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Delineation of Geothermal Energy Potentials in Parts of Calabar Flank, Southeastern Nigeria Using Aeromagnetic Data.

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ABSTRACT
In tackling energy-related challenges in Nigeria; the exploration of an alternative source of energy (Geothermal Energy) comes to the limelight as it is generated below the earth subsurface. This work focuses on the delineation of geothermal energy potentials in parts of Calabar Flank, in southeastern Nigeria using Aeromagnetic Data. The aim is to understand the geothermal energy potentials and structural of parts of the Calabar flank by studying the various geothermal, geological, and structural parameters using Aeromagnetic Data. The methodologies applied are quantitative for structural analysis and qualitative using spectral analysis and 3D Euler Deconvolution. The study area lies within Latitude 5°30'00" N - 6°30'00"N and Longitude 7°30'00"E - 8°30'00"E respectively. Results from the 3D Euler analysis revealed the depth range of 0.25 Km to 4.018 Km. the spectral Analysis revealed a depth range of Magnetic source (Zt) is (-)0.564 Km to (-)0.828 Km, the Z₀ is (-)4.261 Km to (-)5.999Km and the average depth to basement thickness is (-)4.825 Km. The Curie Point Depth, Geothermal Gradient, and Heat flow yield an average depth of (-)9.452 Km, a value of 61.893 CKm⁻¹, and 154.983 mWm⁻² from the Spectral Analysis. Some structural features such as trending faults, and fractured basements was observed at the NE-SW of the study area and this correlated to the relatively high heat flow and geothermal gradient at the NNE-SSW part is associated with thermal structures, mineralogical and tectonic history from the NE-SW trending fault in the study area is suitable for geothermal energy exploitation.
Keywords: Geothermal Energy, Aeromagnetic Data, Curie Point Depth, Spectral Analysis, 3D Euler Deconvolution, Calabar Flank.

1 INTRODUCTION

Due to the recent changes in population growth, increase in industrialization, economic demand, and sustainable development; the need for accessible, eco-friendly, and renewable sources of energy is on the rise across developed and developing countries. To bridge this gap, alternative sources of energy such as geothermal energy in frontier regions across the globe are in high demand. Geothermal energy is defined as one of the cleanest, naturally sourced renewable forms of energy derived from the earth’s subsurface, radioactive decay of several elements found beneath the Earth’s core, and the combination of the heat radiating from the sun. This energy gotten from the earth’s subsurface comprises a source (molten magma), pathway (fractured basement and fault), and a reserve (surface and underground enclave). Among the renewables, geothermal energy can produce year-round constant power, a significant differentiation from both solar and wind power, which must wait for the sun to shine or the wind to blow, respectively. In, Nigeria, several locations as been postulated to have geothermal energy potentials such as parts of Calabar Flask falls under the lower and mid-Benue Trough, Chad Basin, Sokoto Basins, Ikogwusi Hot springs, and Niger Delta Basin (Chukwu et al., 2018; Abraham et al., 2017; 2018; Abraham and Nkitnam, 2017, Odumuodu, 2012, and Anakwuba and Chinwuko, 2012). These aforementioned locations host potential energy sources for heating plants, agriculture, power supply, domestic and industrial applications. The application of geothermal energy is classified into direct and indirect uses depending on the temperature, source, gradient, and environment of deposition. Compared to other renewable energies, geothermal energy is very enormous, underutilized heat and power resources that emit little or no greenhouse gasses (Dipippo and Renner, 2014).

Over the years, high geothermal energy potentials at some locations in Nigeria have also been documented (Nwachukwu, 1976 and Avbovbo, 1978) as the Calabar flank present huge potentials for exploration and exploitation of geothermal energy (Odumuodu, 2012). The Calabar Flank is coined out of the West African Rift System separating Africa from South America and the opening of the Atlantic Ocean as shown in (Figure 1) (Carter et al., 1963; Cratchley and Jones, 1963; Wright, 1976; Ajayi and Ajakaiye, 1981; Adighije, 1981; Agagu and Adighije, 1983; Ofogebu, 1984; Benkhelil, 1989; Ogunmola et al., 2016; Abdullahi et al., 2019b). This led to the formation of the major parts of the Benue Trough in the southern sedimentary basin, creating sub-basins within the Trough (Abraham and Nkitnam, 2017). It is bounded by the Oban-massif to the north, the Calabar Hinge line delineating the Niger Delta sedimentary basin in the south (Ilozobhie et al., 2016). It is separated from the Ikpe Platform to the west by a Northeastern-Southwestern trending fault/basement horst that is separated by Ikang Trough (Reijers and Peters, 1987). Some of the sedimentary structures such as faults, graben, horst, and fractured basement rocks from volcanic intrusions in sediments contribute to the elevated temperature of Calabar Flank. The search for geothermal energy focuses on locations where geological processes have high temperatures that are near the surface such that the heat contained can be gainfully utilized.
Rainfall droplet flows into the subsurface and into these fissure cracks, joints, fractures, faults; this water is heated up by the underlying rocks leading to a thermal source point.

Several methods are used for the delineation of geothermal energy in a sedimentary environment, which includes: Seismic method that uses Bottom Hole Temperature (BHT) data from geophysical logs, Landsat-ETM imagery from satellite imaging systems, Gravity method using the gravimeter, and magnetic method using the airplanes to map the magnetic property of a terrain. Each of these methods investigates different rock properties to know which possesses geothermal properties.

However, for this study, the magnetic method, which is the most preferred of all geophysical techniques will be used to analyze part of Calabar Flank in Nigeria.

