



# Study of Curie point depth and heat flow from spectral analysis of aeromagnetic data for geothermal potential of Gubio, Chad Basin, Nigeria

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## Abstract

Aeromagnetic data of Gubio area, Chad Basin, northeastern Nigeria, were interpreted quantitatively by employing spectral analysis technique with the aim to estimate the Curie point depth, geothermal gradient and heat flow in order to determine the geothermal nature of the area. Data enhancement (reduction to pole, RTP and band pass filter) was performed on the total magnetic intensity (TMI) map of the area using oasis Montaj software. The enhanced map was divided into four overlapping blocks, and each block was subjected to spectral analysis. The results gave Curie point depth values ranging from 10.63 to 20.07 km, with deepest depth at the northeast, while the shallowest depth was observed to be conspicuous in the southeastern part of the study area. The estimated geothermal gradient ranges from 28.90 to 54.57 °C km<sup>-1</sup> with an average value of 40.26 °C km<sup>-1</sup>, with low values in the northeast direction, and increases towards southeast. The average geothermal gradient of 40.26 °C km<sup>-1</sup> indicates the possibility of hydrocarbon generation and accumulation in Chad basin. The estimated heat flow values range from 72.24 to 136.43 mW m<sup>-2</sup> with an average value of 100.65 mW m<sup>-2</sup>, the highest values are found around southeastern part of the study area, and the lowest values are within the northeastern part. The areas of geothermal anomalies with gradient above 50 °C km<sup>-1</sup> may be good areas for geothermal reservoir exploration for an alternative source for power generation.

**Keywords** Spectral analysis · Aeromagnetic data · Curie point depth · Geothermal gradient · Heat flow · Electricity generation · Gubio areas

## 1 Introduction

The anomalies of the magnetic field of the Earth resulting from the magnetic properties of the underlying rocks are the purpose of magnetic survey in studying the sub-surface geology. Though many rock-forming minerals are efficiently not magnetic, some rock types possess enough magnetic minerals to produce substantial magnetic anomalies. Magnetic anomalies are also produced by ferrous objects which are made by man. Magnetic survey therefore has a broad application in archaeological surveys, detection of buried metallic objects and investigation

of regional geological structure. Magnetic survey can be carried out at sea, on land and in the air. The operational speed of aeromagnetic survey enables it to be quite attractive in the exploration for kinds of ore deposit that have magnetic minerals [1] and permits abundant areas of the surface of the Earth to be covered rapidly for regional reconnaissance.

Near-surface volcanic rocks that are generally of importance in geothermal exploration are mapped by magnetic method, but the ability of the method to identify the depth at which the Curie temperature (the Curie point isotherm depth) is reached is its maximum potential. At critical

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temperature known as Curie temperature, ferromagnetic materials show an observable fact characterized by a loss of almost all magnetic susceptibility. Nwankwo et al. [2] observed that different minerals which are ferromagnetic have different Curie temperatures, but the Curie temperature of titanomagnetite which is the magnetic mineral that is very common in igneous rocks is within the range of a few hundreds to 580 °C. The depth at which the Earth's Fe–Ti oxide minerals lose their ferromagnetic property is known as Curie point depth (CPD) [3]. The temperature of Curie isotherm is 550 °C ± 30 °C. Several geothermal reservoirs got their heat from this point which is believed to be the depth for geothermal source. The degree of growth in temperature per unit depth in the Earth owing to the outflow of heat from the centre is known as the geothermal gradient. On the average, the temperature gradient between the centre of the Earth and the outer limits of the atmosphere is about 1 °C km<sup>-1</sup> [4].

Magnetic survey measures local magnetic field characteristics of a survey area. The technology merely senses minerals that react to magnetic fields. Therefore, it is employed only for mineral survey but can also be valuable for coal, oil and gas exploration as a reconnaissance tool. A number of studies have revealed that magnetic data can be used to determine the thermal structure of the Earth's crust in a variety of geologic environments [5–7]. Magnetic survey provides Geophysicists with the picture of the subsurface mineral make-up of the survey area. So they can detect specific ore deposits like iron ore, and different rock types. The Earth is like a huge moving magnet, and its molten metal core generates a magnetic field termed the magnetosphere that envelopes the Earth. Other terrestrial elements such as magnets and iron likewise generate their own magnetic fields that interact with the Earth's magnetosphere. Scientists have studied these interactions and found out that different minerals possess their specific magnetic characteristics. Geophysicists measure existing magnetic fields by either land-based or aerial instrument readings recorded by a magnetometer. Magnetic data can be gathered aurally using either aeroplane or a helicopter with the magnetometer extending at the front of the aircraft, as in the case with helicopters or trailing behind the aircraft, as in the case for aeroplanes. Readings are noted as the aircraft travels along predetermined flight route. This technique of data gathering yields lower spatial resolution than ground-based magnetic imaging. It covers much broader extent, so more terrain can be mapped.

