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Spectral Analysis Aimed at Delineating the Curie Point Depth and Geothermal Potentials in Parts of Lower Benue Trough

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ABSTRACT
The need to increase power generation in Nigeria necessitates the quest for alternative sources of energy which are green, renewable and durable at large. Our aim in this research is to explore zones with geothermal prospects so as to alleviate the nations dwindling hydrocarbon dependence. This research utilized the aeromagnetic technique to investigate the subsurface properties in parts the lower Benue Trough with respect to its sediments, basement rocks and geothermal potentials. Twelve sheets of the aeromagnetic data were used covering Nsukka, Igumale, Ejekwe, Ogoja, Udi, Nkalagu, Abakaliki, Bansha, Okigwe, Afikpo, Ugep, and Ikom areas. These Twelve data sheets covered areas within latitude 5˚30´N to 7˚00´N and longitude 7˚00´E to 9˚00´E. Composite aeromagnetic data was merged to produce a merged map for the study area using Oasis Montaj8.3. The Total Magnetic Intensity (TMI) of the study area depicted intensities ranging from – 47.2 nT to 143.1 nT on merging. This was followed by spectral analysis to generate spectral depths of the deeper and shallow sources from which we calculated the Curie point depth and other geothermal parameters. Spectral analysis results show that the deep depths and shallow depths of the suspected magnetic bodies have an averavge value of 7,035 m and 350 m respectively. Curie depths show that the magnetic rock materials in the study area lose their magnetism due to temperature increase at depths between 4 km to 21 km which suggests that the source of the magnetic anomaly in those areas are highly magnetic. The geothermal gradient of the study area ranges from 25 $^0Ckm^{-1}$ to 125 $^oCkm^{-1}$ while the heat flow of the study area range from 80 mWm^{-2} to 365 mWm^{-2} which suggests that the study area is a good source of geothermal energy with areas like Okoroba and Okorroba showing the highest potential.

Keywords:
Total Magnetic Intensity,
Aeromagnetic Data,
Geothermal Gradient,
Curie Depth,
Heat flow.

INTRODUCTION

Nigeria's rapid population growth and industrial development have resulted in a continuously rising demand for electricity. Despite being Africa's largest oil producer, the country continues to experience chronic shortfalls in power generation and distribution, largely due to its heavy dependence on hydrocarbons for energy supply. This reliance not only exposes the economy to fluctuations in global oil prices but also limits the diversification of Nigeria's energy portfolio. Consequently, there is a pressing need to explore sustainable and renewable alternatives that are environmentally friendly, durable, and capable of meeting long-term energy needs (Ijeh et al., 2024). Geothermal energy represents one of the most promising green energy resources because it is clean, renewable, and relatively stable compared to solar and wind, which are affected by weather and seasonal variability. Across Africa, studies have highlighted the geothermal potential of rift systems and intracontinental basins, where crustal thinning, magmatism, and tectonism enhance heat flow (Ezeh et al., 2022). The Benue Trough of Nigeria, a major intracontinental rift basin, stands out as a particularly significant province due to its thick Cretaceous–Tertiary sedimentary fill, abundant intrusive bodies, and complex tectonic framework. These geological characteristics strongly influence its subsurface heat distribution and suggest potential for geothermal resource development (Chukwuemeka et al., 2023). Aeromagnetic methods have long been employed in subsurface exploration because they provide a cost-effective means of delineating crustal structures, basement morphology, and intrusive bodies. In geothermal studies, they are particularly useful because spectral analysis of aeromagnetic data allows the estimation of Curie point depth, from which geothermal gradients and heat flow can be derived (Ijeh et al., 2024). Previous aeromagnetic studies in the Lower Benue Trough have revealed variable basement depths, shallow intrusive features, and significant thermal anomalies, supporting the idea that the basin hosts viable geothermal prospects (Abdullahi & Idi, 2022). Despite these indications, systematic geothermal investigations in the southern and lower segments of the Benue Trough remain limited. This gap is notable given the tectono-magmatic history of the region, which includes Santonian compressional folding, extensive Cretaceous intrusions, and the development of anticlines and synclines that may serve as structural traps for both heat and fluids (Onu, 2017). Identifying and characterizing zones of anomalous heat flow in this part of the basin is therefore critical for reducing Nigeria's dependence on hydrocarbons and supporting a transition to a diversified energy future. The present study addresses this gap by employing high-resolution aeromagnetic data to investigate the subsurface characteristics of parts of the Lower Benue Trough. Twelve aeromagnetic sheets covering Nsukka, Igumale, Ejekwe, Ogoja, Udi, Nkalagu, Abakaliki, Bansha, Okigwe, Afikpo, Ugep, and Ikom were merged and analyzed. Spectral analysis was used to estimate the depths of shallow and deep magnetic sources, Curie point depths, geothermal gradients, and heat flow distribution across the study area. This work provides a contribution to the growing body of knowledge on geothermal energy resources in Nigeria and highlights the potential of the Lower Benue Trough as a viable green energy province.

