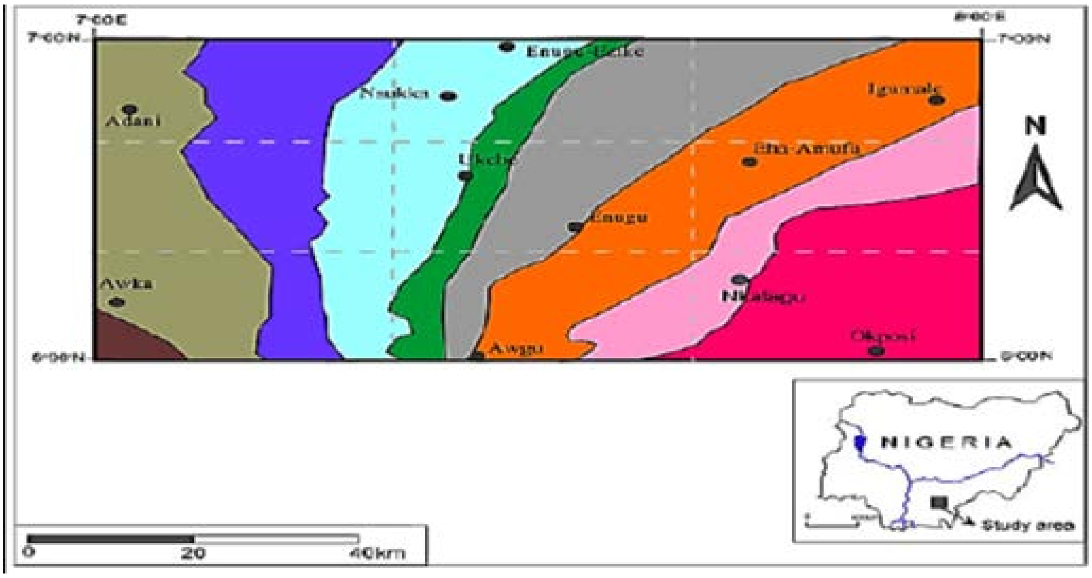

Figure 2: Geology map of the study area.

Method of Study

Four sheets of high-resolution aeromagnetic data covering Nsukka, Igumale, Udi, and Nkalagu areas were sourced from the Nigeria Geological Survey Agency (NGSA) [19]. Acquired at a nominal flight height of 76 meters along N-S flight lines with a 500-meter inter-line spacing, the data included measurements of the total magnetic field intensity B (nT).

The data sheets underwent consolidation and integration using Oasis Montaj and Surfer 13 software to generate the Total Magnetic Intensity (TMI) map for the study area. Subsequent processing involved the removal of regional magnetic effects through filtering (regional-residual separation), resulting in a residual magnetic map. Vertical and horizontal derivative maps were then derived from the residual magnetic intensity grid using Oasis Montaj software, enhancing shallow geological features and delineating geologic boundaries.

Source Parameter Imaging (SPI) was employed on the residual maps to determine the thickness of the sedimentary pile, providing insights into the depth to the magnetic basement. The filtered images (residual gradients) were utilized for lineament extraction, which underwent merging, tracing, and clockwise measurement from the North, facilitated by Arc GIS program. Statistical analysis and plotting of the mapped lineaments were conducted in the form of rose diagrams using RockWorks software.

Finally, these maps underwent visual analysis, considering amplitude and shape characteristics, and identifying anomalous boundaries, volcanic zones, lineaments, and other regional structures with potential associations to petroleum accumulations.

Results

The analysis of aeromagnetic data has provided valuable insights into the geological features and potential hydrocarbon indications in the lower Benue trough. The key findings are summarized below:

Total Magnetic Intensity (TMI)

The TMI map showcases distinct low and medium-to-high magnetic anomalies across the study area (refer to Figure 3). Low magnetic intensities, ranging from -51.05 nT to 8.23 nT, predominate in Enugu Ezike, Nsukka, and Awgu. Conversely, medium to high magnetic anomalies, with values from 13.23 nT to 128.45 nT, are prevalent in Igumale, Adani, Enugu, Nkalagu, Okposi, Udi, and Ukehe. Both trends of low and medium to high magnetic intensities run approximately east-west. The observed magnetic patterns correlate with local and regional magnetic features.