To determine the geothermal nature of Gubio in Chad basin, northeast Nigeria, Curie isotherm depth and heat flow were estimated by employing spectral analysis in interpreting aeromagnetic data over the place. Above the Curie temperature (580 °C for magnetite), ferromagnetic materials lose their magnetism since the thermal energy

is adequate to uphold a random arrangement of the magnetic moments of the iron minerals [8]. Depth to certain geological features had been derived over the years through spectral analysis of potential data [9]. Spectral method which is found on the properties of the energy spectrum of huge and multifarious aeromagnetic data is a quantitative interpretational method. It uses the 2-D fast Fourier transform and changes magnetic data from space domain to frequency domain. The main benefit of spectral study is its capability to sieve nearly all the noise from the data while still ensuring that no information is missing in the course of interpretation by data overlapping. Such methods of spectral investigation offer quick depth evaluations from regularly spaced digital field data. 2-D procedures of spectral analysis of aeromagnetic anomalies have been described by [9, 10].

### 1.1 Location and geology of the study area

Gubio is located in Bornu State at lower part of the Chad basin, northeastern Nigeria. It lies within latitude 12.0°–12.5° north and longitude 12.5°–13.0° east. The area is approximately 3025 km<sup>2</sup>. The geological map of Nigeria showing the location of Chad basin and the study area is shown in Fig. 1. Chad basin has been described as a broad sediment-filled depression stranding northeastern Nigeria and adjoining parts of the Chad Republic. However, recent ideas have postulated the subsurface of the area as belonging to the northern part of the Benue Trough [11]. Its beginning is mostly credited to the rift system that developed in the initial Cretaceous when the African and South American Lithospheric plates parted and the Atlantic opened. Deposition in the area started with shallow marine sediments referred to as pre-Bima unconformably lying on the Basement Complex rocks. The succeeding regression gives way to the deposition of a thick sequence of the continental Bima Sandstone during Albian–Cenomanian times [12]. The Bima Sandstone is overlain conformably by the transitional Gongila Formation, which consists of basal limestone and Sandstone/Shale sequence. The blue–black Fika Shales overlie the Gongila Formation conformably and appear to have been deposited under a submerged (transgression) environment. These Shales are occasionally gypsiferous and contain thin persistent limestone. The Gombe Sandstone is a continental sequence of estuarine and deltaic sediments deposited over the marine Fika Shales. This Sandstone consists of lenses of siltstones and mudstone with ironstone at the lower beds. The middle part is characterized by well-bedded Sandstone and siltstone [13], while the upper part contains poor quality coals and characterized by cross-bedded Sandstone. The end of the Cretaceous was marked by a period of uplift and erosion. The first deposits in the Nigerian sector of