Location and Geology of the Study Area

The study covers parts of the southeastern part of Nigeria. It lies between latitude 5˚30´N to 7˚00´N and longitude 7˚00´E to 9˚00´E. It covers a total surface area of about 12,100 square kilometers, and is within the Lower Benue Trough. Figure 1 shows the major locations within the study area. The Lower Benue Trough in which the study area falls into is a subdivision of the Benue Trough which is classified as a Sedimentary Basin. The Benue Trough is characterized by sediments within the age of Cretaceous to Tertiary, these sediments before the mid-Santonian age experienced compressional folds, uplifts and faults due to tectonic activities and this accounts for over one hundred anticlines and synclines. The Abakaliki anticlinorium and the Afikpo syncline in the Lower Benue Trough, the Lamurde anticline and Dadiya syncline in the Upper Benue Trough, the Giza anticline and the Obi syncline in the Middle Benue Trough all resulted from such deformation (Obaje, 2009).

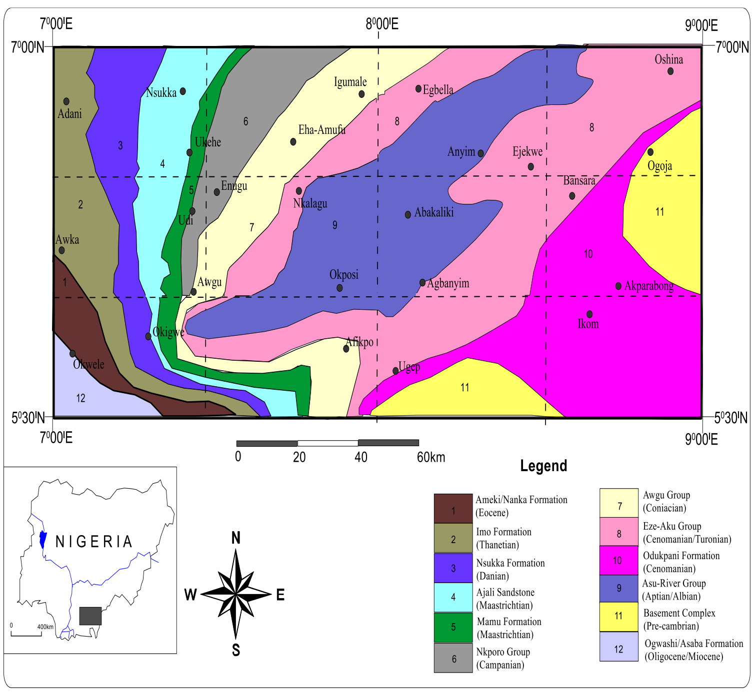

Figure 1: Geology map of the lower Benue Trough showing location of the study area (redrawn after Reyment, 1965)

MATERIALS AND METHODS

Twelve sheets of aeromagnetic data over Nsukka area, Igumale area, Ejekwe area, Ogoja area, Udi area,Nkalagu area, Abakaliki area, Bansha area, Okigwe area, Afikpo area, Ugep area, and Ikom area were obtained from the Nigerian Geological Survey Agency, NGSA. The Twelve maps covered areas with latitude 5˚30´N to 7˚00´N and longitude 7˚00´E to 9˚00´E, the data was acquired from the survey carried out in different phases between 2005 and 2010 by FUGRO Airborne Survey for the Nigerian Geological Survey Agency, NGSA. The data was acquired at a flight altitude of 80meters above ground surface, at a tie line spacing of 2000meters and at a flight line spacing of 500meters. The data was made available as XML file (Extensible Marked Language) and as a Merged Total Magnetic Intensity image map as shown in Figures 2 and Table 1.

Table 1: Details on the Twelve Sheets of Aeromagnetic Data Used

Sheet number	Area	latitude	Longitude	Scale
287	Nsukka	6˚30´N to 7˚00´N	7˚00´E to 7˚30´E	1:500000
288	Igumale	6˚30´N to 7˚00´N	7˚30´E to 8˚00´E	1:100000
289	Ejekwe	6˚30´N to 7˚00´N	8˚00´E to 8˚30´E	1:500000
290	Ogoja	6˚30´N to 7˚00´N	8˚30´E to 9˚00´E	1:100000
301	Udi	6˚00´N to 6˚30´N	7˚00´E to 7˚30´E	1:500000
302	Nkalagu	6˚00´N to 6˚30´N	7˚30´E to 8˚00´E	1:100000
303	Abakaliki	6˚00´N to 6˚30´N	8˚00´E to 8˚30´E	1:500000
304	Bansha	6˚00´N to 6˚30´N	8˚30´E to 9˚00´E	1:100000
312	Okigwe	5˚30´N to 6˚00´N	7˚00´E to 7˚30´E	1:500000
313	Afikpo	5˚30´N to 6˚00´N	7˚30´E to 8˚00´E	1:100000
314	Ugep	5˚30´N to 6˚00´N	8˚00´E to 8˚30´E	1:500000
314	Ikom	5˚30´N to 6˚00´N	8˚30´E to 9˚00´E	1:100000

