INVESTIGATION OF THE GEOTHERMAL POTENTIAL WITHIN BENUE STATE, CENTRAL NIGERIA, FROM RADIOMETRIC AND HIGH RESOLUTION AEROMAGNETIC DATA

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ABSTRACT

The study focuses on the analysis of high resolution Aeromagnetic data for the estimation of geothermal potential within the eastern part of Lower Benue Basin and correlating the results from the analysis of radiometric concentration data of the study area. The study area covers a total area of 18,150 km^2, six aeromagnetic sheets cover the area, major towns are Markudi, Gboko,Otukpo, Agena, Akwana and Katsina-Ala, it is bounded by latitude 7.00^0 and 8.00^0 and longitude 8.00^0 and 9.50^0. The aeromagnetic data was subjected to Fourier analysis and then spectral analysis of 12 sub sections was carried out. From the spectral analysis, the depth to the top of magnetic sources varies from 0.28 Km to 0.36 Km while the depth to the bottom of magnetic sources varies from 5.52 Km to 9.63 Km. The modified Curie depth method was employed in evaluating the Curie point depth, heat flow and geothermal gradient were also obtained. The region found to have a shallow Curie depth of 9 km at the south-western and south-eastern part of the study area has an average geothermal heat flow 103.98 Wm^{-2}. The geothermal gradient also has a value of 62°C/km and 30°C/km respectively with an average value of 41.59 ^{o}C/km, anomalous high heat flow of 153.35, and 135.62 Wm^{-2} was obtained within around Katsina- Ala and Oturkpo respectively. Correlating this result with the analysis of the radiometric values covering the study area, the ternary map shows that potassium and thorium radioactive content is noticeably high within these areas where relatively high heat flow values were obtained, The radioactive heat production within the two exothermally active areas was estimated to be1.47 µW/m^{3}and 2.21 µW/m^3 respectively this can be associated with the occurrence of these elements.

Key words: *Geothermal potential. Heat flow, Ternary map*

1. Introduction

The reliability of geothermal energy source and its efficiency in the generation of electricity cannot be overemphasised, generally the knowledge of the geothermal gradient of an area helps in determining the suitability of such location for sitting geothermal plants for the generation of electricity that can be utilised for industrial, domestic and recreational activities (Adedapo et al., 2013).

Among all other sources, the earth's heat is believed to have being derived from the decay of radioactive isotopes of uranium, thorium, potassium elements, as well as heat released from the electromagnetic effects of the earth's magnetic field and heat released during tidal force on the earth as it spins along its axis and rotates since the land cannot flow like water, it compresses and distorts thereby generates heat (Adedapo et al., 2013).

The study of subsurface temperature, geothermal gradients and heat flow in association to the Curie-Point Depth (CPD) is crucial in understanding the thermal maturation of sediments and the past thermal regimes in a basin. Measurements have shown that a region with significant geothermal energy is characterised by an anomalous high temperature gradient and heat flow (Tselentis et al., 1991).

The Depth to Bottom Magnetic Source (DBMS) or Curie Point Depth (CPD) 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 (where the magnetisation is lost) (Nagata, 1961: Ofor and Udensi, 2014). It is therefore expected that geothermically active areas would be associated with shallow Curie point depth (Nuri et al., 2005)

The DBMS values may also be controlled by major lineaments and faulting, sub-crustal reworking, plume activities and the plate motion causing Himalayan orogeny (Bansal et al., 2013).

Geophysical survey is more appreciated when two or more geophysical methods are employed, therefore this research also undertook a further qualitative analysis of radiometric data over the study area of concentrations of Uranium, Thorium and Potassium with high heat flow and geothermal gradients to correlate and complement the result obtained from the analysis of Aeromagnetic data.

In thermally normal continental regions, the average heat flow is about 60mWm^{-2}. Values between 80-100 mWm^{-2}are good geothermal source, while values greater than 100m Wm^{-2}indicate anomalous conditions (Cull and conley, 1983; Jessop *et al*., 1976)

Location of the study area

The study area covers the eastern part of lower Benue trough, it is bounded by latitude 7.00^0 and 8.00^0 and longitude 8.00^0 and 9.50^0 (figure 1.0) and six HR aeromagnetic map sheets number 250, 251, 252, 270, 271 and 272, with a total area of 18,150 km^2 , cover part of Markudi, Gboko, Otukpo Agena, Akwana, and Katsina-Ala. The physiological features recognized in the area is the river Benue running over the upper part of the study area. The major factor that influenced the choice of the location for the research was the sitting of Akiri warm spring 43^{0}C arround the Benue Trough and Ruwan Zafi spring 54^{0}C at the Nothern part of Benue Trough.

