ASSESSMENT OF GEOTHERMAL POTENTIAL IN PARTS OF NIGER DELTA, NIGERIA, USING HIGH RESOLUTION AEROMAGNETIC DATA

BY

OSEZUA, Blessing Ehinome
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DEPARTMENT OF PHYSICS
SCHOOOL OF PHYSICAL SCIENCES
FEDERAL UNIVERSITY OF TECHNOLOGY
MINNA, NIGER STATE

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ABSTRACT

Geothermal potential in parts of Niger Delta region corresponding to Warri, Kwale, Burutu and Patari was assessed using spectral analysis of aeromagnetic data. The study area covers a total area of 12,100 km^2 and it is bounded by latitudes 5°00′ and 6°00′N and longitudes 5°30′ and 6°30′E. The total magnetic data of the area was subjected to spectral analysis using Matlab, Oasis Montaj and Surfer 13 software's. Regional/residual separation was applied on total magnetic intensity map and thereafter the residual map was divided into 16 overlapping blocks. Spectral analysis was done on the overlapping blocks and showed variations of high and low magnetic signatures. The Centroid depth and depth to top boundary were obtained from the plot of log of power spectrum against wavenumber. These two parameters were used to determine the Curie point depth (CPD). The Curie point depth obtained was then used to determine the geothermal gradient and the heat flow over the study area. The result of the study shows that the deepest depth of sedimentary thickness was found in the central region and ranges between 11 km and 13 km. From the same central region corresponding to Uvwie, Udu, north of Ughelli and Isoko, shallow Curie point depth vary between 16 km and 30 km. The corresponding geothermal gradient and the heat flow values varying from 19 to 36 ^{o}C/km and 28.00 to 88.00 mW/m^2 respectively. Therefore, harnessing geothermal potential in this area is probable within the central region and would be an added advantage to power generation in Nigeria.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Geothermal energy is the heat energy that is generated and stored in the earth and comes from the subsurface of the earth. The earth's internal heat is obtained from radioactive decay of radioactive materials and the continual heat losses from the earth's formation.

The temperature at the core-mantle boundary may reach over $4000℃$ $w$hich causes some of the rocks in the center of the Earth to melt and form hot molten rocks called magma. This heat also causes the mantle to behave plastically resulting in parts of the mantle convecting upward since it is lighter than the surrounding rock. Rock and water is heated in the crust, up to $370℃$ as the core – mantle boundary temperature reaches up to $4000℃$. This energy can be used for many applications but most importantly to generate electricity. (Otobong and Onouvughe, 2016).

Geothermal energy is a sufficient and renewable energy source which can be used to generate unlimited electricity, for cooking, industrial application, swimming, agricultural application and heat pumps. There has never been a more urgent time to look into the generation of electric power from this source to complement the ones being used, Nigeria as a country cannot be left out from the possibility of exploring geothermal energy (Ewa and Kryrowska 2010).

Due to the many benefits of geothermal energy such as; unlimited power supply, environmental friendliness, low emission of greenhouse gases, and global availability more attention has been given to it in other countries as an alternative source of energy. All these benefits make geothermal energy a very vital contributor to the global energy productions in an environmentally friendly way (Sui *et al.*, 2019).

In Nigeria the massive increase in population and the under-utilization of renewable sources such as geothermal energy is one of the causes of insufficient supply of electric power generation and uneven electric power distribution (Bamisile, 2014).

Adequate power generation is one of the vital roles for economic, financial and social growth of a country. Limitation in exploring other sources of energy in the Niger Delta has led to increase joblessness among youths as many multi-national companies as well as small and medium scale enterprises (SMEs) have fold up, crime rate and other social vices also have increased tremendously. Energy and poverty reduction are not only closely related but also with the socioeconomic development, which involves productivity, income growth, education and health. These challenges emphasize the need to explore all available renewable energy sources to map out a new energy future for Nigeria (Abraham and Nkitnam, 2017).

Geothermal energy is considered as one of the most favorable expectation and dependable energy resources for Nigeria and most especially in the Niger Delta. It is renewable, hardly affected by the weather and always available to provide a reliable and steady output. Future growth is expected that geothermal energy reach more than 3% of the global electricity demand by 2050 (Geothermal, 2018). If explored in the Niger Delta will reduce the need for imported fuels for power generation, mass rural-urban drift and therefore encourage agriculture, health and socioeconomic activities.

High resolution aeromagnetic survey is considered the best method for geothermal exploration, it is used to locate the hidden intrusive rocks, find the areas with reduced magnetization (Curie depth) which causes thermal activities and determine the top to basement depth (Dasgupta *et al.,* 2013). The aeromagnetic data will be interpreted using spectral analysis method to estimate the Curie point depth, Heat flow and the geothermal gradient in the study area.

This work focuses on assessing the geothermal potential in parts of Niger Delta using high resolution aeromagnetic data. The outcome of this research work will determine the Curie point depth, Heat flow and the geothermal gradients which are the three main parameters considered in geothermal exploration; hence ascertain whether the study area is suitable for a geothermal site.

