ESTIMATION OF DEPTH TO BASEMENT, HEAT FLOW AND HYDROCARBON POTENTIALS FROM ANALYSIS OF AEROMAGNETIC DATA IN SOME PARTS OF BIDA BASIN

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Abstract

This study investigated the thickness of sedimentary pile, hydrocarbon potential and heat flow in Central Bida Basin using aeromagnetic data. The study area covers about 12,100 km², between latitude 8°30′N to 9°30′N and longitude 5°00′E to 6°00′E. Digital magnetic data consisting of Total Magnetic Intensity TMI with geospatial attributes covering four (4) sheets were used in this study. Data enhancement operations were applied to the TMI maps to improve interpretation. Depth estimates to the magnetic basement from power spectrum analysis and source parameter imaging methods showed that the thickness of the sediments range from 1.47 km to 2.95 km. Estimated geothermal gradient ranges from about 10.0 - 16.5 °C/100m (100-165°C/km), while heat flow values ranges from 2.50 – 4.10 Wm^{-2}. Two prominent structural trends in the Northeast – Southwest and Northwest – Southeast directions were identified. Mineralization within the study area seems to be structurally controlled. This study suggests that most parts of the study area will not be favourable for hydrocarbon generation because of the high geothermal gradient and heat flow.

Introduction

The aeromagnetic method has very outstanding attributes compared to other geophysical prospecting techniques; it has the most rapid rate of coverage at a relatively low cost per unit area captured. It has been applied for reconnaissance surveys in petroleum prospecting and to detect trend, depth and approximate topography of the basement. It has also been used to outline and estimate of the depth to intra-sediment structures such as fault, fold and other tectonic features. The method is also widely used in location of the geometric features such as shapes, size and extent of metallic ore deposits (Walsh, 1989).

The study area is situated in the central part of Bida sedimentary basin, North-Central Nigeria, and it is bounded by latitude 08 ° 30'N - 09 ° 30'N and longitude 005 ° 00'E - 006 ° 00'E; and covers an area of about 12,100 sq. Km (Figure 1) It covers topographic sheets 182 (Mokpa), 183 (Egbako), 203 (Lafiagi) , and 204 (Pategi). The Bida Basin, also known as the Mid-Niger Basin or Nupe Basin, is one of the inland sedimentary basins in Nigeria. The inland basins of Nigeria constitute one set of a series of Cretaceous and later rift basins in Central and West Africa whose origin is related to the opening of the South Atlantic Ocean. Commercial hydrocarbon accumulations have been discovered in Chad, Niger and Sudan within a rift trend. In SW Chad, exploitation of the Doba discovery (with an estimated reserve of about 1 billion barrels of oil) has caused the construction of a 1070 km-long pipeline through Cameroon to the Atlantic coast (Mohammed *et al*., 1999). In the Sudan, some "giant fields" (Unity 1 & 2, Kaikang, Heglig, etc) have been discovered in the Muglad Basin (Mohammed *et al*., 1999).

One of the problems confronting Nigeria's existence today is agitation for resource control by some sections of the country. Most of the inland sedimentary basins have not yielded hydrocarbon in commercial quantities. Presently, the production of Nigeria's crude oil comes from the Niger Delta basin (Obaje, 2009). There is therefore the need to have a re-look into these inland basins to appraise potentials for hydrocarbons accumulations of commercial quantity. Several geological and geophysical studies have been carried out in the basins by various workers (Ojo and Ajakaiye, 1989; Ojo, 1990; Idornighie and Olorunfemi, 1992; Sunmonu and Dimri, 2001; Udensi, 2001; Udensi et al., 2003; Udensi and Osazuwa, 2004; Megwara et al., 2013; Megwara and Udensi, 2013) but none of these were able to reach any conclusive results to motivate explorations. This study will therefore apply modern geophysical tools and software on recent magnetic data in the area with the aim of evaluating depth to basement, Heat Flow and hydrocarbon potentials.

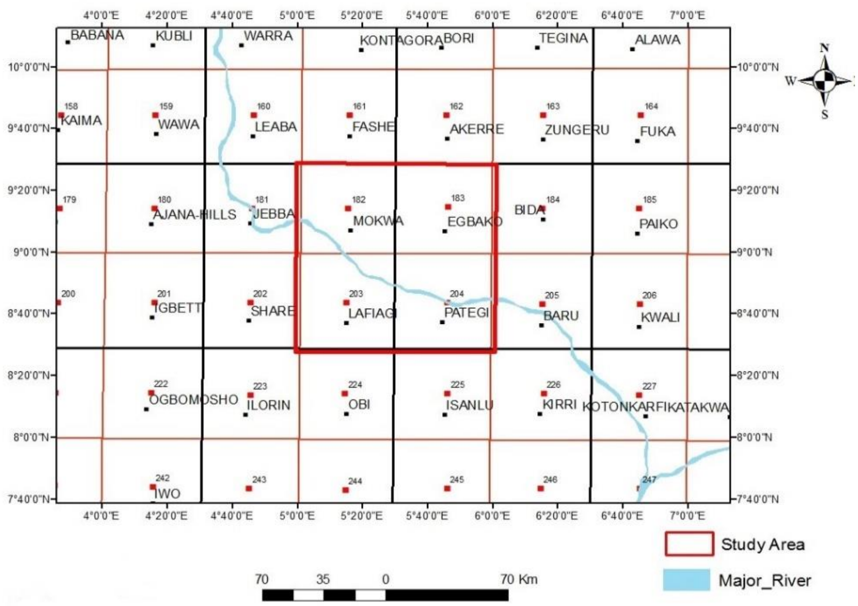

Fig. 1: Base map of study area.

