

# Determination of The Curie Point Depth, Thermal Gradient and Heat Flow of Parts of Central And North-Eastern Nigeria Using Spectral Analysis Technique

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## Research

**Keywords:** Aeromagnetic data, Curie point depth, Heat flow, geothermal gradient

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**DETERMINATION OF THE CURIE POINT DEPTH, THERMAL GRADIENT AND  
HEAT FLOW OF PARTS OF CENTRAL AND NORTH-EASTERN NIGERIA USING  
SPECTRAL ANALYSIS TECHNIQUE**

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## **Abstract**

Radially power spectrum was applied to the aeromagnetic data covering an area 36,300km<sup>2</sup> and bounded by latitudes 7.5° N and 11.5° N and longitudes 7.5° E and 10.5° E., divided into 35 square blocks (with 50% overlapping and approximately 64 by 64 data points) and each block analysed using the spectral centroid method to obtain depth to the top, centroid and bottom of magnetic sources. The result shows that the curie point depths, range from 17.711km to 34.34km, with a mean value of 26.21km, geothermal gradient, range from 16.89 °C km<sup>-1</sup> to 32.75 °C km<sup>-1</sup>, with a mean value of 22.83 °C km<sup>-1</sup> and heat flow, range from 42.22 mWm<sup>-2</sup> to 81.87 mWm<sup>-2</sup>, with a mean value of 57.07 mWm<sup>-2</sup>. These results correlate with the existing geothermal and geo-tectonic signatures of the area. Hence, the possibility of the existence of geothermal resources in the study area and its possible exploration is not far fetch.

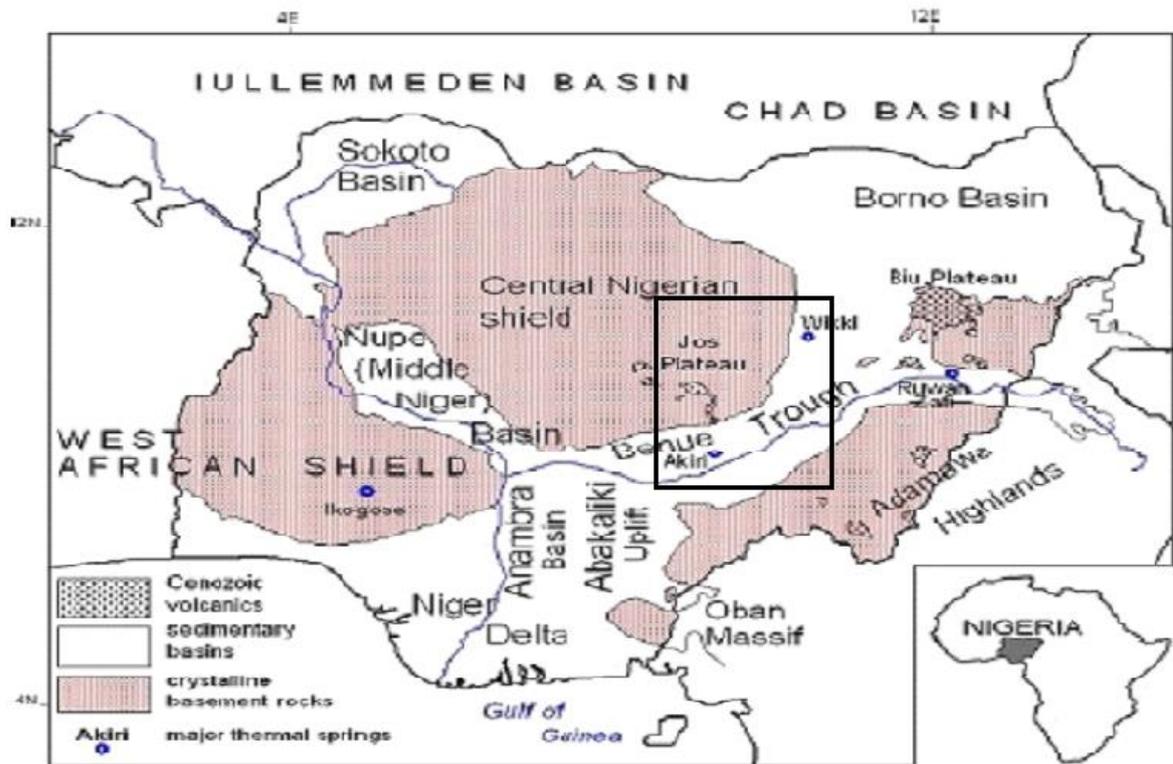
**Key Words:** Aeromagnetic data, Curie point depth, Heat flow, geothermal gradient.

## Introduction

The Curie point depth is the theoretical surface where ferromagnetic minerals are converting to paramagnetic minerals and it is assumed to have a temperature of approximately 580 °C, above which the former loses its magnetism and can be considered an indicator of the bottom of a magnetic crust. Hinze et al., 2013, in the Laboratory experiments they carried out, showed that ferromagnetic materials lose their magnetism above the Curie temperature (580 °C) because the thermal energy is sufficient to maintain a random alignment of the magnetic moments of the iron minerals. Also, Manea and Manea, 2011 opined that, an estimate of the bottom of magnetized crust represents a direct indicator of the Curie isotherm, and variations in the thickness of the magnetized crust can be explained as variations in temperature.

Magnetic minerals warmer than their Curie point depth temperatures are paramagnetic and are essentially nonmagnetic. The present study attempts to determine the depths to the top and bottom of the magnetized crust and to characterize the heat flow within the study area using Curie point depth (CPD) estimates from spectral analysis of aeromagnetic data. In this study, the spectral analysis technique will be utilized in order to estimate the CPD from aeromagnetic data over the study area bounded by latitudes 7.50'N to 11.50'N and longitudes 7.50'E to 10.50'E located within the central and northeast Nigeria (Fig.1. and Fig. 2). The study area covered 36,300 km<sup>2</sup> and it is made up of the cretaceous Benue trough, Precambrian basement Complex, Sedimentary Basins (Gongola and Yola Basins), Jurassic younger Granites, and tertiary – recent sediments of the central and north-eastern Nigeria (Carter et al., 1963; Ekwueme, 1987; Kogbe, 1989; Farnbauer and Tietz, 2000; Reyment, 1965; Adelana et al., 2008). Also, two prominent Hot Springs are located within the area, Wiki hot spring in Yankari, Bauchi state and Akiri hot spring in Awe, Nasarawa state (Fig.1.). These warm springs makes the study very significant as they are clear indication of surface manifestation of geothermal activities within the study area. The possibility of harnessing

geothermal resources in the area for economic and other purposes are not far fetch. This cannot be over emphasised, as the current over dependence of Nigeria on fossil fuel (oil and natural gas) has constituted an obstacle to the development of geothermal energy resources in the country and technological advancement. Nur et al., 1999; Obaje, 2009; Eletta and Udensi 2012; Salako 2012; Abdulsalam et al., 2013; Ikumbur et al., 2013; Igwesi and Umego 2013; Bello et al., 2017; Mohammed et al., 2019; Abdullahi et al., 2019, have done several works in different parts of the world both on local and regional scale using the magnetic method to determine the Curie point depth. Results obtained from this study will be invaluable in the development and a better understanding of the thermal and crustal structure of the study for geothermal exploration and exploitation.



□ Study Area

● Surface Geothermal manifestation - Hot springs.

Fig.1: Geological setting and location of areas with major geothermal manifestation (Hot springs) in Nigeria (After Kurowska and Schoeneich, 2010).

