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Basement Depth Re-Estimation and Structural Trend Analysis of Sokoto Basin Northwestern Nigeria Using SPI and Analytic Signal Methods of Aeromagnetic Data

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ABSTRACT

Aim of the Study: The study's objectives were to establish the depth of the magnetic basement, identify the linear characteristics connected to the basin, and extrapolate the impact of the structure on the region's overall tectonic history.

Methodology: The basin spans latitude 11°00ᴵ to 13°30ᴵN and longitude 4°30ᴵ to 6°30ᴵE. It is situated at the eastern part of Iullemeden basin. Results of the study revealed total magnetic intensity (TMI) range of -1503.47nT to 1224.93nT with average of -139.27nT. Residual magnetic field anomaly result showed a range between 770.25nT to 1385 95nT. Tilt derivative result showed a range of values between -1.57054nT/km to 1.57054nT/km.

Findings: Magnetic lineament map showed major lineament in direction NE-SW and NW-SE. The lineament map also revealed cross conjugate faults. Lineament density map revealed spatial distribution and rose diagram of the lineament confirmed that the dominant trend is in the direction of Northeast- Southwest. The result of Analytic signal showed an average depth of 3.4930nT per kilometer and a thickness value of 6.986nT per kilometer. SPI result revealed an average depth and thickness as 3.1km and 6.2km respectively. Analytical signal and SPI technique results showed that the study area's north, northeastern, and northwestern regions have mineral potentials whereas the study area's south and southeast had hydrocarbon potential.

Conclusion: Despite the sedimentary thickness, the basin may not produce hydrocarbon due to the structural deformation of the basin which reflected as cross conjugate faults dominated in the potential study area. These areas with hydrocarbon potential is suggested for further geological study such as seal-fault-analysis to ascertain the sealing of the fault for hydrocarbon accumulation.

Keywords: Cross-Conjugate, Faults, Hydrocarbon, Mineralization, Basement, Lineament.

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Introduction

When compared to other geophysical approaches, the aeromagnetic method stands out due to its quick rate of coverage and affordable price per unit area studied. In order to identify rocks or minerals with exceptional magnetic properties, magnetic surveys are mostly used to look for abnormalities or disruptions of the subsurface magnetic field strength (Sunmonu and Alagbe, 2011; Alagbe, 2015). The subsurface magnetic field varies because of the change in the amount of magnetite in the rock surface, aeromagnetic surveys map these fluctuations, distribution and magnetic minerals beneath the earth's sub-surface and changes in the subsurface basement susceptibility. Ordinary variations appear where the subsurface basement complex nears the earth's surface and ferromagnetic mineral concentrations are concentrated.

Quantitatively mapping the magnetic basement depth is the main goal for interpretation of aeromagnetic data and survey. The basin architecture gives basic information on petroleum development and mineral exploitation which is provided by the sedimentary thickness interpretation of the subsurface magnetism. Discrete, bodies isolation with suitable shaped and moderately high magnetism are advantageous to all methods that are used when determining the depth to magnetic source. The functions are constructed from the data such that it peaks over the source. This is the first step in finding the position and depth to the source by gridded potential field data. Analytical signal amplitude (ASA) is an illustration of such a function.

The majority of magnetic field surveys aim to create images for in-depth geological analysis, and gridding is frequently tuned to minimize noise in the images of Total Magnetic Intensity (TMI) or its enhancement, like Analytic Signal Amplitude. Grids that have undergone image processing have better details and maps that are easier for non-specialists to understand. Given its speed, affordability, and versatility, the aeromagnetic method is a geophysical tool that can be used to expose both large- and small-scale characteristics, such as variations in basement type, magnetic intrusion, volcanic materials, basement surface, and fault structures.

One method for figuring out how deep the magnetic source body is, the Source Parameter Imaging (SPI) method. The ability to display the depths on an image or map is one benefit of the SPI approach. Thurston and Smith (1997) are the authors of the methodology. It distinguishes and describes sedimentary thickening zones from elevated or uplifted basement regions; it calculates the depths to magnetic earth sources. This employs different methods for determining automatically depth to source magnetic set-data grids. The result can be used to pinpoint locations with high mineral deposits concentration and hydrocarbon potential.

Landscape elements that are linear and express underlying geological characteristics like faults are called structural lineaments. If other ground truths are taken into account, areas with lower lineament density indicate plane grounds primarily composed of sedimentary rocks and could potentially be used as a site for a hydrocarbon reservoir. Conversely, zones with higher lineament density indicate the proximity of the basement subsurface and could potentially be used as a site for mineral deposits (Emberga *et al.*, 2016).

Structural trend analysis could be explained involving the interpretation of rotations, translations distortions and dilations combined to alter the orientation and location, shape and size of a rock, which include rigid and non-rigid-bodies movement. Structural trend analysis simplifies tectonic setting of a region.

The Structural trend concept development can occur at the center of a geological structure which can excite the animated sequential dip profile through the structural dip or edge to the areas of great development (e.g.fold amplitude and fault slip) and center of the Earth's structure (Opara, *et al.*, 2014).

The structural trend pattern can be formed by these interruption can affect the stability of the mountain, it may be evaluate initially by the use of simple tectonic analysis. Most analyzes proffer relevant details about structure existence that contributed towards the revelant shift of an unstable Plate movement and the kind of failure that may occur (wedge sliding, planar sliding and toppling). (Cratchley & Jones, 1965; Betts, *et al.,* 2007; Ofoegbu, 1983; 1984 and Nwachukwu, 1972). As a result, some of the tectonic and structural features can be easily seen on aeromagnetic maps (Betts *et al.*, 2007). According to many researchers (Betts *et al.,* 2007; Prieto, 1996; Gunn, 1997a&b), variations in metamorphic grade, composition, age of an area and deformation history, can be deduced by recognizing and mapping changes in magnetic fingerprints.

