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Curie Point Depth and Heat Flow Investigations Over Parts of Bida Basin - Implication for Geothermal Potential

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ABSTRACT

This paper investigates Curie point depth and heat flow over parts of Bida Basin Nigeria using Aeromagnetic data. The study area is between Latitudes 8.5^{o}N and 9.5^{o}N and Longitudes 5.5^{o}E and 6.5^{o}E being represented by four aeromagnetic maps in 16 overlapping blocks involving towns like; Pateji, Baro, Bida and Agbaje. Depth Estimations were made using Spectral Analysis from which estimates of Curie point depth, geothermal gradient and heat flow were made. Heat flow estimated from spectral inversion revealed seven geothermally active areas with the following values; 60.45mWm^{-2} (Pategi), 60.91mWm^{-2} (Baro), 60.99mWm^{-2} (Baro), 65.87mWm^{-2} (Bida), 67.67mWm^{-2} (Agbaje) and 64.00mWm^{-2} (Agbaje).These areas (Agbaje for instance) are recommended for further geothermal exploration.

Introduction

The Bida Basin is a NW-SE structure extending from Kontagora in Niger State of Nigeria to areas slightly beyond Lokoja in the south (Adeleye, 1974). The study area is located between Latitude 8.5^{0}Nand 9.5^{0}N and longitude is 5.5^{0}E and 6.5^{0}E. It is enclosed in four aeromagnetic maps of the Geological Survey agency of Nigeria with the major towns in the area including Pateji, Baro, Bida and Agbaje. Aeromagnetic data was used to determine the Curie point depths (CPD), geothermal gradients and heat flow potentiality over parts of Bida Basin, Nigeria. Various studies have shown correlation between Curie temperature depths and average crustal temperature, leading to geologic conditions in a number of regions around the country.

The assessment of variation of CPD of an area can provide valuable information about the regional temperature distribution at depths and the concentration of sub-surface geothermal energy (Tselentis, 1991). One of the important parameters that determine the relative depth of the CPD with respect to sea level is the local thermal gradient i.e. heat flow. Measurements have shown that a region with significant geothermal energy is characterized by anomalous high temperature gradient and heat flow. It is therefore to be expected that geothermally active areas would be associated with shallow CPD (Nur et al, 2005). Adewumi et al (2019) obtained Curie point depth range from 10.88km to 35.51km with an average value of 23.22km and a geothermal gradient for sixteen blocks ranging from 16.33^{o}Ckm^{-1} at the centre of the southern region Bida Basin to 53.30^{o}Ckm^{-1} at the northeastern and northwestern regions with an average of 28.98^{o}Ckm^{-1}; while the heat flow ranges from 40.99mWm^{-1} to 133.80mWm^{-1} with an average value of 76.19mWm^{-1}. They deduced that the area might be a good indicator of geothermal energy with minimum CPD, maximum geothermal gradient and heat flow since demagnetized rocks confirm a hot rock quantity in the crust that can be harnessed for geothermal potential.

Kasdi and Nur (2012) estimated Curie point depth deduced from spectral analysis of magnetic data over Sarti and environs of North-Eastern Nigeria. They determined Curie depth which varied between 26km to 28km and the geothermal gradient between 21^{o}Ckm^{-1} and 23^{o}Ckm^{-1} while the heat flow values ranged from 53mWm^{-2} to 58mWm^{-2}. They also noted an inverse correlation between estimated curie depth and heat flow measurements.

Geology of the Study Area

The Bida Basin otherwise known as the Mid-Niger Basin or the Nupe Basin is a NW–SE trending intracratonic sedimentary basin extending from Kontagora in Niger State of Nigeria to areas slightly beyond Lokoja in the south (fig. 1). It is located in the northeast and southwest by the basement complex while it merges with Anambra and Sokoto basins in sedimentary fill comprising post orogenic molasse facies and a few thin unfolded marine sediments (Adeleye, 1974). The basin is a gently down warped trough whose genesis may be closely connected with the Santonian orogenic movements of southeastern Nigeria and the Benue valley, nearby Fig.1).