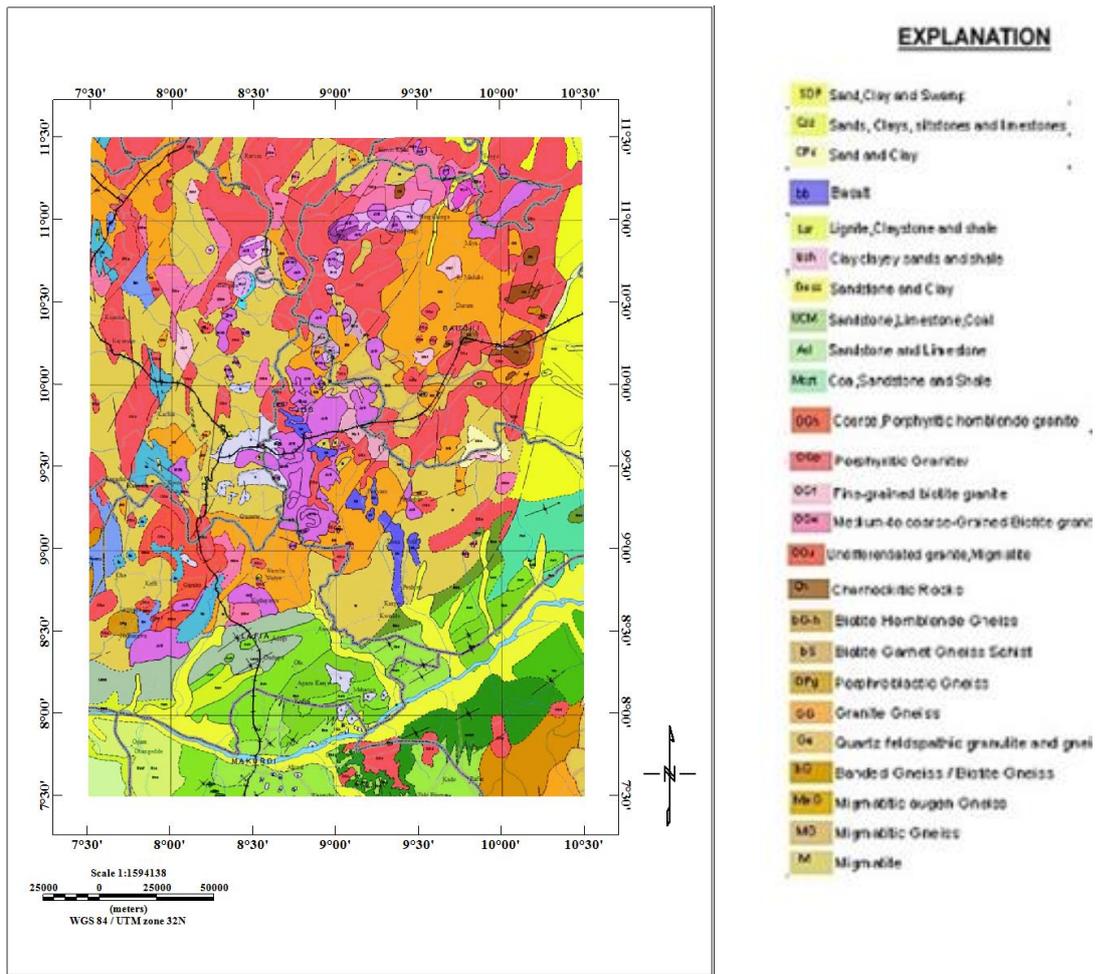


Fig.2: Geological Map of the study area (adapted after NGSA, 2010)

## MATERIALS AND METHODS

The idea of using the magnetic method to determine the Curie point depth was based on the theory proposed by Bhattacharyya (1966) and developed by (Spector and Grant, 1970; Blakely, 1988; Blakely, 1995; Tanaka et al., 1999) were they stated that geomagnetic anomalies collected from aeromagnetic data can be utilise to compute the curie point depth of an area. Bhattacharyya and Leu, 1975; Byerly and Stolt, 1977; Blakely and Hassanzadeh, 1981; Blakely, 1988; Smith and Braile, 1994; Tanaka et al., 1999; Chiozzi et al., 2005; Eppelbaum and Pilchin, 2006; Trifonova et al., 2009; Aboud et al., 2011, all used geomagnetic anomalies, which are retrieved from magnetic survey (Aeromagnetic data) to estimate the Curie point depth. The high resolution aeromagnetic dataset, which consist of sheet 102 - 107, 124 - 129, 145 - 150, 166 - 171, 187 -192, 208 - 213, 229 – 234 and 249 – 254 utilized for this study was obtained as controlled maps of total magnetic intensity on a scale of 1:100000 compiled by the Nigerian Geological Survey Agency as a part of the nation-wide aeromagnetic survey between 2005 and 2010. The survey was flown in drape mode using real time global positioning system at a sensor mean terrain clearance of 80-100m. Traverse and Tie line spacing were 500m and 2000m respectively in NW-SE and NE-SW directions and the data were recorded at a sampling interval of 100m (NGSA, 2010) and stored in grid form. The study area is covered by forty-eight aeromagnetic maps of total-field intensity in  $\frac{1}{2}^{\circ}$  by  $\frac{1}{2}^{\circ}$  sheets. The data were initially pre-processed by Fugro Airborne Survey and Consultant teams, pre-processing operation included micro levelling, removal of cultural effects as well as filtering for noise contents. Total magnetic field intensity maps of the area comprising of the sheets (Fig. 3) were plotted using Oasis Montaj software (version 8.4). The composite colour map (Fig. 3) effectively displayed both long wavelength and short wavelength features. Oasis Montaj software (version 8.4) grid maths was used to generate the residual magnetic field intensity map Fig.4. from the total magnetic field intensity grid.

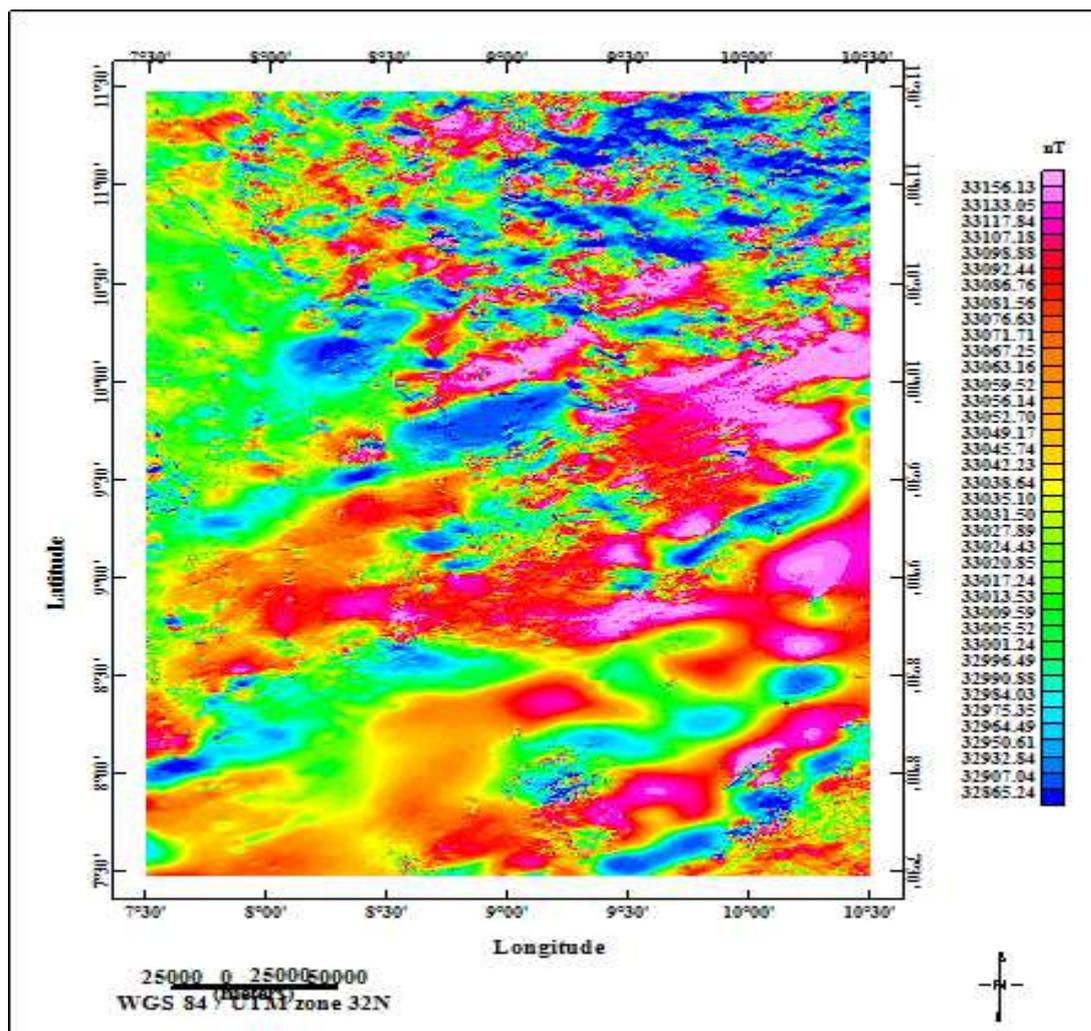
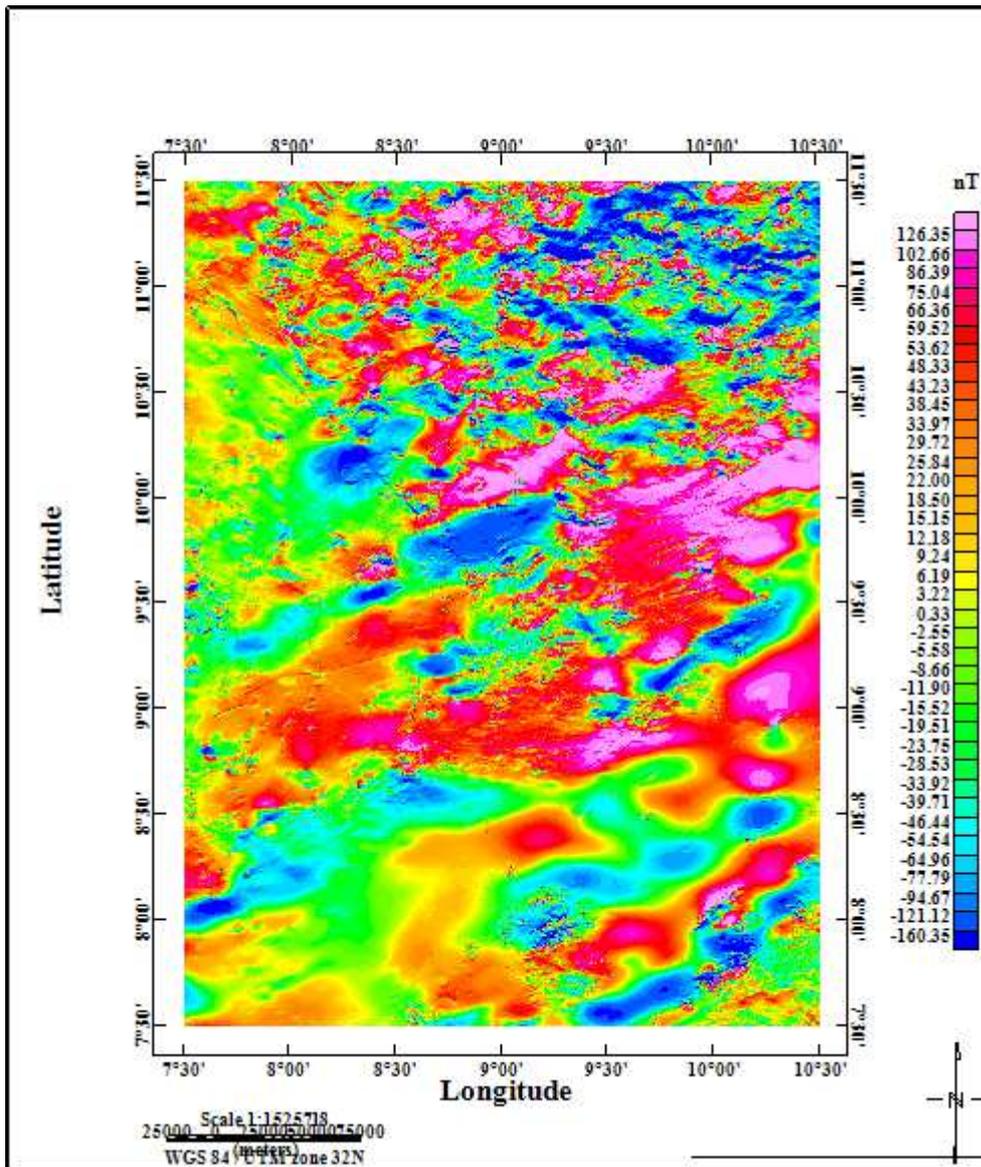


