Original Research Article

Geothermal Gradient, Curie Point Depth and Heat Flow Determination of Some Parts of Lower Benue Trough and Anambra Basin, Nigeria, Using High Resolution Aeromagnetic Data

Abstract

Background and Objective: This study, which is bounded within Latitude 6^0 00'-6^0 30'N and Longitude $7^0$00' 7^0 30'E with an approximate area of about 3025 km^2 within parts of lower Benue trough and Anambra basin of Nigeria, aims at outlining the regional temperature distribution and delineating areas that are geo thermally responsive by determining: the heat change per unit distance, the heat flowing from the earth's interior to the outer surface and the deepest depth at which the minerals loss their magnetic properties within the study area without any heat data. **Materials and Methods**: For the aim to be achieved, the data was subjected to quantitative analysis with the aid of the WingLink, ArcGIS, Origin Pro 8, Ms Excel and sulfer 10 software's. Regional-residual was applied on the total magnetic intensity map and thereafter the residual divided into sixteen (16) overlapping windows. Spectral depth analysis was performed upon the overlapping windows and this revealed depth due to low frequency and high frequency components. The depths due to the low frequency components exemplify the Curie depth point (CPD). **Results**: The average sedimentary thickness or the average depth due to the low frequency part was ascertained to be -5 km while the geothermal and heat flow varies from -25.2 $^oCkm^{-2}$ to -38.9 $^oCkm^{-2}$ and from -64.4 mWm^{-2} to -97.3 mWm^{-2} but with average values of -32.1 $^oCkm^{-2}$ and -80.1 mWm^{-2} respectively. **Conclusion:** These results suggest alternative geothermal energy resource to be plausible within windows 2, 4, 8, 10, 12, 15 and 16 and presence of some amount of sedimentary thickness within the area of study.

Keywords: WingLink, ArcGIS, CPD, Windows, Heat flow, Geothermal gradient, HRAM, Raster, CSV.

INTRODUCTION

Aeromagnetic technique is a type of geophysical technique in which a magnetometer is towed behind an aircraft. Aeromagnetic data has been, and will continue to be, handy in the geophysical and geological investigation of the earth's interior. Umeanoh (2015) asserted that aeromagnetic data can be used in mapping magnetic basement in sedimentary rocks and delineating igneous bodies within sedimentary sections as well as locating lineaments and structures which could be possible host to varying earth resources like groundwater, minerals and hydrocarbon. Aeromagnetic method has been used majorly for the estimation of depth to basement and thickness of sediments within sedimentary basins. Although this method was used in mapping igneous and metamorphic rocks and structures related to them because these rocks have high magnetization compared to other rocks[2, 3].

Despite being used in delineating architectural framework of the earth's subsurface geology, the aeromagnetic method, can be applied successfully in defining geothermal gradient of an area via spectral analysi.s. It was pointed out that the assessment of variations of the Curie isotherm of an area can provide valuable information about the regional temperature distribution at depth and the concentration of subsurface geothermal energy [4]. The Curie-point temperature varies from region to region, depending on the geology of the region and mineralogical content of the rocks. Therefore, one normally expects shallow Curie-point depths in regions that have geothermal potential, young volcanism and thinned crust [4, 5]. In order to determine the Curie-point depths, i.e. the bottom of the magnetized rocks, and to map these depths, a frequently used method is the analysis of magnetic data.

The Benue trough is based on lead-zinc mineralization, limestone deposits, coal deposits, coal deposits, pyroclastics, brine spring and brine Lake [1]. Interestingly, the Benue trough especially the lower Benue trough has been studied deeply by researchers, students and private organizations using either a combination of magnetic, gravity or any other geophysical technique for mineral exploration. Currently aeromagnetic studies has received the kind of attention other geophysical techniques have received. Many authors [6-9] have carried out studies on magnetic anomalies to estimate bottom depths of the related bodies for various purposes through the application of various techniques. However, some authors [4, 5] have also undertaken determination of Curie-point depths (CPD) within some major basins of the world.

In the present study, the objective is to estimate the average sedimentary thickness, geothermal gradient, Curie Point Depth (CPD) as well as the heat flow within the study area. This aids in viewing the thermal structure of the crust. The CPD nevertheless can be defined as the deepest level in the earth crust containing materials which creates discernible signatures in a magnetic anomaly map [11]. In other words, the further the depth, the material changes from a ferromagnetic material to a paramagnetic one. However, one of the important parameters that determine the relative depth of the Curie isotherm with respect to sea level is the local thermal gradient, that is, heat flow [12]. This Curie Isotherm, generally, has a temperature of 550℃ ± 30℃ [11]. This point is assumed to be the depth for the geothermal source (magmatic chamber) where most geothermal reservoirs tapped their heat from in a geothermal environment. Measurements have shown that a region with significant geothermal energy is characterised by an anomalous high temperature gradient and heat flow [4]. It is therefore expected that geothermally active areas would be associated with shallow Curie point depth [13]. It is also a known fact that the temperature inside the earth directly controls most of the geodynamic processes that are visible on the surface [14]. In this regard, Heat flow measurements in several parts of African continent have revealed that the mechanical structure of the African lithosphere is variable [15].

