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Depth to Basement Determination Using Source Parameter Imaging (SPI) of Aeromagnetic Data: An Application to Upper Benue Trough and Borno Basin, Northeast, Nigeria

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ABSTRACT

Source Parameter Imaging (SPI) of aeromagnetic data covering latitude 9.5^0 – 12.0^0 and longitude 9.5^0 – 12.0^0, which corresponds to upper Benue trough and southern Borno basin, northeast, Nigeria, was carried out for the purpose of investigating the sedimentary thickness beneath the subsurface. The study area is covered by 25 aeromagnetic maps. The aeromagnetic maps were digitized on a 3 km by 3 km grid and later compiled to produce a combined aeromagnetic data file of the study area. The 3 km spacing interval imposed a Nyquist frequency of 0.167 km^{-1} while the data file comprised 7921 data points. The Polynomial Fitting method was applied in the regional–residual separation. 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 later served as input grids for SPI processing. First order derivative was adhered to, as the method is much more sensitive to noise at higher order of derivative. The result of the Source Parameter Imaging (SPI) has its highest sedimentary thickness of about 5.0 km around Gombe, AkoGombe, Bulkachuwa and Damaturu areas. The shallow sedimentary thickness could also be found in basement complex around Bauchi, Kaltungo inlier and volcanic areas at the eastern part of the study area. Detailed seismic survey and soil sample tests should be carried out around Gombe, AkoGombe, Damaturu and Bulkachuwa, these areas were suggested as having the highest sedimentary thickness of about 5.0 km, as this may determine the presence of hydrocarbon.

Keywords: Aeromagnetic data, Polynomial fitting, Source Parameter Imaging and Sedimentary thickness

INTRODUCTION

The search for mineral deposits and hydrocarbon (oil and gas) has been a major business challenge in Nigeria since the pre-colonial era and the 1960s respectively. The bedrock of Nigeria's economy has been the solid mineral and currently the lucrative oil sector due to its high profitability. Over 80 percent of the country's revenue comes from export and domestic sales of the oil and gas upon which over 140 million growing population depends on. As the hydrocarbon potential of the prolific Niger delta becomes depleted or in the near future may be exhausted due to continuous exploitation, attention needs to be shifted to other sedimentary basins. The Upper Benue Trough and Borno basin in particular is one of those basins being suspected to have high hydrocarbon potential, besides economic mineral deposits concentration. Recently, the petroleum potential of the trough has been of great interest to geologists and geophysicists. The Nigerian government through the Nigerian National Petroleum Corporation (NNPC) and many oil companies had invested heavily in this part of the basin prospecting for oil which remains elusive up to today. However, efforts are still on and more money is still being sunk into the area with the hope of finding oil in the near future. This study will be very useful on a reconnaissance basis for oil and mineral prospecting in the area.

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 oil/gas and mineral deposits concentration. This study area is bounded by latitudes 9.50’N to 12.00’N and longitudes 9.50’E to 12.00’E located within the Upper Benue Trough and southern Borno Basin, Northeast Nigeria (Figure 1). It is approximately 275,000 km^2 and was covered by 25 aeromagnetic maps.

GEOLOGY OF THE STUDY AREA

The study area covers extensively the Upper Benue Trough, some parts of Chad Basin (Southern part of Bornu Basin), the Younger Granites (province of Bauchi area) and the Basement Complex, Figure 1 and Figure 2. All the rocks in the area belong either to the Upper Cretaceous or to the Precambrian. All the above mentioned units have already been described in detail by various workers (Buchanan *et al.*(1976), McCurry (1976), Ajibade(1976), Eborall(1976), Wright (1976) and Bowden and Turner (1974)). The sandstones of the Upper Benue Trough and the lower part of the Bornu Basin belong to the Upper Cretaceous and they are underlain by the Precambrian rocks of the Basement Complex.

