Determination of Thermal Structure of the Crust Beneath the Gongola Basin, Upper Benue Trough, Nigeria

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Abstract

Geothermal energy resources have been established globally to be among the sustainable and environmentally harmless means of energy generation. The data for this study came from the Earth Magnetic Anomaly Grid 2 version 3 (EMAG2V3). It was acquired at a flying elevation of 4 km above the ellipsoid and has a resolution of 2-arc minutes (3.66 km). This research aim to study the thermal structure of the crust beneath the Gongola Basin so as to determine the heat flow, geothermal gradient and the Curie point depth. In this study, the creation of an air satellite magnetic map of the Gongola Basin is accomplished through the use of a fractal magnetization approach. However, Curie point depth (commonly known as bottom most of magnetic sources depth) measure the distance between two points in space, depth to bottom magnetic source (DBMS). Geothermal characteristics of the area was evaluated using Oasis Montaj. So the earth magnetic field is utilized to determine the depth of anomalous sources that ranges from few meters to tens of kilometers. The top depth ranges from 3.4465km to 10.942km, the centroid depth ranges from 14.045km to 31.338km, the geothermal gradient ranges from 10.2566°C/km to 23.4445°C/km and the heat flow ranges from 25.6415mW/m² to 58.84mW/m². The study identify a point (11°63E, 10°12N) with optimal values (26.44°C/km, 66.11mW/m²) at a distance 21.9km which is above the typical optimal values obtained in stable continental craton as obtainable in African plate.

Keywords: Curie Point; Geothermal Gradient; Gongola Basin; Thermal Structure
INTRODUCTION

Geothermal energy has continued to gain attention in the global community as an alternative to environmentally harmful fossil fuels (Yusuf, Sani, and Abiri, 2022). In many countries, geothermal energy currently contributes to a substantial percentage of their energy generation (Baioumy et al. 2014). Despite several attempts by geoscientists to study geothermal potentials in many parts of the world, some information regarding the crustal temperature contents of certain regions are not thoroughly understood (Abraham et al. 2019; Obande et al. 2014). Geoscientists frequently utilized field geological mapping techniques with the aim of examining the sedimentary basin structural geological settings (e.g. Isyaku, 2018). Some of the most widely utilized geophysical tools are Seismic, Gravity and Magnetic techniques. Due to the fact that the density difference between Basement Rocks and sediments closely resembles a hyperbolic function, gravity methods for calculating basement depth are ruled out. Spectral methods have been used to figure out how far away magnetic sources are at the top and bottom.

These studies assumed that the crust has completely uncorrelated random magnetization. Scholars look at the shape of the power spectrum of geo-magnetic anomalies and figure out how far away the top and bottom of a magnetic layer are. The magnetization of the crust is more akin to fractal behavior. Therefore, magnetic properties are fractal in nature, and most borehole data fit this fractal behavior well. The magnetic properties of the underlying rocks generate anomalies in the Earth's magnetic field, which are employed in a magnetic survey to examine subsurface geology (Mono et al., 2018; Isyaku, 2018). The purpose of a magnetic survey is to investigate subsurface geology by analyzing anomalies in the Earth's magnetic field induced by the magnetic properties of the underlying rocks (Likkason, 2014). Complete crustal section may be mapped at a variety of sizes, from the strongly magnetic basement at a very large scale to the weakly magnetic sedimentary contacts at a tiny scale. Despite the obvious benefits, because of the field's dipolar structure and additional polarization effects, interpretations of magnetic data lack uniqueness.

Geologic limitations, on the other hand, can significantly minimize the level of uncertainty. Magnetic surveys collect data from rock unit's deep underground as well as those at or near the surface (Likkason, 2014). Abraham et al., (2015) used the fractal causes distribution method on aeromagnetic data to figure out the geothermal system of the Wikki Warm Spring region. He estimated the depth to bottom of magnetic sources (DBMS). The chosen computational method is based on statistical methods for determining depth from the radial power spectrum, with a fractal distribution of magnetic sources assumed. The acquired data indicate an average thermal gradient and heat flow value, indicating shallow DBMS in the northeastern region of the WWS (Wikki Warm Spring) area and increase toward the southwestern region when regional variation patterns of estimate depths are studied.