Figure 1: Map of Calabar Flank (Adopted from Peter et al., 1987)

The aeromagnetic method is used in the delineation of the geothermal gradient of a sedimentary terrain, mapping of intra-basement structures, and mineral exploration using aeromagnetic datasheets. The aeromagnetic technique is a type of geophysical method in which a magnetometer is towed by an aircraft to survey a particular geological terrain (Bello et al., 2017). This method is the most effective as it makes use of magnetic susceptibility that can be relative to geothermal studies. It is used to determine the magnetic anomaly, geothermal gradient, rapid depth to basement estimation, architectural properties, topography, the geometry of a sedimentary basin, access to petroleum and mineral resources, delineate igneous rocks within a
sedimentary terrain, etc. This method is the most essential tool applied in modern geological mapping, as it is a rapid, cost-effective, and easy technique for locating various geological features, and earth’s components (Anakwuba and Chinwuko, 2012).

The analysis of aeromagnetic data at the Calabar Flank is to produce a determine the geothermal properties from the Curie Point Depth, Geothermal Gradient, and Heat Flow for depth and temperature estimations respectively.

The Principles of the aeromagnetic survey is similar to the use of hand-held magnetometer operations, but allows much area coverage over a short time, as the aircraft flies over a grid-like dimension with line spacing determining the resolution of the data, and its designated height per unit area (Abraham et al., 2018). During the flight, the magnetometer records tiny variations in the intensity of the ambient magnetic field. This is due to the temporal effects of the constantly varying spatial variation, solar wind in the earth’s magnetic field, regional magnetic field, and local magnetic field in the target zone.

High-Resolution Aeromagnetic data has been applied all over the world by several researchers in structural studies, estimation of depth to basement, thermal crustal studies. These include, amongst others. (Connard et al., 1983, Thurston and Smith, 1997, Selim and Aboud, 2014, Abdelrahman and Essa, 2015 and Longo et al., 2015).

However, not many studies have been done to determine the potentials of geothermal energy in the area by understanding the geothermal properties and structural interpretations of the study area. Also, the crustal studies will be a potential tool to unravel the viable content as it will help interpret the subsurface structural configuration and thermal properties respectively.

This research is therefore intended to evaluate the vital aeromagnetic anomalies, structural interpretation in the study area in delineating, analyzing, and proposing a hypothesis on the structural and thermal interpretation for geothermal energy potentials investigations.

The research will focus on some part of the Calabar flank located at the Lower Benue Trough in Nigeria with a coordinate of latitude 5°30'00"N - 6°30'00"N and longitude 7°30'00"E - 8°30'00"E.

2 MATERIALS AND METHOD

2.1 Geologic Setting and Tectonics of the Study Area

The Calabar Flank Sedimentary basin from (Figure 2) was formed by the incipient rifting of tectonic plated during the continental drift of South America from Africa plate and the opening of the South Atlantic Ocean in the Albian age (Whiteman, 1982). This southern sedimentary basin is framed on the Precambrian Oban Massif and Calabar hinge line at the northward direction, delineated by the Niger Delta basin at the southward direction, contiguously connected to Doula Basin and Cameroon volcanic ridge to the east, and Ikpe Platform by northeastern-southwestern trending fault to the west (Reyment, 1965). There is a notable lithological similarity between the carbonate development of West African South Atlantic Coastal basins and the Calabar Flank (Obi et al., 2018).
The Calabar Flank is characterized by crustal block faulting and other structural basement features such as horst, graben, and complex joints that align towards the coastal basins of Gabon, Angola, and Congo. The Calabar Flank can be referred to as Lower Benue Trough, as it is composed of Cretaceous deposits. Areas such as Creek town, Okoyong, Ekpriikang, and other parts are located within Cross River state, and they all have a sedimentary thickness that ranges from 2.0 to 3.5 km respectively (Benkhelil, 1982; Reijers, 1996). The structural pattern features of Calabar Flank ranges from faults, horst-and-graben, joints, folds, and unconformities (Reijers, 1996). The numerous horst structures around parts of Calabar Flank make them susceptible to overheating from the adjacent Oban Massif Basement and this gives an indication of geothermal energy potentials in the study area (Obi et al., 2018). It is a general belief that the geological structures of a particular lithology influences the geothermal field energy distribution in the upper part of the earth crust (Kurowska and Schoeneich, 2010).

Figure 2: Geology of Lower Benue Trough showing Calabar Flank

The absence of evaporates facies were closed off from the Calabar Flank by the Guinea Ridge, and carbonate development between the Southwestern-African coastal basins and the Calabar Flank. These structures were classified over a typical divergent plate boundary, with a raft continental margin that is single evolutionary geologic history (Nwajide, 2013). The Benue Trough extends from the Gulf of Guinea to the Chad Basin and hypothetically proven that it formed the Y-shaped (RRR) triple junction ridge system that initiated the displacement of the Afro-Brazilian plates in the Early Cretaceous age (Kogbe, 1989). The basement complex was formed from metamorphic and igneous rocks with Tertiary to Recent volcanic rocks. Cretaceous sediments connected with some volcanic satiates the Benue Trough up to 6000 m and form part of a mega-rift system generally referred to as the West and Central Africa Rift System (Obaje, 2009; Abubakar, 2014).
geological structure and history in Nigeria influence geothermal exploration within each geological province. The products of magmatic and volcanic activities, for instance, are numerous within the Benue trough. The sedimentary deposits within the towns of Calabar flank include: Abakaliki, Eket, Ikom, Ikot-Ekpene, Uwet, and Ugep. Ikpe towns respectively have the youngest deposit of Benin Formation that is aged between Paleocene to Eocene in (Figure 3). Its sediments range from Cretaceous to Tertiary in age; and are classified into eight different formations by several authors who study the environment starting from the deposition of the Asu River Group (Eze et al., 2017).

