

ASSESSMENT OF GEOTHERMAL POTENTIAL OF SOKOTO BASIN. NORTHWESTERN NIGERIA USING SPECTRAL CENTROID ANALYSIS OF HIGH-RESOLUTION AEROMAGNETIC (HRAM) DATA

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Abstract

This work aimed at estimating depth to the bottom of magnetic sources (DBMS) using spectral centroid analysis of high resolution aeromagnetic (HRAM) data over Sokoto Basin in the northwestern part of Nigeria. The area is bounded by latitude 10.00° to 14.00°N and longitude 3.50° and 7.00°E with a total area of 111,925 km². The HRAM data, acquired from the Nigerian Geological Survey Agency (NGSA), were divided into twenty two (22) overlapping blocks of the sizes of, 110 × 110 km. In the centroid method for estimating DBMS, two power spectrum plots were plotted for each of the twenty two overlapping blocks. The high-wavenumber part whose slopes lead to the depths to the top of magnetic sources (Z_t) and the low-wavenumber part whose slopes lead to the centroid depth of the magnetic sources (Z_0). These depths values were subsequently used to determine, DBMS obtained from $Z_b = 2Z_0 - Z_t$. The result shows a variation in DBMS between 11.13 and 27.83 km with an average of 18.57 km. The study area is found to have geothermal potential in the northcentral part of the study area owing to shallow values of DBMS.

Keywords: Magnetic source, Basin, high resolution, Spectral Analysis, Centroid method

Introduction

Aeromagnetic surveys due to spatial changes in the strength of the magnetic field over the surface of the earth have been used as a method for geophysical exploration for many years (Manzella, 1999 and Nwankwo, 2009). In modern geophysical surveys, aeromagnetic anomaly data reflect the lateral variations in the earth's magnetic field. These variations are related to changes of structure, susceptibility of magnetic materials in the crust, temperature increment with depth, and related minerals present in the rock. Airborne survey can be utilized as a multipurpose data in different fields such as exploration, medical physics and environmental studies (Manzella., 1999).

Estimation of depth to the bottom of magnetic sources in a regional survey can be referred to as the Curie depth, which corresponds to depth at which the magnetic signal is lost due to earth interior heat in the earth's subsurface. DBMS in an area can provide valuable information about the local and regional temperature distribution with depth and the concentration of the 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 geothermal gradient i.e. heat flow (Hisarli, 1996). Measurements have shown that a region with shallow DBMS is characterized by an anomalous high temperature gradient and heat flow (Tselentis 1991). It is therefore expected that geothermal active area would be associated with shallow DBMS (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). The DBMS is preferred because it may not be precisely known whether the estimated depth is really controlled by the temperature or magnetomineralogy, the DBMS is a regional estimation of heat depth and it is appropriately used to compliment geothermal data in regions where deep borehole temperature are not available due to huge amount of money required for it. This work aimed at filling the missing gap in the depth of geothermal resources information of

the study area. High Resolution Aeromagnetic data used in this study is processed and corrected by the Nigerian Geological Survey Agency in 2009, acquired from aircrafts flown at height of 80 m with 500 m line spacing, 80 m mean terrain clearance and the tie line spacing of 500 m. This new low height survey data which is digitally high in resolution has been adjudged to be better than the previous 1970's low resolution analogue data by the NGSA. The results of this study also provide digitally-driven geothermal record and maps that would serve as a guide and baseline data for future regional geothermal study.