The very concept underlying magnetic prospecting is the existence of a magnetic dipole or monopoles within the rocks constituting the earth[1].

Magnetic force expression, F between two magnetic monopoles of strength P_1 and P_2 is given by:

$$F = \frac{p_1 p_2}{\mu r^2} \qquad 1$$

Where

P_1 and P_2 are dipoles

r is in meters and it is the distance between P_1 and P_2

μ is the free space permeability

The above Coulomb's equation is the basic underlying principle of magnetic prospecting. Magnetic monopole, P_1 or P_2 exert force per unit pole strength and it can be expressed as:

$$\mathrm{H} = \frac{P}{r^2} \qquad 2$$

Where

P is the magnetic monopole
r is the distance between the force in question and the magnetic monopole
H = strength of the magnetic field

Generally, the existence of a monopole has never been accounted for. Basically, magnetic monopoles or dipole are made up of positive and negative poles separated by a distance. The force produced and thus existing between monopoles can be estimated by vectorially adding the forces generated by each of the monopoles or dipole. The force generated by a simple bar magnetic can be compared to the force generated by a dipole.

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Magnetic materials positioned within a magnetic field will acquire magnetic force and will experience magnetic induction. Due to the inducing field, one can measure the strength of the magnetic field known as the intensity of magnetization, Ji, induced on the material and this is expressed as:

$$J_i = kT \qquad 3$$

Where

J_i is the magnetization

k = susceptibility of the magnetic material

T = inducing field.

LOCATION AND GEOLOGIC SETTINGS OF THE STUDY AREA

The study area is located in Enugu state and parts of Anambra state, south-east Nigeria. The coordinates are Latitude 6^0 00’-6^0 30’N and Longitude $7^0$00’ 7^0 30’E. The study area falls within the Lower Benue Trough and parts of Anambra basin. The Benue Trough generally has been subdivided into three: the Upper Benue Trough at the NE Nigeria, the Middle Benue Trough and the Lower Benue Trough. The Lower Benue Trough has somewhat developed different tectonic history resulting in the formation of the Anambra Basin to the west and Abakaliki Anticlinorium to the east[1].

The Anambra Basin remained a stable platform supplying sediments to the Abakaliki depression during a period of spasmodic phase of platform subsidence in the Turonian. Following the flextural inversion of the Abakaliki area during the Santonian uplift and folding, then the Anambra Basin was initiated. Four Cretaceous depositional cycles where recognized in the Lower Benue and each of these was associated with the transgression and regression of the sea[17]. The opening of the Atlantic Ocean in the Middle Albian to Upper Albian gave rise to the transgression of the first sedimentary cycle. The Asu River group which consist predominantly sandstone and shale was deposited at this time. Between the Upper Cenomanian and Middle Turonian, the second sedimentary deposition of the Ezeaku Shale occurred. The third sedimentary circle occurred from Upper Turonian to the Lower Santonian leading to deposition of the Awgu Shale and Agbani Sandstone. The fourth and final depositional phase took place during the Campanian-Maastrichtian transgression. It was at this time that the Nkporo Shale, Owelli Sandstones, Afikpo Sandstone, Enugu Shale as well as the coal measures including the Mamu Formation, Ajali Sandstone and Nsukka Formation was deposited[17]. Fig.1 shows the study area and the regional geology of the Lower Benue trough. The geological map (Fig 2) of the study was extracted from the regional geologic map and redigitized using the Arc GIS software for enhanced interpretation of the aeromagnetic map. Visually inspecting the map shows five main formations within the study area. These include: Nkporo Shale Formation, Mamu Formation, Ajali Formation, Nsukka Formation and Ameki Formation. The ages of the formations range from Maastrichtian to Campanian and to Eocene (Ameki formation).

MATERIALS AND METHODS

This research work made use of a digitized High Resolution Aeromagnetic (HRAM) data compiled by Fugro Airborn Service on behalf of the Nigerian Geological Survey Agency (NGSA) in 2009. The Composite Total Magnetic Intensity (CTMI) map with sheet number 301 was obtained in comma separated variable (CSV) format and in half degree sheet. The aeromagnetic data in CSV format was later transformed into a raster format (Fig 3). The high resolution survey was carried out at flight line spacing of 500 meters and at a ground clearance of about 100 meters while the tie line spacing was 2 km at flight line direction of NE-SW.

The acquisition of the HRAM data initially took place in Ogun state in the year 2003. Thereafter, between year 2004 and 2009 the rest of the country was divided into project areas referred to as Phases I and II covering 44% and 56% respectively of the total area. The raw data was pre-processed using Oasis montaj software by the NGSA and was transmitted as IGRF corrected total magnetic intensity (TMI) data and was also saved in CSV file format.