Residual Magnetic Intensity (RMI)

The RMI map reveals elongated magnetic lows with intensities ranging from -52.80 nT to 54.11 nT, dominating Nsukka, Awgu, and Awka, while medium to high ridge-like magnetic anomalies (4.28 nT to 54.11 nT) are mapped in Enugu, Okposi, Udi, and Ukehe (see Figure 4). Unlike the TMI, the RMI is characterized by local magnetic features with low magnetic intensities. Both low and medium to high magnetic anomalies trend predominantly in the northeast-southwest direction, with minor occurrences in an east-west trend. These anomalies correspond to sagged and uplifted sections of the underlying magnetic basement, indicating potential faulted structures.

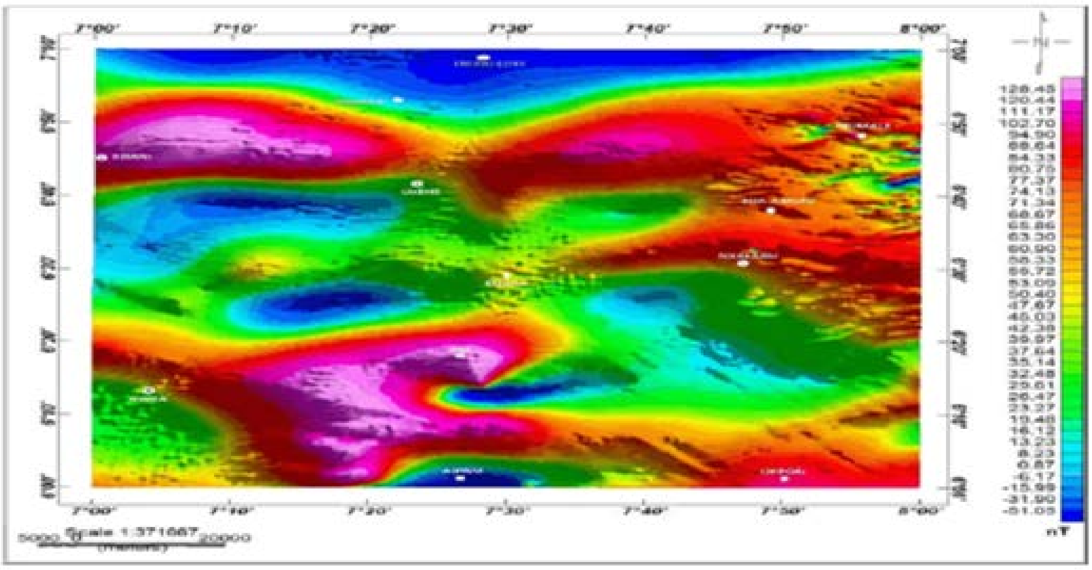

Figure 3: Total Magnetic Intensity (TMI) map of the study area.