Brief geology of the study area

The geology map of the study area Figure 1 shows that the western part of the study area host Sedimentary formation of middle Eocene age (sandstone, clay and limestone) and the eastern part host the undifferentiated old biotite granites.

Benue trough is known to be major structural feature in the Eastern part of Nigeria and an important element in the tectonic framework of Africa and the entire Benue Trough is believed to have evolved as a result of the continental separation of Africa and South America (King, 1950), and is variously described as a rift system (Cratchley and Jone,1965), an extensional graben system (Stoneley,1966;wright,1968), a third failed arm or anaulacogen of a three-armed rift system related to the development of domes associated with hotspots (Burke,1976;Olade, 1978).

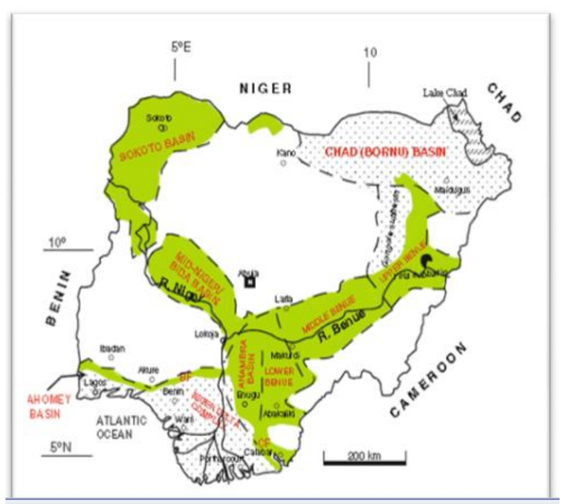

Figure 1: Geology map of Nigeria showing the location of Benue Trough (NGSA)

Sedimentation in the Lower Benue Trough commenced with the marine Albian Asu River Group, although some pyroclastics of Aptian – Early Albian ages have been sparingly reported (Ojoh, 1992). The marine Cenomanian – Turonian Nkalagu Formation (black shales, limestones and siltsones) and the interfingering regressive sandstones of the Agalaand Agbani Formations rest on the Asu River Group. Mid-Santonian deformation in the Benue Trough displaced the major depositional axis westward which led to the formation of the Anambra Basin. Post-deformational sedimentation in the Lower Benue Trough, therefore, constitutes the Anambra Basin. Rock type at the Eastern portion of the study area is identified as undifferentiated Older granite, mainly porphyriticgranitized gneiss with porphyroblasticgranite (Figure 2). Rock type at the western portion is identified as Gwandu formation of middle Eocene age of (sandstone, clay and limestone) on the Asu group are the lithologic units at the surface within the sedimentary basin. River Alluvium depositionidentified along the river channel.

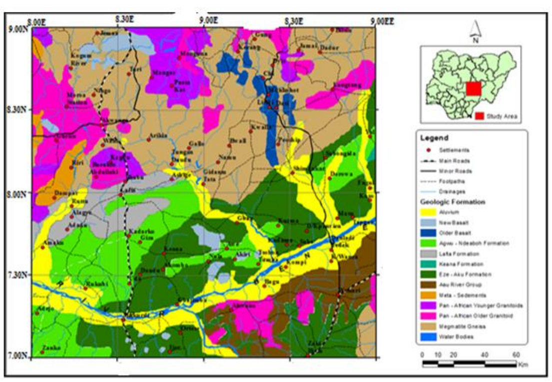

Figure 2, A simplified Geology map of the Study Area

2, Methods

The calculation of DBMS in this study is based on statistical methods of depth determination from the radial power spectrum of the magnetic field (Spector and Grant, 1970; Bhattacharryya and Leu, 1975; Okubo et al., 1985, Blakely, 1995; Tanaka and Matlsubayashi, 1999; Ross *et al.*, 2006; Trifonoya *et al*.,2009; *Bensal et al.*,2011; Bensal et al.,2013). These approaches assumed a random uniform uncorrelated distribution of sources. The power spectrum, P, for a 2D assemblage of bodies can be written as follow (Spector and Grant,1970; Blakely,1995).

$$P(K_X K_Y) = 4\pi^2 C^2 \lfloor\theta_m\rfloor^2 \lfloor\theta_f\rfloor^2 e^{-\left(1-e^{-\lfloor K\rfloor(Z_B-Z_t)}\right)1^2} \quad (1)$$