The Location and Geology of the Study Area

The Sokoto Basin in the northwestern part of Nigeria is bounded by latitude 10.00° to 14.00° N and longitude 3.50° and 7.00° E with a total area of $111,925 \text{ km}^2$, it cuts across six states of the nation, these are; Sokoto, Zamfara, Kebbi, Katsina, Kaduna and Niger. Sokoto Basin is one of the inland basin in Nigeria (Figure 1) and consists of gentle undulating plain of sedimentary rocks, underlain by basement rocks consisting of igneous and metamorphic rock. Its climate is tropical continental and is dominated by two opposing air masses, tropical maritime and tropical continental. The tropical maritime is moist and blows from the Atlantic ocean while the tropical continental air, which is dry blows from the Sahara Desert. The basin is a semi-arid region marked by wet and dry season's weather. The annual rainfall is between 500 mm in the north and 1300 mm to the south. Within the Sokoto basin there is considerable variation in rainfall distribution with mean annual rainfall ranging from 350 mm at Kurdula in the extreme northwest and 670 mm at Sokoto Airport. The rainy season, which usually starts from May or June of each year, lasts till September or early October depending on the rain fall pattern for each year while dry harmattan season is between November and March. Moreover, the basin is characterized by two extreme temperatures relative to tropical position.

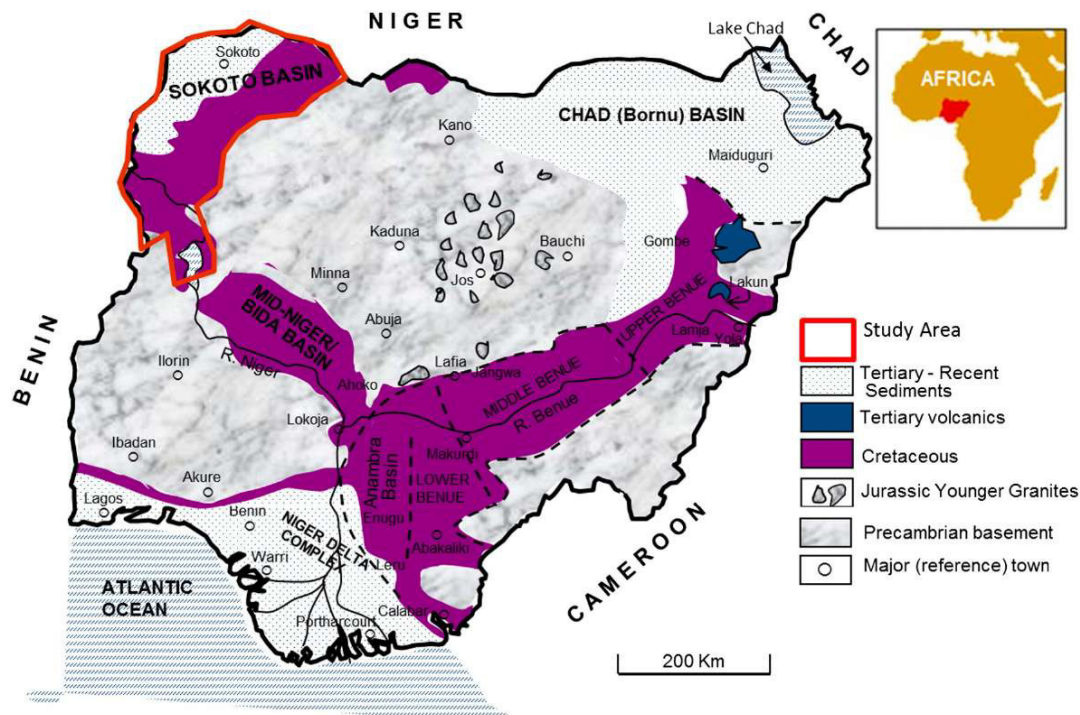


Figure 1: Geological Map of Nigeria showing Sokoto Basin (Modified after Obaje *et al.*, 2004)

The highest temperature during the hot season is usually experienced in the month of March/April while very cold temperature during extreme cold harmattan season is usually experienced in the month of November and February.