Data reduction and processing like magnetic compensation, data checking and editing, diurnal variation removal, tie line leveling, micro leveling and geomagnetic reference removal was carried out by Nigerian Geological Survey Agency, NGSA using Oasis Montaj software. Composite aeromagnetic data was merged to produce a merged map using Oasis Montaj8.3, this combination is valid because the coordinates are serial. This was performed to enable one work on the aeromagnetic data as a single data set to make the work accurate and better defined. Total magnetic intensity maps are normally displayed as images, contours or profiles, the application of various transformation and filtering processes before these data sets are displayed produces secondary results with improved information content that is clearly observable. For the purpose of easier handling of the large data, the residual blocks of the study area was subdivided into 35 spectral cells (Figure 3) of 55.5km by 55.5km in order to accommodate longer wavelength so that depth a little above 10 km could be investigated. Digital signal processing software Fourpot program employing the fast Fourier transform technique was used to transform the residual magnetic data into the radial energy spectrum for each block. The average radial power spectrum was calculated and displayed in a semi-log figure of amplitude versus frequency. Spector and Grant, (1970) have shown that the Log-power spectrum of the source have a linear gradient whose magnitude is dependent upon the depth of the source. Graph of logarithm of the spectral energy against frequencies was modeled and written out in the first 5 rows of Table 2.

