Investigating the Geothermal Energy Potentials within the Central Benue Trough Nigeria: Insight from Airborne Potential Field Data

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Abstract:- **This research focuses on using geothermal parameters of Curie point depth, geothermal gradient and heat flow from spectral techniques of aeromagnetic data in finding the possible geothermal hot spots existing around this region of the Benue Trough Nigeria in order to help solve the energy-related challenges facing the country. The study adopted qualitative methods of total magnetic intensity (TMI), reduction to the magnetic equator (RTE) as well as quantitative interpretations of spectral analysis which involved division of the reduction toequator map into 25 equal overlapping spectral blocks and the log of spectral energies were plotted against wave number. The Centroid depth (Z_0) and depth to top boundary (Z_t) obtained from the plots, were used to calculate the Curie point depth (CPD), which was later used for computation of geothermal gradient (GG) and heat flow (HF) of the area. The results computed shows that, Curie point depth, ranged from 8.61 to 36. 04 km with an average depth of 14.81 km, the geothermal gradient ranged between 16.09 to 70.81 °C /km, with an average value of 45.39 °C /km while the heat flowranged from 40.23 to 177.03 mWm^{-2}, with an average value of 113.49 mWm^{-2}. It observed from the contour maps that, the deepest Curie point depth is located southwestern part of the area, while the shallower and moderatedepths spreads across approximately 65% of the total research area. The geothermal and heat flow contourmaps showedgeothermal energy hot spotsaroundSouthwestern, Eastern and Northernparts areascorresponding to Otobi, Otukpo, Taraku, Nov, Moi Igbo, Igbor, Wannune, Lafia, Giringwe, Fiyayiand Eastern parts of Kastina- Ala. Thus, this hot spot areas is suitable for geothermal energy exploitation/explorationand harnessing this areas will address the power challenges across the states of this study and Nigeria at large.**

***Keywords*:-** *Airborne Magnetic Data, Curie Point Depth Isotherm, Geothermal Gradient, Heat Flow, and Geothermal Energy Potentiality.*

I. INTRODUCTION

Nigerianhas been faced with this history of inadequate production of electricity, which has given rise to insufficient power supply and distribution over the years. This is because, the existing power plants can only generate less than or equal to 4,000 MW despite its installed capacity of 12,500 MW (Power Africa, 2018). This challenging factor of inadequate supply of electricity will continue to face the country because the increase in population and industrialization has exceeded the demands for the energy generated. Therefore, there is urgent need to locate an alternative source of energy (renewable energy) like geothermal energy. Geothermal energy has become a sustainable and alternative source of energy in many countries of the world today. The biggest advantage geothermal energy is its constant availability, cost effectiveness, unpolluted and clean source of energy. The geothermal energy results from the decay of isotopes of Potassium, Uranium and Thorium and the formation of the earth molten magma (Downing and Gray, 1986). This energy is also manifested on the terrestrial surfaces in form of volcanoes and fumaroles (openings where volcanic gases are released), hot springs, steaming grounds, altered grounds and geysers (Ochieng, 2013). The essential components of this geothermal system include; heat source, recharge regime, permeable reservoir and cap rock. The scholarly publications of (Jessop *et al.*, 1976; Cull and Conley, 1983) opined that, in normal thermal continental regions, the average heat flow is about 60mWm^{-2}, whereas heat flow values of 60 -100/110 mWm^{-2} good geothermal source, while values in excess of 100/110 mWm^{-2} indicates anomalous conditions. The growing interest in finding sources of energy that are renewable, friendly, and capable of reducing greenhouse gas emissions, which will be relatively sufficient for the growth of our Nation's economy influenced the choice of this research work on investigating the geothermal system of parts of the central Benue Trough Nigeria, which if harnessed will address the power challenges across the states of this study and Nigeria at large. In this study, we shall use aeromagnetic data of the area as reconnaissance tool to study the regional geothermal system of the Benue Trough. This region of the Benue Trough (Central Benue Trough) was chosen because of the evidence of hot springs located across the region. The publications of (Babalola, 1984; Garba *et al.*, 2012; Sedara and Joshua, 2013; Ikechukwu *et al.*, 2015;

Abraham and Nkitnam 2017; Okiyi *et al.*, 2021) listed some known thermal or warm springs situated in the Central (middle) regions of the Benue Trough. This thermal or warm springs are Keane-Awe Thermal Springs (32 °C), Akiri Warm Spring (54 °C) and Lamurde Hot Spring or RuwanZafi (35 °C), near Numan. Few geophysical investigations have been carried out by earth scientists in the Central (middle) Benue Trough Nigeria, which has proven to have geothermal potentials (Akinnubi *et al.*, 2018;Ayuba and Nur, 2018;Aliyu *et al.*, 2018; Salako *et al.*,2020; Abdulahi and Kumar, 2020; Tende *et al.*, 2021; Ayatu *et al.*, 2023; Aigbedion *et al.*,2022; Ngene *et al.*,2022). However, in view of this crustal temperature studies across the area, the results of this present study would add to the existing/available geophysical informations that will aid the campaign for geothermal exploration and exploitation in the region.

II. LOCATION AND GEOLOGY OF THE STUDY AREA

The study area which is located between latitudes $7^{\circ}00'$ and $8^{\circ}30'$ North and longitudes $8^{\circ}00'$ and $9^{\circ}30'$ E; is within Benue, Nasarawa and parts of Taraba states of the Cental Benue Trough. It has a total coverage area of about 27,225 km^2. (Cratchley and Jone, 1965; Whiteman, 1982) stated that, the Current research area located within the Benue Trough Nigeria, is an extensive Cretaceous folded rift basin that cuts across Nigeria with an extension of about 100 km from the fringe of the Niger Delta in the eastern part of the country through the Gongola Basin to the Bornu Basin in the North. The width of the basin is approximately 250km (Whiteman, 1982). The Benue Trough as one of the inland sedimentary basins in Nigeria aligned in the NE-SW direction, is part of the long stretch arm of the Central African rift system that originated from the early Cretaceous rifting of the Central and West African basement uplift (Obaje, 2004). The basin is sub-divided into the Lower, Middle (Central) and Upper Benue Trough. According to (Reyment, 1965; Short and Stauble, 1967; Murat, 1972; Nwachukwu, 1972; Olade, 1975), the depositional history of the Benue Trough is characterized by several phases of marine regression and transgression, which is mainly the Cenomanian and the Santonian deformations. The scholarly publication of Offodile, (1976) stated six cretaceous sedimentary formations in the Central Benue Trough, this includes; Asu River Group, Keana Formation, Awe Formation, Ezeaku Formation, Awgu Formation and Lafia Formation. The oldest formation, Asu River group being middle to Albian of age and the youngest, Lafia Formation is of the Maestrichtian age (Obaje, 2004). However, the current study area which is within the Central Benue Trough is underlain by alluvial deposits along river coasts, younger basalt flows encountered around EzeAku Groups and Agwu formations. The Nkporo, Agwu, Lafia –Wukari, Eze-Aku, Asu-River and Bima formations which consists of lithological compositions of shale, mudstone, limestone, sandstone, sandy shale, black shale, siltstone, feldspathic sandstone calcerious sandstone, shelly limestone and sandstone intercalations. There are exposures of basement rocks which are mainly igneous intrusives; this are biotite granite, rhyolite, porphyritic granite, quartzite and undifferentiated schists, including phyllites, banded gneiss/ biotite migmatiteporphyroblastic gneiss silicified, sheared rocks and large quartz veins that intruded into the sedimentary overburden as shown in Fig. 2.