![Figure 3: Geological Map of the Study Area](image)

2.2 Sources of Data
The four High-Resolution aeromagnetic datasets used in the research consist of sheets 313 (Afikpo), 314 (Ugep), 322 (Ikot-Ekpene/ Ikpe), 324 (Uwet) presented n XYZ Geosoft format will be utilized for this study for the delineation of geothermal energy potentials in $\frac{1}{2}^\circ$ by $\frac{1}{2}^\circ$ sheets. This HRAM dataset was obtained as standard maps of the Total Magnetic Intensity on a scale of 1:90,000 compiled by the Nigerian Geological Survey Agency (NGSA), during the nationwide aeromagnetic survey executed between the years 2005 and 2010 with the aim of encouraging natural resource exploration in Nigeria. The survey was flown in drape mode using a real-time global positioning system at a sensor mean terrain clearance of 80-100m, proton precession magnetometer, transmitter loop, and a receiver loop (x-z). The traverse line spacing was 500m while the tie line spacing was 2000m respectively in NW-SE and NE-SW directions, an average flight elevation of 80,000 m, and the data were recorded at a sampling interval of 100m (NGSA, 2010) and stored in grid formats.
The National Grid Database delivered in American Standard Code for Information Interchange (ASCII) file in Geosoft format was used to organize the HRAM data, and with the use of The International Geomagnetic Reference Field (IGRF-13), the geomagnetic reference was removed from the data. The total area covered is about 12,100 Km\(^2\) from the four sheets used on a scale of 1:90,000.

### 2.3 Method of Data Analysis

The dataset was firstly pre-processed by the Fugro Airborne Survey team, which includes; pre-processing operation included micro leveling, removal of cultural effects as well as filtering for noise contents. The pre-processed data were quality controlled for isolated spikes and other spurious data which bear no correlation with geology. The geologic map of the study area was plotted using the QGIS and the contouring was executed by the Surfer Version 32 software.

The filtering of the HRAM data was done to improve the signal-to-noise ratio while reducing other noise energies in the data. The Oasis Montaj\(^\text{Tm}\) software (version 8.4) was used to plot the Total Magnetic Intensity (TMI) which contained both regional and residual data. The regional magnetic anomaly was removed from the Total Magnetic Intensity (TMI) to give the resident anomaly map by fitting a linear surface to the digitized aeromagnetic data using a first-order Polynomial Fitting technique.

Two methods were used for the interpretation of the aeromagnetic data to the study area: qualitative and quantitative. The qualitative method deals with the physical interpretation by extracting the physical geologic information from maps and grids to determine the structural features of the study area. The aim of qualitative interpretation is to map visible structural features from the TMI map. The maps are contoured using Oasis Montaj\(^\text{Tm}\) software where color gradations represent areas enclosed between successive contours.

Quantitative interpretation involves the mathematical approximation of depth and 3-D dimension of magnetic anomalies with the use of theorems to determine the geothermal energy potentials of the study area. Firstly, the application of mathematical low pass and high pass filters which include; First Vertical Derivative (FVD), Second Vertical Derivative, First Horizontal Derivative (D\(_x\), D\(_y\)), Reduction-to-Pole.

The observed magnetic anomaly is transformed into the Residual Magnetic Data that measure if the ambient magnetic field and magnetization were both vertical by reduction to pole. The Reduction-to-Pole (RTP) procedure involved the removal of the non-vertical magnetic component and positioned at the magnetic pole. It helps to define boundaries between different magnetic susceptibilities and their varying basement lithologies.

Mathematically, Reduction to Pole (RTP) is expressed by:

\[
\Phi = \frac{1}{\sin x + i \cos 1. \cos (D - Y)}
\]  

(1)

Where, \(i = \) Complex number, \\
\(x = \) Inclination for amplitude correction, \(x > 1\) \\
\(D = \) geomagnetic declination \\
\(Y = \) wave number direction.
The effect of the second derivative is to suppress regional magnetic anomalies and enhance local (residual) magnetic anomalies in the study area.

For the magnetic depth estimation; 3D Euler Deconvolution and Spectral Analysis was incorporated into the study to determine the geothermal gradient, curie point depth, and heat flow using mathematical modelling. 3D Euler Deconvolution is used to determine the depth to shallow magnetic bodies with the help of x, y, and z derivatives to estimate the depths and locations to the magnetic anomalous targets (sphere, vertical cylinder, horizontal cylinder, thin dyke, pipe, etc.)

The significance of the location and depth estimates obtained by 3D Euler Deconvolution is given by the specificity of the chosen parameters like the grid cell size, window size, chosen depth uncertainty tolerance, etc. The selection of the grid cell size should be based on the grid spacing and the wavelength of the anomalies to be analyzed, as the software Geosoft Oasis Montaj™ allows a square window size of up to 20 grid cell units. If the wavelengths of the anomalies are significantly longer or shorter than the window size, the 3D Euler method does not yield appropriate results. In general, 3D Euler Deconvolution yields results for each window position; therefore, it is necessary to eliminate solutions with high uncertainties.

The Geosoft Oasis Montaj™ version 8.4 and Microsoft Excel software is incorporated into the 3D Euler Deconvolution processing and it reports the depth and location uncertainties as a percentage of the depth below the recording sensor position. As a matter of principle, low Structural Indexes values are associated with source bodies which give rise to low gradients, thus depth estimation solutions with low SI values have high uncertainties. The results of the Euler method are displayed in ordinary maps as point solutions combining the location (position of solution) and the depth (color range). Given the choice of an appropriate structural index, 3D Euler Deconvolution will lead to a clustering of solutions, which can be interpreted.