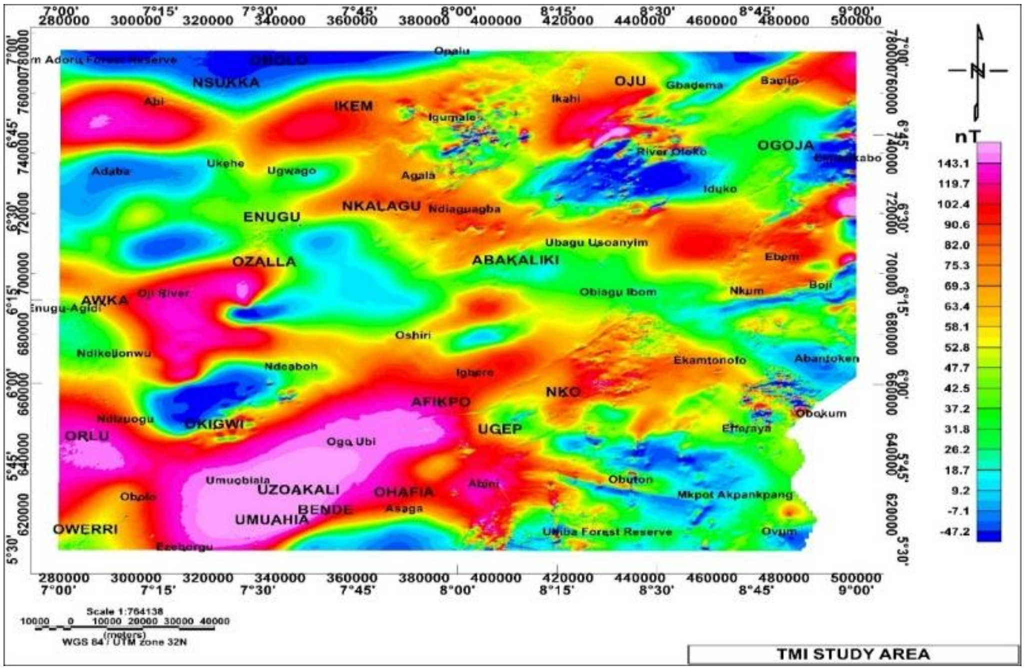

Figure 2: Merged Total Magnetic Intensity (TMI) image map of the study area

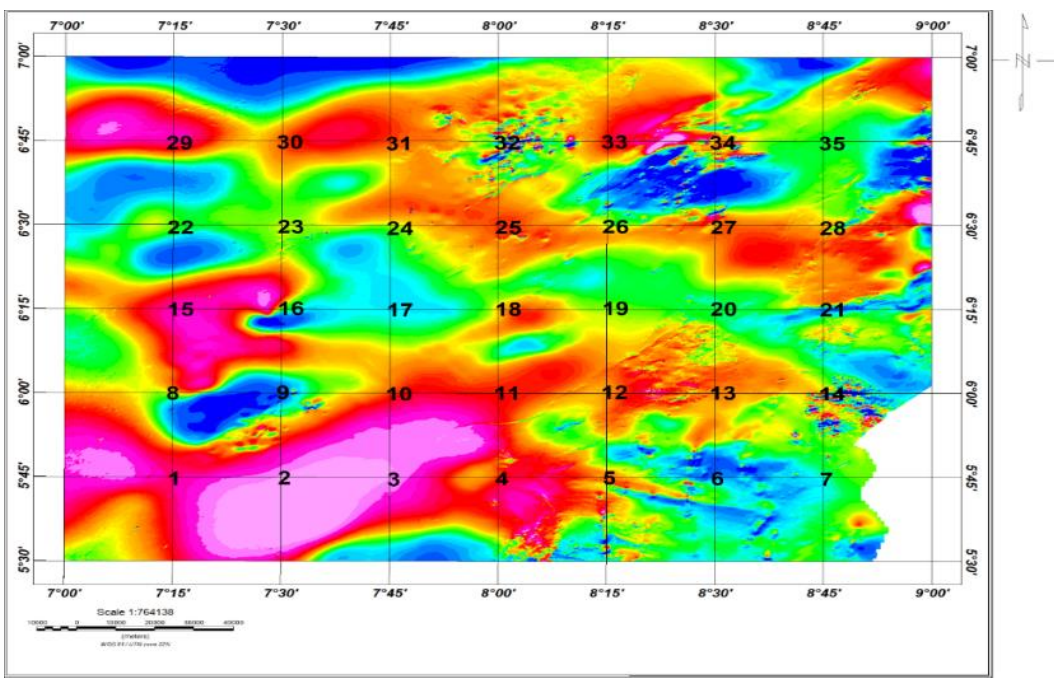

Figure 3: Spectral Blocks of the study area

RESULTS AND DISCUSSION

The TMI of the study area shown in Figure 2 has magnetic anomalies ranging from – 47.2 nT to 143.1 nT. The Northwestern part of the study area has the least magnetic anomalies with Nsukka and Obolo areas having the least magnetic anomaly which suggests that there are little or no magnetic ore bodies. Conversely, Uzuakoli, Orlu and Oji river all in the South Western part of the study area have high magnetic anomalies suggesting that there a magnetic intrusives in the areas. Other areas with high magnetic anomalies include Nkalagu, Ikem, Ikahi, igbere and Bamio areas. Igumale and Okigwe are comprised of both magnetic sources and sedimentary basins due to its mixed magnetic responses of both positive and negative magnetic responses in the TMI map.

For each of the 35 spectral cells, a spectral graph was plotted. For each cell in the spectral plot, two linear segments could be identified which implies that there are two magnetic source layers in the study area. Each linear segment group points are due to anomalies caused by bodies occurring within a particular depth range. The line segment in the higher frequency range is from the shallow sources (D_1) and the lower harmonics are indicative of sources from deep seated bodies (D_2). The values of the depths as obtained from the spectral plots are as shown in Table 2.

Table 2: Table of Values

Spectral Block	Mid-Longitude (Dec.deg)	Mid-Latitude (Dec.deg)	Deep Depth D1 (m)	Shallow depth (D2) m	Curie Depth Point (m)	Curie Depth Point (km)	Geothermal Gradient (^{o}C/km)	Heat Flow (mW/m^2)
1	7.25	5.75	6326.684	527.072	12126.3	12.1263	47.82994	142.4376
2	7.5	5.75	7390.441	559.952	14220.93	14.22093	40.78496	121.4576
3	7.75	5.75	9145.76	474.637	17816.88	17.81688	32.55339	96.94401
4	8	5.75	5670.629	515.693	10825.57	10.82557	53.57688	159.5519
5	8.25	5.75	5708.896	406.731	11011.06	11.01106	52.67431	156.8641
6	8.5	5.75	8796.089	526.841	17065.34	17.06534	33.98702	101.2134
7	8.75	5.75	2462.495	256.864	4668.126	4.668126	124.2469	370.0072
8	7.25	6	5837.683	483.199	11192.17	11.19217	51.82196	154.3258
9	7.5	6	7551.865	441.594	14662.14	14.66214	39.55767	117.8028
10	7.75	6	5325.816	340.608	10311.02	10.31102	56.25048	167.5139
11	8	6	7549.238	289.047	14809.43	14.80943	39.16424	116.6311
12	8.25	6	8913.225	386.745	17439.71	17.43971	33.25744	99.04067
13	8.5	6	7351.427	363.707	14339.15	14.33915	40.44871	120.4563
14	8.75	6	4442.648	229.061	8656.235	8.656235	67.00373	199.5371
15	7.25	6.25	9908.103	211.889	19604.32	19.60432	29.58532	88.10508
16	7.5	6.25	7459.414	272.115	14646.71	14.64671	39.59933	117.9268
17	7.75	6.25	6214.734	311.546	12117.92	12.11792	47.86299	142.536
18	8	6.25	6487.188	333.187	12641.19	12.64119	45.88176	136.6359
19	8.25	6.25	8124.44	318.308	15930.57	15.93057	36.40798	108.423
20	8.5	6.25	9157.511	223.602	18091.42	18.09142	32.0594	95.47288
21	8.75	6.25	4629.673	255.676	9003.67	9.00367	64.41818	191.8373
22	7.25	6.5	7621.601	278.824	14964.38	14.96438	38.75871	115.4234
23	7.5	6.5	6573.375	318.052	12828.7	12.8287	45.21114	134.6388
24	7.75	6.5	6495.654	296.372	12694.94	12.69494	45.68751	136.0574
25	8	6.5	6282.424	209.415	12355.43	12.35543	46.94291	139.796
26	8.25	6.5	7846.304	295.328	15397.28	15.39728	37.66899	112.1783
27	8.5	6.5	8339.967	358.725	16321.21	16.32121	35.53658	105.8279
28	8.75	6.5	7332.246	391.439	14273.05	14.27305	40.63602	121.0141
29	7.25	6.75	7474.212	250.679	14697.75	14.69775	39.46184	117.5173
30	7.5	6.75	6688.027	291.503	13084.55	13.08455	44.32708	132.0061
31	7.75	6.75	5693.304	294.034	11092.57	11.09257	52.28723	155.7114
32	8	6.75	7404.399	350.948	14457.85	14.45785	40.11661	119.4673
33	8.25	6.75	6495.745	304.501	12686.99	12.68699	45.71613	136.1426
34	8.5	6.75	10525.33	396.582	20654.08	20.65408	28.08162	83.62707
35	8.75	6.75	8088.205	439.022	15737.39	15.73739	36.85491	109.7539
Minimum			**2462.495**	**209.415**	**4668.126**	**4.668126**	**28.08162**	**83.62707**
Maximum			**10525.33**	**559.952**	**20654.08**	**20.65408**	**124.2469**	**370.0072**
Average			**7035.205**	**350.618**	**13722.92**	**13.72292**	**46.98887**	**139.9329**