Similar to this, alterations in an area's magnetic signatures might offer information that may spur the development of a condensed structure's history that might be explained in terms of structural events series (Betts, *et al.,* 2007; Betts, 2003). However, using geophysical anomaly patterns which are primarily defined by their anomaly amplitudes, magnetic lineations spacing, and geometries of magnetic source, it is feasible to identify unique units (Gunn, 1997a&b; Prieto, 1996 and Betts, *et al.,* 2007).

Sokoto basin is located in Northwest Nigeria. It covers about 25,000 sq/ miles. Its latitude range from 11^0 00^1 and 13^0 30^1 N and its longitudes ranged from 4^0 $30^1$and 6^0 30^1 E. It is bounded on the north and west by Niger and on the south-west by Dahomey which include some parts of Sokoto, Gwandu Emirates (now Divisions) in Sokoto province and Argungu. Sokoto basin is one of the sedimentary basin in Nigeria. It occupies about 1/10 of a big larger sedimentary and structural basin centered in Niger area, it is also referred to as Bassin c'es lullemeden (Anderson and Ogilbee, 1973).

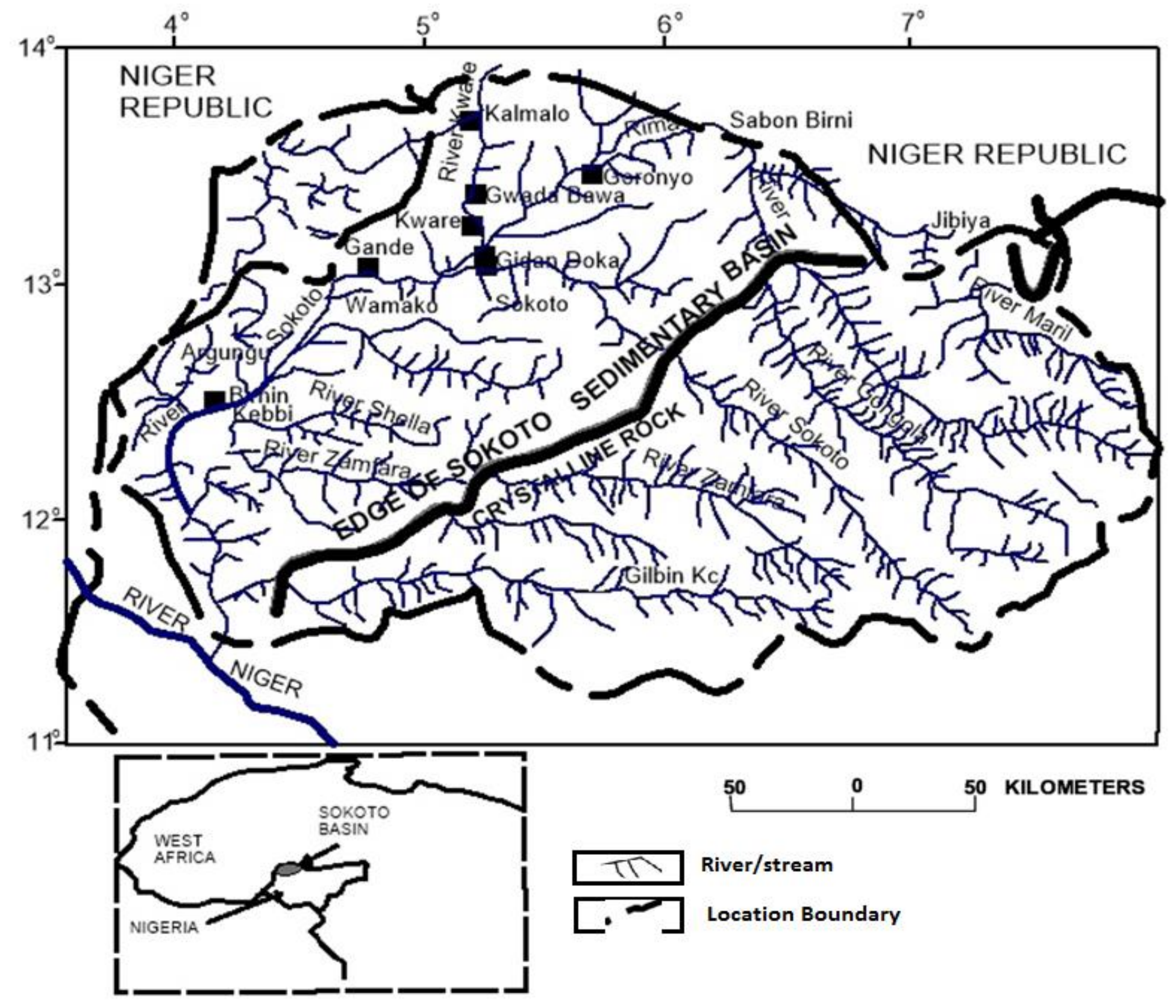

Figure 1: *Topographic map of the Research area*

According to Ofoha et al. (2016), there were four primary stages of deposition during which sediments in the Sokoto Basin accumulated. The formations that made up Sokoto basin are Gwandu, Gamba, Dange, Gundumi and Dukamaje Formations. Gundumi Formations, is composed of grits and clays, which is the Pre-Maastrichtian continental intercalaire of West Africa, it lies beneath the Pre-Cambrian Basement unconformable. The Maastrichtian Rima Group, is composed of fossiliferous Dukamaje Formation, friable sandstones and mudstones (Taloka and Wurno Formations), were overlaid unevenly on top of them. The Paleocene Continental Terminal is made up Dange, Gamba and the calcareous Kalambaina Formations.

These strata have a mild northwesterly dip and thickness of about 1200m maximum close to the Niger Republic border (Ofoha *et al.,* 2016 and Obaje *et al.*, 2013). Dange Formation is the main rock type harboring the nodular phosphate, has been reviewed by Okosun (1989). According to reports, the formation is made up of black siltstone, brown to dull yellow marl facies, and grey, brown, and black shale. In the grey shale, the marl is found as two inter-beds. The formation contains rather thick inter-beds of black shale and black siltstone facies. Silty shale could operate as a bridging facies between the Dange Formation and the lower Wurno Formation, but if not, the contact is abrupt.

