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Interpretation of Aeromagnetic Data Over Birnin-Kebbi And Its Adjoining Areas Using First Vertical Derivative And Local Wavenumber Methods.

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Abstract: *The total-field aeromagnetic data over Birnin – Kebbi and its adjoining areas, bounded between longitudes 4.00^{0}E to 5.00^{0}E and latitudes 11.50^{0}N to 12.50^{0}N were obtained and analyzed for subsurface lineament and depth analyses using first vertical derivative and local wavenumber methods. Orientational analysis of the lineaments inferred from the first vertical derivative map suggests that the major subsurface structural trends in the area were oriented along ENE-WSW, NE-SW and E-W directions while minor trends were along NW-SE, NNE-SSW, NNW-SSE and N-S directions. Result obtained from the depth analysis, as shown by the depth- to- basement map, suggested sedimentary thickness between 0.77 km to 2.31 km with the deepest areas, around Giru, associated with sedimentary thickness between 2.0 km to 2.31 km. The estimated sedimentary thickness and the temperature regime around the deepest areas were interpreted to be sufficient enough to warrant further hydrocarbon investigations.*

Keywords: *Sokoto basin, lineaments, first vertical derivative, local wavenumber, sedimentary thickness*

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I. Introduction

The study area, bounded between longitudes 4.00^{0}E to 5.00^{0}E and latitudes 11.50^{0}N to 12.50^{0}N, is located in the central parts of the Sokoto basin, northwestern Nigeria (Fig. 1). The basin is among the six sedimentary basins in Nigeria. The rest of the basins include the Bornu basin, the Bida basin, the Dahomey basin, the Benue Trough and the Niger- Delta basin. Among the six basins, the Niger-Delta is the only one where hydrocarbons in commertial quantity are presently being explored. However, the restiveness in the area which immensely affects the quantity of the hydrocarbons being drilled and the dwindling low price of the petroleum product trigged the government of Nigeria to diversify as well as search for more hydrocarbons from the other sedimentary basins in the Country.

Magnetic method is one of the geophysical prospecting techniques being used in analysis of the magnetic field emanating from the Earth's interior (Telford *et al.,* 1990). Magnetic maps usually reflect variations in the magnetization contrast of the subsurface geologic structures. These variations are related to changes in structures and magnetic susceptibilities (Adetona and Abu, 2013). One of the key functions of aeromagnetic survey is delineation of subsurface structures, which often act as structural traps for minerals/ hydrocarbons, and estimation of sedimentary thickness which suggests areas within sedimentary basins where detailed investigations of hydrocarbons may be concentrated (Telford *et al.*, 1990). Predominant studies carried out in the area were based in spectral analysis of the magnetic data over various portions of the basin and 2.5D modeling of selected profiles across the basin (Shehu *et al*., 2004; Adetona *et al*., 2007; Bonde *et al*., 2014; Nwanko and Shehu, 2015). The result from these studies suggested sedimentary thickness between 1.0 to 2.7 km in the basin. It is worth mentioning that depths obtained using spectral methods are generally average depth which may