1. Geologic setting of the study area

The study area is covered by the Cretaceous sediments of the Bida Basin and the Precambrian Basement Complex of North Central Nigeria (Fig. 2). The Cretaceous sediment uncomformably overlie the Precambrian rocks (Obaje, 2009). The Nupe Formation, Older Granite, Undifferentiated Schists, Granite Gneiss and Migmatite are the major rocks found in the study area. Bida Basin is an intracratonic sedimentary basin extending from Kontagora in Niger State to areas slightly beyond Lokoja in Kogi state, all in Northcentral Nigeria. It is delimited in the northeast and southwest by the basement complex while it merges with Anambra and Sokoto Basins in sedimentary fill comprising post orogenic molasse facies and few thin unfolded marine sediments (Obaje, 2009). The basin is a gently downwarped trough whose genesis may be closely connected with the Santonian orogenic movements of southeastern Nigeria and the nearby Benue Valley. The basin is a NW-SE trending embayment, perpendicular to the main axis of the Benue Trough and Niger Delta Basin. It is frequently regarded as the north-western extension of the Anambra Basin, both of which were major epicenters during the third major transgressive cycle of southern Nigeria in Late Cretaceous time (Irumhe *et al*., 2019)

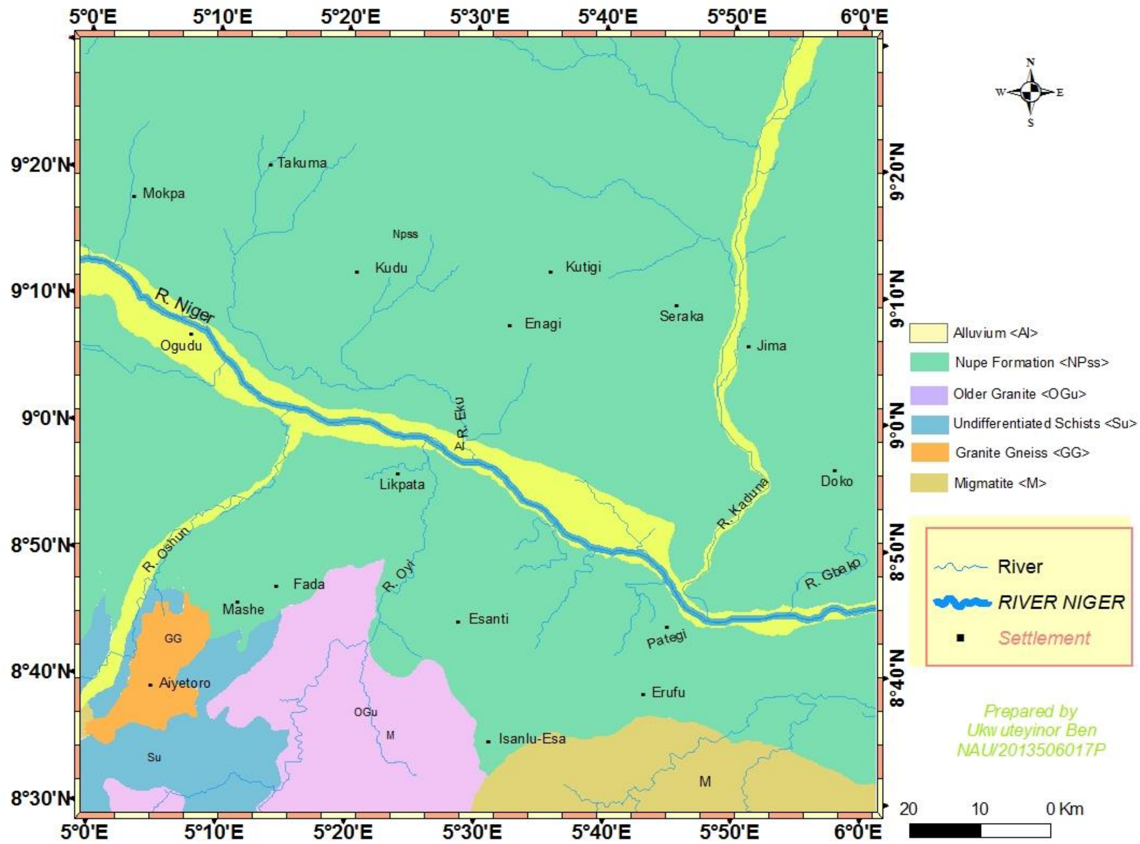

Fig. 2: Geological map of the study area (digitized, modified and adapted from NGSA, 2004).

