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Application of high resolution aeromagnetic data for determination of depth to magnetic sources using source parameter imaging in Niger State, Nigeria

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ABSTRACT

Source Parameter Imaging (SPI) is a pivotal geophysical technique, particularly in aeromagnetism, for delineating subsurface geological structures through the analysis of magnetic anomalies. This study applies SPI to high-resolution aeromagnetic data over Baro and its surrounding areas in Niger State, Nigeria, to estimate the depth to magnetic sources. The research emphasizes the characterization of magnetic sources in terms of depth, geometry, dip, and susceptibility contrast. Data processing techniques, including regional field removal, residual anomaly mapping, and reduction to the magnetic equator, were employed to enhance data accuracy and interpretability. The findings reveal significant variations in sedimentary thickness, suggesting potential hydrocarbon reservoirs, particularly in the northern region, characterized by deeper basins. This study underscores the necessity of further exploration, integrating advanced seismic studies and drilling, to assess the hydrocarbon potential accurately. The SPI-derived insights provide a valuable framework for strategic hydrocarbon exploration in Nigeria's interior basins, contributing to the nation's energy security and economic growth.

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Keywords: Aeromagnetic data, inclination, depth measurement, imaging, anomalies

1. INTRODUCTION

Aeromagnetic surveys have become a valuable tool in geophysical exploration and mapping of subsurface geological structures (Thompson *et al.,* 2017). These surveys measure the Earth's magnetic field variations from an aircraft, providing crucial information about the distribution and properties of subsurface magnetic sources. However, interpreting the collected aeromagnetic data and extracting meaningful geological information can be challenging due to the complex nature of magnetic source distributions (Dietze*et al.,* 2008). A magnetic survey aims to investigate subsurface geology on the basis of anomalies in the Earth's magnetic field resulting from the magnetic properties of the underlying rocks. Source parameter imaging for depth determination using magnetic data is a geophysical technique used to estimate the depth and location of subsurface magnetic sources. This method is commonly employed in mineral exploration, archaeological studies, and geologic mapping. Source parameter imaging using magnetic data aims to achieve several objectives in geophysical exploration and geological investigations. These objectives are crucial for understanding subsurface structures, characterizing geological features, and making informed decisions in various fields, including mineral exploration, environmental studies, and archaeology. Source parameter imaging using magnetic data is a powerful geophysical technique employed to unveil the hidden mysteries of the Earth's subsurface. This methodology is specifically designed to shed light on the depth and location of subsurface magnetic sources, making it invaluable in a wide array of scientific and industrial applications, including mineral exploration, environmental studies, archaeological investigations, and geological mapping.

The fundamental premise of source parameter imaging is to decipher the enigmatic behavior of magnetic anomalies, unravelling their secrets buried beneath the Earth's surface. Magnetic anomalies, caused by variations in magnetic properties within the Earth's crust, often serve as vital indicators of subsurface geological structures and mineral deposits. These anomalies can be enigmatic, and understanding their depths and characteristics is pivotal for informed decision-making (Gordienko, 2019). This is where source parameter imaging comes into play, as it seeks to fulfil the paramount objective of estimating the depth to magnetic sources accurately. In this pursuit, source parameter imaging delves into the world of geophysics, where precise measurements of the Earth's magnetic field at or above the surface are collected through magnetic surveys.

These measurements, obtained using specialized instruments like magnetometers, capture deviations from the background magnetic field caused by subsurface magnetic materials. From there, a journey of data analysis and mathematical modeling unfolds. This journey encompasses several key objectives. First and foremost, source parameter imaging strives to determine the depth of magnetic sources, a feat that can unlock geological insights and guide resource exploration. It seeks to map the spatial distribution of these sources, shedding light on their locations beneath the Earth's surface. Furthermore, it aims to characterize the shape, magnetic susceptibility, and orientation of the sources, offering a comprehensive understanding of the subsurface features. The journey of source parameter imaging is both a science and an art, requiring the integration of physics, mathematics, and geological expertise.

Geoscientists employ inversion techniques, which involve the comparison of observed magnetic data with simulated data based on different subsurface models. This iterative process refines depth estimates and shapes the final image of the subsurface magnetic sources. The outcomes of source parameter imaging are often presented as depth maps, cross-sections, or three-dimensional visualizations, providing geoscientists and decision-makers with a window into the Earth's hidden treasures. These insights not only inform resource exploration but also contribute to environmental management, infrastructure planning, and archaeological preservation. In a nutshell, source parameter imaging on magnetic data is a remarkable geophysical tool that peels back the Earth's layers to reveal the secrets of subsurface magnetic sources. Its ability to determine the depth and characteristics of these sources makes it indispensable in diverse fields, enhancing our understanding of the Earth's dynamic and enigmatic subsurface realm. This research work is aimed to determine the depth to magnetic sources using source parameter imaging (SPI) by developing and refining SPI methodologies, acquiring high-resolution aeromagnetic data, filtering and processing magnetic data, and assessing its applications in mineral exploration, geological modeling, and hazard assessment.

2. LOCATION OF THE STUDY AREA

The study area is located at latitudes 8º 30′ and 9º 00′ and with longitude 6º 00′ and 6º 30′. The study area with major town Baro which is a town in Niger State in Nigeria as shown in Fig. ****. Niger State is a state located in the North Central part of Nigeria. It is known as the "Power State" due to its significant hydroelectric power generation potential. In terms of geology, Niger State is characterized by diverse rock formations and mineral resources. Here are some key features: Basement Complex: The southwestern part of Niger State is underlain by the Basement Complex, which consists of crystalline rocks such as granite, gneiss, and schist. These rocks are some of the oldest in Nigeria, dating back billions of years. Sedimentary Basins: The state is also part of the Sokoto Basin, which is a major sedimentary basin in Nigeria. It is rich in various sedimentary rock formations that have economic importance. The basin contains deposits of limestone, shale, clay, and sandstone. Niger River: The Niger River, one of Africa's major rivers, flows through the state. It plays a crucial role in the geography and geology of Niger State, shaping the landscape and providing opportunities for irrigation and hydroelectric power generation. Mineral Resources: Niger State is endowed with various mineral resources. Some of the minerals found in the state include gold, limestone, gypsum, iron ore, kaolin, tin, and columbite.