The spectral depth estimation method is based on the magnetic field principle at the surface that’s considered the integral of magnetic signatures from all depths. The power spectrum of the surface field can be used to identify the depths of source ensembles in performing the spectral analysis of aeromagnetic data (Spector and Grant, 1970). This same technique can be applied in the identification of depth of magnetic basement characterization on a moving data sub-grid/window basis, merely by the selection of the steepest and deepest straight-line segment of the power spectrum, assuming that this part of the spectrum is sourced consistently by the contrasts of the surface-basement magnetism.

For small windows of data, the limited number of grid nodes often leads to power spectra becoming jagged at the start or end. This is the reason for omitting the first point in the automated determination of the deepest straight-line segment of the power spectra. To define a straight line on the basis of a set of points (in the least square statistical manner) a minimum of 2 points is required, but more are preferable. Increasing the number of points used to define the straight-line segment may conflict with obtaining the deepest characteristic source depths, as the slope of the power spectrum reduces for increasing wavenumber / decreasing wavelength. Depth results are generated for the entire dataset using different wavenumber ranges and window sizes. A potential field grid may be considered to represent a series of components of different wavelengths and directions. The logarithm of the power of the signal at each wavelength can be plotted against wavelength, regardless of direction, to produce a power spectrum. The power spectrum is often observed to be broken up into a series of straight-line segments. Each line segment represents the cumulative response of a discrete ensemble of sources at a given depth. The depth is directly proportional to the slope of the line segment. Filtering such that the power spectrum is a single straight line can thus enhance the effects from sources at any chosen depth at the expense of effects from deeper or shallower sources.
Fourier transformations have been applied in estimating depth to magnetic sources of the anomaly of the digitized aeromagnetic data to compute the Fourier (amplitude) spectrum. This is plotted on the Logarithmic scale against frequency manually. The plot shows the straight-line segments which decrease in slope with increasing frequency. The slopes of the segments yield estimates of depths to magnetic sources.

Given a residual magnetic anomaly map of dimension L×L digitized at equal intervals, the residual intervals, and the residual total intensity anomaly values are expressed by (Tanaka et al. 1999), in terms of double Fourier series expansion:

\[ T(x, y) = (x + a)^n = \sum_{n=1}^{N} \sum_{m=1}^{M} P^n_m \cos \left( \frac{2\pi}{L} (nx + my) \right) + Q^n_m \sin \left( \frac{2\pi}{L} (nx + my) \right) \]  

Where, L = dimension of the block, 

\( P^n_m \) and \( Q^n_m \) = Fourier amplitude and 

N, M = number of grid points along the x and y directions respectively.

Equation (2) can be combined into a single partial wave thus:

\[ P^n_m \cos \left( \frac{2\pi}{L} (nx + my) \right) + Q^n_m \sin \left( \frac{2\pi}{L} (nx + my) \right) = C^n_m \cos \left( \frac{2\pi}{L} (nx + my) \right) - \delta^n_m \]  

Where: \((C^n_m)^2 = (P^n_m)^2 + (Q^n_m)^2\), \(C^n_m\) is the amplitude of the partial wave and \(\delta^n_m\) is the appropriate phase angle.

The wave frequency is denoted as; \(F_{m}^{n} = \sqrt{n^2 + m^2}\). Using the two-dimensional Fourier transform pair can be written as (Bath, 1974)

\[ G(U, V) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(U, V) e^{-j(Ux+Vy)} dx dy \]  

\[ g(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(U, V) e^{-j(Ux+Vy)} dx dy \]  

Where, U and V, are the angular frequencies in the x and y directions respectively, \(G(u, v)\) when broke up into real and imaginary parts can be postulated as;

\[ G(u, v) = P(u, v) + jQ(u, v) \]  

The energy density spectrum is given as;

\[ E(u, v) + |G(u, v)|^2 = P^2 + Q^2 \]

2.4 Estimation of Curie Point Depth

The estimation of Curie Point (basal) depth \(Z_b\) of the magnetic source can be delineated using two methods; examining the shape of isolated anomalies (Bhattacharyya and Leu, 1975) and examining the spectrum of magnetic anomalies and depth to magnetic sources by transferring spatial data into the frequency domain. (Spector and Grant, 1970).

The methods for estimating the depth extent of magnetic sources are classified into two; those that examine the shape of isolated anomalies (Bhattacharyya and Leu, 1975) and those that examine the patterns of the anomalies (Spector and Grant, 1970). However, both methods provide the relationship between the spectrum
of the magnetic anomalies and the depth of magnetic sources by transforming the spatial data into the frequency domain. In this research, the method adopted is the latter. To obtain the depth to Curie point, Spectral analysis of 2-dimensional Fourier transform of the aeromagnetic data has to be performed using Oasis Montaj software (version 8.4) in this study. The deepest level in the earth's crust with a temperature of 580°C or 1060°F where ferromagnetic materials (magnetite) are converted to paramagnetic material is assumed to be the point for geothermal sources where most geothermal reservoirs tapped their heat in the earth subsurface. This point also offers a window for a better view of the thermal structure of the crust. From the power spectrum, two linear segments were drawn from each graph, with the calculation of their various gradients which was used to determine the depth to the centroid ($Z_o$) of the magnetic source from the slope of the longest wavelength in equation (8). The depth of the top boundary ($Z_t$) of that distribution from the slope of the second-longest wavelength spectral segment from equation (9) (Okubo et al., 1985), and (10) respectively. Using the (Tanaka et al., 1999, and Okubo et al., 1985), we can determine the Curie Point Depth, ($Z_b$) in equation (11).

\[
\text{Slope } (M1, M2) = \frac{\text{Log Energy}}{\text{Frequency}} \tag{8}
\]

\[
Z_o = -\frac{M1}{2\pi} \tag{9}
\]

\[
Z_t = -\frac{M2}{2\pi} \tag{10}
\]

Where $m_1$, $m_2$ = Slopes of the 1st and 2nd 
- = Depth of the subsurface

\[
Z_b = 2Z_o - Z_t \tag{11}
\]

Where, $Z_b$ = Curie Depth
$Z_o$ = centroid of the magnetic layer and
$Z_t$ = top bound.