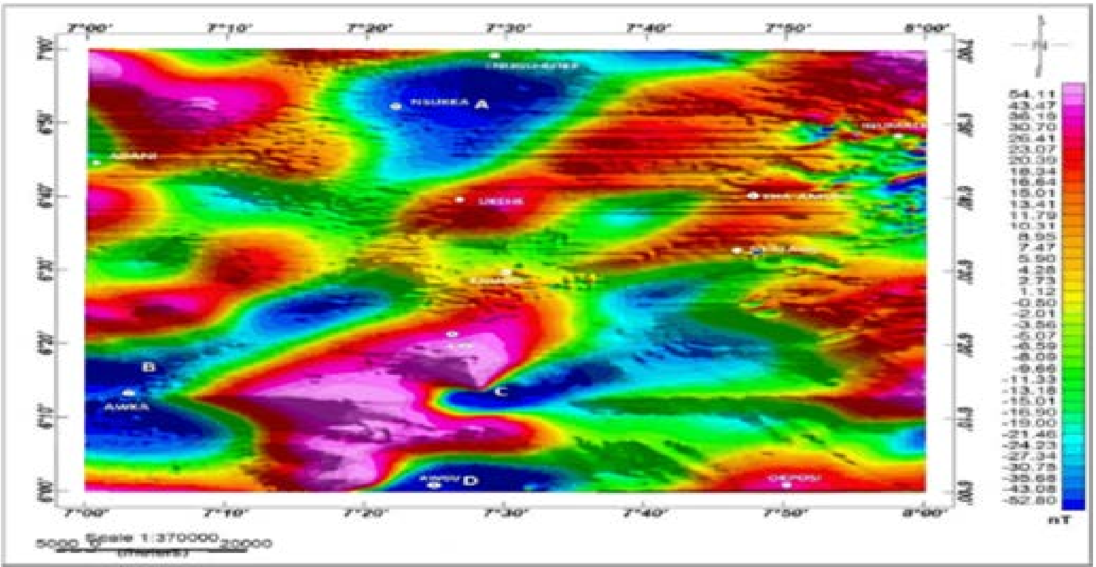

Figure 4: Residual Magnetic Intensity (RMI) map of the study area.

Source Parameter Imaging (SPI)

The SPI map illustrates significant depth variations across the study area, with depths ranging from -95.5 m to -3318.8 m. Shallow to medium depths, varying from -95.5 m to -561.7 m, are observed in Nsukka, Ukehe, Enugu, Udi, Igumale, Eha-Emufu, and Awka. Deeper depths, ranging from -604.49 m to -3318.9 m, are predominantly found in the southeast. These variations in depth are attributed to the tectonic upwarp and downwarp of the magnetic basement, indicating areas with thicker sediment cover (downwarped) and thinner sediment cover (upwarped).

Magnetic Lineament

The magnetic lineament map depicts widespread and dense lineament distributions in Udi, Okposi, and the western and northeastern parts of Enugu and Nkalagu areas, with sparse distributions in other regions. These lineaments, characterized by both short and long linear features, crisscross and intersect each other, forming fault closures that could potentially serve as traps for hydrocarbon accumulations.

Lineament Orientation Analysis

Lineament orientation analysis indicates dominant orientations of NE-SW and NNE-SSW lineaments, with minor occurrences of NW-SE, N-S, and E-W orientations. These orientations provide insights into the structural framework of the study area.

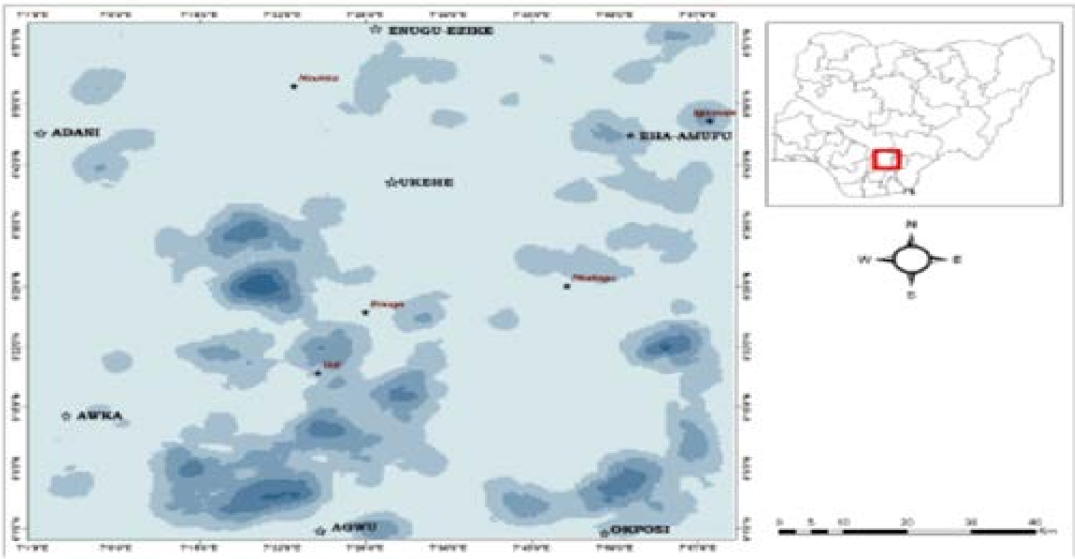

Figure 5: Magnetic lineament density map of the study area.