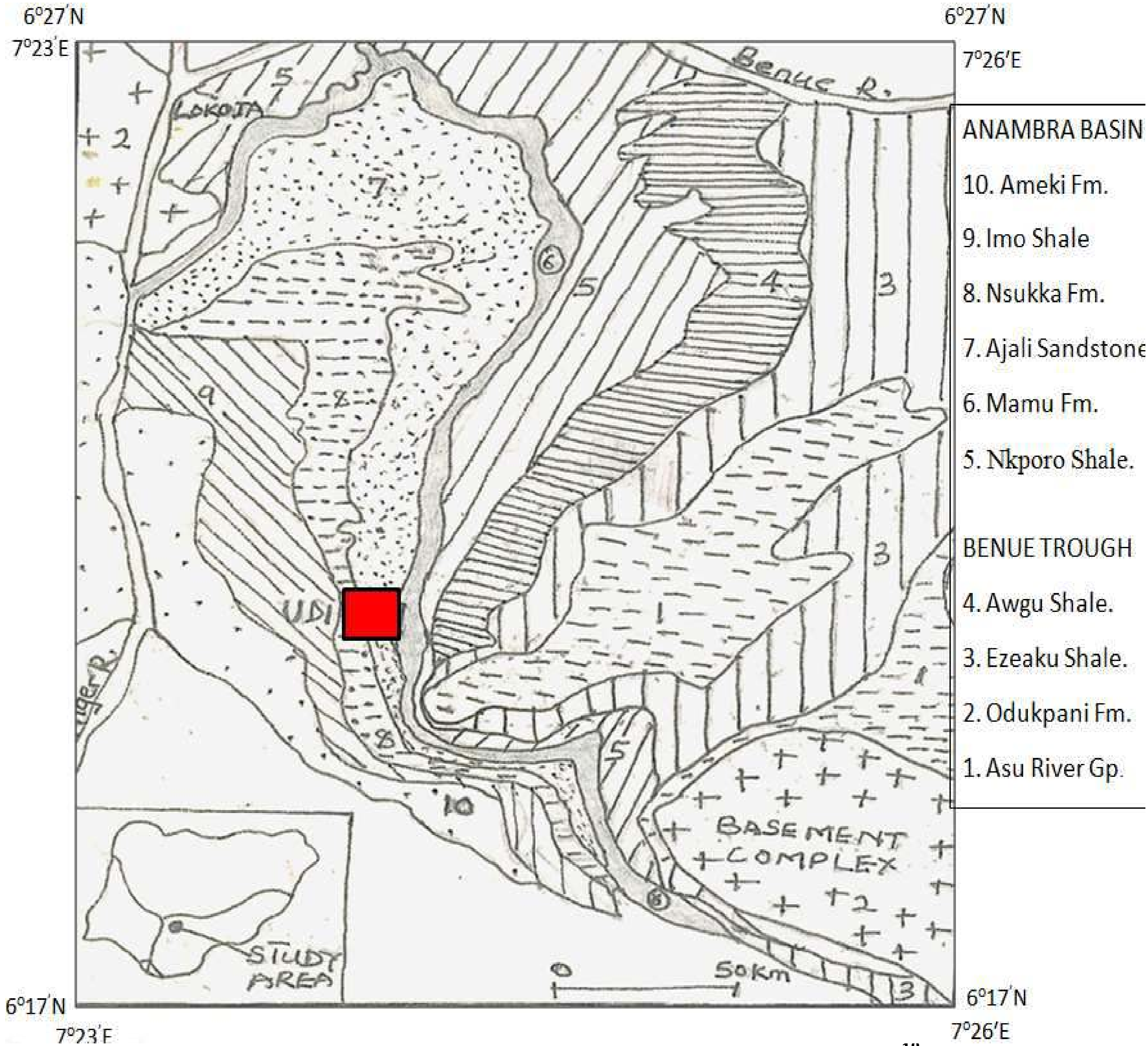

Fig.1: Regional Geology of the Lower Benue Trough showing the study area [18]

