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Full Length Research Article

GEOTHERMAL PROSPECTIVE AREAS IN THE NORTHERN SECTOR OF BIDA BASIN AND ENVIRONS, NORTH-CENTRAL NIGERIA

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ABSTRACT

With the deteriorating electrical power supply in Nigeria, it is imperative that more alternative sources are explored. This research work is carried out to assess part of the Bida basin as a possible source of geothermal energy that will help to augment the electric power generation in the country. The study was carried out within the northern sector of the Bida Basin and environs and the area which lies between Longitudes $5^0$00'00" – $7^0$00'00" E and Latitudes $8^0$30'00" – $10^0$30'00" N. Sixteen (16) half degree high resolution aeromagnetic data in a block grid format was utilised for this research. To enhance data for interpretation the total magnetic intensity (TMI) map was subjected to regional-residual separation using Oasis Montaj (version 7.0.1) software. To minimize the effect of frequency noise caused by tiny structures near ground surface, the residual magnetic map was upward continued and further divided into sixteen square blocks with each block windowed and subjected to spectral analysis using Matlab (version R2010a) software. Surfer 11 surface mapping software was used for data contouring. Results obtained from the analysis revealed a Curie point depths ranges from 9 – 17 km over the study area, a geothermal gradient range from 32 – 65 ^{0}C km^{-1}, and heat flow ranges from 83 – 163 mWm^{-2}. From interpretation of heat flow map, the prospective areas with anomalous geothermal conditions recommended for geothermal exploitation are areas around Masamagu, Mokwa, Bokani, Lapai, Agaie and Agena.

Keywords: Northern Bida Basin, High resolution Aeromagnetic, Curie depth, Geothermal gradient, Geothermal heat.

INTRODUCTION

In recent times one of the leading researches that have received significant attention is exploring potential areas for geothermal energy exploitation. Geothermal energy has gained widespread acceptance as a source of energy in respect to electricity power generation. This research has become imperative considering the dwindling fossil fuel supply in Nigeria, which has possibly contributed to the deteriorating electricity power supply since about 86 percent of the power generating stations in Nigeria uses natural gas (Oyewo et al., 2018). The need to source for more energy sources that will augment the continued electricity power supply in the country now and in the nearest future prompted this research work. The choice of the study area is tied to its proximity to the Nigerian national electricity grids located in Jebba, Kwara State, as well as Kanji and Shiroro in Niger State.

Geoscientists have used both the direct and indirect methods to study the geothermal history of the earth's subsurface [Okubo et al., (1985); Nwanko et al., (2011); Saibi et al., (2015) etc.]. The direct method involved direct measurement performed in drilled boreholes while the indirect methods are based on geophysical data analysis as utilised in this work. One important method of examining geothermal history of the crust is the estimation of the Curie point depth (CPD), from analysis of aeromagnetic data. 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). Bhattacharyya and Leu (1975) also defined Curie point depth as the theoretical surface with a temperature of approximately 580^{0}C and can be considered an index of the bottom of a magnetic source, due to ferromagnetic minerals converting to paramagnetic minerals.

Estimations of Curie point depth from analysis of aeromagnetic data began in the 19th century. The main attempts to use spectral data for depth estimates stem from a publication by (Spector and Grant, 1970). They showed that for an ensemble of prismatic blocks with infinite depth extent the logarithmic radial energy spectrum of the total magnetic intensity consists of a straight line whose gradient is related to the average depth to the tops of the prisms. Furthermore, in the case of a double ensemble of prisms, two gradients would normally be obvious in the spectrum, with the steep gradient related to the deeper sources and the low gradient related to the shallow sources. Spector and Grant (1970) however, said it is important to realise that the slope of spectra can only be used to calculate average depths when the sources are an ensemble of uncorrelated magnetic poles. Significant corrections for the average width of the prismatic bodies and their depth extent must be applied before any accurate depth estimation can be attempted for the spectra of ensembles of prismatic blocks (Spector and Grant, 1970).

Later, researchers used Curie point depth criteria for geothermal exploration. For example: Okubo et al., (1985) estimated the CPD of Kyushu Island (Japan) from aeromagnetic data and compared them with volcanic localities. Tanaka et al., (1999) mapped the Curie point depth in East and Southeast Asia. Results of their analysis showed that Curie point depth are shallower than 10 km for volcanic and geothermal fields, and is between 15-25 km for Island areas and ridges and is deeper than 20 km in plateaus and trenches. Hsieh et al., (2014) determined the Curie depth from spectral analysis of magnetic data in Taiwan. Results obtained shows that the lowest Curie point depth of 6 km corresponds to areas with higher geothermal gradient of 88 ^{0}C/km and the highest value of 17 km corresponded to areas of low geothermal gradient of 36 ^{0}C/km. Saibi et al., (2015) mapped the Curie point depth of western Afghanistan and the result shows that the area is characterized by four (4) Curie point depths: Shallow Curie depths

(~ 16 - 21 km), intermediate Curie depths (~ 21 - 27 km), deep Curie depths (~ 25 - 35 km) and very deep Curie depth (~ 35 - 40 km)

In recent times, estimate of depth to Curie point, determination of geothermal energy and heat flow from analysis of aeromagnetic data was used by some researchers in Nigeria among who are: Nwanko et al., (2011) who estimated the heat flow from spectral analysis of airborne magnetic data of northern Nupe (Bida) basin of north central Nigeria. Result of the analysis showed that geothermal gradient varies between 10 and 45 $^{o}C\ km^{-1}$, while the ensuing heat flow varies between 30 to 120 mWm^{-2}. Kasidi and Nur (2013) estimated the Curie point depth, geothermal gradient and heat flow as inferred from aeromagnetic data over Jalingo and environs N.E Nigeria. Results of their analysis indicates Curie point depth varies between 24 and 28km, geothermal gradient varies between 21 and 23 $^{0}C\ km^{-1}$, while the heat flow varies between 53 and 61 mWm^{-2}.