In figure 4, the deep magnetic sources in the areas are depicted employing a Contour map. The map reveal the depths of the deep seated causative bodies within the study area, the deepest of these depths Ikoku, Awka and Umuahia area. This deepest depth ranges from 8100m and 10500m, the depth is displayed as color blue by the maps legend seen across the map. From Basua down to Obar Hills area had the shallowest structures ranging from 2.1 to 4.1km. The intermediate depths are observed between Ikem and Agunta, Between Okpulu and Owerri, and lastly between Ndiro and Ofunkpa with depths within 4.1 and 8.1 km. The shallow magnetic sources depths variations shown in figure 5 has a unique trend in depth distributions, ranging from 580m to 200m, the trend for the lowest depths within the study area has an obvious trend in anomalies Nw-SE. These regions have depths of 320m and below. The map is said to be unique because of its uniform anomaly pattern or trend shallowest to slightly intermediate sources forming an oval shaped body, the intermediate to deepest sources at the top left and the bottom right of the map.

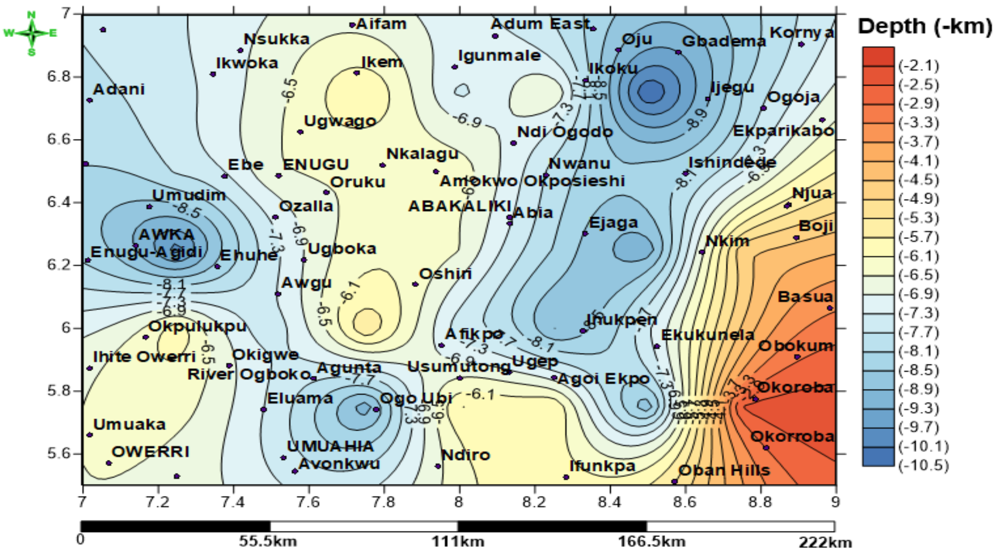

Figure 4: The deep magnetic source depth variation (D_1)

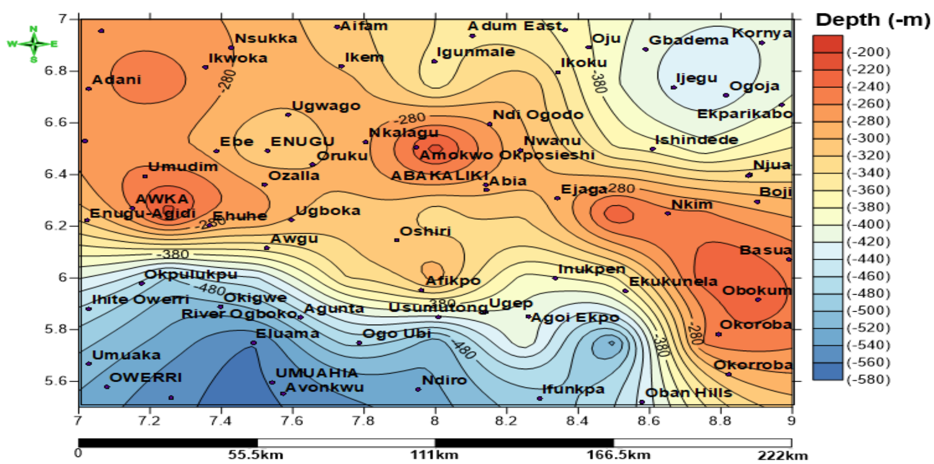

Figure 5: The Shallow magnetic source depth variation (D_2) emphasizing the depth variation across the Basin

