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Research Paper

Spectral Depth Analysis and Source Parameter Imaging in The Investigation of Geothermal Potentials of Ikogosi Warm Spring, Ekiti State, Nigeria.

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Abstract

An integrated approach consisting of spectral depth analysis and source parameter imaging, has been used in this study to investigate the geothermal potentials around the Ikogosi warm spring. The Ikogosi warm spring is in the south-western part of Ekiti State of Nigeria and lies on the geographic latitude of 7°35'N and longitude 5°00'E. The warm spring temperature is around 37°C near the foot of the eastern slope of the north-south trending ridge from a thin quartzite unit. The aeromagnetic data utilized in the study covers sheets 243 and 244 in the index map of Nigeria aeromagnetic data. Aeromagnetic data was acquired and processed by Fugro Airborne Surveys on behalf of Nigerian Geological Survey Agency (NGSA), was used in the study. The Geosoft Oasis Montaj 8.4 version software was used for the analysis. Minimum curvature technique was used to produce the corrected Total Magnetic Intensity (TMI) map of the study area. The depths to magnetic sources estimated from spectral depth analysis that ranges from 0.15 – 0.35 km are consistent with the depth information from the source parameter imaging (SPI) that ranges from 0.13 to 0.40 km. The Curie Point Depth (CPD) or Curie Isotherm Depth derived from the spectral depth analysis in the study area is estimated to be 14.65 km, this is considered quite shallow and it can be attributed to a magmatic intrusion in depth around Ikogosi area. The computed geothermal gradient at Ikogosi warm spring area ranges from 71.8 – 84.79 $^oC/km$ while the geothermal heat flow computed for the warm spring ranges from 179.51 to 211.96 mW/m^2.

The result of the work suggests the existence of geothermal potentials in the study area which could support a geothermal power plant if given consideration by the government and interested private investors. As geothermal is not widely known in Nigeria, this research work will shape the untapped geothermal potentials thus engendering socio-economic development of Nigeria in particular and sub-Saharan region of Africa.

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I. Introduction

Nigeria energy generation is currently considered to be grossly inadequate and cannot support the social economic activities of the country. Too-much dependence on fossil fuel as sources of power generation is gradually becoming obsolete as a result of the irreversible environment degradation that is associated with it, hence the gradual paradigm shifts to more environmentally friendly and renewable energy sources such as the one this work has addressed is inevitable geothermal energy resource. Aside the consideration for the environment, the socio-economic impacts that the geothermal energy source will have on people around the study area cannot be over-emphasized. There are several known and unknown thermal springs in Nigeria, few were reported within the crystalline province and some within the Middle Benue Through (Bako, 2010; Kurowska and Schoeneich, 2010; Garba *et al*., 2012); Ikogosi warm spring in Ekiti State, and the Wikki warm spring in Bauchi State (Yankari) are the best-known springs in Nigeria. The first known is the Ikogosi warm spring (Precambrian basement and schist belt). The spring is a low enthalpy system, its temperature being around 37ºC (Oladipo *et al*., 2005).

Given the possible existence of geothermal resources at Ikogosi warm spring, some research works had previously been carried out notably amongst them are that of Olorunfemi et al. (2011), Abraham, et al. (2011), Ojo et al. (2011), and Abraham et al. (2014). These studies considered the Ikogosi warm spring as housing a great potential for geothermal energy and hence sets out to examine the depths, composition, temperatures, and chemical content of the subsurface using various geophysical parameters. Abraham *et al.* (2014) arrived at results concerning the geothermal potential of the Ikogosi warm spring region. Their results presented average CPD for the Ikogosi warm spring area as 15.1±0.6 km and location centered on a host quartzite rock unit. This current work combined spectral depth analysis and source parameter imaging techniques to estimate the Curie Point Depth of around 14.65 km that was used for computation of geothermal gradient (84.79 ^{o}C/km) and geothermal heat flow (211.96 mW/m^2) of the study area. The result suggests possible existence of geothermal resources that can support a geothermal energy plant. This will in turn engender socio-economic development of Nigeria in particular and sub-Saharan region of Africa.

II. Location and Geology of Study Area

The Ikogosi warm spring is in the south-western part of Ekiti State of Nigeria. Ikogosi warm spring lies on the geographic latitude of 7°35'N and longitude 5°00'E (Figure 1) within the central region of the area covered by this study. It is situated between lofty steep-sided and heavily forested, north-south trending hills about 27.0 km east of Ilesha, and about 10.5 km southeast of Efon Alaye (Rogers et al., 1969). The warm spring is in a quiet town called Ikogosi that has a rich culture, in the Western part of Ekiti State where warm and cold flow parallel, and meet somewhere to form a confluence, with each maintaining its thermal quality (Adeyemi, 2016). The warm spring has a temperature of around 70^{o}C at the source and 37^{o}C after meeting the cold spring as the meeting point of the two spring serves as unique attraction to tourists.

A well-landscaped 116-hectare resort is located around the warm spring at Ikogosi-Ekiti with a view to give tourists and visitors a long-lasting experience. Located within the Precambrian basement complex of South Western Nigeria, it is at an altitude of 450 to 500m (Adegbuyi and Abimbola, 1997) above the mean sea level. The dominant geology of Nigeria is constituted mainly of crystalline Precambrian basement complex and sedimentary rocks of Cretaceous recent sediments.