2. Data description and methods

The aeromagnetic data used in this study, covering sheets 182 (Mokwa), 183(Egbako), 203 (Lafiagi) and 204 (Pategi), were obtained from the Nigerian Geological Survey Agency on a scale of 1:100 000. The data was acquired in 2009 along a series of NW – SE with a flight line spacing of 500m and tie line spacing of 5 km. The flight line direction is in the direction of 135° azimuth and the tie line direction is in 45° azimuths. The flying altitude was 80m above the terrain. The average magnetic inclination and declination across the survey was 9.75° and 1.30° respectively and the projection is WGS 1984. The geomagnetic gradient was removed from the data using the International Geomagnetic Reference Field formula (IGRF) of 2008.

The digital data of the study area consisting of the Total Magnetic Intensity was windowed from the National Grid Data base delivered in ASCII file in Geosoft Grid File format (.grd). The TMI data was further digitized in ESRI ArcGIS software for onward processing and interpretation with WingLink software and MS Excel. The data was later converted to Microsoft Excel format for easy use with other applications. Filtering was done on separate signals of different wavelength to isolate and enhance any anomalous feature within such wavelength. Data enhancement operations of Reduction-to-Pole and Upward continuation was performed on the data. Reduction to pole RTP operation is a mathematical operation which entails removing the dependence of magnetic data on the magnetic inclination i.e. converting data which were recorded in the inclined Earth's magnetic field to what they would have been if the magnetic field had been vertical. This method simplified the interpretation because for sub-vertical prisms or sub-vertical contacts (including faults), it transforms their asymmetric responses to simpler symmetric and antisymmetric forms. The RTP was performed on the digitized aeromagnetic data of the study area via fast Fourier filtering programs in order to remove the dipolar nature of the magnetic field. Baranov (1957) derived the following equations for reduction to pole;

$$g' = -\mu T\,(O) - \frac{1}{2\pi} \iint T\,(\rho, \omega)\omega_3\,(\omega)\, \frac{d\rho}{\rho}\, d\omega \qquad (1)$$

Where following Baranov's notation;

$$\omega_3\,(\omega) = 2 \sum_{K=1}^{\infty} (-\eta)^k \;\; k(k+\mu) \cos k\,\omega$$

g' = total magnetic field at point O, reduced to the pole,

μ = sin I, I being the inclination of the observed magnetic field,

$T\,(\rho, \omega)$= total field at the magnetic observation point (p, w) (polar coordinates) with reference to the calculation point at the origin where the observed field is T(0), and

$\eta = \; (I - |\sin(I))|cos(I)$

The reduction to the pole of magnetic data is an auxiliary method of qualitative analysis. This allows the production of a pseudo magnetic map where the magnetization vector of the rocks and the measured total field are both in vertical direction. The contribution of remnant magnetization is supposed to be insignificant. Upward continuation is a way of enhancing large scale (usually deep) features in the survey area as performed on the data. The operation attenuates anomalies with respect to wavelength; the shorter the wavelength, the greater the attenuation. Upward continuation tends to accentuate anomalies caused by deep sources at the expense of anomalies caused by shallow sources (Mekonnen, 2004).

The frequency response of the upward continuation is given as:

$$Fu(u, v, h) = e^{-2\tau h}(u^2 + v^2)^{1/2} \quad (2)$$

Where h = height to which the field is continued, u and v, are the angular frequencies in the x and y directions respectively. Depths to magnetic sources were estimated using spectral analysis and Source Imaging Parameter. The Total Magnetic Intensity TMI data, after filtering and data enhancement operations, was windowed into sixteen blocks and data smoothened by moving average method in order to estimate the depth to magnetic sources using spectral analysis. A fast Fourier transform was carried out on the smoothed data from which log spectral energy and spectral frequency were obtained for each windowed portion. A plot of log spectral energy was made against spectral frequency. Slopes of lines of best fit were generated which were divided by 2π to obtain the depth to magnetic basement according to Specter and Grant, (1970).

The Source Parameter Imaging (SPI) function is a quick, fast, and powerful method for calculating the depth to 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 especially with a sound knowledge of the local geology. The SPI method estimates the depth from the local wave number of the analytical signal.

The Curie point depth is the theoretical surface with a temperature of approximately 580^{o}C and can be considered an index of the bottom of a magnetic source, due to ferromagnetic minerals converting to paramagnetic minerals. The method used to estimate Curie point depth is based on the spectral analysis of magnetic data.

The basic 2-D spectral analysis method was described by Spector and Grant, (1970). They estimated the depth to the top of magnetized rectangular prisms (Z_t) from the slope of the log power spectrum. Bhattacharyya and Leu (1977) further calculated the depth to the centroid of the magnetic source bodies (Z_o). Okubo et al., (1985) developed the method to estimate the bottom depth of the magnetic bodies (Z_b) using the spectral analysis method of Spector and Grant (1970).

From the slope of the power spectrum, the upper bound and the centroid of a magnetic body can be estimated. The lower bound of the magnetic source can be derived as;

$$Z_b = 2Z_o - Z_t \quad \text{(Tanaka et al., 1999)} \qquad (3)$$

Where Z_b is the Curie point depth, Z_t is the upper bound depth, and Z_o is the bottom depth.