Here, $k_x$and $k_y$are the wave numbers in the x- and y-directions;$C_m$is a constant of proportionality; $\theta_m$is the power spectrum of the magnetization; $\theta_m$and $\theta_f$are the directional factors related to the magnetisation and geomagnetic field respectively; and $Z_t$and $Z_b$are the top and bottom depths of the magnetic sources. After annual averaging, Eq. (1) can be written as

$$P|k| = A_1 e^{-2|k|Z_t}(1 - e^{-|k|(Z_b-Z_t)})^2 \quad (2)$$

Where A_1 is a constant, k is the wave number and $P|k|$ power spectral density Equation (2) can be simplified to compute the centroid depth $Z_0$of the magnetic source from the low-wave number part of the power spectrum as follows:

The centroid depth is calculated from the low wave number part of the scaled power spectrum as

$$ln\left(P(K)^{\frac{1}{2}}/K\right) = \lfloor K\rfloor Z_0 \quad (3)$$

Where *ln* is the natural logarithm, P(k) is the radially average power spectrum, k is the wavenumber (2π/km). A is a constant depending on the properties of magnetization and its orientation and Z_0 is the centroid depth of the magnetic sources (Tanaka and Matsubayashi, 1999). For the high wave number part, the lower spectrum can be related to the top of magnetic sources by a similar equation:

$$ln\left(P(K)^{\frac{1}{2}}/K\right) = \lfloor K \rfloor Z_1 \quad (4)$$

Where B is a constant: Z_1 is the depth to the top of the magnetic sources. The depth of the bottom of magnetisation Z_b is:

$$Z_b = 2Z_0 - Z_t. \quad (5)$$

Summarily, the depth to the base of the magnetic source (i.e. the Curie point depth) is calculated in four steps (Tanaka and Matsubayashi, 1999) as follows:

Step 1: Calculate the radially averaged power spectrum of the magnetic data in each window;

Step 2: Estimate the depth to the top of the magnetic source (Z_t) using the high wave number portion of the magnetic anomaly power spectra;

Step 3: Estimate the depth to the centroid of the magnetic source ((Z_o) using a lower wave number portion of the magnetic anomaly power spectra; and,

Step 4: Calculate the depth to the base of the magnetic source (Z_b) using $Z_b = 2Z_0 - Z_t$. The value of $Z_b$is the Curie point depth/DBMS.

Also the heat flow of the study area which has an assumption that the direction of the temperature variation is vertical and the temperature gradient ${dT}/{dz}$is constant; Fourier's law takes the form:

$$q = -k\, {dT}/{dz} \quad (6)$$

where, q is heat flow and k is thermal conductivity.

The Curie temperatureθ°Ccan also be defined as:

$$\theta°\mathrm{C} = \left({dT}/{dz}\right)d \quad (7)$$

Where, d is the curie-point depth (as obtained from the spectral magnetic analysis). Therefore the Geothermal gradient in the relation to the heat flow q. Tanaka *et al* 1999):

$$q = k\, {\theta°\mathrm{C}}/{d} \quad (8)$$

Geothermal gradient ($\frac{\nabla T}{\nabla Z}$) of the study area was further estimated using curie point temperature of 580°C and thermal conductivity of 2.5$Wm^{-1}°C^{-1}$ which is the average thermal conductivity for igneous rocks is used in the study as standard (Nwankwo et al.,2009).

However, using an average thermal conductivity, value of 2.5$Wm^{-1}°C^{-1}$ (Nwankwo *et al*,. 2011; Tanaka *et al*,.1999), we then calculate the value for $\frac{\nabla T}{\nabla Z}$ geothermal gradient in the study area using the empirical relation between, curie depth Temperature and depth as shown in (equation 9).

$$\frac{\nabla T}{\nabla Z} = {580°\mathrm{C}}/{d} \quad (9)$$

Radiometric data processing

The Terrestrial radiation is mostly produced by the decay of the three natural radio isotopes ^{232}Th, ^{238}U and ^{40}K.

As radioactive decay is a random process, smoothing was carried out on the data to remove the noise, and the accuracy of all measurements and estimation was governed by statistical laws. The profiles of counting rates are noisy and the data cannot be contoured until they have been smoothened.

Correction for variation in attitude, atmospheric radon and cosmic radiation are made on the data, the data is then processed to produce results which are expressed as concentration of ^{232}Th, ^{238}U and ^{40}K. This is based on calibration data collected over source of known ground concentration and radiation levels (Coetzee,2008).