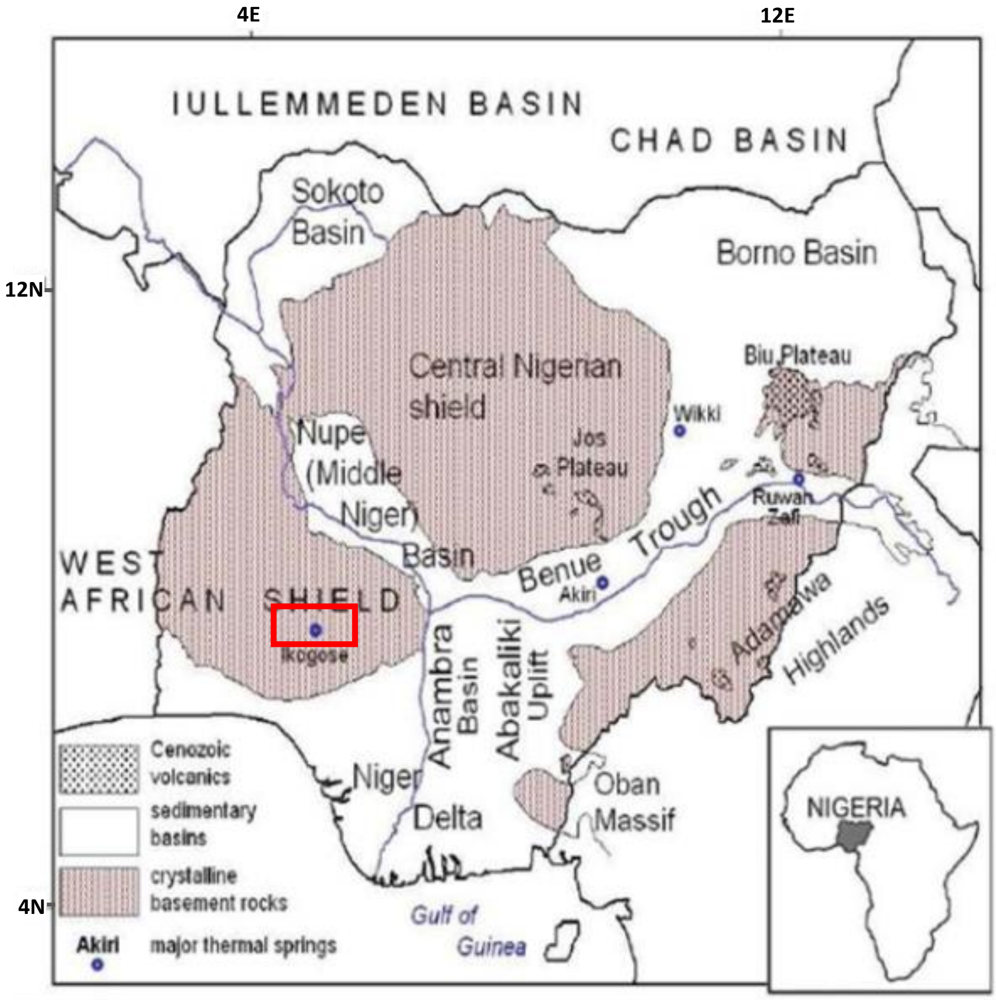

Figure 1, Geological Map of Nigeria showing major structural units and warm springs. (after Kurowska and Schoeneich, 2010)

The warm spring temperature is 37°C near the foot of the eastern slope of the north-south trending ridge from a thin quartzite unit within a belt of quartzite which includes quartz-mica schist and granulitic migmatite east of Ilesha. The Okemesi quartzite member is characterized by a North-South trending ridge called the Efon ridge (Elueze, 1998; Oyinloye, 2011). The quartzitic rocks are composed of dominant quartz with muscovite, chlorite and sericite occurring in minor proportions (Adegbuyi and Abimbola, 1997). It was suggested that the source of springs in the Efon Psammite formation is associated with a faulted and fractured quartzite band sandwiched between schists (Rogers *et al*., 1969). Geochemical data of Ikogosi shows that quartzite is largely metamorphosed sandstones containing minor arkosic intercalations (Elueze, 1998).

Based on petrology, a medium pressure Barrovian and low medium pressure types of metamorphism had been suggested for the Precambrian basement rocks in South Western Nigeria (Oyinloye, 2011). It is believed that the intersections of the NNE-SSW epeirogenic belts with the NW-SE fracture trends in Nigeria coincide with the centres of warm springs like the Wikki (Bauchi State) and Ikogosi (Ekiti State) springs. The issue of the springs is controlled by permeability developed within the quartzite because of intergranular pore spaces coupled with fracturing of the relatively competent quartzite (Rogers, 1969).

III. Materials and Methods

The aeromagnetic data utilized in the study covers sheets 243 and 244 in the index map of Nigerian aeromagnetic data. The data was acquired and processed by Fugro Airborne Surveys on behalf of Nigerian Geological Survey Agency (NGSA). The survey was acquired in drape mode using real time global positioning system at sensor mean terrain clearance of 80 meters, flight line spacing of 500 meters, tie line spacing 5000 meters, flight line trend 135^0, tie line trend 45^0 and the data recording interval was 0.1 seconds or less (~7m). The elementary aeromagnetic data corrections to remove the effects of offsets, external time-varying field, and Earth's core magnetic field were performed. With these corrections, the magnetic anomalies on the aeromagnetic maps are majorly consequential of the upper crustal geology of the study area.

The data used in the study is presented in the XYZ format. X and Y are coordinates pointing north and east respectively, while Z is the measured magnetic field intensity at the point with all external noise and IGRF removed. The field data corrections are the processing operations designed to remove unwanted features in the data. The common corrections are diurnal corrections, levelling, IGRF removal, altitude corrections and terrain correction.

The software utilized in this work is Geosoft Oasis Montaj 8.4 version software. Minimum curvature technique was used to produce the corrected Total Magnetic Intensity (TMI) map of the study area. The corrected Total Magnetic Intensity (TMI) data was upward continued to a height of 100 m to remove the very high frequency/short wavelength components associated with near-surface magnetic noise and produced a denoised Total Magnetic Intensity (TMI) data. The geomagnetic inclination (I), -10.26° and declination (D), -1.21° of the study area were estimated from International Geomagnetic Reference Field (IGRF) calculator at the geographic coordinate, X – 5.00° and Y – 7.75°, approximately the center of the study area. Apparently, the geomagnetic inclination of the study area is very low and closer to the geomagnetic equator, I = 0°. Consequently, the computation of a pole-reduced magnetic field, free of procedural artefacts, is problematic, and the best solution is to reduce the aeromagnetic data to the geomagnetic equator. Reduction to the geomagnetic equator is relevant to symmetrizing and centering magnetic anomalies over their sources for better interpretation at a very low geomagnetic latitude. The denoised TMI data was therefore reduced to the equator of Earth's geomagnetic field using the calculated geomagnetic inclination and declination, and the resulting Reduced-to-Equator (RTE) data. To obtain the regional and residual magnetic fields of the study area, wavelength filtering was carried out on the RTE data.

