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The Source Parameter Imaging (SPI) method for estimation of depth to buried magnetic sources from gridded digital data of the Sokoto Basin, Nigeria: Implications in exploration Geophysics.

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Abstract:

Analysis of high resolution aeromagnetic data over the study area has been carried out using Source Parameter Imaging SPI™ to explore for hydrocarbon potential in the entire Sokoto basin of Nigeria. It is bounded by longitudes 3.50 °E and 7.00 °E and latitudes 10.00 °E and 14.00 °N. Three grids (dx, dy and dz) were obtained before the SPI was calculated. Those grids were use of Oasis Montaj by carefully using appropriate cut-off wavelength of the area. Those grids later serve as input grids for SPI calculations. The result shows that the Sedimentary thicknesses in the north central part is much higher than those of the southern part of the study area, the SPI values vary gradually within these sub-basins in the northcentral. As one traverses the basin from the north towards the southwest the sedimentary thickness decreases and rest directly on the Precambrian basement. However, profiles across these sub-basin in the north, revealed that Sedimentary thickness range from 460 m to 3009.5 m. The profile 1 corresponds to the Gwandu Formation, which forms the Post-Paleocene continental terminal and occurs in the northwestern part of Sokoto. While the profile 2 corresponds to Kalambaina and Dange Formations, which constitute the Sokoto group and is of marine origin. This marine sedimentary layer dips gently and thickens gradually towards the northcentral, with a maximum thickness of over 3000 m near border with Niger Republic, is attributed to deep seated volcanic and magnetic sources. While areas of shallow seated magnetic bodies in the southern part attributed to presence of sandstones, ironstones, shales, graphites, limestones, intrusives and other near-surface magnetic minerals, ranges from 154. 0 m to 1000 m. The general trend in the orientation of the TMI and SPI map are found to be predominantly in the NE-SW and NW-SE related to the Pan – African Orogeny trends. Therefore, Dange and Kalmalo with sedimentary thickness of over 3.0 km could be sufficient for hydrocarbon maturation.

Key words: Aeromagnetic, Anomaly, SPI images, Sedimentary, and Sokoto Basin

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1. INTRODUCTION

This study determined the magnetic basement depth beneath the study area through source parameter imaging (SPI) technique using HRAM data in order to appraise its hydrocarbon potential. The Source Parameter Imaging (SPI™) method computes source parameters from gridded magnetic data (Thurston and Smith, 1997). The advantages of the SPI method over Euler deconvolution or spectral Fourier method for magnetic depths are that no moving data window is involved and the computation time is relatively short. 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 this work, the SPI technique was used for determining the sedimentary thicknesses in the study area, depths to different magnetic source layers within the study area, and basement topography displaying the spatial variation in sedimentary thickness within the study area using the 2009 HRAM data. Aeromagnetic surveys flown in Nigeria in the 1970's with a flight line spacing of 2 km, average terrain clearance of

152.4 m, and a nominal tie line spacing of 2 km have played a key role in understanding the country's regional geology. However due to their low resolution, they have become of limited use. As a result, a nationwide High Resolution Airborne Geophysical (Magnetic, electromagnetic and Radiometric) surveys were carried out for the Nigerian Geological Survey Agency in 2009. The acquisition, processing and compilation of the new data, which was partly financed by the Federal Government of Nigeria and the World Bank as part of major project known as the Sustainable Management for Mineral Resources Project, were carried out by Fugro Airborne Surveys Ltd. The High Resolution Airborne Geophysical Digital Data were acquired from aircrafts flown at height of 80 m with 500 m line spacing, 80 m mean terrain clearance and the tie line spacing of 500 m. This new low height survey data which is digitally high in resolution has been adjudged to be better than the previous 1970's low resolution analogue data by the NGSA. The Source Parameter Imaging (SPI) of aeromagnetic fields over the area would differentiate and characterise regions of sedimentary thickening from those of uplifted or shallow basement and also to determine the depths to the magnetic sources. The results could be used to suggest whether or not the study area has the potential for hydrocarbon. Since part of this basin (Iullemmeden Basin) in Niger Republic have found petroleum in commercial quantity and Nigeria part may not be of exception. If hydrocarbon is found in this basin, it will add to the hydrocarbon reserve base of the country and thereby boost the economy base of Nigeria.

