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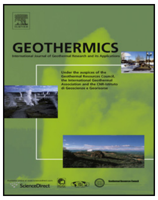

Estimation of depths to the bottom of magnetic sources and ensuing geothermal parameters from aeromagnetic data of Upper Sokoto Basin, Nigeria

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ABSTRACT

An estimate of depths to the bottom of magnetic sources (DBMS) in the upper part of Sokoto Basin, north-west Nigeria has been made from the modified centroid method based on a fractal source distribution of magnetic sources and spectral analysis of aeromagnetic data. DBMS is used as an estimate of the Curie-point depth and hence a proxy for temperature at depth. Aeromagnetic maps covering an area bounded by latitudes 12.5° N and 13.5° N and longitudes 4.0° E and 6.0° E were digitized at an equal spacing of 1 km. Six profiles were subsequently mapped out on the magnetic data covering different geological parts for the purpose of spectral centroid analysis. The result shows that the DBMS varies between 11.37 km and 28.18 km. Consequently, geothermal gradient varies between 20.58 °C/km and 51.02 °C/km, while the ensuing heat flows vary between 51.45 mW/m^2 and 127.55 mW/m^2. The thermal structure of the earth's crust is one of the main parameters controlling geodynamic processes. This study is crucial for quantitative understanding of the geo-processes and rheological/rock-physics parameters in the study area.

1. Introduction

This work estimates depths to the bottom of magnetic sources (DBMS) and ensuing geothermal parameters from airborne magnetic anomaly data of Upper Sokoto Basin, north-west Nigeria. The DBMS is an important parameter in understanding the temperature distribution in the crust and the rheology of the Earth's lithosphere (Ravat et al., 2007). Studies have shown that DBMS can be regarded as a proxy for an estimate of Curie-point depth (CPD) of magnetic materials, where rocks loose their ferromagnetic properties due to an increase in temperature in the crust (Tanaka et al., 1999; Bansal et al., 2011). Characteristically, Curie temperature in continental crust is about 580 °C (Ross et al., 2006). The term DBMS is used in literatures to emphasize that estimated depths are derived from regional magnetic anomaly data and not from direct temperature information (Bansal et al., 2011), as direct measurement of temperatures is restricted only to very shallow depth. The DBMS is preferred because it may not be precisely known whether the estimated depth is really controlled by the temperature ("Curie depth") or only by the magnetomineralogy. Therefore, the DBMS which is more closely related to regional structures than near-surface structures is appropriately used to compliment geothermal data in regions where deep boreholes are unavailable.

Regional studies around the world analyzing DBMS and/or CPD include: (Guimarães et al., 2013; Gabriel et al., 2011, 2012; Bansal et al., 2011, 2013; Bansal and Anand, 2012; Nwankwo et al., 2011; Ross et al., 2006). There is minimal record of studies on regional geothermal structure and geodynamic processes in the Sokoto Basin. Ojo and Ajakaiye (1976) using the gravity method suggests that the sedimentary thickness, which is statistically equivalent to the basement depth or depth to the top of magnetic sources (DTMS), is about 2 km. Umego (1990) indicated that the DTMS varies from 1.0 km to 1.6 km. Shehu et al. (2004) and Adetona et al. (2007) from spectral analysis of the aeromagnetic data of the Sokoto Basin reported maximum DTMS of 1.39 km and 1.93 km respectively. Bonde et al. (2014) obtained from a 2D modelling of aeromagnetic data of the basin, DTMS varying from 1.42 km to 2.7 km. An assessment of DBMS in the area would significantly compliment the available geophysical information and also contribute to the understanding of the geothermal structure, crustal characterization and geodynamic processes in the basin.

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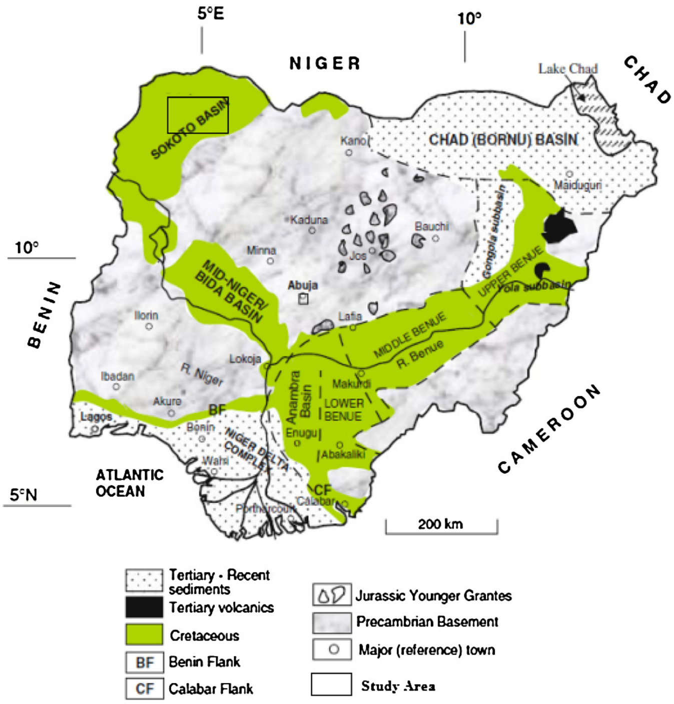

Fig. 1. Geological map of Nigeria (after Obaje, 2009).