1.2 Location of the Study Area

The area of study is located in Niger Delta, it is bounded by latitudes 5° and 6°N and longitudes 5.5°and 6.5°E with an estimated total area of 12,100 km^2. This comprises the following areas; Burutu, Patani, Warri, Ughelli, Uvwie, Ahoada, Kwale, Isoko and Ndokwa, (Figure 1.1). The Niger Delta region lies within the southern sedimentary basin at the southern flanks of the lower Benue Trough (Obaje, 2009). The area is characterized by a wetland ecosystem that is found in the Atlantic coast of southern Nigeria with a subsurface area covering over 70,000 km^2. The basin is dominated by limited hills and mountains and the dominance of rolling plains. It is characterized by a tropical climate with rainy and dry seasons. The mean temperature ranges between 25°C and 29°C, with the annual rainfall range between 2000 mm and 4000 mm. The rainy season in the Niger Delta lasts from March to October, with a little dry spell experience during the August break due to monsoon winds from the southwest that carries moisture from the ocean into the hinterland (Floyd, 1969). The dry season lasts from November to February with harmattan experienced between December and February that is caused by tropical continental air mass from the north.

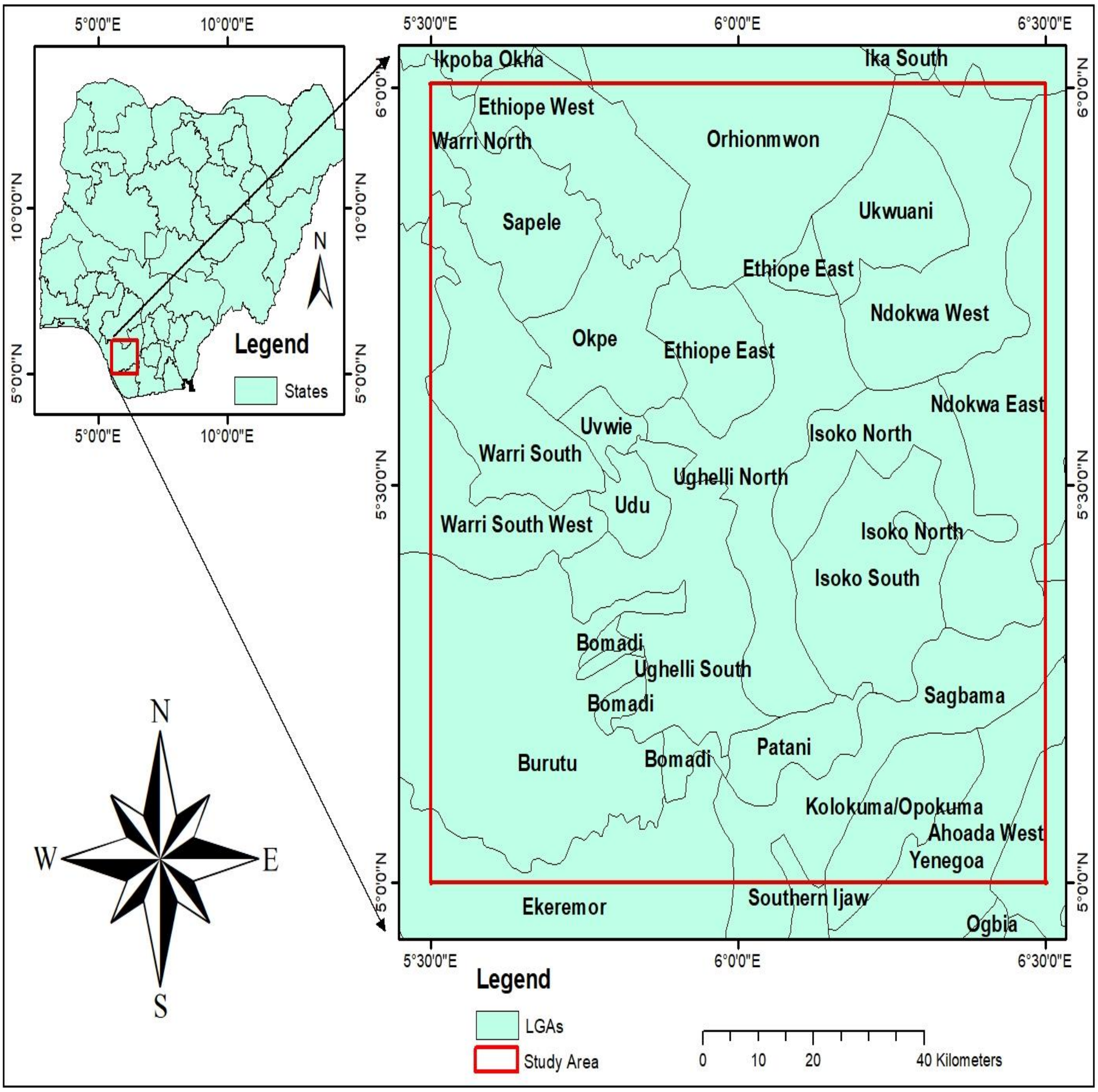

Figure 1.1: Location map of study area

1.3 Statement of the Research Problem

Over the years Nigeria and most countries in Africa have been known to rely solely on hydro and fossil fuel for the generation of power supply, as a result, much have not been put into consideration on other alternative sources present (Lawal *et al.,* 2018). The limited supply of electric power in the Niger Delta and country at large has made other sectors such as agriculture, health and socioeconomic activities dormant. This has over the years caused a great rural-urban drift. Most communities in the study area have become a remote base village leaving it non-industrialised and inaccessible to commercial activities and foreign investors.

To enhance economic activities of the study area and country at large, efforts are being made to search for alternative sources of electricity generation. These include solar and wind power generations. However, these forms of power generation depend on climatic conditions just like the hydropower generation; hence they may not generate sufficient electricity throughout the year and keeping the Niger Delta area full of pollutants. However, 60% to 70% of the population still does not have knowledge about the use of geothermal resources. Geothermal energy as a sustainable and renewable energy source is still widely untapped as an alternative source aside the already known source of power supply in the area.

