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Geothermal resource potentials estimation from the interpretation of aeromagnetic data over parts of Southwestern Nigeria

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Abstract

In a bid to explore unconventional electricity generation sources and reduce effects of fossil fuels, this study evaluates geothermal resource potentials over parts of Southwestern Nigeria, precisely depth to the bottom of magnetic source (DBMS), heat flow, geothermal gradient and their relationships. Regional-residual anomaly separation was conducted, and spectral analysis was applied on the residual anomaly component of 14 aeromagnetic data sheets. Depth to the bottom of magnetic source varies between 1.87 and 6.26 km, with average value of 3.50 km, heat flow varies between 23.18 and 77.38 mWm^{-2}, with average value of 43.79 mWm^{-2}, while geothermal gradient varies between 9.27 and 30.95 °C/km with average value of 17.52 °C/km. Northcentral region has the highest heat flow (77.4 mWm^{-2}), followed by Northeast (68.3 mWm^{-2}), Southwest has the least (< 40.0 mWm^{-2}) while Southeast has values in between the extremes. A comparison between the average heat flow and that of 'thermally stable' continental regions of the world (60 or 65) mW/m^2 gives 72.98 or 67.37% respectively. The estimated heat is probably from mantle plumes, radioactive sources or heat generated from pressures within basements that are overlaid by thick thermally insulated sediments, hence hot magmatic fluid flows into fractured basement and cause hydrothermal alterations of surrounding rocks. Since most geodynamic operations depends on thermal structure of the earth's crust, the result of this study has undoubtedly contributed significantly to the body of existing thermal knowledge and closed the information gap regarding crustal temperature distribution at depth in Southwest part of Nigeria and Nigeria in general.

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1. Introduction

The necessity for non-conventional and clean renewable energy sources has become more widely recognized in an effort to decrease the impact of global warming, rising environmental pollution, increasing levels of greenhouse gases (GHG), and scarcity of fossil fuels, in addition to industrial development, population growth, and Nigeria's current 300% increment in Electricity Tariff and prevailing inadequate system for generating, transmitting, and distributing adequate electricity. One of those possible sources is the

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geothermal energy which has proved to be very effective in countries like United States of America which is leading, followed by Indonesia, Philippines, Turkey, and New Zealand. It has also been projected that the Global Geothermal Market will grow through 2021-2025. Geothermal Energy is the thermal energy produced in the Earth's crust as a result of the radioactive decay of rocks. This energy is harvested using geothermal heat pump, by pumping-in water or an antifreeze solution to absorb the heat before turbines convert it into electric power. Unlike other renewable energy sources such as solar and wind, geothermal energy is readily accessible and emits paltry 16.67% of the carbon dioxide produced by a natural gas power station.

For several decades, oil firms have been searching and exploring the Nigeria's sedimentary basins for hydrocarbons, however not enough is known about the geology, geotechnics and geophysics of the country's Precambrian crystalline region. Fundamental to the assessment of geothermal energy in an area is the depth to the bottom of the magnetic source which is the maximum depth in the earth crust containing structures that express distinguishable geophysical or geological signatures in a magnetic anomaly map, it is therefore considered that the depth at which the geothermal resource (magmatic chamber) can be explored occurs at a temperature of 550 ± 30 degrees Celsius. The depth to the magnetic sources provides crucial information concerning regional and local temperature distribution, in addition to the heat flow and geothermal gradients of an area. The aforementioned provides avenue for an improved understanding of spatial thermal composition of the earth crust via aeromagnetic data interpretation. A regional aeromagnetic data analysis over Bida Basin was conducted by Ref. [1]. The study concluded that ranges between 15.60 to 29.60 km, with the ensuing heat flow between 48.40 to 93.10 mWm^{-2} while thermal gradient ranges between 19.60 to 37.30^{o}C/km. An analysis of aeromagnetic data over Wikki warm spring area of Northwestern Nigeria was carried out by Ref. [2]. The results show an average depth to the bottom of magnetic source of 10.72 km, thermal gradient of 54°C/km and heat flow of 135.28 mW/m^2. Heat flow investigation over parts of the Southern Bida Basin in Nigeria and its neighboring basement rocks using both aeromagnetic and radioactive data was done by Ref. [3]. Their research showed heat flow values ranging from 69.17 to 124.82 mWm^{-2}. An analysis of aeromagnetic data over the Ikogosi warm spring in Ekiti state was undertaken by Ref. [4]. The depth to the bottom of magnetic source and geothermal gradient of the area were estimated to be 5.8 km and 112°C/km respectively. Ref. [5] measured temperature variation with depth in the Niger Delta area using borehole temperature data from oil wells. The results showed that geothermal gradient was between 1.3/100 to 4.7°C/100 m and the value increases northwards to about 5.5°C/100 m in Anambra Basin. Also, Ref. [6] investigated the geothermal conditions within Sokoto and the sedimentary basins part of Chad. The results indicate higher geothermal gradients of between 7.6 and 5.9°C/100 m. Also worthy of interest in Ewa and Kryrowska [5] is the thermal springs and seepages around the sediments of Benue Trough, comprising the Akiri and Ruwan Zafi with temperature of about 54°C. The results of their investigation is indicative of the presence of some geothermal anomalies. An assessment of the heat flow anomalies in Nupe Basin, West Central Nigeria was done by Nwankwo *et al*. [6]. The results suggest heat flow ranging between 30 and 120 mWm^{-2}, while geothermal gradient ranges from 10 and 45℃/km in southern part of Nupe Basin. Some studies have also been conducted in different parts of Nigeria [7–11].

However, very many of these studies have been localized around hot/warm springs. When examining geothermal resources, the average heat flow in thermally stable part of the continent is often greater than 60 mWm^{-2}, while heat flow ranging between 80 to 100 mWm^{-2} means an anomalous geothermal condition [11, 12]. Till date, regional geothermal resource investigation is still not widely known in Nigeria especially in Southwestern region, though there have been few estimations of subsurface temperature distribution in oil wells from the exploration for hydrocarbons, and shallow water wells in South-South Nigeria, some of which were corroborated with geothermal surface manifestations. Much of these researches have not been carried out within the Precambrian basement area of Nigerian on a large scale as we have in the current study. This study lays more emphasis on the determination of depth of the bottom of magnetic source (DBMS), heat flow, geothermal gradient, their relationships cum dynamics, and identifying areas of high geothermal potential through the interpretation of aeromagnetic data covering parts of Southwestern Nigeria. The spectrum analysis methodology has the benefit of eliminating noise from the data while preserving relevant information during the process, this is unlike other geophysical techniques [13]. Since thermal structure of the earth crust controls most geodynamic activities, this study in no small measure will contribute to the few available thermal information and shorten the gap of inadequate crustal temperature data at depth in Southwest in particular and Nigeria in general.