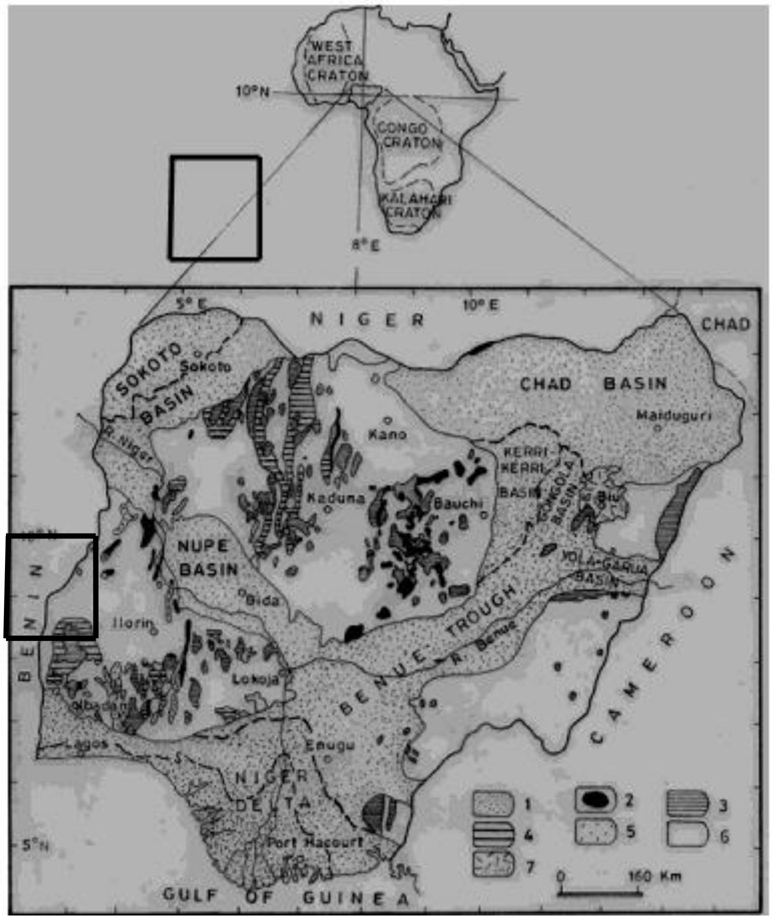

Figure 1. Geological map of Nigeria, 1 = Cretaceous-Recent sediments; 2=Younger Granites; 3 = Older Granites; 4 = Undifferentiated Metasediments; 5 = quartzite and quartzite schist; 6 = Undifferentiated basement complex and 7 = Tertiary volcanics (From Geological map of Nigeria 1994: compiled by the Geological Survey of Nigeria).

not reflect the actual depth to the individual magnetic sources while modeling along selected profiles may not reflect the actual basement depths over the an entire area. In this study, the first vertical derivative (FVD) and the local wavenumber (LWN) methods will be used to delineate and estimate the actual depths to the top of subtle geological sources beneath the study area with the main aim of identifying areas which may require further hydrocarbon investigations.

Geology of the Study Area

The sediments of Sokoto basin, according to previous works (Kogbe, 1981; Adeleye, 1975; Okosun, 1995 ; Obaje *et al.,* 2013) were accumulated during four main geologic phases. The first phase of deposition began in the Lower Cretaceous, with the deposition of Illo and Gundumi Formations unconformably on the Precambrian basement. The two Formations were made up of grits and clays that constitute the pre-Maastrichtian "continental intercalaire" of West Africa (Kogbe, 1979, 1981). The Formations were overlain unconformably by the Maastrichtian Rima group, consisting of mudstones and friable sandstones (Taloka and Wurno Formations), separated by the fossiliferous, shaley Dukamaje Formation (Kogbe, 1979, 1981). The Dange and Gamba Formation , mainly shales separated by the calcareous Kalambaina Formation constitute the Paleocene Sokoto group which overlies the Rima group. The overlying continental Gwandu Formation which is of tertiary age forms the post-Paleocene continental terminal.

The surface geology map (Fig. 2) shows that the sedimentary units, in the study area, were mostly confined in the northern and upper portion of the southern half of the area. However, Precambrian basement rocks consisting of gneisses, schists and granites were observed predominantly in the southern half. The schists were observed to be deformed and intruded by granites and gneiss in the southeastern part of the area.

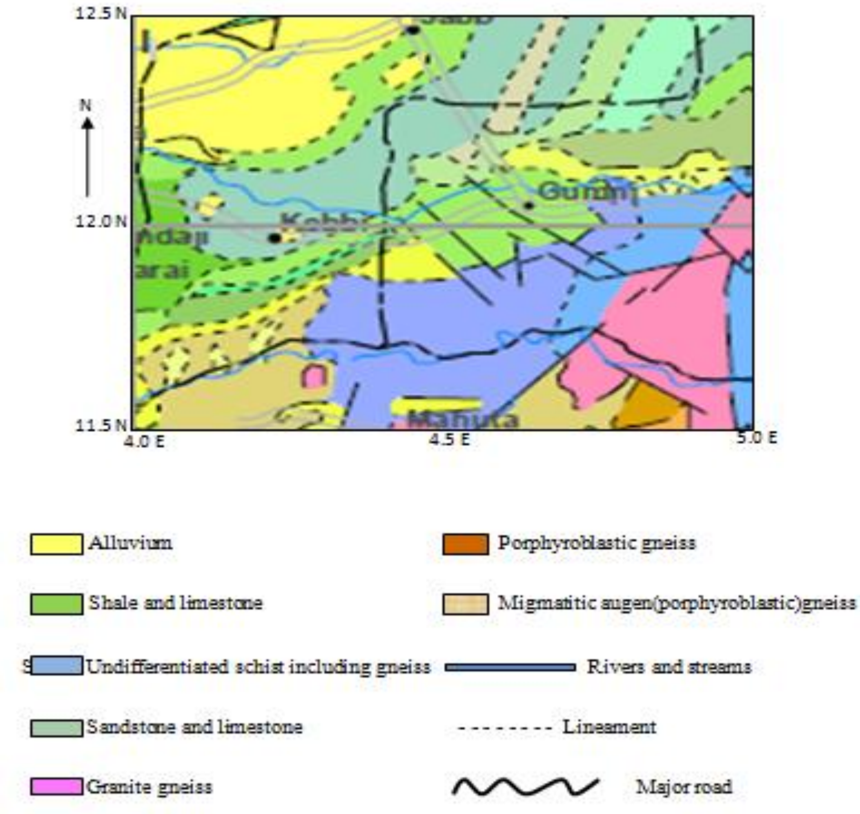

Figure 2. Geologic Map of the Study Area

Brief Theory of the Methods Used

(i). First Vertical Derivative

Magnetic field being a potential field obeys the Laplace's equation which states that the sum of the rates of change of the field gradient in three orthogonal directions is zero. This can be mathematically expressed as:

$$\nabla^2 B = 0 \tag{1}$$

Where B refers to the magnetic field. Equation (1) can further be expressed as

$$\nabla^2 B = \frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2} + \frac{\partial^2 B}{\partial z^2} = 0 \tag{2}$$