Geology of the Area

Sokoto Basin in the northwestern Nigeria constitutes the southeastern portion of the Iullemeden Basin, which extends from Mali and the western boundary of Niger republic through northern Benin Republic and Northwestern Nigeria into Eastern Niger Republic and it covers an area of about 800,000 km². The rock unit are predominantly clay alternating with gritty sand unit, they are ill-sorted, poorly consolidated with gravel overlying the pre-Cambrian basement uncomfortably, consist of a gentle undulating plain with an average elevation varying from 250 to 400 m above sea- level 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, the Nigerian Sector of the Iullemeden Basin is underlain by basement rock consisting of igneous and metamorphic rocks. The basement is directly overlain by Cambrian beds to the north in the Tassaili and the Hoggar mountains. As one traverses the basin from the north towards the southwest the formations become younger in age and rest directly on the pre-Cambrian basement. This situation is referred to as an overlap where progressively younger beds rest upon the older series (Kogbe 1979). The sediments of the Sokoto basin were deposited under varied environmental situations ranging from continental to marine events. The sedimentary rocks in the basin have been classified under four major categories. Overlying the pre-Cambrian basement unconformably is the first category is known as the Illo and Gundumi formations, made up of grits and clays. They are overlain uncomfortably by the second category known as maastrichtian Rima group, consisting of mud stone and friable sandstone (Taloka and Wurno formation) separated by the fossiliferous, Shelly Dukamaje formation. The Dange and Gamba formation (mainly shale's) separated by the calcareous Kalambaina formation constitute the third category known as Sokoto group which is of marine origin. The fourth category is known as the Gwandu formation forms the post-Paleocene continental terminal occurs in the northwest and southern parts of Sokoto. This sediment dips gently and thickens gradually towards the northwest, with a maximum thickness of over 1,200 m near the frontier with Niger republic. The geological map of the Sokoto basin of northwestern Nigeria is shown on Figure1.

Data Acquisition and Analysis

A total of Thirty eight (38) sheets of HRAM data grid on a scale of 1:100,000 with 7,426,917 data points used for this research work were purchased from the Nigerian Geological Survey Agency, Abuja-Nigeria. The sheet were number: 1 - 5, 8 - 13, 26 - 31 48 - 53, 71 -74, 94 - 97, 116 - 119 and 138 - 139 were assembled using OASIS MONTAJ into contoured gridded digital data referred to as the total magnetic field intensity (TMI) map (Figure 2). Sokoto Basin in the Northwestern part of Nigeria is covered by the new most recent Nigeria`s Nationwide High Resolution Airborne Geophysical Surveys carried out for the Nigerian Geological Survey Agency by Fugro Airborne Services in 2009 and Supported by International funding agencies such as the World Bank. Digital data from these airborne magnetic and radiometric surveys were acquired along a series of NW-SE, with 1,104,174 line km as total lines, flight lines spacing of 500 m, average flight elevation of 80 m, tie line spacing of 2 km, with NE-SW as the tie line direction.