The Upper Benue Trough comprises the area extending from the Bashar-MutumBiyu line as far north as the “Dumbulwa-Bage high” of Zaborski*et al.* (1998), which separates it from the Bornu Basin. Early studies of the Upper Benue Trough and Southern Bornu Basin were carried out by Falconer (1911), Jones (1932), Raeburn and Jones (1934) and Barber (1965). The basis for all later work was provided by Carter *et al. (*1963), who undertook a regional study of the area covered by the Geological Survey of Nigeria 1/250,000 Series map sheets 25 (Potiskum), 36 (Gombe) and 47 (Lau). The Upper Benue Trough has since become known in greater detail and has been almost entirely remapped through the work of Allix (1983), Benkhelil(1985, 1986 and 1988), Popoff (1988), Guiraud, Ajakaiye and Ugodulunwa (1989), Guiraud (1990a, 1991a and 1993) and Zaborski*et al.* (1998).

Figure 1. Location of the Study Area (parts of Upper Benue Trough and southern Bornu Basin). Adapted from Whiteman (1982)

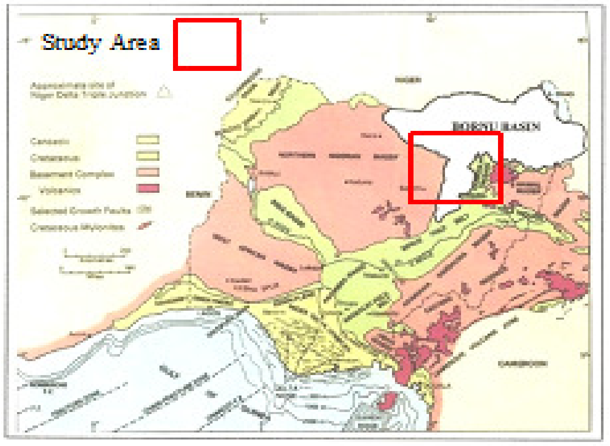


Figure 1. Location of the Study Area (parts of Upper Benue Trough and southern Bornu Basin). Adapted from Whiteman (1982)

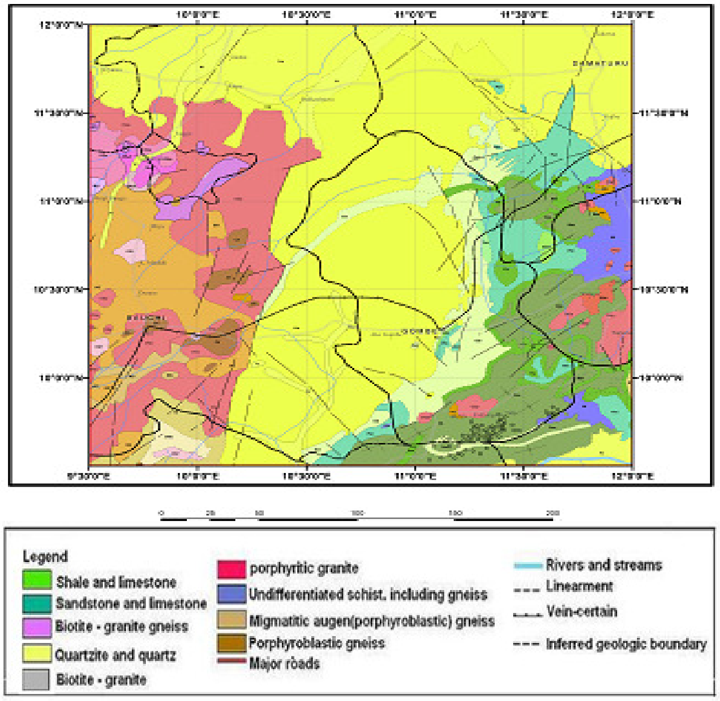


Figure 2. Map of selected profiles for modelling on the geologic map to scale 1:2000000