2. Geology and Location of the Study Area

The largely nearly circular sedimentary basin generally referred to as the Iullemmeden Basin of West Africa extends from Mali and the western boundary of the republic of Niger through northern Benin republic and North-western Nigeria into Eastern Niger, Figure 1. The basin which covers an area of about 800,000 km^2 has its centre in the North of Niamey in Niger Republic and lies entirely with the Pan African province of West Africa.

The Sokoto Basin is located in the northwestern 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.

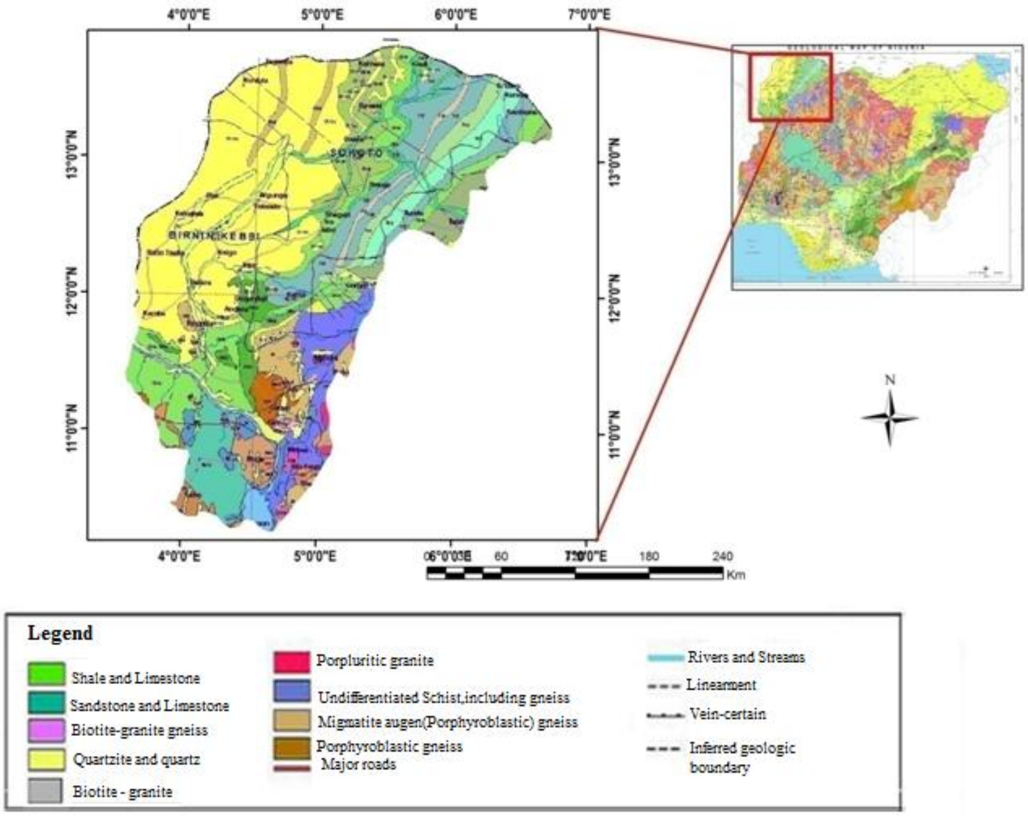

Figure 1. Geologic map of Sokoto Basin (Adapted from Nigerian Geological Survey Agency, 2006).

The Sokoto Basin forms the South-eastern sector of the Iullemmeden Basin, one of the young (Mesozoic – Tertiary) inland cratonic sedimentary basin of West Africa (McCurry, 1976 and Obaje, 2009). The basin like other intra-continental basins of the region and African continent in general developed by epeinogenic warping of stretching and rifting of technically stabilized crust. These movements commenced around the beginning of the Paleozoic and continued upper cretaceous and more responsible for the south western propagation of sediments deposited within the basin (Kogbe, 1979 and 1981).

Since the pioneering work of Falconer (1911) there have been three different detailed stratigraphical classifications of sediments in the area (Raeburn and Tettan, 1930; Jones, 1948 and Kogbe, 1981). The latest works have all reviewed and improved on the detail of the stratigraphical succession as laid down by the earlier works.