In mineralogically studies, low phosphatic nodular disseminations and thin phosphatic nodular beds are seen in the brown and grey shale and siltstone facies. Gypsum lenses and stringers have also been discovered in the shales. Foraminifera and ostracod were used to date the Dange Formation as late Paleocene (Okosun, 1995).

The phosphate nodules shows erratic forms, and many have erratic surface striations. Some of them exhibit bioturbation characteristics. There are two frequent sorts of nodules: those that are cream in color and light in weight, and those that are grey to black, heavy and severely indurate. Another type typically has an external surfaces that are highly polished. Nodular beds, are made up of closely spaced nodules in a matrix of silt, clay, shale, and disseminations in shale or siltstone, they are the two ways that nodules can be found (Okosun, 1989). Geochemistry and mineralogy of the phosphate nodules was revealed by Adeleke and Akande (2004).

The lowlands of Rima River, Sokoto River and major tributaries are covered in Quaternary-aged alluvium. In addition to the local unconfined groundwater bodies, these rocks are home to three (3) significant artesian aquifers (Adelana and Olasehinde, 2014; Anderson and Ogilbee, 1973).

The basin sediments are not uniform with the underlying complex and have been subject to a number of marine transgressions over the Mesozoic and Tertiary, resulting in the deposition of a series of sediments. The extent of the basin was gradually altered by these transgressions, leading to series of an overlap and younger outcrops as one moved toward the northwest (Adelana & Olasehinde, 2014; Kogbe, 1989).

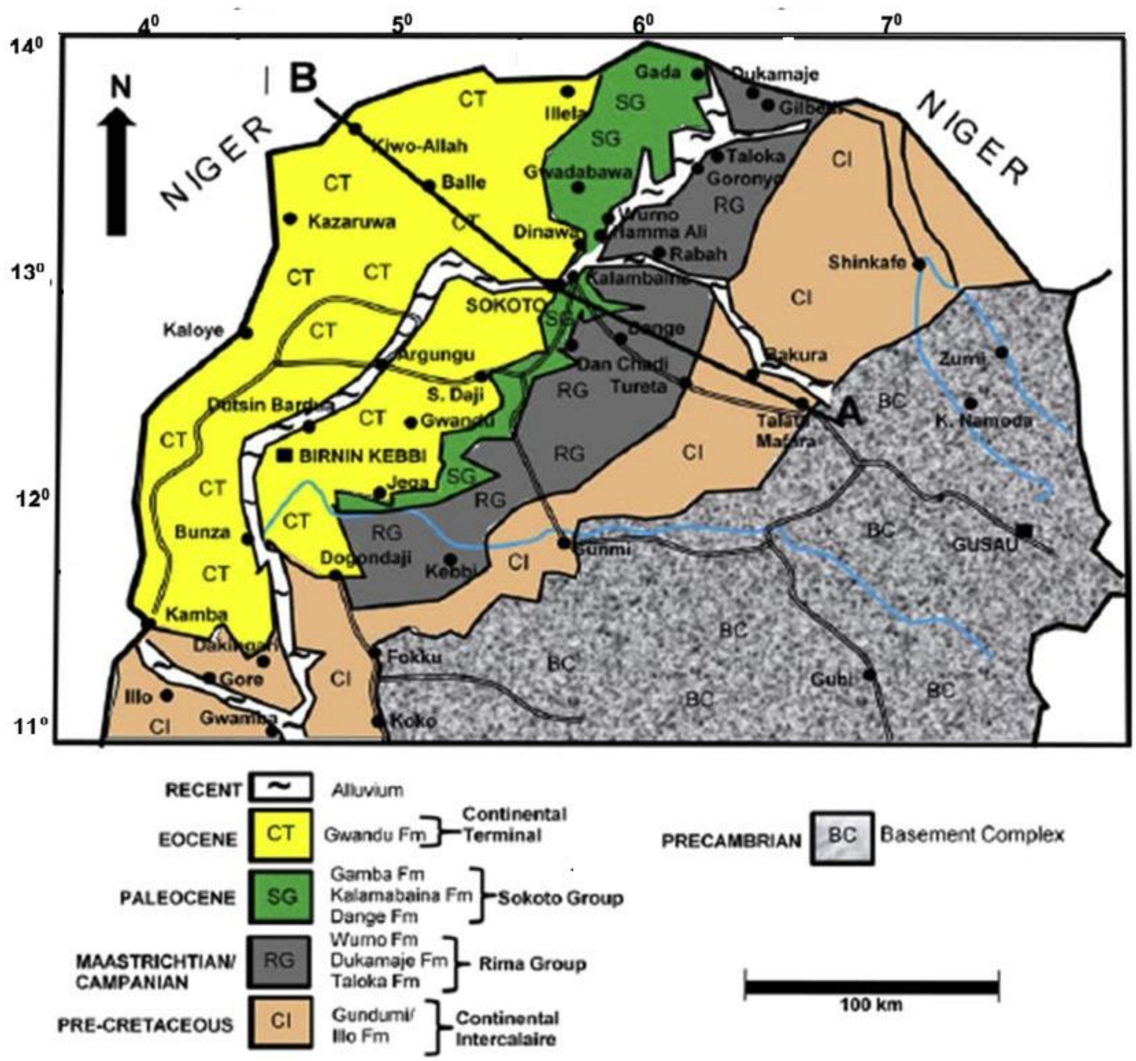

Figure 2: *Geologic Map of the Study Area*

Materials and Method

Sokoto basin was studied using sixteen (16) sheets of high resolution aeromagnetic map (HRAM), which included; Binji (9), Sokoto(10), Rabbah(11), Isah(12), Argungu(28), Dange(29), Gandi(30), Talata(31), Tambawal(50), Gummi(51), Anka(52), Maru(53),Fokku(73), Donko(74), Gwashi(75) and Dan-Guibi(76). The Nigerian Geological Survey Agency (NGSA) mapped the sheets on a scale of 1:1000,000. Regional map correction was done based on International Geomagnetic Reference Field (IGRF). The maps were carefully digitized. The digitized map obtain from the data were used to generate the Total Magnetic Intenstiy (TMI) of Sokoto Basin using Oasis Montaj software. The magnetic gradient were eliminated from the data set using IGRF, and the resultant residual anomaly map of the basin was created. The residual anomaly data was analyzed using Analytic signal and SPI methods to measure the depth of the research area's magnetic basement. The research area's magnetic profile, which displayed different patterns of variation in the magnetic susceptibility of the Sokoto basin's basement rock, was also created.