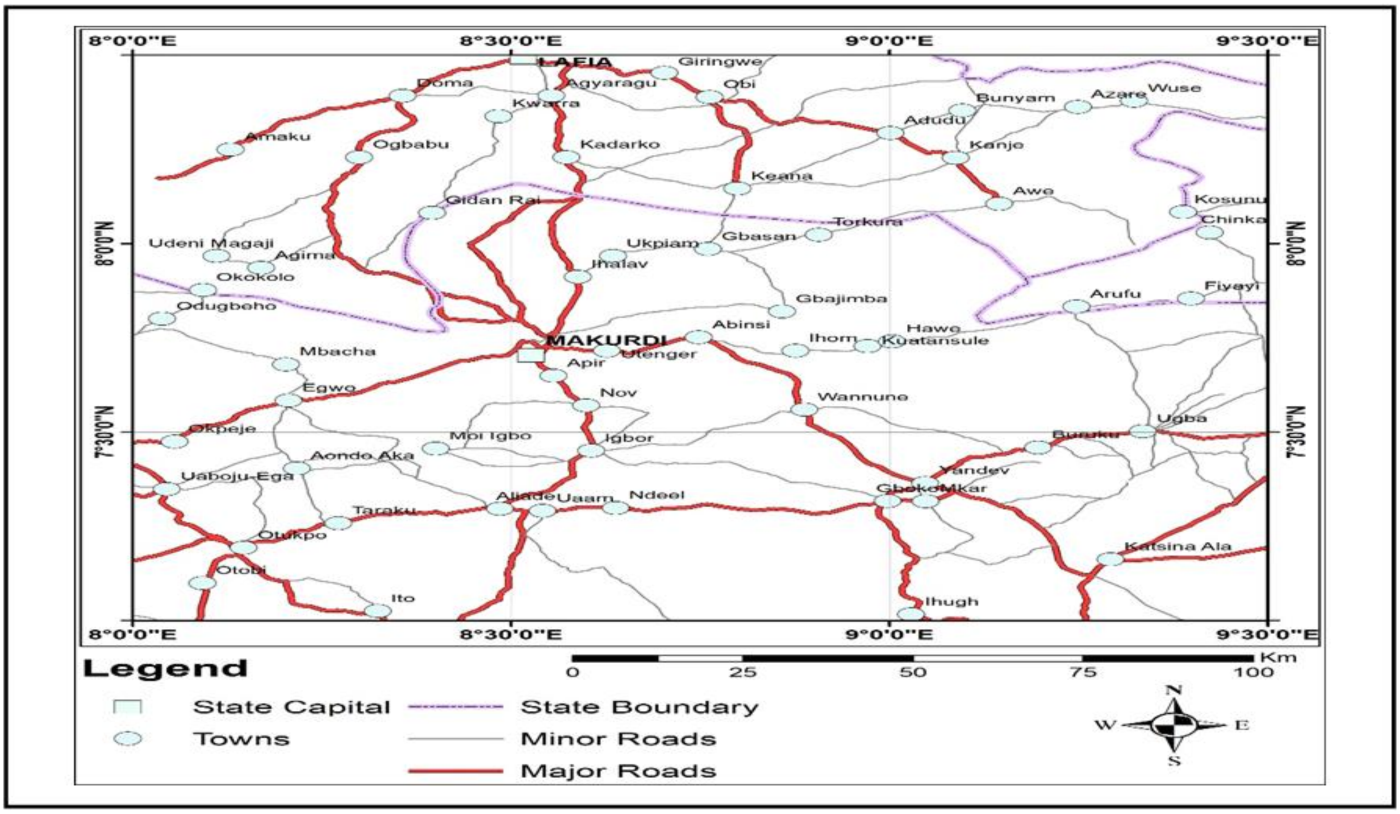

Fig 1 Location Map of the Study Area

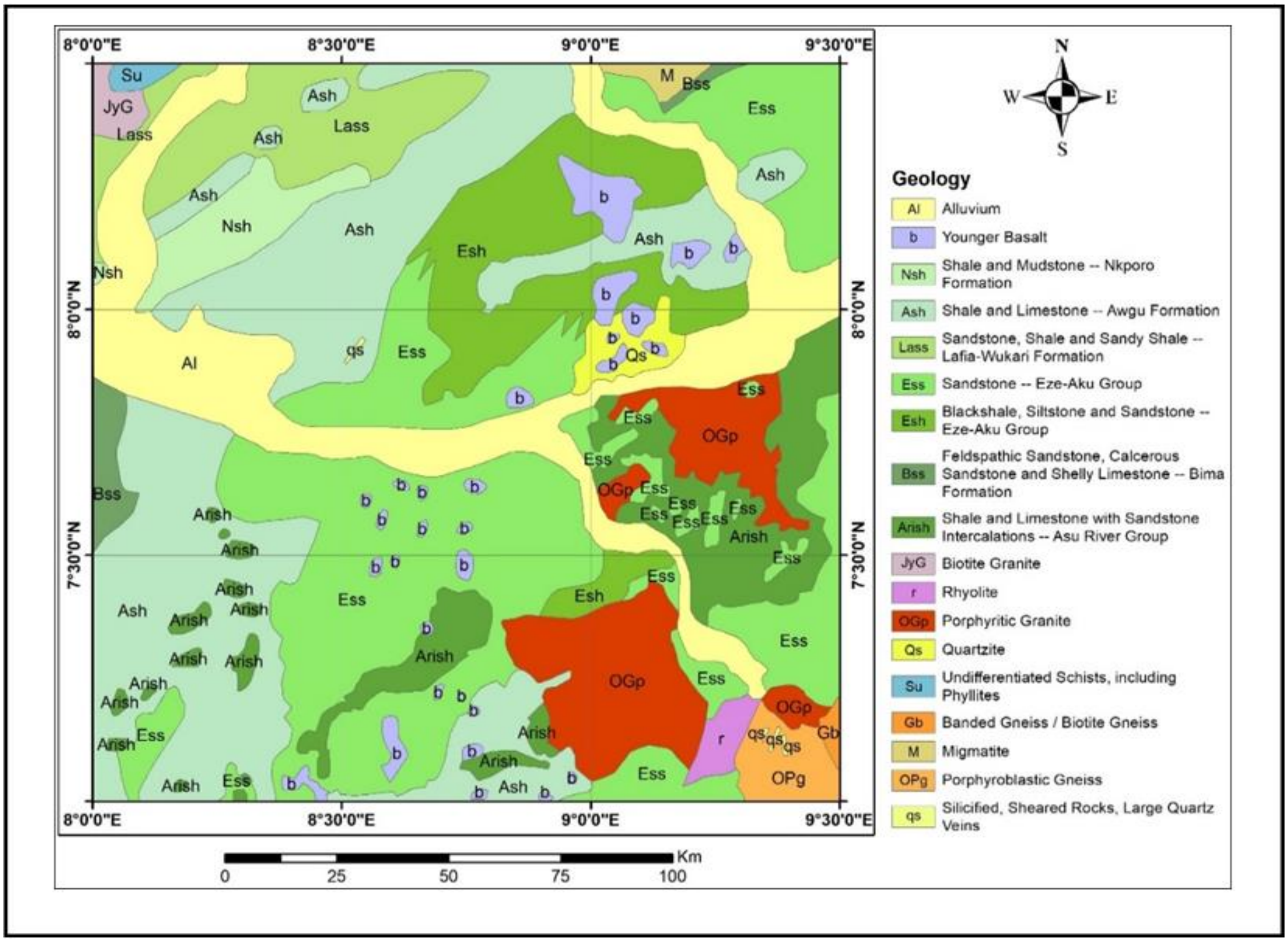

Fig 2 Geology Map of the Study Area

III. MATERIALS AND METHODS OF DATA ANALYSIS

A. *Materials*

The materials adopted in the current study are softcopy digitized data sheets of Doma (230), Lafia (231), Akiri (232), Agana (250), Makurdi (251), Akwana (252), Otupko (270), Gboko (271) and Katsina Ala (271) carried out in Nigeria between the year 2005-2009 by Nigeria Geological Survey Agency (NGSA). A flight altitude of 0.08 km, tie and flight line spacing of 2 km and 0.5 km was used for data acquisition. This digital data acquired was made available on scale of 1:50000. The Software applications employed for the study are the Oasis Montaj 8.4, ArcGis, MATLAB, and Surfer 14.

B. *Method of data analysis*

The process started with merging the nine (9) aeromagnetic data sheets covering the study area to form a single data base using the Oasis Montaj 8.4 software, such that the Total Magnetic Intensity (TMI) map of the area will be produced using Bi-directional line gridding method. Thereafter, the Total Magnetic Intensity map produced was reduced to the equator (TMI-RTE), this was done in accordance with the I.G.R.F 2005 standard reduction method using equation 1 below. Amplitude corrections of inclination -9.3 and declination of - 1.7 was used as basic inputs. This is because reduction to magnetic equator is specifically carried out in low magnetic latitudes regions in which the study area falls (i.e. areas with geomagnetic inclination less than 15°). This filtration technique centers the peaks of low magnetic anomalies over their sources or exact positions.

$$T(\theta) = \frac{\{\sin I - i\cos I \cos(D-\theta)\}^2 \times \{-\cos^2(D-\theta)\}}{\{\sin^2 I_a + \cos^2 I_a \cos^2(D-\theta)\} \times \{\sin^2 I + \cos^2 I \cos^2(D-\theta)\}} \quad (1)$$

If , =1. Where, = TMI reduced to the Equator, = Geomagnetic inclination, = Inclination for amplitude correction (never less than), D = Geomagnetic declination,Sin I = Amplitude component andicosIcos(D -) = phase components.

- *Spectral Analysis*

The Spectral depth estimation technique developed by Spector and Grant (1970) entails estimating and interpreting the spectrum of a potential field data (Rabeh, 2009). This technique is based on the principle that the magnetic field measured at the surface can be considered as an integral of signature from all depths (Rabeh, 2009). The Fast Fourier Transform (FFT) algorithm, which computes the Discrete Fourier Transform (DFT) is a mathematical tool employed for spectral depth analysis and a regularly spaced data such as aero potential field data (aeromagnetic data). This algorithm used for spectral analysis, when applied to the aero geophysical data converts the spatial (real space) data to a frequency data. Telford *et al.