The usually shallow DBMS is attributed to magmatic intrusion in the subsurface, and it highlights the presence of large-scale tectonic events, notably the basin-initiating event, in shaping thermal history. The data will aid in determining where additional geothermal energy exploration in the area should be dug (boreholes). Also, (Nwankwo & Shehu, 2015) used spectral analysis of recently acquired high resolution aeromagnetic (HRAM) data of the entire Sokoto Basin in northwestern Nigeria, to evaluate Curie-point depths, geothermal gradients, and near-surface heat flow. Magnetic source depth at the top, centroid, and bottom are determined by analyzing each of the twenty-two (22) overlapping blocks of the HRAM data using the spectral centroid approach. The depth readings were used to calculate the geothermal gradient, Curie-point depth (CPD), and near-surface heat flow in the research area. Such heat flow values suggest that there are unusual geothermal conditions in the basin,
and they should be high chances for geothermal exploration in the area. Spring et al., (2014) evaluate the geothermal potential of the WWS area using aeromagnetic data. The magnetic sources' distance from the top and centroid of the study region was determined using the spectral approach.

The power spectrum of magnetic anomalies had to be used to estimate the basal depth of the anomalies. Heat flow measurements averaged 170 milliwatts per meter, with an estimated CPD of 8 kilometers and a geothermal gradient of 68 °C/km. Section, (2002) employed the use of new high-resolution aeromagnetic data by applying the spectral analysis method for estimating the CPD, temperature gradient, and the heat flow data. Yusuf, Sani, and Abiri, (2022) determined the Curie-point depths (CPD), temperature gradients, and heat flow data over the Gongola Basin area but computed using a spectral analysis method in order to have a preliminary view of the geothermal implications (prospect) of the area. The study however, was unable to employ the use fractal analysis method.

In the study, we used the fractal spectral approach to determine how the magnetic basement's depth varies in specific regions of the Gongola Basin, such as in the north. In what follows, we start by introducing the known sedimentary basins in the study area. Then, we explain the spectral method and show how it can be used to figure out the depth of the magnetic basement using a set of synthetic result. There are a lot of factors that can change how the CPD is estimated. Using the fractal spectral method to figure out the CPD isn’t a good way to do this. Later, we show the magnetic basement map of the Gongola Basin and look at other geological data to figure out what it means. However, this study’s objective is to ascertain the crust's thermal condition from the Curie Point Depths (CPDs). The CPD is the depth at which, as a result of rising temperature, the dominant magnetic mineral in crust transitions from a ferromagnetic to a paramagnetic condition. It depicts the rough heat flow of the crust across the study area (e.g Springer et al., 2014). High Resolution Aeromagnetic Data acquired by the Nigerian Geological Survey Agency (NGSA) in the year 2009 was used for the research.

THEORICAL BACKGROUND

The power spectrum of a scaling distribution is frequency dependent in contrast to the white noise which is frequency independent, and it is conceptually defined as:

\[ P(K) = AK^{-\beta} \]

P stands for power spectrum, k for wave number, and A stands for constant. The scaling exponents' values show the degree of correlation; the higher the value, the stronger the long-range correlation. Curie point depth calculations are done using Fourier domain methods on aeromagnetic data, assuming a random and uncorrelated distribution of sources. Few recent research has suggested that fractal distribution of sources can be better estimated in detail. There are two methods used in estimating Curie point depth CPD, which are:

- The centroid method
- Fractal magnetization method

Two steps are involved in estimating the Curie point depth using the centroid method: (a) computing centroid depths from the power spectrum of magnetic field data, and (b) converting those centroid depths to Curie depths (Bansal et al., 2016). This method expresses the power spectrum of the entire magnetic field in terms of the top depth and thickness of the magnetic body (Blakely, 1996). The magnetic anomaly can be defined as

\[ P(K_x,K_y) = 4\pi^2C_m^2 \varphi_m(K_x,K_y)\left|\theta_m\right|^2\left|\theta_f\right|^2e^{-2|k_0|Z_0} \times \left(1 - e^{-|k|Z_b-Z_0}\right)^2 \]

Abdullahi Ali et al., DUKOPAS 9 (3b): 322-334, 2023
Kx and Ky are the respective wavenumbers, Cm is the constant of proportionality, $\phi$ is the power spectrum of magnetization and geomagnetic field, $Z_t$ and $Z_b$ are the top to bottom depth respectively. $\Theta_m$ and $\Theta_t$ becomes constant by taking the radial average, as equation 2 becomes

$$P(K) = A_1 e^{-2|k|Z_t} \times (1 - e^{-|k|(Z_b - Z_t)})^2$$

The right-hand side of equation 3 remains constant for very thick magnetic bodies, and $A_1$ does too. As a result, the previous equation becomes:

$$P(K) = A_1 e^{-2|k|Z_t}$$

The top depth of an anomalous magnetic body can be determined using Equation 4 above, and the centroid depth of the magnetic body can be expressed as

$$\ln\left(\frac{P(K)^{1/2}}{K}\right) = A_2 - |k|Z_0$$

The depth that is derived using the top and centroid depths is the Curie point depth. And is expressed as follows.

$$Z_b = 2Z_0 - Z_t$$

Centroid has become highly popular for estimating Curie point depth from aeromagnetic data, and it is being used to estimate Curie point depth from aeromagnetic data.

