Curie depth isotherm deduced from spectral analysis of Magnetic data over sarti and environs of North-Eastern Nigeria

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The purpose of the study was to estimate the Curie point depth and Heat flow in Sarti and Environs, which was deduced from spectral analysis of aeromagnetic data over the basement complex of North-Eastern Nigeria. The area covered was 6,050 km² and bounded by latitudes 7° 00' and 8° 00' N and longitudes 10° 00' and 12° 00' E. The Aeromagnetic maps were digitised at an equal interval of 2km and the regional value removed using plane surface polynomial and upward continued technique. The resulting residual data were subsequently divided into 8 overlapping blocks for the purpose of this study. The Curie point depth varies between 26-28km and the geothermal gradient varies between 21 and 23 Ckm⁻¹, while the heat flow values range between 53 to 58 mWm⁻². These results are consistent with the existing geothermal and geotectonic regime in the area. Spectral analysis of the data in conjunction with heat flow values revealed an almost inverse linear relationship between heat flow and Curie depths, these was used to construct Curie isotherm from the existing data. However, the study has shown a possibility for geothermal resources to exist in the study area. In view of that, the results obtained from this study could be very important for geothermal exploration

KEY WORDS: Aeromagnetic data, Curie Isotherm, Heat flow, geothermal reservoir.

INTRODUCTION

The study presented in this research concerns the evaluation of the total aeromagnetic anomalies for estimation of Curie point depth and heat flow in Sarti and Environs North-Eastern Nigeria, which has in the past received limited attention from geologists especially geophysicists. This may be due to lack of immediate geologic and economic values, even though it is fast becoming an important study area for geoscientists. In view of the fact, that increased efforts to explore for new and more energy locations, being part of Cameroon Volcanic Line in Nigeria. Moreover geophysical study in the area is minimal, with no records of crustal temperature studies. Curie depth isotherm in conjunction with heat flow assessment would significantly compliment the geophysical information of the area to bridge the gap of lacking crustal temperature information.

The study area is located between latitude 7° 00’ and 8° 00’ N and longitude 10° 00’ and 12° 00’ E, North - Eastern Nigeria. The area is characterised by rugged terrain. It is one of the crystalline pre-Cambrian basement blocks in Nigeria. The study area was subjected to periods of regional metamorphism, tectonism and magmatism which led to the development of fractures and faults as well as the emplacement of intrusive and dyke like structures (Ofoegbu, et al, 1992).

The assessment of variations of the Curie isotherm of an area can provide valuable information about the regional temperature distribution at depth and the concentration of subsurface geothermal energy (Tselentis, 1991). One of the important parameter that determines the relative depth of the Curie isotherm with respect to sea level is the local thermal gradient. i.e. heat flow (Hisarli, 1996). Measurements have shown that a region with significant geothermal energy is characterised by an anomalous high temperature gradient and heat flow ((Tselentis 1991). It is therefore to be expected that...
Figure 1. Geologic map of study area (After GSN 2006)

Geothermically active areas would be associated with shallow Curie point depth (Nuri et al 2005). It is also a known fact that the temperature inside the earth directly controls most of the geodynamic processes that are visible on the surface (Nwankwo et al 2011). In this regard, Heat flow measurements in several parts of African continent have revealed that the mechanical structure of the African lithosphere is variable (Nur et al 1999).

The idea of using aeromagnetic data to estimate Curie point depth is not new and it has been applied to various parts of the world, either by analyzing isolated magnetic anomalies due to discrete sources or employing the frequency domain approach. The present paper utilizes spectral analysis to estimate the Curie isotherm depth and heat flow to determine the geothermal history of the region. The Curie Point Depth is known as the depth at which the dominant magnetic mineral in the crust passes from a ferromagnetic state to a paramagnetic state under the effect of increasing temperature (Nagata, 1961). For this purpose, the basal depth of a magnetic source from aeromagnetic data is considered to be the Curie Point Depth. Thermal structure of the crust involving Curie Point Depth estimations have been published for various tectonic settings by several authors such as Blakely and Hassan zadeh, 1981; Connard et al., 1983; Okubo, et al., 1985, 1989; Blakely, 1988; Okubo and Matsunaga, 1994; Hisarli, 1996; Banerjee, et al., 1998; Tanaka, et al., 1999 and Nur et al, 1999.

**Geology of the study area**

The study area is located within the North-eastern Basement complex which bordered to the East and South by republic of Cameroun. Geologically, it consists of various rock units which have been reported to occur in this area (figure.1). Sarti and Environs is underlain by Precambrian basement rocks consisting of Gneiss Migmatites complex, remobilized by the Pan-African deformational episode (600-500 ma) and uplifted relative to the surrounding area (Nnange et al 2001).

The major rock unit includes;

a. Undifferentiated granite, migmatites, granite gneiss, porphyroblastic gneiss, Medium to coarse grained biotites and fine grain biotites granite.
b. Bima Formation (Felspathic calcareous Sandstone).
c. Pindiga Formation (calcareous Sandstone and shale limestone).
d. Tertiary Volcanic rocks (basalts and rhyolite).

