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Analytic Signal and Spectral Centroid Methods for Interpretation of Magnetic Anomalies: Applicability to the entire Sokoto Basin, Nigeria

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ABSTRACT

Sokoto Basin in northwestern Nigeria is bounded by latitudes 10.00°N and14.00°N and longitudes 3.50 °N and 7.00 °E and has a total surface area of about 111,925 km2. This study is in line with the Federal Government of Nigeria's effort on hydrocarbon exploration in inland basins beyond Niger Delta region of Nigeria for a sustainable economic development in Nigeria. The digital residual data acquired from NGSA covered the entire Sokoto Basin was divided into twenty two (22) overlapping blocks and each block analyzed using spectral (Fourier) centroid method to obtain Regional estimation of depths to top of anomalous magnetic bodies. These depths indicate clearly the magnitude of variations in depth of both the basement topography and other intrusive in the area, these depths information were subsequently used to generate the contour and the 3D map of the area. An analytic signal method was then used to generate a map on which the amplitude of displayed function is directly and simply related to a physical property of the subsurface rocks. The depths to top of magnetic sources in the study area regarded as sedimentary thickness was found to range between 0.59 and 2.11 km with an average of 1.22 km. The 2D analytic signal map of the study area revealed occurrence of faults and magnetic minerals, mostly trending in the north-west direction and being dominant in the area in terms of distribution due to broader central African rift system. Those anomalies whose amplitude varies between 0.043 and 0.130 m and (pink and red) are observed to be well distributed in the study area. Another major observed anomalies ranging between 0.0018 and 0.0042 m (blue colour) are observed in the southeastern parts of the area. Observed at the north central, and northwestern part of the area are amplitude ranging between 0.0113 and 0.0173 m (yellow colour) correspond to areas with thick sedimentary cover while Blue and pink areas correspond to areas with thin sedimentary cover. However, the minimum thickness of sediment required for hydrocarbon generation is 2.3 km if other conditions are favorable. Therefore, hydrocarbon exploration may not be feasible in the basin, the area is therefore recommended for detail mineral and geothermal investigation.

Keywords: Residual anomaly, Spectral centroid, Analytic signal, Sedimentary thickness, and Basement topography

INTRODUCTION

Airborne geophysical surveys are an extremely important aspect of modern geophysics and compared with ground geophysical surveys it allow faster, cheaper coverage, of large areas with no restriction. Over the last decade there has been increase in the use of airborne magnetic and more recently, gravity in the petroleum exploration industry. The early use of potential field (gravity and Magnetic) methods in petroleum was to map sedimentary basin thickness while high resolution surveys are used to investigate basement trends and intra-formational structures. In modern geophysical surveys, aeromagnetic anomaly data reflect the lateral variation in the earth's magnetic field. These variations are related to changes of structure, susceptibility of magnetic materials in the crust, temperature increases with depth, and related minerals present in the rock.

In many countries of the world including Nigeria, government agencies and private investors have employed aeromagnetic method to survey most of their countries in search for hydrocarbon for mapping strongly magnetic basements on regional scale and for delineating weakly magnetic sedimentary contacts at local scale. With the use of aeromagnetic data, it has been possible to locate intra sedimentary faults and lithological contacts. Airborne geophysical surveying is the process of measuring the variation of different magnetic sources buried at the earth's subsurface. The Niger-Delta basin in south southern Nigeria have been explored and exploited for hydrocarbon for several decades with considerable success (Nwachukwu,1985; Obaje et al., 2004) and for political reasons, the government has encouraged extensive hydrocarbon exploration in inland basins, especially in the northern part of the country. In this work, the spectrocentroid technique was used for determining the sedimentary thicknesses in the study area. While the analytic signal was used to Identify location and shape of the source of the magnetic anomalies, Therefore, the work presented in this paper using spectrocentroid and analytical signal to estimate depth and shape of the sources, is an assessment of the regional aeromagnetic anomalies of Sokoto basin Nigeria for preliminary hydrocarbon studies to diversify the nation source of revenue.