Fig.3: Total magnetic field intensity map of the study area.



**Fig.4: Residual magnetic field intensity map of the study area.**

## Curie point depth estimation

The technique for computing the depth extent of magnetic sources, which deals with the examination of the patterns of the anomalies, and provide the relationship between the spectrum of the magnetic anomalies and the depth to magnetic sources, by transforming the spatial data into frequency domain proposed by Spector and Grant (1970), was adopted in this study and has been proven to be reliable in the calculation of average depth to magnetic crust. It stipulates that, from graphs of the logarithms of the spectral energies for the various blocks, one can estimate the depth to Centroid ( $Z_o$ ) of the magnetic source from the slope of the longest wavelength part of the spectrum

$$\ln\{\Phi_{\Delta T}(|k|)^{1/2}/|k|\} = \ln D - |k|Z_o \quad (1)$$

Where  $\ln\{\Phi_{\Delta T}(|k|)^{1/2}/|k|\}$  is the radially averaged power spectrum of the anomaly,  $|k|$  is the wave number, and  $D$  is a constant and estimate the depth to the top boundary ( $Z_t$ ) of that distribution from the slope of the second longest wavelength spectral segment (Okubo et al, 1985),

$$\ln[\Phi_{\Delta T}(|k|)^{1/2}] = \ln B - |k|Z_t \quad (2)$$

Where  $\ln[\Phi_{\Delta T}(|k|)^{1/2}]$  is the radially averaged power spectrum of the anomaly,  $|k|$  is the wave number, and  $B$  is the sum of constants independent of  $|k|$ . According to (Okubo *et al.*, 1985; Tanaka *et al.*, 1999), the basal depth ( $Z_b$ ) of the magnetic source can be calculated from the equation,

$$Z_b = 2Z_o - Z_t \quad (3)$$

The obtained basal depth ( $Z_b$ ) of magnetic sources in the study area is assumed to be the Curie point depth (Bhattacharyya and Leu 1975 and Okubo et al., 1985).

## Estimation of Heat flow and thermal gradient

The expression for the calculation of heat flow and thermal gradient values as derived from Fourier's law (Fourier 1955) is given by;

$$q = \lambda \frac{dT}{dZ} \quad (4)$$

Where  $q$  is the heat flow and  $\lambda$  is the coefficient of thermal conductivity. In this equation, it is assumed that the direction of the temperature variation is vertical and the temperature gradient  $\frac{dT}{dZ}$  is constant. According to Tanaka, et al, (1999), the Curie temperature ( $\theta$ ) can be obtained from the Curie point depth ( $Z_b$ ) and the thermal gradient  $\frac{dT}{dZ}$  using the following equation;

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

Provided that there are no heat sources or heat sinks between the earth surface and the Curie point depth, the surface temperature is  $0^\circ\text{C}$  and  $\frac{dT}{dZ}$  is constant. The Curie temperature depends on magnetic mineralogy. The commonest magnetic substance in the earth is magnetite ( $\text{Fe}_2\text{O}_4$ ), with Curie temperature approximately  $580^\circ\text{C}$  (Nwankwo et al., 2011). From equation (4) and equation (5), the heat flow ( $q$ ) can be express as;

$$q = \lambda \left\{ \frac{\theta}{Z_b} \right\} \quad (6)$$

In this equation, the Curie point depth is inversely proportional to the heat flow (Tanaka et al. 1999; Stampolidis, et al., 2005). In this research, the Curie point temperature of  $580^\circ\text{C}$  and thermal conductivity of  $2.5\text{Wm}^{-1} \text{ }^\circ\text{C}^{-1}$  as average for igneous rocks was used as standard (Nwankwo et al., 2011) in the study area. In order to compute the thermal gradient and heat flow, Equation (6) was utilised. See Table 1 below.

Radially power spectrum was applied to the residual magnetic field intensity grid map of the study area divided into 35 square blocks (each block covers a square area of 110 by 110km, which approximately represent a square grid of 64 by 64 data points, **c1 – c2**, (Fig.5) with 50% overlapping) and each block analysed using the spectral centroid method to obtain depth to the top, centroid and bottom of magnetic sources. The analysis was carried out using computer software (Oasis Montaj (version 8.4), Grapher 8, Microsoft Office and Surfer 15). The depth values were subsequently used to evaluate the Curie-point depth (CPD), geothermal gradient and near-surface heat flow in the study area.