2. Location and geology of the study area

The area of study is bounded by latitudes 12.50° N and 13.50° N and longitudes 4.00° E and 6.00° E. It covers an area of about 24,200 km^2 and is situated in the north-west region of Nigeria.

The geology of Sokoto Basin – which is the local name for Iullemmeden Basin in north-west Nigeria – has been described by various authors (Kogbe, 1979, 1981; Obaje, 2009). The entire Iullemmeden basin extends from Mali and the western boundary of Niger Republic through northern Benin Republic and north-west Nigeria into eastern Niger Republic (Fig. 1). The entire basin covers an area of about 800,000 km^2. The Nigerian sector of the basin consists predominantly of a gently undulating plain with an average elevation varying from 250 m to 400 m above sea-level (Kogbe, 1979). This plain is occasionally interrupted by low mesas. A low escarpment, known as the "Dange Scarp" is the most prominent feature in the basin and it is closely related to the geology (Obaje, 2009).

The sediments of the Iullemmeden basin (Figs. 2 and 3) were accumulated during four main phases of deposition (Kogbe, 1981):

i. Pre-Maastrichtian "Continental Intercalaire" of West Africa: overlying the pre-Cambrian basement unconformably, the Illo and Gundumi Formations, made up of grits and clays.
ii. Maastrichtian Rima Group: consists of mudstones and friable sandstones (Taloka and Wurno formations), separated by the fossiliferous, shelly Dukamaje formation.
iii. Paleocene Sokoto Group: the Dange and Gamba formations (mainly shales) separated by the calcareous Kalambaina formation.
iv. Post-paleocene continental terminal: the overlying continental Gwandu formation.

These sediments dip gently and thicken gradually towards the north-west, with a maximum thickness of over 1200 m near the frontier with Niger Republic.

3. Calculation of the DBMS, geothermal gradient and heat flow

Several robust approaches have been employed in the estimation of DBMS (Spector and Grant, 1970; Bhattacharyya and Leu, 1975; Blakely, 1995; Maus et al., 1997; Ravat et al., 2007; Bouligand et al., 2009; Bansal et al., 2011). The modified centroid method recently developed by Bansal et al. (2011) is applied in this study. The calculation of DBMS using the conventional centroid method is based on the spectral analysis of the anomalies of the magnetic field (Okubo et al., 1985; Tanaka et al., 1999). Application of spectral analysis to interpretation of magnetic anomalies has been extensively described (Bhattacharyya, 1966; Bhattacharyya and Leu, 1975, 1977; Spector and Grant, 1970; Shuey et al., 1977). Bhattacharyya (1966) derived an expression for the power spectrum of the total magnetic field intensity (TMI) over a single rectangular block, which was generalized by Spector and Grant (1970) by assuming that the magnetic anomalies are due to an ensemble of vertical prisms. They demonstrated that contributions from the depth, width and thickness of a magnetic source ensemble could affect the shape of the power spectrum. The dominant term, which controls this spectral shape, is the depth factor. The power spectral density ($P(k)$) and DTMS (Z_t) are related by the equation (Spector and Grant, 1970; Tanaka et al., 1999):

$$\ln(P(k)^{1/2}) = A - 2\left|k\right| Z_t \tag{1}$$

where A is a constant and k is the wavenumber. Okubo et al. (1985) subsequently defined a centroid depth (Z_0), which also relates to the power spectral density as follows:

$$\ln\left(\frac{P(k)^{1/2}}{k}\right) = A_1 - \left|k\right| Z_0 \tag{2}$$

where A_1, is a constant. The centroid depth (Z_0) and DTMS (Z_t) may be related to DBMS (Z_b) as (Bhattacharyya and Leu, 1975; Okubo et al., 1985):

$$Z_b = 2Z_0 - Z_t \tag{3}$$

The conventional centroid method described in Eqs. (1) and (2) assumes random and uncorrelated distribution of sources whereas in the real situation the source distribution follows correlated fractal distribution of sources (Bansal and Dimri, 2010, 2013; Bansal et al., 2011, 2013; Maus and Dimri, 1996). Bansal et al. (2011) suggested a modified centroid method. They opined that this new method has many advantages over the conventional method. In conventional method, the data is filtered before depth estimation or few points corresponding to high wavenumbers are discarded as otherwise the DBMS are unrealistically very deep. Filtering and discarding of few points is a subjective approach unlike the modified method that does not require pre-filtering of the data. For the fractal distribution of sources, the centroid depth (Z_0) of the body is thus related to the power spectral density as follows (Bansal et al., 2011):

$$\ln\left(k^{\beta}\frac{P(k)}{k^2}\right) = A_2 - 2kZ_0 \tag{4}$$

where β is a scaling exponent which depends on the geology or fractal distribution of susceptibility and can be ≤ 2 and A_2 is a constant. Bouligand et al. (2009) recounted that spectral peaks in power spectrum could only be found for low values of β, which disappears at higher values and therefore, suggested that reasonable values of scaling component vary from 1 to 2 for 2D magnetic bodies. Ravat et al. (2007) had earlier concluded that higher scaling components do not also provide reasonable values for 3D bodies. In furtherance, Bansal and Dimri (2013) revealed that a scaling component of 1.5 and above may result in overcorrection of power spectrum at