Most of these rock units were subjected to periods of regional metamorphism, tectonism and magmatism,
which led to the development of fractures and faults as well as the emplacement of intrusive and dyke like structures (Doleritic intrusive) Ofoegbu et al (1992). The basalt in this area belongs to the Cenozoic Volcanic rocks of Cameroon Volcanic Line (CVL) which are found in Ruru Sama and around Fillinga. The Volcanic ranges from basalts to trachytes and composed basically of alkali basalt (ghonganmu, et al., 1999).

**Data Acquisition and Analysis**

The aeromagnetic data which consist of sheet 254, 255, 256, 257, 274, 275, 276, and 277 utilized for this paper was obtained as controlled maps of total magnetic intensity on a scale of 1:100,000 compiled by Geological Survey of Nigeria (GSN 1975). The relevant survey was conducted along a series of SE - NW profile with a spacing of 2km, a nominal tie line spacing of 20 km and an average flight elevation above terrain of 150 m. The geomagnetic gradient was removed using the international Geomagnetic Reference Field formula (IGRF) of the 1st January, 1974. The magnetic map was digitized at an equal interval of 2cm x 2 cm in the N-S and E-W grid lines giving a data matrix of (56 x 112). To eliminate regional field, a plane surface has been fitted to the data by multi-regression least-square analysis, and expression for the regional obtained was:-

\[
T(x, y) = 7770.55 + 1.742x - 0.178y
\]  

(1)

Where \(x\) and \(y\) are unit of spacing of the digitized magnetic data.

Residual data were then obtained as the deviations from the total intensity data from the fitted plane surface. The points sampled on the square grid were contoured using Computer software (surfer 8.0) and this represents the total intensity magnetic map (figure 2). However, the residual magnetic values obtained from the plane surface were also contoured using surfer 8.0 (Figure.3). This gives residual magnetic map of the study area.

**Curie point depth estimation**

The methods for estimating the depth extent of magnetic sources are classified into two categories; 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). How ever, both methods provide the relationship between the spectrum of the magnetic anomalies and the depth to magnetic sources by transforming the spatial data into frequency domain. In this research, the method adopted is the later. To obtain the depth to Curie point, Spectral analysis of 2-dimensional Fourier transform of the aeromagnetic data...
The obtained basal depth (Z_b) of magnetic sources in the study area is assumed to be the Curie point depth (Bhattacharyya and Leu, 1975) and Okubo et al, (1985) and the Graphs of the logarithms of the spectral energies for various blocks using the software were obtained from which Table 1 was extracted as shown on Figure 4. below.

**Estimation of Heat flow and thermal gradient**

The heat flow and thermal gradient value was calculated in the study area, the calculation was expressed by Fourier's law with the following formula:

\[ q = \lambda \frac{dT}{dZ} \]  \hspace{1cm} (4)

Where \( q \) is the heat flow and \( \lambda \) is the coefficient of thermal conductivity. In this equation, it is assumed that the direction of the temperature variation is vertical and the temperature gradient \( dT/dZ \) is constant. According to Tanaka, et al, (1999), the Curie temperature (9) was obtained from the Curie point depth (Z_b) and the thermal gradient dT/dZ using the following equation:

\[ \theta = \left( \frac{dT}{dZ} \right) Z_b \] \hspace{1cm} (5)

Provided that there are no heat sources or heat sinks between the earth’s surface and the Curie – point depth, the surface temperature is 0°C and dT/dZ is constant. The Curie temperature depends on magnetic mineralogy. Although the Curie temperature of magnetite(Fe3O4), in view of that, the curie temperature is approximately 580°C, and an increase in titanium (Ti) content of titanomagnetite (Fe2x,Ti3O4) causes a reduction in Curie temperature (Nwankwo et al 2011)

In addition to that, from Equation (4) and Equation (5) a relationship was determined between the Curie point depth (Z_b) and the heat flow (q) as follows.

\[ q = \lambda \left( \frac{\theta}{Z_b} \right) \] \hspace{1cm} (6)
Figure 4. Graphs of the logarithms of the spectral energies for various blocks using Four Pot software (Markku 2009).
In this equation, the Curie point depth is inversely proportional to the heat flow, Tanaka et al. 1999; Stampolidis, et al. 2005. In this research, the Curie point temperature of 580 °C and thermal conductivity of 2.5Wm⁻¹°C⁻¹ as average for igneous rocks was used as standard (Nwankwo et al 2011) in the study area. In order to compute the thermal gradient and heat flow of the region, Equation (6) was utilised. See Table 1 below.

Relationship between Curie Depth and Heat Flow

To investigate any possible relation between heat flow and the obtained Curie depths, We present the current results in Figure 5. Considering Curie depths and heat flow in the study area, Figure 5 shows that, the heat flow decreases with increasing Curie depth.