2. Geology of the study area

The study area is located between latitudes 6°23′ and 7°38′ and longitudes 3°53′ and 5°8′. The region is underlain by two geologic units (Figure 1); the Basement Complex Rocks (about 90%) and the Sedimentary Basins located in the coastal areas and the ensuing river tributaries around Lagos state and parts of Ondo state [14, 15]. The basement complex of Southwestern Nigeria originated from the Pan African orogenic belt, located between the west African/Congo Cratons and towards the South of Tuareg Shields [16], and it is largely made up of three rock units; the migmatite and gneiss controlled (Liberian to Pan-African age), the schists (meta-sediments) with quartzites and other minor lithologies structuring a long, narrow, north-south trends, and lastly the intrusive granitic rocks, otherwise referred to as Older Granites (Late Precambrian to Early Palaeozoic age) and lastly, the Jurassic Younger Granites [17]. The migmatite in particular vary from coarsely blended gneisses to diffused textured rocks of diverse grain sizes and are often porphyroclastic in nature. On the contrary, sedimentary rocks are made-up of poorly bedded grits, conglomerate, sandstone, shale, silts, silty shale, clay, mudstone, and sometimes intruded by igneous/dolerite dykes etc. These sedimentary rocks come in different

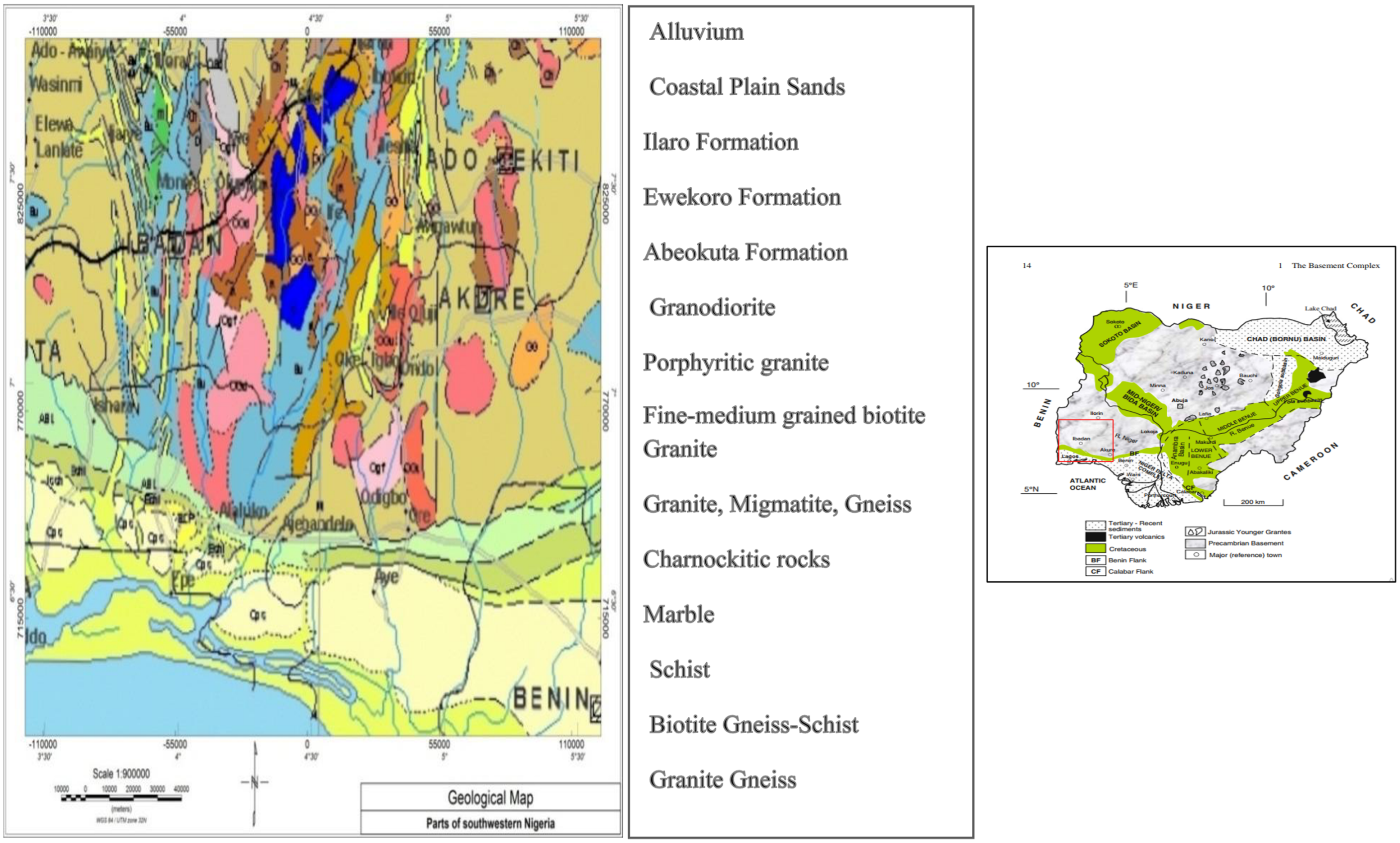

Figure 1: Geological map of the study area (Nigerian Geological Survey Agency, 2010).

thicknesses and expresses single or multiple cycles developmental processes as characterized by continental facies overlain by costal facies and successively by continental sediments, and overlies the Precambrian complex, exhibiting various unconformities, often indurated and controlled by fracture flow, depending on the level of fracturing and weathering.