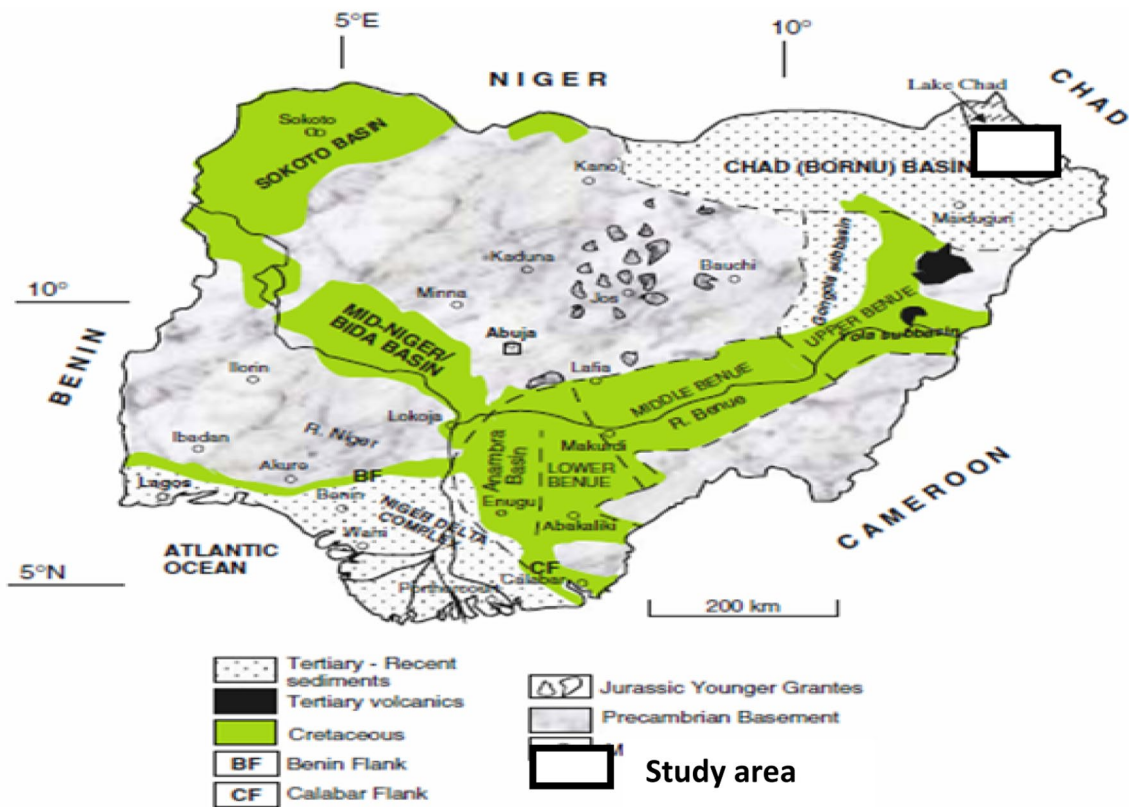


Fig. 1 The geological map of Nigeria showing the location of Chad Basin and study area [15]

the Basin after this period is the loosely cemented coarse to fine-grained Sandstone—the Kerri–Kerri Formation [12]. Massive claystone and siltstone with bands of ironstone and conglomerate occur locally in this Formation. The Sandstones are often cross-bedded, and lignite (low-grade coal) occurs near the base of the Formation. Angular unconformity was thought to exist between the Kerri–Kerri Formation and the Gombe Sandstone. The Chad Formation is Pleistocene in age and composed of an argillaceous sequence in which three well-defined arenaceous horizons occur. A minor unconformity indicated by a plinth of laterite is identified in a borehole as separating the Kerri–Kerri Formation from the Chad Formation [14]. Figure 2 shows the geological map of Gubio.

**1.2 Data source**

The aeromagnetic data set used in this study was obtained from the Nigerian Geological Survey Agency (NGSA). Fugro Airborne Surveys acquired the aeromagnetic data by means of a 3x Scintrex CS2 Cesium vapour magnetometer in 2009. The airborne magnetic survey was flown at 80 m elevation along flight lines spaced 500 m apart. The flight line direction was 135°, while the tie line direction was 225°. The Gubio aeromagnetic data were recorded in

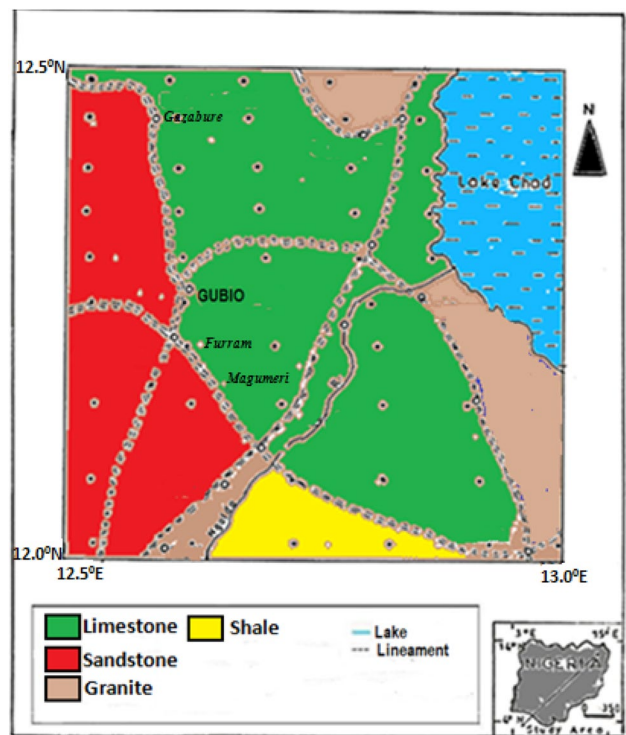


Fig. 2 The geological map of the study area

digital form ( $X, Y, Z$  text file) after removing the geomagnetic reference field (IGRF). The northing and easting of Gubio are represented by  $X$  and  $Y$  in metres, and the magnetic field intensity measured in nano-Tesla is represented by  $Z$ .