Equation (2) relates the measured field variations along the orthogonal map dimensions m and n to the field's variation in the vertical z direction which is perpendicular to the map. Taking the Fourier transform of equation (2), the FVD is expressed as (Hinze *et al*., 2013)

$$\frac{\partial B_{m,n,z}}{\partial Z} = \left[-2\pi\sqrt{f_m^2 + f_n^2}\,\right] B_{m,n,z} \tag{3}$$

Where f_m and f_n are wavenumbers along m and n directions respectively.

(ii). Local Wavenumber Method

For a profile (1-D) data, the complex analytic signal was defined as (Nabighian, 1972)

$$A(x,z) = \frac{\partial M(x,z)}{\partial x} - j\frac{\partial M(x,z)}{\partial z} \tag{4}$$

where M(x,z) is the magnetic field intensity, $j^2 = -1$ and x and z are the Cartesian coordinates.

The amplitude and phase of the analytic signal are expressed as (Thurston and Smith, 1997):

$$|A| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \tag{5}$$

and

$$\theta = tan^{-1}\left(\frac{\partial M}{\partial z} \middle/ \frac{\partial M}{\partial x}\right) \tag{6}$$

The local frequency f, defined as the rate of change of local phase along the x direction, is expressed as (Thurston and Smith, 1997)

$$f = \frac{1}{2\pi} \frac{\partial}{\partial x} tan^{-1} \left(\frac{\partial M}{\partial z} \Big/ \frac{\partial M}{\partial x} \right) \quad (7)$$

The LWN is related to the local frequency, f, through the equation

$$k = 2\pi f \quad (8)$$

Using differential operator on equation (7), the expression for the LWN for a 2D potential field data is expressed as (Phillips, 2000)

$$k\,(x, y) = \frac{1}{|A(x,y)|^2} \left(\frac{\partial^2 M}{\partial x \partial z} \frac{\partial M}{\partial x} + \frac{\partial^2 M}{\partial y \partial z} \frac{\partial M}{\partial y} + \frac{\partial^2 M}{\partial Z^2} \frac{\partial M}{\partial z} \right) \quad (10)$$

Where $|A(x, y)|^2$, for a 2D case, is given by (Roest *et al*., 1992)

$$|A(x, y)|^2 = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \quad (11)$$

Smith *et al*. (1998) showed that the LWN is related to the depth (h_0) via the relation

$$k = \frac{(s+1).h_0}{h_0^2 + x^2} \quad (12)$$

Equation (12) shows that the peak of the LWN is independent of magnetization direction. Hence, the method can be applied in low latitude regions without necessarily applying the phase shift correction using the reduction to equator filter. For a contact body, the structural index (S) is zero, hence from equation (12),

$$h_0 = \frac{1}{k} \quad (13)$$

II. Materials And Methods

Four aeromagnetic maps covering the entire study area were obtained from Nigerian Geological Survey Agency (NGSA) as part of the nationwide survey between 1974 to 1976. The aeromagnetic survey was flown at an altitude of 0.15 km above the terrain along N-S flight lines spaced 2 km apart with 20 km tie-line spacing. To obtain the total-field magnetic intensity (TMI) values, the maps were gridded at an equal spacing of 1.5 km and total magnetic field intensity (TMI) values at the grid points were read and recorded, thus, generating 73x73 matrix of TMI values. To analyze the magnetic effects associated with the crustal rocks (i.e. residual field), the Earth's main field, represented by a first degree plain surface, was estimated using multi-regression analysis, and removed from the TMI values.

To delineate the subsurface magnetic lineaments, the first vertical derivative (FVD) values were estimated, in the frequency domain, using the first Fourier transform (FFT) method. To achieve that, the residual magnetic field intensity values were transformed from space to frequency domain and multiplied with a FVD filter, as suggested by equation (3). The product was inverse Fourier transformed back into the space domain to obtain the FVD values. Following Anudu *et al.* (2014), the colour shaded image of the FVD anomalies, obtained using the Oasis Montaj software, was on-screen digitized to delineate the magnetic lineaments. The orientation of the inferred lineaments were measured, with respect to the geographic north, and grouped into a class interval of 15°. Subsequently, a rose diagram of the magnetic lineaments, obtained using the Grapher (version 10) software was employed to display the trends of the inferred lineaments for quantitative trend analysis.