The obtained basal depth ($Z_b$) of the magnetic sources in the study area is Curie Depth Point (CPD). The Geothermal gradient is defined as the rate of increase in temperature per unit depth in the earth from the core heat flow, it helps to determine geothermal reservoirs. For every 1°C temperature increase, there is a depth of 75 feet decrease in the earth subsurface, and its S. I. unit is mW/m². Equation (12) is used to determine the geothermal gradient.

Fourier’s Law is the fundamental relation required when considering heat conveyance. Hypothetically, to calculate the one-dimensional case of the geothermal gradient $\frac{dT}{dz}$ it is assumed that:

(i) The surface temperature which is 0°C,

(ii) The direction of temperature variation is vertical and temperature gradient $\frac{dT}{dz}$ is constant, and

(iii) There is no magnetic source at the CPD.

\[
\frac{dT}{dZ} = \frac{\theta_c}{Z_b} \tag{12}
\]
The relationship between the Curie isotherm depth \( (Z_b) \) and the heat flow \( (q) \) is given by equation (13). Thus, the heat flow, \( (q_z) \) can be calculated from the temperature gradient using the Fourier’s Law:

\[
q_z = -k \frac{\theta_c}{Z_b} = -k \frac{dT}{dZ} \tag{13}
\]

Where, \( Z_b \) = heat flow/flux and \( K \) = thermal conductivity coefficient \( (2.5 \text{ Wm}^{-1} \text{ C}^{-1}) \) (Turcucotte and Schubert, 1982; Tanaka et al., 1999; Nwankwo, and Shehu, 2015).

The Curie temperature \( \theta_c \) to be 580°C can also be defined as:

\[
\lambda = \left( \frac{dT}{dZ} \right) Z_b \tag{14}
\]

Where, \( Z_b \) is the curie-point depth (obtained from the spectral magnetic analysis). The Curie Point depth, \( Z_b \) and heat flow, \( q_z \) can form a relationship between them called coefficient of thermal conductivity:

\[
q = \lambda \left( \frac{\theta_c}{Z_b} \right) \tag{15}
\]

Where = coefficient of thermal conductivity and = Curie temperature.

The surface temperature is 0°C and remains constant provided that there are no heat sources for heat sinks between the earth’s surface and the curie-point depth. Also, the Curie temperature generally depends on magnetic mineralogy (Tanaka et al., 1999). Although some uncertainties about the magnetization depth may affect the assumed Curie temperatures and basal depth due to lithological contrast rather than a thermal boundary.

Any given depth to a thermal isotherm will be inversely proportional to the heat flow, as heat flow and geothermal gradient are calculated using the formula below (Bansal et al., 2011; Nwankwo and Shehu, 2015; Tanaka et al., 1999).

In addition, the spectral analysis will also be applied in the determination of curie point depth, geothermal gradient, and heat flow of the study area during the interpretation.

3. RESULTS AND DISCUSSION

3.1 Total Magnetic Intensity Map

The Total Magnetic Intensity Map gives a complex pattern of the magnetic anomaly of both long and short wavelength which is contour in gammas, consisting of both Regional and Residual fields allocated to deep-seated and shallow-seated magnetic bodies within the study area. The regional field is composed of mostly deep-seated magnetic bodies, while the residual field is composed of shallow-seated magnetic bodies which happen (the study focus). The composite color map in Figure 4 shows both the wavelength and short-wavelength features.

The study area has Total Magnetic Intensity (TMI) map values of 33002.7 gammas to a maximum of 33133.2 gammas based on the colors at the legend as shown in Figure 4. The highest TMI are colored in light pink, the higher TMI are colored red, and the high TMI are colored dark-blue.

However, for the qualitative interpretation, the high TMI values which range from 33120 gammas to 33160 gammas colored pink; occur at the south-western part of the TMI map of the study area and cut across...
Santonian-Cenomanian Eze-Aku Shale Group, Nkporo Shale Formation, and Asu River Group. The middle TMI ranges from 33060 gammas to 33119 gammas colored red to golden-brown and predicts the Oligocene-Eocene Ameki Formation. Its geologic formations slightly cut across the Nkporo Shale/Afikpo Sandstone. Conversely, the lowest TMI ranges from 33002.7 gammas to 33059 gammas colored light green to dark blue, and it is located along the southeast and northwest region. This gives a low land with slightly steep formations.

Along the South-Eastern part of the map, these ranges show a possible tensional fault that results in a normal fault that can give rise to geothermal energy potentials. This fault extends towards the northern part of the map with steep structures and intertwine with underlying marine consolidated sandstones, Schist/Phyllites, Asu Sandstone, Mylonite, conglomerate, and breccias.

The SSE – NNE part of the map shows huge clusters due to tectonic events in the basement, and this signifies fault, fractures, and other intrusive bodies in the study area.