Since Z_b is the lower bound depth of the magnetic body, it suggests that ferromagnetic minerals are converted to paramagnetic minerals due to temperature higher than approximately 580°C. Therefore, the obtained bottom depth of the magnetic source, Z_b was assumed to be the Curie point depth. In order to relate the Curie point depth (Z_b) to Curie point temperature (580°C), the vertical direction of temperature variation and the constant thermal gradient were assumed. The geothermal gradient (dT/dZ) between the Earth's surface and the Curie point depth (Z_b) can be defined by Equation.

$$dT/dZ = 580^oC/Z_b \qquad (4)$$

Where dT/dZ = temperature gradient, 580°C is the Curie point temperature.
A relationship equally exists between heat flow on the earth and the geothermal gradient. The basic relation for conductive heat transport is the Fourier's law. In one-dimensional case under assumptions that the direction of temperature variation is vertical and temperature gradient (dt/dz) is constant; Fourier's law takes the form:

$$q_z = -k dT/dz \qquad (5)$$

Where q_z = the heat flow, k = thermal conductivity.
Provided there are no heat sources or heat sinks between the earth's surface and the curie-point depth, the surface temperature is 0°c and dT/dz is constant. The Curie temperature depends on magnetic mineralogy. Although the Curie temperature of magnetite (Fe_3O_4), for example, is at approximately 580°C, an increase of titanium (Ti) contents of titan magnetite ($Fe_{2x}Ti_xO_3$) causes a reduction of the Curie temperature. A Curie-point temperature of 580°c and thermal conductivity of 2.5 $Wm^{-1}{}^oC^{-1}$ as average for igneous rocks is used as standard in the study.

3. Results and Discussion

3.1 Qualitative interpretation

The qualitative interpretation of a magnetic anomaly map begins with a visual inspection of the shapes and trends of the major anomalies, delineation of the structural trends, closer examination of the characteristic features of each individual anomaly, etc. These features majorly bother on the relative locations and amplitudes of the positive contour parts of the anomaly (magnetic highs) and negative contour parts of the anomaly (magnetic lows) Sharma, (1976).

The qualitative interpretation carried out in this work bothers on the production and interpretation of the composite anomaly maps of the area. The total magnetic intensity map of the study area (Fig. 3) shows that a great variation in magnetic intensity exists within the study area ranging from -29.2nT - 115.9nT. Low magnetic intensity values are prominent at the central east and the mid northwestern part of the study area. Intermediate values occur at the northeastern and southwestern parts while very high magnetic intensity values are prominent around the southeastern and the mid part extending towards the northern part. It is generally believed that zones of low magnetic intensity correspond to sedimentary rocks; those of intermediate intensity are associated with granitic rocks, while zones of high magnetic intensity are characterized by basic igneous rocks. The aeromagnetic map of the study area is relatively subdued in a manner characteristic of sedimentary terrain. A basin is characterized by smooth contours and low magnetic contours while the surrounding basement area shows steep gradients and high relief in the magnetic contour.

The residual map of the study area (Fig. 4) shows anomalies of high (red coloured) and low (blue coloured) magnetic intensity value with predominant NE - SW and NW-SE trends and steep gradients which are distributed throughout the area. The dominant long wavelength anomalies with spatial scales of several kilometers are certainly due to deep seated basement under the basin. The magnetic highs (red coloured) and lows (blue coloured) are usually paired together, with the highs usually on the north side of lows. The anomalies in the magnetic field of the earth may be considered to arise from three principal sources (Bird, 1997). These are lithologic variation, basement structures and sedimentary sources. The magnetic intensity values ranges from -53.412 nT to 45.288nT. The maximum intensity value of 45.288nT is observed around Kutigi, east of Pategi, and Isanlu Esa while the minimum value -53.412 nT is recorded at the northwest and central part of the study area.

The reduction to pole map (Fig. 5) shows more closely and conspicuous contours, while with the RTP map anomalies are easily identified. The northern portion of the study area shows negative susceptibility indicating the presence of sediment and greater depth to magnetic basement. The central portion and a pocket of other areas show high (positive) magnetic susceptibility. These areas consist of igneous or metamorphic rocks of high magnetic mineral content. Magnetic intensity varies between -88.2 to 197.3 nT in RTP map.