The procedure for the estimation of the depth to the top of magnetized bodies, using the LWN method, was implemented using the SPI module of the Oasis Montaj (version 7.01) software. The process began with the estimation of the values of the horizontal and vertical derivatives of the residual magnetic field intensity values which were further employed to estimate the values of the LWN grid using equation (10). Next, the locations of the source edges were determined from the LWN grid using the algorithm of Blakely and Simpson (1986) as outlined by Bournas *et al*. (2003). Finally, the estimated depth values were obtained at the contact locations using equation (13).

III. Results And Discussion

The total magnetic intensity (TMI) map of the study area (Fig. 3) shows TMI values ranging from 32796 nT to 32895 nT, with an average value of 32851 nT. High TMI values were observed to be predominant in the western half of the study area while low and intermediate TMI values were predominant in the eastern half of the study area. Most of the anomalies in the TMI map have predominant tectonic trends in the E-W, NE-SW and NW-SE directions.

The residual magnetic map of the study area (Fig. 4) was found to be associated with magnetic values ranging from -55.6 nT to 33.3 nT. The negative residual magnetic values were observed to be more predominant in the dominant portions of the southern and north central half of the study area while positive magnetic values were occupying the predominant portions of the

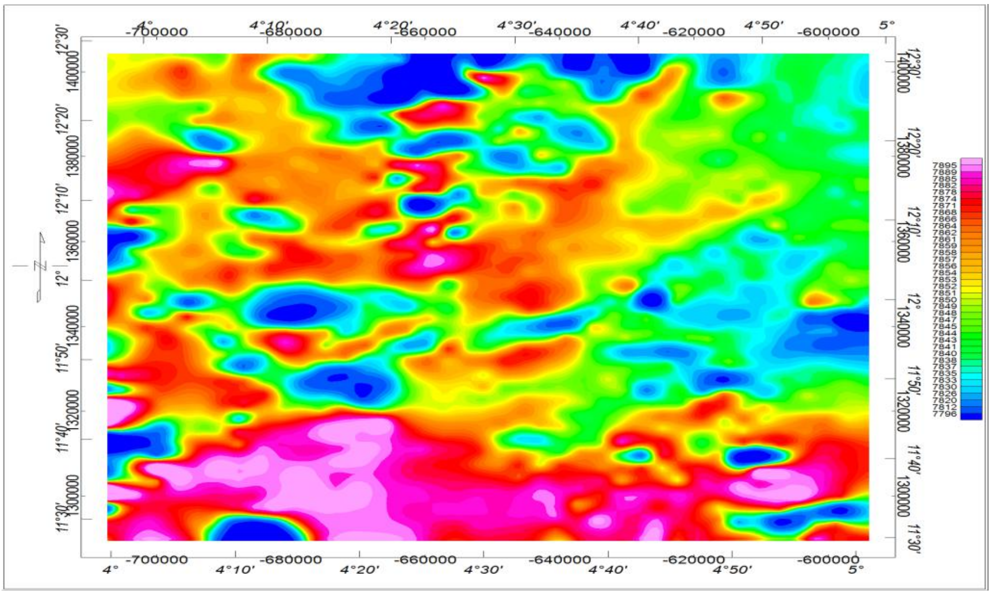

Figure 3. Total Magnetic Intensity (TMI) Map of the study area. To obtain the actual TMI values, 25000 nT should be added.