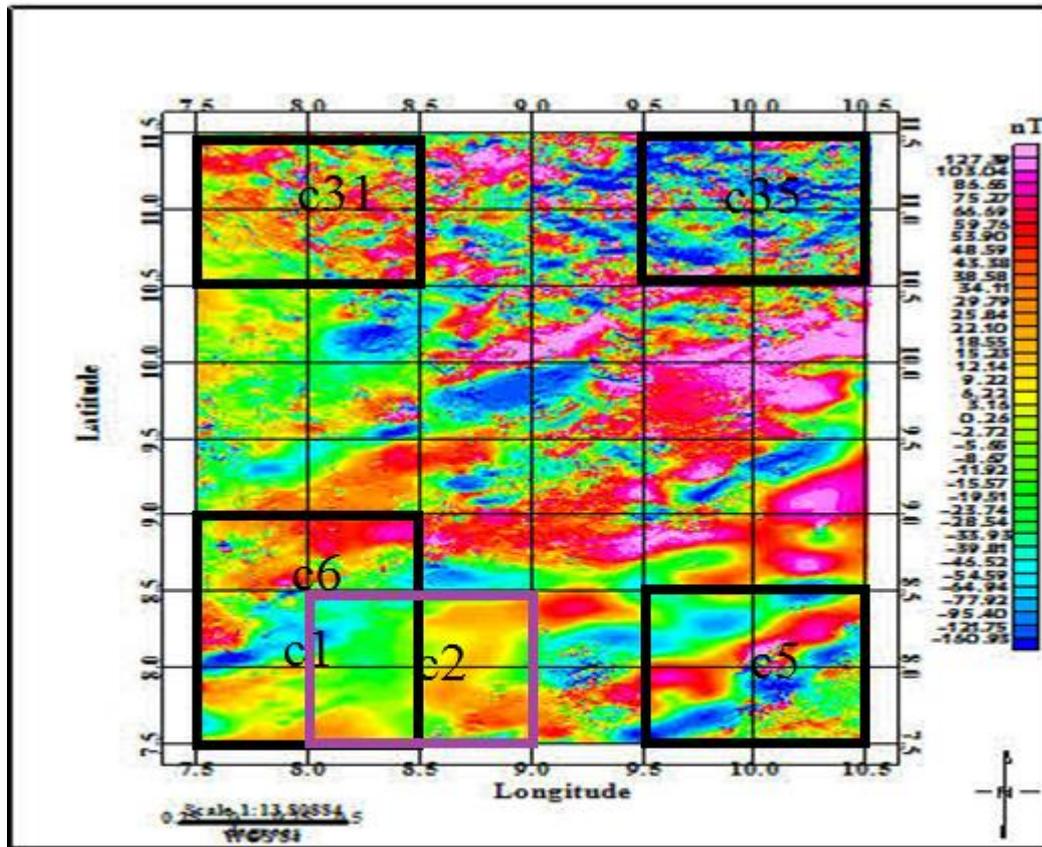


Fig.5: Residual magnetic field intensity divided into thirty-five square windows (110km by 110km each) from c1 to c35 at 50% overlapping.

## Results and Discussion

Radially power spectrum was applied to the aeromagnetic data of the study area divided into 35 square blocks (with 50% overlapping). Fig.6 shows the sample graphs of the logarithms of the spectral energies for plots of blocks c33 and c34. The determined values of the basal depth or depth to the magnetic source  $Z_b$ , for blocks c33 and c34 using their determined  $Z_o$  and  $Z_t$  values in equation (3) are 11km and 13km respectively. The results of the determined values of  $Z_o$ ,  $Z_t$  and  $Z_b$  for the thirty-five blocks are shown in table 1. The curie point depths, range from 17.711km to 34.34km, with a mean value of 26.21km, geothermal gradient, range from

16.89 °C km<sup>-1</sup> to 32.75 °C km<sup>-1</sup>, with a mean value of 22.83 °C km<sup>-1</sup> and heat flow, range from 42.22 mWm<sup>-2</sup> to 81.87 mWm<sup>-2</sup>, with a mean value of 57.07 mWm<sup>-2</sup>. The curie point depth of the study area compare favourably with what was recorded over Sarti and environs of North-Eastern Nigeria (range from 24 to 28km, Kasidi and Nur (2012)), Jalingo and Environs, North-Eastern part of Nigeria (range from 26 to 28km, Kasidi and Nur (2013)), the eastern Chad basin, Nigeria ((Mafa - Bama and Maiduguri - Gwoza areas) (range from 21 to 32 km , Anakwuba, et al., (2016))), the entire Bida Basin in north-central Nigeria (range from 16 to 30 km, Nwankwo and Sunday (2017)), part of the upper Benue trough corresponding to Kaltungo, Guyok, Lau and Dong areas, north eastern Nigeria (range from 12 to 34 km, Mohammed et al., (2019)) and the Upper Benue Trough (range from 24 to 33km, Nur et al., (1999)).

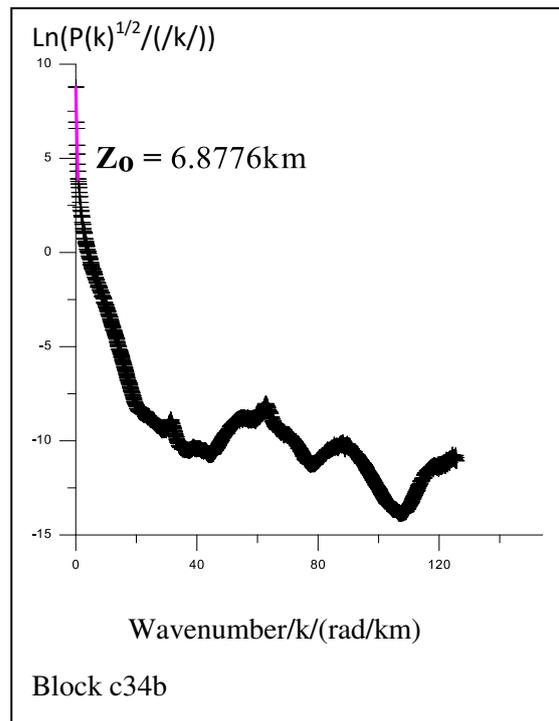
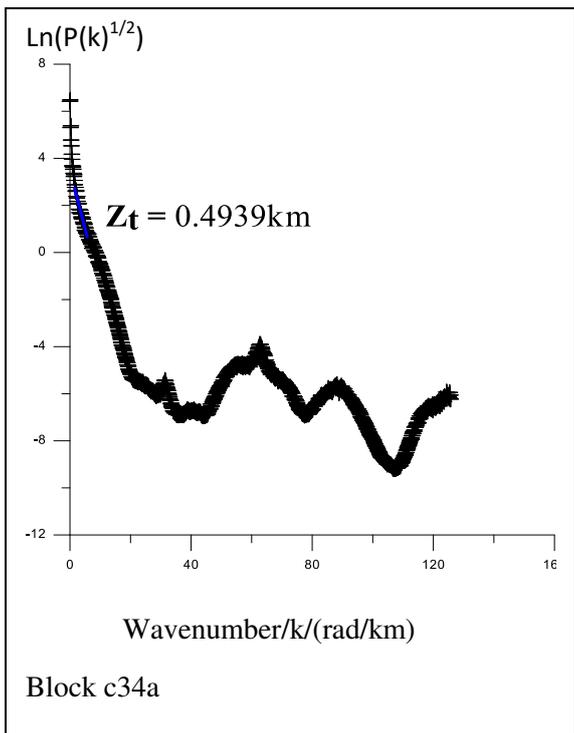
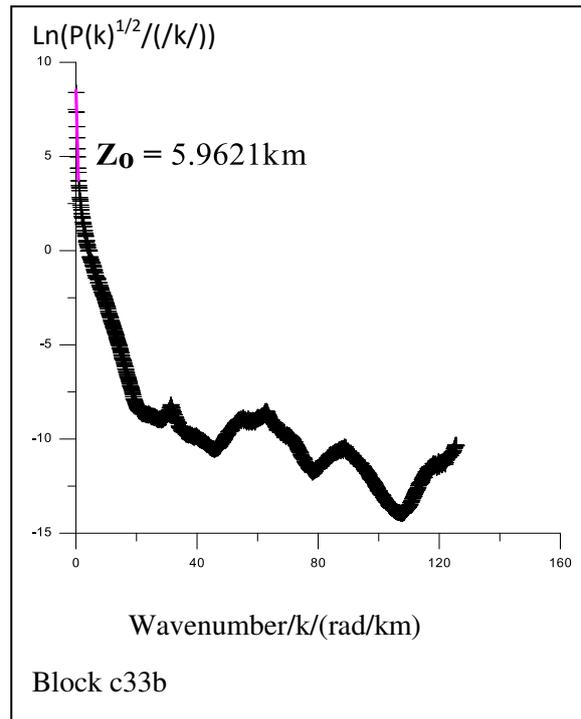
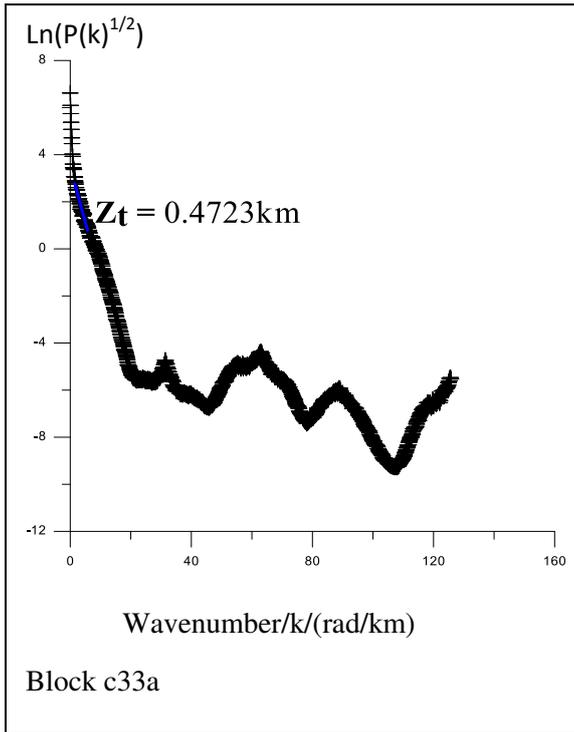


Fig.6: Graphs of the logarithms of the spectral energies for blocks c33, and c34, showing the determined values of  $Z_0$  and  $Z_t$ . using Grapher 8 software and the calculated Curie point depths are 11km and 13km respectively.