Geology of the study area

The study area is the northern sector of the Bida basin and environs and lies between Longitudes 5^{0}00'00" – 7^{0}00'00"E and Latitudes 8^{0}30'00" – 10^{0}30'00"N located in the north-central part of Nigeria (Fig. 1).

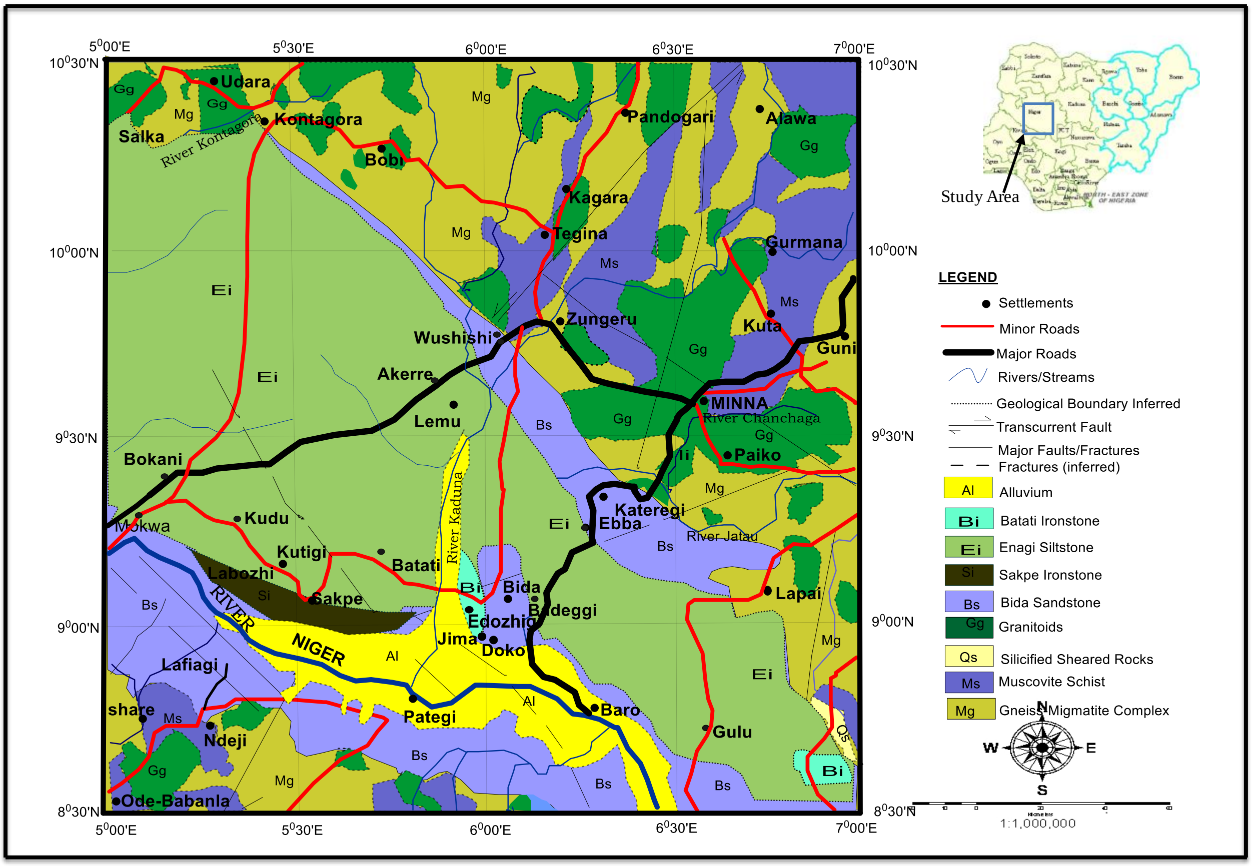

Figure. 1: Geological map of northern Bida basin and environs. (Adopted from Barka, 2020)