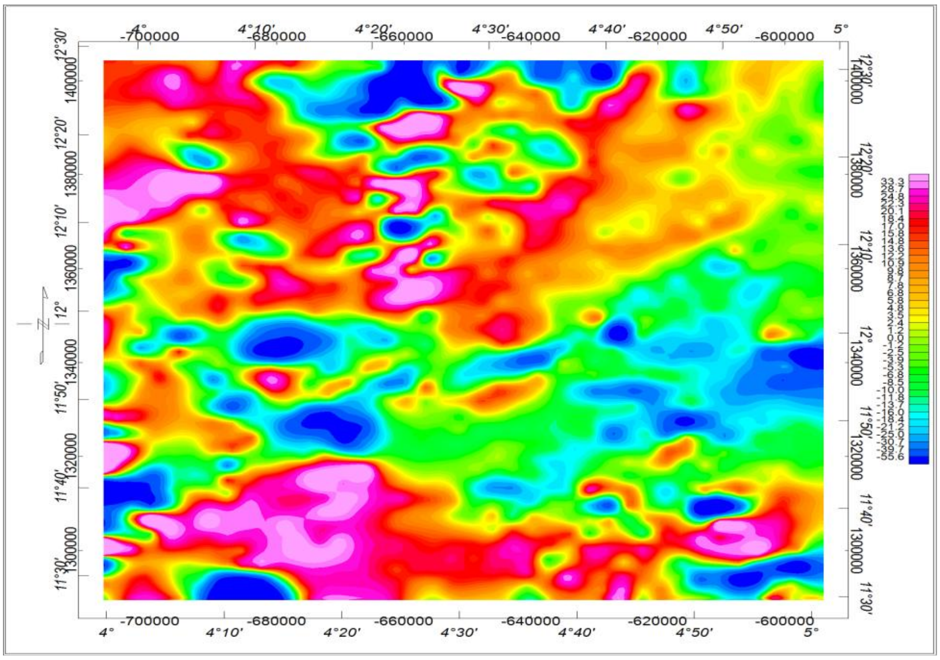

Figure 4. Residual magnetic map of the study area

Northern half and the extreme lower portion of the southern half of the study area. Generally, areas of negative magnetic anomalies, in the low latitude regions, correspond to higher magnetization contrast and vice-versa (Reynolds, 2011; Oyeneyi *et al*., 2016). Thus, in correlation with the surface geology (Fig. 2), the northern half, which is predominantly covered by sediments, correlates with the high residual magnetic values predominant over that portion. The low residual magnetic values, which dominate over the upper portion of the southern half, the extreme eastern part and some portions of the extreme northern half of the study area correlate with regions associated with the exposed basement rocks. However, the high residual magnetic intensity values over the lower portion of the southern half suggests that basement rocks in that portion might have lost their magnetization either due to intense weathering and/or contact metamorphism.

Figure 5 shows that the inferred structural lineaments, oriented along different directions, have affected the subsurface of the study area. Comparison with the surface geology suggests the prevalence of the lineaments both in the basement exposed portions and the sedimentary part of the study area. This suggests structural control for the emplacement of the basement rocks and the sedimentation pattern in the study area. Result obtained from the orientational analysis of the inferred lineaments (Fig. 6) shows that the direction of the inferred subsurface faults are trending along ENE-WSW, E-W, NE-SW, WNW-ESE, NW-SE, NNW-SSE, NNE-SSW and N-S directions. Among these trends, the ENE-WSW, E-W and NE-SW were inferred as the major trends while the WNW-ESE, NW-SE, NNE-SSW, and N-S trends were inferred as minor trends. Further orientational analysis of the lineaments in the NE, SE, SW and NW sections of the study area (Fig. 7) suggested that the ENE-WSW trend is the dominant trend in the western half and the E-W trend is the dominant trend in the eastern half while the WNW-ESE and the NW-SE are

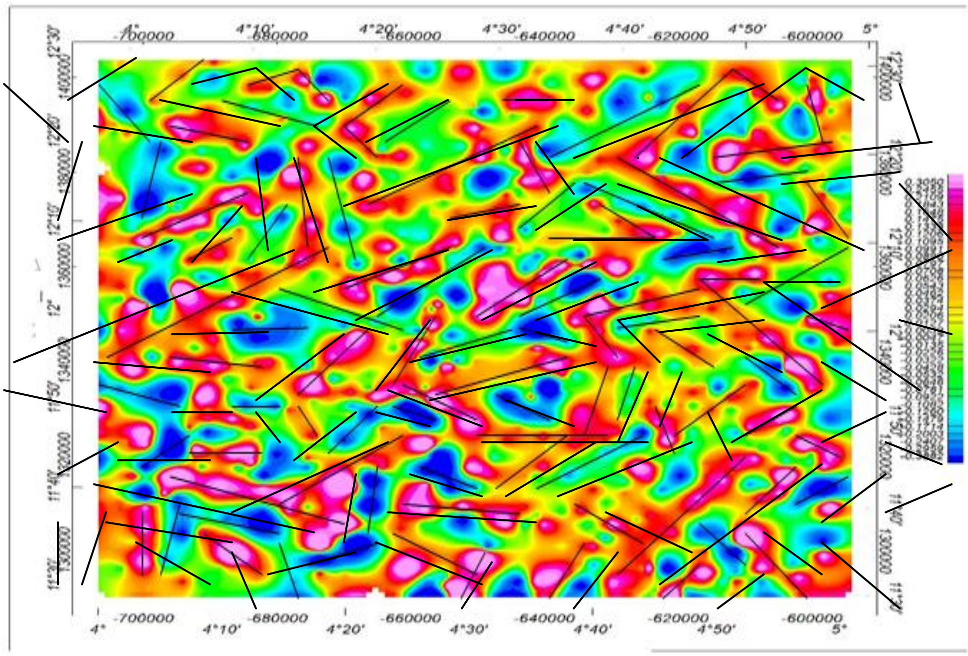

Figure 5; FVD map with the inferred lineaments superposed.