![Map showing the 24 blocks for spectral and fractal method analysis](image)
GEOLOGY AND LOCATION OF AREA
The earliest sedimentary rock in the Gongola Basin (Fig. 1) is the Bima Formation. It has a continental shape (braided, lacustrine, or alluvial fan). The formation is composed of sandstones, mudstones, shale, and clay. The transitional (Barrier Island/deltaic) Yolde Formation eventually buried the Bima Formation. The rock is composed of cross-bedded sandstone, shale, and clay stones when the environment changed from a continental to a marine one.

The Northern Benue Trough has two major sub-basins, branches into an E-W trending Yola arm and N-S trending Gongola basin separated by an area shallow basement rocks traversed by four major NE-SW trending sinistral Strike slip faults. The stratigraphic succession which comprises the continental Aptian – Albian Bima Formation, the Cenomanian transitional Yolde Formation.

In the Gongola Basin, the Pindiga Formation was represented by Kanawa Member, Gulani, Dumbulwa and Deba Fulani (Daban Fulani) Members. The Dukul Formation, Jessu Formation, Sekuliye Formation, Numanha Shale and the Lamja Sandstone (all of the Yola Sub-basin) are the facies equivalents of the Pindiga Formation in Gongola Sub-basin. The Gombe Formation, overlies the Campano-Maastrictian Fika Shale. In Upper Benue Trough, the Gongola Basin is an arm that runs from north to south. It is part of the Benue Trough, which runs for 1000 km. The research area lies between the Latitudes 90 52' 55''N and 100 34' 17''N and longitudes 10o 38' 37''E (Fig. 1) and 11o43' 56''E. The proposed area of study lies on the map (Abraham et al., 2015).

Figure 2: Geological map of Nigeria showing the study area (after Sarki Yandoka, 2015)
MATERIAL AND METHOD

Oasis Montaj is a powerful suite of modeling and analysis tools that can be used to gain a more in-depth understanding of the Earth’s subsurface and sub-sea environments, among other things. Everything from ground and airborne survey geophysics to geochemistry to geology can be processed and mapped in a single dynamic 3D environment, which allows the data to be processed faster and effectively.

FRACTAL MAGNETISATION METHOD

The gravitational and magnetic forces exhibit fractal behavior, and a magnetization model was used to estimate the lowest point to the bottom of magnetic sources because magnetic susceptibility and crust magnetization, in particular, exhibit fractal properties that may be detected. (Quintero et al. 2019.Pdf, n.d.). The proposed technique for estimating Curie depth for fractal distributions of sources where scaling exponents are present is based on the assumption that the power spectrum of the magnetic field is used to estimate the top depth and thickness of the magnetic body at the same time.  (Bansal et al., 2016). The scaling exponent and depth component of the radial average of the power spectrum are expressed as (Bansal et al., 2016).

\[
P(K) = C - 2Kz_t - tK - \beta \ln(K) + \ln \left[ \int_0^\infty \left( \frac{w^2}{k^2} \right)^{-1-\beta/2} dw \right]
\]

where \( k \) is the wavenumber, \( z_t \) is the top depth, \( t \) is the slab thickness, and \( \beta \) is the source distribution scaling exponent, and \( w \) is the wavenumber in vertical plane. For predicting top depth based on the shape of the power spectrum of satellite data, the value of scaling exponents was fixed. For a reliable estimation, manual checking of the calculated parameter is required. For scaling dispersion of sources, a proposed modified centroid approach for estimating Curie depth from aeromagnetic data has been proposed. This method, which is comparable to the standard centroid method for scaling distributions of sources, computes Curie depth in two phases.

Top depth:

\[
\ln \left( K^\beta P(K) \right) = A_2 - 2Kz_t
\]

Centroid depth:

\[
\ln \left( k^\beta \frac{P(K)}{K^2} \right) = A_3 - 2Kz_0
\]

HEAT FLOW

The essential relation for heat flow conveyance is given by Fourier law, which takes the form (Abraham, Obande, Chukwu, Chukwu, et al., 2015).

\[
q = \theta \frac{dT}{dz}
\]

Using the following equation, the Curie temperature (\( \theta \)) can be calculated using the CPD \( z_b \) and the thermal gradient \( dT/dz \).

\[
\theta = \left( \frac{dT}{dz} \right) z_b
\]
In this equation, the surface temperature is assumed to be zero and the $dT/dz$ (geothermal gradient) constant. This relation implies that regions of high heat flow are associated with shallower sources, whereas regions of lower heat flow are associated with deeper sources.