The Bornu Basin (or "Maiduguri Subbasin" of Avbovbo, Ayoola and Osahon, (1986)) is the south-western part of the Chad Basin (Figure 1). The Cretaceous sediments in the Bornu Basin are almost entirely concealed by the continental Pliocene to Pleistocene Chad Formation (Carter *et al.*(1963),Barber Barber (1965) and Miller *et al.* (1968)), which reaches a thickness of over 1500 m (Olugbemiro, 1997). Descriptions of the Bornu Basin have been given by Raeburn and Jones (1934), Matheis (1976), Avbovbo*et al.* (1986), Okosun (1995a) and Olugbemiro (1997). Those parts of the Chad Basin to the north and east were reviewed by Bellion (1989) with important subsequent accounts having been given by Schneider and Wolf (1992) and Genik (1992 and 1993). The latter provided detailed descriptions of the concealed east Niger, Bongor, Doba, Dosco and Salamat rifts. The Southern part of the Bornu Basin is covered by the Geological Survey of Nigeria 1/250,000 Series map sheets 25 (Potiskum). Raeburn and Jones (1934), Barber (1965) and Avbovbo*et al.* (1986) produced the geological maps of parts of the area to the north.

MATERIALS AND METHOD

The aeromagnetic dataset used for this study was obtained from the Nigerian Geological Survey Agency as a part of the nation-wide aeromagnetic survey between 1974 and 1980. The magnetic data were collected at a nominal flight altitude of 154.2 m along approximately N-S flight lines (nearly perpendicular to predicted geological strikes in the area), spaced 2 km apart. The component of the field measured was the total magnetic field. The study area is covered by twenty five aeromagnetic maps of total-field intensity in ½º by ½º sheets. These are numbers 83 - 87, 106 - 110, 128 - 132, 149 - 153 and 170 – 174 on a scale of 1:100,000. The magnetic values were plotted at 10nT (nano Tesla) interval. The actual magnetic values were reduced by 25,000 gammas before plotting the contour maps (Huntings, 1976). This means that the value of 25,000 gammas should be added to the contour values so as to obtain the actual magnetic field at a given point. A correction based on the international Geomagnetic Reference Field, IGRF, and epoch date January 1, 1974 was included in all the maps. The data used were digitised on a 19 x 19 grid systems using ILWIS. The spacing imposes a Nyquist frequency of 1/2.895 km, approximately 3.0 km. Thus, the magnetic feature that can be defined by the digitised data has a narrowest width of 3.0 km. This gridding system was supported by previous studies with crustal magnetic anomalies (Ajakaiye, Hall and Millar, (1985),Udensi (2000) and Udensi and Osazuwa (2002), which shows that the spacing is suitable for the portrayal and interpretation of magnetic anomalies arising from regional crustal structures. Figures 3 (a and b) and 4 (a and b) are the total magnetic intensity map of the study area and the residual magnetic map of the study area respectively.

Source Parameter Imaging (SPI)

The Source Parameter Imaging ^{TM} (SPI^{TM}) 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 (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 (Thurston and Smith, 1997)estimates the depth from the local wave number of the analytical signal. The analytical signal $A_1(x, z)$ is defined by Nabighian (1972) as:

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

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:

$$\frac{\partial M(x,z)}{\partial x} \Leftrightarrow -\frac{\partial M(x,z)}{\partial z} \;\ldots\ldots\ldots\ldots\ldots\; (2)$$

where⇔ denotes a Hilbert transformation pair. The local wave number k_1 is defined by Thurston and Smith (1997) to be

$$k_1 = \frac{\partial}{\partial x}\tan^{-1}\left[\frac{\partial M}{\partial z}\Big/\frac{\partial M}{\partial x}\right] \;\ldots\ldots\ldots\ldots\ldots\; (3)$$

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-derivative operators are linear, so the vertical derivative of (2) will give the Hilbert transform pair,

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

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

$$A_2(x,z) = \frac{\partial^2 M(x,z)}{\partial z \partial x} - j\frac{\partial^2 M(x,z)}{\partial^2 z} \;\ldots\ldots\ldots\ldots\ldots\; (5)$$