Source Parameter Imaging (SPI) assumed a model called step-type. Depth to magnetic source was calculated as follows;

$$\text{Depth} = \frac{1}{K_{(max)}}$$

Where $K_{(max)}$ is the peak value of the local wavenumber K over the step source.

$$K = \sqrt{\left(\frac{dA}{dx}\right)^2 + \left(\frac{dA}{dy}\right)^2 + \left(\frac{dA}{dz}\right)^2}$$

Tilt derivative

$$A = \text{Tan}^{-1} \left[\frac{dT/dz}{(dT/dx)^2 + (dT/dy)^2}\right]$$

T = Total magnetic field anomaly grid.

Analytic Signal Method

A magnetic component's horizontal and vertical gradients are combined to create the analytic signal. First-order magnetic field derivatives involves vertical and horizontal derivatives and the first vertical integration are necessary for an analytical signal (AS). The vertical derivative of a magnetic field measures how the magnetic field changes with depth or height, whereas the horizontal derivative measures the differences in magnetic anomaly value in a specific location relative to its neighboring position. These derivatives are based on the idea that rock susceptibilities at the ground's surface affect magnetic field rates of change more so than those at further depths (Alagbe, 2015; Subasinghe, *et al.*, 2014). The first vertical derivative is a technique for improving anomalies over bodies that intends to reduce magnetic anomaly complexity and sharpens anomalies over causative bodies, enabling clear imaging of the underlying structure. Short wavelength will be amplified and regions of variable data resolution in the magnetic grid data will be clearly identified with the help of transformation. it may produce noisy results. The applications of analytic signal to magnetic interpretation was pioneered by Thurston and Smith 1997. Nabighian was used for 2D case, as a tool to estimate depth and position of sources.

$$A(x, y) = |A(x, y)|.\exp(j\varphi)$$

$$|A(x, y)| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2}$$

$$\varphi = \tan^{-1}\left(\frac{\partial M}{\partial z} \middle| \frac{\partial M}{\partial x}\right)$$

|A| = 2D analytic signal amplitude, φ = local phase. A = recurring idea in the normalized derivative, it is the idea of mapping angles, that is function of angle formed from the gradients of the magnetic anomaly.

Result and Interpretation

The basement depth of the sedimentary basin of the study area was mapped quantitatively using magnetic analysis. The primary goal was to identify the sedimentary thickness of the basin geometry for probable hydrocarbon and mineral prospect. The values obtained from the magnetic field interpretation was based on the depth to magnetic source. The investigative area’s large and small scale properties, such as the magnetic intrusion, basement surface, sedimentary thickness and structural trend, have been revealed thanks to the aeromagnetic approach, a more expedient, affordable, and adaptable geophysical tool. The total magnetic intensity (TMI) showed the underlying basement of the research area. The value ranged between -1503.47 to 1224.93nT and the average value is -139.27nT. Zones with light colours describe areas with high magnetic intensity while zones with dark colour are zones with low magnetic intensity, the areas with black colours have very low broad magnetic anomaly. This is shown in Fig. 3. Southeastern parts of the research zone revealed very low magnetic strength the areas involved Wuya, Anka, Isa and Dengebe areas while magnetic intensity high strength were revealed towards North, North-West and North-East.

The magnetic intensity high of these parts can be a resultant of trough from basement subsidence, igneous intrusion or magnetic uplift. The magnetic intensity highs cover most fragments of the research area around Silame, Shagari, Bimasa, Sokoto and Wurno. They are seen as linear features. Very high values of magnetic anomaly between 1200nT to 1225nT revealed a sign of magnetic uplift (Bonde *et al.,* 2014; Nwokocha *et al.,* 2016). The magnetic uplift is assumed to intrude into the sedimentary overburden and it is trusted to contain mineral deposit. The parts with low magnetic strength may be as a result of sediments (that is sedimentary rocks and non-magnetic sources). Crystalline basement rocks and Igneous rocks always give rise to high magnetic intensity values while sedimentary rock or altered basement rock gives rise to low magnetic intensity values. The residual, reversed and regional magnetic maps were obtained from the total field intensity map of the research area using polynomial fitting techniques as shown in fig.4, fig.5 and fig.6 respectively. Surface geology of the research area showed a strong link with the residual magnetic intensity map, this was done by removing the regional magnetic intensity field from the total magnetic field using the polynomial fitting approach (fig.4). The reduction to the pole (RTP) transformation was done, the residual magnetic field anomaly likewise displayed a strong association with the research area's geology.

The regional field of the data's first vertical derivative showed a trend direction of NW-SW, indicating that this direction is the research area's predominate regional trend. According to the study's fig.6, the residual magnetic field intensity values ranged from -770.25 to 1385.95nT. Parts with high values of residual anomaly are represented with red, pink, and purple colours, they are seen in Shagari, Silame and Wurno aeromagnetic sheets while the low values were represented with blue and black; the sheets involved are Anka, Dengebe, Wuya and Isa sheets.

Areas with low magnetic values in the residual map (fig.6) typically reflect low magnetization zones, whereas zones with high residual magnetic values typically reflect high magnetization zones, suggesting that the area is linked to intensive tectonic/magmatic activity.