### 1.3 Methodology and analysis of data

Gridding of potential field data is the greatest vital phases of data analysis. Imaging, processing and interpretation need the data to be changed to an equally spread out two-dimensional (2-D) grid [16, 17]. The method of spreading data into a correspondingly spaced grid of cells in a stated coordinate system is known as gridding. Since the collected XYZ data were over broadly parted parallel lines which could have led to certain points along the investigation not collected, it is vital that the data be gridded. The smallest curvature technique was employed to produce the grids [18, 19]. This technique fits a minimum curvature surface (the smoothest possible surface that will fit given data values) to data points. To attain this, RANGRID GX of the Oasis Montaj software was employed. To circumvent over- or undersampling centred on the selection distance of the data, a grid size of 200 was used. The gridding of the aeromagnetic data produces the total magnetic intensity (TMI) map. Data enhancement such as reduction to pole (RTP) and band pass filter method was performed on the TMI data using oasis Montaj software. Reduction to pole removes the dependence of magnetic field data on the magnetic inclination of the geomagnetic field, by transforming the observed (measured) magnetic field anomaly into the anomaly that would have been measured if the magnetic field had been vertical. In other words, it restores the magnetic effect to appear as if it was collected from the North Pole ( $I=90^\circ$ ). RTP simplifies the shapes of magnetic anomalies and makes them appear like positive anomalies located directly above the source expected for induced magnetized bodies [20]. The band pass filter was applied to the potential field data in order to remove the effects of the top surface.

Spectral analysis method was employed in order to estimate the Curie point depth, geothermal gradient and the heat flow in the area. To perform the analysis, the study area was subdivided into four equal overlapping spectral blocks. Each block covers a square area of 27.5 km by 27.5 km in order to accommodate longer wavelength, so that depth to the centroid greater than 5 km could be investigated. To convert the magnetic data into the radial energy spectrum for every block, FOURPOT and Microsoft excel program using the fast Fourier transform (FFT) method were employed. The average radial energy spectrum was evaluated and exhibited in a logarithm figure of energy against frequency. Using Excel chart wizard as

log of energy (FFT magnitude) versus frequency in cycle per metre, graphs of radial average energy spectrum were plotted in MS Excel. For each block, two linear segments were drawn from each graph, and their gradients (Eq. 1) were used to calculate the depth to the centroid ( $Z_0$ ) and the depth to the top boundary ( $Z_t$ ) using Eqs. 2 and 3, respectively. Steps for determining depth to top bound and centroid have been discussed at length by a number of authors [21–24]. The Curie point depth ( $Z_b$ ), thermal gradient ( $\frac{dT}{dz}$ ) and the heat flow ( $q$ ) of the study area were calculated using Eqs. 4, 5 and 6, respectively. The FOURPOT and Surfer 10 software were used to construct the 2D Curie isotherm depth, likewise, the geothermal gradient and heat flow of the study area, respectively.

$$\text{Slope } (m_1, m_2) = \frac{\text{Log Energy}}{\text{Frequency}} \quad (1)$$

$$Z_0 = -\frac{m_1}{4\pi} \quad (2)$$

$$Z_t = -\frac{m_2}{4\pi} \quad (3)$$

where  $m_1$  and  $m_2$  are slopes of the first and second segment of the plot, respectively, and the negative sign (–) indicates the depth to the subsurface. The Curie point depth ( $Z_b$ ) is calculated using [25]:

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

The geothermal gradient  $\left[\frac{dT}{dz}\right]$  between the Earth's surfaces is defined by Eq. 5 [22, 25] as:

$$\left[\frac{dT}{dz}\right] = \frac{\theta}{Z_b} \quad (5)$$

580 °C is the Curie temperature for magnetite [24, 25]. Equation 6 shows the relationship between the Curie isotherm depth ( $Z_b$ ) and the heat flow ( $q$ ) [25, 26]:

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

where  $\lambda = 2.5 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$  is the average thermal conductivity [25, 26].

## 2 Results and discussion

### 2.1 Estimation of Curie point depth, geothermal gradient and heat flow

The TMI map (Fig. 3) shows the general magnetic anomaly of the basement rocks and the inherent variation in