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

$$k_2 = \frac{\partial}{\partial x}\tan^{-1}\left[\frac{\partial^2 M}{\partial^2 z} \Big/ \frac{\partial^2 M}{\partial z \partial x}\right] \ldots\ldots\ldots\ldots\ldots (6)$$

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

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

$$\frac{\partial M}{\partial x} = 2KFc\sin d\,\frac{h_c cos(2I-d-90)+xsin(2I-d-90)}{h_c^2+x^2} \ldots\ldots\ldots\ldots\ldots (7)$$

$$\frac{\partial M}{\partial z} = 2KFc\sin d\,\frac{xcos(2I-d-90)+h_c sin(2I-d-90)}{h_c^2+x^2} \ldots\ldots\ldots\ldots\ldots (8)$$

where K is the susceptibility contrast at the contact, F is the magnitude of the earth's magnetic field (the inducing field), $c = 1 - cos^2 isin^2\alpha$, α is the angle between the positive x-axis and magnetic north, i is the ambient-field inclination, $\tan I = \mathrm{sini}/cos\alpha$, 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

$$M(x,z) = 2KF_{cw}\frac{h_1 sin(2I-d)-xcos(2I-d)}{h_c^2+x^2} \ldots\ldots\ldots\ldots\ldots (9)$$

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

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

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 wavenumbers, we obtain, after some simplification, a remarkable result as:

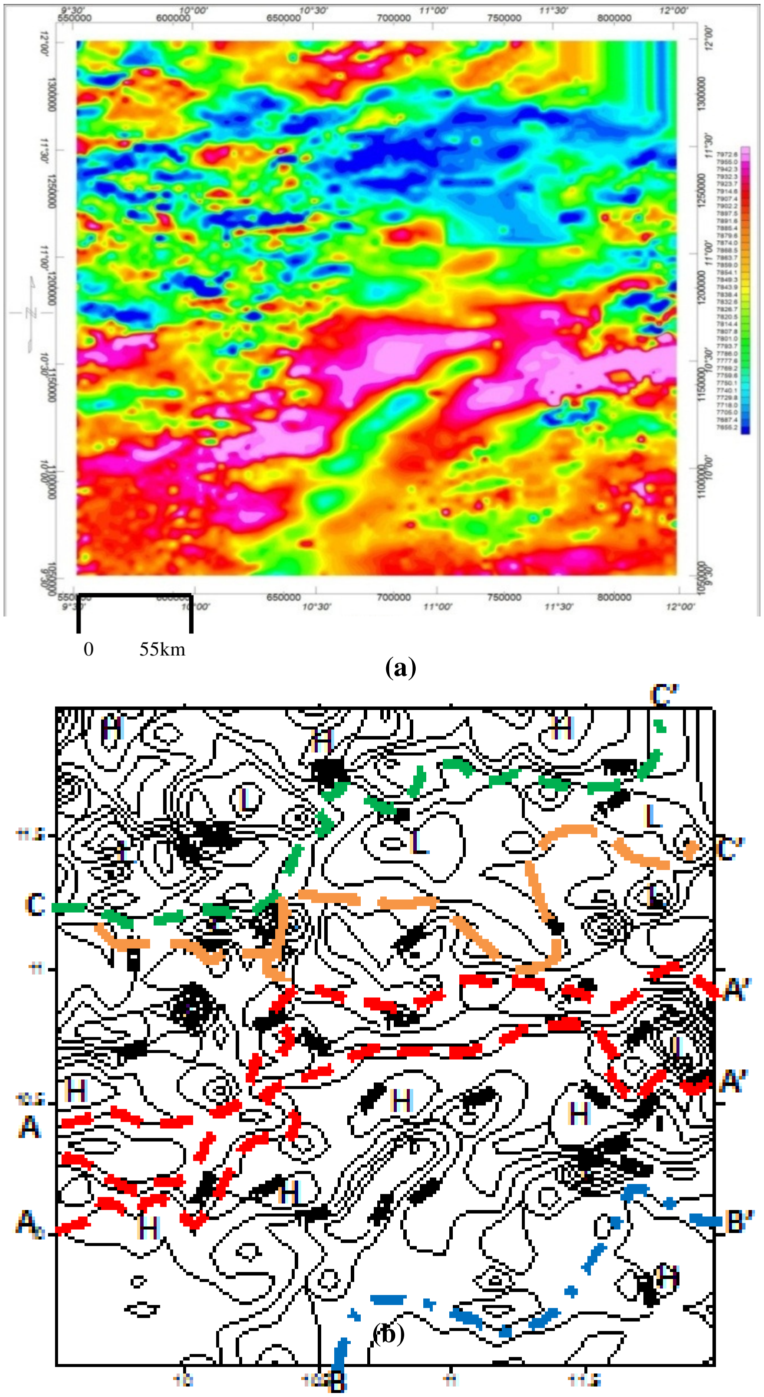
$$k_1 = \frac{(n_k+1)h_k}{h_k^2+x^2} \qquad \ldots\ldots\ldots\ldots\ldots (11)$$