Location and Geology of the Study Area

The Sokoto Basin located in the north western part of Nigeria is bounded by latitudes 10.00 °N and 14.00 °N and longitudes 3.50 °E and 7.00 °E (Figure 1). It has a total surface area of about 111, 925 km^2, which cuts across six provincial states in Nigeria, namely Kaduna, Katsina, Kebbi, Niger, Sokoto and Zamfara., is one of the inland basins in Nigeria. It is a sedimentary basin and consists of gentle undulating plain, underlain by basement rocks consisting of igneous and metamorphic rocks.

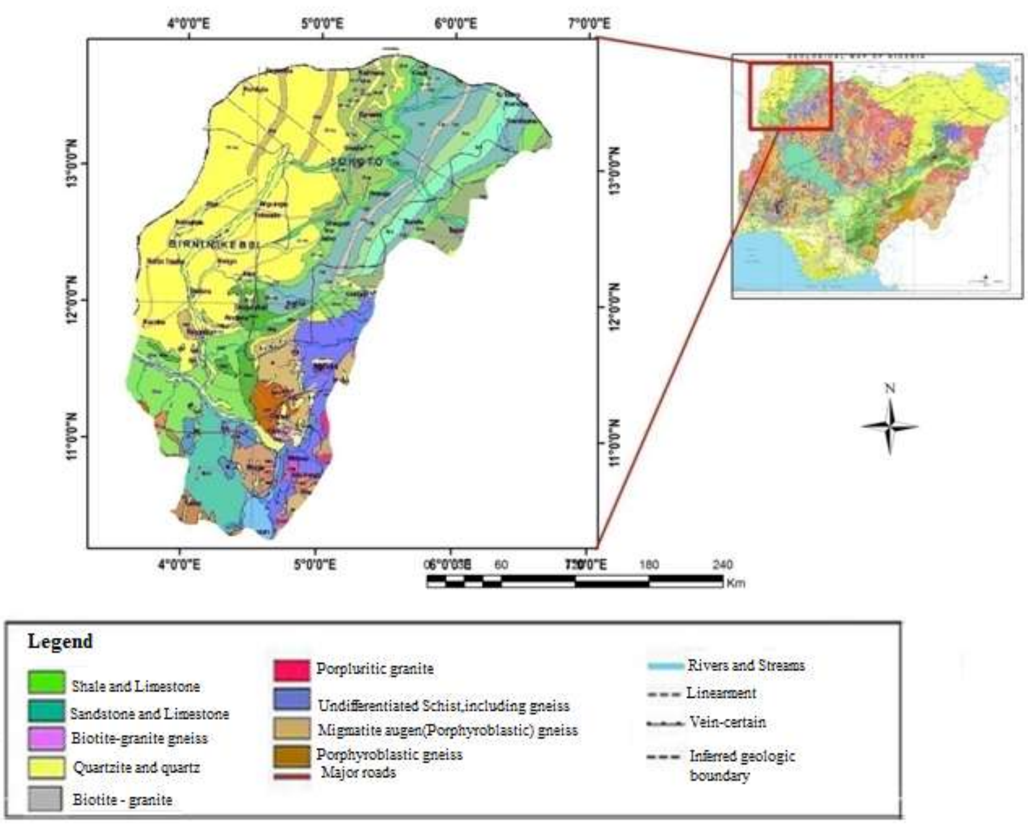


Figure 1: Geologic map of Sokoto Basin (Adapted from Nigerian Geological Survey Agency, 2006).

The basin is underlain to the east and south by Precambrian basement rock consisting of igneous and metamorphic rocks. The basement is directly overlain by Cambrian beds to the north in the Tassaili and the Hoggar mountains. As one traverses the basin from the north towards the southwest the formations become younger in age and rest directly on the Precambrian basement. This situation is referred to as an overlap where progressively younger beds rest upon the older series (Kogbe, 1979). The sediments of the Sokoto basin were deposited under varied environmental situations ranging from continental to marine events. Sokoto basin in the northwestern sectors of the Iullemeden basin has sedimentary rocks laid down under varied environmental situation ranging from continental to marine event. Sokoto basin is a region with great potential for future large-scale economic development, due to warm and bountiful mineral resources such as renewable and non renewable energy sources, farmland, water through irrigation project and borehole. The most important economics mineral in the Sokoto basin are the industrial minerals consisting of clays, limestone, gypsum, phosphate, ironstone, laterites, gravel, lignite and phosphate.