**Table.1: Calculated Average Curie point depth, Geothermal gradient and Heat flow from spectral analysis**

Blocks	Depth to Centroid ( $Z_0$ ) (Km)	Depth to top boundary ( $Z_t$ )(km)	Curie Depth ( $Z_b$ ) (Km)	Geothermal gradient ( $\frac{dT}{dz}$ ) ( $^{\circ}\text{C}/\text{km}$ )	Heat Flow (q) ( $\text{mWm}^{-2}$ )
c1	15.311	0.775	30	19	48
c2	15.244	0.428	30	19	48
c3	15.152	0.270	30	19	48
c4	14.622	0.269	29	20	50
c5	9.790	0.322	19	30	75
c6	14.527	0.498	28	20	51
c7	13.744	0.432	27	21	54
c8	14.366	0.393	28	20	51
c9	15.991	0.440	31	18	46
c10	14.720	0.302	29	20	50
c11	17.409	0.477	34	17	42
c12	16.620	0.405	32	18	44
c13	14.850	0.304	29	20	49
c14	12.206	0.404	24	24	60
c15	12.994	0.451	25	23	57
c16	9.997	0.353	20	30	74
c17	9.006	0.301	18	33	82
c18	13.986	0.401	28	21	52
c19	13.709	0.335	27	21	54
c20	13.704	0.479	27	22	54
c21	13.200	0.392	26	22	56
c22	10.479	0.381	20	28	70
c23	13.316	0.467	26	22	55
c24	10.476	0.450	20	28	71
c25	16.751	0.487	33	18	44
c26	15.669	0.432	31	19	47
c27	13.657	0.436	27	22	54
c28	14.490	0.477	28	20	51
c29	10.743	0.488	21	28	69
c30	9.805	0.436	19	30	76
c31	14.501	0.408	28	20	51
c32	11.622	0.421	23	25	64
c33	11.912	0.441	23	25	62
c34	11.042	0.438	22	27	67
c35	10.377	0.412	20	28	71

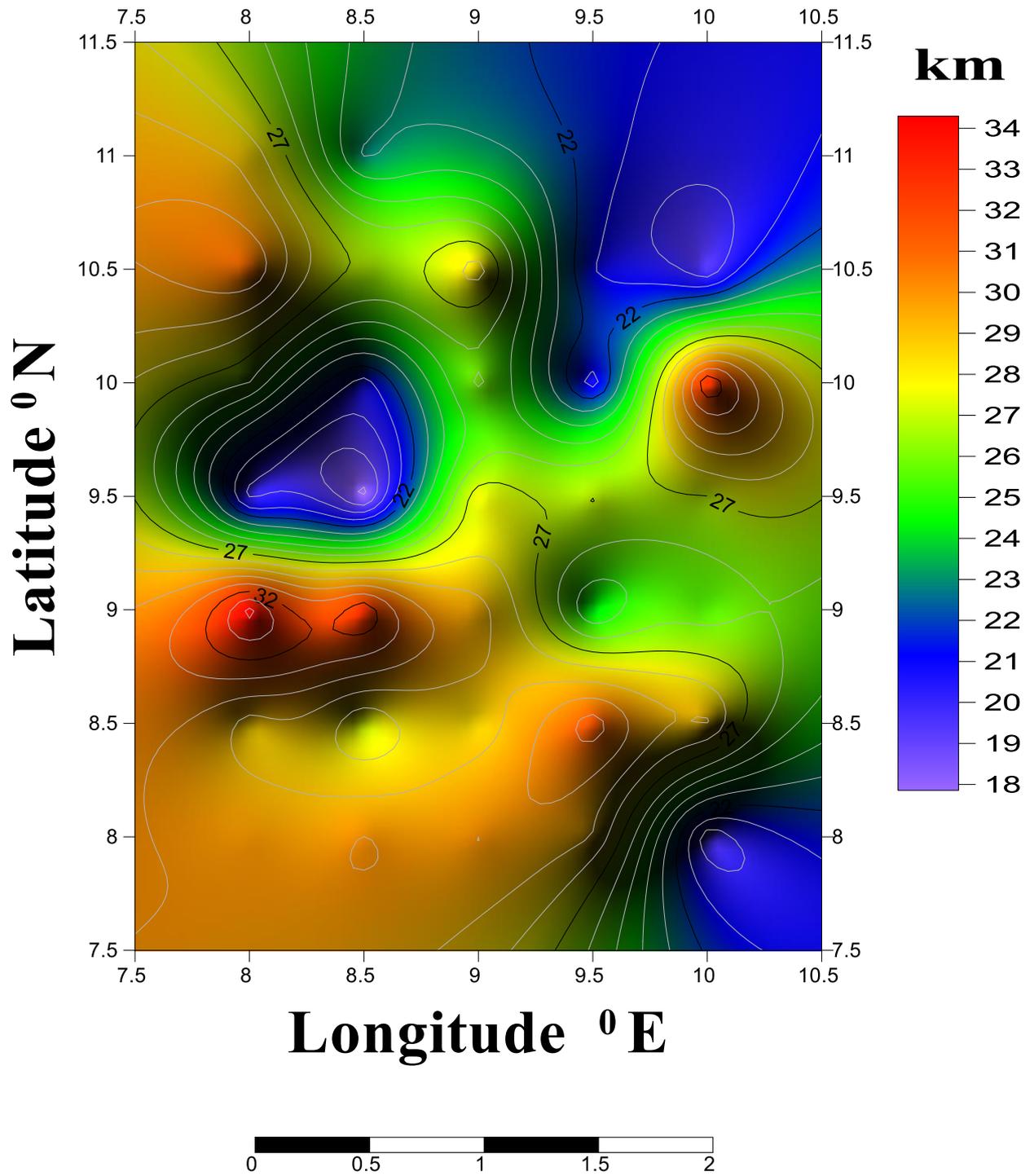


Fig.7: Curie point depth map of the study area using Surfer 8 software.