The basin is flanked by the north-central and south-western Precambrian Basement Complex rocks. The Precambrian Basement rocks consist of the Migmatite-Gneissic Complex dated Archean to early Proterozoic [2,700 to 2,000 Ma], the Schist Belt and intruding both the Migmatite-Gneiss Complex and the Schist belt is the granitoid plutons of the Older Granite suite dated Late Proterozoic to early Phanerozoic [750 to 450 Ma] (Obaje, 2009). The basal stratigraphic unit within the study area comprises of Bida Formation aged Campanian – Maastrichtian and consist of basal conglomerate and a successions of cross-bedded white to grey sandstones intercalated with koalinitic clays which were derived from deeply weathered Basement Complex rocks (Nwajide, 2013). This formation is overlain by the Sakpe Formation which is Maastrichtian in age (Whiteman, 1982) and comprises mainly of oolitic and pisolitic ironstones with sandy claystones locally, at the base, followed by dominantly oolitic ironstone exhibiting rapid facies changes across the basin (Obaje et al., 2013). The Enagi Formation overlies the Sapke Formation and consist of siltstone and subordinate sandstone, claystone and siltstone/sandstone intermix. The Enagi Formation is also associated with the Kudu Shale Member, a coally dark-grey to black shale unit of mire facies (Okosun et al., 2007; Obaje et al., 2013). Maastrichtian age has been suggested for Enagi Formation (Nwajide, 2013). The Batati Iron Formation constitutes the uppermost units in the sedimentary sequence of the northern Bida basin. The Batati Formation consists of argillaceous, oolitic and goethitic ironstones with ferruginous claystone and siltstone intercalations and shaley beds occurring in minor proportions, some of which have yielded near shore shallow

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marine to fresh water fauna (Obaje et al., 2013).

MATERIALS AND METHODS

Materials

Sixteen high resolution total magnetic intensity aeromagnetic maps each on a scale of 1:100,000 were utilised for this research. The high resolution aeromagnetic data was acquired between year 2004 and 2009 using 3X Scintrex CS3 Cesium Vapour Magnetometer. The following flight parameters were used in data acquisition: flight line spacing was 500 meters, terrain clearance was 80 meters, flight direction was in the NW-SE, tie line spacing was 2 kilometres and tie line direction was in the NE-SW direction. Softwares used for data analysis include: Oasis Montaj version 7.0.1, Matlab version R2010a and Surfer 11.

Methods

To enhance data for interpretation the total magnetic intensity (TMI) map of the study area in a grid format was subjected to regional-residual separation. To minimize the effect of frequency noise caused by tiny structures near ground surface, the residual magnetic map was upward continued to 15 km and was further divided into sixteen square blocks; each windowed block was 55 x 55 km in size. The estimation of the Curie point depth was based on spectral analysis of each of the block. Bhattacharyya and Leu (1975) presented that depth to bottom (z_b) of a magnetic source body could be estimated using two methods. Firstly, by estimation of depth to the centroid (z_0) of the magnetic sources from the slope of the longest wavelength part of the spectrum and is related by the formula:

$$\ln\left[\frac{p(s)^{½}}{/s/}\right]\ln\mathrm{A} - 2\pi/\mathrm{s}/\,Z_O \qquad (1)$$

Where p(s) is the radially averaged power spectrum of the anomaly, /s/ is the wave number and A is a constant.
Secondly, estimation of depth to the top (Z_t) of the magnetic sources was obtained from the second slope of the longest wavelength spectral subdivision and is related by the formula:

$$\ln[p(s)^{½}]\ln\mathrm{B} - 2\pi/\mathrm{s}/\,Z_t \qquad (2)$$

where p(s) is the radially averaged power spectrum of the anomaly, /s/ is the wave number and B is the sum of constants independent of /s/.

From the spectral analysis carried out on each block using the Geosoft Magmap package in the Oasis Montaj version 7.0.1 environment, the spectral data for each block as radial SPC files were imported into Matlab version R2010a. The depth to the upper bound (Z_t) and the centroid (Z_o) of the magnetic bodies were estimated from the slope of the log power spectrum by fitting a straight line through the steepest and gentle wave number parts of the averaged frequency scaled power spectrum. The lower bound (Z_b) of the magnetic source corresponding to Curie point depth was derived from the equation given by (Bhattacharyya and Leu, 1975) as:

$$Z_b = 2Z_O - Z_t \qquad (3)$$

Tanaka et al., (1999) presented that the basic relationship for conductive heat flow is the Fourier's law. In order to relate the Curie point depth (Z_b) to Curie point temperature variation, the vertical direction of temperature variation and the constant thermal gradient was assumed. The geothermal gradient (dT/dZ) between the earth and the Curie point depth (Z_b) was defined by the equation:

$$dT/dZ = 580\,^{\circ}\mathrm{C}/Z_b \qquad (4)$$

where 580^{0}C is the Curie temperature at which ferromagnetic minerals are converted to paramagnetic minerals.
Furthermore, the geothermal gradient was related to heat flow (q) using the formula:

$$q = \lambda(dT/dZ) = \lambda\,(580^{\circ}\mathrm{C}/Z_b) \qquad (5)$$

where λ is the coefficient of thermal conductivity. A thermal conductivity of 2.5 $Wm^{-1}\,{}^0C^{-1}$ given by (Stacey, 1977) being the average for igneous rocks was used to compute the subsurface heat flow.
The data so obtained from the computation of curie depth, geothermal gradient and heat flow over the study area were used to generate the Curie isotherm depth, geothermal gradient and heat flow maps of the study area before further interpretation.

RESULTS

The total magnetic intensity (TMI) data over the study area ranges from 33,110.48 nT to 32,932.11 nT (Fig. 2). The residual magnetic map over the study area (Fig.3), has attributes of positive and negative anomalies scattered in different parts of the map. The positive anomalies with an amplitude range between 11.83 nT/m to 124.08 nT/m are represented by light blue to magenta colours. The negative anomalies with amplitude range of -37.75 nT/m to -4.55 nT/m are represented by deep blue colours on the map.