and

$$k_2 = \frac{(n_k+2)h_k}{h_k^2+x^2} \qquad \ldots\ldots\ldots\ldots\ldots (12)$$

Where n_k is the SPI structural index (subscript k = c, 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 contact, 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.



(a)

(b)

Figure 3: Total magnetic intensity map of parts of Upper Benue Trough and southern Bornu Basin: (a) was obtained with Oasis and (b) was obtained through Surfer 8. Unit of total magnetic intensity is nano tesla (nT) and contour Interval is 40nT. Magnetic 'Highs' (H) and 'Lows' are depicted with 'H' and 'L' respectively. AA' BB', CC' are the paleo-structures noticed to have passed through the study area as noted by Ajakaiye*et al.* (1991). AA' BB', CC' represents the Romanche, Chain and St. Paul paleo-structures respectively.

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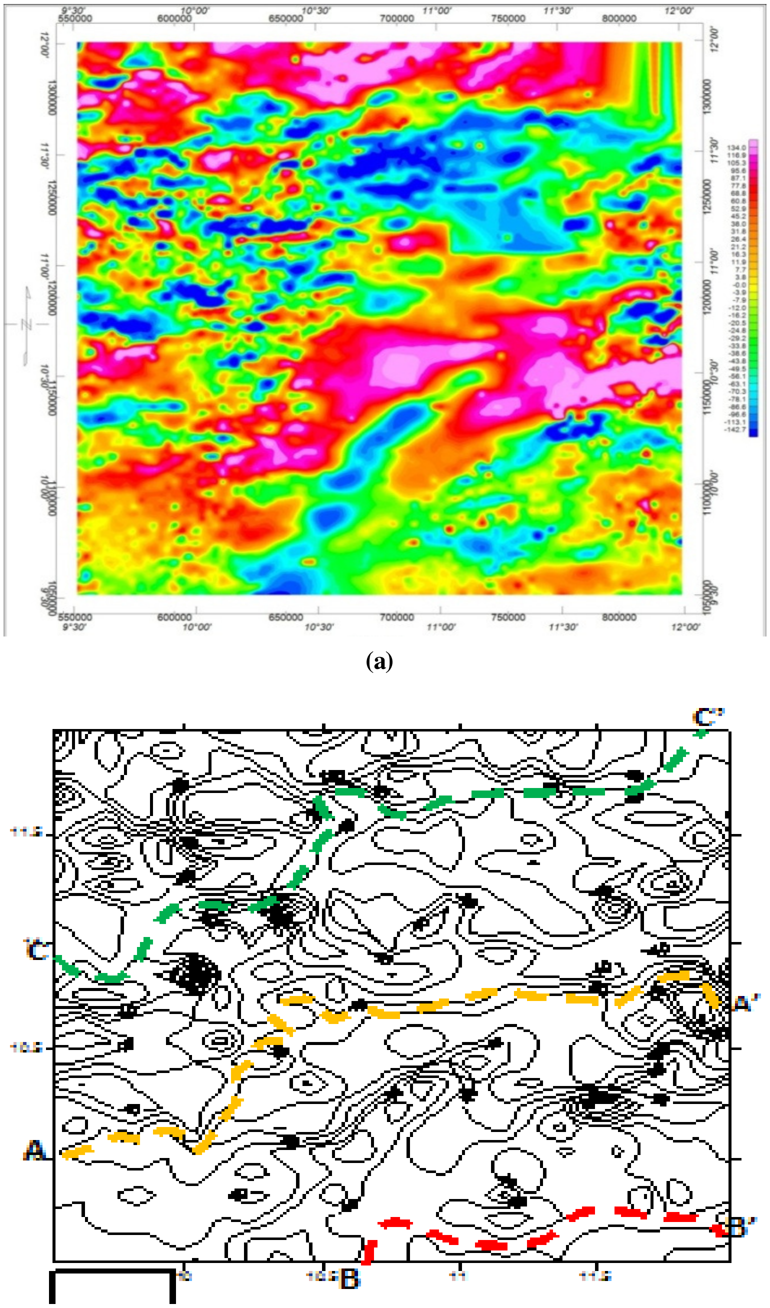