3. Materials and methods

3.1. Materials

The aeromagnetic data was obtained sequel to the Nationwide Airborne Geophysical Survey by Fugro Airborne Survey Services for the Nigeria Geological Survey Agency (NGSA) [18]. The map scale is 1: 100000 series. Data measurements and collection were made by three (3) ScintrexCS2 Cesium Vapour Airborne Magnetometers, on a flight elevation of 100 meters, along NW-SE flight lines at 500 m interval and a NE-SW Tie Line at 5000 m line interval. The survey also included 135 degrees for Flight Line Trend and 225 degrees for Tie Line Trend, as well as 80 meters for Sensor Mean Terrain Clearance, recorded at 0.05 seconds interval. For this study, fourteen (14) aeromagnetic data sheets covering Ibadan (Sheet No. 241), Iwo (Sheet No. 242), Ilesha (Sheet No. 243), Ado-Ekiti (Sheet No. 244), Abeokuta (Sheet No. 261), Ife (Sheet No. 262), Ondo (Sheet No. 263), Akure (Sheet No. 264), Ijebu-Ode (Sheet No. 280), Lekki-Epe (Sheet No. 281), Okitipupa (Sheet No. 282), Siluko (Sheet No. 283), Mahin (Sheet No. 296) and Okowu (Sheet No. 297) were used. Data from the Aeromagnetic Anomaly Map was extracted using GEOSOFT Oasis Montaj Software as the Maps are in GEOSOFT Grid File Format, while the diurnal magnetic variations were eliminated using International Geomagnetic Reference Field [19]. The regional fields were deducted from total magnetic intensity values (Figure 2) at the grid cross point using Oasis Montaj Software Programme, in order to obtain the Residual magnetic values (Figure 3). The logarithms of the spectral energies versus the estimated frequencies for different blocks were plotted. From each graph, a linear segment from the low-frequency part of the spectra could be extracted, which represents contributions from the deeply seated subsurface anomalous bodies. The depth to the magnetic sources (Figure 4) was computed from the estimation of the slope of the linear segments to ascertain the depth to causative bodies, then the geothermal gradient (Figure 5) and heat flow (Figure 6) were determined. Among the earliest studies on the estimation of depth to the magnetic sources using spectral interpretation of geomagnetic data are those of Refs. [16] and [20] who published analyses for various regions of the United States. Other investigations involve parts of; Japan [21, 22], Greece [23, 24], Portugal [25], Bulgaria [26], Turkey [27, 28]. Furthermore, Ref. [29] showed the relationship between spectrum of anomalies and magnetic source depths by transforming spatial data into frequency domain.

3.2. Methods

3.2.1. Depth to the Bottom of the Magnetic Source (DBMS) Estimation (Z_b)

Following the recommendations of Okubo *et al.* [21], the depth to the bottom of the magnetic source is evaluated in two procedures; first is the distance from the slope of the spectrum's longest wavelength portion to the centroid of the magnetic sources (z_o), as follows;

$$In\ H(s) = In\ A - 2\pi s z_O, \tag{1}$$

while slope of the spectral segment with the second longest wavelength is used to estimate the depth to the top boundary (z_t) of that distribution as;

$$In\ H(s) = In\ B - 2\pi s z_t, \tag{2}$$

where $H(s)$ is the radially averaged power spectrum of the anomaly, s is the wave number while A and B are constants independent of s.

The depth to the bottom of the magnetic Sources (Z_b) is therefore determined from equation (3) [21, 30] as follows;

$$z_b = 2z_0 - z_t. \tag{3}$$

The radial spectrum's logarithmic plot would result in a straight line with a slope (m) of (-2z). The ensemble's mean depth of burial hence becomes [14]:

$$Z = \frac{-m}{2}. \tag{4}$$

Equation (4) applies when the frequency unit is in radians per kilometer. In a case where the frequency unit is measured in cycles per kilometer, the corresponding relation becomes:

$$Z = \frac{-m}{4\pi}. \tag{5}$$

3.2.2. Geothermal parameters estimation: Heat flow and geothermal gradient

The heat flow (Q) and thermal gradient (GTG) is calculated using Fourier's heat transfer law expressed as:

$$Q = k(\frac{dT}{dz}) = k(\frac{\theta}{z_b}). \tag{6}$$

Let Q be heat flux (W/m^2) while k is the thermal conductivity (W/(mK)). The average thermal conductivity for igneous rocks is taken to be 2.5 $Wm^{-1}\ °C^{-1}$ [28, 31].

The geothermal gradient (GTG) is derived from the Curie temperature θ, (θ = 580°C in the continental crust) and it is expressed [27, 28, 30, 32];

$$GTG = \frac{dT}{dz} = \frac{\theta}{z_b} = \frac{580°C}{z_b}. \tag{7}$$

The average gradient depth in areas that are distant from the edges of tectonic plates is about 25–30°C/km [33]. As a result of this relationship, rocks typically have higher thermal conductivity as one descends into the earth. Unfortunately, we don't have precise data regarding the thermal conductivity of deep-seated rocks. By combining equations (6) and equation (7), the relationship between depth to the bottom of the magnetic sources and heat flow (Q) can be established thus;

$$z_b = k\frac{\theta}{Q}. \tag{8}$$

Equation (8) suggests that shallower isotherms correlates with areas of high heat flow and vice versa [30, 34].

4. Results and discussion

4.1. Depth to the Bottom of the Magnetic Sources (Z_b), Geothermal Gradient (GTG) and Heat Flow (Q)

4.2. Relationship among Depth to the Bottom of the Magnetic Sources (Z_b), Geothermal Gradient (GTG) and Heat Flow (Q)

To probe further into any possible relationship among these geothermal parameters, graphs of the inferred Heat Flow Q (m/Wm^2) versus Depth to the Bottom of the Magnetic Sources Z_b (km), and Geothermal gradient ($^0C/km$) GTG versus Depth to the Bottom of the Magnetic Sources Z_b (km) were plotted which gave an inverse linear relationship. Also plotted was the graph of heat Flow Q (m/Wm^2) versus Geothermal gradient, which exhibited a direct linear relationship.