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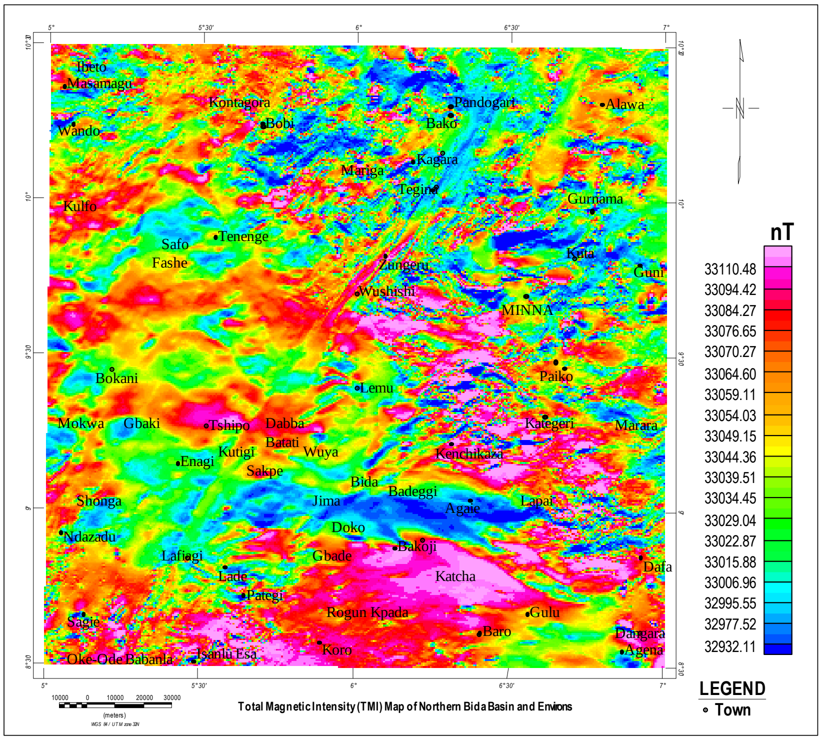

Figure. 2: Total Magnetic Intensity (TMI) Map of Northern Bida Basin and Environ (Adopted from Barka, 2020)

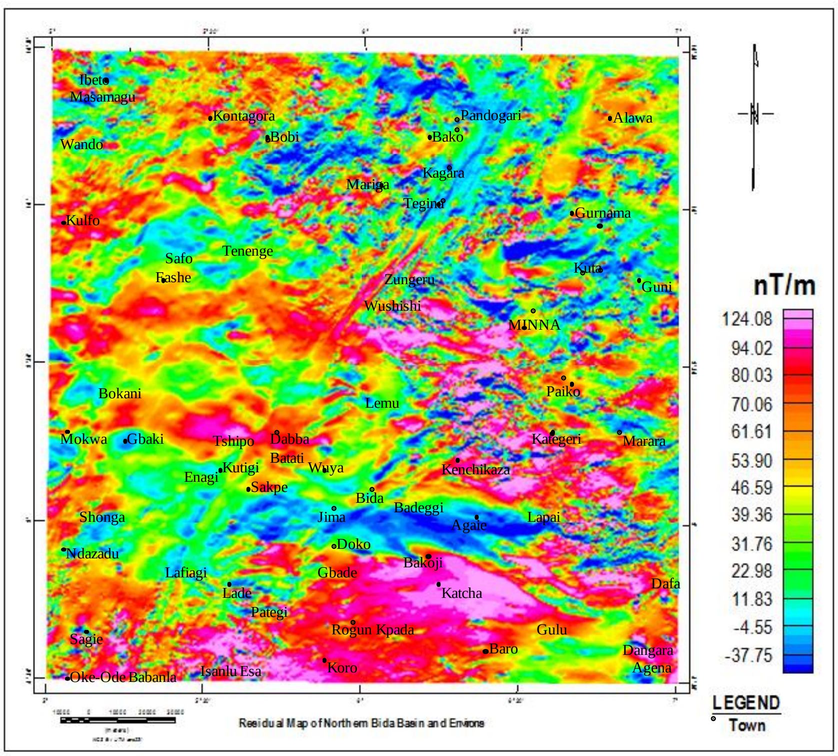

Figure. 3: Residual Magnetic Map of Northern Bida Basin and Environs (Adopted from Barka, 2020)

The upward continued to 15 km residual magnetic map (Fig. 4) revealed a range of magnetic anomalies from 22.23 nT to 72.12nT thereby, further demarcate the area into high, moderate and low magnetic anomaly zones.