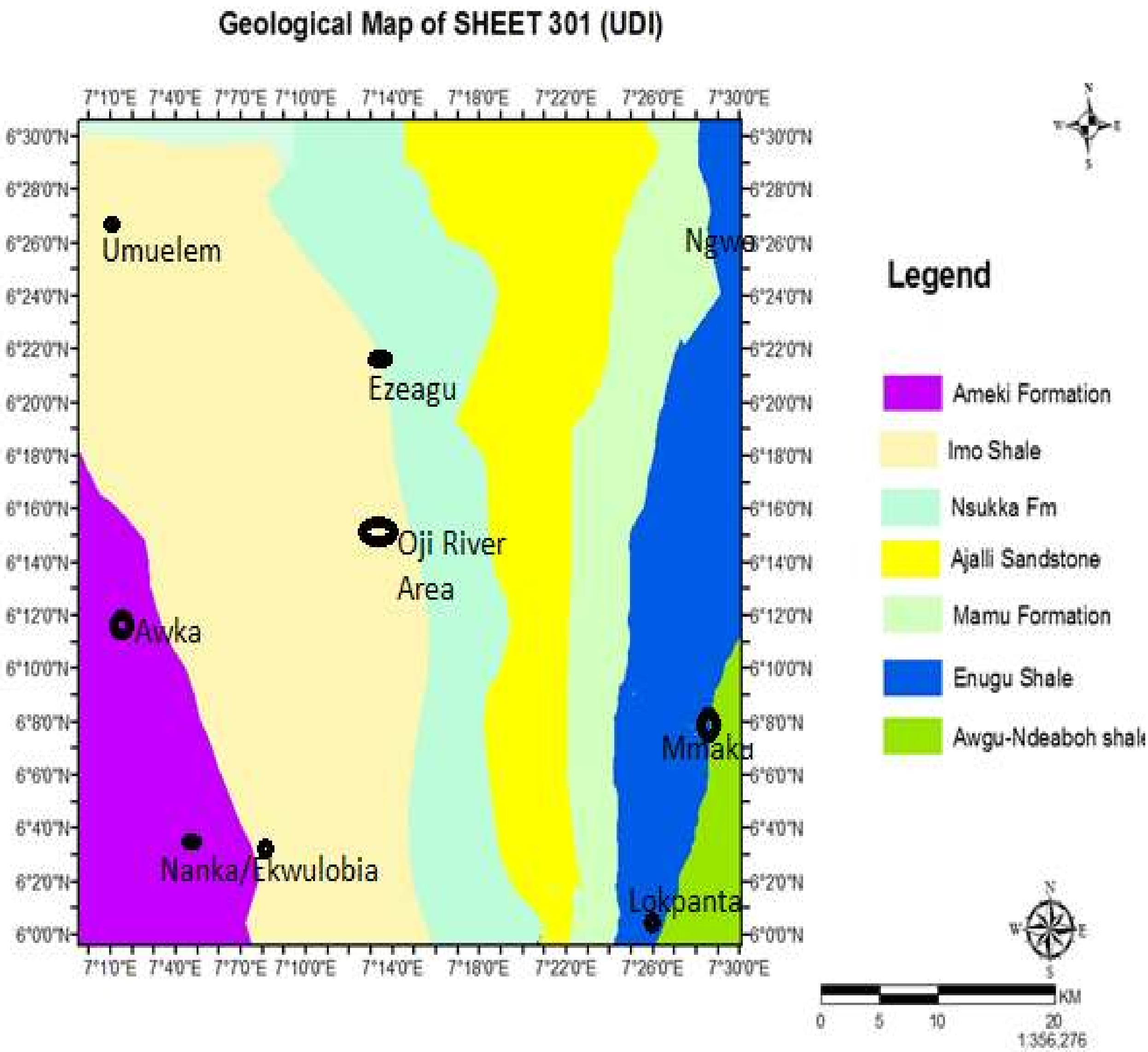

Fig. 2: Geologic Map of the Study Area (Sheet 301 and Re-digitized using the Arc GIS)