Data Acquisition and Methods

Thirty eight (38) digital half degree high resolution aeromagnetic (HRAM) maps each having an area of 55 km x 55 km (sheet number 1 - 5, 8 – 13, 26 – 31, 48 – 53, 71 -74, 94 – 97, 116 – 119 and 138 - 139) on a scale of 1:100,000 with a total 7,426,917 data points were used in this work. The whole data, which were procured from the Nigerian Geological Survey Agency (NGSA) and assembled into composite total magnetic field intensity (TMI) map (Figure. 2), range between 32487.96 and 33423.06 nT with an average of 33060.70 nT and a standard deviation of 38.314. This nationwide regional scale data (HRAM) has been processed and corrected and a constant TMI value of 33000 nT was removed for easier computation by the NGSA before the eventual publication as HRAM colour Maps.

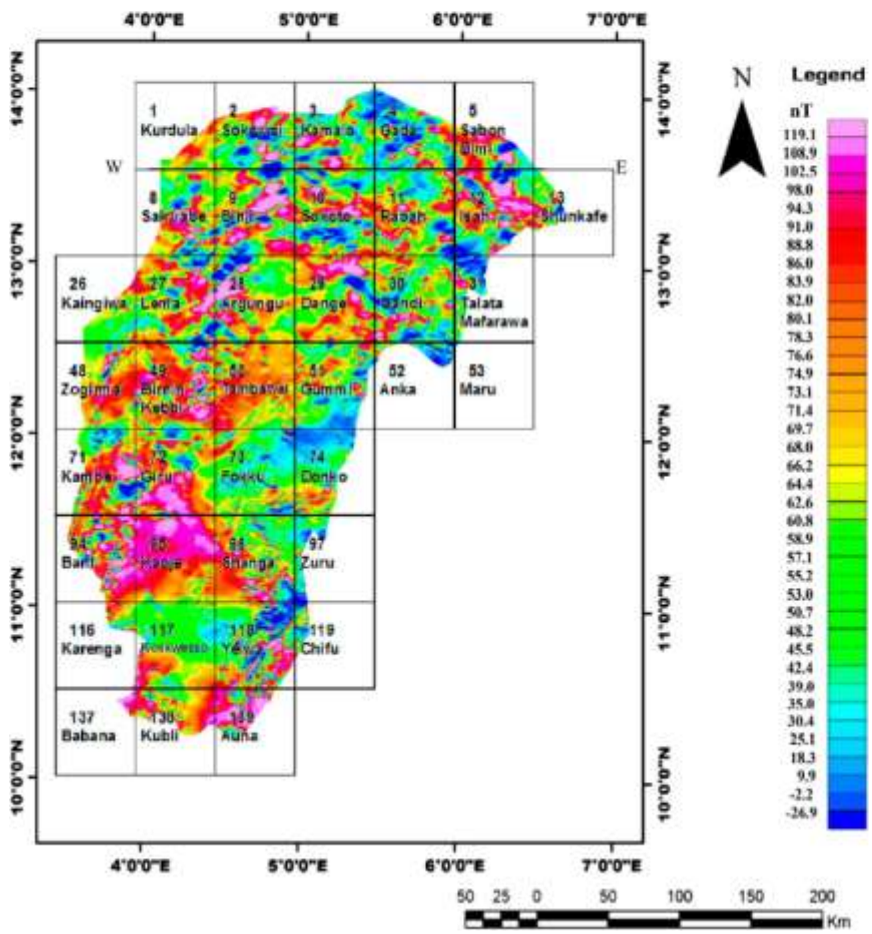


Figure 2: Total Magnetic Intensity Map (TMI) of Sokoto Basin with superimposed Federal survey half degree sheets and showing major towns flown over. A constant 33,000 nT had been removed.