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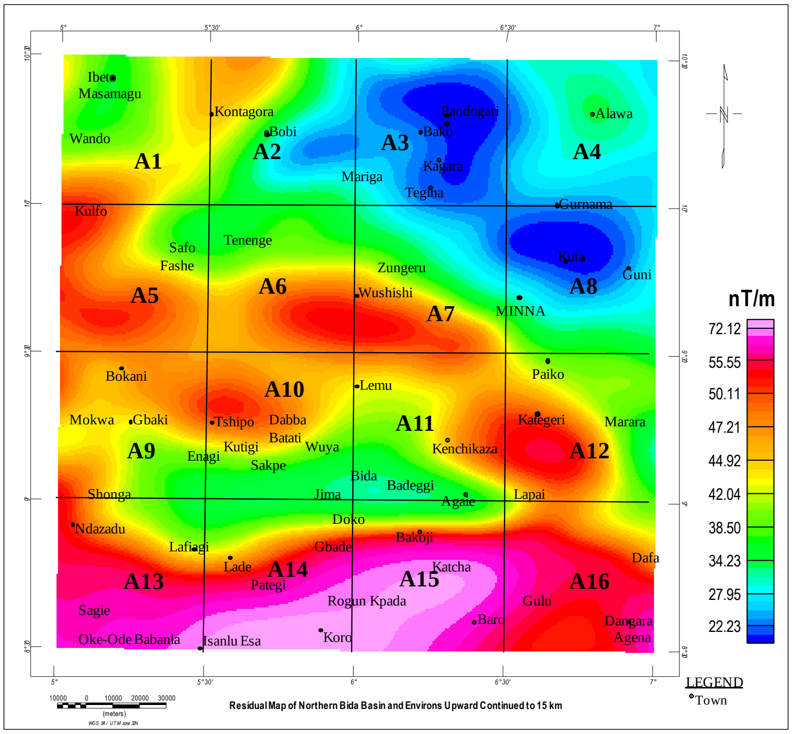

Figure. 4: Residual Magnetic Map of Northern Bida Basin and Environs (Upward Continued to 15 km) Showing blocks A1 - A16.

From the spectral analysis of each block (Fig. 5), the average depth to the top (Z_t) and the centroid (Z_0) of the magnetized bodies were obtained from the slope of the log power spectrums. The lower bound (Z_b) of the magnetic source corresponding to Curie point depths were derived from equation 3. The depth results obtained from each spectral block and the computed Curie point depths are listed in table 1. The Curie point depth map of the study area (Fig.6) revealed a Curie point depths ranges from 9.76 – 17.72 km.

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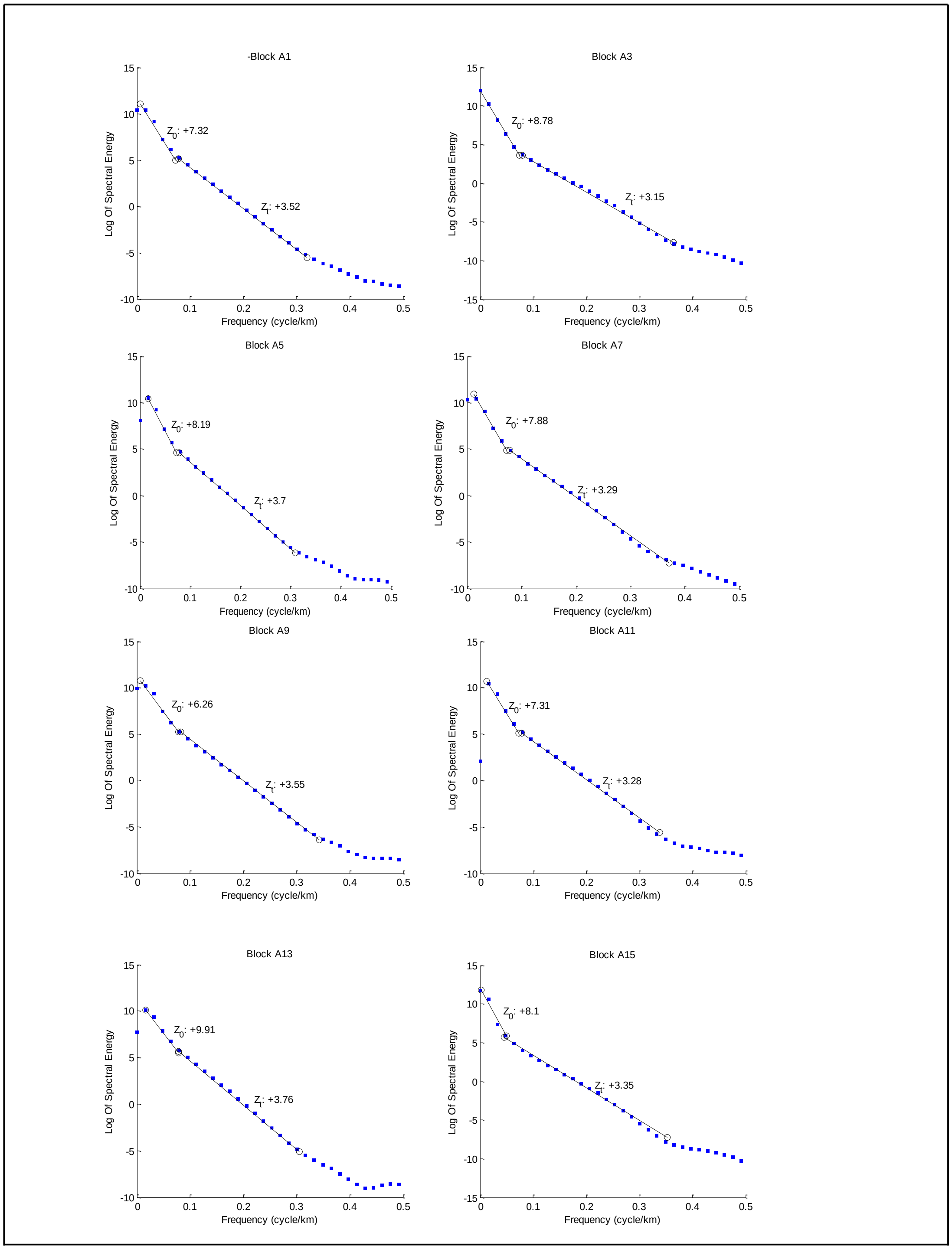

Figure.5: Spectral depth from selected blocks out of the 16 blocks.