The basin is a NW–SE trending embayment, perpendicular to the main axis of the Benue Trough and the Niger Delta Basin. It is frequently regarded as the northwestern extension of the Anambra Basin, both of which were major depocentres during the third major transgressive cycle of southern Nigeria in Late Cretaceous times (fig.2). Interpretations of borehole logs, as well as geophysical data across the entire Mid-Niger Basin suggest that the basin is bounded by a system of linear faults trending NW–SE (Kogbe et al., 1983). Gravity studies also confirm central positive anomalies flanked by negative anomalies as shown for the adjacent Benue Trough and typical of rift structures (Ojo, 1984; Ojo and Ajakaiye, 1989). The Benue Trough is a

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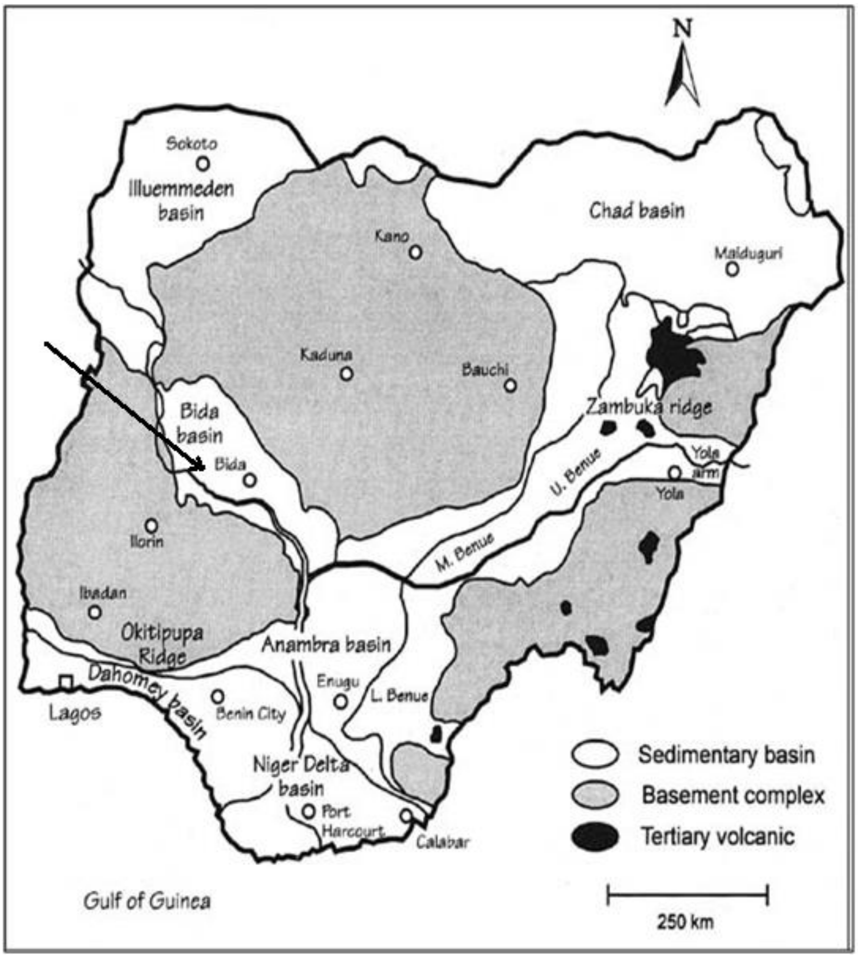

Figure 1. Map of Nigeria showing Bida basin (Obaje et al. 2004)