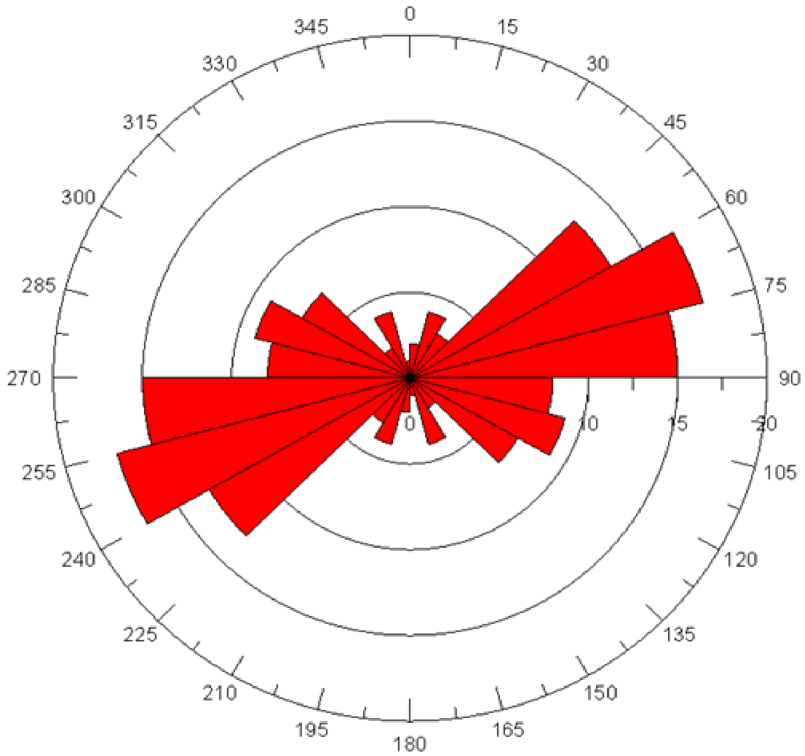

Figure 6. Rose Diagram for the trends of the lineaments in the study area.

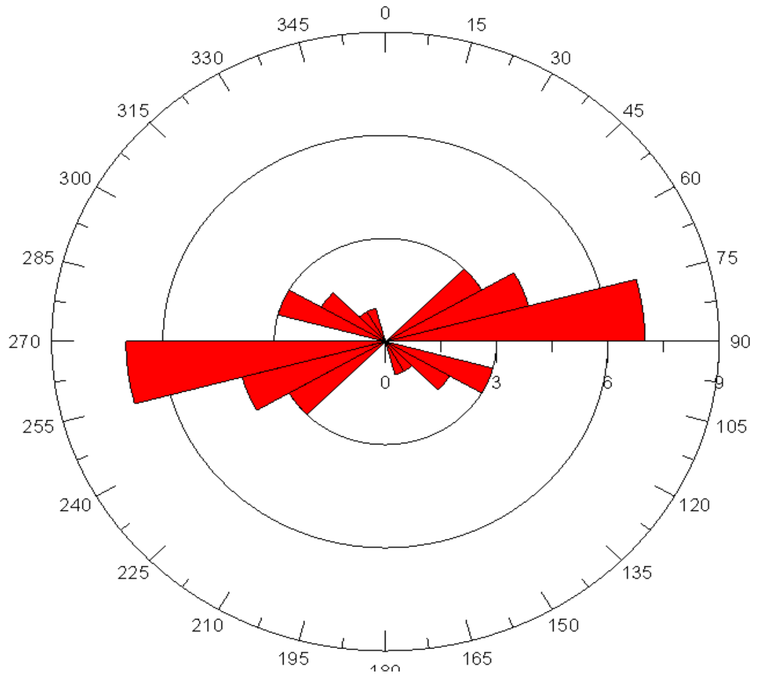

Figure 7a. Rose diagram for the trends of the lineaments in the NE part of the study area.