A low-pass filter and a high-pass filter were used to separate the wavelength and frequency components that correspond to the regional field and residual field respectfully. A low-pass filter was used to generate the regional magnetic field of the study an area because it is capable of accentuating low frequency/long wavelength associated with large-scale and deep-seated magnetic sources. while a high-pass filter was utilized to generate the residual magnetic field of the study area because it accentuates high frequency/short wavelength associated with small-scale (localized) and shallow-seated magnetic sources, To have an overview of the frequency/wavelength components of the RTE data of the study area, a radially average power spectrum of the RTE data was generated and a cut-off wavelength value of 5000 m (5 km) was interactively and visually chosen for both the low-pass filtering and high-pass filtering of the RTE data. In view of the estimation of Curie Point Depth (CPD)/Curie Isotherm Depth (CID) through spectral analysis of the aeromagnetic data, a band-pass filter, with cut-off wavelength values ranging from 1500 m (1.5 km) to 5000 m (5 km), was applied to the RTE data.

3.1 Spectral Depth Analysis for Curie Depth Estimation

The Curie Point Depth/Curie Isotherm Depth estimation requires the deepest magnetic sources within the Earth's crust. To emphasize the broad features at depths within the limits of the Earth's crust, the short wavelength anomalies within the crust and long wavelength anomalies at depths beyond the crust were removed from the reduced-to-equator (RTE) data of the study area. For these purposes, a simple band-pass filter (full pass 1.5 km – 5 km) was designed from the appearance of the radially average power spectrum and applied to the RTE data of the study area. The band-pass filtered magnetic intensity data was used for the spectral depth analysis. The band-pass filtered magnetic intensity data was divided into 55 overlapping spectral blocks, about 20 km x 20 km in size, and each spectral block overlapped the adjacent blocks by 50% (Figure 2).

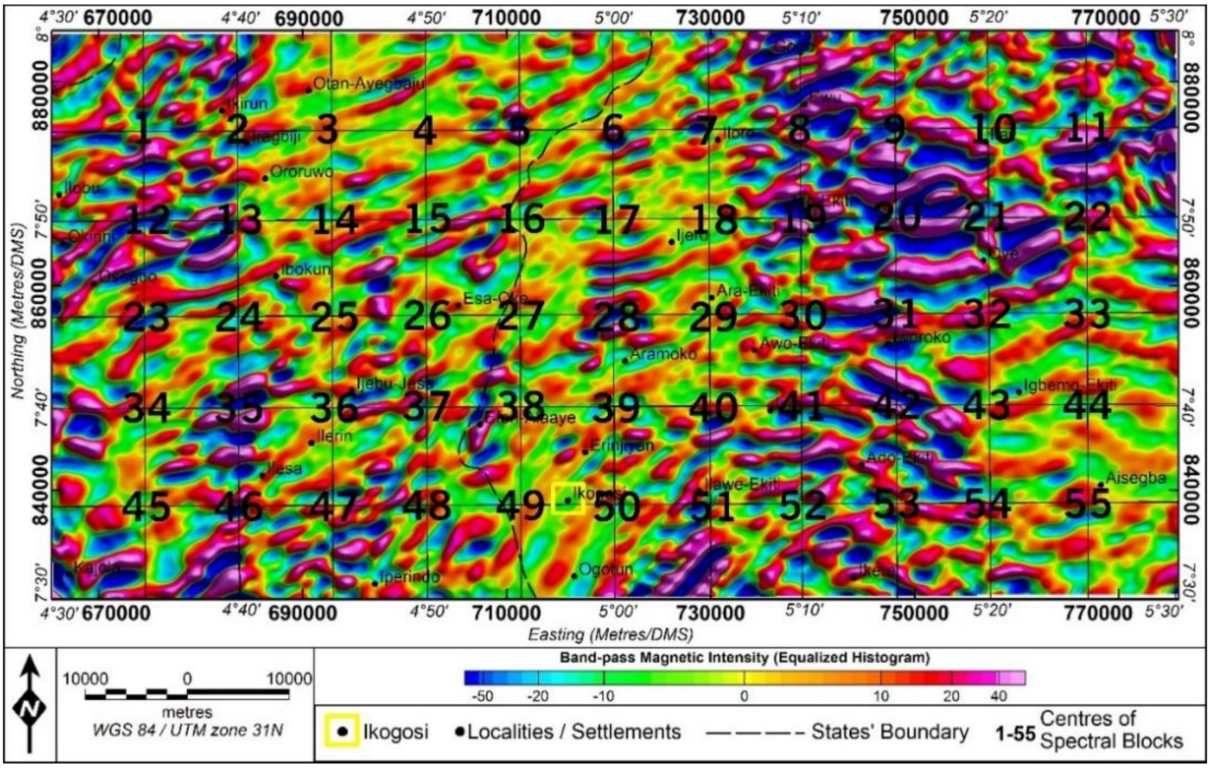

Figure 2, Map of the Division of the Study Area into Spectral Blocks, underlain by the Band-Pass filtered Magnetic Intensity Data of the Study Area

The radially averaged power spectrum of each block was computed to determine the depth to top and the depth to centroid of magnetic sources which are assigned to the center of each block (Figure 2). The depth to the top of magnetic sources was computed from the slope of the second segment of the power spectrum using Spector and Grant (1970) method given as:

$$Z_t = -\frac{s}{4\pi} \qquad (1)$$

where, Z_t is the depth to top of magnetic source, s is the slope of the second segment of power spectrum plot, and π is the mathematical constant, – 3.142. While the depth to the centroid of magnetic sources was computed from the slope of the first segment of the power spectrum using a simplified Fractal method given as (Demarco et al., 2020).

The depth to centroid of magnetic source is the slope of the first segment of power spectrum plot.

$$Z_o = -\frac{s}{2} \qquad (2)$$

where, Z_o is the depth to centroid of magnetic source, s is the slope of the first segment of power spectrum.

The depth to bottom of the magnetic sources, which is presumably the Curie Point Depth or Curie Isotherm Depth – the theoretical surface with a temperature of approximately 580^0C, was computed using the theoretical formula (Bhattacharya 1964, Okubo et al. 1985)

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

where, Z_b is the depth to bottom of magnetic source, Z_t is the depth to top of magnetic source, and Z_o is the depth to centroid of magnetic source. The computed depth to bottom of the magnetic sources of the spectral blocks was gridded to generate the map of depth to Bottom/Curie Isotherm Depth.