More so, the basement surfaces of the study area create a tectonic image of the area in terms of active tectonic zones showing intense folds and inactive tectonic zones indicating smooth surface of the study area as shown in (Figure 4) this shows that the area is slightly tectonically active.

Furthermore, due to the closeness of the earth’s core to the surface and combined by a fault at the asthenosphere; the thermal temperature of the formation will be high giving room to geothermal energy potentials in the study area.
3.2 Reduction-to-Pole:

The observation at the Residual Anomaly Map (Figure 5) shows various trends, closures, and structural features throughout the map especially at the SSE – NNE part of the map. The study area also reveals positive anomalous bodies at the SSE, NE, and Central parts of the map, which were bounded by areas of negative residual values. The positive residual anomalies indicated several occurrences of magnetic activities which served as channels for primary mineralization of most near-surface rocks containing magnetic minerals. The negative residual anomalies values postulated areas of low magnetization which are mostly underlain by deeply seated magnetic bodies within the sedimentary basin.
3.3 Analytic Signal
The Analytic signal map shown below displays the major anomalies trending SW-NW, NE-SW, and E-W
directions respectively as shown earlier on the Residual Anomaly Intensity (RMI) map (Appendix 1).
The Analytical Signal magnitude ranges from 0.002 nT/m to 0.023 nT/m. Analytic signal magnitude ranging
0.0165 nT/m to 0.023 nT/m represents the pink color. From 0.0042 nT/m to 0.0093 nT/m represent the red,
orange, yellow, and green colors for the Analytic Signal magnitude that represents a medium. The lower
Analytic Signal magnitude is from below 0.0092 nT/m with light and dark blue colors occurring all the map.

3.4 Derivatives
3.4.1 Horizontal Derivatives
The first and second (d_x and d_y) horizontal derivative map of the Residual Map Intensity (RMI) was obtained
by calculating the Pythagoras sums of the gradient in the orthogonal direction of the study area.
The resultant effect of the calculation resulted in the three horizontal derivative maps displayed below in
(Figures 6) respectively.
3.4.2 Tilt Angle Derivative

The Tilt angle derivative is used to provide a direct estimation of the source location using the calculation from the 3D Euler equation similar to that of Salam et al., (2005). The Tilt angle can be defined as (Miller and Singh, 1994):

\[ \theta = \tan^{-1} \left( \frac{\frac{dM}{dz}}{\frac{dM}{dh}} \right) \]  \hspace{1cm} (16)

Where:

\[ \frac{dM}{dh} = \sqrt{\left( \frac{dM}{dx} \right)^2 + \left( \frac{dM}{dy} \right)^2} \]  \hspace{1cm} (17)

\( \frac{dM}{dx} \), \( \frac{dM}{dy} \), and \( \frac{dM}{dz} \) = derivatives of the magnetics field \( M \) in the \( x \), \( y \), and \( z \) directions as the wavelength leads to

\[ k_x = \frac{d\theta}{dx} = \frac{1}{A^2} \left( \frac{dM}{dh} \frac{d^2M}{dx dz} - \frac{dM}{dz} \frac{dM}{dh} \right) \frac{1}{(dh/\sqrt{dx^2 + dy^2})} \]  \hspace{1cm} (18a)

\[ k_y = \frac{d\theta}{dy} = \frac{1}{A^2} \left( \frac{dM}{dh} \frac{d^2M}{dy dz} - \frac{dM}{dz} \frac{dM}{dh} \right) \frac{1}{(dh/\sqrt{dx^2 + dy^2})} \]  \hspace{1cm} (18b)

and

\[ k_z = \frac{d\theta}{dz} = \frac{1}{A^2} \left( \frac{dM}{dh} \frac{d^2M}{dz^2} - \frac{dM}{dz} \frac{dM}{dh} \right) \frac{1}{(dh/\sqrt{dx^2 + dy^2})} \]  \hspace{1cm} (18c)

Where:
\[ A = \sqrt{\left(\frac{dM}{dx}\right)^2 + \left(\frac{dM}{dy}\right)^2 + \left(\frac{dM}{dz}\right)^2} \]  

(19)

is the total gradient of the magnetic field. The resultant effect of the calculated tilt angle is displayed at the tilt angle derivative map (Figure 7) below.

\[ (x - x_0) \frac{d^2M}{dx^2} + (y - y_0) \frac{d^2M}{dy^2} + (z - z_0) \frac{d^2M}{dz^2} = \eta(B - M) \]  

(20)

Where; \( x, y, \) and \( z \) are the source coordinates;
\( B = \) the base level of the magnetic field
\( \eta = \) value of anomaly attenuation rate known as structural index.

![Figure 7: Horizontal Derivative of Tilt Map of the Study Area.](image)

3.4.3 First Vertical Derivative (FVD)

The First Vertical Derivative (FVD) yielded a positive feature with values ranging from 0.001 nT to 0.017 nT could be attributed to the mafic (basic) rocks while the negative features with values from -0.025 nT to -0.001 nT could be attributed to felspathic rocks respectively. It also delineates high frequency features more clearly in areas where they are shadowed by large-amplitude, low-frequency anomalies (Figure 8).

Mafic rocks are basic rocks with high concentrations of iron, magnesium, and other minerals like mica, biotite, and pyroxene which are in little concentration. They are found in the forms of Migmatite, Conglomerates,
Schist/Phyllites, Magnetite Gneiss, Mylonites, etc. Felspartic (Felsic) rocks are acidic rocks that have a high concentration of feldspar, silicon, and little proportion of minerals such as quartz, orthoclase Felsic rock, muscovites, potassium-rich plagioclase, aluminum, etc. Rocks found in this area include Porphyritic Granite, Awi Sandstone, etc.