From the values of D_1 and D_2 in Table 2, the deep depth range of the magnetic sources range from 2.46 km to 7 km while the shallow depth ranges from 0.21 km to 0.58 km. The Curie depth values reveal that the magnetic rock materials in the study area lose their magnetism due to temperature increase at depths between 4 km to 21 km, Intrusive dykes, particularly those that are still geologically young or actively cooling, will influence the CPD by raising the temperature of surrounding rocks. If these dykes are near the surface or relatively shallow, the CPD will tend to be shallow (i.e., a lower depth, indicating higher temperatures). From figure 6, the areas with low CPD ranging from 4 to 12km have the highest potential for the occurrence of geothermal resources, these areas point towards the presence of intrusive dykes that are deep seated with shallow CPD. The low CPD is observed at the bottom right part of the map from Gasua down to Oban hill, it is also found around Okpulukpu, between Ikem and Ugwago, between Awgu and Oshiri, and lastly between Ndiro and Agoi. Areas with shallow Curie depths typically have higher temperatures near the surface, making them favorable locations for geothermal exploration. Such areas may be prime sites for geothermal energy because the heat can be accessed more easily. Conversely, areas with deeper Curie points indicating lower surface temperatures (13-21km) such as

Awka, Umuahia, Ejaga, between Ikoku and Ijegu, Igunmale, and Agoi Ekpo less favorable for geothermal resources, as the temperature gradient is lower, and the heat source may be deeper, making it more difficult to access. Areas with both shallow CPD and evidence of intrusive dykes or active volcanic systems are the most likely candidates for high geothermal potential.

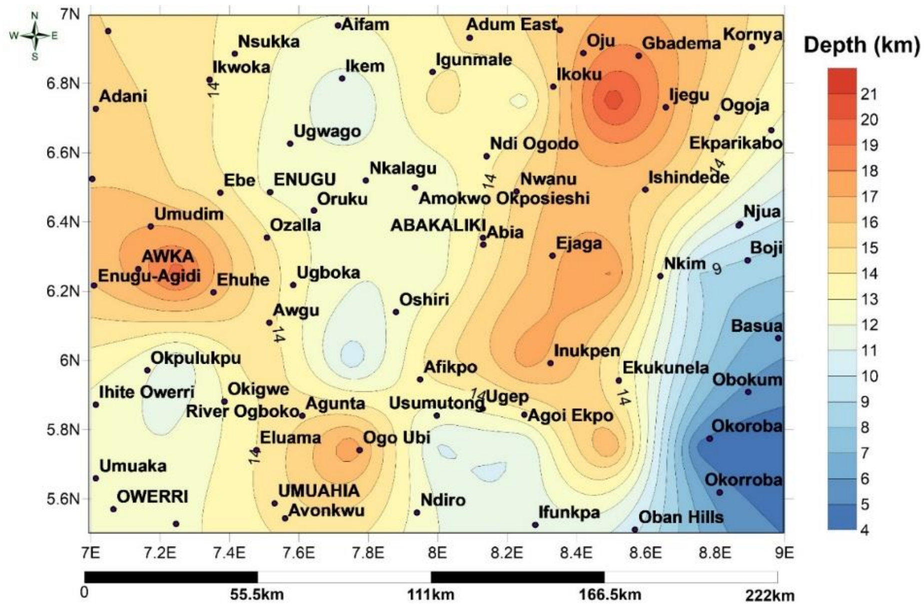

Figure 6: The Curie point depth map over the study area

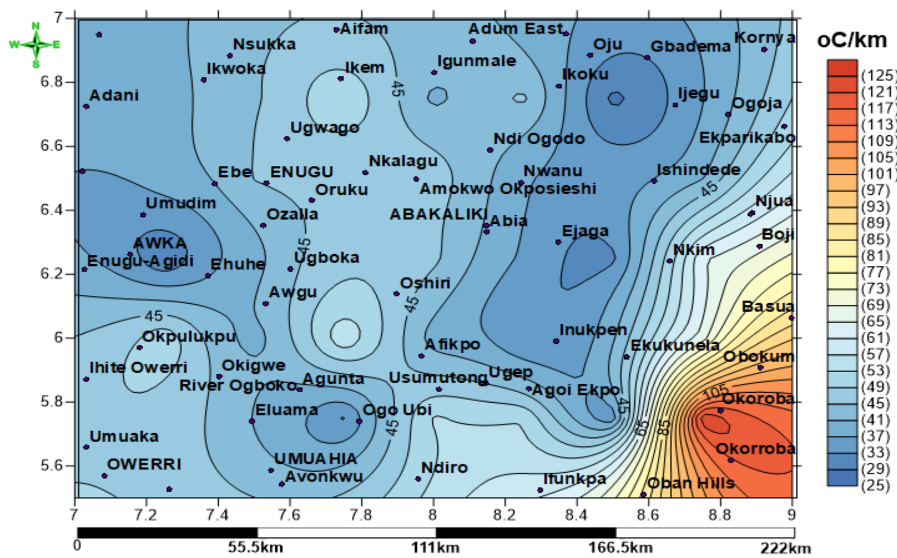

Figure 7: The geothermal gradient map showing the rate of temperature variation with depth