Aim and objectives

To determine the depth to magnetic sources using source parameter imaging.

Objectives

i. Develop and refining of SPI methodologies suitable for the study area, considering factors such as geological context, magnetic field variations, and data acquisition techniques.
ii. Collecting high-resolution magnetic data through aeromagnetic surveys.
iii. Characterization of magnetic sources in terms of their geometry, dip, and susceptibility contrast, providing a comprehensive view of the subsurface features.

iv. Filtering of the data from noises that may affect it and by removing the regional trend and producing the residual magnetic anomaly map. By carrying out further filtering such as reduction to equator, upward continuation and using source parameter imaging map to estimate the depth to magnetic sources.
v. Applications: To assess the practical applications of SPI-derived depth information, such as its utility in mineral exploration, geological modeling, or hazard assessment.

Geology of the study area

In the west of Nigeria, the geology of Niger is made up of very old crystalline basement rocks that were created in the late Archean and Proterozoic aeons of the Precambrian (as shown in figure 3) and are more than 2.2 billion years old. Neoproterozoic and Paleozoic activities such as glaciation and the Pan-African orogeny caused the Volta Basin, Air Massif, and Iullemeden Basin to form, as well as several ring complexes. As a result of complicated mineralization and laterite weathering, Niger now contains extensive mineral resources, including uranium, molybdenum, iron, coal, silver, nickel, cobalt, and other resources.

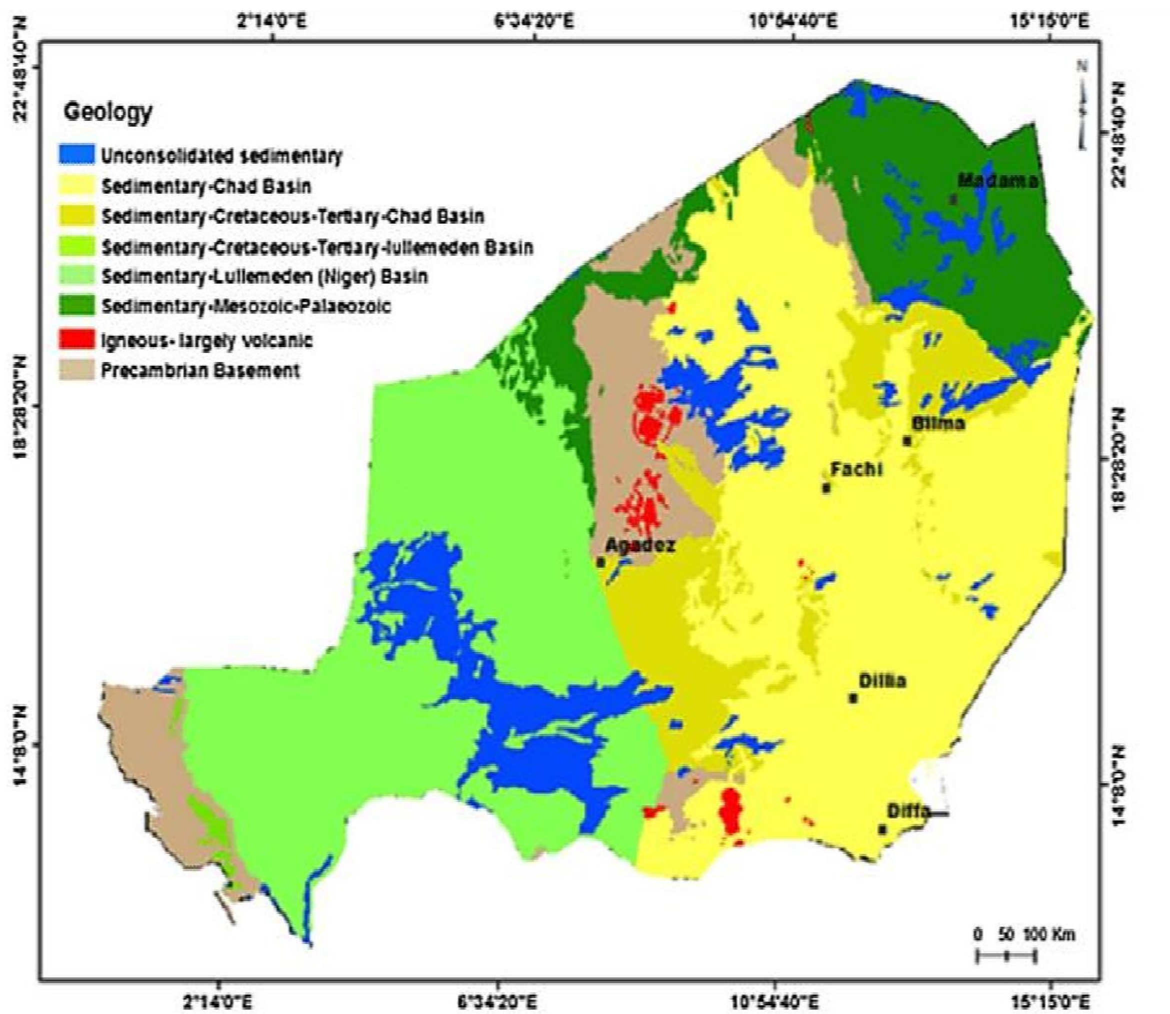

Figure 1. Geologic map of Niger State (Alhassan*et al.,* 1970).