According to Jones (1948) the depositional history of the sediments of the basin can be summarized as follows:

1. A continental period represented by the Illo and Gundumi formations. These beds are probably lower cretaceous and are certainly younger than cenomanian.
2. Marine period commencing in the moastrichtian into the Eocene, during which the Rima Group and clay-shale and calcareous groups (Eoceic) were laid down.
3. A movement of elevation (Alphine Orogeny) probably in the late Eocene times leading to the retreat of the sea and accompanied by gentle.
4. A continental period represented by the Gwandu Formation that is probably of upper tertiary age.

In the Sokoto basin, water resource can be divided into precipitation, surface water and ground water. Prominent surface water are the rivers Rima and Sokoto, joining close to Sokoto town, while the Buusuru and Gangera rivers flow in a northerly direction joining Rima near Sabon-

Birni. The Sokoto, Zamfara and Katsina tribute on the other hand flow west wards to join Sokoto basin is a region with great potential for future large-scale economic development, due to warm and bountiful mineral resources, geothermal energy, farmland and water through irrigation project and borehole thereby boosting food production. The most important economics mineral in the Sokoto basin are the industrial minerals consisting of clays, limestone, gypsum and phosphate other are ironstone and laterites, gravel and lignite.

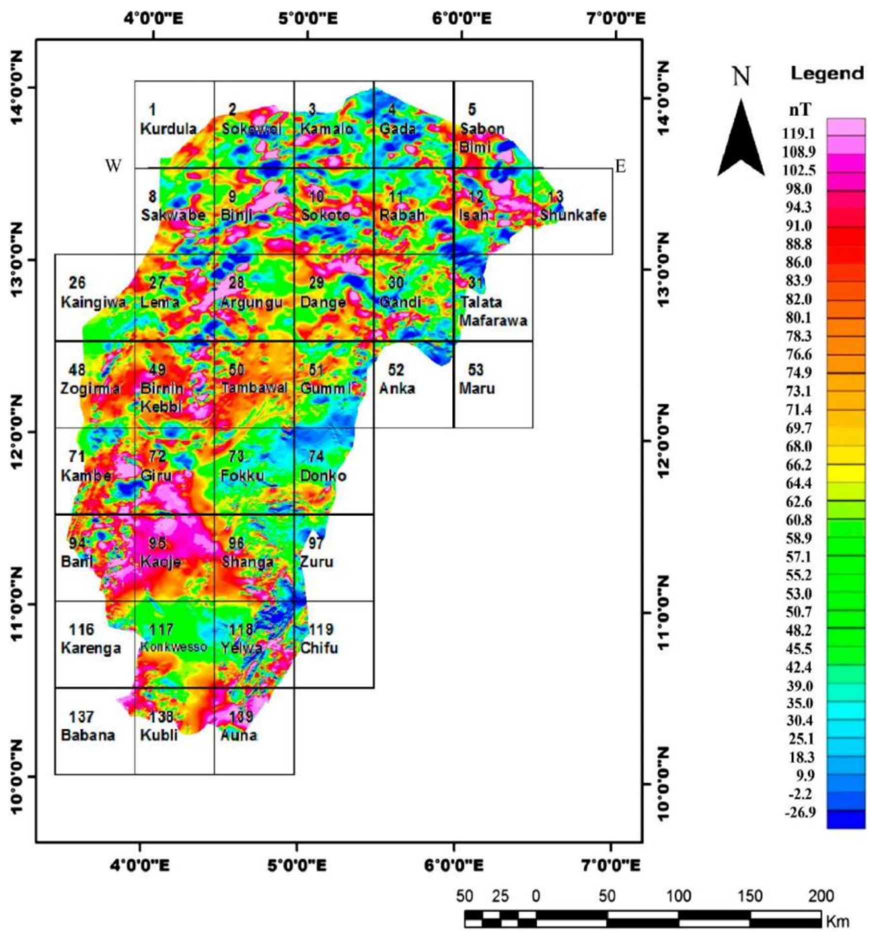

Figure 2. Total Magnetic Intensity Map (TMI) of Sokoto Basin with superimposed Federal survey half degree sheets and showing major towns flown over. A constant 33,000 nT had been removed.