1.4 Justification of the Study

Curie-point depth of an area can provide valuable information about the regional temperature distribution at depth and the potential of subsurface geothermal energy which can be of great advantage when considering the area for exploration of geothermal energy. Geothermal active areas are associated with shallow Curie point depth and high heat content which is of great advantage. The result from this work will provide information to ascertain the viability of the study area for geothermal energy exploration. This work will greatly contribute to the use of other alternative source of electric power generation and boost the economy of the nation and social wellbeing of the area.

1.5 Aim and Objectives

The aim of this project is to assess geothermal potential in parts of Niger Delta Basin using high resolution aeromagnetic data.

The objectives are to:

i. Determine the sedimentary thickness, Centroid and Curie point depth of magnetic source using spectral depth analysis.

ii. Determine the geothermal Gradients and heat flow within the study area.

iii. Delineate the geothermal potential zones in the study area.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Review of Geological Work in the Area

Nigeria lies between latitudes 4°N and 15°N and Longitudes 3°E and 14°E, within the Pan African mobile belt in between the West African and Congo cratons. It composed of crystalline rocks which were formed from the previous Precambrian and sedimentary basement rocks from the Cretaceous to recent. The basement complex is one of the major components that form part of the Pan-African. It is the oldest rock in the Basin which is closer to the coast Precambrian continental basement crops intruded by the igneous Mesozoic and overlained by the Cretaceous sediments. The Nigerian basement was affected by the Pan-African orogeny that came from the plate collision between the passive and continental margin of West Africa. The crystalline igneous and metamorphic rocks constitute the Precambrian-Palaeozoic basement complex which occur in the eastern region of the country and extend through the north central to the north eastern part of Nigeria. The Geological map of Nigeria showing the study area (Fig 2.1) comprises of seven inland basins namely the Niger Delta, the Anambra Basin, the Benue Trough, the Chad Basin, the Sokoto Basin, the Bida-Nupe Basin and the Dahomey Basin, all infill with sediments varying in age from the Cretaceous to recent (Obaje, 2009).