3. MATERIALS AND METHODS

The high-resolution aeromagnetic dataset used for this study was obtained from the Nigerian Geological Survey Agency as a part of the nation-wide aeromagnetic survey between 2005 and 2010. The survey was flown in drape mode using real time global positioning system at a sensor mean terrain clearance of 80 – 100 m. Traverse and Tie line spacing were 500m and 2000m respectively in NW-SE and NE-SW directions and the data were recorded at a sampling interval of 100m (NGSA, 2009) and stored in grid form. The grid is of sheet number 205 which is transformed into total magnetic map.

The study area Baro lies between latitudes 8º 30′ and 9º 00′ with longitude 6º 00′ and 6º 30′. This study area's total intensity magnetic map (Figure 2) displays anomalies of high and low magnetic intensity values with predominate E - W pattern, as well as steep gradients that are dispersed throughout the area. There are three main causes of the abnormalities in the earth's magnetic field. These include sedimentary origins, basement structures, and lithologic variance (Bird, 1997). The study area's maximum intensity value of 136.9 nT is found in the east, while its minimum value of -61 nT is found in the northeast. Thus, variations in magnetic fields are responsible for the 197.1 nT of magnetic relief in the region.

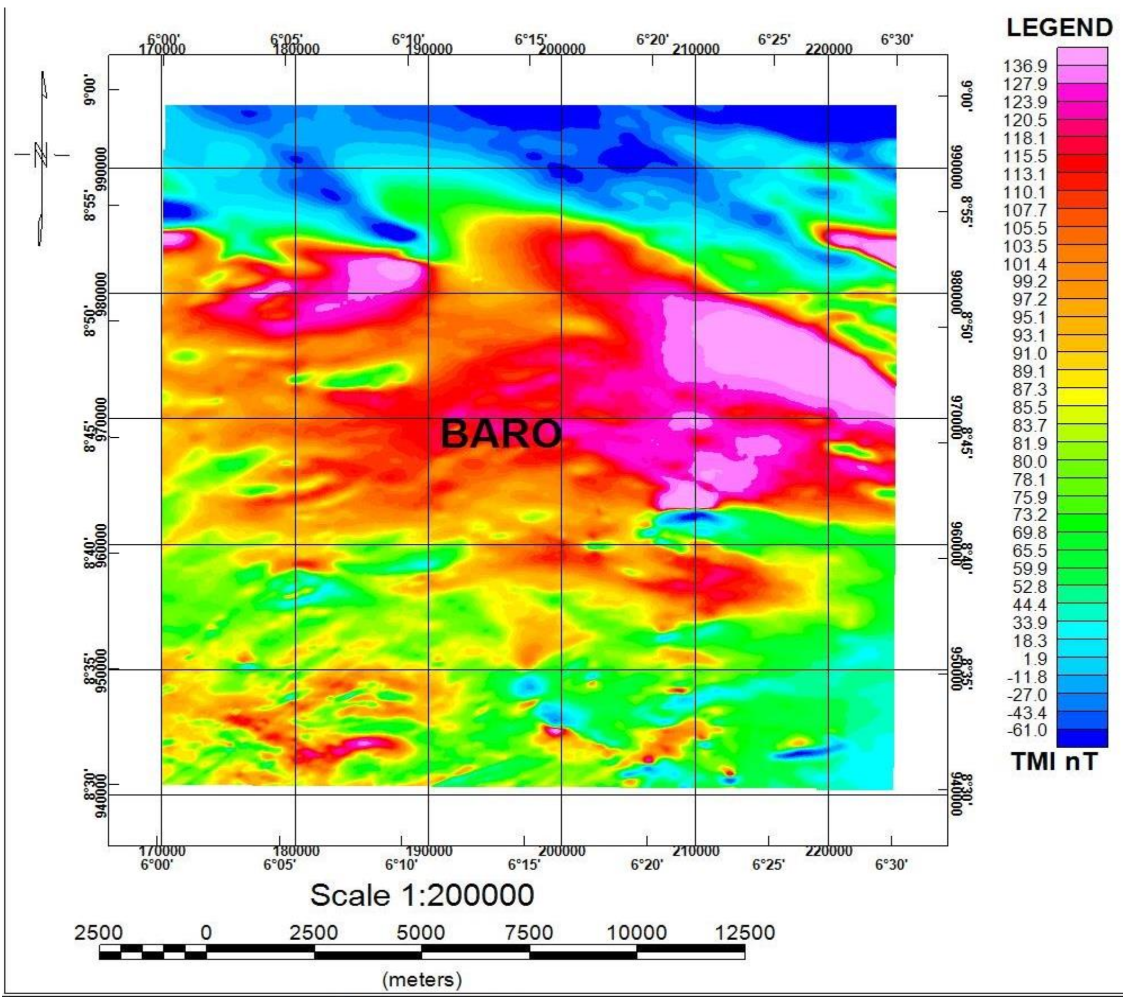

Figure 2. Total magnetic field intensity map.

Data processing

Data processing refers to the transformation and manipulation of raw data into a more meaningful and structured format to extract valuable information, make informed decisions, and facilitate further analysis. It involves a series of steps and techniques to clean, organize, and analyse data.

Magnetic field anomaly separation

Magnetic anomaly field separation is a geophysical data processing technique used to distinguish and isolate various components within a total magnetic field dataset. This process is essential for identifying and characterizing magnetic anomalies or disturbances caused by subsurface geological features or sources of interest. The primary components typically separated during magnetic anomaly field separation are the regional field, the induced magnetization, and the residual magnetic anomaly. The total magnetic intensity field map ranges from -61 nT to 136.9 nT. The difference in the lowest and highest bouguer anomaly is 197.9 nT the highest occurring at the eastern part trending to the western direction and the lowest.