From the geothermal gradient map in Figure 7, the study area has its geothermal gradient ranging from 25 ^{0}Ckm^{-1} to 125 ^{o}Ckm^{-1} with its highest value being at the south eastern part of the study area with a value of 125 ^{o}Ckm^{-1}. The geothermal gradient map shows how temperature increases with depth in the Earth's crust. In the context of intrusive dykes and geothermal resource potential of the study area, interpreting the map involves understanding how both temperature and geological structures interact to determine the potential for geothermal energy. e can identify intrusive dykes Okoroba and Okorroba, around Okpulukpu, between Ikem and Ugwago, and finally between Awgu and Oshiri axis, these dykes are vertical or near-vertical fractures in the Earth's crust filled with magma or solidified lava. These dykes are typically formed when magma rises through fissures and cools below the surface. The presence of these dykes indicates that the area may be thermally active or recently active. Magma below the surface can significantly increase the temperature in nearby rocks, which can affect the geothermal gradient. A higher gradient suggests a greater temperature increase per unit of depth, which indicates a higher geothermal potential, therefore area with geothermal gradient within 50 to 125°C/km are regions with the highest geothermal potentials and suggests deep seated intrusive dykes while area with geothermal gradient ranging below 50 °C/km suggests shallow seated Igneous rocks. In areas with intrusive dykes, the geothermal gradient might be steeper near the dykes due to the presence of hot magma or partially molten rock beneath the surface. This suggests elevated temperatures, making these areas promising for geothermal resource exploitation. Areas where dykes intersect the surface or are near other geological features, such as faults, may have localized hotspots where the geothermal gradient is significantly higher, indicating areas of higher thermal conductivity and better geothermal energy prospects.

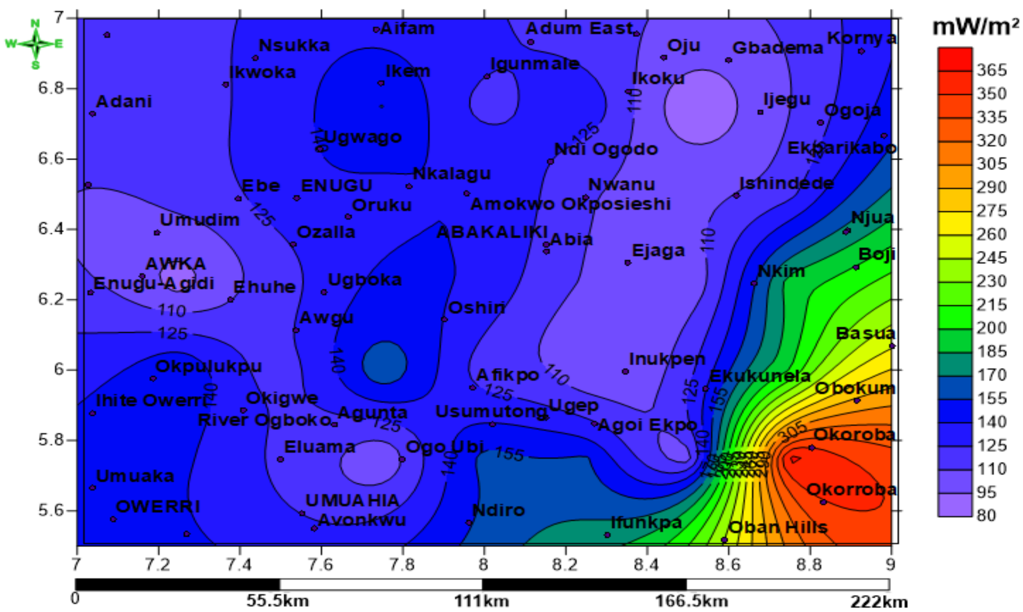

Figure 8: The heat flow map

The heat flow of the study area (Figure 8) also has the same trend with the geothermal gradient with a range of 80 mWm^{-2} to 365 mWm^{-2} where the South-Eastern part has the least values implying that it may be composed more of sediments than other parts of the study area which are made of more basements inferred from the high heat flow values. The heat flow map depicts the transfer of heat from the Earth's interior to the surface. This heat is generated primarily from the Earth's internal temperature, radioactive decay, and tectonic processes. The heat flow map depicted a region with abundance of heat coming from the earth's interior to the surface, the least heat flow being 80 mW/m² characterized by the map meets way above the minimum range of heat flow to be classified as high heat flow. The region is rich in heat energy with its maximum heat flow at areas identified earlier as suspected intrusive dykes. These areas include areas within Southwest and Northeast of Okoroba and Okorroba axis. They had heat flow above 200 mW/m². In areas with high heat flow, the temperature gradient suggests that deeper geothermal resources are more likely, especially if the heat flow is less than or equal to the regional baseline. These deeper resources may be suitable for electricity generation while shallow resources can be used for low-temperature geothermal energy applications (heating or cooling) and these resources are found in areas like Okpulukpu, between Ikem and Ugwago, and finally between Awgu and Oshiri (125 mWm^{-2} to 155 $mWm^{-2)}$. High heat flow in regions with intrusive dykes can indicate areas where geothermal reservoirs may be found at relatively shallow depths. This would make it easier and cheaper to drill and access geothermal energy, enhancing the potential for exploitation.