Table 1: Values of depth to Top(Z_t), Centroid (Z_0), Basal (Z_b), Geothermal gradient and Heat flow over Northern Bida Basin and Environs

S/No.	Spectral Block	Longitude		Latitude		Depth (Km)			Geothermal Grad.(^{0}C km^{-1})	Heat Flow (mW m^{-2})
		X_1	X_2	Y_I	Y_2	Z_t	Z_0	Z_b		
1	A1	$5^0$00`	$5^0$30`	$10^0$00’	$10^0$30’	3.52	7.32	11.12	52	130
2	A2	$5^0$30`	$6^0$00`	$10^0$00’	$10^0$30’	3.19	10.04	17.61	33	83
3	A3	$6^0$00’	$6^0$30’	$10^0$00’	$10^0$30’	3.15	8.78	14.41	40	100
4	A4	$6^0$30’	$7^0$00`	$10^0$00’	$10^0$30’	3.28	10.5	17.72	32	83
5	A5	$5^0$00`	$5^0$30`	$9^0$30’	$10^0$00’	3.7	8.19	12.68	46	115
6	A6	$5^0$30`	$6^0$00`	$9^0$30’	$10^0$00’	2.95	8.39	13.83	42	105
7	A7	$6^0$00’	$6^0$30’	$9^0$30’	$10^0$00’	3.29	7.88	12.47	47	118
8	A8	$6^0$30’	$7^0$00`	$9^0$30’	$10^0$00’	3.8	10.2	16.6	35	86
9	A9	$5^0$00`	$5^0$30`	$9^0$00’	$9^0$30’	3.55	6.26	8.97	65	163
10	A10	$5^0$30`	$6^0$00`	$9^0$00’	$9^0$30’	3.2	8.39	13.58	43	108
11	A11	$6^0$00’	$6^0$30’	$9^0$00’	$9^0$30’	3.28	7.31	11.34	51	128
12	A12	$6^0$30’	$7^0$00`	$9^0$00’	$9^0$30’	3.68	10.1	16.52	35	88
13	A13	$5^0$00`	$5^0$30`	$8^0$30’	$9^0$00’	3.76	9.01	16.06	36	90
14	A14	$5^0$30`	$6^0$00`	$8^0$30’	$9^0$00’	3.22	7.83	12.44	47	118
15	A15	$6^0$00’	$6^0$30’	$8^0$30’	$9^0$00’	3.35	8.1	12.85	45	113
16	A16	$6^0$30’	$7^0$00`	$8^0$30’	$9^0$00’	3.48	6.62	9.76	59	146

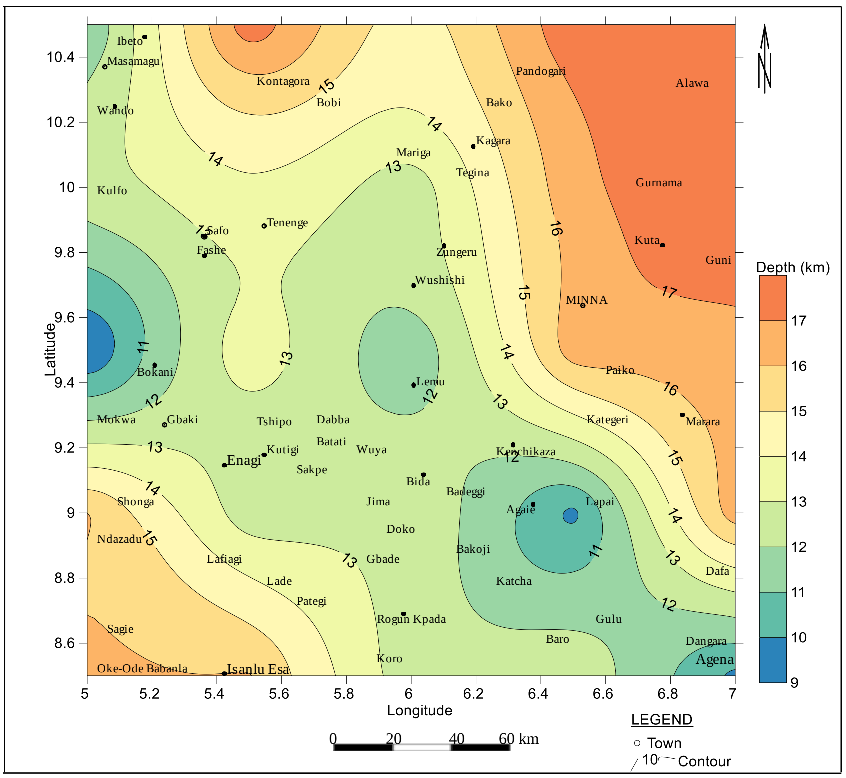

Figure.6: Curie Isotherm Map of Northern Bida Basin and Environs (Contour interval = 1 km)