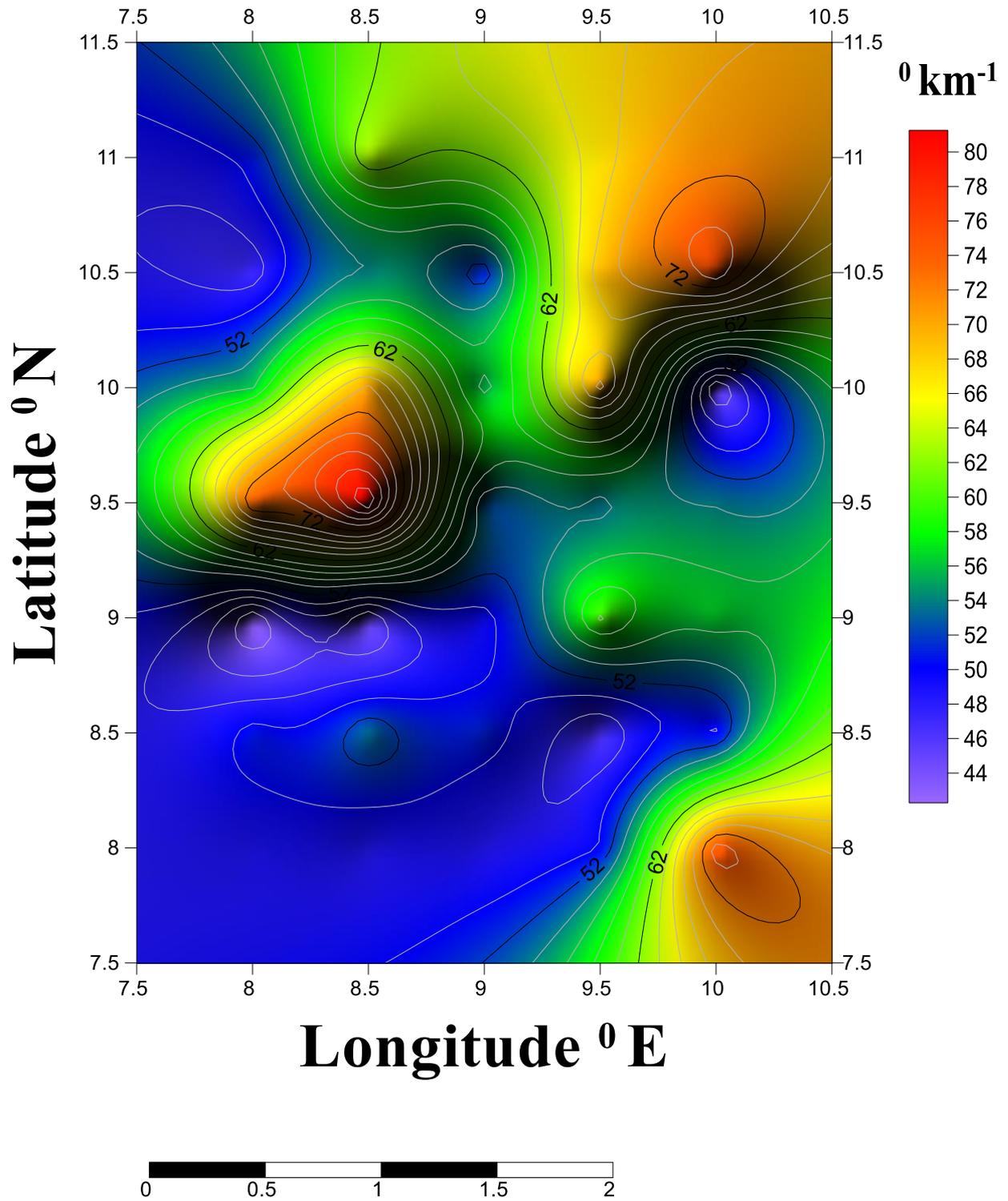


Fig.8: Geothermal gradient map of the study area using Surfer 8 software

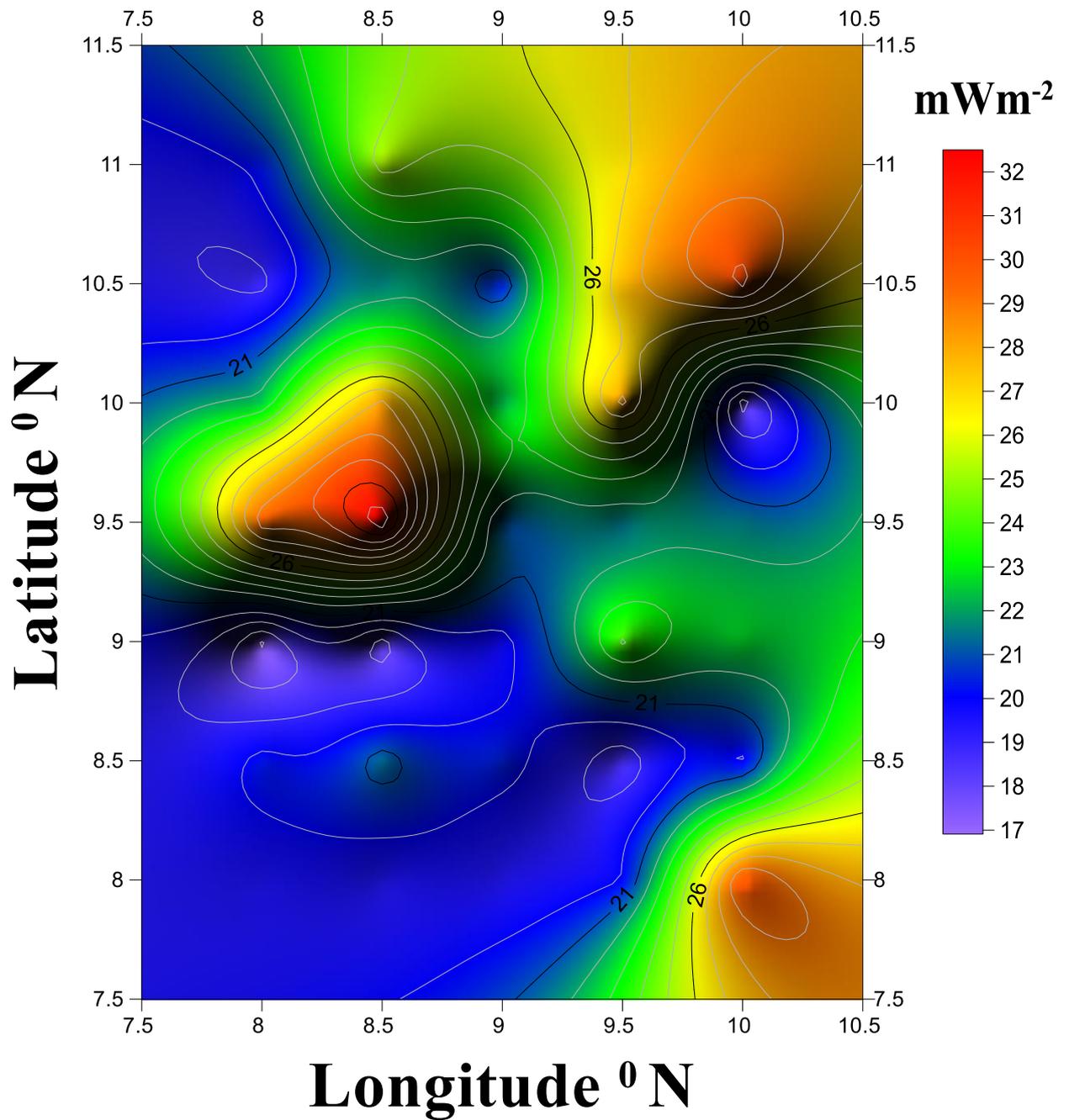


Fig.9: Heat flow map of the study area using Surfer 8 software.

## **Conclusion**

In this research, high resolution aeromagnetic data has been used to investigate the present of anomalies and the curie point depth of the study area. The quantitative (Spectral analysis) interpretation technique was chosen to achieve the outlined objectives of this research. From (Fig.7.) the curie point depths are deeper in the south, southwest, northwest, and northeast of the study area and shallower in the extreme northeast, southeast and part of the west. From Fig.8., the thermal gradient tends to be higher mainly in the north, central and extreme southeast of the study area and lower in most of the south, extreme southwest and extreme northwest. From Fig.9, the heat flow tends to be higher mainly in the north, central and extreme southeast of the study area and lower in most of the south, extreme southwest and extreme northwest. The above characteristics of these areas according to Stein and Stein (1994) and Tanaka et al., (1999), reveals that, they might probably be good sources for geothermal and thereby recommended for both geothermal exploration and exploitation.

## **Declarations**

### **Availability of data and materials**

Not applicable

### **Competing interests**

The authors declare that they have no competing interests.

### **Funding**

Not applicable

### **Authors' contributions**

George Idena ODIDI carried out the data acquisition and processing, participated in research analysis, drafting of the manuscript and interpretation of results. Abu MALLAM participated in supervision of processing, review of technical processing steps, assessment and analysis of results and approval of the version to be published. Naeem NASIR participated in review and analysis of results. All authors approved the final manuscript.

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# Figures

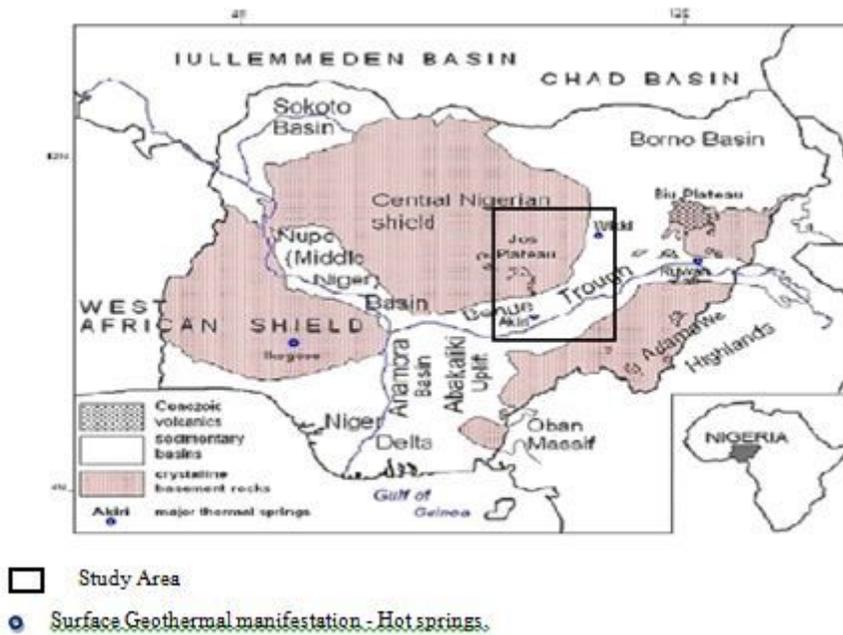


Figure 1

Geological setting and location of areas with major geothermal manifestation (Hot springs) in Nigeria (After Kurowska and Schoeneich, 2010).