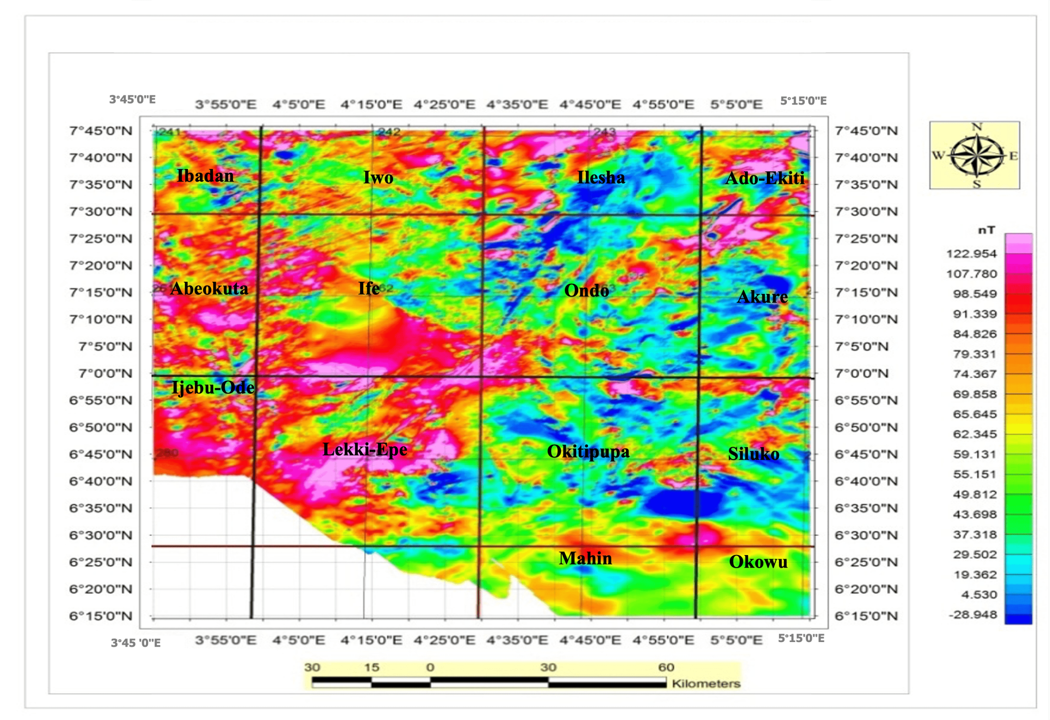

Figure 2: Total magnetic field intensity map of the study area (Add 33,000 nT to the legend value).

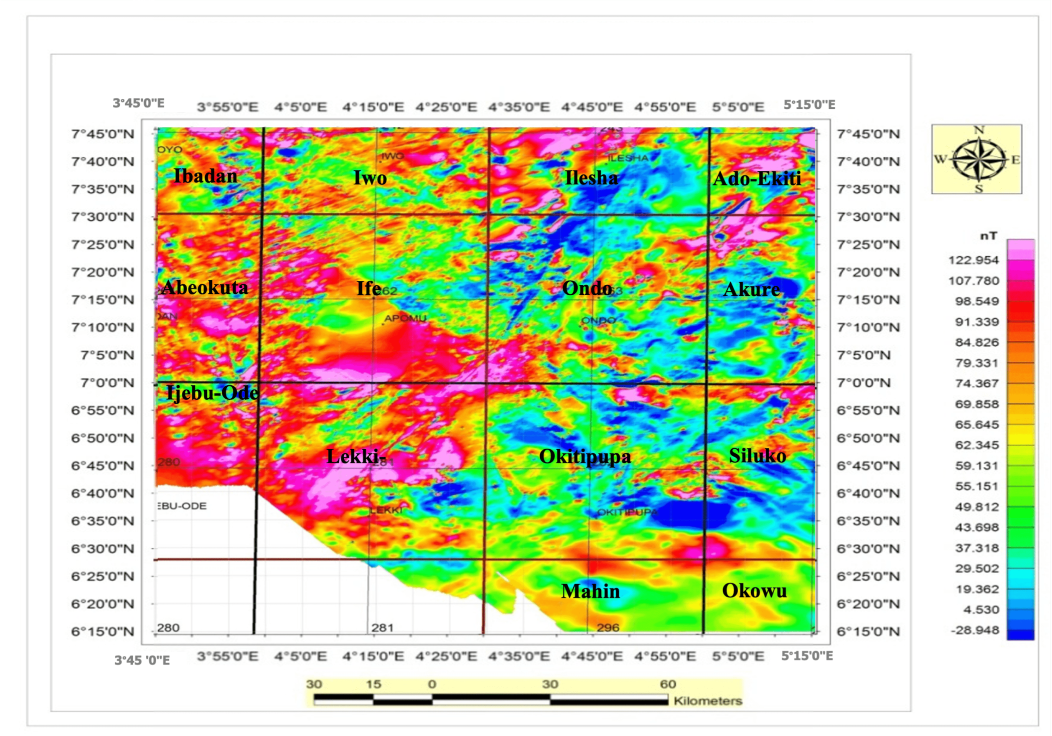

Figure 3: Residual magnetic field intensity map of the study area (Add 33,000 nT to the legend).

4.3. Discussion

The total magnetic field intensity embodies a combination of both long and short wavelengths features over the study area and these variations are due to corresponding changes in the magnetization of rocks beneath the magnetometer. The residual magnetic field intensity map (Figure 3) shows magnetic intensities ranging from -81.4755 to 73.4458 nT. The magnetic high of magnitude 73.4458 nT observed in the western and Northern parts of the study area (basement complex area) consisting of Oyo (Sheet No.