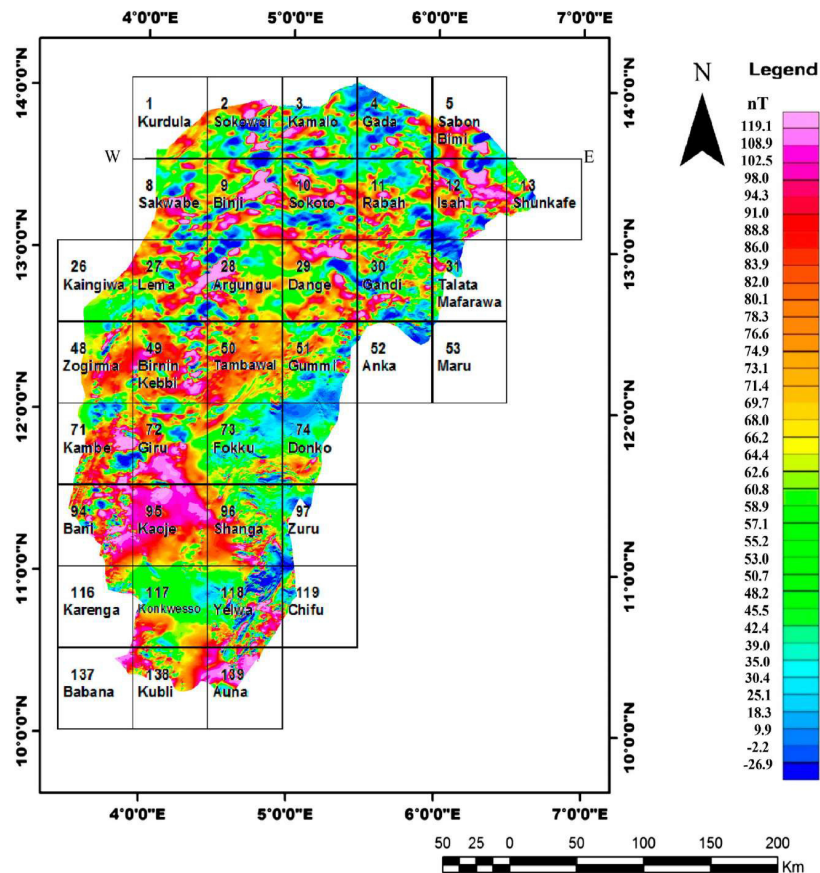


Figure 2: Total Magnetic Intensity Map (TMI) of Sokoto Basin showing major towns flown over

Magnetic method for estimating the DBMS was based on the theory of Bhattacharyya and Leu (1975) which examine the shape of isolated magnetic anomalies when the anomalies data are analyzed into spectra of the total field for estimating the depths to the bottom of magnetized bodies in the crust. This method provides the relationship between spectrum of magnetic anomalies and the depth of a magnetic source by transforming the spatial data into frequency domain. The magnetic method of estimating the DBMS of a polarized rock mass can be classified into two: (1) those that study the shape of isolated magnetic anomalies (spectral centroid) as used in the present study, (2) those that study statistical properties of pattern of magnetic anomalies (like Spector and Grant, 1970). The spectral centroid method applied in the present study has been described as very suitable for regional magnetic survey for geothermal resources (Tanaka *et al.*, 1999, Shuey *et al.*, 1977 and Ravat *et al.*, 2007) also Nwankwo and Shehu 2015) has also shown that it gives a better estimates of DBMS with less depth error compared with other. The nationwide regional scale data (HRAM) has been processed and corrected and a constant TMI value of 33000 nT was removed for easier computation by the NGSA before the eventual publication as HRAM colour Maps. The composite map was then divided into twenty two (22) overlapping blocks, each block with spectral window of 110 km x 110 km for the purpose of 2D spectral analysis while ensuring that essential parts of the anomaly were not cut out by the blocks. Two dimensional Power spectrums of magnetic anomalies by Fourier transformation using Geosoft Oasis montaj were obtained for each block.

The mathematical models of the centroid method are based on the examination of the shape of isolated magnetic anomalies introduced by Bhattacharyya and Leu (1975, 1977) and the study of the statistical properties of magnetic ensembles by Spector and Grant (1970). Following the introduction of power spectral density of total magnetic field by Blakely (1995), Tanaka *et al.*

(1999) showed that the top bound and the centroid of magnetic sources can be calculated from the power spectrum of magnetic anomalies, and consequently used to estimate the DBMS of the magnetic source. In practice, the centroid depth is calculated from the low wavenumber part (i.e high frequency) of the wavenumber-scaled power spectrum as:

$$\ln (P(k)^{1/2}/k) = A - |k|Z_0 \quad (1)$$

where $P(k)$ is the azimuthal averaged power spectrum, k is the wave- number ($2\pi/\text{km}$), A is a constant and Z_0 is the centroid depth.