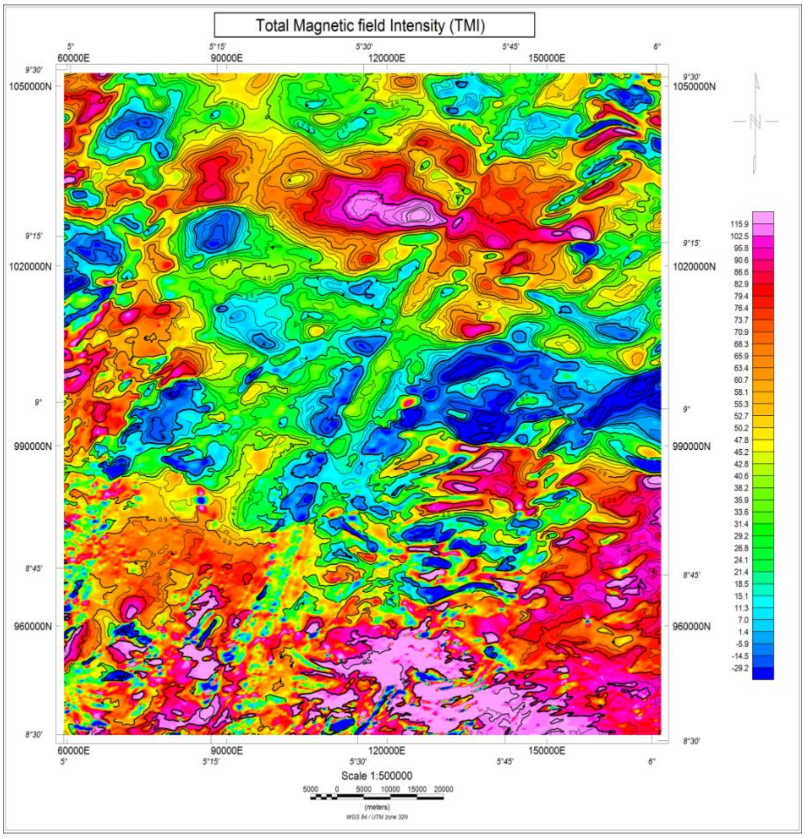

Fig. 3: Total magnetic intensity map of the study area

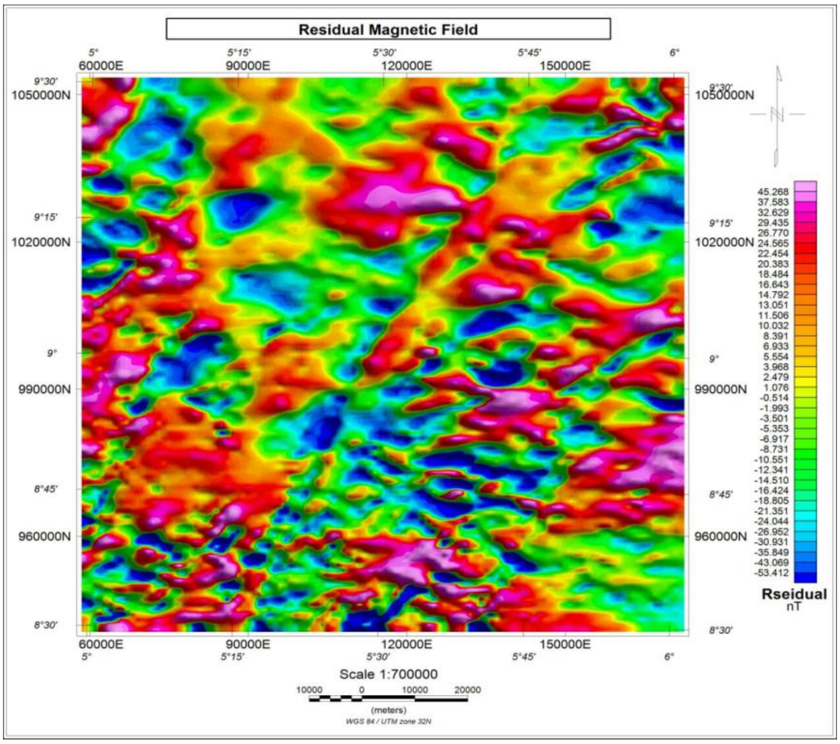

Fig. 4.: Residual map of the study area

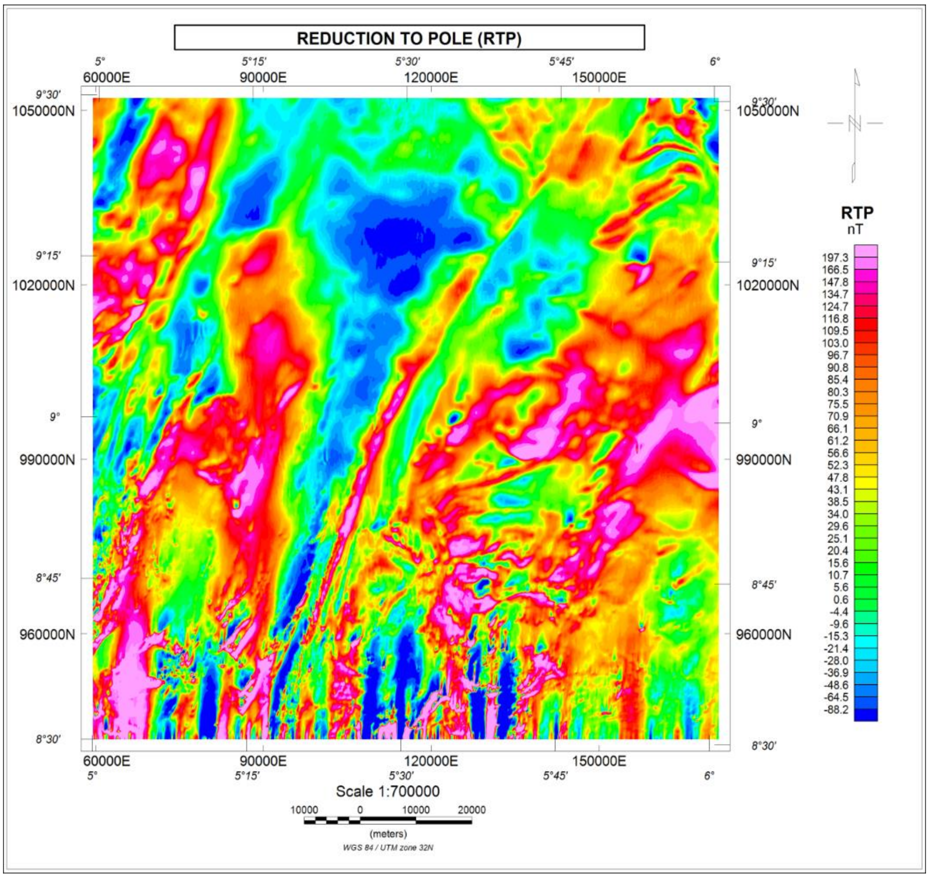

Fig. 5: Reduced to Pole map of the study area

3.2 Quantitative interpretation

A quantitative interpretation of potential field data estimates three types of information about the source of geologic interest: the depth, contrast in physical properties and source geometries. Depth-to-magnetic source estimation and modeling are quantitative techniques. Depth determination provides information on the thickness of sedimentary pile, basement architecture and structures necessary for mineral and hydrocarbon accumulation. Depth determination can be estimated with 7% error (Bain, 2000). The depth estimation methods employed in this study includes; spectra analysis, and source parameter imaging. In order to get a more accurate depth to source the study area was divided into smaller square blocks of dimensions 40x40 km and the average depth was computed for each block. The depth to magnetic basement from the spectral analysis varies from 1850 m to 2950 (fig. 6). The greatest depths are around Mokpa about 2.95km. The southern part of the study