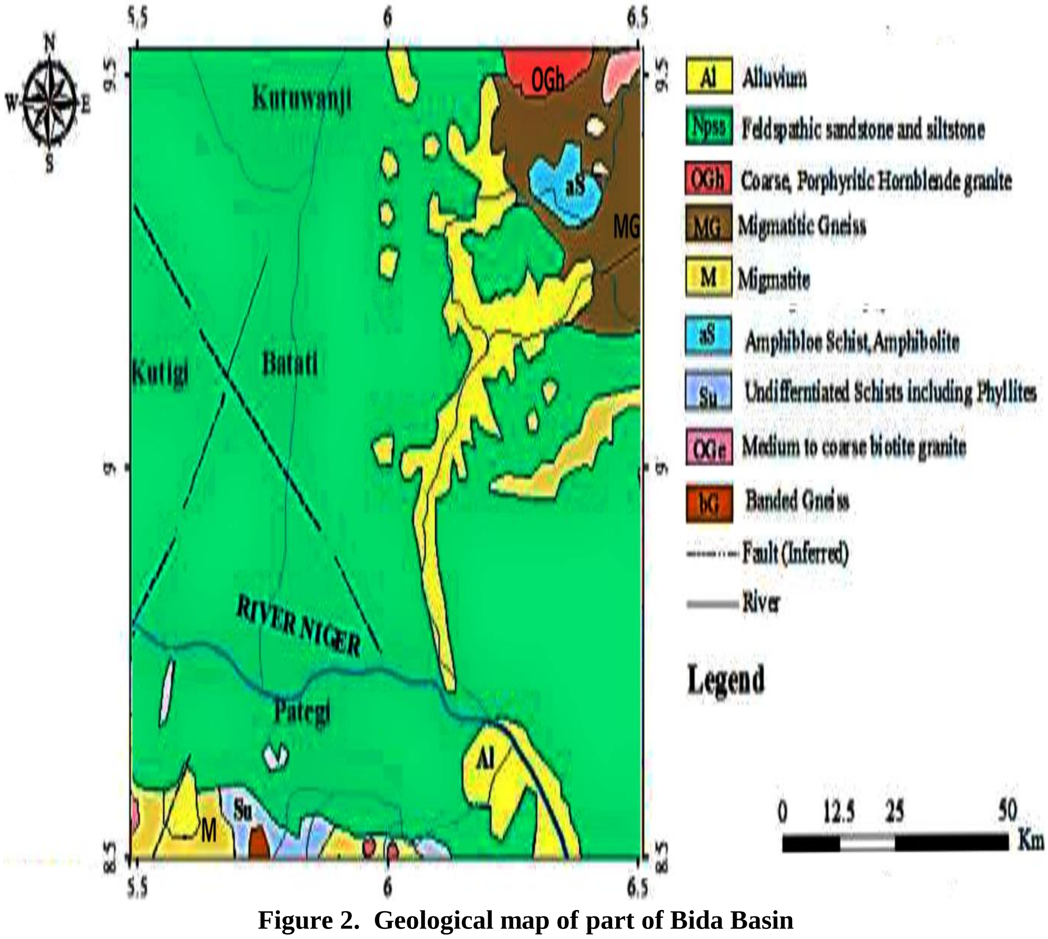

Figure 2. Geological map of part of Bida Basin

failed arm of a triple junction (aulacogen) that existed beneath the present position of the Niger Delta during the Cretaceous times. The trough is filled with over 5,000 m of predominantly Aptian to Maastrichtian sediments in the lower, middle and upper Benue geographical regions.

Data and Methodology

The Four High Resolution Aeromagnetic data sheets used in this study came from the Nigerian Geological Survey Agency and was surveyed in 2009. The survey flight line elevation was above 80km, hence a higher resolution in digital form. The Aeromagnetic sheets are for Pategi, Baro, Bida and Agbaje. Geosoft Oasis-Montaj version 8 was used to filter, process and analyze the potential fields while Surfer 12 software was used to generate the 2D and 3D plots thus enhancing interpretations. Spectral analysis was used to determine the Curie point depth, Curie temperature and heat flow of the study area.

Adopting the method presented by Tanaka et al (1999), the first step is to estimate the depth to the top of the magnetic source (Z_t) which is derived from the slope of high wave number portion of the power spectrum (see Fig. 3 for a sample plot from one of the computed spectra blocks) utilizing the expressions;

$$\boldsymbol{In\left[\Phi_{\Delta T}(|k|)^{1/2}\right] = InB - |k|Z_t} \qquad (1)$$

where, B is a constant and Z_t is the top bound depth.

The depth to centroid (Z_o) of the magnetic source is similarly derived from the slope of the low wave number portion of the spectrum that is given in equation (2);

$$\ln[\Phi_{\Delta T}(|\mathbf{k}|)^{½}] / |\mathbf{k}| = \ln D - |\mathbf{k}| Z_o \qquad (2)$$

where, B and D are sums of constants independent of $|\mathbf{k}|$.