3.2 Computation of Source Parameter Imaging (SPI)

SPI is a procedure for automatic calculation of source depths from gridded magnetic data. The depth solutions were gridded to produce a SPI depth map. It is based on complex analytic signal using second order derivates that significantly reduces the interference of anomaly features. The SPI method yields solutions grids which show the edge locations, depths, dip, and susceptibility contrasts. These depth results are independent of the magnetic inclination and declination, so it is not necessary to use a pole-reduced/equator-reduced input grid (Thurston and Smith, 1997). SPI assumes a step-type source model. For a step, the following formula holds:

$$Depth = \frac{1}{K_{max}} \tag{4}$$

Where, K_{max} is the peak value of the local wavenumber of K over the step source.

$$K = \sqrt{\left(\frac{\partial\theta}{\partial x}\right)^2 + \left(\frac{\partial\theta}{\partial y}\right)^2} \tag{5}$$

$$\theta = \tan^{-1}\left[\frac{\frac{\partial T}{\partial z}}{\frac{\partial T}{\partial h}}\right] = \frac{FVD}{THD} \tag{6}$$

Where, θ is the tilt angle, $\frac{\partial T}{\partial z}$ and $\frac{\partial T}{\partial h}$ are the First Vertical Derivative (FVD) and Total Horizontal Derivative (THD) of the total magnetic field, T, respectively. SPI first computes θ and K. Then it finds peak values K_{max} using the Blakely test. These peak values are used to compute depth solutions.

In this study, the SPI was applied to the Residual Magnetic Intensity and result gridded to generate an SPI depth map.

3.3 Computation of Geothermal Gradient

The geothermal gradient of each spectral block (Figure 2) was computed using the mathematical formula (Tanaka et al., 1999):

$$\frac{\partial T}{\partial z} = \frac{\theta_c}{Z_b} \tag{7}$$

Where, $\frac{\partial T}{\partial z}$ is the geothermal gradient of a region, Z_b is the depth to the bottom of magnetic sources or the Curie point depth or the Curie Isotherm Depth of a region, and θ_c is the standard Curie point temperature of 580^0C.

3.4 Computation of Geothermal Heat Flow

The geothermal heat flow of each spectral block was computed using the Fourier's law according to Tanaka et al. (1999) with the formula:

$$Q = \lambda\frac{\partial T}{\partial z} = \lambda\frac{\theta_c}{Z_b} \tag{8}$$

Where, Q is the geothermal heat flow of a region, $\boldsymbol{\lambda}$ is the thermal conductivity (given as 2.5 W/m°C), $\frac{\partial T}{\partial z}$ is the geothermal gradient of a region, Z_b is the depth to the bottom of magnetic sources or the Curie point depth or the Curie isotherm depth of a region, and θ_c is the standard Curie point temperature of 580^0C.

IV. Result and Discussion

The Total Magnetic Intensity (TMI) around the study area is considered relatively lower than the surrounding. The TMI in absolute value at Ikogosi warm spring is about -15.62 nT (Figure 3) while the reduced-to-equator magnetic intensity is 6.35 nT. The TMI in the northwestern direction of the study area is well pronounced with the maximum value in excess of 120 nT which is similar to the total magnetic intensity in the north-eastern section of the study area. The magnetic anomalies observed in the TMI map is in correspondence of the rock type in the study area and environs. At the Ikogosi warm spring, the lithology constitutes predominantly quartzite within the Precambrian basement complex

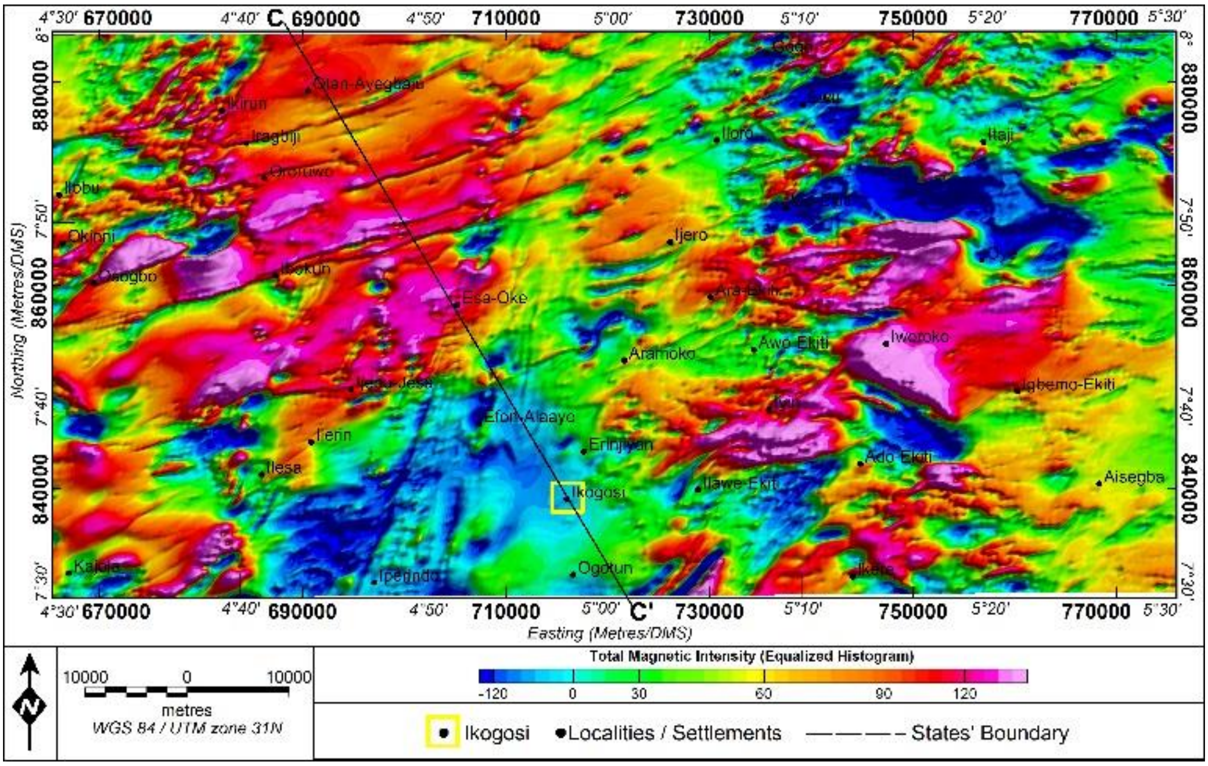

Figure 3, Total Magnetic Intensity (TMI) Map of the Study Area

The results of computation of the power spectrum selected around the study area is presented in figures 4, 5, 6 and 7. The computed depth to the top (Z_t) of magnetic sources ranges between 0.13 km to 0.34 km in the entire study area and it is computed to about 0.17 km at Ikogosi warm spring location. The computed depth to centroid of magnetic source Z_o ranges between 3.5 km to 18.64 km with that of Ikogosi warm spring resulted 7.28km. The depth to the bottom of the magnetic sources Z_b which is presumably the Curie Point Depth or Curie Isotherm Depth in the study area ranges from 6.84 km to 34.78 km. However, the computed CPD for Ikogosi warm spring location in this work is around 14.65 km. Studies have indicated that the Curie Point Depth is related to geological framework. According to Tanaka et al. (1999) disclosed that the Curie Points Depth are shallower than about 10 km at volcanic and geothermal areas, 15-25 km at island arcs and ridges, deeper than 20 km at plateaus, and deeper than 30 km at trenches. The CPD around Ikogosi aligns with the first category considering the presence of warm spring.