* (1990) stated that, the major advantage of Spectral depth technique is its capacity to filter virtually all the noise from the data and loosing no information during the data processing by overlapping data operations which are easier in the transform domain. The potential field data (magnetic or bouguer) anomalies caused by shallow sources are specifically more dominant by higher wave number components than those emanating from deep structures. This effect would be calculated by computing the power spectrum of the anomalies since the long power spectrum has a linear gradient whose magnitude is dependent upon the depth of the sources (Spector and Grant, 1970).

The analysis started with division of the Reduction to the magnetic equator (RTE) map into twenty five overlapping blocks as thus; block 1 – 25 of spectral probe of 55 km by 55 km such that longer wavelengths can be accommodated and give room for the depth analysis of the area. Thereafter, each of the 25 blocks was subjected to a Log Power Spectrum (a filtering technique) of the oasis Montaj software. This transformed the magnetic data from real space to wavenumber or frequency domain via Fast Fourier Transform (FFT) algorithm application. This art generated the spectral energies from which the depth values relating Z_0 (depth to the centroid) and Z_t (depth to the top boundary) was estimated from the slope of the first and second longest wavelengths portion of the spectrum adopting the algorithm of equation 2 and 3 respectively. The SPC file of the twenty five blocks obtained from this analysis were exported into Microsoft Excel worksheets one after the other, thereafter, these 25 spectral (SPC) energy files were inputted into a spectral program plot (SPP) developed with MATLAB. The twenty five (25) spectral energies were plotted with the developed Matlab program such the depth values of (Z_0 and Z_t) were obtained. A typical example plot of energy against frequency (wavenumber) is as shown in.

$$\ln\left[\frac{\sqrt{P_{(s)}}}{|s|}\right] = \ln A - 2\pi|s|Z_o \quad (2)$$

Where $P_{(s)}$ is the radially mean power spectrum of the anomaly, *A* is a constant and |s| is wavenumber

$$\ln\left[\sqrt{P_{(S)}}\right] = \ln B - 2\pi|s|Z_t \quad (3)$$

Where *B* is total amount of constant independent of |*s*|.