Regional Field Removal

Regional field removal is a crucial step in the processing of magnetic data when studying magnetic anomalies caused by subsurface geological features or sources of interest. The regional field, also known as the regional magnetic background or the long-wavelength component, represents the magnetic field variations associated with large-scale geological structures and is typically not of primary interest when investigating localized anomalies. Removing the regional field allows for a clearer and more focused view of the magnetic anomalies. By applying polynomial fitting least square analysis with Oasis Montage version 8.4, a plane surface was fitted to the digital data in order to remove the regional magnetic field, which is the anomaly connected to low frequency components. The treatment in this method is based on statistical theory, and the matching of regional features by a polynomial surface of low order revealed the leftover features as a random error. The mathematically describable surface providing the best match to the magnetic field that can be achieved within a given level of detail is computed using the observed data, typically using least squares (Skeels, 1967; Johnson, 1969 and Dobrin, 1988). The residual is the difference between the magnetic field value as it truly is and this surface, which is thought to be regional.

Even though only a few features are missing, the residual map (Figure 3) and the total magnetic intensity map have significant similarities, indicating that the basement is the residual map's primary source of information. The residual map displays colour ranges similar to the total magnetic intensity anomaly grid map, with red denoting high and blue denoting low and steep gradients that are dispersed across the area. The maximum intensity value of 130.6 nT is noted in the north eastern region towards the north through to the west, while the minimum value of -49.1 nT is recorded at the study area's southeast corner slightly near the south and at both extreme edge of the north and the northeast. The residual magnetic intensity anomalies generally trend in a NE-SW direction. The middle and southern portions of the research area are dominated by long wavelength anomalies, which are undoubtedly caused by a deep seated basement, while the northern and western fringes are dominated by the short wavelength anomalies.

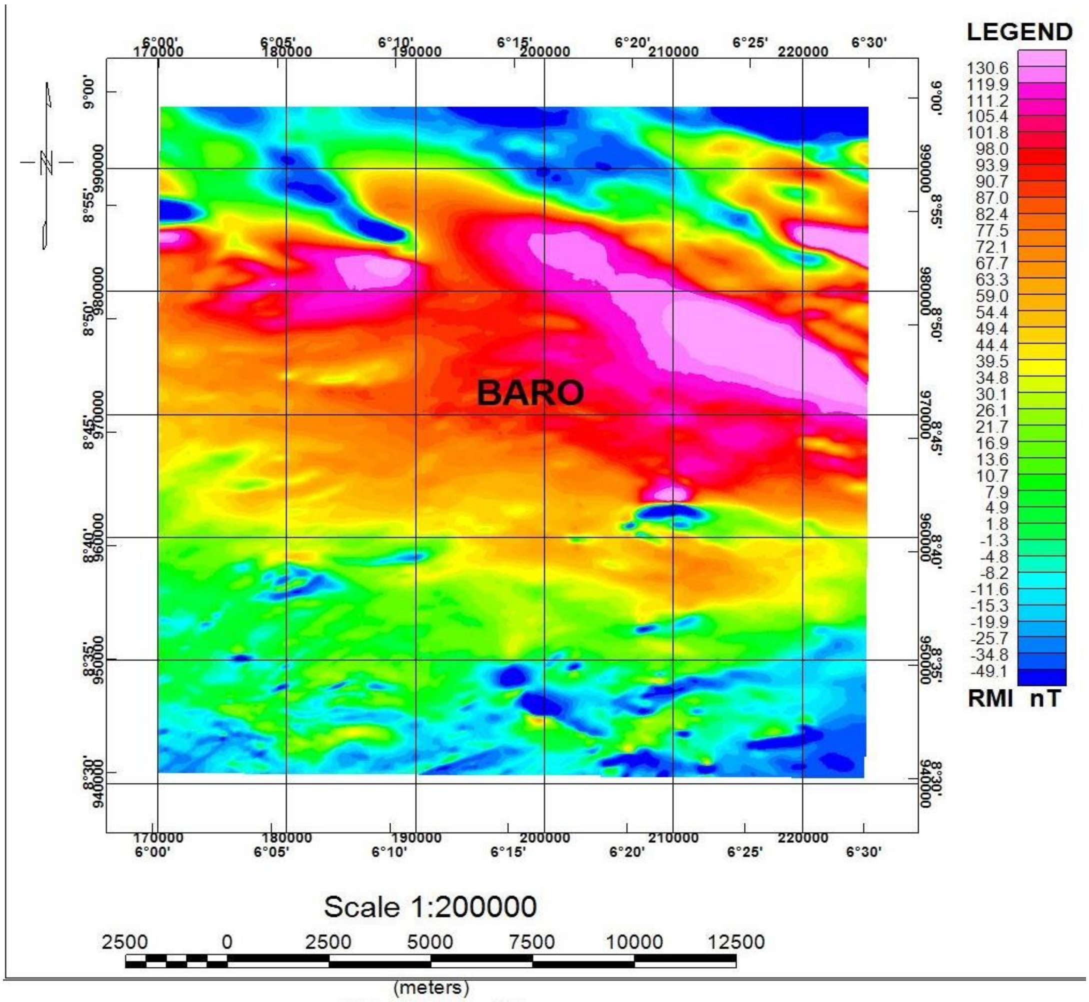

Figure 3. Residual magnetic map.

Reduction to magnetic equator

Reduction to the magnetic equator is a geophysical data processing technique used in magnetic field analysis, primarily for studying the Earth's magnetic field and its variations. This process involves transforming magnetic field data to a theoretical location called the "magnetic equator." This transformation helps to simplify and visualize magnetic anomalies more clearly, especially when dealing with magnetic data collected at various latitudes with different magnetic inclinations. The reduction to magnetic equator map (Figure 4) of the study area has higher values at north-eastern part nearer to the central and at the north western part. The highest value 141.9nT and the lowest with the value -41.8nT. The range is 173.7nT. By performing this technique, the recorded TMI is converted into the abnormality that would have been detected if the ambient field and magnetization were both horizontal. Thus, magnetic anomalies over their causative source may exist, making it easier to understand geological characteristics. The magnetism of sedimentary rocks is low and typically exhibit minimal magnetic reactivity. Consequently, the main according to, the magnetic characteristics of the subsoil determine the causes of magnetic abnormalities.

The reduction to the equator for this investigation was done on September 5, 2023, using the magnetic field measurements. Declination (Dm) is equal to -0.212° and inclination (Im) is equal to -13.751°.