**RESULTS AND DISCUSSION**
Residual maps were used to emphasize shallower anomalies and demonstrate the geographical distribution of magnetic anomalies caused by shallower source bodies or magnetic anomalous entities that intruded closer to the surface. Following that, using Equation. (6), the depths to the top ($Z_t$), centroid ($Z_o$), and bottom ($Z_b$) of magnetic sources for each block were estimated, and the resulting geothermal gradients and heat flow were calculated using Equation. (10) and (11).
Figure 4: Power spectrum plot for Block 1

Figure 5: Power spectrum plot for Block 2

Figure 6: Power spectrum plot for Block 3
To calculate CPD, two plots were created for each of the 24 blocks, i.e., wavenumber-scaled power spectra and power. The group of blocks in the previous figure is a typical illustration. While the slope of the second plot's lower wavenumber section leads to the estimation of centroid depth ($Z_0$), the slope of the first plot's high-wavenumber portion leads to the estimation of the depth to the top of magnetic sources ($Z_t$).
Table 1. Estimated top depths, centroid depths and curie point depths, and calculated heat flow and geothermal gradients using different values of alpha

<table>
<thead>
<tr>
<th>Block number</th>
<th>Zt (km)</th>
<th>Zo (km)</th>
<th>Zb (km)</th>
<th>Alpha value</th>
<th>GT (°C/km)</th>
<th>HEAT FLW (mW/m²)</th>
<th>LONG</th>
<th>LAT</th>
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Figure 9: CPD map of the study area
According to (landscape evolution, 2013), in a normal continental crust, a typical geothermal gradient of the earth surface is about 25°C/km. However, this gradient is not sustained but decreases to not more than 16°C/km and a mean heat flow of 65 mW/m². The study identified a point (11°63'E, 10°12'N) with optimal values (26.44°C/km, 66.11 mW/m²) at a distance 21.9 km which is above the typical optimal values obtained in stable continental cratons as obtainable in African plate, which is a potential side for geothermal exploration. Figure 9 depicts a map of the variation in CPD across the research area. A close examination of the map reveals sections or regions within the research area with moderate to high CPD anomalies.

CONCLUSION
The determination of thermal structure of the crust beneath the Gongola Basin with satellite data using fractal analysis revealed that the centroid method produced CPD estimates with greater percentage differences than its fractal modification. CPD calculations based on centroid fractals were expected to be more accurate. The study found that the Curie-point depths vary between 21.9331 and 56.5489 km, while the basement depths, which are also used as a proxy for sedimentary thickness, vary between 3.4465 and 10.942 km. The resulting heat flow varies between 25.6415 and 58.8390 mW m². The geothermal gradient varies between 10.25661 and 26.4441 °C/Km. The calculation of the curie depth, geothermal gradient, and
heat flow rate across the area found that the average curie depth for the area is 39 km, the average geothermal gradient is 15.8 OC/km, and the average heat flow rate over the area is 39.5 mW/m². The observed geothermal gradient correlated well with known values for the research location. The centroid-fractal approach could aid with the research of the thermal and geologic structure of the crust, as well as assessing locations with geothermal and oil potential. The minimum CPD value of 21.9331 km was found for block 12 and furthermore, the largest CPD value found in block 20 was 56.5489 km. The presence of shallow CPDs/high heat flow/high temperature gradients in the eastern regions. This result is similar to work of Section, (2022). More so, some fumaroles (Wikki warm spring) near basement areas (Alkaleri areas) in the western part of the study area, as well as the Ruwan-Zafi warm spring near the Lamurde anticlinal area, showed relative conformity with the areas of moderate-high heat flow/moderate-shallow CPDs presented in this study. It also agrees the work of Yusuf, Sani and Abiri (2022) indicating that locations depicting a high magnetic susceptibility contrast from a generated analytic signal map, as well as high temperature gradients, high heat flow, and shallow CPDs are attributed to crustal thinning along the sedimentary basin and magmatic intrusions along basement areas, respectively.

REFERENCES
Saada, S.A. 2016. Curie point depth and heat flow from spectral analysis of aeromagnetic data over the Northern part of Western Desert, Egypt. Journal of Applied Geophysics 134: 11-
100