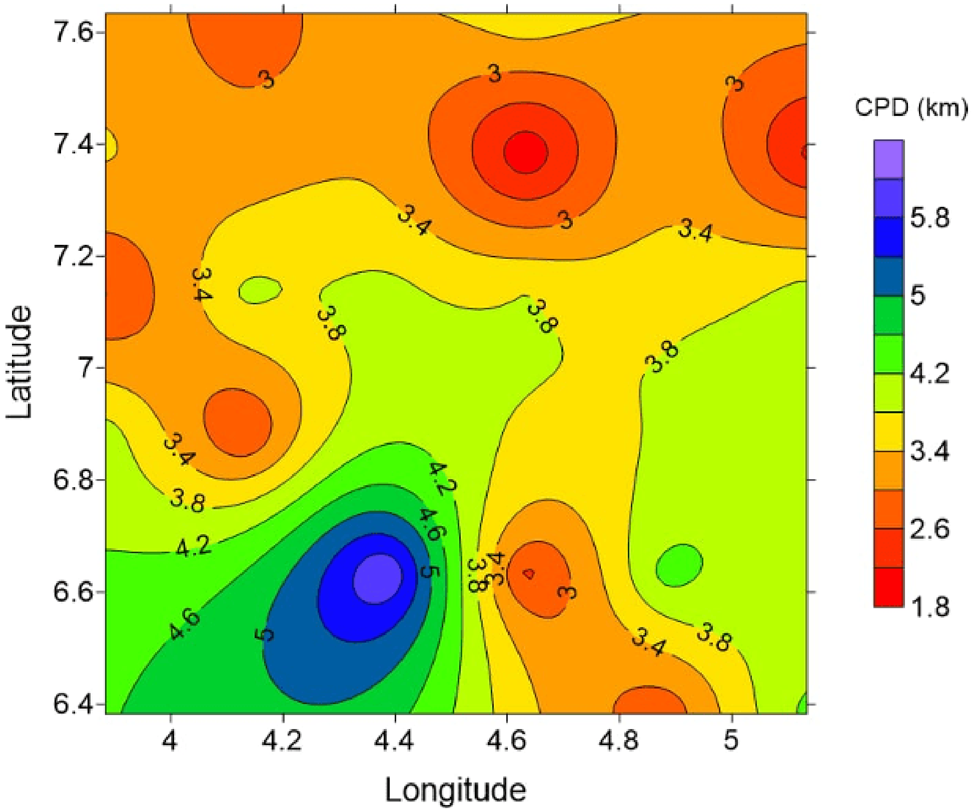

Figure 4: Depth to the Bottom of the Magnetic Sources (Z_b) contour map of the study area (contour interval of 0.4 km).

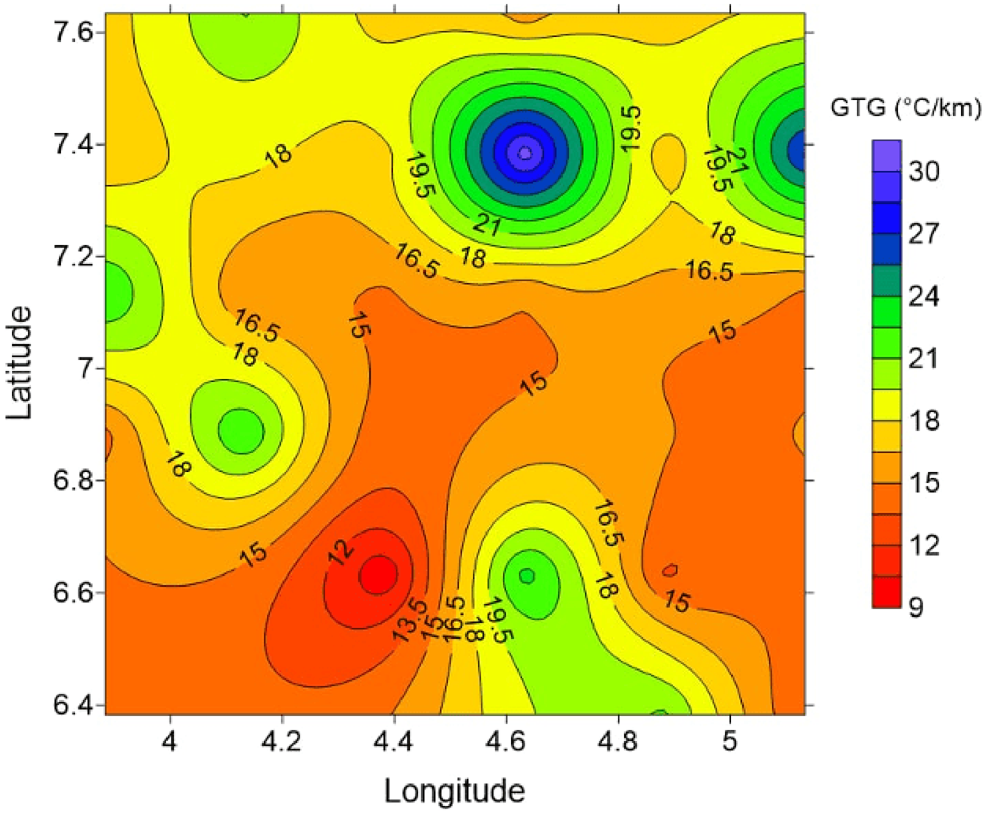

Figure 5: Geothermal gradient contour map of the study area (contour interval of 1.5°C/km).

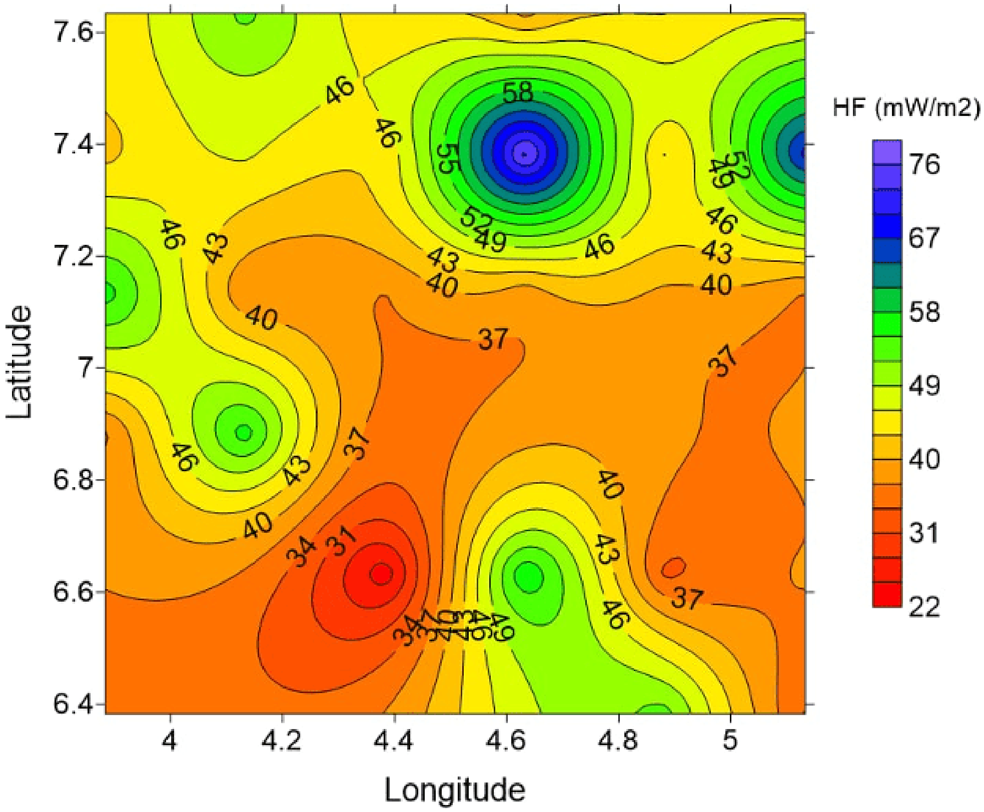

Figure 6: Heat flow contour map of the study area (contour interval of 3 mW/m^2).