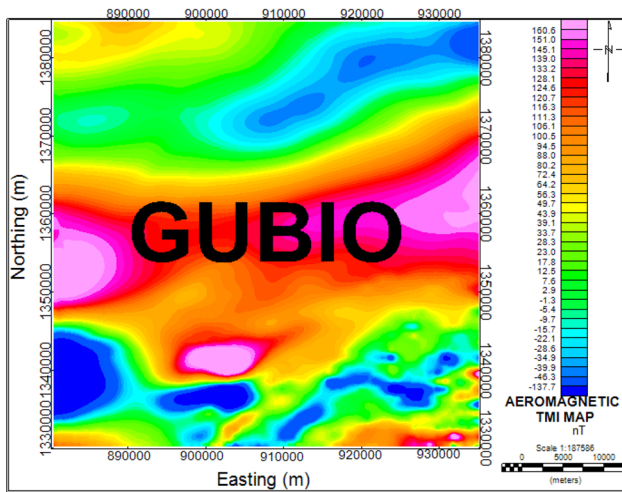


Fig. 3 Total magnetic intensity (TMI) map of the study area

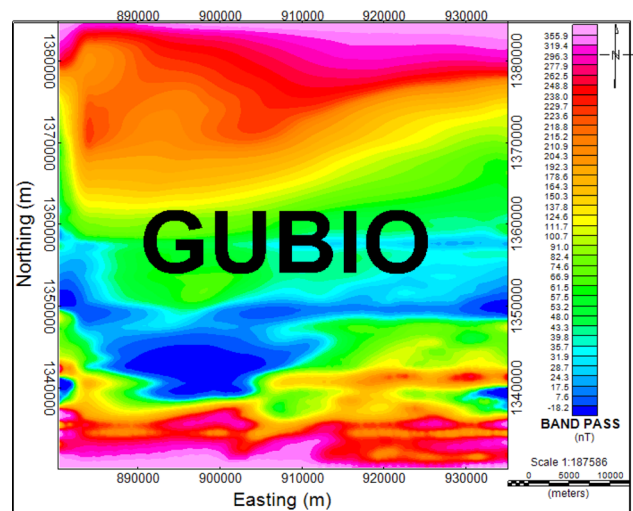


Fig. 5 Band pass magnetic map of the study area

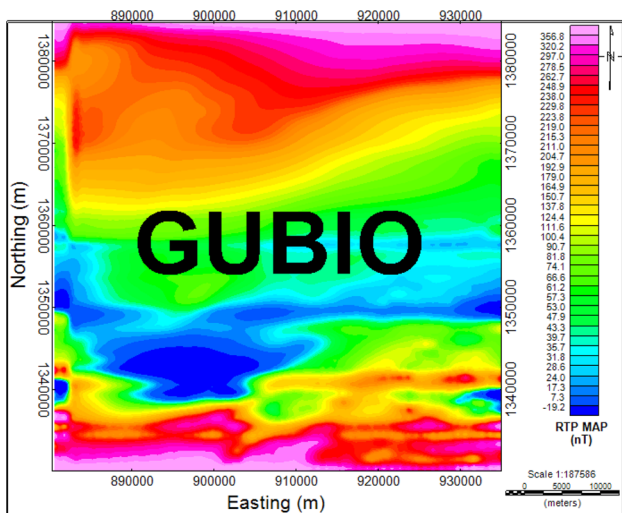


Fig. 4 Reduction to pole (RTP) map of the study area

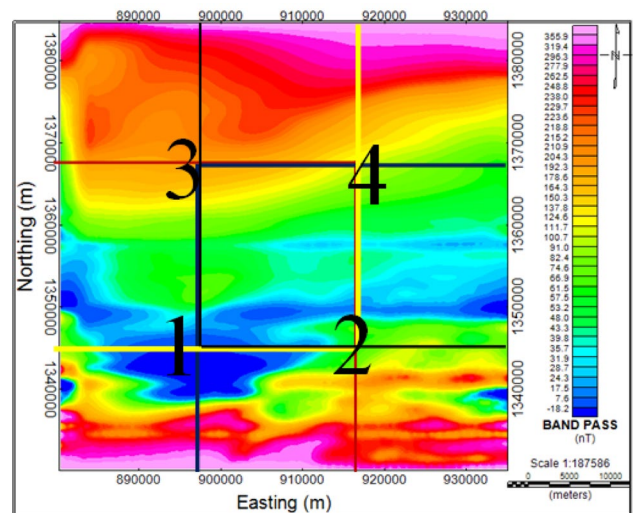


Fig. 6 Division into four overlapping spectral blocks for geothermal analysis

the basin under study. The 2D TMI map of the study area shows that TMI values range from  $-137.7$  to  $160.6$  nT, which revealed that the area is magnetically heterogeneous. Areas of very strong TMI values ( $139.0$ – $160.6$  nT) are probably caused by near-surface igneous or metamorphic rocks of high magnetic susceptibility values. The areas between  $-137.7$  and  $-34.9$  nT are most likely due to sedimentary intrusion and presence of other non-magnetic sources like Sandstones. The reduction to pole, RTP, (Fig. 4) obtained from the TMI map ranges from  $-18.2$  to  $355.9$  nT. The band pass filter (Fig. 5) was applied to RTP map in order to remove the effect of the top surface. The band pass filter map was subdivided into four equal overlapping spectral blocks (Fig. 6). Figure 7 shows the graphs for the four spectral blocks. Two

linear segments were recognized for every block, which suggests that there are two magnetic source layers in the study area. The gradient of the deep (black colour) and shallow (red colour) line segments were first assessed, and the depth to centroid ( $Z_0$ ) and depth to top boundary ( $Z_t$ ) were evaluated (Table 1). Curie point depth ( $Z_c$ ), thermal gradient ( $\frac{dT}{dz}$ ) and the heat flow ( $q$ ) of the study area were also calculated (Table 1).