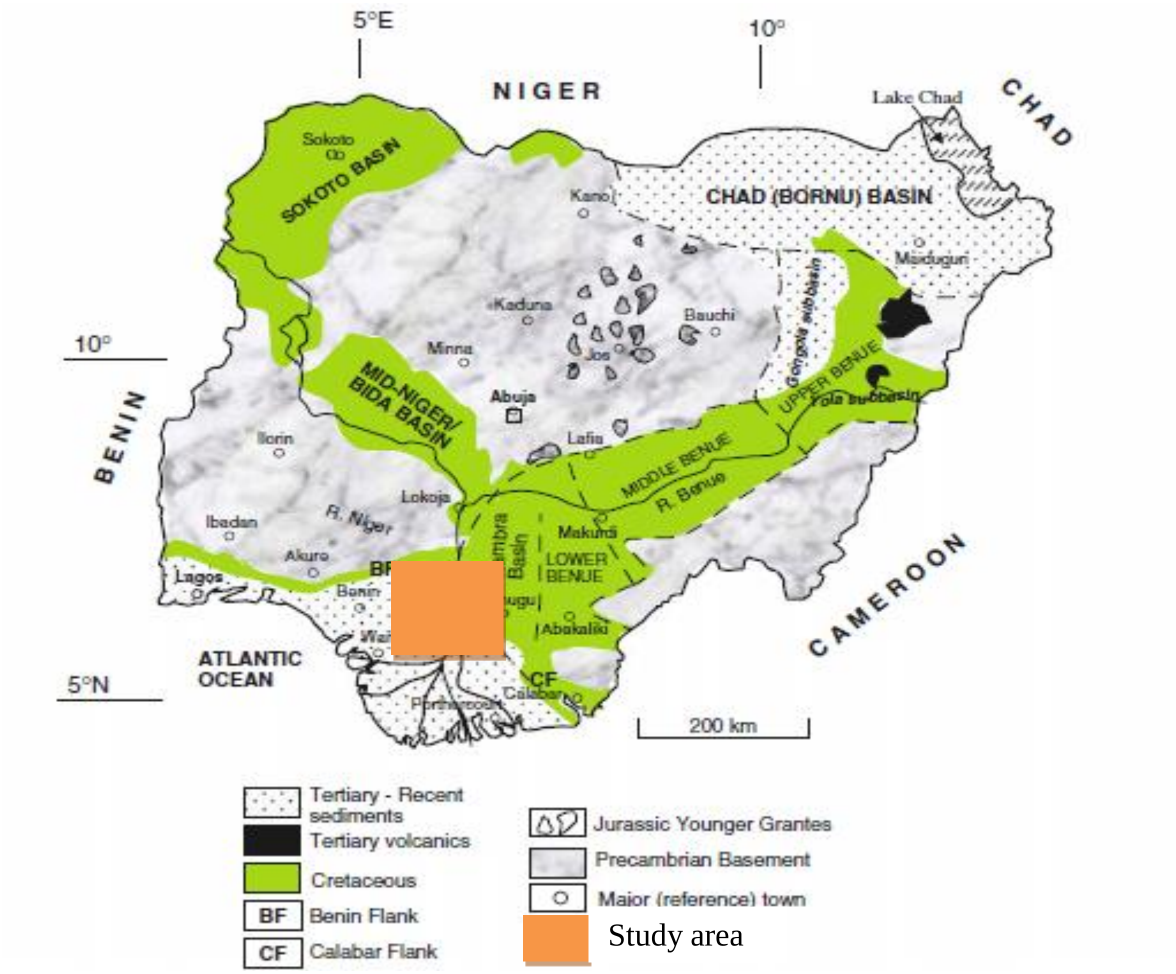

Figure 2.1: Geological Map of Nigeria showing the study area (Modified after Obaje, 2009).

2.2 Geology of the Study Area

The study area Figure 2.2 lies within parts of Niger Delta, bounded by latitudes 5°00′ and 6°00′N and longitudes 5°30′ and 6°30′E and underlies an area of about 12,100 Km^2 which was previously built over an older transgressive Paleocene pro delta. It is one of the largest sub aerial basins in Africa, situated at the intersection of the Benue Trough and the South Atlantic Ocean where a triple junction developed during the separation of the continents of South America and Africa in the late Jurassic (Whiteman, 1982). Subsidence of the African continental margin and cooling of the newly created oceanic lithosphere followed this separation in early Cretaceous times. Marine sedimentation took place in the Benue Trough and the Anambra Basin from mid-Cretaceous onwards. The Niger Delta started to evolve in early Tertiary times when clastic river input increased and several faults were formed (Doust and Omatsola, 1989). Generally, the delta prograded over the subsidizing continental-oceanic lithospheric transition zone and during the Oligocene spread onto oceanic crust of the Gulf of Guinea. The weathering flanks of out-cropping continental basement sourced the sediments through the Benue-Niger drainage basin. The delta has since Paleocene time's prograded a distance of more than 250 km from the Benin and Calabar flanks to the present delta front (Evamy et al., 1978). Thickness of sediments in the Niger Delta has an average of 12 km covering a total area of about 140,000 km^2. The subsurface lithostratigraphic units of the area are the petroliferous Agbada formation which overlies the transgressive marine Akata formation which is the major hydrocarbon rock source (Chukwu et al., 1991) and the Benin formation.