- *Estimation of Curie point Depth, Geothermal Gradient and Heat Flow*

The Curie point depth (basal depth) Z_b was calculated using equation 4 adopted by (Tanaka *et al.*, 1999; Eletha and Udensi, 2012;Salako *et al.*, 2020).

$$Z_b = 2Z_0 - Z_t \quad (4)$$

Where, Z_0 is depth to the centroid and $Z_t$is depth to the top boundary

The Geothermal gradient which is the rate of increase in temperature per unit depth in the earth due to outflow of heat from the center was calculated using the equation 5 as suggested by Tanaka *et al.* (1999), that the Curie temperature ($\boldsymbol{\theta}$) can be calculated using the equation stated below:

$$\theta = \left(\frac{dT}{dZ}\right) Z_b \quad (5)$$

Re-writing equation 4, the geothermal gradient can be obtained as;

$$\frac{dT}{dZ} = \frac{\theta}{Z_b} \quad (6)$$

Hence, the geothermal gradient was calculated using equation 6

Heat flow which is the flow of heat energy by conduction, convention and radiation in sediments was calculated taking a one-dimensional case under assumption that the direction of temperature variation is vertical and the temperature gradient is constant, Fourier 's law takes the form of equation 7

$$q_z = k\frac{dT}{dz} \quad (7)$$

Where q_z heat flow and k is the thermal conductivity.A Curie temperature value of $\boldsymbol{\theta}$=580°C and thermal conductivity k= 2.5Wm^{-1} ^{0}C^{-1} which is the average thermal conductivity for igneous rocks were employed in the study as standard (Eletha and Udensi, 2012 and Salako *et al.*, 2020)

IV. RESULTS AND DISCUSSION

- *Total magnetic intensity and Reduction to the magnetic equator*

The total magnetic intensity and reduction to the equator maps (Fig. 3a and 3b) is characterized by positive and negative anomalies ranging from -58.49 to 99.80 nT and -53.92 to 96.97 nT respectively, indicating high (pink to red colours), moderate (yellow) and low (blue) in magnitude depicting that the area is magnetically heterogeneous. The high/positive anomalies may be attributed to shallow basements and regions of igneous intrusions within the sedimentary basin or basement resulting from magmatism as observed in the geologic map of the study area whereas the low/ negative anomalies depicted sedimentary terrains as well as deep seated structures in the area.

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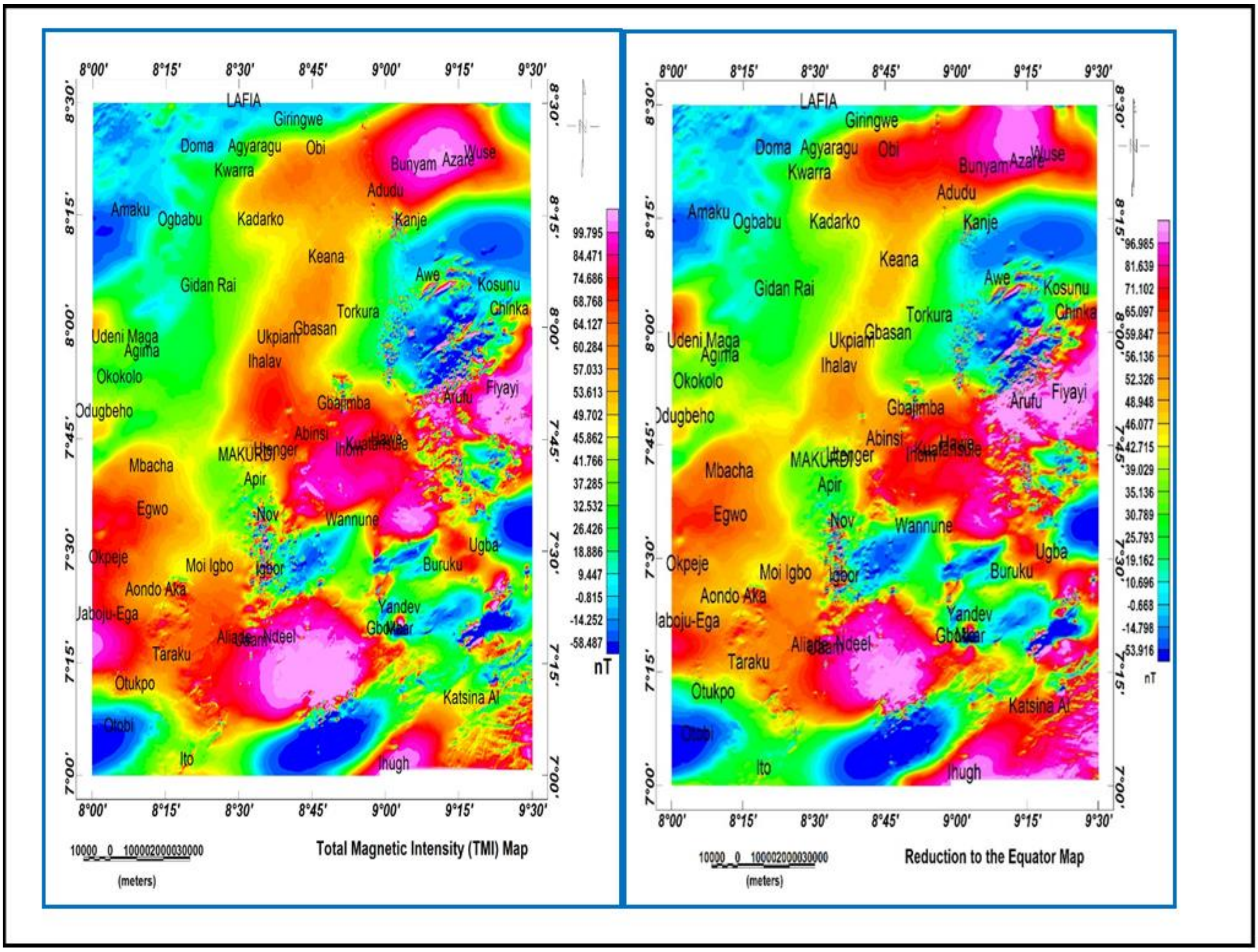

Fig. 3a: Total Magnetic Intsesity Map of the area. (3b) Reduction to the Eqautor Map of the area.