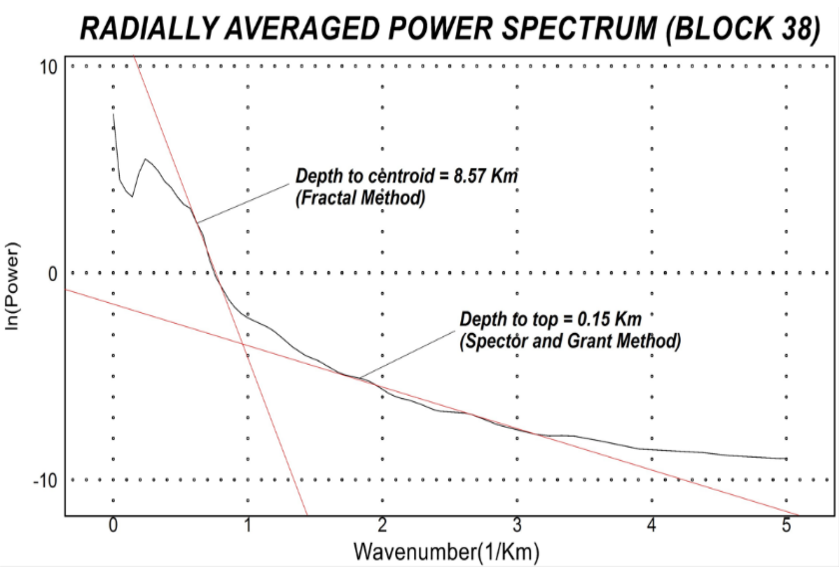

Figure 4, Radially Averaged Power Spectrum of the Spectral Block 38 of the Study Area.

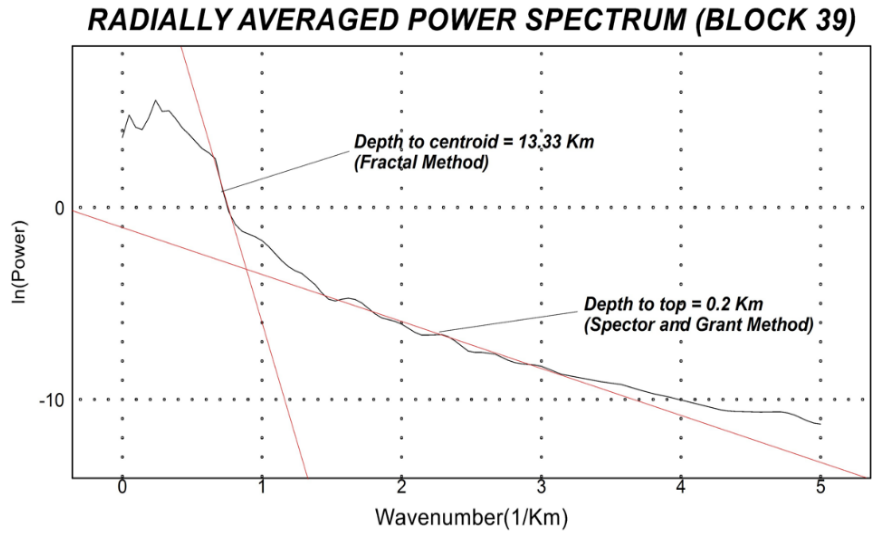

Figure 5, Radially Averaged Power Spectrum of the Spectral Block 39 of the Study Area.

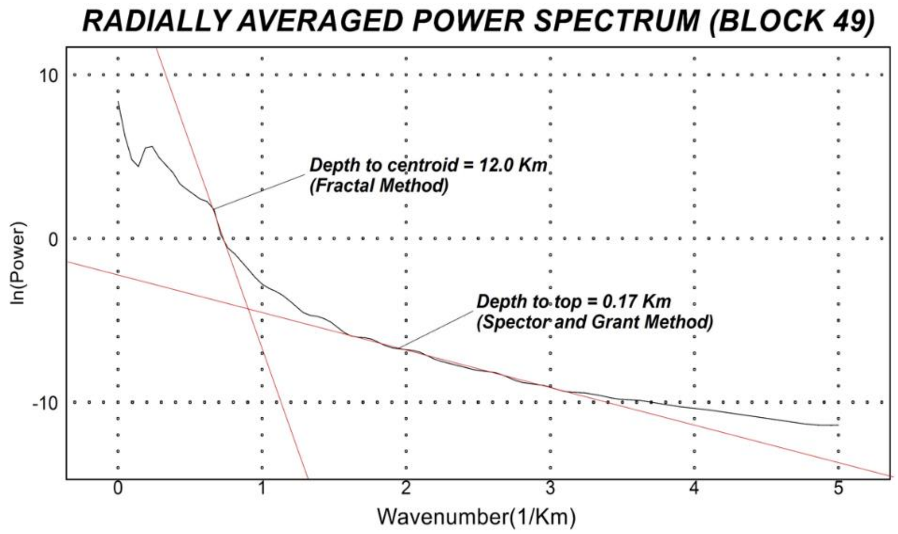

Figure 6, Radially Averaged Power Spectrum of the Spectral Block 49 of the Study Area