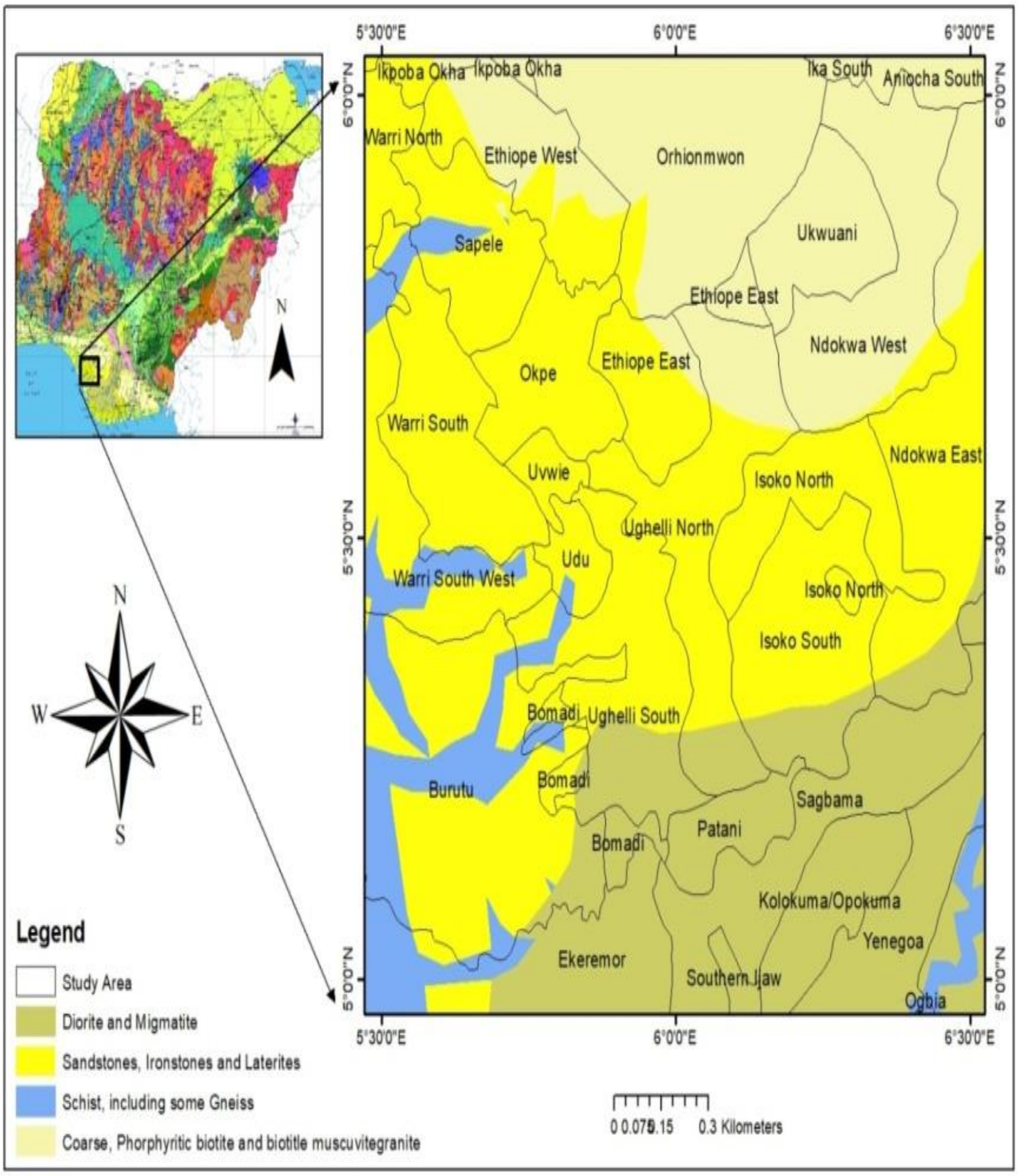

Figure 2.2: Geology Map of study area (Adapted from NGSA 2009)

Outcropping units of the Niger Delta include the Imo formation and Ameki Group which consists of Ameki, Nanka, Nsugbe and Ogwashi-Asaba formations. The three main subsurface litho-stratigraphic units recognised are the marine Akata Shales situated at the base of the Delta, the petroliferous parafic Agbada Formation which began in the Eocene and continued to the Paleocene and the continental Benin sands of late Eocene to recent deposit of alluvial and upper coastal plain sands that are up to 2000 m thick. According to Otobong et al. (2016) the Niger Delta has depositional environments ranging from marine, transitional and continental setting of the area.

2.3 Review of Geophysical literature

Ajala et al. (2021) investigate the sedimentary thickness for hydrocarbon potential over parts of Adamawa using magnetic method. They subjected the total magnetic intensity to residual/regional separation. Three depths estimating techniques (source parameter imaging, Euler deconvolution and spectral) were applied on the residual map to obtain the thickness of sediments in the study area. The results of these methods shows a thick sedimentation of 4.42 km, 4.20 km and 4.17 km at the north-eastern part of the study area and shallow depth of 0.06 km, 0.10 km and 0.42 km at the southeast, southern and southwest part of the study area respectively. Therefore, the study area was found to have good potential for hydrocarbon exploration.

Salako et al. (2019) assessed the geothermal potential in parts of middle Benue Trough, North-east of Nigeria. Spectral analysis of aeromagnetic data and radiometric data was used to determine the geothermal potentiality of the study area. The spectral analysis was used to differentiate the magnetic effect from top to bottom of magnetised area in the crust to obtain the Curie Point Depth of the study area. It was found that the region is characterised by Curie Depth of 17.04 km and 27.4 km and a high heat flow of 50.02 mWm^{-2} and 85.1 $mWm^{-2}$with highest values in the southern part (Akiri and Ibi) and north-western part (Pankshin) of the area. Also they used the aero-radiometric data covering the study area to estimate the radiometric heat contribution. The analysis of aero-radiometric data shows that the area possesses high content of Uranium, Potassium and Thorium. The radioactive heat production values vary between 1.58 μW/m^3 and 2.53 μW/m^3 with an average of 2.21 μW/m^3. The study indicates that the study area possessed a good source of geothermal potential.