The Radiometric heat analysis according to Salem and Fairhead indicates that, radiometric heat production (H) is related to the decay of primarily, the radioactive isotopes ^{232}Th, ^{238}U and ^{40}K and can be estimated based on the concentration (C) of the respective elements through the expression;

$$H(\mu W/m^3) = P(9.52C_u + 2.56\ C_{Th} + 3.48C_K)\ 10^{-5} \qquad (10)$$

Where;

H = radioactive heat production

P = density of rock adapted from (Telford *et al.*, 1990), C_U, C_{Th}, C_K are concentrations of uranium, thorium and potassium respectively.

The concentration of the three radiometric elements is read from the radiometric map covering the study area with high geothermal gradient.

3. Analysis and Interpretation

The Total Magnetic Intensity (TMI) map of the study area as shown in figure 3 indicate regions of high (H) and low (L) with a magnetic intensity values ranging from -691.5nT to 614.6 nT respectively. The high magnetic anomalies trends from the north-eastern to the south-western part of study area, also the low magnetic anomalies were found south, north-eastern part and edge of south-western part of the study area.

The high magnetic anomalies might be as a result of basement intrusion into the sedimentary while low magnetic anomalies are associated with the thick sedimentation.

The High resolution aeromagnetic (HRAM) data was interpreted quantitatively by subjecting it to fourier and Spectral depth analysis with the aim of determining the depth to basement as well as the basement morphology. The TMI was windowed into twelve overlapping windows or sub-sheets. Upon each of the windows Fast Fourier Transform (FFT) and subsequently spectral depth analysis was undertaken this art decomposed the anomalies into its energy and wave number components. Thereafter a plot involving Energy versus wave number in cycle/km was made. A straight line is then manually fit to the energy spectrum both in the higher and lower portion (figure 4).

Basically, two depth source models; H_1 and H_2 were revealed and further estimation of heat flow, geothermal gradient and curie depth were carryout using equations 5, 8 and 9. The depth to the deeper magnetic bodies (H_1) figure 5, varies between 5.52 km and 9.63 km but with an average value of about 7.42km while the depth due to the shallow causative magnetic sources (H_2) figure 6 varies between 0.28 km and 0.36 km but with an average depth value of 0.31 km (Table 1).

The Curie point depth of the study area figure 7 shows that the depth varies from 9 km to 18.6 km from south to the south-eastern part. The most pronounced high Curie depths were found at lower edge of Gboko with an approximate depth 18.6 km.

Also, two Shallow curie-point depths were observed at the South-eastern part (Katsina-Ala) and South-western part (Oturkpo) of the study area with a depth of 9.0 km and 10.2 km respectively, which may be due to the some intriguing techno-thermal effect related to a combination of subsidence, uplift, faulting, compression and volcanism Bansal *et al.*, 2013

The heat flow, figure 8 is observed to have value range from 75 mWm^{-2} to 153.35 mWm^{-2} with an average value of 103.98 Wm^{-2}. Anomalous heat flow (153.36, 135.61mWm^{-2}) observed both south-eastern (Katsina-Ala) and lower edge south-western (Oturkpo) were within the igneous rock that outcrop in the area, located within shallow Curie depths The lowest Heat flow value were observed at the lower edge of Gboko and Makurdi value at 75 mWm^{-2} The geothermal gradient result

Figure 9 has a range of 30^{0}C/km to 61^{0}C/km with an average value of 41.59 ^{0}C/km. High values of geothermal gradients were recorded at the extreme edge of south-eastern part and lower edge of south-western part of the study.

Figure 3, TMI map with the area location within the study area with IGRF of 33000 nT removed from the field values