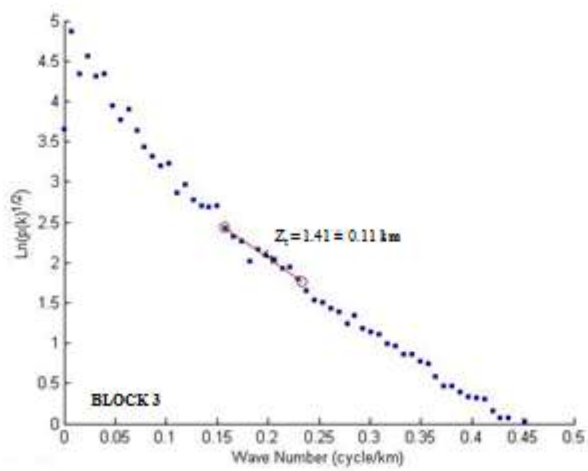
International Geographical Reference Field (IGRF) removal is a mathematical representation of the earth's main magnetic field due to sources in the core. Once it is removed from the data, the remaining data becomes residual magnetic anomaly due solely to subsurface rocks. The composite map Figure 2, i.e the residual digital data was then divided into twenty two (22) overlapping blocks, for the purpose of 2D spectralcentroid analysis while ensuring that essential parts of the anomaly were not cut out by the blocks.

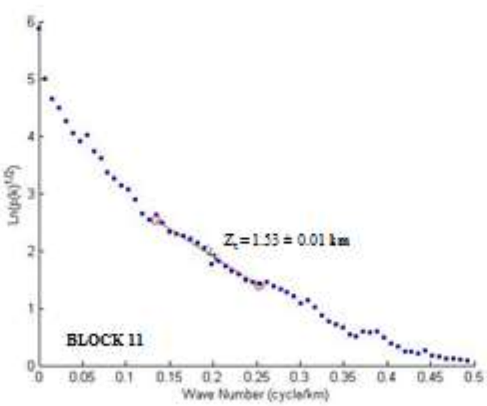
Theory of the spectral centroid analytical signal

Spectral models of magnetic interpretation are based on the examination of the shape of isolated magnetic anomalies (Bhattacharyya and Leu, 1975; 1977), statistical properties of magnetic ensembles (Spector and Grant, 1970) and power spectral density of total magnetic field (Blakely, 1995). The depth to the top of the magnetic source was consequently estimated from the slope of high wavenumber portion of the power spectrum as (Tanaka *et al*, 1999):

$$\ln\left(P(k)^{1/2}\right) = B - |k|Z_t \qquad (1)$$

where B is a constant, and Z_t is the depth to the top of magnetic sources.





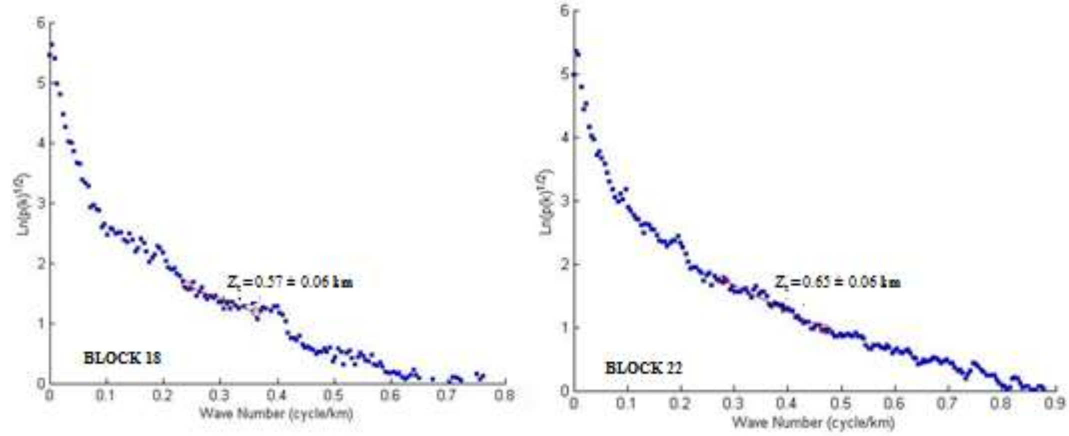


Figure 3: power spectrum plots for blocks (3, 11, 18 and 22).