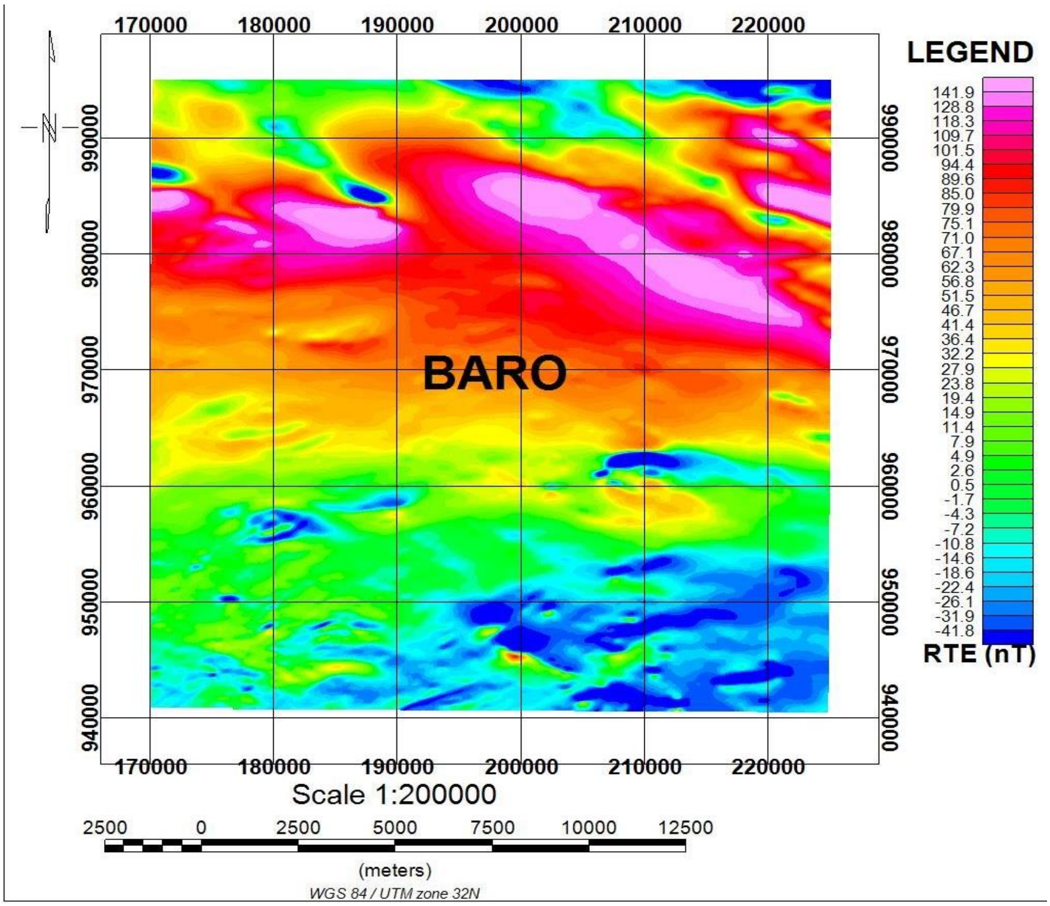

Figure 4. Reduction to magnetic equator map.

Upward Continuation

Upward continuation is a geophysical data processing technique used to enhance and emphasize shallow features in geophysical datasets, such as magnetic data. It involves mathematically moving the data to a higher elevation or elevation plane above the Earth's surface. This process is particularly useful for highlighting near-surface anomalies while suppressing the influence of deeper sources. The upward continuation technique was done on the data set up 100, 500 and 1000 m as shown in Figure 5, 6 and 7. Upward continuation up to 100 m showing the highest value to be up to 126.2 nT to 138.7 nT and the lowest value to be as low as -38.3 nT. The highest value is at the north east and also at the north western region while the lowest value is at the south east. It follows this trend for upward continuation up to 100 m, 500 m and 1000 m where the highest magnetic anomaly found at the upward continuation up of 100 m and the lowest magnetic anomaly found at upward continuation up to 1000 m.

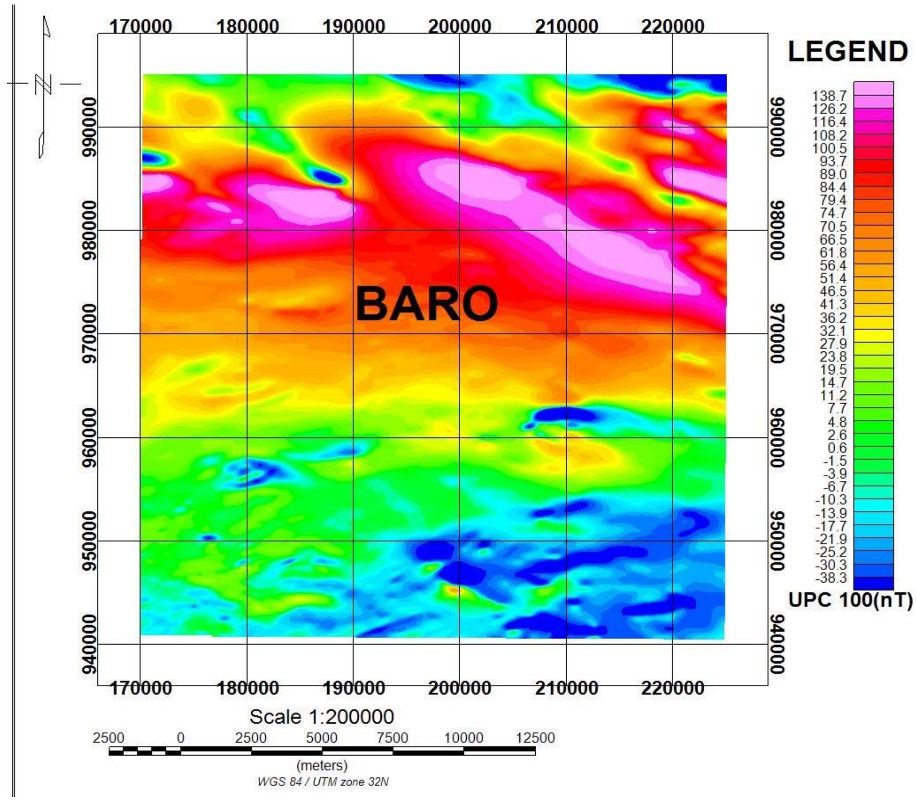

Figure 5. Upward continuation map up to 100m of the study area.