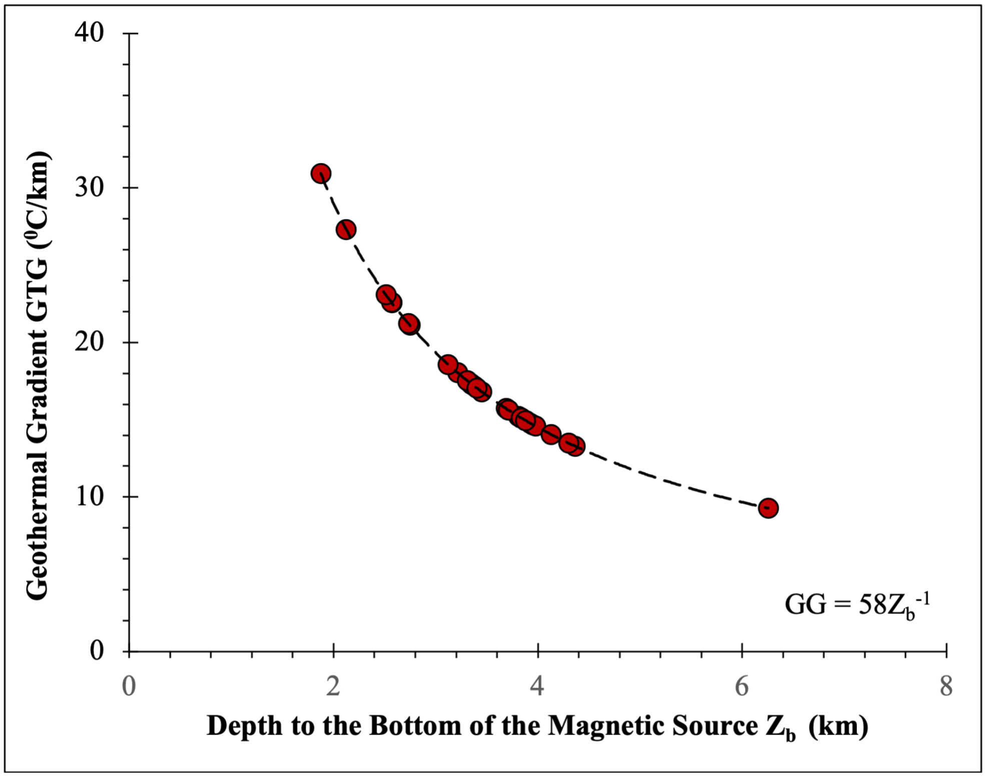

Figure 7: Relationship between Geothermal Gradient (GTG) and Depth to the Bottom of the Magnetic Sources (Z_b).

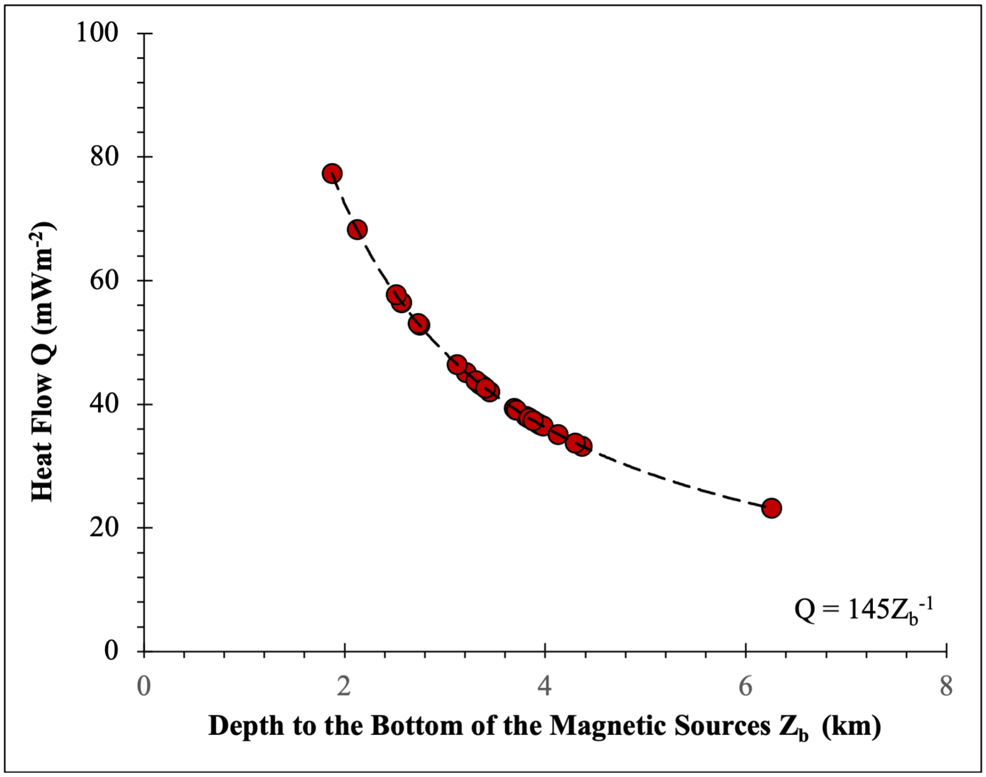

Figure 8: Relationship between Heat Flow (Q) and Depth to the Bottom of the Magnetic Sources (Z_b).