The geothermal gradient of the study area was calculated from equation 4 and the computed geothermal gradient values on table 1 ranges from 32 – 65 ^{0}C km^{-1}, these values were used to generate the geothermal gradient map (Fig.7). Using the heat flow equation 5, heat flow over the study area was estimated using a Curie point temperature of 580 ^{0}C (temperature at which ferromagnetic minerals loses their ferromagnetic properties) and a thermal conductivity of 2.5 Wm^{-1} ^{0}C^{-1}. The calculated heat flow values on table 2 ranges from 83 – 163 mWm^{-2} and these values were used to produce the heat flow map of northern Bida basin and environs (Fig.8).

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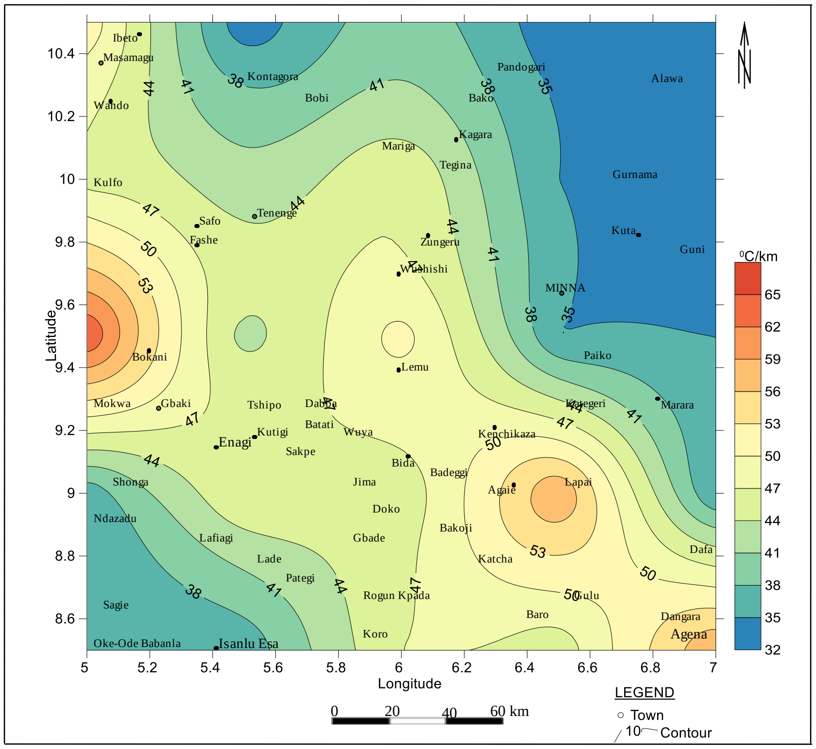

Figure. 7: Geothermal Gradient Map of Northern Bida Basin and Environs (Contour interval = 3 °C/km)

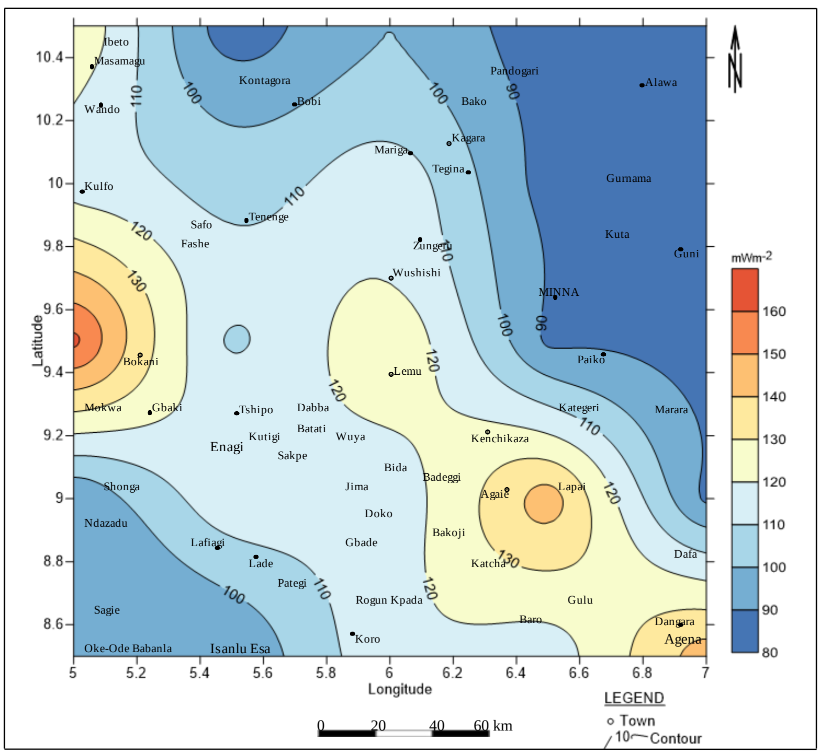

Figure.8: Heat Flow Map of Northern Bida Basin and Environs (Contour interval = 10 mWm^{-2})