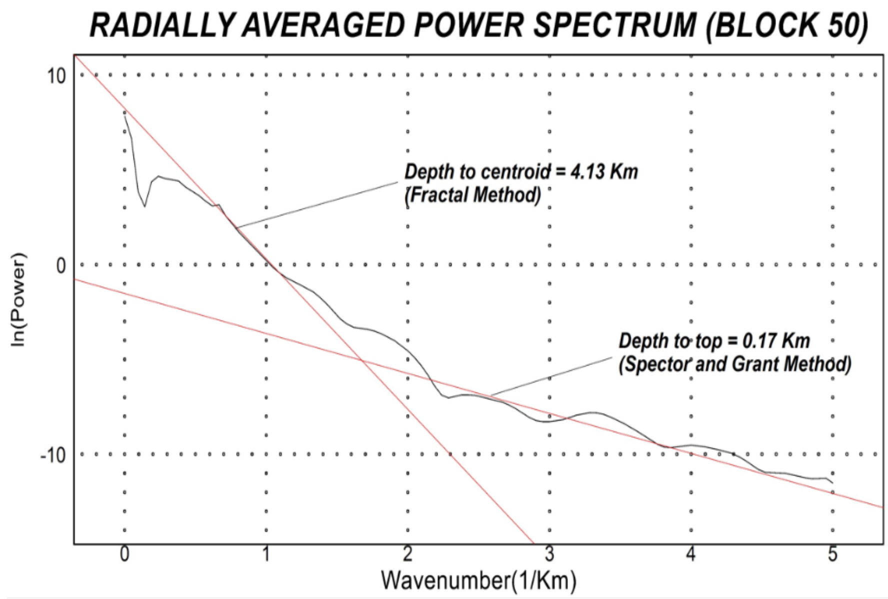

Figure 7, Radially Averaged Power Spectrum of the Spectral Block 50 of the Study Area.

The SPI derived depth to top of magnetic source in the study area generally ranges between 0.13 km to 0.4 km except in some parts with high absolute values. In this study, it is observed that the depth estimates from spectral analysis are consistent with the depth information from the SPI depth map (Figure 8). Importantly, the degree of consistency from the two independent estimations of depth to top of magnetic sources serves as quality check for the work. The depths to magnetic sources estimated from spectral depth analysis that ranges from 0.15 – 0.35 km are consistent with the depth information from the source parameter imaging (SPI) that ranges from 0.13 to 0.40 km.

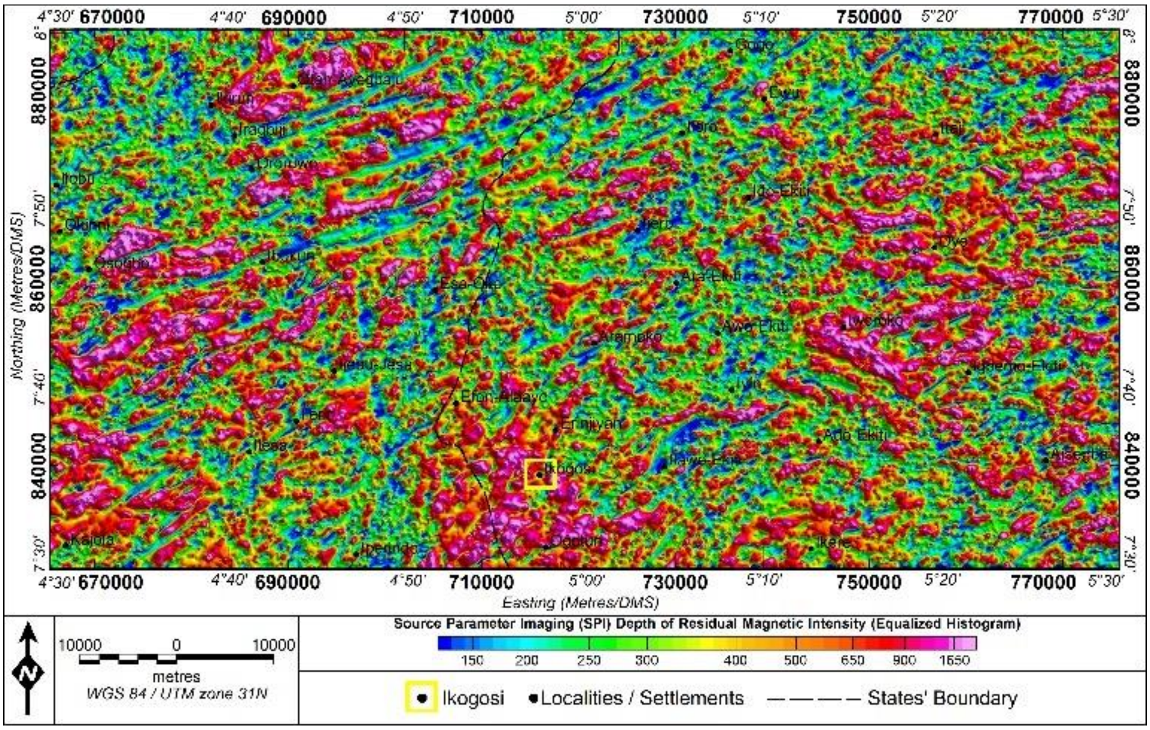

Figure 8, Source Parameter Imaging (SPI) Map of the Residual Magnetic Intensity Data of the Study Area.

The map of depth to bottom/Curie depth Isotherm in figure 9 indicates that the Curie Point Depth around Ikogosi warm spring is found at shallower depth relative to the rest of the study area.