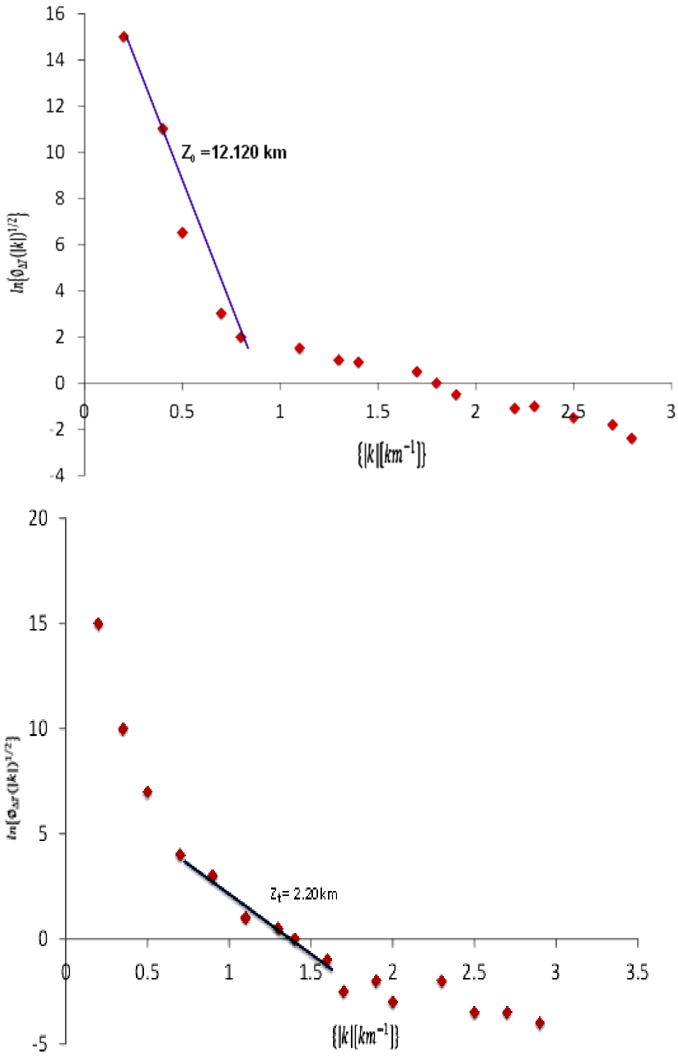

Figure 3. Sample computations of Z_0 and Z_t values from Abgaje.

Therefore from the slopes of power spectrum, the upper bound and centroid of a magnetic body can be estimated. The lower bound (Z_b) of the magnetic source can be derived (Okubo et al 1985; Tanaka *et al* 1999) from;

$$\boldsymbol{Z_b = 2Z_o - Z_t} \qquad (3)$$

Table 1. Estimated Curie Depth Point, Temperature, and Heat Flow.

Location	Spectral Blocks	LONGITUDE (Degrees)		LATITUDE (Degrees)		Estimated Depths (km)			CPD (km)	Geothermal Gradient	Heat Flow (q) (mWm^{-2})
		x_1	x_2	y_1	y_2	D_1	(D_2) Z_t	Z_0	$Z_b = 2Z_o - Z_t$	$\frac{dT}{dz} = 580^oC/z_b$	$\lambda\frac{dT}{dz}$ at $\lambda = 2.5wm^{-1}k^{-1}$
Pategi	A	5.50	5.75	8.50	8.75	0.332	0.742	13.62	26.498	22.888	57.22
	B	5.75	6.00	8.50	8.75	0.724	2.764	14.01	25.256	22.965	57.41
	C	5.75	6.00	8.75	9.00	0.235	3.375	13.97	24.565	23.611	59.02
	D	5.50	5.75	8.75	9.00	0.584	3.974	13.98	23.986	24.181	60.45
Baro	E	6.00	6.25	8.50	8.75	0.575	3.234	13.52	23.806	24.364	60.91
	F	6.25	6.50	8.50	8.75	0.564	2.282	13.75	25.218	22.999	57.50
	G	6.25	6.50	8.75	9.00	0.893	3.864	13.82	23.776	24.394	60.99
	H	6.00	6.25	8.75	9.00	0.697	3.985	13.29	22.595	22.669	56.67
Bida	I	5.50	5.75	9.00	9.25	0.138	3.157	14.67	26.183	22.152	55.38
	J	5.75	6.00	9.00	9.25	0.454	3.256	14.16	25.064	23.141	57.85
	K	5.75	6.00	9.25	9.50	0.873	2.865	14.75	26.635	21.776	54.44
	L	5.50	5.75	9.25	9.50	0.935	2.687	12.35	22.013	26.348	65.87
Agbaje	M	6.00	6.25	9.00	9.25	0.673	3.254	14.98	26.706	21.718	52.67
	N	6.25	6.50	9.00	9.25	0.762	3.693	12.56	21.427	27.069	67.67
	O	6.25	6.50	9.25	9.50	0.524	2.200	12.12	22.040	26.316	65.79
	P	6.00	6.25	9.25	9.50	0.368	2.403	12.53	22.657	25.599	64.00

Where, Z_b is the lower basal depth of the magnetic body. Z_0 is the centriod of the magnetic body and Z_t is the top bound depth of the magnetic body.