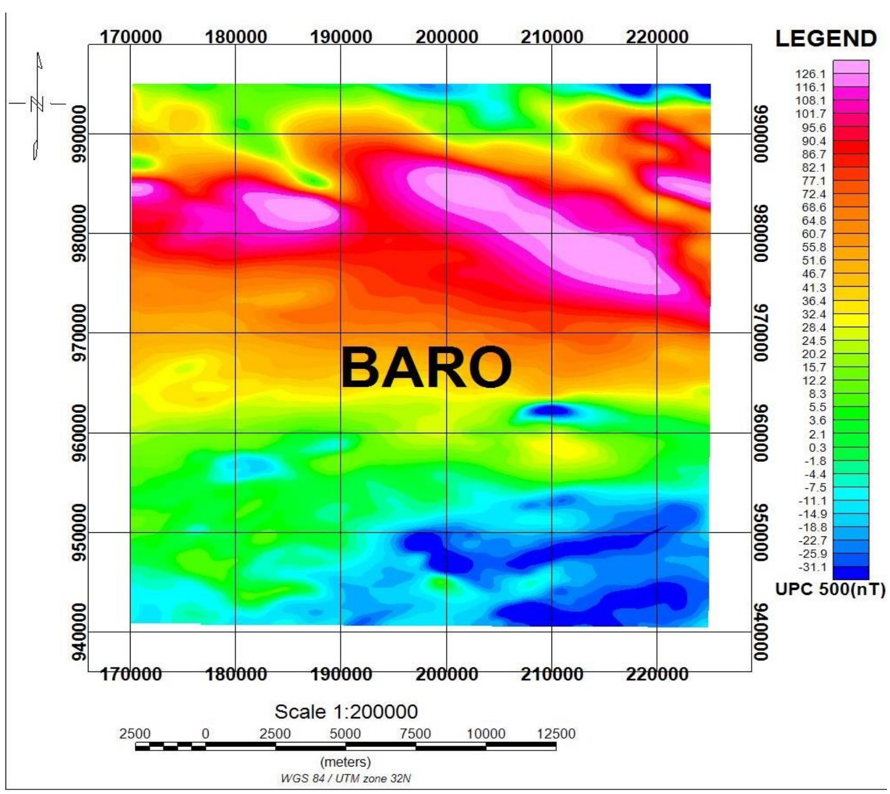

Figure 6. Upward continuation map up to 500m of the study area.

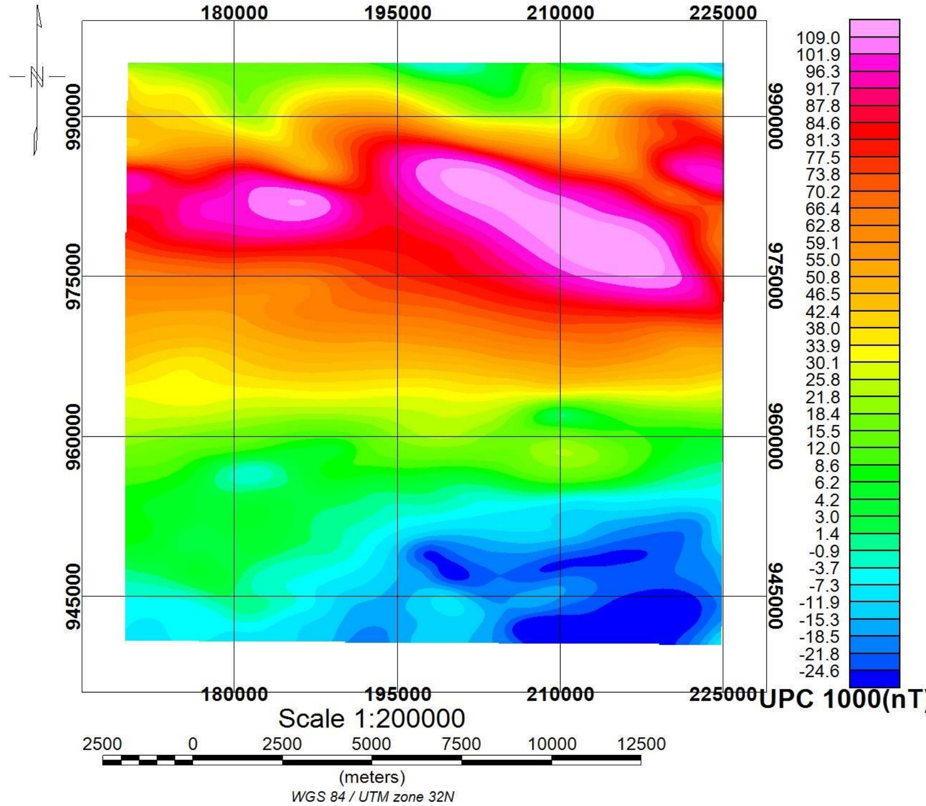

Figure 7. Upward continuation map up to 1000m of the study area.

Source parameter imaging

Source parameter imaging is a geophysical technique used to estimate the properties of subsurface sources or geological features responsible for observed geophysical data. The method utilises the relationship between source depth and the local wavenumber (k) of the observed field, which can be calculated for any point within a grid of data via horizontal and vertical gradients. At peaks in the local wavenumber grid, the source depth is equal to n/k, where n depends on the assumed source geometry (analogous to the structural index in Euler deconvolution). Peaks in the wavenumber grid are identified using a peak tracking algorithm and valid depth estimates isolated (Blakely and Simpson, 1986). The advantages of the SPI method over Euler deconvolution or spectral depths are that no moving data window is involved and the computation time is relatively short. On the other hand, errors due to noise can be reduced by careful filtering of the data before depths are calculated.