The depth to the top of the magnetic source is derived from the slope of high wavenumber part (i.e low frequency) of the power spectrum as:

$$\ln (P(k)^{1/2}) = B - |k|Z_t \quad (2)$$

where, B is a constant, and Z_t is the depth to the top of magnetic sources. Tanaka *et al.*, (1999) advocated fitting the slope rather to a higher wavenumber part of the spectrum arguing that the linearized equation for the depth to the top is valid for wavelengths greater than the thickness of the layer. Fitting the slope to a higher wavenumber part of the spectrum as suggested by Tanaka *et al.*, (1999) leads to deeper magnetic bottom estimates that, at times, appear to be desirable (Ravat *et al.*, 2007). Finally, the depth to the bottom of the magnetic source (Z_b) for each block was obtained from the relation (Okubo *et al.*, 1985):

$$Z_b = 2Z_0 - Z_t \quad (3)$$

Results and Discussion

Power and wavenumber-scaled power spectra plots were made for each of the 22 overlapping blocks for the purpose of estimating DBMS. A typical example for block 6 and 19 is shown in Figure 3. Table 1 shows the results of estimated DBMS for the 22 blocks.

The range of the depths to the top of magnetic sources is from 0.59 to 2.11 km with an average of 1.22 km and the centroid depth range from 6.27 to 14.30 km with an average of 9.90 km, while the depths to bottom that is the curie point depth (CPD) range from 11.13 to 27.83 km with an average of 18.57 km. The Z_t interpreted as sedimentary thickness in the study area is averagely shallow, this could be attributed to magmatic and volcanic intrusive rocks into the sedimentary formation. This suggests that significant geothermal resources can be found below the sedimentary formation, shallow depth to basement as observed in block 15, 18 and 20 could induce high magnetic effect from the granitic basement in the southern part of the study area.

These results showed a shallow DBMS. Generally, areas with shallow DBMS correspond to high geothermal potential (Bansal *et al.*, 2011). Since shallow DBMS and high heat flows are significant in determining the geothermal potential of an area. Rabah, Kamalo border with Niger, Sokoto, Dange, Argungu, Sakwabe, Lema, Isah, Kambe of the study area are potential area for geothermal energy exploration.