(a)

(b)

Figure 4. Residual-magnetic map of parts of Upper Benue Trough and southern Bornu Basin: (a) was obtained with Oasis and (b) was obtained through Surfer 8. Unit of total magnetic intensity is nano tesla and contour interval is 40nT. AA' BB' and CC' are the same as explain in Figure 3.

RESULTS

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 later served as input grids for SPI processing. First order derivative was adhered to, as the method (SPI) is much more sensitive to noise at higher derivative order. Therefore, careful filtering of data was ensured so as to have good estimates of the local wave number and hence the depth. Figure 5 is the depth estimates obtained from the source parameter imaging (SPI).

The Figure (Figure 5) shows the depth estimate of the upper basement depth (i.e. top of the sediment/basement interface) Smith *et al.* (1998). The white areas/ portion of Figure 5 are the areas where the derivative used to estimate the local wave number are so small that the SPI structural index cannot be estimated reliably. The model-independent local wave number had been set to zero in that portion. From Figure 5, the depth to sedimentary/basement interface varies between 0.96 km and 5.862 km. The highest depth can be found at the south-central part to the north-eastern part. However, relatively higher depth scattered around northern and southern parts.

The result from SPI agrees to some extent with the result from spectral depth determination Salako and Udensi (2013). The numeric values are very much in agreement, but the areas delineated as highest depth differs from both method. The shallowest region however agrees both in location and values. Results from both depth estimate methods agreed largely with other published works in the study area.According to Avbovbo et al. (1986) found out that thickness of over 10km was obtained around Maiduguri depression, but less than 5km was later proved from seismic reflection data;.Nur, Onuoha and Ofoegbu (1994) obtained 1.6km to 5km for deeper source around middle Benue, while 60m to 1.2km was obtained for shallow magnetic source; Nwogbo (1997) got 2km to 2.62km for deeper source and 70m to 0.63km for shallow source from spectral analysis of upper Benue trough; Udensi and Osazuwa (2003) obtained a maximum depth of 3.39km at Nupe Basin; Nur (2000) obtained depth range of 625m to 2.219km for deeper source and an average of 414m for shallow source at upper Benue trough; Nur (2001) got a depth range of 420m to 8km southwest of Chad basin. Other workers whom this present work had largely corroborated include: Likkasson, Ajayi and Shemang (2005), Nur (2003), Nur, Ofoegbu and Onuoha (2003), Nur (2001), Osazuwa, Ajakaiye and Verheijen (1981), Ofoegbu (1984a) and Ofoegbu 1988.