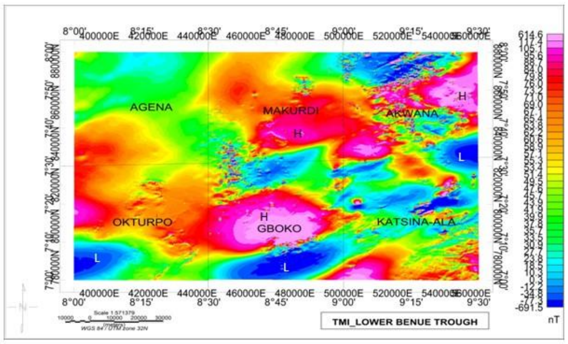

Figure 3, TMI map with area Location

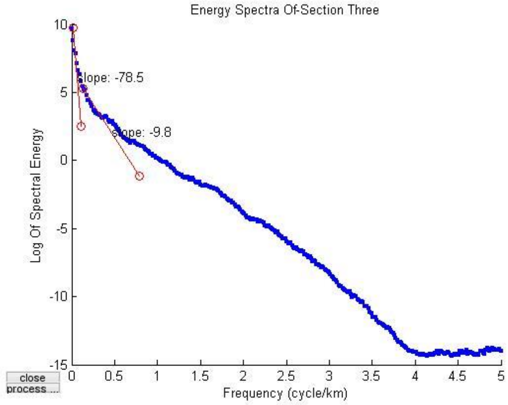

Figure 4. The plot of the log of spectral energy against frequency

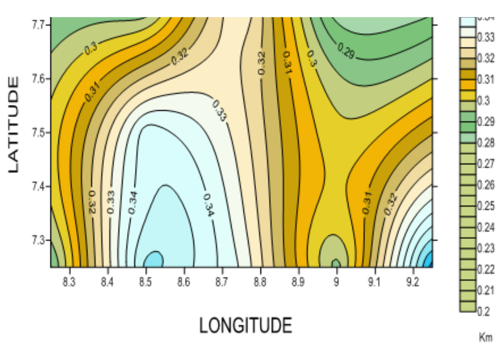

Figure 5. Shallow depths contour map of the study area

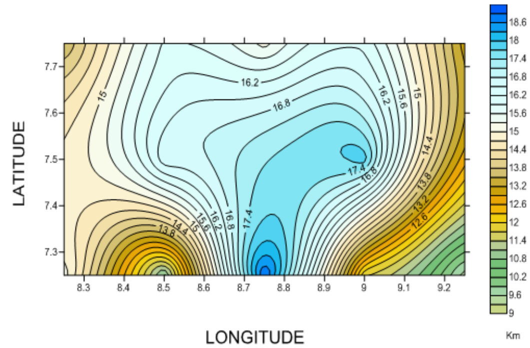

Figure 6, The Currie Point Depth contour map of the study area

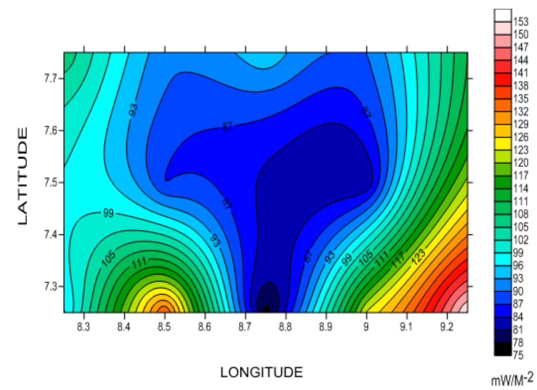

Figure 7. The Heat Flow contour map of the study area

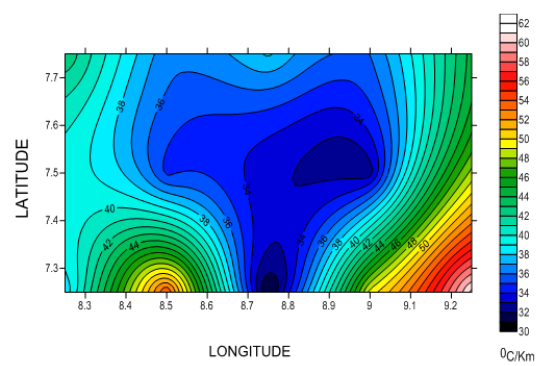

Figure 8, The geothermal gradient contour map of the study area

SECT N	LAT (°N)	LONG (°E)	GRADIENT (D1)	DEPTH H1 (Km)	GRADIENT (D2)	DEPTH H2 (Km)	CURIE-POINT (Km)	GEOTHER GRADI (^{0}C/km)	HEAT FLOW (mW/m^2)
1	7.25	8.25	97.00	7.718	3.64	0.290	15.146	38.293	95.732
2	7.25	8.75	121.00	9.628	4.20	0.334	18.921	30.654	76.634
3	7.25	9.25	61.70	4.909	4.56	0.363	9.456	61.338	153.346
4	7.75	8.25	86.80	6.906	3.63	0.289	13.524	42.887	107.217
5	7.75	8.75	97.50	7.758	4.15	0.330	15.185	38.195	95.487
6	7.75	9.25	83.80	6.668	3.54	0.283	13.054	44.432	111.079
7	7.25	8.50	69.40	5.522	4.42	0.352	10.692	54.245	135.612
8	7.25	9.00	75.60	6.015	3.68	0.293	11.738	49.413	123.533
9	7.75	8.50	102.00	8.116	3.60	0.286	15.945	36.375	90.936
10	7.75	9.00	103.00	8.195	3.50	0.278	16.112	35.997	89.993
11	7.50	8.50	107.00	8.514	4.31	0.343	16.684	34.763	86.907
12	7.50	9.00	114.00	10.567	18.50	2.944	18.189	31.887	79.718