Calculating the depth of magnetic sources is rapid, simple, and effective with the Source Parameter Imaging (SPITM) function. Tests on actual data sets with drill hole control have showed its accuracy to be +/- 20% see Fig.8. While SPI has the advantage of creating a more comprehensive collection of coherent solution points and is simpler to use, its accuracy is comparable to that of Euler deconvolution. (Thurston and Smith, 1997) indicate that one of the stated objectives of the SPI approach is to provide images that are simple for someone who is knowledgeable about the local geology to comprehend. The source parameter imaging approach is a complicated one that involves two or three steps of mathematical processing from different grids. The Oasis montaj software version 8.4 was used to conduct this transform by processing the magnetic residual data as input data. The SPI processing function in the menu bar of the Oasis montaj software also uses the output grids from dx, dy, and dz as input grids to create the source parameter imaging grid map. First order derivative must be mentioned since higher derivative orders make the (SPI) approach more susceptible to noise. Consequently, the data was meticulously screened.

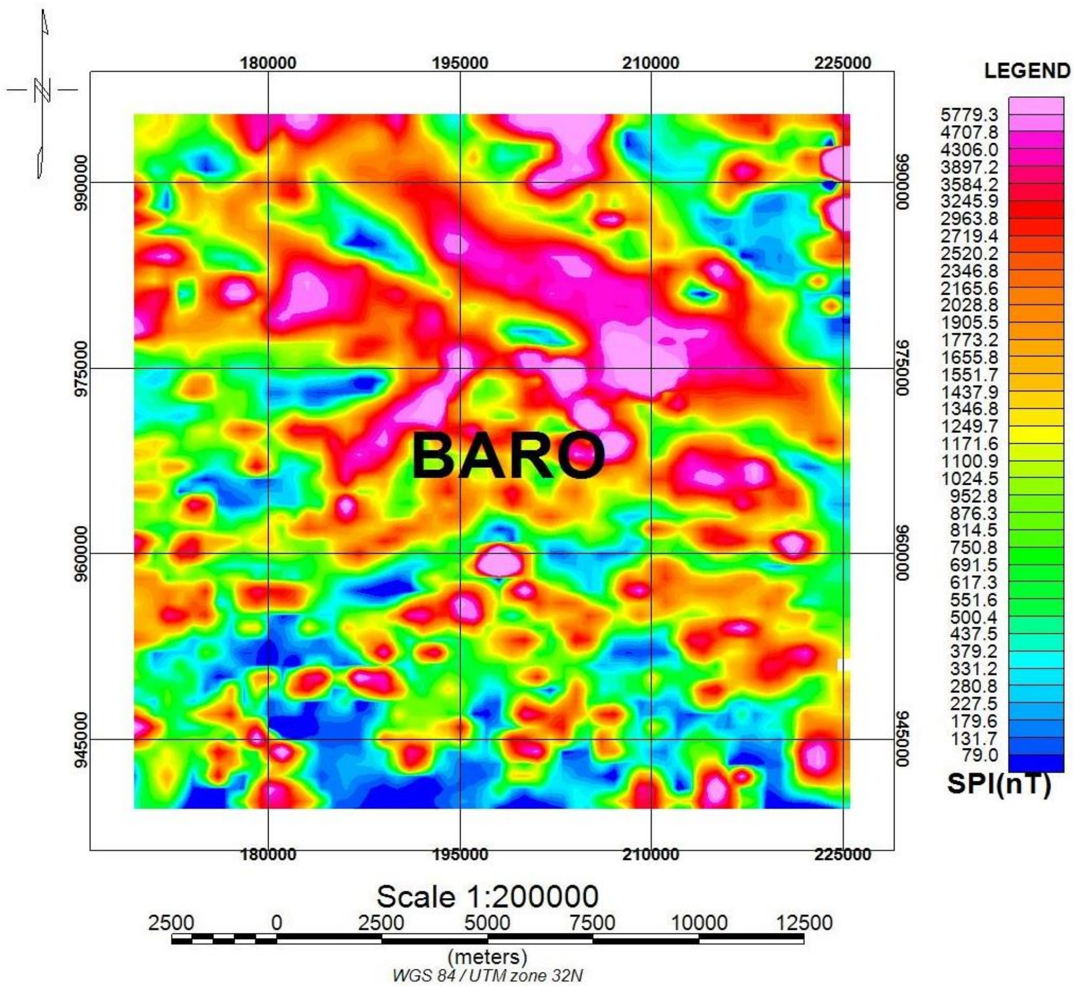

Figure 8. Source parameter imaging map.

Data interpretation

This parameter's source In order to determine the depth of the magnetic sources in the study area, an imaging interpretation approach using regional residual separation was used to the total magnetic intensity map. This method is excellent for quickly determining sediment thickness and can help reveal more about the local geology. As comparisons to the terrain reveal information about the magnetic sources at depth that can be directly compared to a geologic map, a great deal of insight about the sediment thickness depth of the area come to bear. Smith *et al.* (1998) determined the depth to the magnetic basement as well as the effect of near-surface anomaly sources from the Source Parameter Imaging results. The SPI grid map over Baro and its surroundings can be classified into three primary sections: shallow, medium, and deeper depths, while there are also tiny depressions in some places. High magnetic intensity values are present in the research area's northern region, which are depicted by the colour red-pink. Dark-green-blue coloration denotes low magnetic intensity levels, which are predominant in the southern region.