➢ *Spectral Analysis*

The division of the reduction to the equator map into 25 equal overlapping spectral blocks and the plotting of the log of spectral energies against wave number generated values for the Centroid depth (Z_0) and depth to top boundary (Z_t). The values obtained were used to calculate the Curie point depth (CPD), which was later employed for computation of geothermal gradient (GG) and heat flow (HF) of the area. Table 1 summarized the results from the 25 overlapping blocks. The samples of graphs of spectral energy against frequency (wavenumber) obtained from block 1-25 is shown in Figures 4a & b.

Table 1 Summary of the Results of Spectral Analysis from the 25 Overlapping Spectral Blocks

Blocks	Long. (°)	Lat. (°)	Depth to centroid Z_0 (Km)	Depth to top Z_t(Km)	Curie Point Depth Z_b (Km)	Geothermal Gradient (°C/Km)	Heat Flow (mW/m^2)
1	8.25	8.25	8.41	1.61	15.21	38.13	95.33
2	8.50	8.25	9.41	2.20	16.62	34.90	87.25
3	8.25	8.25	10.70	3.50	17.90	32.40	81.00
4	9.00	8.25	8.90	3.37	14.43	40.19	100.48
5	9.25	8.25	8.27	4.53	12.01	48.29	120.72
6	8.25	8.00	5.96	3.31	8.61	67.36	168.40
7	8.50	8.00	5.86	2.45	9.27	62.57	156.43
8	8.75	8.00	6.08	2.06	10.10	57.43	143.58
9	9.00	8.00	6.99	1.66	12.32	47.08	117.70
10	9.25	8.00	6.89	1.38	12.40	46.77	116.93
11	8.25	7.75	5.66	3.13	8.19	70.81	177.03
12	8.50	7.75	6.02	3.36	8.68	66.82	167.05
13	8.75	7.75	6.22	2.65	9.79	59.24	148.10

14	9.00	7.75	7.57	2.29	12.85	45.14	112.85
15	9.25	7.75	8.14	2.59	13.69	42.37	105.93
16	8.25	7.50	5.88	2.77	8.99	64.52	161.30
17	8.50	7.50	13.00	2.89	23.11	25.09	62.73
18	8.75	7.50	17.20	4.70	29.71	19.52	48.80
19	9.00	7.50	8.12	5.84	10.40	55.77	139.43
20	9.25	7.50	5.88	2.10	9.66	60.04	150.10
21	8.25	7.25	14.90	6.93	22.87	25.36	63.40
22	8.50	7.25	19.60	3.16	36.04	16.09	40.23
23	8.75	7.25	11.20	3.96	18.44	31.45	78.63
24	9.00	7.25	6.56	1.83	11.29	51.37	128.43
25	9.25	7.25	9.93	2.30	17.56	33.03	82.56
					Av. = 14.81	**Av.= 45.39**	**Av. =113.49**