DISCUSSION

The Curie isotherm map of northern Bida basin and environs showed that the Curie point depth ranges from 9 – 17 km. Shallow circular Curie point depths of the range 9 - 12 km were recorded within the sedimentary basin. It was also observed from the Curie isotherm map that, there was a general decrease in Curie point depth from areas covered by migmatite gneiss complex rocks from the north, north-east, east and south-western areas towards the sedimentary basin at the central part . Curie point was found to be deepest (>17 km) around Alawa, Gurnama, Kuta and Guni to the north-east and Oke-Ode Babanla to the south-west (Fig. 6). Saibi et al. (2015) in their work characterized the Curie point depths as: shallow Curie depth (~16 -21 km), intermediate Curie point depth (~21 - 27 km), deep Curie depth (~27 - 35 km) and very deep Curie depth (~35 - 40 km). Comparing these values with the result of Curie point depths obtained (9 -17 km), indicates that the study area is characterised by shallow Curie point depth environments. These authors also shows that, shallow Curie point depths can be associated with recent volcanic/magmatic activities and thin crust whereas, deep Curie point depths are related to cooled or old crust. In the case of this study, the study area is associated with thin crust since Bida basin is so unique among the other sedimentary basins Nigeria in that it is characterised by an absence of volcanics (Rahaman et al., 2019).

The geothermal gradient map of northern Bida basin and environs showed an increasing geothermal gradient from 32 – 44 ^{0}C km^{-1} from the north-eastern and south-western part of the study area mostly over the Basement Complex rocks to 45 - 65 ^{0}C km^{-1} around the central part which is overlain by sedimentary rock. It is therefore apparent that areas of high geothermal gradient (45 – 65 ^{0}C km^{-1}) correspond to areas of low Curie point depth (9 – 12 km) in the study area. Tanaka et al., (1999) pointed out that at volcanic geothermal areas, the Curie point depths are normally shallower than 10 km, and at Island areas and ridges are in the range of 15 to 25 km and are deeper than 25 and 30 km at plateaus and trenches respectively. Geothermal energy does also occur in areas where basement rocks that have relatively normal heat flow are covered by thick blanket of thermally insulated sediments Ufor and Udensi (2014).

As revealed from the Curie point isotherm and the heat flow maps of northern Bida basin and environs, the geothermal prospective areas have a Curie point depths varying from 9 – 12 km and occurs within the sedimentary basin. This depth range is an indication that the geothermal heat is neither sourced from volcanic activities nor in island, ridges, plateau and trenches as depicted by (Tanaka et al., 1999). It is therefore, suggested that the geothermal energy is sourced from areas where thick cover of thermally insulated sediments overlies basement rocks. The thermally insulated sediments which overlie the basement rock in the area can be tied to the shale sequence (Kudu member) of the Enagi Formation as reported by (Obaje et al., 2013).

Jessop et al., (1976) showed that the average heat flow in thermally normal continental regions is around 60 mWm^{-2}. In their contribution they went further to say values in excess of about 80 - 100 mWm^{-2} are indicative of geothermal anomalous conditions. In this study, anomalous geothermal conditions have been assigned values in excess of the upper bound limit of 100 mWm^{-2} given by Jessop et al., (1976). From the heat flow map of northern Bida basin and environs, the estimated heat flow within the area ranges from 80 to 160 mWm^{-2}. This shows that the study area is characterized by both the normal and anomalous geothermal continental conditions. The normal geothermal continental conditions of the range of 80 to 100 mWm^{-2} within the study area were observed in areas around Kontagora and Bobi to the northwest, Pandogari, Bako and Kagara to the north, Alawa, Gumama, Kuta and Guni to the northeast. Minna, Paiko, Marara to the east, Oke-Ode Babanla, Sagie Ndazalu and Isanlu Esa to the southwest. The geothermal anomalous region with geothermal conditions of above 100 mWm^{-2} was observed to trend in the NW-SE direction occupying mostly the central part of the study area and is overlain by thick sequence of sedimentary rock averaging 1.7 km.

Conclusion

The Curie point depth was estimated from spectral analysis on residual magnetic anomaly data covering the study area. The estimated Curie point depth ranges from 9 – 17 km, comparing this range with other research works, it depicts that the study area is generally a characteristic of the shallow Curie point depth environs. Within the central part of the study area overlain by sedimentary rocks the Curie point depth is shallowest ranging from 9 - 12 km and this corresponds with high geothermal gradient of 45 – 65 ^{0}C km^{-1} and high geothermal heat flow of above 100 mWm^{-2}. The shallow Curie point depth within the central part of the basin is an indication of crustal thinning. The thinning of crust here serves as a medium through which heat from the mantle could easily access the surface hence high heat flow is recorded within this region particularly in places where thick blanket of Kudu shale member of the Enagi Formation covers the crust. Areas with moderately high Curie point depth of the range 13 - 17 km indicating thickening of the crust were observed over area with basement rocks exposures and this correspond with low geothermal gradient of 32 – 44 ^{0}C km^{-1} and perhaps low geothermal heat flow of 80 – 100 mWm^{-2}. From computed heat flow the prospective areas with anomalous geothermal conditions above 100 mWm^{-2} recommended for further geothermal exploration and exploitation are areas around Masamagu, Mokwa, Bokani, Lapai, Agaie and Agena.

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