From the First Vertical Derivative (FVD) map, the most positive features are more pronounced in the Southwestern part of the map which is underlain by Schist/Phyllites, Mylonites, and Magnetite Gneiss. The SE-NE part of the map has the most conspicuous occurrence of mafic and feldspathic rocks respectively as shown on the geologic map of the study area. Most of the negative features are sparsely scattered along the SW-NW, and Central part of the map.

Figure 8: First Order Vertical Derivative Map of the Study Area.

3.5 Magnetic Depth Estimation

Two 3D Euler Deconvolution and Spectral Analysis were imbibed for the determination of Magnetic Depth in the study area using the enhanced Residual Anomaly data.

The 3-D standard Euler Deconvolution of the aeromagnetic data of the study area was used based on different structural indices models. For the course of this study the structural index for horizontal cylinder in (Appendix 2) was applied because of the sedimentary basin. This process established the standard Euler Solutions for the study area.

Based on the potential field data, Euler’s equation can be expressed as:

\[
(x - x_o) \frac{dT}{dx} + (y - y_o) \frac{dT}{dy} + (z - z_o) \frac{dT}{dz} = N(B - T) \tag{21}
\]
Where;
N = dependent on the source geometry,
B = Total Magnetic potential (regional) field
\((X_o; Y_o; Z_o)\) = The positions of the magnetic source
T = Total field measured at (x, y, z).

Euler solution for Horizontal cylinder and pipes as sources revealed depth ranging from less than -250 m to above -4016 m. I observed an evenly spreader cluster solutions all over the map (Figure 9). The maximum depth was above \(-4018\) m and trended along the NW-SW, S, W, and Central section of the map. These areas which are underlain by Mafic and Felsparitic rocks like Branded -Magnetite Gneiss and Porphyritic Granite. The Euler depth ranged from less than -250 m to above -4018 m for magnetic source bodies agrees with the result from spectral analysis.

The structural interpretation of the study area is somewhat complex because all the geologic models are seen to occur within the study area. The reason been that this area is highly fractured and faulted.

![Figure 9: Standard Euler Deconvolution Map of the Study Area showing cluster solutions for Structural Index.](image)

The resultant effect from the 2D spectral depth analysis shows two magnetic layers. The first layer depth \((D_1)\) represents the depth to the shallower magnetic source which was derived by Slope 2 \((S_2)\). The spectrum values vary from -3.541 Km to -5.200 Km with an average value of -3.177 Km. The first layer is also attributed to the depth of the magnetic rocks of the crystalline basement which intruded into the various sedimentary formations in addition to the few formations found on the surface (Figure 10).

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The second layer ($D_2$) is the depth to the crystalline basement which is represented by the first Slope ($S_1$). The depth to the crystalline basement rocks ranges from -2.678 Km to -3.769 Km with an average of -4.204 Km. $D_2$ values represent the average depths to the basement complex in the blocks considered.

Figure 10: Sample Plots of Frequency against Spectral Energies determined values of $S_1$($Z_o$) and $S_2$ ($Z_t$) for estimated depths using Grapher 8 software.
Figure 11: Spectral Depth Map of the Depth of Shallower Magnetic Source and Depth to Deeper Magnetic Source Body of the Study Area.

Note: The negative values show that the depth is below the sub-surface and should bear a negative value.

The spectral depth map above (Figure 11) reveals the sedimentary thickness, as there is thinning towards the Northeastern part of the map. The deeper depth can be found at the Northern part of the map with red, and orange color indications, and it is estimated -4.200 Km (-4,200 m) to -4.825 Km (-4,825 m), while the shallower depth is predicted by yellow, green, light blue and dark blue colors which range from -4.826 Km (-4,826 m) to -5.999 Km (-5,999 m) respectively. This direction is in agreement with the areas where the crystalline basement outcrops are found.

The graphs show that increases from the center part to the northwestern and southern part of the study area. The pairs of plots show two slopes where S1 represents the contributions from the deepest magnetic sources which have been abandoned due to the reduced dimensions of the areas covered by these sections (deeper and shallower magnetic sources). More so, the Logarithm E plot against the Spectral energy should present a straight line where the slope is 2z.

The 3D Euler Deconvolution and Spectral Analysis methods were imbibed to compare the depth estimation, direction of the fault trends, and the results were correlated to get a better understanding of the study area.
3.6 Geothermal Properties

3.6.1 Curie Point Depth Estimation

From the table (Appendix 3), one can estimate the depth of the \( Z_o \) of the magnetic source from the slope of the longest wavelength part of the spectrum. The results of the determined values of \( Z_o \), \( Z_t \), and \( Z_b \) for the 16 blocks are shown in the table (Appendix 3). The Curie Point Depth, CPD values range from (-)7.956 km to (-) 11.172 km, with a mean of (-)9.452 km.

The curie point depth of the study area is mainly dependent upon the geological conditions and one of such is the presence of the Northeastern and Southwestern trending tectonic fault. Curie point depths are often shallower than 10 km for volcanic and geothermal fields, from 15 to 25 Km predicts island arcs and ridges, and deeper than 20km predicts plateau and trenches (Tanaka et al., 1999). Generally, the above units that comprise high heat flow values often correspond to volcanic, basement complex, and metamorphic regions that affect the Curie depth and heat flow respectively. More so, the tectonically active regions affect the Curie depth and heat flow.