Since Z_b is the basal depth of the magnetic body, it suggests that ferromagnetic minerals are converted to paramagnetic minerals at the temperature of approximately 580^0C. Therefore the obtained bottom depth of the magnetic source Z_b, is assumed to be the Curie Point Depth.

In order to relate the Curie point depth (Z_b) to Curie point temperature (580^0C), the vertical direction of temperature variation and the constant thermal gradient were assumed. The geothermal gradient (dT/dz) between the Earth's surface and the Curie point depth (Z_b) can be defined by equation (4) (Maden, 2010).

$$\frac{dT}{dZ} = \frac{580^oC}{Z_b} \qquad (4)$$

Further, the geothermal gradient can be related to the heat flow q by using the formula expressed in equation (5).

$$q = \lambda\left[\frac{dT}{dZ}\right] = \lambda\left[\frac{580^oC}{Z_b}\right] \qquad (5)$$

Where λ is the coefficient of thermal conductivity; from the above equation, the Curie point depth is inversely proportional to heat flow. The heat flow values were determined within the region using the corresponding CPD values and thermal conductivity value of $2.5Wm^{-1}k^{-1}$ for all igneous rocks (see equation (5)). (Hsien-Hsiang et al, 2014).

Results and Discussion

Curie Point Depth is greatly dependent upon geological conditions. CPD are shallower than 10km for volcanic and geothermal fields, between 15km - 25km for island arcs and ridges and deeper than 20km in fairly level high ground and long narrow ditch (Tanaka et al., 1999). Generally, the units that comprise high heat flow values correspond to volcanic and metamorphic regions since these two units have high heat conductivities. Additionally, tectonically active regions affect the curie depth and heat flow.

According to Jessop et al., 1976, the average heat flow in thermally "normal" continental regions is around $60mWm^{-2}$, values in excess of about $80mWm^{-2}$ - $100mWm^{-2}$ indicate anomalous geothermal conditions. Accordingly, seven prospects with heat flow values of $60.45mWm^{-2}$, $60.91mWm^{-2}$, $60.99mWm^{-2}$, $65.87mWm^{-2}$, $67.67mWm^{-2}$, $65.79mWm^{-2}$ and $64.00mWm^{-2}$ are recommended for further geothermal exploration (Table 1). Geothermal gradients in these areas may provide good source(s) of geothermal energy, with their curie temperatures greater than or equal to 24^oC being reached at depths of greater than 2km.

From the derived table (table1), the depth to the centroid (Z_o) ranges from 12.12km – 14.98km. The equivalent Curie point depth ranges from 21.427km to 26.706km. Low Curie point depths observed in the study area are areas possibly mixed with both basement and sedimentary rocks (figs 4 and 5). The obtained Curie point depth reflects the average local curie depth point values of 24.276km across the study area. Heat flow values for the study area ranges from $52.67mWm^{-2}$ to $67.67mWm^{-2}$.

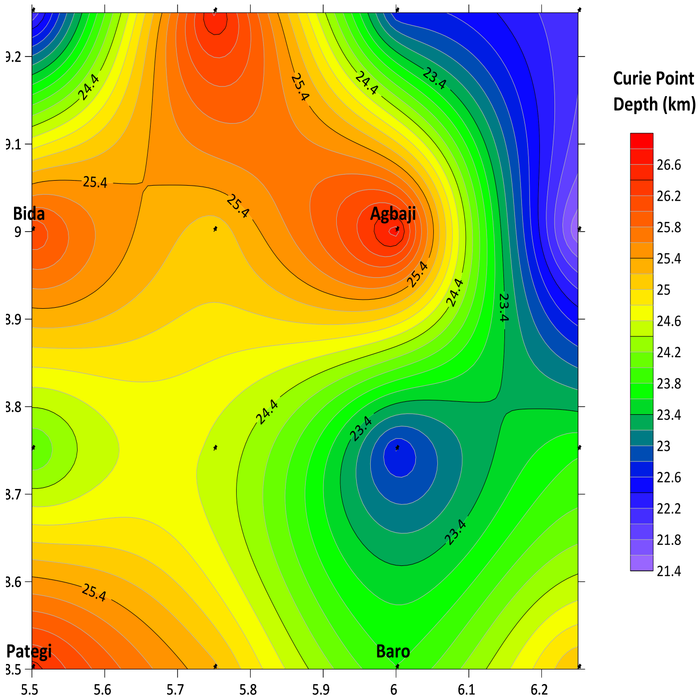

Figure 4. Map showing the Curie point depth of Study Area.