Theory of the analytical signal

The amplitude A of the analytic signal of the digital residual magnetic field were calculated from the three orthogonal derivatives of the field using Oasis montaj software The analytic signal is the square root of the sum of the squares of the derivatives in the *x*, *y*, and *z* directions grids of the magnetic field (Roest *et al*, 1992):

$$A(x,y) = \sqrt{\left(\frac{dT}{dx}\right)2 + \left(\frac{dT}{dy}\right)2 + \left(\frac{dT}{dz}\right)2} \qquad (2)$$

A(x, y) is the amplitude of the analytic signal and T is the observed residual magnetic field at (x, y),

RESULTS AND DISCUSSION

Table 1 show the results of estimated depth to the top of the magnetic sources for the 22 blocks ranges from 0.57±0.06 to 2.11±0.02 km with an average of 1.22 ± 0.04 km. these depth values which represent the sedimentary thickness indicated that the thickness of the sedimentary formation decreases progressively as one transverses from the north towards the south. This variation in sedimentary depths in the basin is found to be consistent with those of other workers (Umego, 1990; Shehu *et al.*, 2004; Adetona *et al.*, 2007; Nwankwo and Shehu (2015). In particular, Kurowska and Schoeneich (2010) explained that the thickness of the sedimentary layer in the basin is about 1 km but exceeds 2 km towards the boundary with Niger Republic. These values were used to generate depth to the top of magnetic source maps. Figure 4 and 6, shows that hydrocarbon generation is not feasible because the minimum sedimentary thickness required for hydrocarbon generation is 2.3 km if other conditions are favorable, figure 4. With dominant trending NW – SE, and NE-SW related pan African rift system. In the northcentral part of the map high sedimentary thickness in this part is attributed to deep magnetic sources with long wavelength and low amplitude while in southern part the low sedimentary thickness in this part is attributed to shallow magnetic sources with short wavelength and high amplitude due to occurrence of ironstone, and other magnetic mineral near to the surface

Table 1: Estimated Depths to the top of Sources.

Blocks	Long. (°E) *	Lat. (°N) *	Depth to the Top (Z_t) (Km)
1	4.50	13.50	2.11±0.02
2	5.00	13.50	1.61±0.01
3	5.50	13.50	1.41±0.11
4	6.00	13.50	1.53±0.01
5	4.50	13.00	2.01±0.02
6	5.00	13.00	1.54±0.01
7	5.50	13.00	1.43±0.03
8	6.00	13.00	1.44±0.12
9	4.00	12.50	1.14±0.03
10	4.50	12.50	1.87±0.01
11	5.00	12.50	1.53±0.01
12	5.50	12.50	1.15±0.06
13	4.00	12.00	1.20±0.01
14	4.25	11.75	0.80±0.07

15	4.75	11.75	0.59±0.04
16	4.00	11.50	0.99±0.05
17	4.25	11.75	1.00±0.04
18	4.75	11.75	0.57±0.06
19	4.25	11.25	0.61±0.13
20	4.50	11.25	0.59±0.08
21	4.00	10.50	0.98±0.13
22	4.50	10.75	0.65±0.06
		Average	**1.22±0.04**