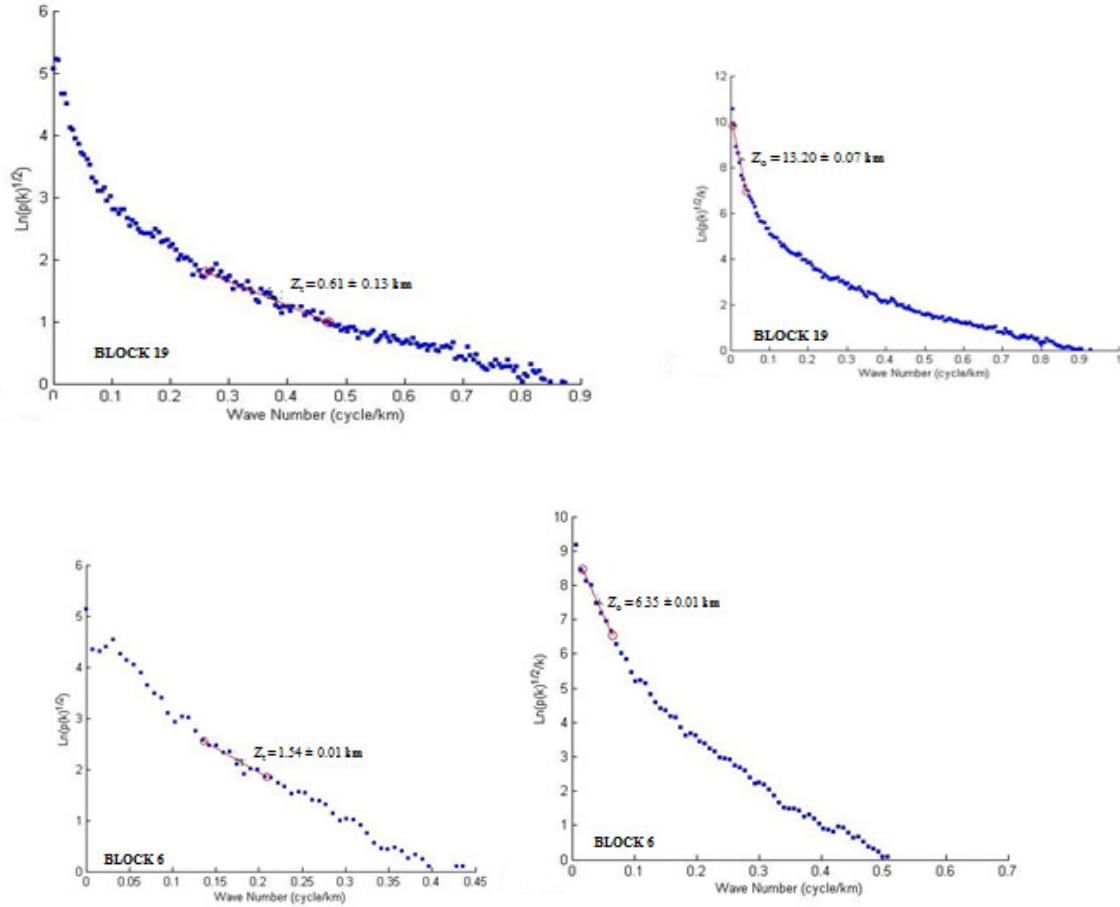


Figure 3: power spectra plots of magnetic sources for block 6 and 19

Table 1: Summary of estimated DBMS from spectral centroid analyses

Block NO	Long. ($^{\circ}\text{E}$)	Lat. ($^{\circ}\text{N}$)	$Z_t(\text{km})$	$Z_0(\text{km})$	$Z_b(\text{km})$
1	4.50	13.50	2.11	7.37	12.63
2	5.00	13.50	1.61	8.17	14.73
3	5.50	13.50	1.41	6.27	11.13
4	6.00	13.50	1.53	9.53	17.53
5	4.50	13.00	2.01	9.03	16.05
6	5.00	13.00	1.54	6.35	11.16
7	5.50	13.00	1.43	7.79	14.15
8	6.00	13.00	1.44	10.00	18.56
9	4.00	12.50	1.14	8.14	15.14
10	4.50	12.50	1.87	8.45	15.03
11	5.00	12.50	1.53	9.04	16.55
12	5.50	12.50	1.15	8.13	15.11
13	4.00	12.00	1.20	8.44	15.68
14	4.25	11.75	0.80	14.20	27.60
15	4.75	11.75	0.59	13.30	26.01
16	4.00	11.50	0.99	8.75	16.51
17	4.25	11.75	1.00	14.30	27.60

18	4.75	11.75	0.57	14.20	27.83
19	4.25	11.25	0.61	13.20	25.79
20	4.50	11.25	0.59	12.20	23.81
21	4.00	10.50	0.98	7.83	14.68
22	4.50	10.75	0.65	13.00	25.35
Average			1.22	9.90	18.57

This depth information was subsequently used to generate CPD maps for Sokoto Basin (Figure 4). Figure 4a shows the basement topography of DBMS with the deepest in the southern part of the study area. A closer look at Figure 4b shows that the shallowest region lies at the northcentral part of the study area, the map also shows NW-SE trending in the south and NE-SW in the north depicting regional magmatic and volcanic condition in the study area. It is commonly known that areas with shallow DBMS correspond to areas with low magnetic anomalies, this explain why Figure 4b with shallow DBMS in the northcentral part agrees with documented digital data Figure 2. The results agrees with (Petters, 1979, Kogbe, 1981, Nwankwo, 2015) and geologic and mineral setting. The results also compared fairly well with what was obtained by Nur *et al.*, (1999) using the 1970s low resolution data. Therefore, this study filled the gap of the lacking baseline regional geothermal data for increase renewable energy options and decrease greenhouse gas emissions in Nigeria.