Mamman et al. (2019) investigated geothermal energy resource potential in parts of south western Nigeria using a high- resolution aeromagnetic (HRAM) data. Spectral analysis was applied in processing HRAM data, which transformed the spatial data into the frequency domain, and provided a relationship between the two-dimensional spectrums of the magnetic anomalies. Results indicated that the average Curie point depth (CPD), average geothermal gradient and the average heat flow within the study area is 8.5 km, 42.5 ℃$km^{-1}$and 55 mWm^{-2} respectively. They observed that equitable promising geological results useful for geothermal exploitation is within longitude 4.2 °E to 4.6 °E and latitude 7.8 °N to 8.2 °N, where the lowest CPD (5.5km), highest geothermal gradient (75℃km^{-1}) and highest heat flow (190 mWm^{-2}) bounded by Oshogbo and Ogbomosho as indicated on the maps. They concluded that such area can be considered for geothermal energy exploration since the demagnetized rocks confirms a hot rock temperature of about 580℃.

Nwobodo *et al.* (2018) determined the Curie Point Depth, geothermal gradient and heat flow of Guzabure and its environs, Chad Basin, Nigeria using Aeromagnetic data. They estimated the CPD from spectral analysis using six aeromagnetic data for determining the nature of the magnetic anomalies which covered the area. Regional anomaly was removed from the total magnetic intensity field to obtain the residual anomaly field using polynomial fitting. The total magnetic intensity of the study area showed the range of magnetic anomalies which vary from -88.4 nT to 238.3 nT while the residual values are from -169.0 nT to 140.5 nT. The residual magnetic field was used to bring into focus local features which tend to be obscured by the broad features of the regional field. The areas of strong positive anomalies likely indicate a higher concentration of magnetically susceptible minerals while areas with broad magnetic lows are likely areas of lower susceptibility minerals. The calculated Curie depths from spectral analysis ranged from 10.220 km to 22.721 km. The result showed that the Curie point depth within the basin is not a horizontal level surface, but is undulating, and the geothermal gradient associated with it ranged from 25.527 °C/km to 56.751 °C/km with an average value of 38.517 °C/km while the corresponding heat flow ranged from 63.818 mWm^{-2} to 141.878 mWm^{-2}. The results of Curie point depth combined with heat flow values showed a distinct inverse linear relationship. The average geothermal gradient of 38.517 °C/km obtained from their work indicates the possibility of hydrocarbon generation in the study area.

Akinubi *et al.,* (2018) carried out research by investigating the geothermal potential within Benue State, central Nigeria from radiometric and high resolution aeromagnetic data. They focused their work on both qualitative and quantitative 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 aeromagnetic data was subjected to Fourier analysis and then spectral analysis. From the spectral analysis, the depth to the top of magnetic sources varied from 0.28 to 0.36 km while the depth to the bottom of magnetic sources varied from 5.52 to 9.63 km. They also employed the modified curie depth method in evaluating the Curie point depth; heat flow and geothermal gradient were also obtained. The region was 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 and 30 °C/km respectively with an average value of 41.59 °C/km, anomalous high heat flow of 153.35 and 135.62 Wm^{-2} was obtained within around Katsina- Ala and Oturkpo of the study area. Correlating this result with the analysis of the radiometric values covering the study area, the ternary map showed that potassium and thorium radioactive content is noticeably high within these areas where relatively high heat flow values were obtained, this is then associated with their occurrence. The radioactive heat production within the two exothermally active areas was estimated to be 1.47 and 2.21 μW/m^2 respectively.

Chukwu *et al.* (2018) further carried out the geothermal energy potential from the analysis of aeromagnetic data of part of the Niger Delta basin. Spectral analysis was used to determine the Curie point depth and the heat flow values in the study area. Results showed that the centroid depth varied between 14,4194 km (within Okigwe-Aba sector) and the 6,7482 km (within Aba- Ahoida region) while the curie depth isotherm varied between 7.4644 km and 24.8600 km below the mean sea level. Therefore, the calculated average geothermal gradient and heat flow for the area was found to be 22.4886 ℃/km and 52.6012 mW/m^2 respectively. Hence, it showed that the area may not be potentially viable as a geothermal source.

Kuforijimi *et al.,* (2017) used both aeromagnetic and aero radiometric data to carry out correlation and mapping of geothermal and radioactive heat production from potassium, Uranium and Thorium to produce the radioelement maps in the Anambra Basin, Nigeria. Each rock type in the study area was outlined and the elements in each of these rocks were used to evaluate the radiogenic heat production. The result from the research ranges between 0.01 – 5.43μWm^{-3}. It was observed that the highest heat produced came from the sedimentary rocks (Shale) with radiogenic heat production value up to 5.43 μWm^{-3}around Aimeke and Ogobia.