* Centre of the blocks

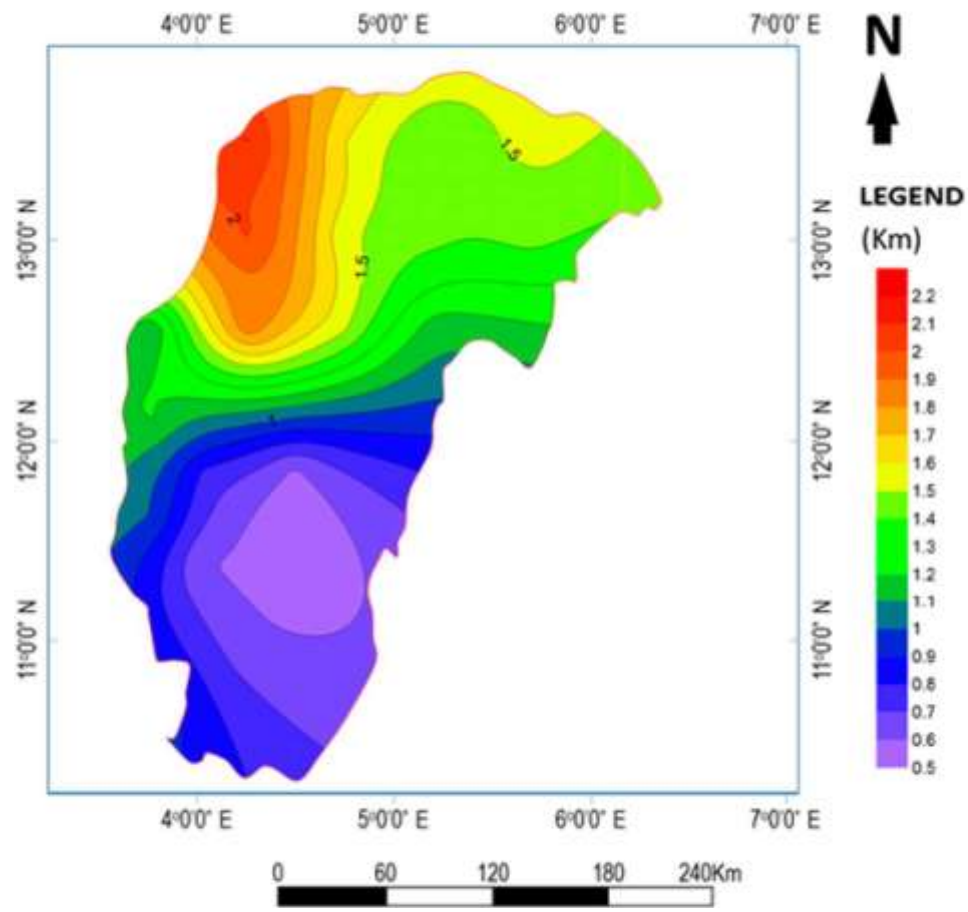


Figure 4: Depth to the top of the magnetic source map of the study area (Nwankwo and Shehu, 2015).

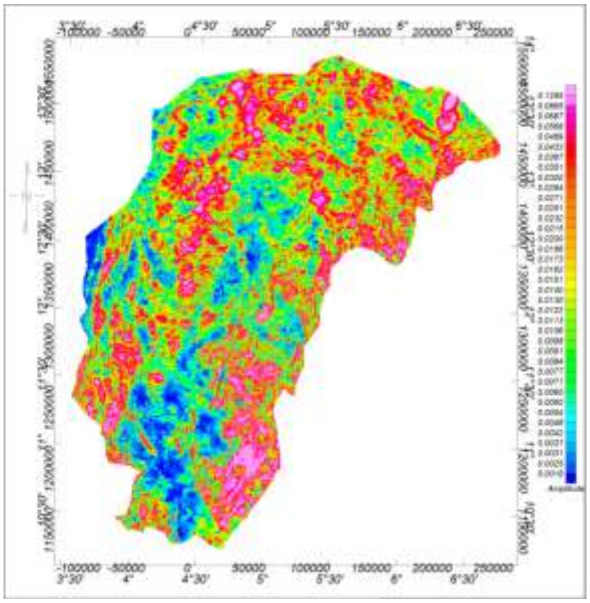


Figure 5: Analytic Signal of Sokoto Basin, Nigeria (Units in amplitude/m)

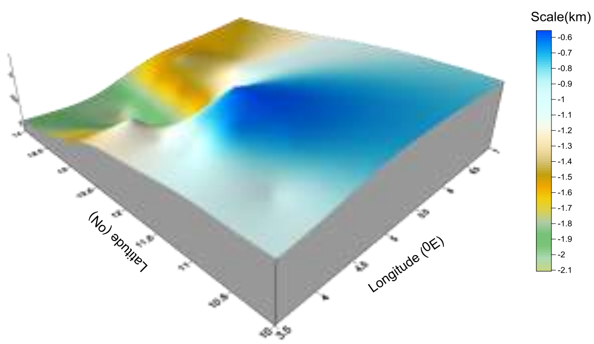


Figure 6: 3-D Model Map of the depth to the top of the magnetic source (Z_t) in km.