Similar to this, many groups of circular anomaly closures of varied amplitudes, which were identified, particularly in the northwest and southwest regions, were thought to be lithological variants of mafic-ultramafic inclusions (Gazala, 1993; Opara *et al.,* 2018).

Zero magnetic contour on the second vertical derivative map of the study region, as shown in fig. 8, overlapped with lithological boundaries. Positive and negative anomalies mostly correspond to surface exposure of mafic and felsic rock, respectively (Opara *et al.*, 2018; Gupta and Ramani, 1982). Second derivative analysis observed value showed values between -0.039815 to 0.0528083. Areas with high values were described with light colours while low values were described with dark colours.

Tilt derivative analysis was derived from the first vertical derivative (1VD) of the total magnetic field (TMI). This is another method used in mapping variations in basement depth from magnetic maps directly. It is also used to derive strikes of geologic contacts/faults. Regions where shallow basement showed up were characterized by numerous closely spaced lineaments with depth -1.57054nT/km was described by very dark colour as shown in fig.9. The areas with light colours denotes basement dip.

Lineaments map of the research area (Fig.10) showed several traced lineaments that were observed in the area where basement outcrops were closer to the surface. Consideration was given to linear features that were 1 km in length or longer. The longer lineaments have the best chance of becoming deeper-penetrating and more fully formed. The lineament trend match the location and pattern of the local Paleo-tectonic fracture regions. Lineaments with longer lateral extension revealed trend in the Northeast-Southwest and Northwest-Southeast directions, this indicates the direction of the last regional tectonic phase.

Because it is thought that large masses of basic magmatic material may have been injected in the lower portion of the continental crust in the investigating area, leading to the upliftment of the basement, the relationship between mineralization and lineament were established in this work (Obaje, 2009; Nwokocha *et al.,* 2016). A map of the area's lineament density from this study (Fig. 11) displayed their spatial distribution. High lineament densities were seen in the research area's northeastern region. The basement rocks here protrude toward the earth's surface. It is possible to hypothesize that the basement's upliftment was caused by the entry of significant amounts of primary magmatic elements.

Low lineament density were observed at the southern parts of the research area. The low lineament densities were attributed to regions with deeply seated basement rocks. Cross Conjugate Faults (CCF), which are predominantly located in the southern and southeastern portions of the research area, were also seen on the lineament map and may be a sign of fluid migration. Fig.12 rose diagram of the local lineaments revealed a predominate tendency that went from northeast to southwest. The rosette blades length corresponds to the square of the relative frequencies of the lineaments. The rose diagram was created from visually extracted lineaments. To create a rose diagram, the lineament's statistical quantification and orientation frequency were specifically taken into consideration. The direction is consistent with the dominant lineament trend in the region. However, because the newer events are more obvious and have a tendency to erase the older ones, the prevailing trend, from NE to SW, reflects the younger tectonic events.