Adewumi *et al.,* (2017) carried out an Estimation of sedimentary thickness using spectral analysis of aeromagnetic data over part of Bornu Basin, Northeast Nigeria. He used spectral analysis to interpret the aeromagnetic data. Polynomial fitting method was adopted for the regional-residual separation of the total magnetic intensity. The residual map was divided into nine spectral sections. His result showed that the sedimentary thickness ranged between 0.29 km and 3.35 km.

The sedimentary thickness of over 3 km was found around the South-eastern part of the study area which corresponds to Gubio town while the minimum sedimentary thickness was found around North-western part of the study area which also corresponds to Borgo town area. Therefore, the maximum sedimentary thickness of 3.35 km suggests the sufficiency for hydrocarbon.

Otobong *et al.,* (2016) researched on the Geothermal energy potential of hot water from oil wells in Niger Delta. He noted that the sedimentary basin of the Niger Delta has majorly been explored for oil and gas resources, with large subsurface temperature especially the Bottom Hole Temperature (BHT) data collected from oil wells, it has been found that geothermal gradient in the Niger Delta ranges from 1.3 °C to 5.5 °C/100m. Therefore, by this range also suitable for geothermal exploration in the area.

Nwankwo *et al.,* (2015) evaluated the Curie-point depths, geothermal gradients and near-surface heat flow from high resolution aeromagnetic (HRAM) data of the entire Sokoto Basin, Nigeria. They used the spectral centroid method to obtain depth to the top, centroid and bottom of magnetic sources. The depth values were subsequently used to evaluate the Curie-point depth (CPD), geothermal gradient and near-surface heat flow in the study area. The result from their work showed that the CPD varied between 11.13 and 27.83

km with an average of 18.57 km, the geothermal gradient varied between 20.84 and 52.11 °C/km with an average of 33.99 °C/km, and the resulting heat flow varied between 52.11 and 130.28 mW$m^{-2}$with an average of 84.97 mWm^{-2}. These heat flow values are suggestive of anomalous geothermal conditions and are recommended for detailed geothermal exploration in the basin.

Abraham et al. (2014) used Spectral analysis of aeromagnetic data to investigate the geothermal energy of Ikogosi Warm Spring-Ekiti State, Southwestern Nigeria. The aeromagnetic data was used to calculate the basal depth of magnetic layer (Curie point depth) in the region. They adopted computational method used to transform the spartial data into frequency domain which provided a relationship between radially average power spectrum of magnetic anomalies and depths to respective sources. Heat flow density and the equivalent depth extent of heat production from radioactive isotopes were also evaluated. The results showed that the average Curie point depth for the study area were 15.1± 0.6 km with heat production depth value of 14.5 km which falls within Curie point margin. The low Curie point depth observed at the warm spring source is attributed to magmatic intrusions at depth. This is also evident from the visible older granite intrusion at Ikere - Ado-Ekiti area, with shallow Curie depths (12.37 ± 0.73 km). Depth extent of heat production provides a depth value (14.5 km) which falls within the Curie point depth margin and could indicate change in mineralogy. They concluded that the area is promising for more geothermal explorations.

Ofor and Udensi (2014) determine the heat flow in the Sokoto Basin using spectral analysis on Aeromagnetic data. The results from depth analysis suggested that the top layer has a range 0.61 - 1.54 km and this depth to the top of basement in the area and has deepest at the North Eastern part toward Niger Republic. The geothermal gradient evaluation varies between 22.18 and 44.62 °C/km with a resultant heat flow value 52.36

to 98.57 mWm^2. The heat flow has general trend not horizontal heat flow is recorded around the Tambuwal area and the study area lies within the thermally normal continental regions and good geothermal sources.

Emujakporue and Ekine (2014) carried out research for the geothermal gradient of Niger Delta Basin using BHT data. They obtained values of 13.46 °C/km to 33.66 °C/km which they attribute to overburden thickness lithology, tectonic activities (growth faults) and hydrodynamics of the basin.

Obande *et al.,* (2014) used spectral analysis of aeromagnetic data for geothermal prospecting in the north-east Nigeria. They estimated the top and the centroid depths of magnetic source from the power spectrum. The results obtained from their work were subsequently used to estimate the bottom depth. The range of CPD varies from 6 km to 12 km according to the heat flow and CPD values of the study area wherein the highest heat flow value and the shallowest CPD occurred near the thermal springs. The Wikki warm spring area was found to have a great energy potential with a shallow CPD and very high heat flow values.

Megwara *et al.*, (2013) used both aeromagnetic and aero radiometric data to determine the geothermal and radioactive heat studies in parts of Southern Bida. Heat from the radiometric data, residual separation of the total magnetic intensity data, and determination of depth to top and bottom of magnetic sources and estimation of field scaling exponent using the Fractal technique were obtained. The result showed that the geothermal heat flow values ranges from 69.167 mWm^{-2} to 124.821 mWm^{-2} with an average value of 90.959 mWm^{-2} and radioactive heat ranging from 0.91 to 4.53 W/m^3 with an average value of 2.28 W/m^3 and hence a prospect area for geothermal heat.