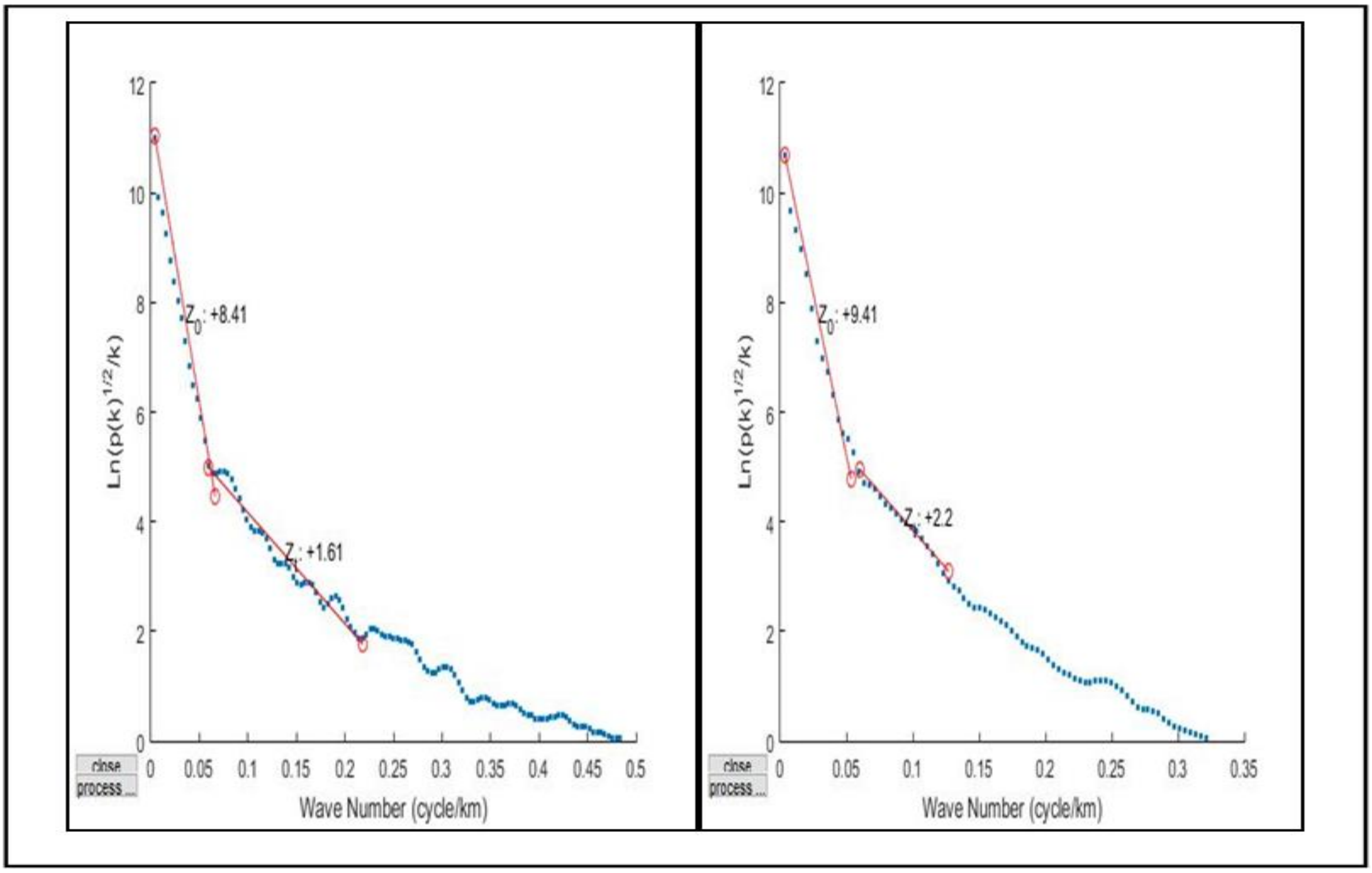

Fig.4a: block 1 Fig.4b: block 2

V. RESULTS AND DISCUSSION

Curie point Depth (CPD). The results of the CPD estimated depth values between 8.61 km to 36.04 km with an average of 14.81 km. The 2D and 3D contour maps (5a & 5b) of the CPD was produced to assist in explaining the results. The contour maps revealed high CPD depths at the south western parts of the area (Ito, Taraku, Otupko, Otobi, Aliade, Ndeel, Igbor Parts, Moi-Igbo, Wannune and Aondo Aka), moderate depths covering about 45% of the total area while the lowest depths were seen at northcentral towards the northwestern and south eastern parts (Keana, Giden Rai, Udeni, Magaji, Agima, Okokolo,Odugbeho, Mbacho, Abinsi, Parts of Gbajimba and Torkura). The scholarly publication of (Bhattacharyya and Leu 1975; Tanaka *et al.*, 1999) stated that, Curie point depth is greatly dependent on the mineralogical contents and geological conditions of an area, because they are shallower in the volcanic and geothermal field. The moderate and low depths values might be as a result of igneous intrusion or dominance of Ezeaku formation (sandstone and limestone) in the area.