Figure 5 is the 2D analytic signal map of the aeromagnetic data depicting major magnetic sources of the study area shows near-surface anomalies whose general trend is predominantly in the NE-SW and NW-SE related to the Pan – African trend. Those anomalies whose amplitude varies between 0.043 and 0.130 m (pink and red) in the northern part of the study area has the occurrence of sandstones, shales, granite, limestones, intrusives depicting large scale tectonic events Observed at the southern part of the area have observed to be well distributed in the northern part of the study deep seated and or magnetic minerals of large areal extent are observed in block 3 and 10, it could also be a consequence of intensive weathering and erosion of the iron formation from plateaus, this may have yielded a local concentration of limonite or magnetite in the area. Another major observed anomalies ranging between 0.0018 and 0.0042 m (blue colour) are observed in the southeastern parts of the area correspond to area with thin sedimentary cover, due to the occurrence of of sandstones, ironstones, shales, graphites, limestones, intrusives and other near-surface magnetic minerals Attributed to magmatic intrusions in the formations it could be due to faults cut by relatively shallow NE – SW faults with major magnetic sources within the sedimentary basin above the basement in the southern part of the study area. Observed at the north central part of the area have low amplitude ranging between 0.0113 and 0.0173 m (yellow colour) this correspond to areas with thick sedimentary due to occurrence of deep seated broadened magnetic bodies as observed in block 1 and 5, these could also be attributed to deep faults, deep seated magmatic and volcanic rock. It could also be a consequence of intensive weathering and erosion of the iron formation from metamorphic and igneous rocks in the area; while Blue areas correspond to areas with thin sedimentary formations

These depths maps figure 4, 5 and 6 indicates clearly the magnitude of variations in depth of both the basement topography and other intrusive in the area. These areas could also be investigated further for the major magnetic minerals like ironstone, sandstones, limestone, granite, and magnetite.

CONCLUSION

Analytic Signal and Depth to source Estimation:

The depth to the top of magnetic sources which represent the sedimentary thickness indicated that the thickness of the sedimentary formation ranges from 0.57±0.06 to 2.11±0.02 km with an average of 1.22 ± 0.04 km. The result agrees with (Umego, 1990; Shehu *et al.*, 2004; Adetona *et al.*, 2007; Nwankwo and Shehu (2015)). These values were used to generate depth to the top of magnetic source maps. The magnitude shows that hydrocarbon generation is not feasible because the minimum sedimentary thickness required for hydrocarbon generation is 2.3 km, figure 4 is trending NW – SE, in the northern part and this could be attributed to young intrusive rocks from magmatic and volcanic rocks into the sedimentary formation., shallow depth to basement as observed in block 16 and 21 could be attributed to presence of sandstones, ironstones, shales, graphites, limestones, intrusives and other near-surface magnetic minerals could have induced high magnetic anomalies from the granitic basement in the southern part of the study area this also agrees with the documented figure 2 data from NGSA.

Results from analytic signal technique showed that the basement in the study area is segmented by faults whose amplitude ranges between 0.0018 m and 0.129 m. the map depicts a faults pattern trending northeast- southwest (NE- SW), and northwest-southeast (NW- SE) related to regional fault in the basin . A change from shallower to deeper magnetic sources is observed as one transverses from southern part to the north, suggesting that the magnetic contact is dipping towards the northern part. The analytic signal map of the gridded digital aeromagnetic data in the study area, enable us to draw conclusions about the structural geology not evident on the geological map of the area. The results from the spectracentroid technique revealed depth to the top of magnetic source in the area is shallower than 2.3 km, which is the minimum thickness of sediment required to achieve a threshold temperature for the commencement of hydrocarbon generation.

Therefore, hydrocarbon exploration may not be feasible in the basin, the study area is recommended for detailed geophysical investigation for major magnetic minerals like ironstone, sandstones, limestone, granite, and magnetite and geothermal energy potential.

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