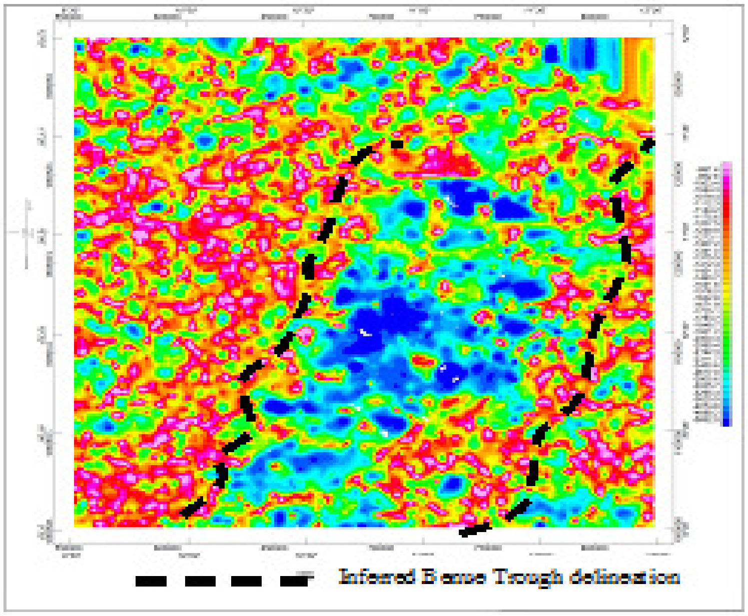

Figure 5. Depth determination from source parameter imaging SPI. The colour bar shows the depth estimates in meters

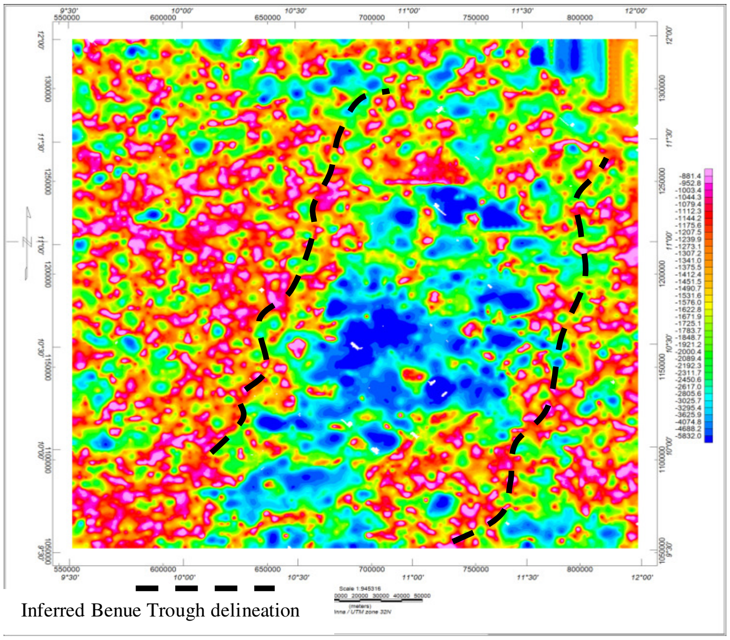

Figure 5. Depth determination from source parameter imaging SPI. The colour bar shows the depth estimates in meters

SUMMARY AND CONCLUSION

Sedimentary Thickness and Hydrocarbon Potential

Presence of hydrocarbon and its potential is enhanced by the thickness of the sediments of the basin, and also by the kindof geological structures existing within the basement that form traps for oil and gas.

The result of the Source Parameter Imaging (SPI) has its highest sedimentary thickness of about 5.0 km around Gombe, AkoGombe, Bulkachuwa and Damaturu areas. The shallow sedimentary thickness could also be found around basement complex and volcanic areas of the study area. Thus the results here agreed with the results obtained from spectral depth determination and upward continued filter.

RECOMMENDATIONS

Detailed seismic survey and soil sample tests should be carried out around Gombe, AkoGombe, Damaturu and Bulkachuwa, these areas were suggested as having the highest sedimentary thickness of over 5.0 km, as this might confirmed the presence of hydrocarbon.

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