That is, Spectral analysis of aeromagnetic data in conjunction with heat flow information revealed an almost inverse linear relation between heat flow and Curie depths and was used to construct the Curie isotherms which were delineated and are presented in Figure 6.

Discussion of Results

The total magnetic intensity (Fig.2) over Sarti and its environs after the digitization showed magnetic signature ranging from 7750nT to 7900nT. The magnetic high of magnitude 7900nT observed in Southern Part of the study area which include, Ruru Sama, Mayo Selbe, Baissa, Gashaka and Fillinga, could be as a result of presence of basaltic rocks belonging to Eastern arm of Cameroon Volcanic Line (CVL). These compared favourably well with geologic map on Figure 1. The residual magnetic map obtained from regional – residual separation (Fig.3) has widespread of closures and nosing in the study area; these closures and nosing are expression of fractures and volcanic arcs of tectonically active Cameroon volcanic line. Most areas of high magnetic susceptibilities are volcanic centres.

Graphs of the logarithms of the spectral energies, from which Curie isotherm depth was computed, showed that the depth to the Centroid ($Z_o$) ranges from 14.520 km to 16.100 km. On the other hand, the depth to the top boundary ($Z_t$) of magnetic sources ranges from 1.430 km to 4.980 km (below sea level) Table 1. The equivalent curie depth range from 26 km to 28 km (b.s.l), these values compares well with what was obtained within and around Upper Benue Trough by Nur et al 1999. The obtained Curie point depth reflects the average local curie depth point values beneath each block. It is also observed that, volcanic centres as shown on the geologic map Fig.1 have shallow Curie point depth of 26km compared to the other basement areas; this could be as a result of upwelling of magma chamber on Cameroon Volcanic line (CVL). The deeper Curie point in the study area could be as a result of isostatic compensation in the region. The obtained Curie point was used to construct Curie isotherm in the study area (Fig 6). These reflect the various depths to curie points which describe the thermal nature of the crust. Previous studies by Stampolidis, et al. (2005) showed that the Curie point depth is linked to the geological context of an area. The values obtained fall in class A classification of Tanaka, et al (1999). Yamano, ( 1995) made an assertion that, shallow Curie point depths are consistent with high heat flow values as seen in back arc, and young volcanic regions. In view of that, the area of shallow Curie point depth of 26km has a geothermal potential which can be utilized.

Using a Curie point temperature of 580°C and the derived curie depths, geothermal gradient variations in

![Figure 5. Heat flow versus Curie point depth in the study area](image-url)
the area was calculated from where the geothermal gradient map was plotted as shown in Fig.7. This is closely related to the heat flow map (Figure 8), meaning that most areas of high heat flow correspond to high geothermal gradient Fig 7.

Spectral analysis of the data in conjunction with heat flow values revealed an almost inverse linear relationship between heat flow and Curie depths (Fig.5), these were used to construct Curie isotherm from the existing data. In most part of the study area, heat flows were found to be less than 60 mWm$^{-2}$. This implies that the heat flows in the study area are not uniform, which possibly indicate that the magma conduits were randomly distributed.

The average heat flow obtained in the study area is...
54.375 mWm$^{-2}$, this may be considered as typical of continental crust.

All current literatures state that the curie point depth and of course heat flow is greatly dependent on upon geological condition. Heat flow is the primary observable parameter in geothermal exploration. Generally, the units that comprise of high heat flow values correspond to volcanic and metamorphic regions since the two rock units have high heat conductivities (Nwanko et al 2011). It is in view of that, the volcanic regions on geologic map of the study area Figure 1, which consist of Ruru Sama and Gashaka, show high heat flow (Figure 6) of the magnitude of 58 mWm$^{-2}$. This makes the study area to have geothermal potentials.

CONCLUSIONS

The Curie point depth for the study area was estimated using surface magnetic data through spectral analysis. The result reveals that, the Curie point depth varies inversely with heat flow; this shows that heat flow in the study area decreases with increase in Curie depth. The inferred Curie point depth obtained ranges from 26 km to 28 km. In addition to that, Curie depth in the study area is shallow in volcanic area of Ruru Sama. This resulted from upwelling of the asthenosphere, which is responsible for the generation of thermal dome in the area. The results compared favourably well with what was obtained by Nur et al (1999). It also confirms that, Curie depths are indirect indicator of the thermal structure of the area.

The average heat flow obtained is 54.375 mWm$^{-2}$, this value is so good that it can be utilize for exploration of an alternative source of geothermal energy especially in volcanic centre of Ruru Sama. The deep Curie point in the middle of the study area is due to isostatic compensation of the basement complex rocks. The knowledge of the depth to Curie point and its heat flow are of interest and can be related to the thermal history of an area. The interpretation of aeromagnetic data to estimate the depth to Curie point isotherm and heat flow over Sarti and environs, contributed to the better understanding of geothermal regime and tectonic activities in the area, which shows a possibility for geothermal resources potentials to explore for new and more energy locations in Nigeria.

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