area, areas south of Pategi and around Aiyetoro which are underlain by Basement rocks are shallower with depths of about 1.85km. The maximum thickness of sedimentary pile is about 2.95km (fig. 6). This is in agreement with the work of Udensi and Osazuwa (2004), who suggested that the average thickness of the sediment pile in the area is 3.39km and in some places greater than 4.5km and about 2.2km in other places.

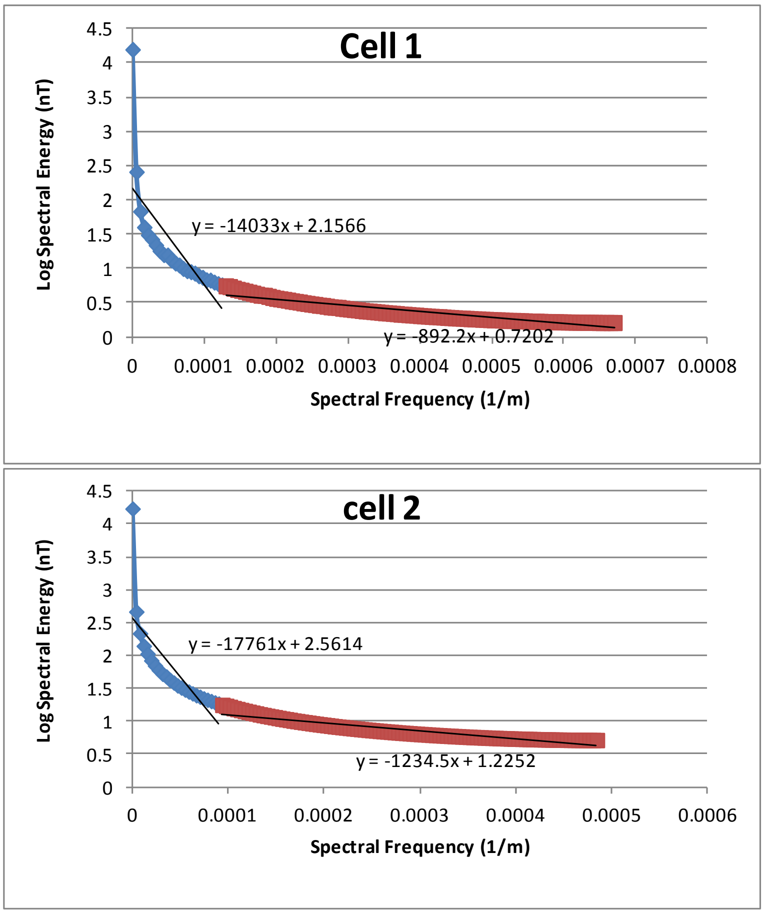

Fig. 6: Representative power spectrum plots of log spectral energy against spectral frequency.

The Source parameter Imaging map (Fig. 7) revealed a depth variation from 597 m to 1474 m. The deepest areas are also in the northern part of the study area, underlain by sediments. The southern edges especially around the basement rocks are shallower. The extreme northeastern part of the study area is shallow and few other places in the north and northwest has depths of about 640 m. According to Ojo (1990), these depth estimates suggest the presence of basement intrusions. Also, few places around the southwestern and southeastern part underlain by basement rocks gave varying depths ranging from about 800m to 1474m. These depth estimates suggest the presences of intra-basement features such as faults and fractures.