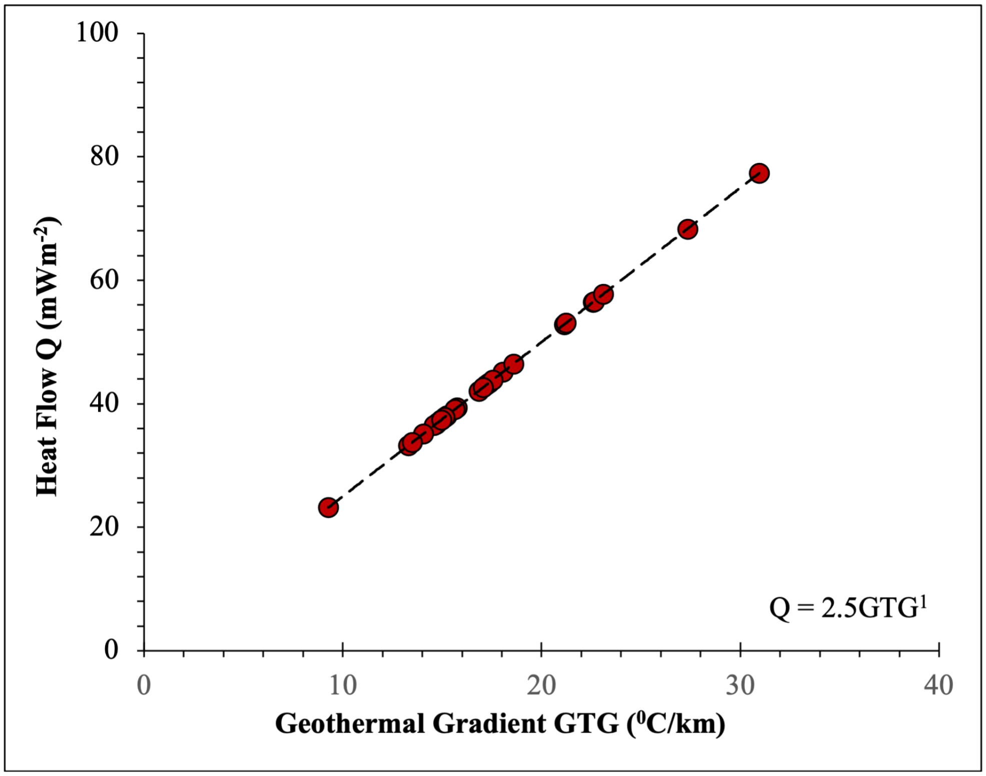

Figure 9: Relationship between Heat Flow (Q) and Geothermal Gradient (GTG).

241), Iwo (Sheet No. 242), Ilesha (Sheet No. 243), Ibadan (Sheet No. 261), Ife (Sheet No. 262), Ijebu-Ode (Sheet No. 280), Lekki-Epe (Sheet No. 281) can be attributed to the influence of shallow basement igneous and metamorphic rock units originating from the reactivated Nigerian-Dahomeyan formations, unlike areas such as; (parts) of Ilesha (Sheet No. 243), Ondo (Sheet No. 263), Akure (Sheet No. 264), Okitipupa (Sheet No. 282) and Siluko (Sheet No. 283) where negative magnetic anomalies were recorded (sedimentary basin area), probably because of the presence of schist. The closures of magnetic low are mostly in areas with thick sedimentary cover whereas closures of the magnetic high are probably due to shallow basements, due to thin sedimentary cover or basic intrusion into the igneous and metamorphic basement rocks [14].

The computed depth to the bottom of the magnetic Sources (Z_b) shows values ranging between 1.87 and 6.26 km. We observed that the depth to the bottom of the magnetic Sources in Northcentral region (2.0 – 3.8 km) is the shallowest, followed by Northeast (2.2 – 3.8 km), Northwest (2.8 – 3.8 km), and then the Southeast (2.6 – 4.0 km), while the Southwestern (3.8 – 6.3 km) part shows the deepest value. The shallow depth to the bottom of the magnetic Sources (Z_b) could be because of the upward flow of magma, or magmatic intrusion into the heavily fractured quartzite units and the intruded older granite units. On the contrary, the deeper magnetic sources observed around Lagos and parts of Ondo state (Southwestern portion) can be attributed to isostatic compensation or recovery. The above result agrees with the conclusion by Ref. [14] that sedimentary rocks have rather low magnetic intensity, the observed intensity over them is largely due to igneous or metamorphic basement rocks or sedimentary rocks with banded iron formations. Studies in recent past [23, 24, 30–32] have shown that depth to the magnetic sources are largely dependent on the geological composition of the subsurface. According to Ref. [30], in volcanic and geothermal regions, depth to the magnetic sources is usually below 10 km, in island arcs and ridges, it is between 15 and 25 km, above 20 km on plateaus, moreover deeper than 30 km and above in trenches. Fortunately, our study area qualifies for the first condition stipulated above, since depth to the magnetic sources is largely less than 10 km in depth across the entire study area, thereby suggesting that the study area is an explorable geothermal field especially the North-central region which showed the shallowest depth to the magnetic sources.

The geothermal gradient has values between 9.27 and 30.95°C/km (Figure 5) with an average value of 17.55 °C/km. The result also shows that the heat flow varies between 23.18 and 77.38 mW/m^2 (Figure 6) with an average value of 43.79 mW/m^2. Heat flow are generally less than 40.0 mWm^{-2} in the Southwestern part of the study area, the Northcentral has the highest heat flow value (77.4 mWm^{-2}) followed by Northeast (68.3 mWm^{-2}) while the Southeastern and other Northern parts has heat flow values in between the two extremes. From these results, the shallowest depth to the magnetic sources corresponds to highest heat flow, which is consistent with global geothermal models and suggestions by Refs. [30, 31, 35, 36]. The high heat flow obtained in the Northeastern, Northcentral, Northwestern and Southeastern part of the area under study is characteristic of the thinning of the crust and suggests that magmatic intrusion of sills into rocks must have altered the local temperature and heat flow by orders of magnitude thus making the Southwestern Nigeria susceptible to possible tectonic activities than the neighboring Nupe Basin, Niger-Delta and Anambra basin. According to the study by Obande *et al.* [11], the mean heat flow in thermally stable continental regions are usually above 60 mWm^{-2}, while the anomalous geothermal regions have heat flow between 80 to 100 mWm^{-2}.

However, geothermal heat values greater than 100 mWm^{-2} demands further investigations, implying very anomalous heat flow [12]. The presence of free flowing springs and waterfalls in our study area coupled with warm temperatures recorded in them confirms that pressure and temperature varies directly with depth and hence serving as very good indication of enormous heat generated in the underlying rocks, as exemplified especially by the Ikogosi warm springs, situated on over 116 km hectares of land. Flowing alongside the warm spring is a cold spring and both meets at a confluence while maintaining their individual thermal properties. The warm spring has a temperature of 70 degrees Celsius at the source and 37 degrees Celsius at the meeting point. Other springs and waterfalls in the region under investigation include, Erin-Ijesha waterfall in Osun state, Arinta waterfall in Ekiti state, and the Effon-Alaaye waterfall in Ekiti state.