A zone of medium magnetic intensity levels, shown by the yellow-orange tint, separates the two portions. Due to the low local wave number, the structural index cannot be accurately computed in the white portions of the SPI grid map (Figure 10). In that section, the model independent local wave number had been set to 0. The area's northernmost low magnetic intensity readings and high SPI readings are likely the result of deep seated sedimentary rocks with weak magnetic susceptibilities.

Sediment thickness and other non-magnetic sources may be the cause of the northern region's low magnetic intensity. The depth of the magnetic sources varies between 79m and 5779.3m, as seen in Figure 10. This is in contract to the result obtained by The north-central and northernmost regions have the thickest sediment layers. However, there are pockets of slightly deeper sediments in the northeast, east and scattered around on the map. In general, the research area's sedimentary thickness appears to rise from south to north. Estimating the depth to magnetic sources is a crucial step in the exploration for hydrocarbon reserves. The utilization of Source Parameter Imaging (SPI) in the context of Baro and its surrounding areas has provided valuable insights into the geological characteristics of the region. The findings of this study have significant implications for the potential presence of hydrocarbon reservoirs in the area. One of the key observations from the SPI analysis is the substantial variation in sedimentary thickness across the surveyed region.

In particular, the northern area of Baro exhibits the most noteworthy sedimentary thickness, averaging approximately 3245.9 to 5799.3 meters, while further south, this thickness diminishes significantly to around 79 meters. This variation in sedimentary thickness can be attributed to the complex geological history and tectonic processes that have shaped the region over millions of years. The northern area's abundant sedimentary thickness is indicative of a deep basin, which is a favourable geological setting for the accumulation of hydrocarbon reserves. Deep basins typically provide the necessary conditions for the formation of source rocks, reservoir rocks, and the entrapment of hydrocarbons. The deeper the basin, the greater the potential for the accumulation of organic-rich source rocks, which are the origin of hydrocarbons. Conversely, the southern region's shallow sedimentary thickness is primarily associated with basement complexes and volcanic areas.

These geological features have a substantial influence on the subsurface structure and composition. In such areas, the sedimentary cover is limited, and the likelihood of finding mature source rocks diminishes. However, this does not rule out the possibility of hydrocarbon reservoirs entirely, as volcanic formations can serve as potential traps for hydrocarbons. The depth of sedimentary basins is not the sole factor in determining the presence of hydrocarbon reserves. Equally important are the types of subsurface geological features that exist within these basins. Source rocks, reservoir rocks, paleo temperatures, and traps play a critical role in the formation and preservation of hydrocarbons. Source rocks are organic-rich sedimentary formations that have undergone geological processes to generate hydrocarbons. These source rocks require specific temperature and pressure conditions to convert organic matter into hydrocarbons over geological time scales.

In deep sedimentary basins, where temperatures are higher due to greater burial depths, the likelihood of finding mature source rocks increases. Reservoir rocks, on the other hand, are porous and permeable formations that can host significant quantities of hydrocarbons. These rocks serve as storage units for the hydrocarbons generated from source rocks. Understanding the distribution and quality of reservoir rocks is essential for assessing the hydrocarbon potential of an area. Paleo temperatures provide valuable insights into the thermal history of a region. Knowledge of past temperature conditions is crucial for evaluating the maturation of source rocks and the preservation of hydrocarbons. In areas where temperatures have been conducive to hydrocarbon generation and preservation, the likelihood of discovering viable hydrocarbon reservoirs is enhanced. Traps represent geological structures that prevent the upward migration of hydrocarbons, ensuring their confinement within reservoir rocks. Common traps include anticlines, fault zones, and stratigraphic traps. The identification of potential traps is a critical aspect of hydrocarbon exploration, as it greatly influences the success of drilling operations.

4. DISCUSSON & CONCLUSIONS

The application of Source Parameter Imaging (SPI) in the Baro region and its surroundings has provided valuable insights into the subsurface geological structures, highlighting variations in sedimentary thickness and potential hydrocarbon reservoirs. The analysis revealed deeper basins in the northern sector and shallower sediments in the south, indicating diverse geological conditions that may be conducive to hydrocarbon accumulation. While the SPI method has proven effective in delineating magnetic source parameters such as depth, geometry, dip, and susceptibility contrast, further exploration involving advanced seismic studies, drilling, and well-logging is essential to confirm hydrocarbon presence and assess commercial viability. Additionally, expanding the exploration scope to other interior basins across Nigeria could significantly enhance the nation's hydrocarbon reserves, bolster energy security, and drive economic growth. However, sustainable resource management, environmental stewardship, and the integration of advanced geophysical technologies will be critical to maximizing the potential benefits of these exploration efforts.

Recommendation

1) **target Deeper Sedimentary Basins:** The deeper portions of the sedimentary basin, as revealed by the SPI analysis, exhibit significant potential for hydrocarbon resources. Detailed geological surveys, advanced seismic studies, and exploratory drilling operations should be conducted to accurately assess the hydrocarbon potential in these zones.
2) **Application of Advanced Geophysical Techniques:** Implement advanced exploration techniques such a 3D and 4D seismic imaging and well-logging tools. These methods will provide a more comprehensive view of the subsurface geology, particularly in areas with complex magnetic properties.
3) **Expansion of Exploration Scope:** Expanding exploration efforts beyond Baro to include other interior basins in Nigeria is recommended. This strategic move will contribute to energy security, economic growth, and the discovery of new hydrocarbon reserves, thereby solidifying Nigeria’s position in the global energy market.

4) **Collaboration with International Experts:** Partnering with international research institutions and experts can provide access to advanced technologies and expertise in deep-sea exploration, further enhancing the chances of discovering substantial hydrocarbon reserves.
5) **Integration of Multi-Disciplinary Data:** Integrate SPI data with geological, geochemical, and petrophysical data to improve the accuracy of subsurface interpretations and reduce uncertainties in depth estimation and structural characterization.
6) **Environmental and Socioeconomic Considerations:** Future exploration activities should prioritize sustainable development, environmental protection, and community engagement to mitigate potential negative impacts while maximizing socioeconomic benefits.

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