Curie point depth is the depth at which magnetic minerals lose their magnetic property. In the study area, the curie depth point is highest around the northeastern and northcentral edges (about5.8km) and decreases towards the northwestern, southeastern and southwestern parts of the study area (Fig. 8). The lowest Curie point depth is about 3.5km. Heat flow estimated ranges from 2.50 – 4.10Wm^{-2}. The heat flow increases from the southern end towards the northern limit of the study area (Fig. 9).

Table 1: Spectral Analysis Data showing slope, depth and coordinates in UTM

Sheet	Slope1	Slope2	Depth 1 (m)	Depth2 (m)	Mid Longitude (m)	Mid latitude (m)
1	-14033.00	-892.20	-2233.42	-141.998	73943.03	955426.70
2	-17761.00	-1234.50	-2826.75	-196.477	101943.00	955426.70
3	-16820.00	-1239.00	-2676.99	-197.193	129443.00	955426.70
4	-18664.00	-1234.70	-2970.47	-196.509	156943.00	955426.70
5	-11781.00	-892.13	-1875.00	-141.987	73943.03	983426.70
6	-12973.00	-892.93	-2064.72	-142.114	101943.00	983426.70
7	-15252.00	-923.35	-2427.43	-146.956	129443.00	983426.70
8	-11661.00	-896.98	-1855.91	-142.759	156943.00	983426.70
9	-11940.00	-897.02	-1900.31	-142.765	73943.03	1010927.00
10	-12056.00	-896.68	-1918.77	-142.711	101943.00	1010927.00
11	-11720.00	-896.96	-1865.30	-142.756	129443.00	1010927.00
12	-11599.00	-896.94	-1846.04	-142.752	156943.00	1010927.00
13	-12622.00	-896.92	-2008.85	-142.749	73943.03	1038427.00
14	-12116.00	-896.95	-1928.32	-142.754	101943.00	1038427.00
15	-11847.00	-896.85	-1885.51	-142.738	129443.00	1038427.00
16	-12128.00	-897.14	-1930.23	-142.784	156943.00	1038427.00