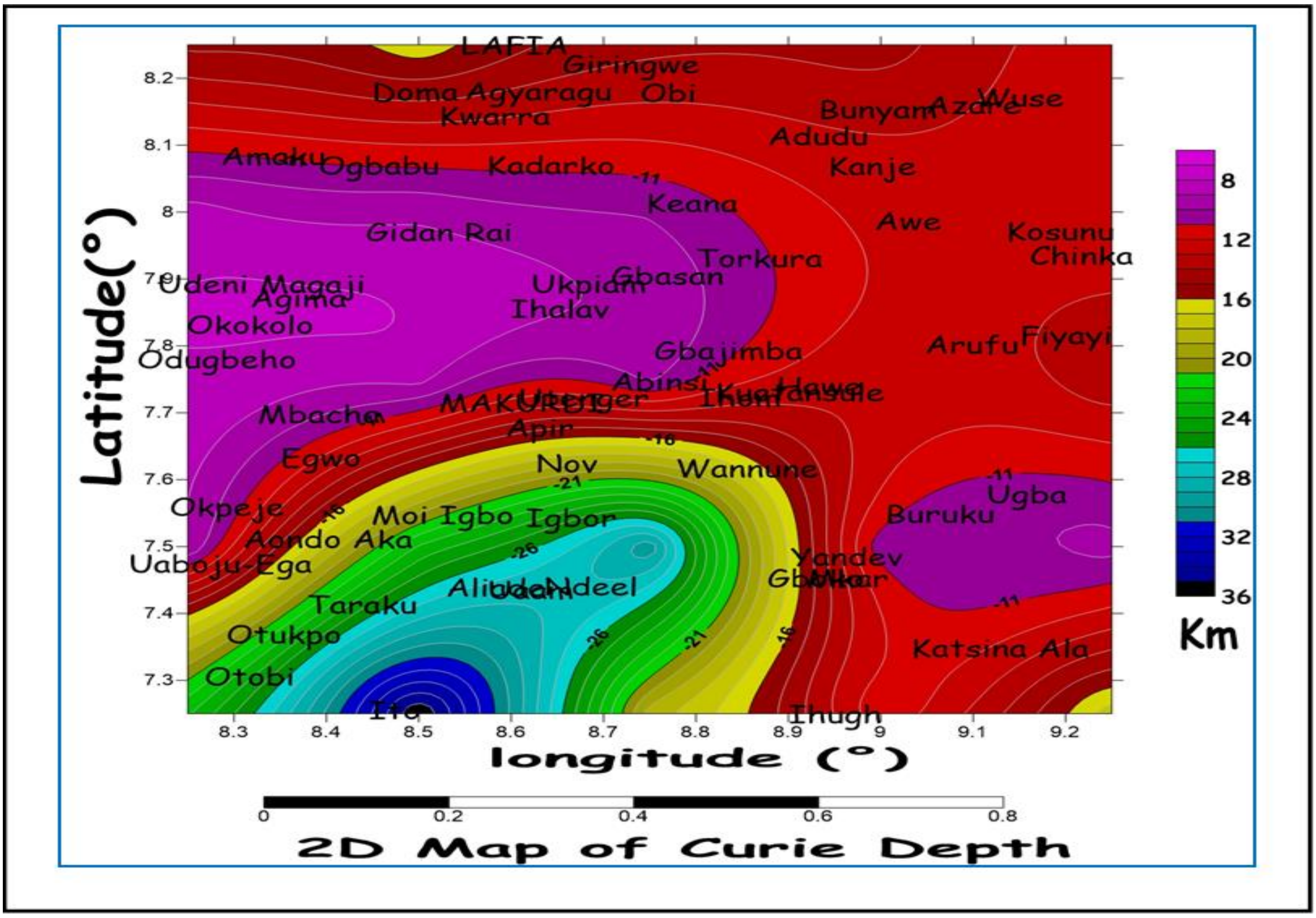

Fig. 5a: 2D contour map of curie point depth of the study area

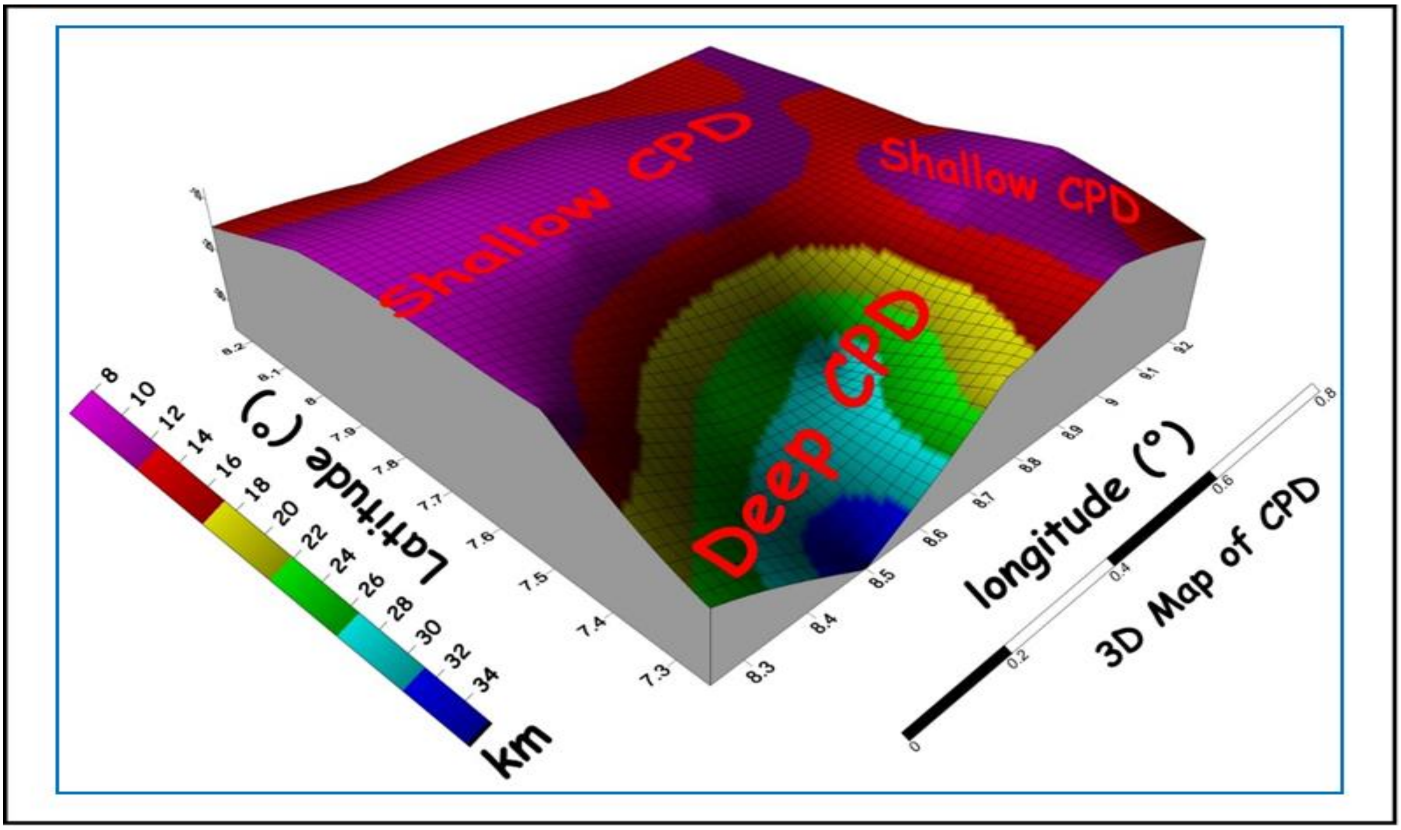

Fig. 5b: 3D contour map of curie point depth of the study area

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VI. GEOTHERMAL GRADIENT AND HEAT FLOW

The geothermal gradient values as calculated ranges from 16.09 to 70.81 °C /km, with an average value of 45.39 °C /km while the heat flow ranges between 40.23 to 177.03 mWm^{-2}, with an average value of 113.49 mWm^{-2}. The results of our study closely agrees with the results of (Akinnubi *et al.*, 2018; Ayuba and Nur, 2018; Aliyu *et al.*, 2018; Salako *et al.*, 2020; Tende*et al.*, 2021; Ayatu *et al.*, 2023; Aigbedion *et al.*, 2022; Ngene *et al.*,2022) who have worked across the Middle Benue Trough Nigeria. The geothermal and heat flow contour maps (Fig. 6 & 7) showed hot spots of geothermal energy exploration around Southwestern, Eastern and Northern parts of the study area corresponding to Otobi, Otukpo, Taraku, Nov, Moi Igbo, Igbor, Wannune, Lafia, Giringwe, Fiyayi and Eastern parts of Kastina- Ala. This hot spots were picked with respect to the geothermal gradient and heat flow values of 24 to 44 °C /km and 60 to 100/110 mWm^{-2} respectively signifying good geothermal source areas, while values in excess of the values stated indicates anomalous conditions as stated by (Jessop *et al.*, 1976). The Geothermal gradient and heat flow contour maps showed a linear relationship in their location and trend as areas with anomalous, low and good spots of geothermal gradient correlates well with areas of anomalous, low and good spots of heat flows and vise versa.