However, Owu waterfall, Soose spring, Kange warms fresh water spring (33.4°C), Ribi warms saline spring (33.2°C) and Igbonla hot spring are all in nearby Kwara state which is located just above our study area. The Igbonla springs for example stands as one of the hottest springs in Nigeria and has a temperature of 51°C. ‘these springs and waterfalls provides similar geothermal signatures and whose geothermal trends can be traced upwards from our study area. Furthermore, the heat flow values were undulating, indicating that the thermal conduits and magmatic intrusions are randomly oriented. Generally, geothermally or tectonically active regions correspond to low depth to the magnetic sources [14], which is linked to increased heat flow, while a thick magnetic crust indicates stable continental regions. The outcome of this study is in agreement with the above conclusions. The reasoning that a thin magnetic crust suggests areas of active crustal movement corresponding to shallow depth to the magnetic sources while a dense magnetic crust implies stable continental regions is supported by the locations of the aforementioned geothermal signatures. The nature of the heat channels and the dependability of the heat source are the most important criteria for the production of geothermal resources in regions with low depth to the magnetic sources. The emplacement of volcanic rocks may be the source of the heat; if the magma cools and is unable to sustain a steady supply of heat, the igneous rock intrusion creates a deep structure that serves as a new conduit for precipitation and groundwater [35].

Since there is paucity of crustal temperature at depth database in crystalline basement complex regions of Nigeria [34, 37], we compared the estimated average heat flow in this study (43.79 mW/m^2) with the average heat flow in ‘thermally stable’ continental regions of the world which is 65 or 60 mW/m^2 [12], values in excess of between 80 to 100 mW/m^2 and above, suggests anomalously active geothermal conditions [12, 37]. The heat flow results from our study indicates 67.37 to 72.98% of the range of values stipulated for stable continental regions aforementioned. The heat flow in our study area is probably coming from mantle plumes, subduction/rift zone or radioactive heat sources. Another possible cause is the heat generated from pressures within the basement rocks that are overlaid by thick thermally insulated sedimentary layer, or igneous (or metamorphic) rock intrusion into the sediments, as a result of which hot magmatic fluid flows to or close to the earth's crust into the fractured basement and caused hydrothermal alterations of the surrounding rock. This is buttressed by the fact that there are documented evidences of seismic/tectonic events and intrusions in the study area.

However, we can deduce that areas with relatively high geothermal energy are certainly related to the former rather than the latter since there have been series of evidence of geothermal and tectonic signatures such as warm springs, waterfalls, seismic events and intrusions in the area. Therefore, regions of high geothermal gradient (Figures 5) and high heat flow (Figures 6) will likely be geothermal energy storage points, especially the Northcentral region having the highest heat flow value (77.40 mWm^{-2}) and followed by the Northeastern region (68.30 mWm^{-2}).

Figure 7 expresses the variations in depth at which rocks loses their magnetism due to the increase in temperature. The graph shows a linearly inverse relationship between geothermal gradient and the depth to the magnetic sources. Also, a graph of heat flow versus depth to the magnetic sources (Figure 8) revealed that the heat flow in the study area decreases with the deepening of the magnetic sources. With reference to our study area, the above statement suggests areas of increased heat flow such as the Northcentral and Northeast correlates with shallow depth to the magnetic sources, whereas regions of low heat flow such as the Southwestern region are analogous with increased depth to the magnetic sources. The spatial difference in the amount of heat flow is due to differences in the structural compositions, rock intrusions and lithological units of the earth's crust. Since the over pressured subsurface formations are related to higher geothermal gradients, the estimation of heat flow hence offers a general perspective of the geothermal energy distribution in the subsurface of the study area. The relationship between heat flow and the geothermal gradient (Figure 9) shows a direct linear relationship, indicating that areas of high heat flow (Northcentral and Northeast) are correlated with high geothermal gradient areas. These locations coincide with the Erin-Ijesha waterfall (Osun states), Arinta waterfall (Ekiti state), Effon-Alaaye waterfall (Ekiti state) and Ikogosi Warm Spring area (Ekiti state). The Ikogosi thermal spring for instance is the most popular warm spring in Southwestern Nigeria, located within the quartzite-schist formation of the basement complex. Also, this same geothermal trend continues northwards to locations where we have the Owu waterfall, Soose spring, Kange warm fresh water spring (33.4°C), Ribi warm saline spring (33.2°C) and Igbonla hot spring (51°C) springs though just above our study area in Kwara state. In addition, the results above prove the fact that depth to the magnetic sources is both linearly and inversely related to heat flow and geothermal gradient as posited by previous studies [30, 31, 34–36, 38]. The results of this study clearly shows that the estimation of depth to the magnetic sources, geothermal gradient and heat flow is related to the thermal and geological composition of the area under investigation.

5. Conclusion

The aeromagnetic anomaly data over parts of Southwestern Nigeria have been interpreted to estimate depth to the magnetic sources, geothermal gradient and heat flow. From the result, the geothermal gradient varies between 9.27 and 30.95 °C/km with an average value of 17.52 °C/km while depth to the magnetic sources varies between 1.87 and 6.26 km, with a mean value of 3.50 km, the heat flow varies between 23.18 and 77.38 mWm^{-2}, having an average value of 43.79 mWm^{-2}. Heat flow are generally less than 40.0 mWm^{-2} in the Southwestern part of the study area, the Northcentral has the highest heat flow value (77.4 mWm^{-2}) followed by Northeast (68.3 mWm^{-2}) while the Southeastern and other Northern parts has heat flow values in between the two extremes. From these results, we observed that areas with shallow depth to the magnetic sources, correspondingly has high geothermal gradient and high heat flow. The observed heat is attributable to mantle plumes, rift zone or radioactive heat sources. It can also be as a result of heat generated due to pressures within the basements that are overlain by thick thermally insulated sedimentary layer, or rock intrusions into the sediments, hence hot magmatic fluid flows to or close to the earth's crust into the fractured basement and caused hydrothermal or structural alterations of the surrounding rocks. This conclusion is supported by the avalanche of records of seismic and tectonic events in Southwestern part of Nigeria. Since most geodynamics activities are dependent on the thermal structure of the earth crust, this study no doubt has contributed immensely to the available thermal information and shorten the gap of inadequate crustal temperature data in Southwestern Nigeria and Nigeria in general.

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