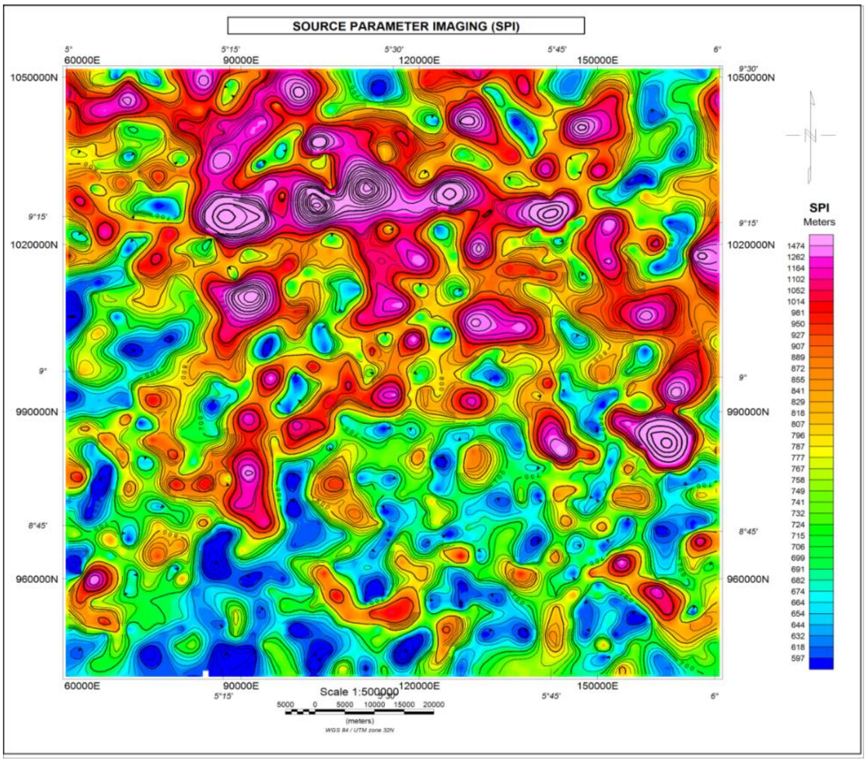

Fig. 7: Source Parameter Imaging (SPI) map of the study area

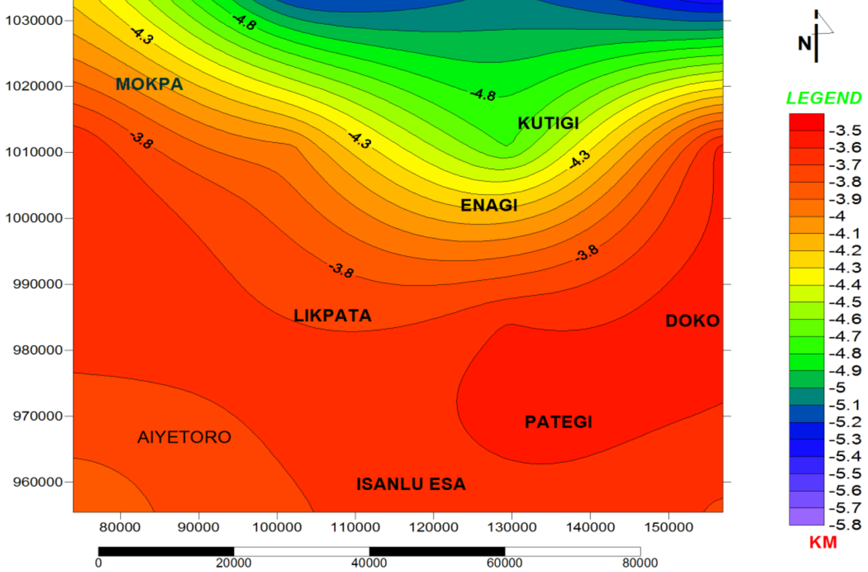

Fig. 8: Curie point depth map of the study area

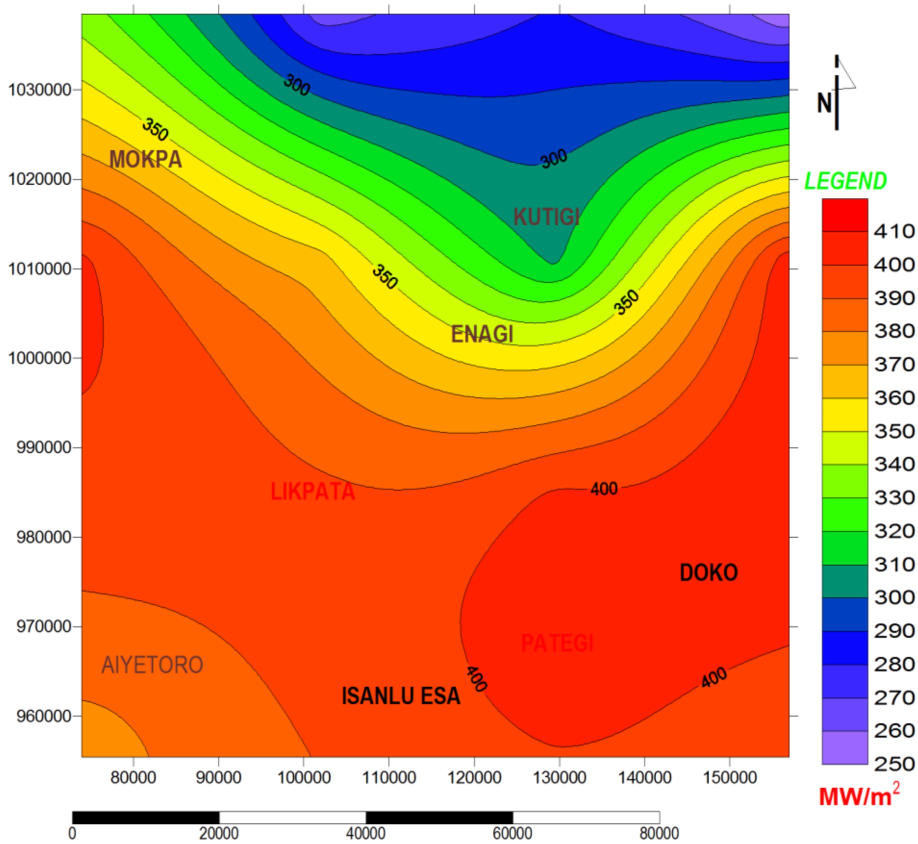

Fig. 9: Heat flow map of the study area

4 Conclusion

The depth to the basement source, thickness of sediments, heat flow and geothermal gradient were determined from spectral analysis and source parameter imaging. Generally, depth to basement depth ranges from 1.88 km to 5.8 km in the study area. The thickness of the sedimentary pile ranges from 0.55km to 2.95km in the north, central, eastern and western parts of the study area. These methods of depth determination employed showed a very good similarity of results. The deepest depth of 5.8km represents the magnetic rocks that were emplaced or intruded into the basement surface underlying the basin. It may also be due to the presence of intra-basement features such as fractures and faults. These deepest depths thus represent the depth to the deeper magnetic source. These deep basement regions are most likely rich in matured sediments required for hydrocarbon generation. Area of similar depth characteristics will make good targets for hydrocarbon prospecting. The minimum sedimentary thickness requirement for hydrocarbon generation, according to Bain 2000, is met in some parts of the study area like Kutigi, Enagi and Mokpa. Hydrocarbon generation and accumulation is not favourable in most areas because of the very high geothermal gradient, heat flow, and shallow thickness of sedimentary pile. Igneous instrusions are identified within some of the study area which is expected to destroy kerogens which are precursors for hydrocarbon generation. Thus, only the northeastern part of the study area (around Kutigi, Enagi, etc) met all the combined requirements of sedimentary pile thickness, structures, geothermal gradient, heatflow, etc, for hydrocarbon generation.

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