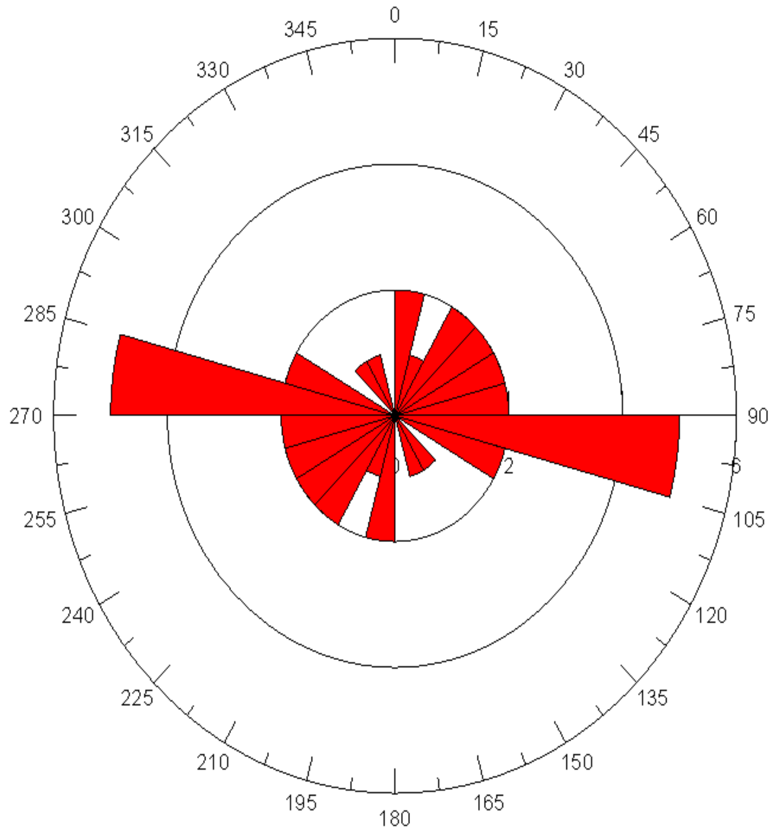

Figure 7b. Rose diagram for the trends of the lineaments in the SE part of the study area.

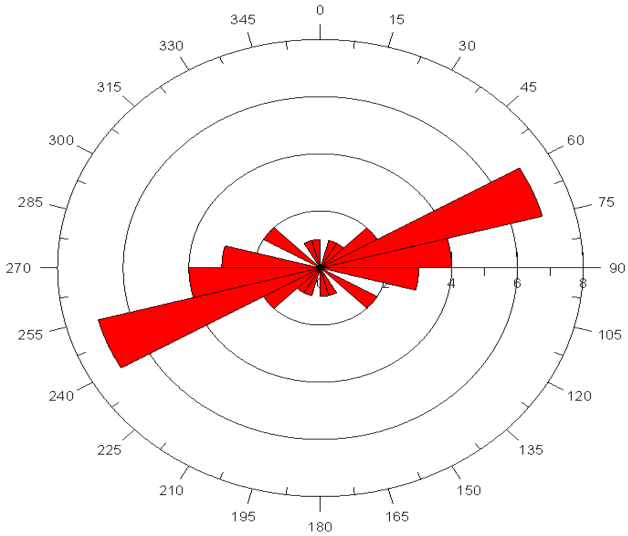

Figure 7c. Rose diagram for the trends of the lineaments in the SW part of the study area.

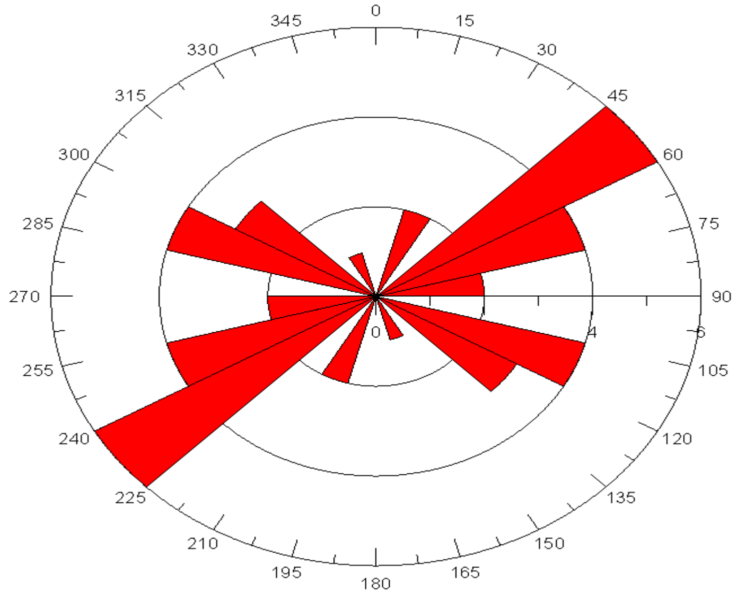

Figure 7d. Rose diagram for the trends of the lineaments in the NW part of the study area.

The most widespread trends in the study area. These inferred trends were interpreted to correspond to the positions and directions of the paleo-tectonic fracture zones, reflecting the effects of the intense stress associated with the pre- Pan- African and Pan-African tectonic episodes in the study area. Alternatively, some of the inferred minor trends were interpreted to have been developed in response to the intense stress associated with epeirogenesis of the major trends. The conjugate pair of NE-SW and NW-SE lineaments were earlier inferred within the entire Sokoto basin while the NNE-SSW, NNW-SSE and N-S lineaments were earlier inferred as trends of major lineament belts cutting across the basin (Ananaba and Ajakaiye, 1987; Ajakaiye *et al*., 1991; Umego *et al*., 1992). The remaining E-W and ENE-WSW trends, inferred in this study, were interpreted as hitherto unmapped lineaments in Sokoto basin. It is worth mentioning that the inferred trends in this study were found to correlate with trends inferred in the Benue trough, Bornu basin, northern Nigerian basement complex and the Nigerian Younger granites province (Ajakaiye *et al*., 1986; Avbovbo *et al*., 1986; Olasehinde *et al*., 1990; Akanbi and Mangset, 2011; Anudu *et al*., 2014; Sanusi and Likkason, 2015; Dahuwa *et al*., 2016; Sanusi and Dahuwa, 2017) suggesting possible genetical relationship.