Magnetic Lineament Density

The magnetic lineament density map (Figure 5) varies from low to high density, correlating with the distribution of lineaments. High lineament densities are observed in Udi and the western and northeastern parts of Igumale and Eha-Amufu areas. In contrast, low lineament densities are mapped in Adani, Enugu-Ezike, Awka, Awgu, Enugu, Nsukka, Okposi, Nkalagu, and Ukehe areas. These variations in lineament density reflect differing degrees of basement tectonics and faulting, with high density indicative of more deformed areas compared to low-density regions.

The aeromagnetic data analysis has provided a comprehensive understanding of the magnetic features, basement lineaments, and depth variations in the lower Benue trough, offering valuable insights into potential hydrocarbon indications in the region.

Discussion

The comprehensive analysis of magnetic parameters (TMI, RMI, and SPI) and Lineaments in the lower Benue trough provides valuable insights into the geological features and potential hydrocarbon indications. The following discussions highlight key findings and their implications [20]:

Magnetic Parameter Maps

TMI Map: The elliptical magnetic lows and ridge-like magnetic highs observed in the TMI map suggest anomalous magnetic features, mostly of regional origin. These patterns could be indicative of underlying geological structures, lithological variations, or depth variations in magnetic sources.

RMI Map: The RMI map reveals distinct elliptical to isolated hemispherical magnetic lows bounded by ridge-like magnetic highs, with trends mostly in the NE-SW direction. The contrast in structural orientation between TMI and RMI maps is attributed to local magnetic susceptibility variations at shallow depths.

SPI Map: The SPI map displays significant depth variations across the study area. Shallow to medium depths is observed in certain regions, while deeper depths predominate in the southeast. These depth variations are linked to tectonic upwarp and downward of the magnetic basement, indicating areas with different sediment cover thicknesses.

Magnetic Lineaments

Distribution and Orientation: Magnetic lineaments are widespread but densely distributed in magnetic highs, particularly in the NE-SW and NNE-SSW orientations. Minor occurrences in NW-SE, E-W, and N-S orientations suggest a complex structural framework in the study area.

Density Analysis: Lineament density analysis reveals variable density across the study area. High lineament density areas (Enugu, Udi, Ukehe, Eha-Emufu, and Igumale) are indicative of more deformed regions, while low lineament density areas (Adani, Enugu-Ezike, Awka, Agwu, Nkalagu, and Okposi) suggest less deformed areas.

Correlation with Sediment Thickness

Sediment Thickness and Hydrocarbon Formation: Areas with shallow basement depths, high magnetic intensities, and high lineament densities (Enugu, Udi, Ukehe, Eha-Emufu, and Igumale) indicate structurally deformed regions with less thick sediment cover, potentially unfavorable for hydrocarbon formation but promising for mineral deposits and groundwater resources.

Thick Sediment Cover and Hydrocarbon Accumulation: Regions with large basement depths, low magnetic intensities, and low lineament densities (Adani, Enugu-Ezike, between Awka and Awgu, and to the NE of Okposi towards Nkalagu) suggest less structurally deformed areas with thick sedimentary cover. These areas are associated with rocks poor in magnetic content, presenting favorable conditions for hydrocarbon source rocks and reservoirs.

Correlation with Geologic Formations

The correlation of the residual magnetic map with the geologic map indicates that areas of low magnetic anomalies with thick sedimentary cover correspond to parts of the Mamu and Nkporo shale formations and Ajali Sandstones. These formations are known for potential hydrocarbon source rocks, and the interbedded marine sandstone facies could provide additional reservoirs [21-26].

Conclusion

The integration of magnetic data with lineament analysis, sediment thickness, and geological formations enhances our understanding of the lower Benue trough's subsurface. While certain areas show indications unfavorable for hydrocarbon formation due to structural complexities and thin sediment cover, other regions with thick sedimentary cover and specific geological formations present favorable conditions for potential hydrocarbon reservoirs. This study sets the stage for further exploration activities, emphasizing the importance of a multidisciplinary approach in understanding the complex geological setting of the lower Benue trough.

Conflict of Interest

No conflicts of interest have been declared.

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