3. MATERIALS AND METHODOLOGY

3.1 Materials

The basin was covered by thirty eight (38) digital half degree HRAM maps. (sheet number 1-5, 8-13, 2631, 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 study. 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 32,487.96 and 33,423.06 nT with an average of 33,060.70 nT and a standard deviation of 38.314. Regional correction which was based on the International Geomagnetic Reference Field (IGRF) was made as well as subtraction of a constant TMI value of 33,000 nT by the NGSA before the eventual publication as HRAM Maps. No further processing was made for the reason. The TMI colours indicate changes in the magnetic field intensity probably due to either changes in geologic boundaries, lithology and/or basement topography of the study area.

3.2 Methodology

The Magnetic sheets were joined together to form composite TMI data figure 2. The TMI data used for this work was subjected to various processing techniques using the Oasis Montaj, the TMI grid were dx, dy and dz. These grids were later served as input grids for SPI processing on which SPI analysis was performed by calculating the local wave number from the analytic signal, is a profile or grid-based method for automatic estimation location and depth to magnetic sources depths in a quick and easy approach. The depth is displayed on an image, is a technique that makes use of an extension of the complex analytical signal to estimate magnetic source depths. The method uses the relationship between source depth and the local wavenumber (k) of the observed digital field data, which can be calculated for any point within a grid of data via horizontal and vertical gradients Thurston and Smith (1997), and Thurston *et al*. (1999, 2002).

The depth to magnetic source was determined through several mathematical processing from various grids.

3.3 Theory of Source Parameter Imaging (SPI)

Source Parameter Imaging SPI technique has been used extensively by Blakely and Simpson (1986), Thurston and Smith (1997), Fairhead *et al.* (2004), Phillips *et al.* (2006) and Salako (2014). It is a profile or grid-based method for estimating magnetic source depths, and for some source geometries the dip and susceptibility contrast. 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 (for example $n = 1$ for a contact, $n = 2$ for a dyke).

According to Thurston and Smith, 1997 SPI is a procedure for automatic calculation of source depths from gridded magnetic data where the depth solutions are saved in a database. These depth results are independent of the magnetic inclination and declination, so it is not necessary to use a pole-reduced input grid. The Source Parameter Imaging (SPI) function is a quick, easy, and powerful method for calculating the depth of magnetic sources. Its accuracy has been shown to be ± 20% in tests on real data sets with drill hole control. This accuracy is similar to that of Euler deconvolution, however SPI has the advantage of producing a more complete set of coherent solution points and it is easier to use. A stated goal of the SPI method according to Thurston and Smith (1997) is that the resulting images can be easily interpreted by someone who is an expert in the local geology. The SPI method estimates the depth from the local wave number of the analytical signal. The analytical signal A1(x, z) is defined mathematically by Nabighian (1972) as:

$$A_1(x,z) = \frac{\partial M(x,z)}{\partial x} - j\frac{\partial M(x,z)}{\partial z} \qquad (1)$$

where M(x,z) is the magnitude of the anomalous total magnetic field, j is the imaginary number, z and x are Cartesian coordinates for the vertical direction and the horizontal direction respectively. From the work of Nabighian (1972), he shows that the horizontal and vertical derivatives comprising the real and imaginary parts of the 2D analytical signal are related as follows:

$$\frac{\partial M(x,z)}{\partial x} \leftrightarrow -\frac{\partial M(x,z)}{\partial z} \qquad (2)$$

where ↔ denotes a Hilbert transformation pair. The local wave number K_1 is defined by Thurston and Smith (1997) to be

$K_1 = \frac{\partial}{\partial x}\tan^{-1}$ (3)

The concept of an analytic signal comprising second-order derivatives of the total field, if used in a manner similar to that used by Hsu *et al.* (1996), the Hilbert transform and the vertical-derivatives operators are linear, so the vertical derivative of (2) will give the Hilbert transform pair,

$$\frac{a^2 M(x,z)}{\partial z \partial x} \Leftrightarrow -\frac{a^2 M(x,z)}{\partial^2 z} \quad (4)$$

Thus the analytic signal could be defined based on second-order derivatives, A_2 (x,z), where

$$\mathrm{A2}\,(x,z) = \frac{a^2 M(x,z)}{\partial z \partial x} - j\frac{a^2 M(x,z)}{\partial^2 z} \quad (5)$$

This gives rise to a second-order local wave number k_2, where

The first and second-order local wave numbers are used to determine the most appropriate model and a depth estimate independent of any assumption about a model.