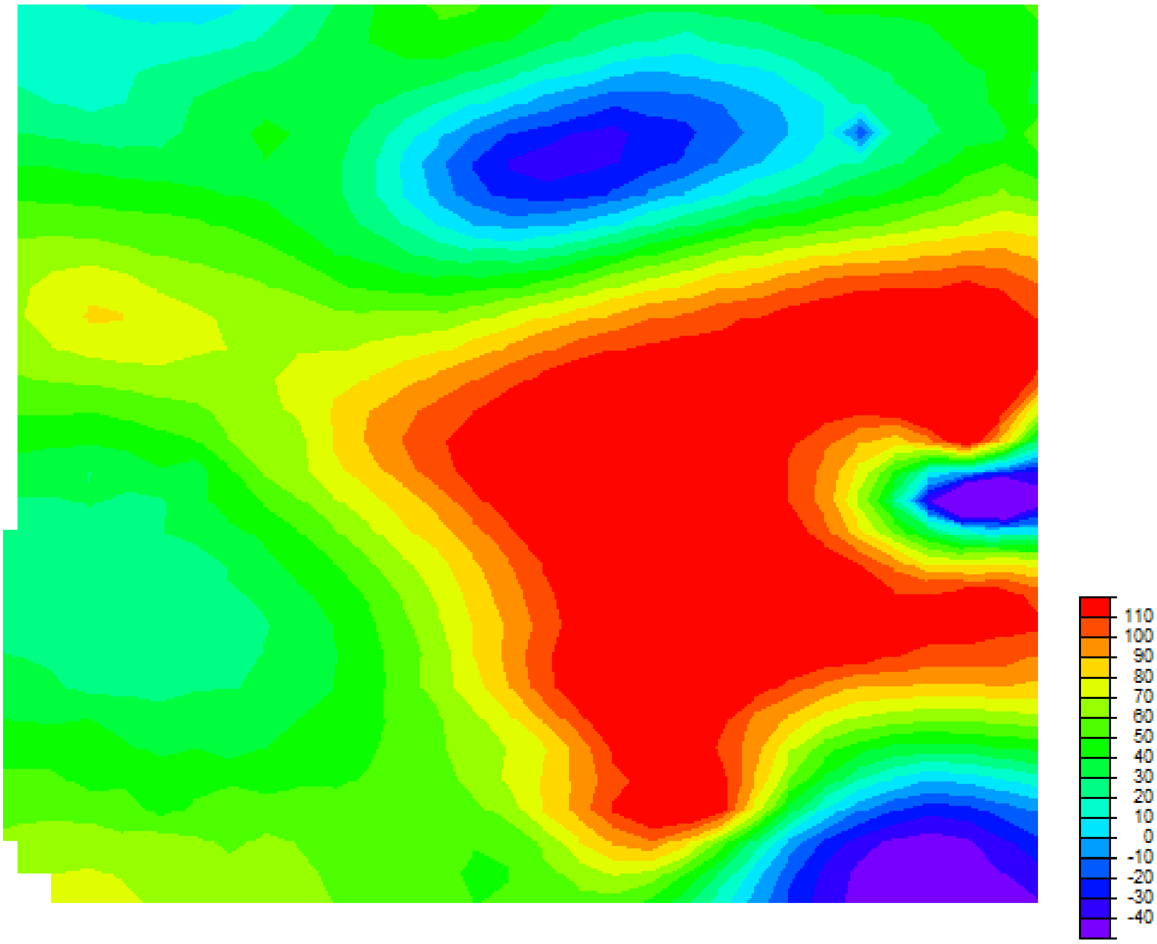

Fig 3: AEROMAGNETIC RASTER MAP OF THE STUDY AREA (nT)

For effective data analysis, processing and interpretation, the WingLink, ArcGIS softwares were used for qualitative interpretation while the MS excel, Surfer 10 and Origin Pro 8 Geophysical software's were used for quantitative interpretation. The data which was obtained in CSV format was opened and digitized in ESRI ArcGIS software for onward processing and interpretation. The data was processed and converted in a format usable by the WingLink visualization software with the aid of the ArcGIS. The digitization was done in grid of 1 km x 1 km spacing and values of TMI, X (latitude) and Y (longitude) were picked at the intersection of the grid nodes.

Manual digitization is the most elementary and least efficient method of digitisation, its accuracy when carefully done, compares favourably with other sophisticated methods using computer programs[14]. The 1 km x 1 km grid points generated over 6000 sample points. The x and y show the coordinates while the z represents the TMI value at the point. This was implemented in ArcGIS 9.3 software and the xyz data was saved as MS Excel file format. The data saved as excel file format was thereafter imported into the Micro soft (MS) excel environment for band pass filtering. The band filtering was carried out so as to create sixteen (16) overlapping spectral windows upon which Fast Fourier Transform (FFT) was performed.

DEPTH DETERMINATION

The depth to sedimentary thickness and its morphology can be determined using spectral depth analysis. Spectral depth technique has being used by several authors in determining the thickness of sediments within their restricted area of study. Aside from the spectral depth method, other automated or semi automated techniques, like Euler Deconvolution, Improved Source Parameter imaging (ISPI), Werner Deconvolution and tilt angle, can as well be used in estimating depth to basement (that is, the thickness of sediments). Therefore, for this study, Spectral analysis is the basis for depth determination using the potential field aeromagnetic data of the study area. It was opined [19] that Spectral analysis has proved to be a powerful and convenient tool in the processing and interpretation of potential field geophysical data. It seeks to describe the frequency content of a signal based on a finite set of data. This technique is believed to provide rapid depth estimates from regularly spaced digital field data, no geomagnetic or diurnal corrections are necessary as these remove only low wave number components and do not affect the depth estimates which are controlled by the high wave number components of the observed field. This technique is based on the shape of the power spectrum for buried bodies with a susceptibility contrast. It is shown for simple bodies [20] and for complex shaped bodies [7] that the depth to the center of mass of the body is easily obtained from the power spectrum of the magnetic field. If the spectrum is plotted on semi-log paper, the slope of the spectrum is equal to the depth to the center of mass. Extremely complex shapes and layering can, however, complicate the spectrum. The spectrum gives information primarily about the location of the top and bottom of a magnetic layer [21]. Nevertheless, this research follows the assumption that magnetic basement is composed of a randomly distributed number of structures. Then by calculating the average of the spectra, the depth for all anomalous sources is determined and this is equivalent to that for a single body at the same depth.

FAST FOURIER TRANSFORM (FFT) PERFORMED ON EACH SPECTRAL WINDOW

FFT mathematical modeling was performed on the 16 spectral aeromagnetic grids (or windows) of 10 km by 10 km for spectral depth analysis using the FFT function in the data analysis tool. For the FFT to be implemented, the 16 grids were imported into the Microcal OriginPro8 software for scientific data analysis and processing. The FFT function was used to separate the TMI data of the windows (called cells) into their frequency component and energy (FFT magnitude or the absolute value of the FFT complex) spectrum. Although, the data was smoothed using smoothing function of the Origin Pro 8. This was necessary since the computed logarithmic energy generally reveals a slowly decreasing mean value within an envelope of erratic rapid variations. The FFT was then performed on the Smoothed TMI data for all the cells. Hence, the discrimination of the anomalies into its energy spectrum and frequency component. To determine the spatial frequency component a sampling interval 1000 m was used applying square window with a one-sided spectrum type normalized to Mean Square Amplitude (MSA). This setting output the Spatial Frequency domain (cycle/m), FFT Complex, and energy (magnitude) spectrum. The log of the energy (Log E) was then plotted against the radial frequency in MS Excel as suggested by Spector and Grant (1970). A straight line is finally visually fit to the energy spectrum, usually in the higher and lower frequency of the figure. The negative of slope of this line is equal to twice the depth (depth= slope/2) to the center of mass of the bodies producing the magnetic field. After the depth has been calculated over one window a new calculation is made over a new window. This continues over the grid until all windows have had their radial spectra calculated and the depths picked.