Figure 8 is the two-dimensional (2D) map of the Curie point depth of the study area. The depth ranges from  $10.63$  to  $20.07$  km. A closer look at the map reveals that the deepest Curie point depth lies in the northeast, while the shallowest is observed to be conspicuous in the southeastern part of the study area. The result displays that the

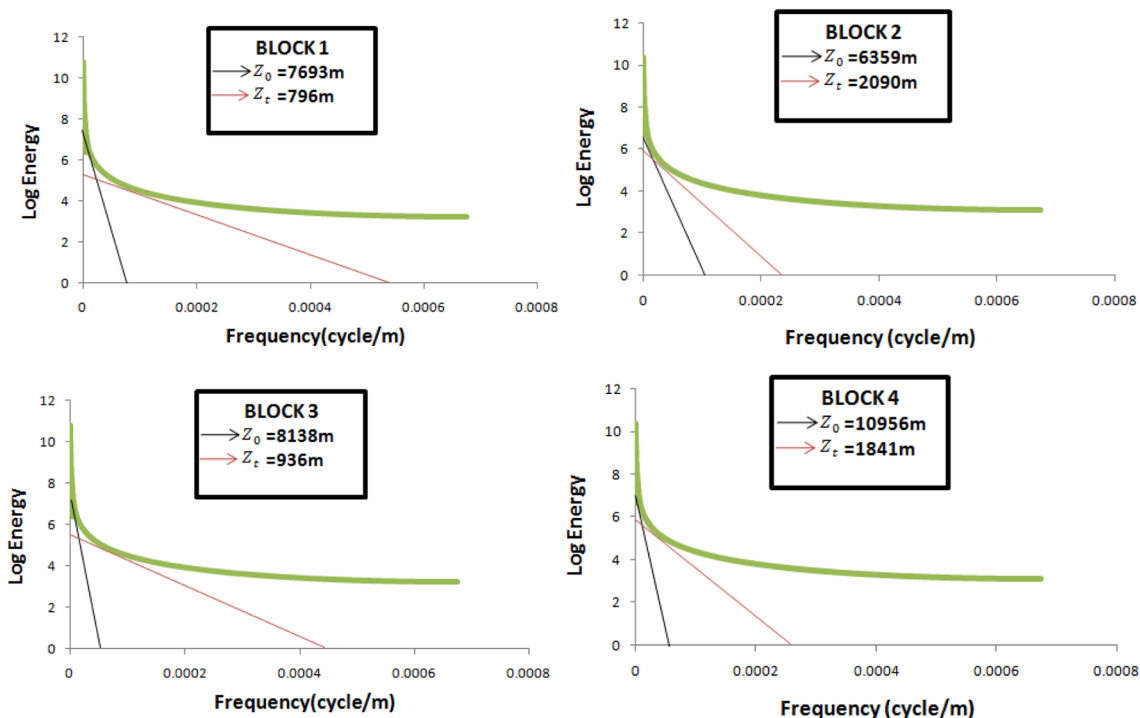


Fig. 7 Spectral plots of logarithm of energy against frequency (cycle per metre)

**Table 1** Calculated Curie depth, geothermal gradient and heat flow

Blocks	Depth to centroid ( $Z_0$ ) in km	Depth to top boundary ( $Z_t$ ) in km	Curie depth ( $Z_b$ ) in km	Geothermal gradient ( $\frac{dT}{dz}$ ) °C km <sup>-1</sup>	Heat flow ( $q$ ) mW m <sup>-2</sup>
1	7.69	0.80	14.59	39.76	99.39
2	6.36	2.09	10.63	54.57	136.43
3	8.14	0.94	15.34	37.81	94.53
4	10.96	1.84	20.07	28.90	72.24
Average			15.16	40.26	100.65

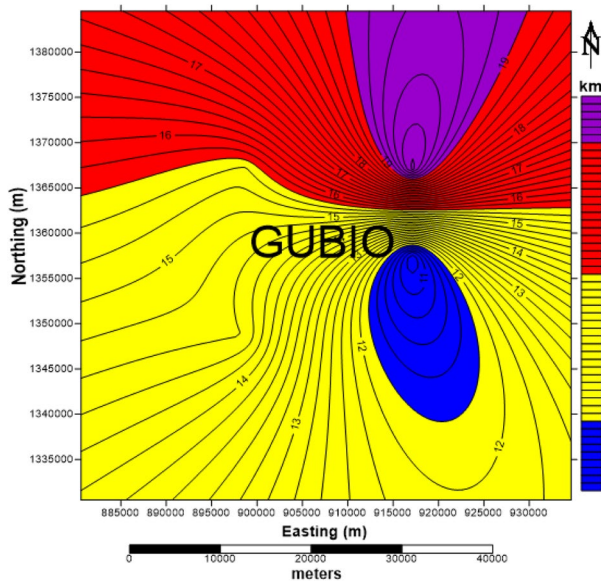
Curie point depth within the basin is not a horizontal level surface, but undulating.