The curie point depth of the study area is similar to what was recorded over parts of Calabar Flank, Southeastern Nigeria compared with other research works (Chukwuka, 2016; Onuba, et al., 2013; Odumuodu, 2012). The Curie Point Depth (CPD) map in (Figure 12) shows a trend at the NE-SW direction with the shallowest value ranging from > (-)7.9 Km to < (-)9.5 Km at the northeastern part of the map, with a color preference of light blue, dark blue, and green color respectively is associated to the Uwet, Adiasim, Ikot-Ekpene, and Aruchukwu. The deepest ranged from > (-)9.5 Km to < (-)11.1 Km at the Southeastern direction with a color representation of yellow, orange, and red in the study areas; is estimated for the Afikpo, Abakiliki, Odoro Ikpe, and Ugep environs. This deeper part was due to the structural inversion of the Benue trough leading to the Afikpo Syncline and the NW-SW trending fault structure.

Kobge and Obialo (1976) proposed that the crustal instability and most tectonic events that occurred during the Santonian were attributed but widespread magmatism, faulting, and folding resulted in the Abakaliki Anticlinorium. Also, the events in the late Santonian were followed by pronounced igneous activities accounting for the occurrence of a large number of intermediate and basic intrusive structures found in the Asu River Group.
3.6.2 Geothermal Gradient and Heat Flow Estimation

The geothermal gradient ranges from $51.916 \text{CKm}^{-1}$ to $72.901 \text{CKm}^{-1}$, with a mean value of $61.893 \text{CKm}^{-1}$ respectively.

Heat flow in the study area was estimated using the depth and thickness information and its values were determined with regards to the region by using the thermal conductivity ($25 \text{Wm}^{-1}\text{K}^{-1}$) and the depths. The result is shown in (Table 4.2) clearly describes that the heat flow ranges from $129.789 \text{mWm}^{-2}$ to $182.252 \text{mWm}^{-2}$, with a mean value of $154.983 \text{mWm}^{-2}$.

It is also observed that the heat flow values decrease from the NE-SW part of the map and increase towards the NE part of the map (Figure 4.20). The shallow DBMS at the north-eastern part of the study area. While the lowest heat flow value is below $130 \text{°CKm}^{-1}$ which is related to the lowest value of the geothermal gradient below $52 \text{°CKm}^{-1}$ and high DMBS at the north-western and southern part of the study area (Figure 13).
3.6.3 Curie Point Depth against Geothermal Gradient and Heat Flow

The Curie Point Depth (CPD) was plotted against the geothermal gradient and heat flow to determine the geothermal energy potential of the study area using the linear formula:

\[ y = -0.1575x + 19.198 \]

\[ R^2 = 0.9878 \]

The high correlation coefficient of 0.9878 which is trending to approximately 1 is observed, thereby making the relationship reliable. This plot reveals that heat flow decreases with an increase in Curie Point Depth and vice versa (Figure 14).

Figure 14: Showing a plot of Curie Point Depth (CPD) against Geothermal Gradient and Heat Flow
This work collaborates with the said principles which state that regions with significant energy can be characterized by an anomalous high-temperature gradient and heat flow and is geothermally linked with a shallow Curie Point Depth (CPD) (Kasidi and Nur, 2013).

**Conclusion**

The geology of Calabar Flank which is a sedimentary basin occurred due to the separation of the African and South American tectonic plates in the Precambrian Era; it has a total sedimentary thickness of about 4.825km, with a variety of featheredge outcrops. The numerous horst structures around parts of Calabar Flank make them susceptible to overheating from the adjacent Oban Massif Basement and this gives an indication of geothermal energy potentials in the study area. Depth to the basement and other structural features of the study area was estimated directed due to its direct relevance to the depositional and thermal structural history of the basin. The Total Magnetic Intensity obtained from digitizing the High-Resolution Aeromagnetic Data ranges from 33002.7 to 33133.2 grammas. The quantitative method was used to estimate structural properties; while the qualitative method used the 3D Euler Deconvolution and spectral analysis to investigate the magnetic depth estimation and geothermal properties to achieve the objectives of the study. The Curie Point Depth (CPD) has a mean value of (-)9.452 Km, a mean value of 61.893CKm⁻¹ for the geothermal gradient, a mean heat flow of 154.983 mW/m² respectively from the spectral analysis. The curie point is extremely high/low in the northeastern/southeastern, and west of the study area. The Geothermal Gradient and heat flow values are higher in the extreme southeast/ north/ central section of the study area. The Curie Point depth is shallower wherever the Heat Flow is high and vice versa. A high amount of geothermal energy (low heat flow, low geothermal gradient, and deeper Curie Point Depth) was observed at areas trending towards the SW- NE part of the study area. This study area is hereby considered as a reserve zone for geothermal energy resources due to the tensional forces that result in normal faults from the tensional force, oblique-slip fault, and fracture zones in the underlying basement complex along with the Southwest, Northwest, and Northeast trends. More so, regions, where the Curie isotherm is relatively high in the crustal surfaces, are often regions of high flow with promising areas for geothermal energy potentials. The results obtained from the plotting of Curie Point Depth against Geothermal, and Gradient Heat Flow support the conclusion that Curie Point Depth is shallow at high Heat Flow. These results show a good prospective site for geothermal energy reserve exploration and exploitation. Other methods like Landsat or satellite imagery, seismic and gravity methods should be employed to get comprehensive geothermal energy and mineralogical potentials in the study area.

**Availability of data**

The supplementary data is affixed for preview

**Competing Interest**

The authors declare no competing interest as regards this manuscript.
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Authors’ contribution
ECOO: Investigation, Writing-Original Draft Preparation, Resource, Visualization. EKA: Supervision, Research Design, Conceptualization and+ Methodology

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