ESTIMATION OF THE CURIE POINT DEPTH (CPD)

The method of Curie Point Depth determination utilizes spectrum analysis technique to separate influences of the different body parameters in the observed magnetic anomaly field [11]. Two basic methods for estimating the CPD have been stated. They include those that examine the shape of isolated magnetic anomalies [7] and those that examine the statistical properties and patterns of the anomalies [22]. These two methods, however, provide the relationship between the spectrum of the magnetic anomalies and the depth of a magnetic source by transforming the spatial data into frequency domain. This research adopted the method in which the top boundary and the centroid of magnetic sources were calculated from the spectrum of magnetic anomalies which were used to estimate the basal depth of magnetic source. For the possible determination of the CPD, the residual data was divided into sixteen (16) overlapping windows as shown below:

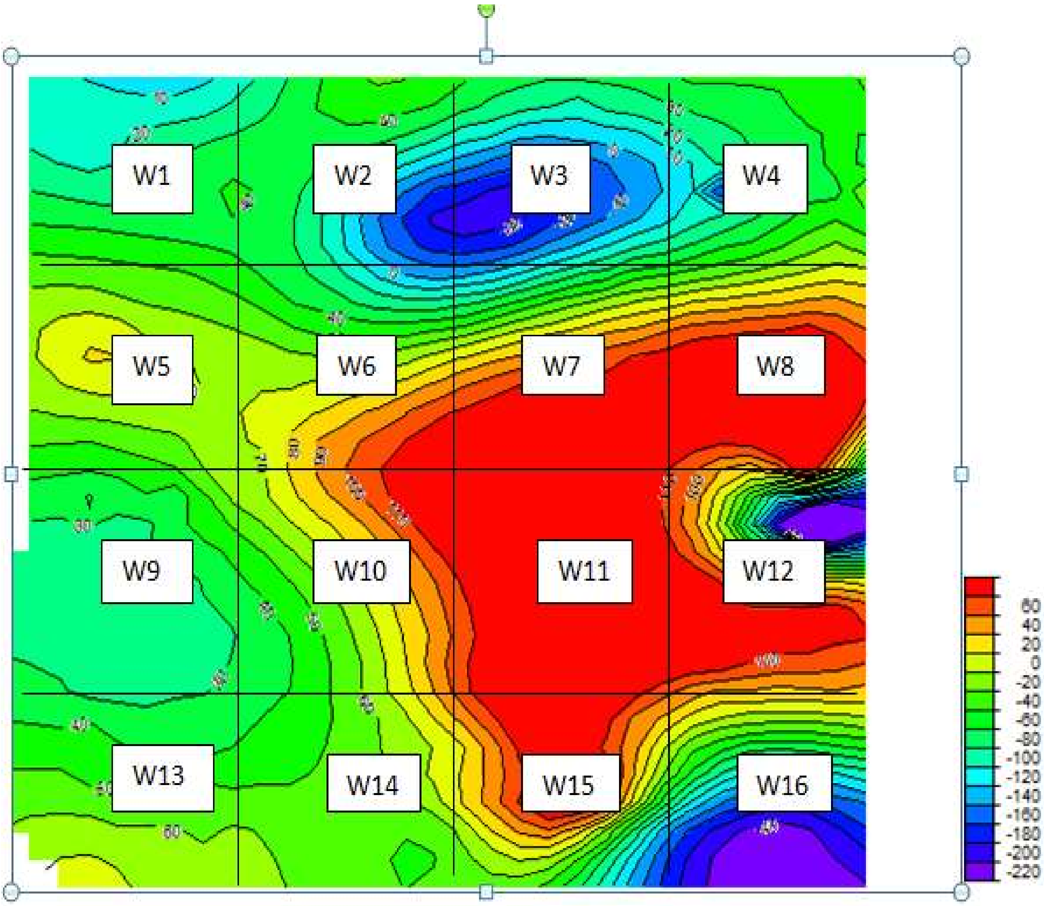

Fig. 4: Sixteen (16) overlapping windows for CPD determination via spectral analysis

Spectral analysis was thereafter performed on the sixteen windows. From the spectral depth analysis the following steps were then undertaken

- **STEP ONE**: Estimation of the depth to Centroid (Z_C) of the magnetic sources from the slope of the low frequency component part of the energy spectrum.
- **STEP TWO**: Estimation of the depth to the top boundary (Z_t) of magnetic sources from the slope of the high frequency component part of the spectral segment.