The range of the calculated geothermal gradient is from 28.90 to 54.57 °C km<sup>-1</sup> with an average value of 40.26 °C km<sup>-1</sup> (Table 1). It has been shown by measurements that an anomalous high temperature gradient and heat flow is a characteristic of a zone with substantial geothermal energy. Figure 9 is the two-dimensional (2D) geothermal gradient map of the study area showing areas of lowest value 28.0 to 30.8 °C km<sup>-1</sup>, intermediate value 30.8 to 50.4 °C km<sup>-1</sup> and highest value 50.4 to 54.6 °C km<sup>-1</sup>.

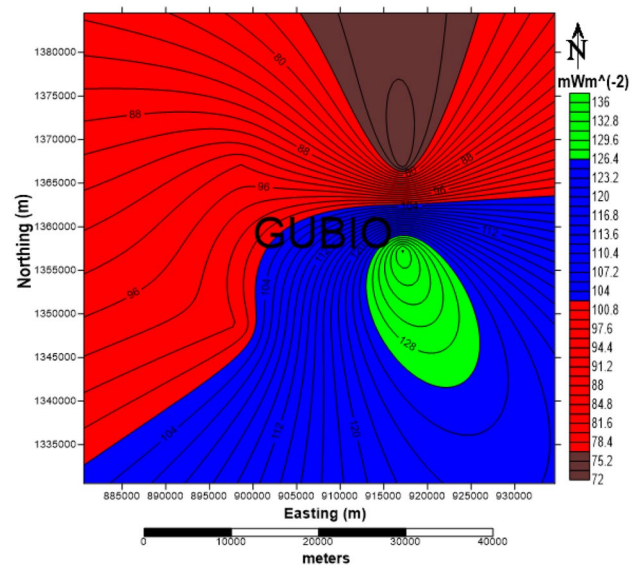
The heat flow values range from 72.24 to 136.43 mW m<sup>-2</sup> with an average value of 100.65 mW m<sup>-2</sup> (Table 1). Figure 10 shows that the highest heat flow values (126.4–136.4 mW m<sup>-2</sup>) are found around southeastern part of the study area, while lowest heat flow values (72–76.8 mW m<sup>-2</sup>) are found around northeastern part of the study area. The quantitative change in Curie depth

observed in Fig. 8 implies that the heat flow in the study area is not uniform. Results of Curie point depth in conjunction with heat flow values confirmed a distinct inverse linear relationship.

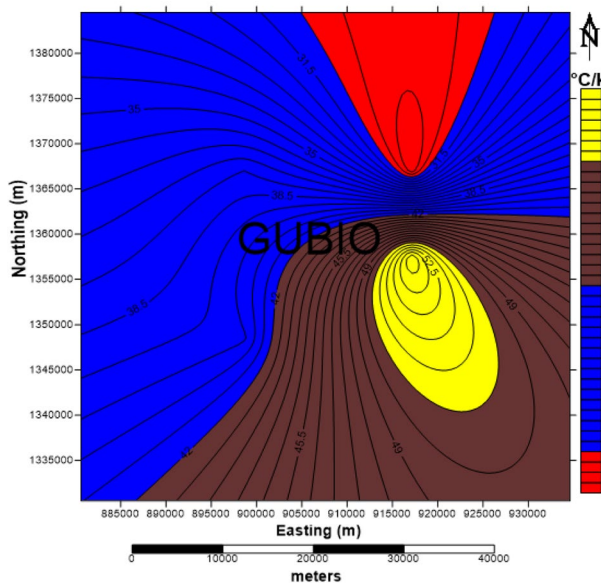
This shows that region of high geothermal energy is characterized by an anomalous high temperature gradient and heat flow. It is therefore expected that geothermally active areas will be associated with shallow Curie point depth. These results compare favourably with the results obtained by earlier researchers that worked in Chad basin. Nwankwo and Ekine [27] got a geothermal gradient in the range of 30–44 °C km<sup>-1</sup> and an average value of 34 °C km<sup>-1</sup> from geothermal gradients of Chad Basin, Nigeria, using bottom hole temperature logs. Nwankwo et al. [2] obtained an average geothermal gradient of 3.4 °C/100 m from bottom hole temperatures and heat flow values in the range of 63.6–105.6 mW m<sup>-2</sup> with average value of 80.6 mW m<sup>-2</sup> from wire-line logs from 14 oil wells in the