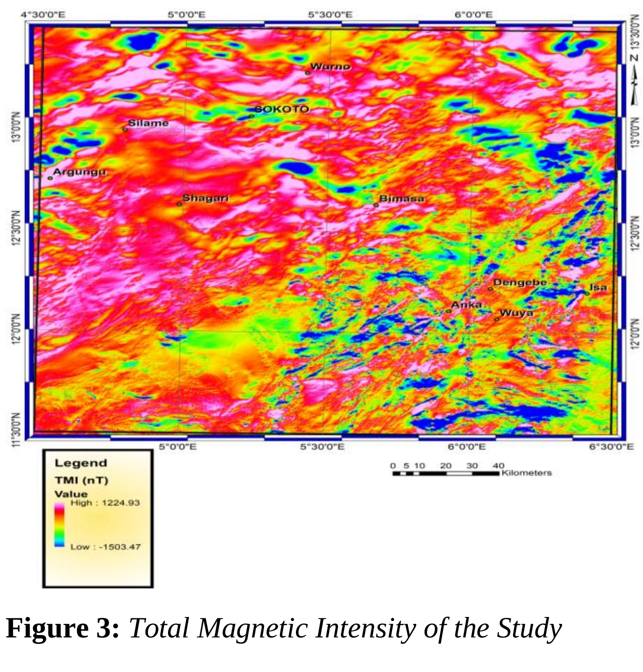

Figure 3: *Total Magnetic Intensity of the Study*

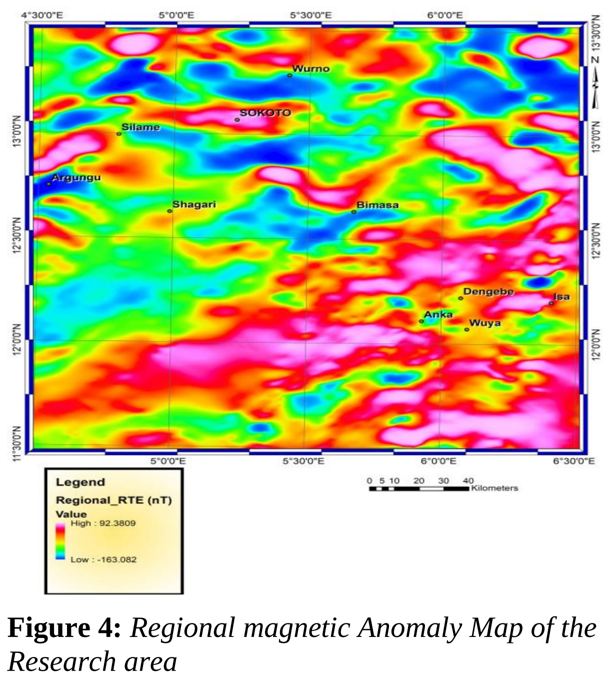

Figure 4: *Regional magnetic Anomaly Map of the Research area*

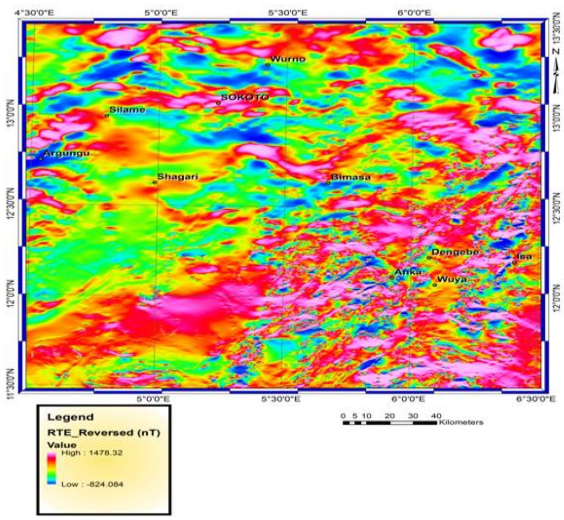

Figure 5: *Reversed Magnetic Anomaly Map of the Research Area*

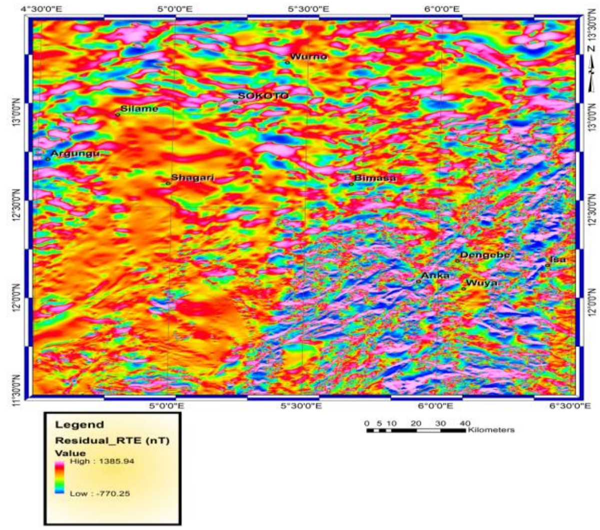

Figure 6: *Residual Magnetic anomaly Map of the Study Area*

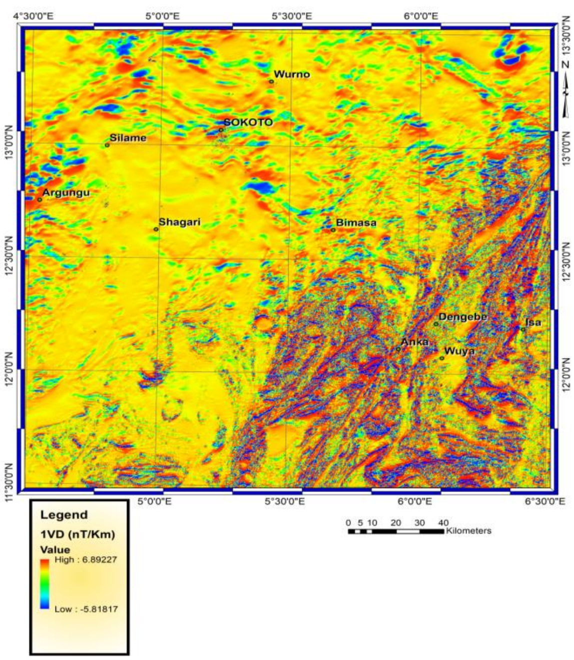

Figure 7: *First Vertical Derivative of the Study Area*

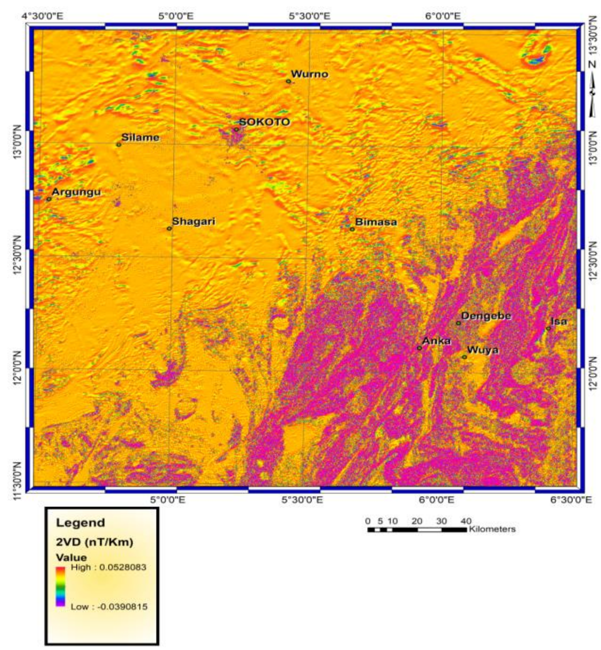

Figure 8: *Second Vertical Derivative of the Study Area*

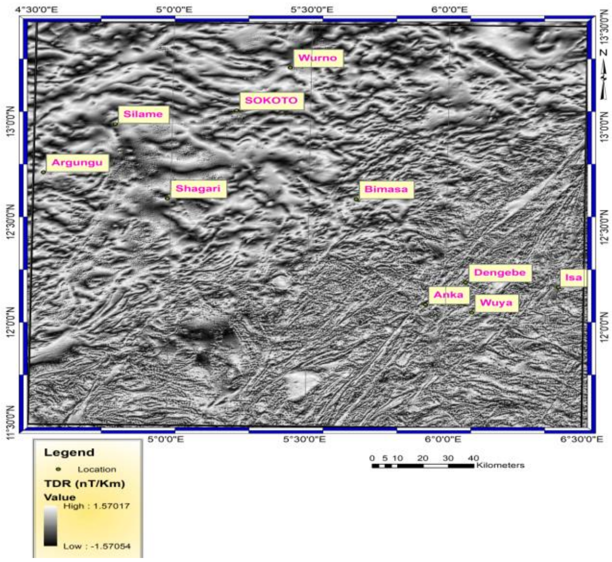

Figure 9: *Tilt Derivative of the Research*

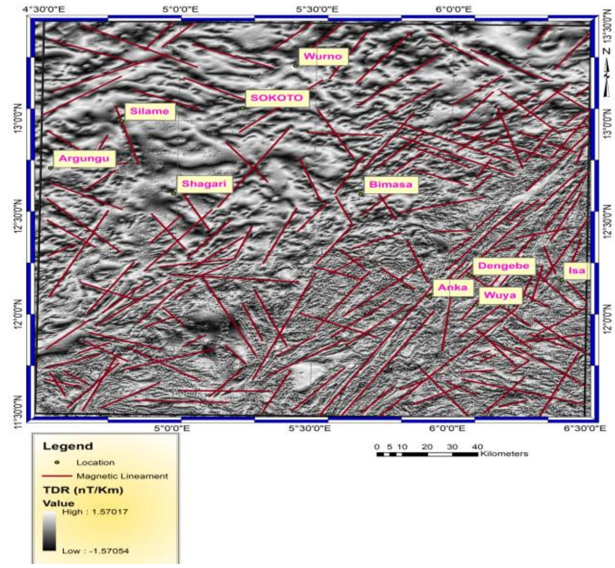

Figure 10: *Magnetic Lineament Map of the Study Area*

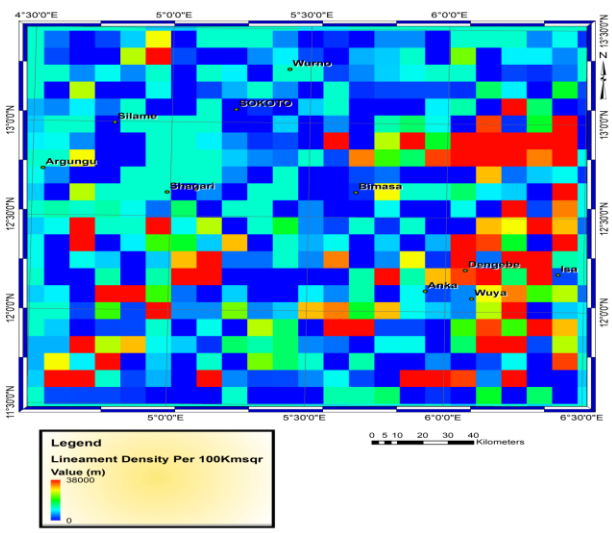

Figure 11: *Lineament Density Map of the Study Area*

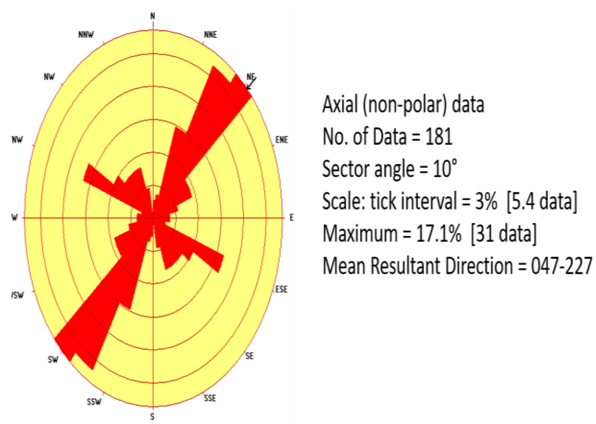

Figure 12: *Rosette Diagram of the Lineament in the Research Area*

Horizontal and Vertical gradients were used to obtain the analytic signal map of the investigative area. The result aimed at deriving the valued depth of magnetic source of the research area and variations in the basement structures. As seen in Fig 13, the Analytic Signal map has revealed and mapped near-surface magnetic minerals. The result has shown anomalies with magnitude between 5.23623e^{-005}nT/Km to 6.9861nT/Km, the regions with dark colours corresponds to low analytic signal and basement is closed to the surface, signifying very high outcrop. This is seen dominant at the western, northwest and southwest regions of the investigative areas. Yellow colour represents zones with deep seated basement. It is seen at the northern, northeast and scanty at southwestern regions of the research areas. The average depth is calculated to be 3.4930nT/km and a thickness of 6.986nT/km.