The calculation of Z_C and Z_T then lead to the calculation of the basal depth Z_b using equation 4 and this is assumed [23,24] as the CPD

$$Z_b = 2Z_C - Z_t \qquad 4$$

Where

Z_b = the basal depth

Z_c = the centroid depth

HEAT FLOW AND THERMAL GRADIENT DETERMINATION

A relation showing one dimensional heat conductive model was used for this study in order to estimate the heat flow and the geothermal gradient in the absence of a heat flow data. This model is based on the Fourier's law [23]. Fourier's law is mathematically expressed as [23]

$$q = \kappa \; {}^{dT}\!/_{dZ} \qquad 5$$

Where

q = the heat flow

κ = the coefficient of thermal conductivity

${}^{dT}\!/_{dZ}$ = an assumed constant as no heat gain or loss above the crust and below the CPD

The Curie temperature (θ_c) is defined [10] as

$$\theta = \left[{}^{dT}\!/_{dZ}\right] Z_b \qquad 6$$

Equating 5 and 6, we have

$$q = \kappa \left[{}^{\theta}\!/_{Z_b}\right] \qquad 7$$

Equation 4 was therefore used in this research work in determining the heat when the Curie point depths were known. For these estimations to be possible, a standard for curie point isotherm of 580^{o}C and thermal conductivity of 2.5 $Wm^{-1}°C^{-1}$ was used [14]. Finally, the geothermal gradient was determined using equation 6, hence we have:

$$\frac{dT}{dz} = \frac{\theta}{Z_b} \qquad 8$$

Where

$\frac{dT}{dZ}$ = geothermal gradient

Z_b = the basal depth

θ = the standard curie point isotherm of 580^0C

Also, $\frac{dT}{dZ}$ can be estimated by applying Fourier's model stated in equation 5, from equation 5 we have:

$$\frac{dT}{dz} = \frac{q}{\kappa} \qquad 9$$

Where

q = the heat flow

κ = thermal conductivity and is given as 2.5 $Wm^{-1}°C^{-1}$ for igneous rocks

RESULTS AND INTERPRETATION

In this work, quantitative analysis was achieved by using spectral depth analysis in computing the depth to magnetic basement on each of the spectral windows. Performed on each of the windows is FFT. The FFT modeling aided in decomposing each of the window data set into its frequency components. Thereafter, plots showing log of energy (LogE) versus the radial frequency were made. Based on the plots, table 1 which shows the centriod depth (Z_C) and the depth to the top boundary (Z_t) of the magnetic sources was generated. The Z_C is due to magnetic sources within the basement while the Z_T is due to magnetic sources within the sedimentary section. In otherwords, Z_C and Z_t reflect magnetic sources due to deep and shallow seated features. Z_C is a true reflection of Precambrian magnetic basement bodies and these values ranges from -7.7 km to -12.0 km while Z_t possibly depicts magnetic effect due to short wavelength sources and these ranges from - 0.5 km m to - 3.1 km.

Nevertheless, the CPD were computed and this work found out that this varies between -14.9 km and -23 km while the geothermal gradient and the heat flow varies from -25.2 to -37.9 $^oCkm^{-2}$ and -63 to -97.3 $mWm\text{-}^2$ respectively. Summary of the various windows with their various parameters calculated are shown in Fig. 5.

Table 1: Estimation of geothermal gradient and heat flow from CPD via spectral analysis

WINDOW	SLOPE		DEPTH(km)			AVERAGE DEPTH (km)	GEOTHERMAL GRADIENT	HEAT FLOW
	M_1	M_2	Z_c	Z_t	Z_b		($^oCkm^{-2}$)	(mW m-^{2})
W1	-23995.5	-2011.47	-12	-1	-23	-6.5	-25.2	-63
W2	-17762	-1361.91	-8.9	-0.7	-17.1	-4.8	-33.9	-84.8
W3	-23612.7	-3218.74	-11.8	-1.6	-22	-6.7	-26.4	-65.9
W4	-18315.6	-2817.4	-9.2	-1.4	-17	-5.3	-34.1	-85.3
W5	-19116.1	-2461.38	-9.6	-1.2	-18	-5.4	-32.2	-80.6
W6	-20307.3	-3801.76	-10.2	-1.9	-18.5	-6	-31.4	-78.4
W7	-21503.2	-2011.81	-10.8	-1	-20.6	-5.9	-28.2	-70.4
W8	-19213.4	-3322.61	-9.6	-1.6	-17.6	-5.6	-33	-82.4
W9	-22431.8	-1704.3	-11.2	-0.9	-21.5	-6	-27	-64.4
W10	-18334.1	-6231.6	-9.2	-3.1	-15.3	-6.1	-38	-94.8
W11	-15419.3	-1002.18	-7.7	-0.5	-14.9	-4.1	-38.9	-97.3