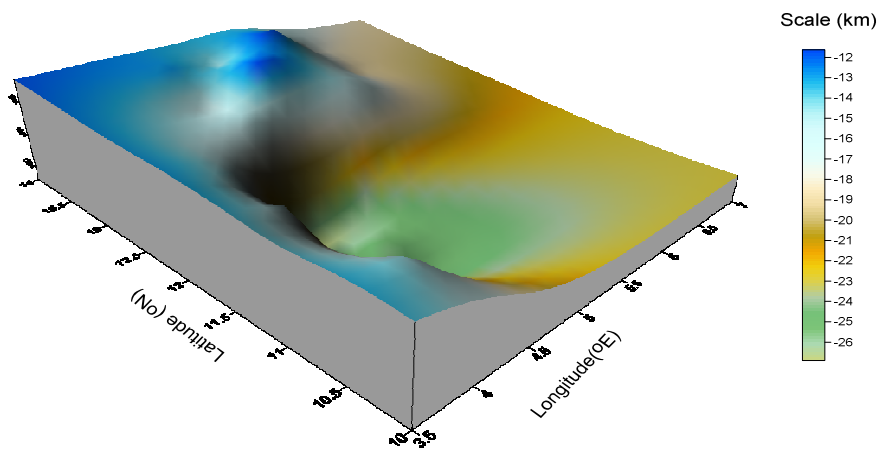


Figure 4(a): 3-D Model Map of the CPD in km

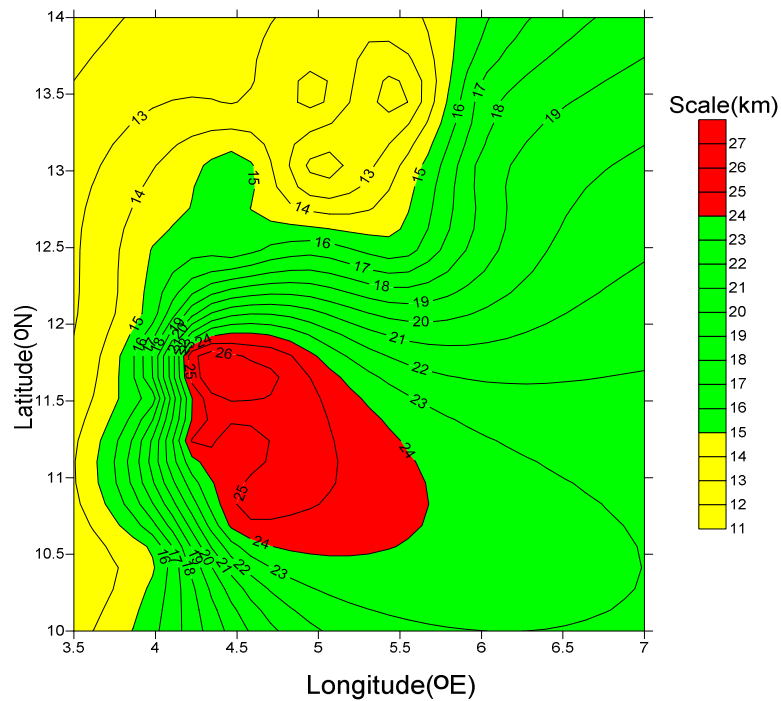


Figure 4(b): CPD map of the study area (contour interval 1km)

Conclusion

High resolution aeromagnetic data (HRAM) has been used to estimate DBMS to infer geothermal potential from the spectral analysis of magnetic field data that is filtered. Previous geothermal work in Sokoto basin were few; with little or no geothermal record, unlike Chad basin in the North eastern Nigeria, hence the result of this study offers better information and promises to prospective Investors and Geoscientist in general on geothermal potential and quantitative understanding of the geo-processes in Sokoto Basin. It also complements geophysical information of the adjoining basins to fill the gap of missing crustal temperature information of the northwestern Nigeria.

The DBMS in the study area is found to vary between 11.13 and 27.83 km with an average of 18.57 km as the CPD in the area indicates that the heat source and geothermal resources are closer to the surface. Regions with shallow DBMS (below 14 km) corresponding to high geothermal potential in the basin, which suggests geothermal conditions (Jessop *et al.*, 1976). The high prospect areas are recommended for detailed integrated ground surveys and detailed laboratory tests on rocks samples. Exploration and exploitation of geothermal heat will definitely provide opportunities to increase energy options, energy market flexibility and decrease greenhouse gases emission in Nigeria.

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