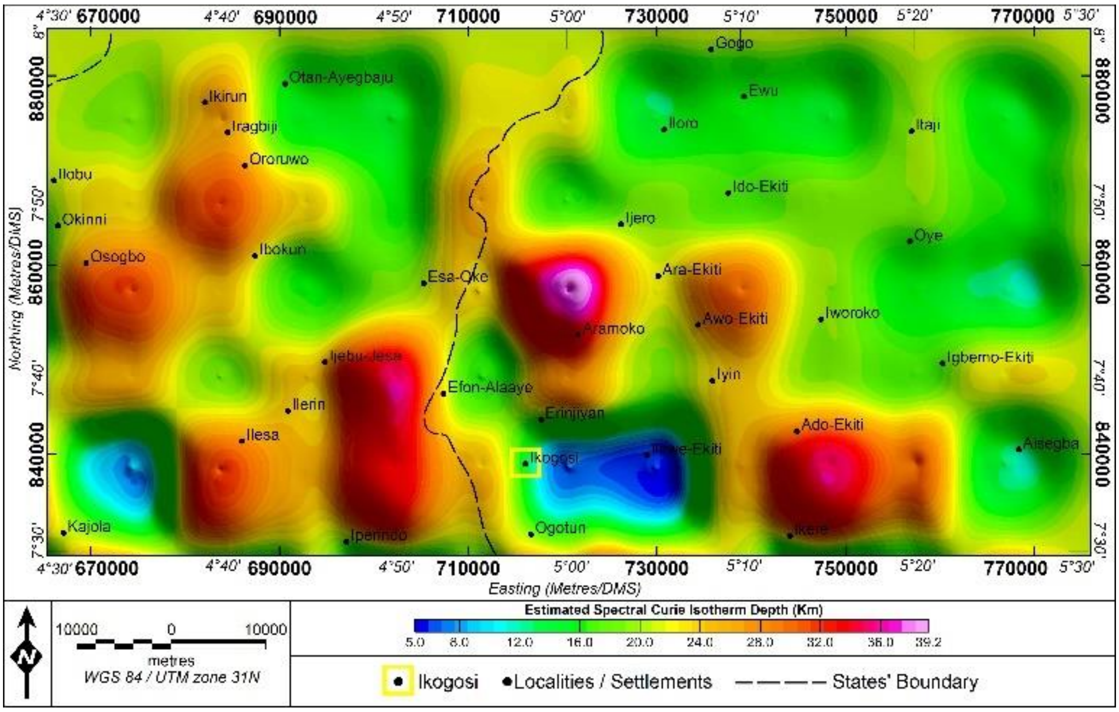

Figure 9, Map of Depth to Bottom/Curie Isotherm Depth from the Spectral Depth Analysis

Table 1: Results of Spectral Depth Analysis of the 55 Blocks.

Spectral Block's Number	Block's Centre X (m)	Y (m)	Spectral Depths Top, Z_t (Km)	Centroid, Z_o (Km)	Curie Isotherm Depth, Z_b (Km)	Geothermal Gradient (°C/Km)	Geothermal Heat Flow, Q (mW/m^2)
1	674187	875428	0.27	10	19.74	29.39	73.47
2	683757	875274	0.26	12.5	24.74	23.44	58.61
3	692710	875428	0.27	7.41	14.55	39.86	99.66
4	701817	875582	0.31	7.14	13.98	41.49	103.71
5	711233	875428	0.26	11.25	22.24	26.08	65.19
6	720340	875428	0.28	11.11	21.94	26.43	66.08
7	729756	875582	0.27	6.82	13.37	43.38	108.44
8	738555	875737	0.17	7.86	15.54	37.32	93.3
9	748125	875582	0.15	7	13.85	41.87	104.66
10	757078	875737	0.17	10	19.83	29.25	73.13
11	766802	875582	0.2	7.5	14.8	39.19	97.97
12	674187	866629	0.23	11.67	23.11	25.1	62.75
13	683603	866475	0.23	15	29.78	19.48	48.7
14	692710	866629	0.29	11.67	23.05	25.17	62.91
15	701972	866629	0.28	8.33	16.38	35.39	88.48
16	711233	866784	0.24	12.5	24.76	23.42	58.56
17	720340	866784	0.21	8.57	16.93	34.26	85.64
18	729756	866629	0.27	10	19.73	29.4	73.5
19	738709	866629	0.21	9	17.79	32.61	81.52
20	748125	866938	0.34	10	19.66	29.5	73.75
21	756923	866784	0.26	10	19.74	29.38	73.45
22	766802	866938	0.2	8.33	16.46	35.23	88.07
23	674341	857214	0.25	15	29.75	19.5	48.74
24	683603	857214	0.17	12	23.83	24.34	60.84
25	692710	857214	0.22	8.33	16.45	35.26	88.16
26	701972	857214	0.23	10	19.78	29.33	73.33
27	711079	857214	0.23	12	23.77	24.4	61.01
28	720495	857214	0.16	18.64	37.11	15.63	39.07
29	729911	857214	0.23	11.25	22.28	26.04	65.1
30	738863	857522	0.21	14.17	28.13	20.62	51.55
31	748125	857368	0.21	10	19.8	29.3	73.25
32	757232	857368	0.21	7.5	14.79	39.22	98.05
33	766957	857214	0.17	6.5	12.83	45.19	112.98
34	674341	848261	0.25	12.5	24.76	23.43	58.58
35	683603	848261	0.21	10	19.79	29.31	73.28
36	692864	848261	0.18	12	23.82	24.35	60.87
37	702126	848261	0.23	17.5	34.78	16.68	41.7
38	711387	848261	0.15	8.57	17	34.12	85.31
39	720495	848106	0.2	13.33	26.47	21.93	54.78
40	729911	848261	0.13	10	19.87	29.19	72.98
41	738863	848261	0.25	12	23.75	24.42	61.06
42	748125	848570	0.18	10	19.82	29.26	73.16
43	757232	848570	0.24	9.09	17.94	32.32	80.81
44	766802	848570	0.13	11.25	22.37	25.93	64.83
45	674341	838536	0.19	5	9.81	59.1	147.74
46	683603	838382	0.28	15	29.72	19.52	48.79
47	692864	838382	0.27	12.5	24.73	23.46	56.64
48	701972	838691	0.35	16.67	32.99	17.58	43.96
49	711387	838845	0.17	12	23.83	24.34	60.85
50	720649	838691	0.17	4.13	8.08	71.8	179.51
51	729756	838536	0.16	3.5	6.84	84.79	211.96
52	739018	838845	0.28	12.5	24.72	23.46	58.65
53	748125	838845	0.27	17.5	34.74	16.7	41.75
54	757386	838999	0.19	14	27.81	20.85	52.13
55	766802	838999	0.32	6.67	13.02	44.56	111.41

The results of the spectral depth analysis of the blocks are presented in tabular form in Table 1.
The estimated geothermal gradient of each spectral block is presented in the Table 1, and the geothermal gradient values of all the spectral blocks were gridded to generate the map of geothermal gradient in the study area. The computed geothermal gradient at Ikogosi warm spring area is around 71.8 – 84.79 °C/km, while in the other places within the study area resulted in maximum geothermal gradient of 59.1 °C/km and minimum 19.5 °C/km. The map of estimated geothermal gradient is shown on figure 10, the anomaly generated by the elevated geothermal is evidenced around Ikogosi warm spring at the southern part of the study area.