W12	-17332.5	-2234.33	-8.7	-1.1	-16.3	-4.9	-35.6	-89
W13	-21334.1	-5604.3	10.7	-2.8	-18.6	-6.8	-31.2	-78
W14	-22332.1	-2101.38	-11.2	-1.1	-21.3	-6.2	-27.2	-68.1
W15	-20119.2	-5770.28	10.1	-2.9	-17.3	-6.5	-33.5	-83.8
W16	-15773.2	-997.08	-7.9	-0.5	-15.3	-4.2	-37.9	-94.8

WINDOW 1 $Z_b = -23$ $Z_c = -12$ $Z_t = -1$	WINDOW 2 $Z_b = -17.1$ $Z_c = -8.9$ $Z_t = -0.7$	WINDOW 3 $Z_b = -22$ $Z_c = -11.8$ $Z_t = -1.6$	WINDOW 4 $Z_b = - 17$ $Z_c = -9.2$ $Z_t = -1.4$
WINDOW 5 $Z_b = -18$ $Z_c = -9.6$ $Z_t = -1.2$	WINDOW 6 $Z_b = -18.5$ $Z_c = -10.2$ $Zt = -1.9$	WINDOW 7 $Z_b = -20.6$ $Z_c = -10.8$ $Z_t = -1.0$	WINDOW 8 $Z_b = -17.6$ $Z_c = -9.6$ $Z_t = -1.6$
WINDOW 9 $Z_b = -21.5$ $Z_c = -11.2$ $Z_t = -0.9$	WINDOW 10 $Z_b = -15.3$ $Z_c = -9.2$ $Z_t = -3.1$	WINDOW 11 $Z_b = -14.9$ $Z_c = -7.7$ $Z_t = -0.5$	WINDOW 12 $Z_b = -16.3$ $Z_c = -8.7$ $Z_t = -1.1$
WINDOW 13 $Z_b = -18.6$ $Z_c = -10.7$ $Z_t = -2.8$	WINDOW 14 $Z_b = -21.3$ $Z_c = -11.2$ $Z_t = -1.1$	WINDOW 15 $Z_b = -17.3$ $Z_c = -10.1$ $Z_t = -2.9$	WINDOW 16 $Z_b = -15.3$ $Z_c = -7.9$ $Z_t = -0.5$

Fig. 5: Succinct view of the various windows and their various depths (km)

DISCUSSION OF FINDINGS

Graph of the spectral energies revealed that the depth due to the deep seated anomalous sources or the centriod depth (Z_c) varies from 7.7 km to 12.0 km. Conversely, the depth due to the shallow bodies or due to the top boundary of magnetic sources ranges between 0.5 km m to 3.1 km while the corresponding CPD ranges from 14.9 km to 23.0 km. The true or average depths for each of the respective windows were calculated and this varies between 4.1 km and 6.1 km. Generally, a true depth of 5.3 km was ascertained within the study area. The depth value of 5.3 km suggests relative sedimentary thickness. These results compare favourably with the results of other researchers[1] within the lower Benue trough. Although with information on the crustal temperature missing in his work, He obtained the depths due to the deep seated sources to range from 7.2 km to 13.0 km while the depths values for the shallow sources varies from 0.4 km to 3.9 km, but on the average, he obtained a true depth of 7 km. Within parts of lower Benue trough, a thickness value of 5.6 km is believed to exist [25]. This result is not a far cry from what was obtained for this study. Also, the CPD values [13] were obtained within the area. The CPD depths were not in variance with those CPD values obtained for this study. However within the study area, the CPD within the study area vary from 23.80 km to 28.70 km. Shallower CPD can be seen towards the southeastern portion of the study area and this falls within the Oji river settlement province perceived to be the crystalline basement area. This is a possible reflection of the thinning of the crust under Benue rift [13]. They further stated that the basement area is as a result of the upwelling of magma on Cameroon Volcanic Line (CVL) during the tertiary period. Hence, the possibility of igneous intrusive that provide appropriate geothermal energy needed for the maturation of hydrocarbon found within that region. This particular findings is therefore in support of the fact that geo thermally active regions are usually shallower as it consist of igneous intrusive that could foster or be detrimental to hydrocarbon maturation. The heat flow within the study area varies between -64.4 mWm^{-2} and -97.3 mWm^{-2} but with an average of about 80.1 mWm^{-2} while the geothermal gradient varies from 25.2 $^oCkm^{-2}$ to 38.9 $^oCkm^{-2}$ but with an average of about 32.1 $^oCkm^{-2}$ existing within the area under review. The heat flow values and the geothermal gradient values obtained further validate the fact that the shallowest depth occurring within window eleven (11) is a good geo thermally active area. Also, windows 2, 4, 8, 10, 12, 15 and 16 are possible geothermal resource areas. These areas will not, thus, be much productive in terms of oil and gas.

CONCLUSION

The study area is characterized with high heat flow and geothermal gradient with relatively low magnetic intrusions which could be detrimental to the quantity of hydrocarbon exploration. Therefore, the high heat flow and moderate geothermal gradient observed in this study are possible tectonically induced rifting and magmatism that occurred during Pan–African Orogeny.

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