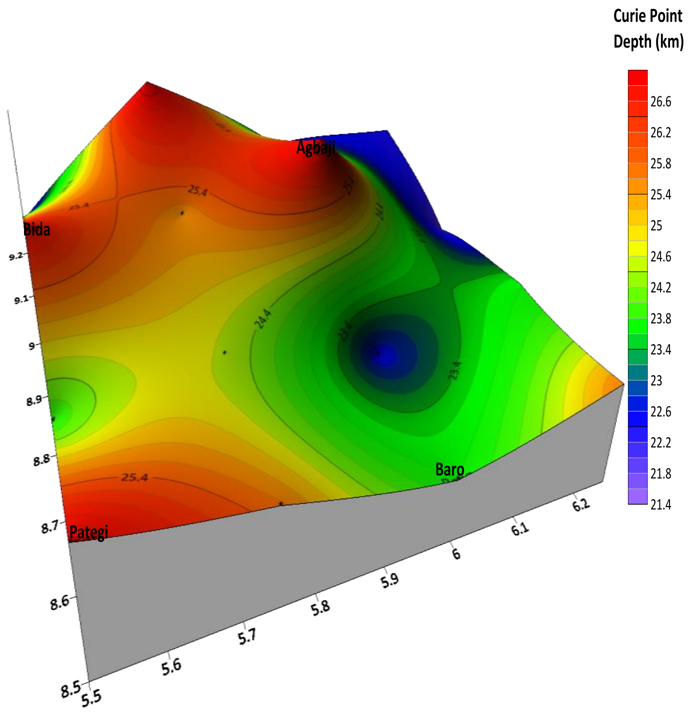

Figure 5. 3D Map showing the Curie point depth of Study Area.

The result so obtained above supports the conclusion that Curie depth is shallower where the heat flow is high. In view of this, the area of shallow Curie point depth of 21.427km has a geothermal potential which can be utilized. The geothermal gradient map (fig. 6) defines region of high geothermal gradient to be south – eastern (SE) part and low geothermal gradient to run from north eastern (NE-SW) part of the study area. The heat flow values here did not exceed $100mWm^{-2}$. This indicates that there is no anomalous geothermal condition in the study area. The low Curie point depth areas show high geothermal heat flow values.

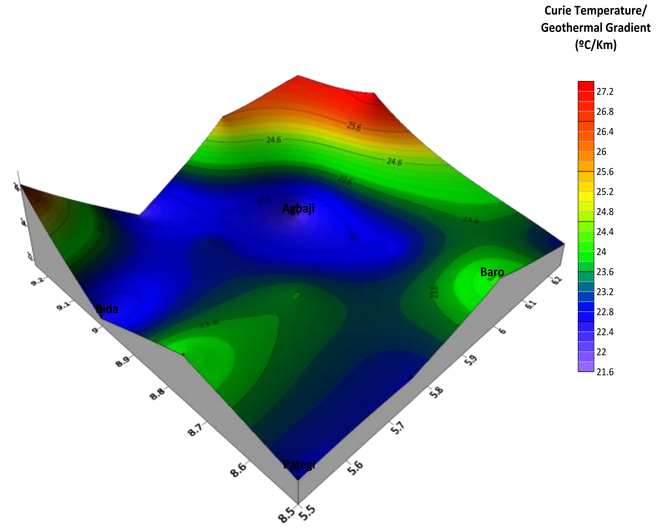

Figure 6. 3D Map of Geothermal gradient of the study area.

The high heat flow at low Curie point depth shows that the mantle is close to the surface where the basement complex is found. Therefore, the geothermal heat source is close to the surface. Jessop *et al.*, (1976) carried out the standard geothermal heat flow values of all regions and maintained that 60mWm^{-2} to 100mWm^{-2} are considered to be prospective heat flow values.