Nabighian (1972) gives the expression for the vertical and horizontal gradient of a sloping contact model as:

$$\frac{\partial M}{\partial x} = 2\mathrm{KFc}\sin \mathrm{d}\frac{h_c\cos(21-d-90)+x\sin(21-d-90)}{h_c^2+x^2} \quad (7)$$

$$\frac{\partial M}{\partial z} = 2\mathrm{KFc}\sin \mathrm{d}\frac{x\cos(21-d-90)+h_c\sin(21-d-90)}{h_c^2+x^2} \quad (8)$$

Where K is the susceptibility contrast at the contact, F is the magnitude of the earth's magnetic field (the inducing field), $c = 1 - \cos^2 i\sin^2\alpha$, α is the angle between the positive x-axis and magnetic north, *i* is the ambient-field inclination, $tan1 = sini/cos\alpha$, d is the dip (measured from the positive x-axis), h_c is the depth to the top of the contact and all trigonometric arguments are in degrees. The coordinate system has been defined such that the origin of the profile line (x=0) is directly over the edge.

The expression for the magnetic field anomaly due to a dipping thin sheet is

$$M(x,z) = 2\mathrm{KF}_{cw}\frac{h_1\sin(21-d)-x\cos(21-d)}{h_c^2+x^2} \quad (9)$$

Reford (1964), where w is the thickness and h_1 the depth to the top of the thin sheet. The expression for the magnetic-field anomaly due to a long horizontal cylinder is

$$M(x,z) = 2\mathrm{KFS}\frac{\sin i}{\sin I}\frac{(h_h^2-x^2)\cos(21-180)+2xh_h\sin(21-180)}{h_c^2+x^2} \quad (10)$$

Murthy and Mishra, S is the cross-sectional area and h_h is the depth to the centre of the horizontal cylinder.

Substituting (7), (8), (9) and (10) into the expression for the first-and second-order (i.e. (3) and (6) respectively) local wave numbers, we obtain, after some simplification, a remarkable result as:

$$K_1 = \frac{(n_k+1)h_k}{h_k^2+x^2} \quad (11)$$

and

$$K_2 = \frac{(n_k+2)h_k}{h_k^2+x^2} \quad (12)$$

where n_k is the SPI structural index (subscript k = x, t or h), and $n_c = 0$, $n_t = 1$ and $n_h = 2$ for the contact, thin sheet and horizontal cylinder models, respectively. From (11) and (12) above, it is evident that the first- and second-order local wave numbers are independent of the susceptibility contrast, the dip of the source and the inclination, declination, and the strength of the earth's magnetic field.

The contract, thin sheet and horizontal cylinder are all two-dimensional models (infinite strike extent), so it is an implicit assumption of the SPI method that the geology is two dimensional. If the body is two-dimensional and there is no interference from nearby bodies, the depth estimate will be reasonable and the structural index should be constant over the entire area for which the response is anomalous.

4. RESULTS AND DISCUSSION

The depth to magnetic source was determined through several mathematical processing from various grids. The pre-processed grids from the residual grid as input grid are dx, dy and dz. These output grids were used as input grids for SPI processing. First order derivative was adhered to, so as to minimize noise, which may occurred at higher order of derivative. Therefore, careful filtering of data was ensured so as to have good estimates of the local wavenumber and that of the depth. Figure 3 is the depth estimates obtained from the source parameter imaging (SPI).

The Figure (Figure 3) shows the depth estimate of the upper basement depth (i.e. top of the sediment/basement interface). The colours in the SPI images are reflecting local variation in the earth's magnetic due to local variation in the magnetism and chemistry of the rocks, and could also be reflecting the undulations in the basement surface. The negatives in the numbers on the legend signify depth to the buried magnetic sources. The SPI images map shows that area of thick sedimentary are in the northern part of the study area, two profiles were drawn across the identified areas of thick sedimentary cover (Fig. 4a and 4b),