The correlation of Ternary count map and geothermal gradient

The ternary map of the study area Figure 10 which is obtained by combining the potassium, thorium and uranium concentration of the area, concentration of each element is shown in distinct colour aggregate with potassium as red thorium as blue and uranium as green, value of concentration of each element (in Emu) are shown on the legend. The potassium concentration is high at the south-eastern part (Katsina-Ala) of the area which hosts undifferentiated old biotite-granites and a pronounced Thorium concentration at the western edge of Oturkpo which host the Emu formation (sandstone, clay and limestone) of Asu group, the ternary map shows relatively high concentration of potassium and Thorium, which indicate that the source of high geothermal values in this region could be traced to the contents of the geological structures.

From the concentration of each of these radioactive elements in the two geothermal active areas, Katsina-Ala and Oturkpo, the estimated radioactive heat production calculated using equation 10 are 1.47 $\mu W/m^3$ and 2.21 $\mu W/m^3$ respectively.

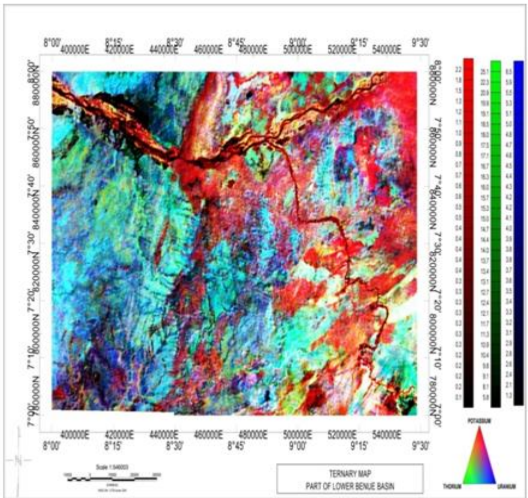

Figure 10, The Ternary count map of the study area

4. Conclusion

The spectral analysis of the aeromagnetic data shows that depth to the deeper magnetic bodies (H_1) varies between 5.52 km and 9.63 km with an average depth value of about 7.42 km, while the depth due to the shallow causative magnetic sources (H_2) Figure 6 varies between 0.28 km and 0.36 km with an average depth value of 0.31 km. The Curie-point depth varies from 9 km to a shallow depth of 19.5 km, shallowest curie depths values were recorded at the south-western part, around Oturkpo and south-eastern part of Katsina-Ala of the study area.

The Heat Flow value ranges from 75 mWm^{-2} to 153.35 mWm^{-2}with an average value of 103.98 Wm^{-2}. Anomalous Heat flows with values from 135.61 to 153.36 mWm-2 were observed at the south-eastern part around Katsina-Ala and the south-western part within Oturkpo, where igneous rocks outcrop in the area. The lowest Heat flow value was observed at the lower edge of Gboko and Makurdi with value around 75 mWm^{-2}. The geothermal gradient result has a range of 30^{o}C/km to 61 ^{o}C/km with an average value of 41.59 ^{o}C/km. High values of geothermal gradients were recorded at the extreme edge of south-eastern part and the lower edge of south-western part of the study area with values of 62 ^{o}C/km and 54 ^{o}C/km respectively. The Lowest geothermal gradients were observed at lower edge of Gboko at 30 ^{o}C/km and Makurdi at 34 ^{o}C/km

The ternary count map of the study area which shows a distinct concentration of potassium content at the eastern part and thorium content at western part of the study area with a striking correlation between the region where the high geothermal gradient were observed and where the potassium concentration is high at the south-eastern part (Akwana and Katsina-Ala) of the area which host undifferentiated old biotite granites and a pronounced Thorium concentration at the western edge (Agena and Oturkpo) of the study area which host Emu formation (sandstone, clay, gravel and limestone) of western Nigeria.

Therefore the south-eastern part (Katsina-Ala) and lower edge of the south-western part (Oturkpo) of the study area could be a viable site for geothermal exploration. The radioactive heat production in these two areas was estimated to be 1.47 μW/m^{3}and 2.21 μW/m^3 respectively.

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