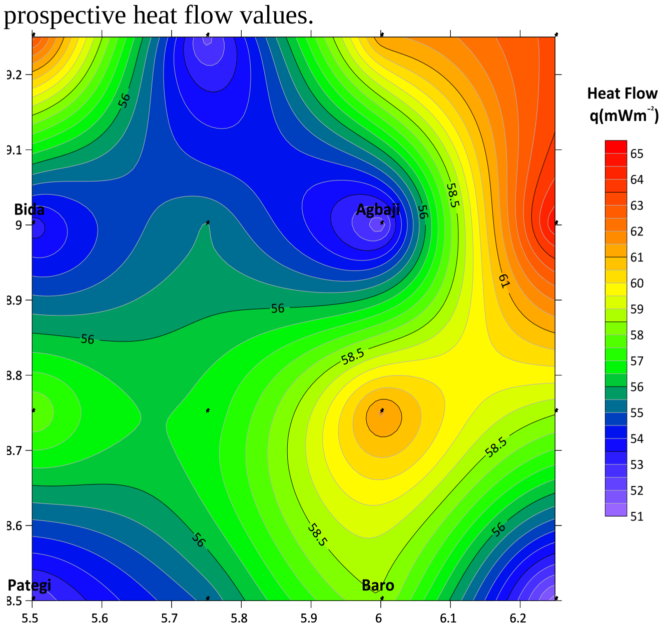

Figure 7. Map showing Heat flow of the Study area.

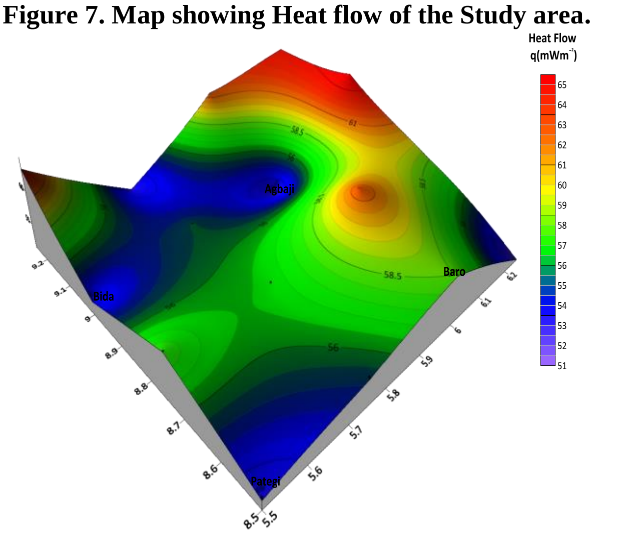

Figure 8. 3D Map of Heat flow within the Study area.

In most part of the study area, heat flows were found to be less than 60mWm^{-2}, this implies that the heat flows in the study area are not uniform, which possibly indicate that the magma conduits were randomly distributed.

Geothermal energy can occur in areas where basement rocks that have relatively normal heat flow are covered by thick blanket of thermally insulated sediments. It can be inferred that the geothermal prospect areas in this study may be areas where thick layer of thermally insulated sediments cover basement rocks since there is no evidence of volcanic activities in the study area, therefore, these areas of high heat flow (Figs. 7 & 8) could be geothermal sources and reservoirs and will be of help in identifying the existence of productive reservoirs at attractive temperature and depth in Bida Basin.

Nwankwo and Ekine, (2010), revealed that sediments with relatively high geothermal gradients mature earlier (low oil window) than those with low gradient values. Thus, under normal circumstances a high geothermal gradient enhances the early formation of oil at relatively shallow burial depths, but it causes the depth range of oil window to be quite narrow, while low geothermal gradient causes the first formation of oil to begin at fairly deep subsurface levels, but makes the oil window to be quite broad.

Conclusion

The Spectral analysis method was used here to determine the CPD, Curie temperature and Heat Flow of the study area. Heat flow estimates on the study area were made using the Curie point depths and geothermal gradient information, taking thermal conductivity coefficient value of 2.5Wm^{-1}k^{-1} into consideration. Seven prospects at Pategi, Baro, Bida and Agbaje with heat flow values of 60.45mWm^{-2}, 60.91mWm^{-2}, 60.99mWm^{-2}, 65.87mWm^{-2}, 67.67mWm^{-2}, 65.79mWm^{-2}, and 64.00mWm^{-2} are recommended for further geothermal exploration because heat flow value here did not exceed 100mWm^{-2}. This shows that there is anomalous heat flow in the study area.

The central part of the study area to its south – eastern part (e.g Agbaje) is the most advisable area to undertake Geothermal exploration owning to their high heat flow values.

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