Figure 4a (NS001) runs from Lema (12.6 ^{o}N and 4.0 ^{o}E) to Kalmalo (13.7 ^{o}N and 5.4 ^{o}E), the Lema sink sub-basin. Average thickness in this sub-basin is 1.2 km although depths of over 2.7 km have been recorded towards Kalmalo in the northern end near border with Niger. Figure 4b (NS002) runs from Dange (12.7 ^{o}N and 5.25 ^{o}E) to Sabon-Birni (13.6 ^{o}N and 6.3 ^{o}E) in the northern end. The average thickness for this sub-basin is 0.7 km with a depth of over 3.0 km been recorded towards Sabon-Birni in the northern end near border with Niger. Profile NS002 is relatively shallower than profile NS001. SPI image also reflects areas of high thickness of the sedimentary cover in the southern part at Kwonkoso and Auna. The average thickness of sedimentary cover in this sub-basin is about 2.2 km but profiles drawn across these regions of high sedimentary thickness revealed gradual increases in sedimentary thicknesses from northcentral part towards northern end near border with Niger.

The data set shows that over the entire study area, thickness of the sedimentary cover in the area increases gradually toward the northern end of the study area. Thicknesses of the sedimentary fill over the basin is very crucial in determining the potential for hydrocarbon generation of a basin, areas with sedimentary thickness value of 3.00 km and above indicate areas with hydrocarbon potential, if other conditions are favourable (Obaje *et al.,* 2014). However, the following towns: Lema, Sokoto, Kalmalo, Dange and Sabon-Birni having sedimentary thicknesses of 3.0 km and above are the most probable areas for hydrocarbon maturation and accumulation in the basin.

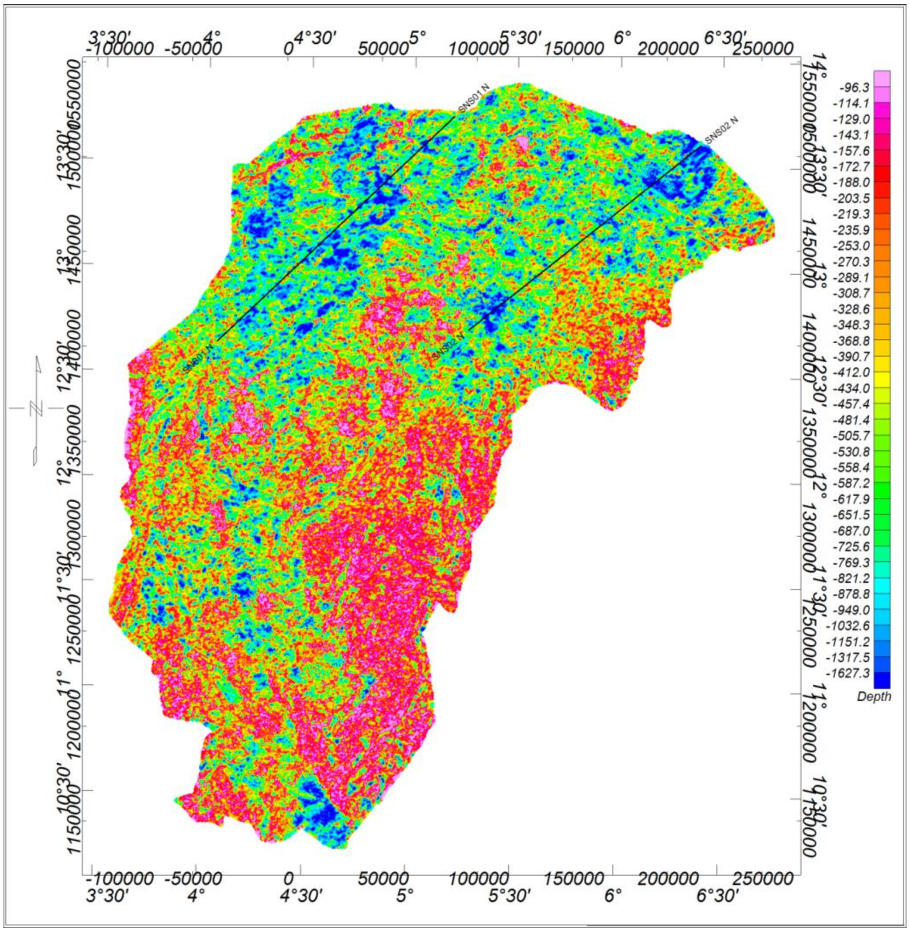

Figure 3. SPI map with profile lines across the two sub-basins (Units: Depth in metre)