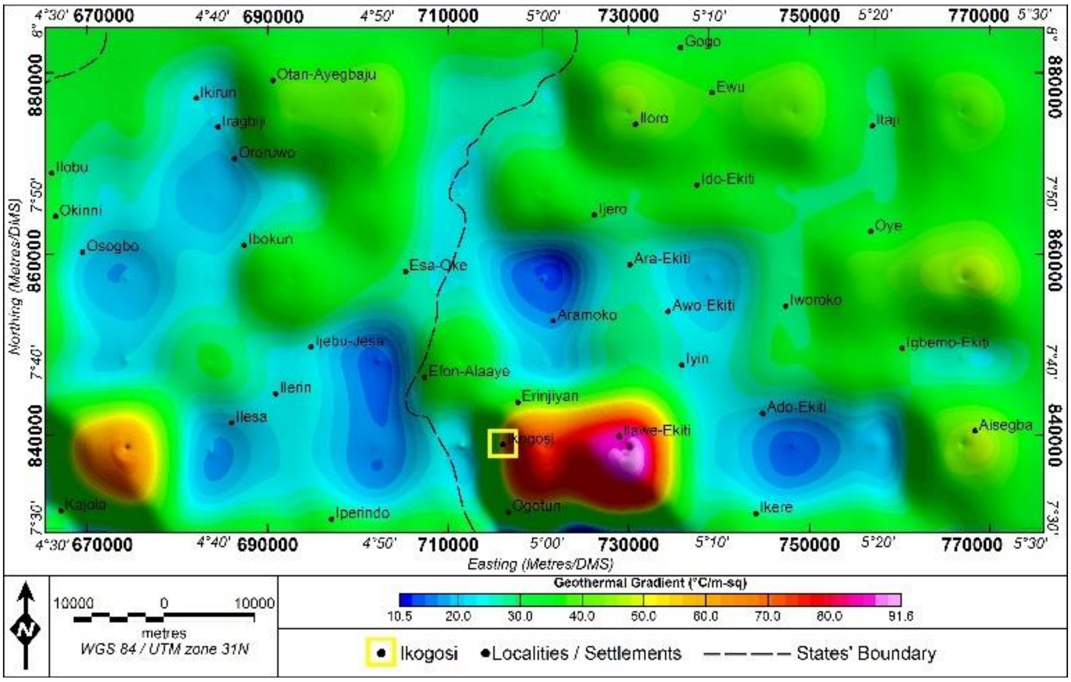

Figure 10, Map of Estimated Geothermal Gradient in the Study Area

The geothermal heat flow computed for Ikogosi warm spring ranges between 179.51 to 211.96 mW/m2 (Table 1). The map of estimated geothermal heat flow (Figure 11) in the study area shows a significant evidence of elevated geothermal heat flow around Ikogosi warm spring while comparing to the other places within the vicinity of the study area.

The computation of the geothermal gradient and geothermal heat flow of the spectral blocks is based on the following assumptions: the direction of temperature variation is vertical, the surface temperature is 0^0C, and the geothermal gradient is constant provided that there is no heat sources or heat sinks between the Earth's surface and the Curie isotherm depth that could cause heat gain or heat loss above and below the Crust.

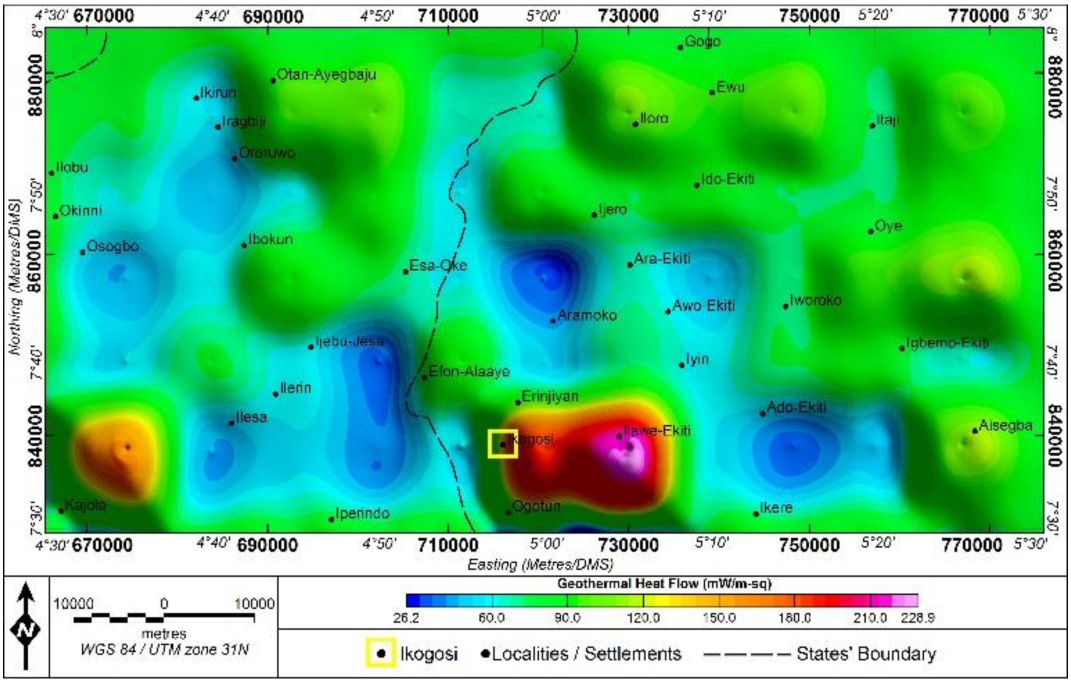

Figure 11, Map of Estimated Geothermal Heat Flow in the Study Area

V. Conclusion

The non-intrusive methods of exploration are considered for their wider coverage, cost effectiveness and to avoid potential environmental issues that are associated with intrusive method. The integration of spectral depth analysis and source parameter imaging techniques to estimate the geothermal potential of Ikogosi warm spring has become very important in harnessing the renewable energy source.

In this study, the result of the aeromagnetic geophysical prospecting methods suggests a primary geothermal reservoir within the upper crust that is possibly depicted by shallow Curie Point Depth (CPD) or Curie Isotherm Depth coupled with considerably high geothermal gradient and geothermal heat flow at the study area. The result of the work suggests the existence of geothermal resources in the study area and it is considered largely in tandem with the results of previous researches that were carried out in the area using similar or different approaches. As geothermal is not widely known in Nigeria, this work will shape the untapped geothermal energy thus engendering socio-economic development of Nigeria in alternative and more environmentally friendly power generation. This has great potential to jump start the much-desired industrial growth in Nigeria.

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Conflict of Interest Declaration.
The authors had no conflict of interest in course of executing the study.

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