**Fig. 8** Curie depth contour map of the study area (contour interval of 0.2 km)



**Fig. 10** Heat flow contour map of the study area (contour interval of  $1.6 \text{ mW m}^{-2}$ )



**Fig. 9** Geothermal gradient contour map of the study area (contour interval of  $0.7 \text{ °C km}^{-1}$ )

Chad basin, Nigeria. The values of the results from this study defer from the values of the results obtained by [28, 29]. Ankwuba and Chinwuko [28] obtained Curie temperature isotherm depth which varies between 21.45 km and 31.52 km, geothermal gradients associated with it range between 17.45 and  $25.64 \text{ °C km}^{-1}$  and the corresponding mantle heat flow is about  $46.00 \text{ mW m}^{-2}$  and  $67.60 \text{ mW m}^{-2}$ . Onyedim and Awoyemi [29] obtained Curie point depths which range between 3.0 km and

$16.7 \text{ km}$ , geothermal gradient that varies between 34 and  $173 \text{ °C km}^{-1}$  and heat flow between 87 and  $446 \text{ mW m}^{-2}$ . The results obtained by [30], however, agree with the results obtained in this study. The calculated Curie depths, geothermal gradient and heat flow values obtained by [30] ranged from 10.220 to 22.721 km, 25.527 to  $56.751 \text{ °C km}^{-1}$  with an average value of  $38.517 \text{ °C km}^{-1}$  and  $63.818\text{--}141.878 \text{ mW m}^{-2}$ , respectively. It is important to note that the works whose results were used in comparison were carried out in different parts of Chad basin. Though the values of the results are not exactly the same, but their significance is good and encouraging and signifies good areas for geothermal reservoir exploration and maturation of hydrocarbon.

The areas of geothermal anomalies with gradients above  $50 \text{ °C km}^{-1}$  found in the present study may be a good prospective for geothermal energy usage in the region for generation of electricity. This agrees with the work of Ewa and Krzysztof [31], which assert that the geothermal gradient above  $50 \text{ °C km}^{-1}$  might be prospective for geothermal energy utilization for electricity generation in Nigeria. The average geothermal gradient of  $40.26 \text{ °C km}^{-1}$  indicates the possibility of hydrocarbon generation in the study area which agrees with the work of Nwankwo and Ekin [27] on estimation of geothermal gradients in the Chad Basin, Nigeria. They showed that sediments with comparatively greater geothermal gradients ( $30\text{--}44 \text{ °C km}^{-1}$ ) mature earlier (low oil window) than the ones with small geothermal gradient values. Hence, great geothermal gradient boosts the early development of oil at fairly shallow burial depths, but it makes the depth

range of the oil window to be quite narrow, while low geothermal gradient causes the first formation of oil to start at fairly deep subsurface levels, but makes the oil window to be reasonably wide. Therefore, result of geothermal gradient obtained in this area is favourable for enhancement of the formation of hydrocarbon.

### 3 Conclusion

The aeromagnetic data of Gubio area, Chad Basin, Nigeria, were interpreted quantitatively by employing spectral analysis. The Curie point depth, geothermal gradient and heat flow were estimated. The estimated values of Curie point depth, geothermal gradient and heat flow vary from 10.63 to 20.07 km, 28.90 to 54.57 °C km<sup>-1</sup> with an average value of 40.26 °C km<sup>-1</sup> and 72.24 to 136.43 mW m<sup>-2</sup> with an average value of 100.65 mW m<sup>-2</sup>, respectively. The shallow CPDs show that the magnetization is limited to the upper crust. Average geothermal gradient of 40.26 °C km<sup>-1</sup> obtained in this work indicates the possibility of hydrocarbon generation and accumulation in Chad basin. Also, the high heat flow may be responsible for maturation of hydrocarbon in Chad basin. Areas of geothermal anomalies with gradients above 50 °C km<sup>-1</sup> estimated in this study are a good prospect for geothermal energy for generation of electricity in Nigeria. Hence, this study provides thermal information that will direct regional geothermal energy exploration in Chad basin. Gubio area, from this study, is likely to be a good area for geothermal reservoir exploration for an alternative source for power generation. Geothermal energy is environmentally friendly and when fully harnessed will reduce emission of gases and particles into the atmosphere thereby safeguarding the ozone layer.

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### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Human and animal rights** This research did not involve human participants and/or animal.

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