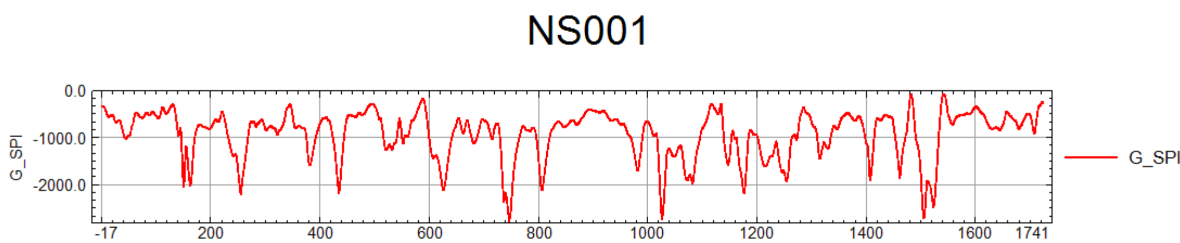

Figure 4a. Profile across Lema- Kalmalo Sub-basin

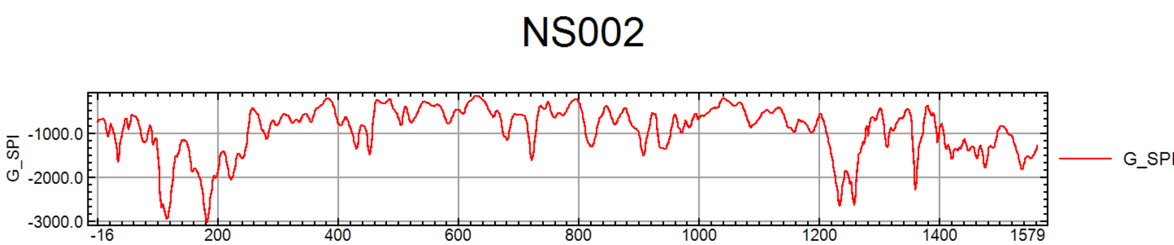

Figure 4b. Profile across Dange- Sabonbirni Sub-basin

5. SUMMARY AND CONCLUSION

5.1 Implications to explorer

SPI image map revealed two main magnetic anomaly zones, depth represented by blue colour and the purple coloured. The blue colour are areas of deeper lying magnetic source bodies hence with thicker sedimentary cover and ranges from 460 m to 3009.5 m with an average depth of 1890.2 m and could be viewed as the magnetic and volcanic basement depth of the studied area. The purple colour is areas of shallow seated magnetic bodies hence are areas of thinner sediment ranging from 154. 0 m to 1000 m with an average depth 479.5 m, and could be viewed as the magmatite and iron stone intrusions into the sedimentary basins. The general trend in the orientation of the TMI and SPI map are found to be predominantly in the NE-SW and NW-SE related to the Pan – African Orogeny trends.

According to wright *et al*., 1985, the minimum thickness for the concealment of hydrocarbon is about 2300 m, the results obtained fall short of this standard. This indicates that the prospect for hydrocarbon accumulation is not feasible. However, highest sedimentary thickness of about 3.0 km around Dange, and Kalmalo are observed which represent 5.3 % of the study area. The shallow sedimentary thickness could also be found in the high magnetic anomalies zone in the south due to occurrence of magnetite and iron stone in the area from the uplifted basement. This results agrees with the results obtained by other researchers that conducted studies in some parts of the basin such as Shehu *et al.,* 2004, Adetona *et al.,* 2007 and Bonde *et al*., 2014 from spectral depth determination, upward continued filter and other technique, however, HRAM data has been adjudged to be better and exacts owing to the high resolution nature of the 2009 data over the 1970s analogue data by the NGSA Abuja.

RECOMMENDATIONS

Dange and Kalmalo areas are the most probable areas for hydrocarbon generation. Detailed seismic survey and soil sample tests should be conducted around Dange and Kalmalo with the highest sedimentary thickness of about 3.0 km, as this might confirmed the presence of hydrocarbon potential.

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