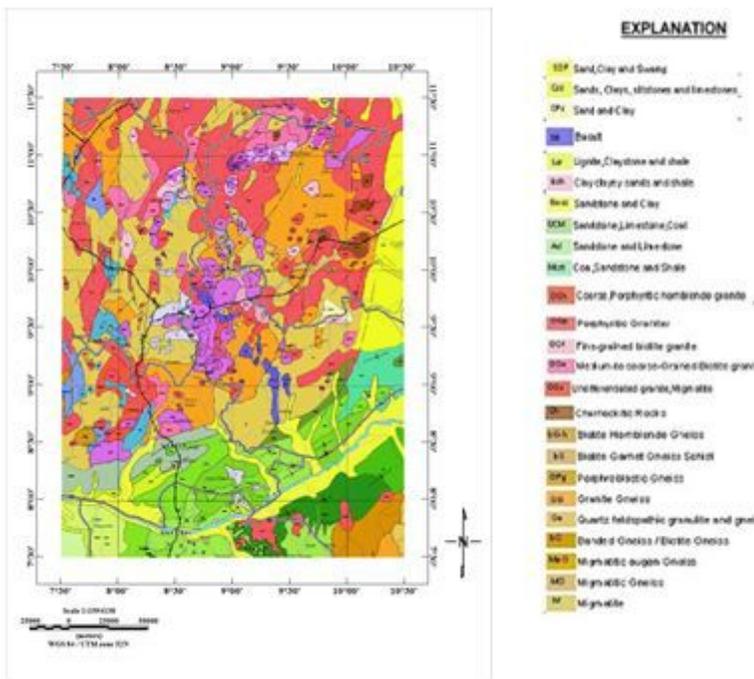


Figure 2

Geological Map of the study area (adapted after NGSA, 2010)

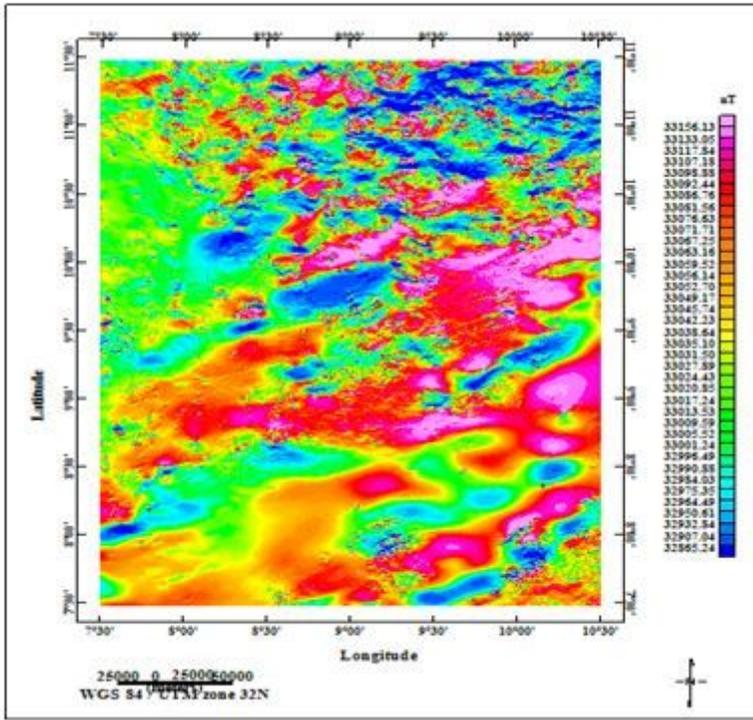


Figure 3

Total magnetic field intensity map of the study area.

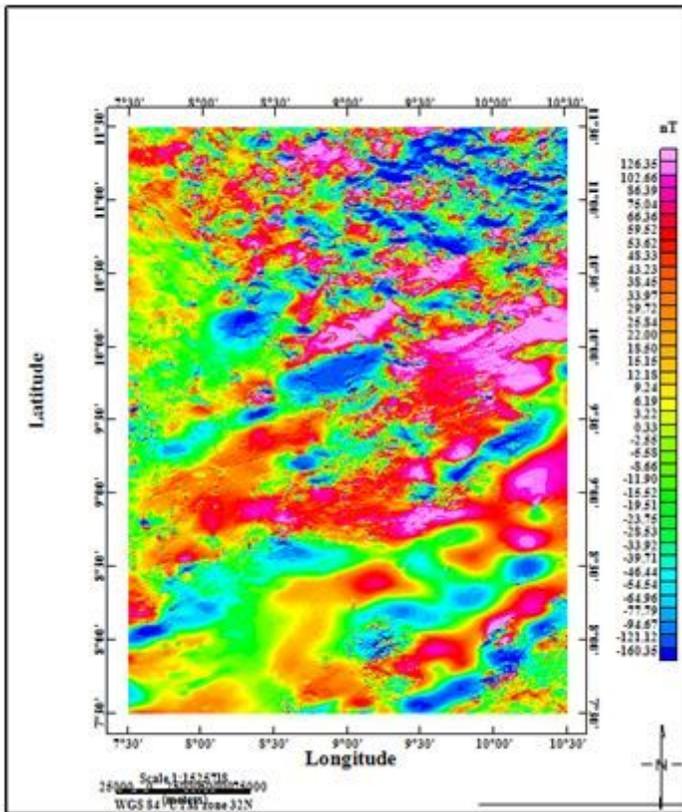


Figure 4

Residual magnetic field intensity map of the study area.

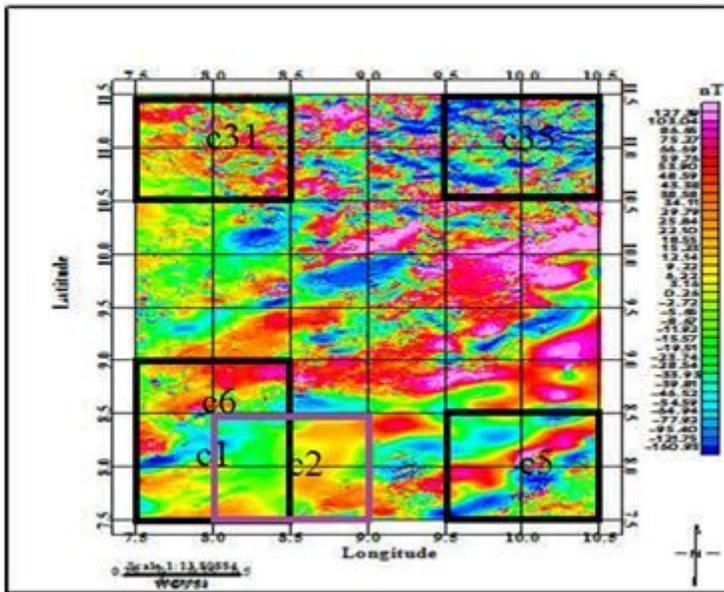
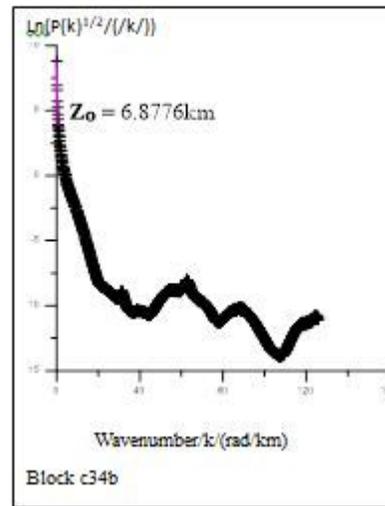
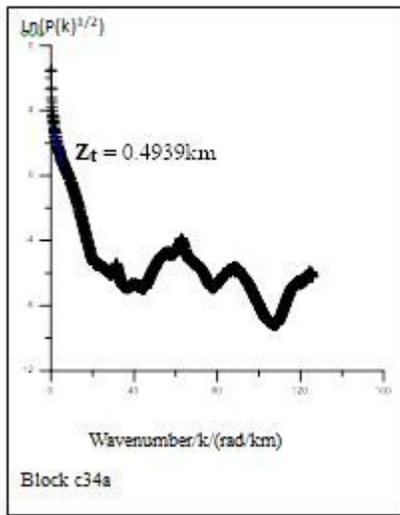
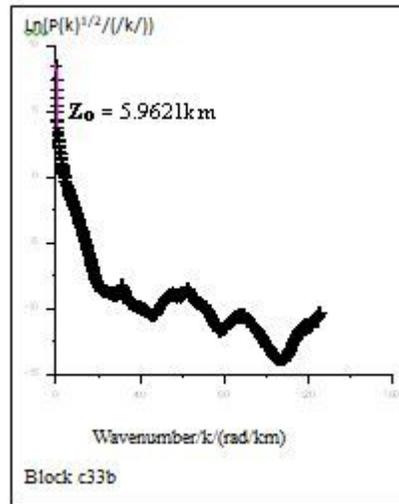
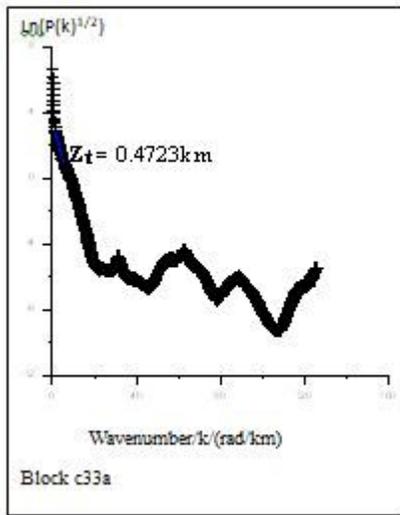