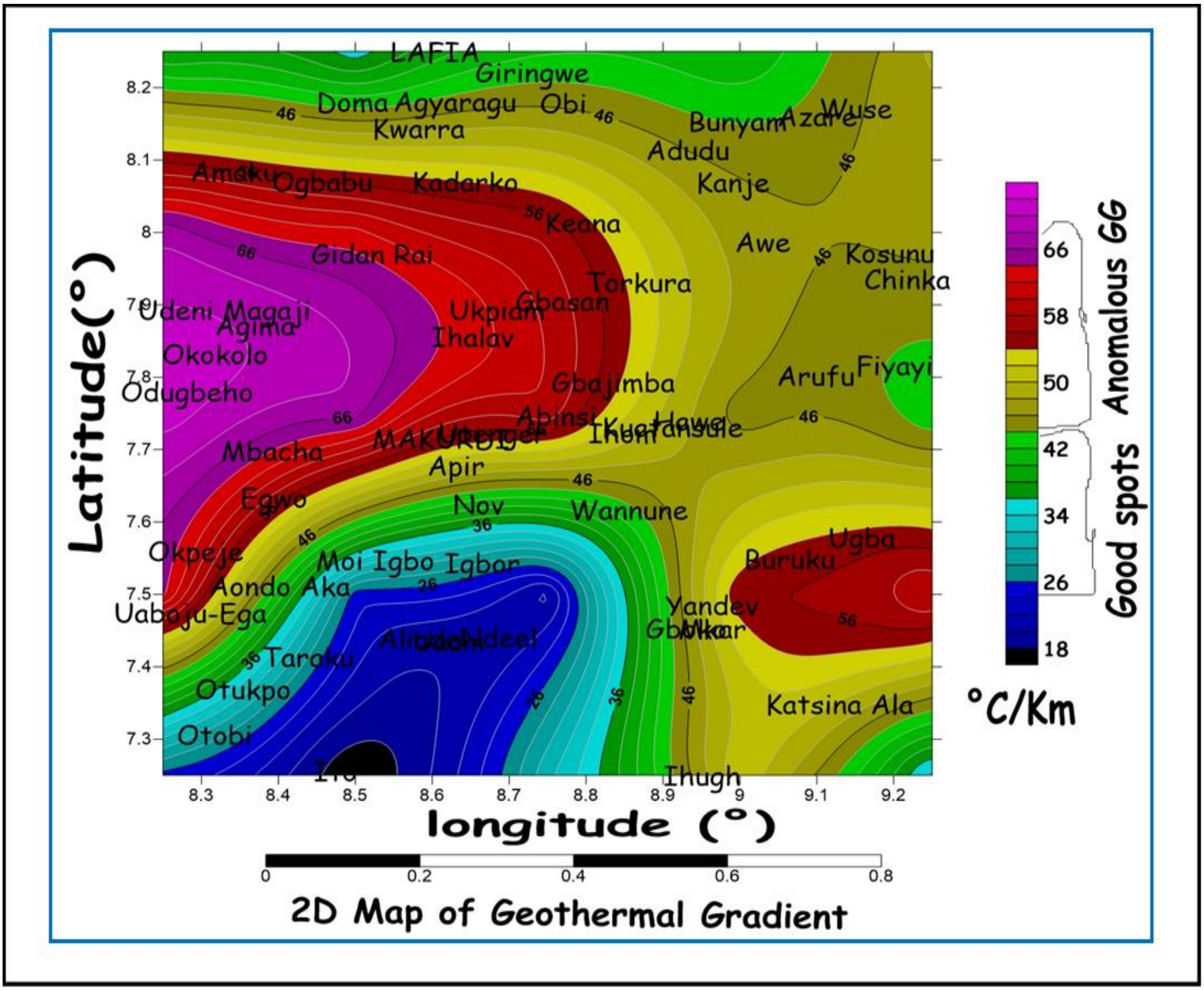

Fig. 6. 2D: Contour map of geothermal gradient of the study area

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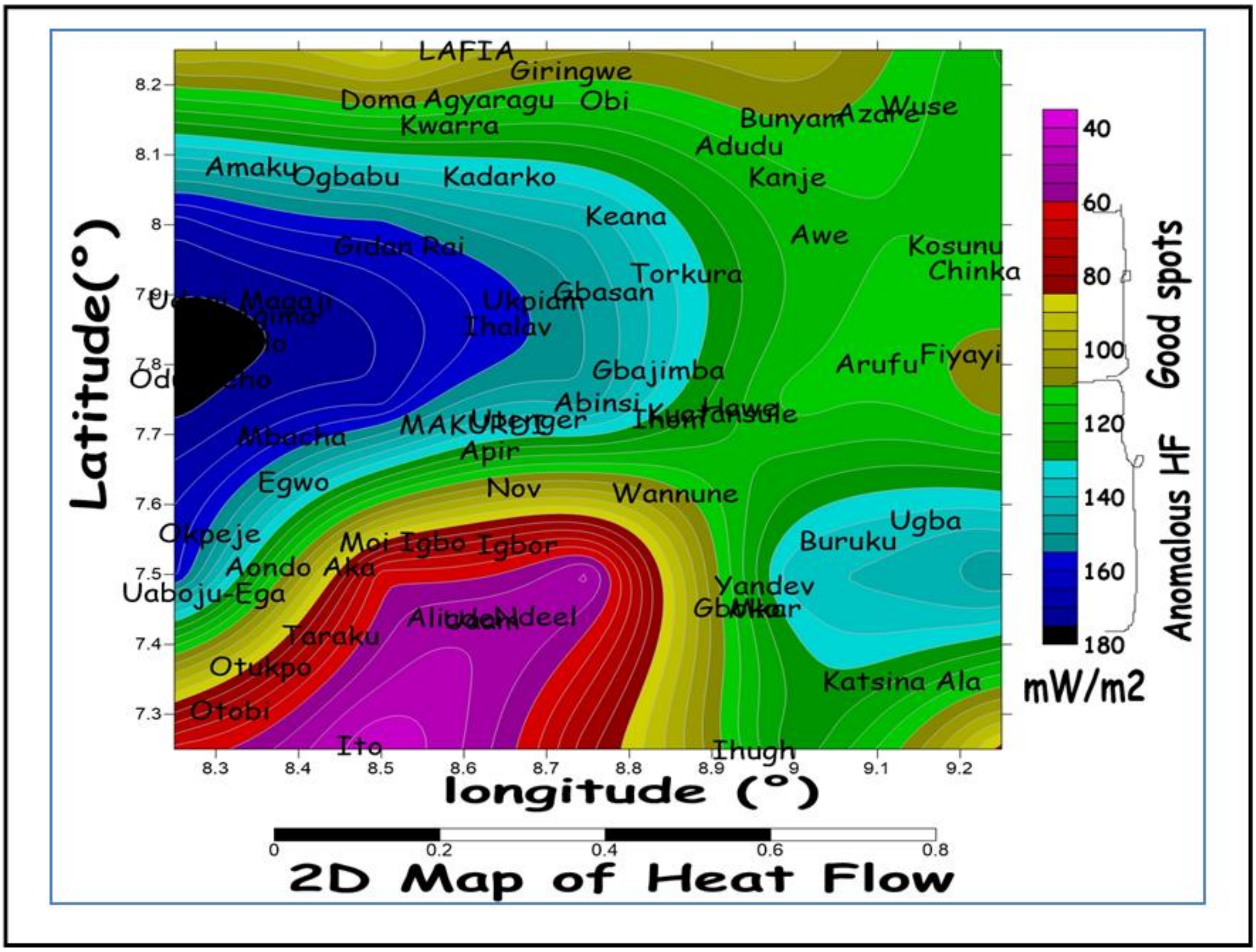

Fig. 7: 2D contour map of heat flow of the study area

VII. CONCLUSION

The spectral analysis of the aeromagnetic data proved very useful in characterizing areas with good geothermal sources and areas with anomalous geothermal sources. Suggested areas like Otobi, Otukpo, Taraku, Nov, Moi Igbo, Igbor, Wannune, Lafia, Giringwe, Fiyayi and Eastern parts of Kastina- Ala weredelineated as hot spots for geothermal energy exploration. The results of the parameters used; Curie point depth (CPD), geothermal gradient (GG) and heat flow (HF) obtained from our study,closely agrees with that ofthe results of(Akinnubi *et al.*, 2018; Ayuba and Nur, 2018; Aliyu *et al.*, 2018; Salako *et al.*, 2020; Tende*et al.*, 2021; Ayatu *et al.*, 2023; Aigbedion *et al.*, 2022; Ngene *et al.*,2022) who have also worked in parts of the study area and environs. This areas delineated are viable site for geothermal exploration and should be harnessed for geothermal energy, which can be used for electricity generation. This will address the power challenges across the states of this study and Nigeria at large and hence help to revamp the country's economy.

- *Competing Interest*

The Authors hereby declare no conflict of interest to this work

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