Figure 8 shows that the depth to the top of the basement structures in the area vary from 0.77 km to 2.31 km with the deepest parts ranging from 2.00 km to 2.31 km. The Figure further shows that the sedimentary thickness in the eastern part of the study area is predominantly shallow with maximum thickness not exceeding 1.2 km which correlates with results from past geologic studies (Kogbe, 1981; Wright *et al*., 1985; Kurowska and Schoeneich, 2010). However, the present study has suggested other deeper areas in the northwestern parts surrounding Giru, the central parts and north of of Birnin-Kebbi area, which are associated with maximum thickness between 2.0 km to 2.31 km.

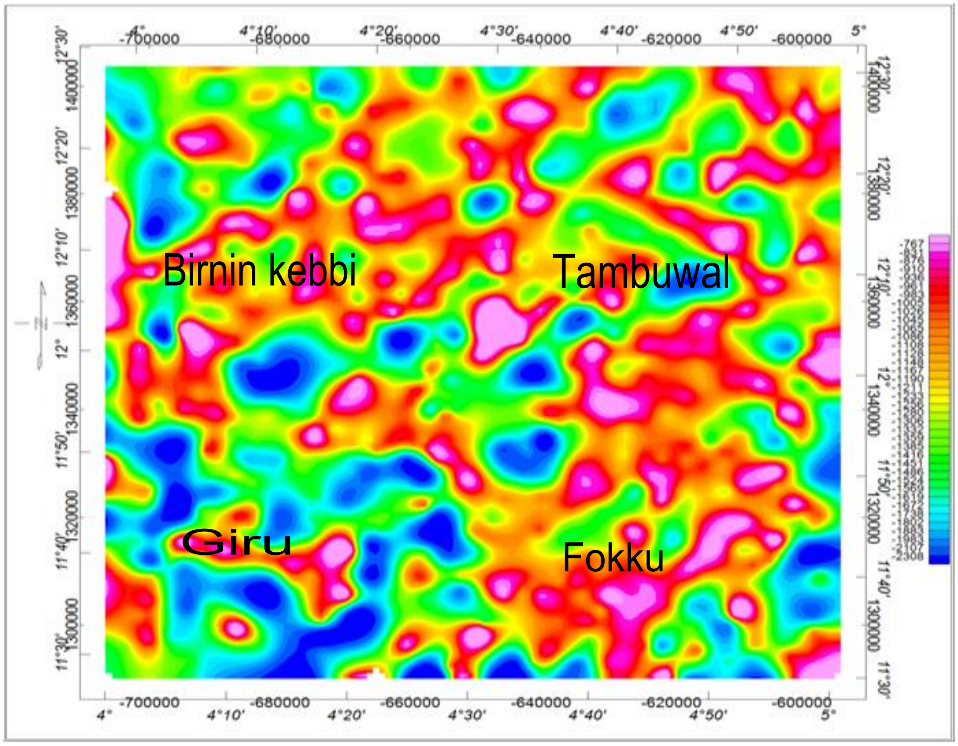

Figure 8; Depth to basement map of the study area obtained using the local wavenumber method

The implication of depth to basement estimation in sedimentary basins is often linked with hydrocarbon generation and accumulation, which is guided by source rock type and contents of its organic matter, thickness of sediments, duration of sedimentation and local temperature gradient (Wright *et al.,* 1985). The minimum subsurface temperature range in which hydrocarbons are formed and expelled from source rocks (i.e. oil window) ranges between 60°C - 120°C which occur at 2 – 4 km depth range (Wright *et al.,* 1985; Mohamed *et al.*, 2014). Based on the estimated average geothermal gradient of 32.0° C/km in the study area (Nwanko and Shehu, 2015), the subsurface temperature within the deepest parts of the study area were inferred to vary between 64°C – 76.8°C, which is sufficient to cause thermal degradation of organic matter. Thus, the thickness of sediments and the temperature regime around the aforementioned areas were interpreted to be sufficient enough to warrant further hydrocarbon investigations. It is worth mentioning that the depth estimates obtained in this study correlate with results obtained from previous studies in the basin (Umego *et al*., 1992; Adetona *et al*., 2007; Shehu *et al*., 2004; Bonde *et al*., 2014; Nwanko and Shehu, 2015; Ofoha *et al*., 2016).

IV. Conclusion

Aeromagnetic data over Birnin- kebbi and adjoining areas, northwestern Nigeria, were analyzed using the FVD and LWN techniques for lineament and depth analysis. Based on the results obtained from the analysis, the following major conclusions are drawn.

(i). The subsurface structures in the area were oriented along ENE-WSW, NE-SW and E-W major and NW-SE, NNE-SSW, NNW-SSE and N-S directions minor trends along.

(ii) The sedimentary thickness and temperature regime around the deeper parts of the study area are sufficient enough to warrants further hydrocarbon investigations in the area.

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