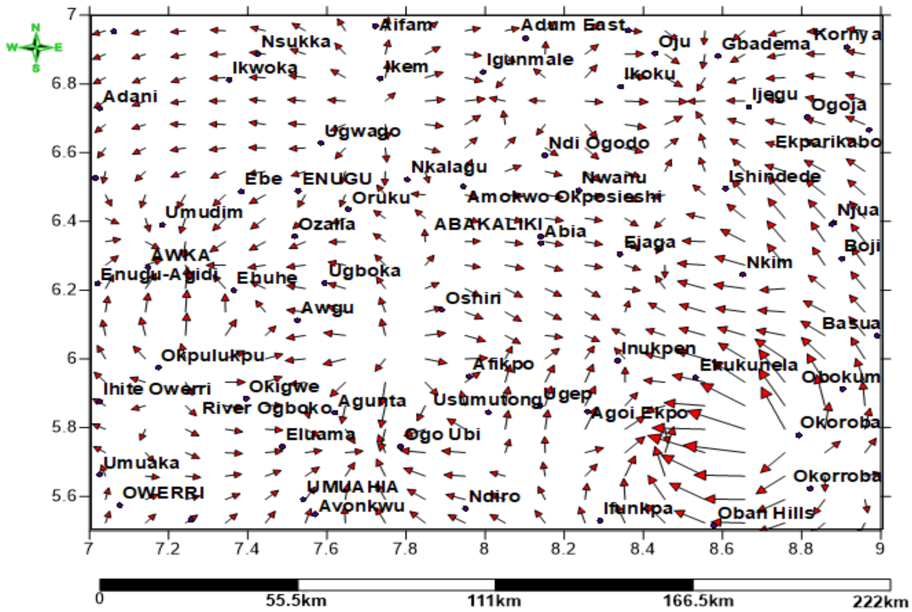

Figure 9: The vector diagram depicting the heat flow direction from the study area

The vector diagram of the heat flow shown in Figure 9 reveals that there are about five diverging points found in Okoroba, Igumale, Ihite Owerri, Ndi Ogodo and Okpulunkpu areas while Awka, Ogo Ubi, Ikoku and Agoi Ekpo areas are the four converging points which shows the likely presence of geothermal source or a mineral as heat flows from high temperature region to lower temperature region. Heat flow direction maps are particularly important when interpreting the relationship between geological features like intrusive dykes and geothermal resource potential. The direction of heat flow gives insight into the movement of geothermal fluids and help identify the most favourable areas for geothermal energy extraction. Heat flow vectors indicate the direction in which heat is moving within the Earth's crust. Heat typically flows from areas of higher temperature (e.g., magma, hot rocks) to cooler areas (e.g., the Earth's surface). From figure 9, the five diverging points found in Okoroba, Igumale, Ihite Owerri, Ndi Ogodo and Okpulunkpu are the areas with higher temperature from which heat flows to other regions, majority of these areas correlates with the areas identified to be intrusive dykes. The magnitude (length of the vector) indicates the intensity of heat flow, while the direction indicates the path the heat takes. For geothermal systems, this is often important in understanding how heat is being transferred to the surface and where it might be most accessible for exploitation which are these areas. The presence of intrusive dykes in the study area creates localized heat flow anomalies and will influence the direction of heat flow by acting as thermal conduits that carry heat from deep beneath the surface to shallower levels. Geothermal resources are typically found in areas where heat flow is concentrated or directed in a way that allows for the accumulation of heat close to the surface. By analyzing heat flow direction, one can infer where geothermal systems may exist and exploitation might be viable.

CONCLUSION

The study used twelve high resolution aeromagnetic data sheet to investigate the geothermal potential of the study area. The data set used generated the Total Magnetic Intensity anomaly map and it was observed that the study area showed both positive and negative magnetic responses implying that there are likely presence of both sedimentary and basement rocks. Spectral analysis was done on the study area using 35 spectral blocks that resulted in deep depths and shallow depths of the magnetic sources with an average value of 7 km and 0.35 km respectively. The Curie depth, geothermal gradient and heat flow for the study area were also obtained with average values of 13.7 km, 46.9 ^{O}C/km and 139.9 mW/m^2 respectively. From the forgoing, it can be concluded that the study area has magnetic sources and as well have geothermal gradient and heat flow convergence which make them viable for mineral and geothermal energy exploration.

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