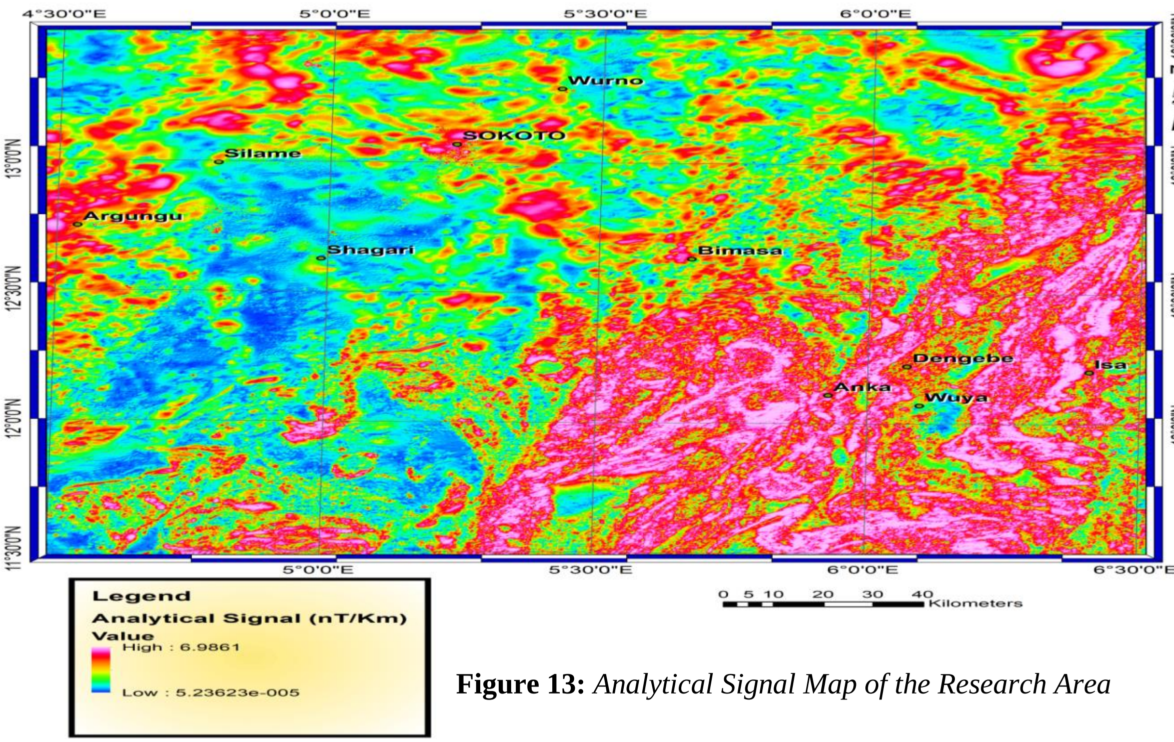

Figure 13: *Analytical Signal Map of the Research Area*

SOURCE PARAMETER IMAGE (SPI): the SPI signal map (fig.14) has revealed the range of values -6908.31m to 754.498m, average of 3.1km and thickness of 6.2km. it is a method used to study depth to magnetic source (sedimentary thickness) of an area. The sedimentary thickness of the basin has been revealed to be 6.2km.

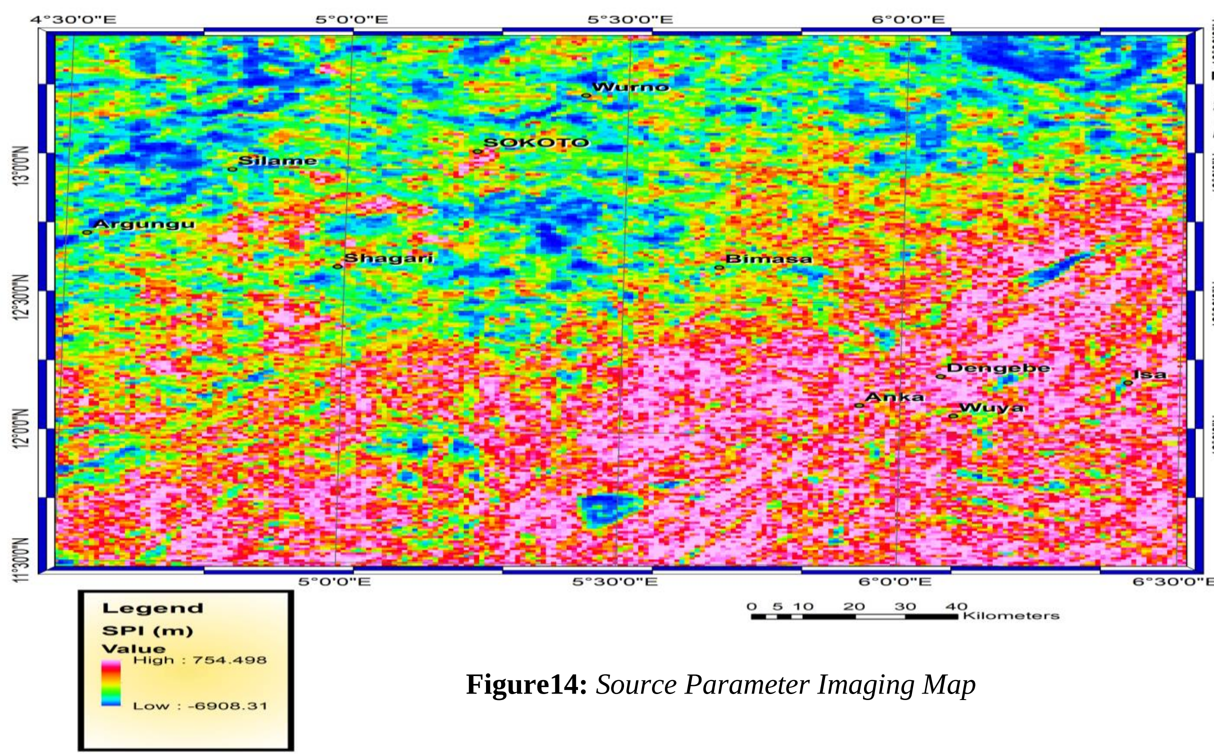

Figure14: *Source Parameter Imaging Map*

To improve the structural tectonic trend of the lineament and structural features in magnetic grids, tilt derivative was applied. With all geometrical and geographical orientations, it performed well on trends and anomalies. The map displayed the standard color scheme, with high values represented by light/white colors and low values by dark/black colors. The south and southeast regions of the research area were illuminated, according to the tilt derivative. Tilt derivative has revealed many recognized linear patterns. Linears from deep sources were shown on the lineament map (Fig. 10), which also displayed regional trends up to a 3 km length. The emergence of the NE-SW structural trend in the Northwestern portion of Nigeria is positively correlated with the structural trend and geometrical orientation of the linear that were recovered from the structural interpretation of the HRAM data of the basin (Fig. 11 and Fig. 9). Analytic signal derivative map revealed the differences in the distribution of magnetic materials in the project area; the sedimentary thickness has been calculated to be 6.9861km and an average of 3.4930nT/km. The Source Parameter Imaging (SPI) of the study area has seen to be an easy and powerful technique for calculating the depth to magnetic source. It showed sedimentary thickness of 6.153km and an average of 3.1km.

Conclusion

In conclusion, the results have revealed structural information on the basin geometry that constituted a reliable contribution to the hydrocarbon exploration process. It has revealed that the research area's southern and southeastern regions have sedimentary thickness enough to harbor hydrocarbon but there were evidence of cross conjugate faults in the area. The northern and northeastern regions have solid mineral potential.

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