Figure 5

Residual magnetic field intensity divided into thirty-five square windows (110km by 110km each) from c1 to c35 at 50% overlapping.



**Figure 6**

Graphs of the logarithms of the spectral energies for blocks c33, and c34, showing the determined values of  $Z_o$  and  $Z_t$ . using Grapher 8 software and the calculated Curie point depths are 11km and 13km respectively.

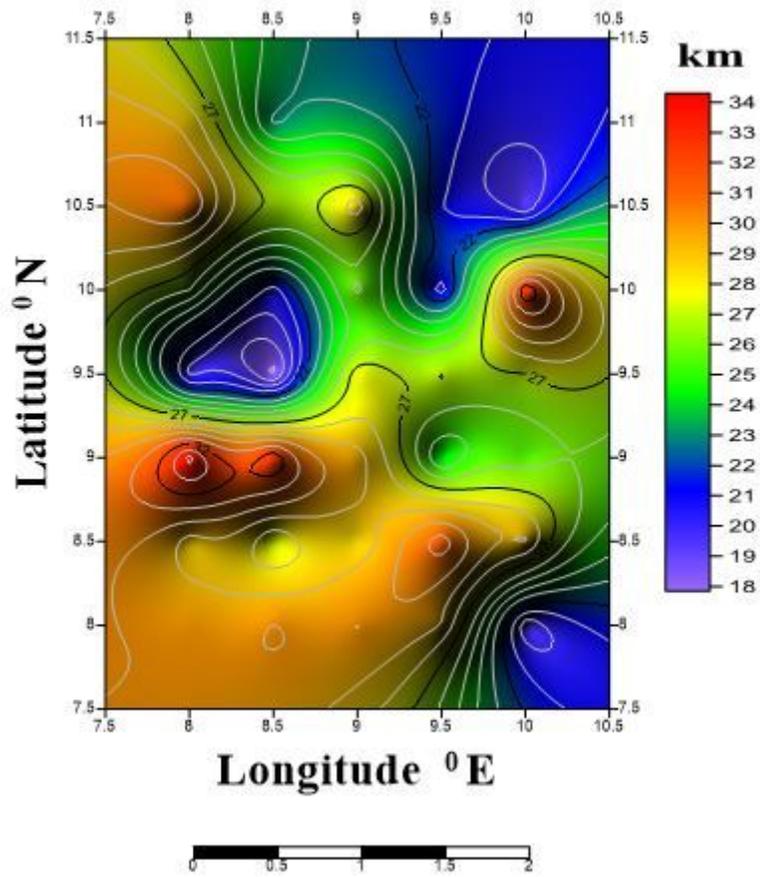


Figure 7

Curie point depth map of the study area using Surfer 8 software.

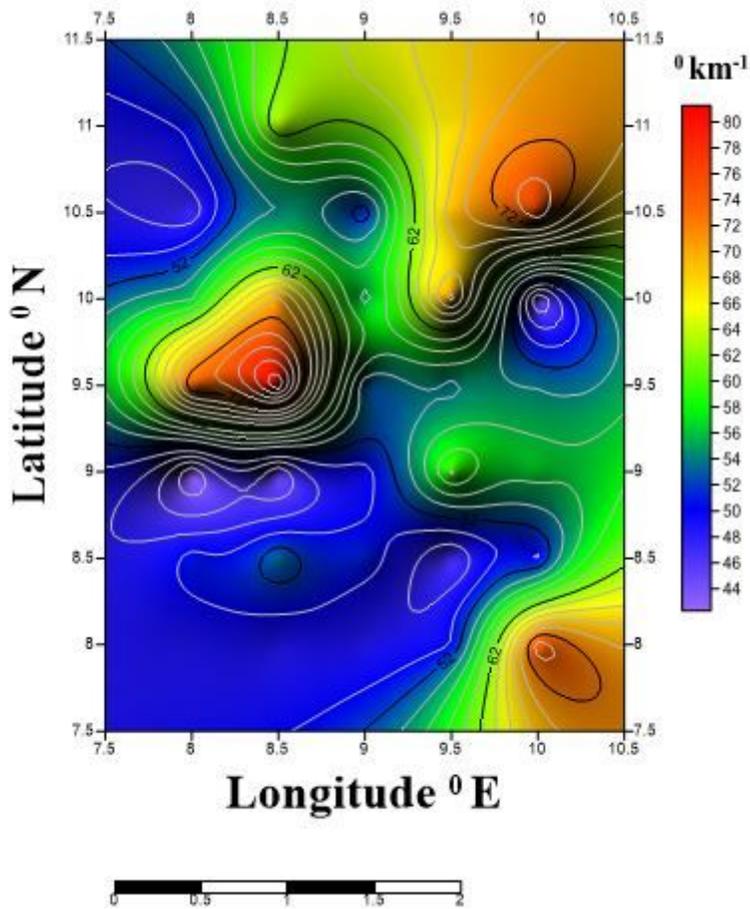


Figure 8

Geothermal gradient map of the study area using Surfer 8 software

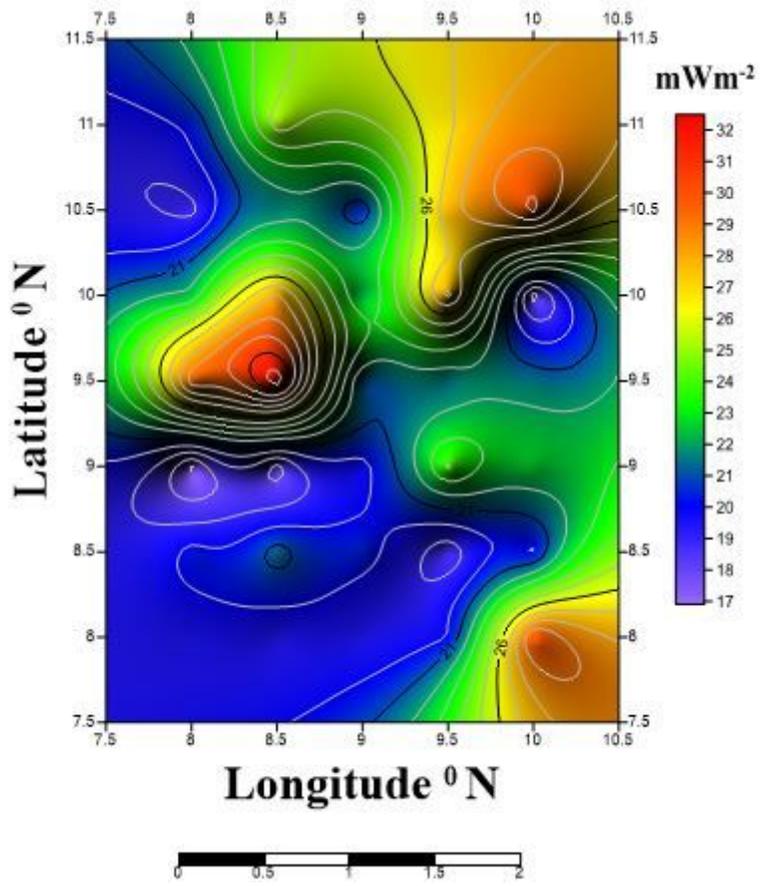


Figure 9

Heat flow map of the study area using Surfer 8 software.