Bemsen, *et al.*, (2013) also analyzed the spectral from aeromagnetic data processing over a part of the southern Bida Basin, Western Nigeria from their conclusion and their result reveal two depth sources in the area. The deeper sources range from 2.81 to 3. 24 km. They concluded in their study that the lower CPD values betray high geothermal potential of an area.

Olumide (2013) analyzed temperature data from boreholes of Niger Delta and created series of geothermal maps. The geothermal gradient from his study ranges from 1.2 °C/100m to 7.56 0C / l00m. His preliminary estimates of geothermal energy resources in depth is in the interval 0 - 4000 m in the Niger-Delta indicated a range of resource value between 400 GJ/m^2 to 1250 GJ/m^2.

Adetona and Mallam (2013) from their recent work, obtained thickness sedimentary over the lower Benue Trough within study area to be approximately 10km and it was observed that the prevalence of magnetic lows within the modelled residual field data show acidic basement (deformation granitic basement). The source parameter Imaging showed a minimum depth of 76.983 meters and a maximum sedimentation thickness of 9.849 km, which also occur within Idah, Ankpa and Udeji axis. The depth estimate by this research particularly around the Anambra basin underneath Idah and Ankpa in Kogi State is of significance interest because it is high enough for the realisation of temperature (approximately 60 °C and higher than this is essential for thermal degradation of Kerosene yielding hydrocarbons).

Olorunfemi *et al.,* (2011) applied analysis method to aeromagnetic data from the region in a bad to determine depths to the bottom of magnetic source (assume curie point depth. CPD). From his calculation from traverses taken across the maps from the region the depth ranges between 4.68 km and 11.38 km.

Adedapo *et al.,* (2013) used subsurface temperature of the Niger Delta sedimentary basin to determine the geothermal gradient analysis of subsurface temperature. The result obtained showed that the geothermal gradient of Niger Delta increases from the central part of the Delta outwards towards the northeastern and the southeastern parts of the Basin with the background geothermal gradient value ranging from 1.2 °C to 7.56 °C/100m. Six geothermal anomalies were used to observe the depths in parts around the study area. The results from the anomalies showed three new positive geothermal anomalies 60 °C/100 m, 6.50 °C/100 m and 7.62 °C/100 m not known were discovered.

2.4 Theory of Aeromagnetic Survey

The Earth possess magnetic field caused by sources in the core. The magnetic field can be likened as that produced by a bar magnet. The Earth's magnetic field induces magnetism within the surface of the Earth in order to determine the location of subsurface features. Magnetism is therefore the combination of all magnetic fields acting on a media. The general theory underlying magnetic surveying is the existence of magnetic dipole within the rocks constituting the earth. Mathematically, magnetic force, F between two magnetic poles of strength P_1 and P_2 is given by:

$$F_m = \frac{p_1 P_2}{\mu r^2} \tag{3.1}$$

where P_1 and P_2 are dipoles, r is the distance between P_1 and P_2 (in meters), μ is the free space permeability.

The Coulomb's law in equation (3.1) is the basic underlying principle of magnetic survey. Magnetic poles, P_1 or P_2 which exerts force per unit pole strength can be expressed as:

$$H = \frac{P}{r^2} \tag{3.2}$$

where H is the magnetic field strength.

Magnetic materials positioned within a magnetic field will acquire magnetic force and will experience magnetic induction. Due to the inducing field, one can measure the strength of the magnetic field known as the intensity of magnetisation, J_i, induced on the material and this is expressed as:

$$J_i = kT \tag{3.3}$$

where J is the magnetisation, k is the susceptibility of the magnetic material and T is the inducing field.

For low external magnetic field such as the earth, the degree in which the body is magnetised is determined by its magnetic susceptibility, k, and is defined as:

$$M = kH \tag{3.4}$$

where M is magnetic polarization, k is magnetic susceptibility and H is Magnetic field intensity.

The measurement of the total magnetic field which includes the external magnetic field and the magnetization is called the Magnetic Induction (B) and is written as

$$B = \mu_o(1 + k)H \tag{3.5}$$

where, μ_o is the magnetic permeability of free space. The unit of B is teslas, which is generally too large to be applied in magnetic work, so gammas (10^{-9} teslas) are more commonly used. B is a vector quantity and in most magnetic work today, the amplitude of B is measured and it is called the total magnetic field.

Magnetic surveys are geophysical methods that involve the measurement of variations of the Earth's magnetic field intensity. Magnetic field variation can be interpreted to determine an anomaly's depth, geometry and magnetic susceptibility (Mickus, 2002). Most common rock forming minerals are characterised by their magnetic behavior and magnetite content which considerably overlap different lithologies which causes magnetic anomalies. A magnetic anomaly is a local or regional disorder caused by a change in the magnetisation. Crustal rocks lose their magnetisation at the Curie point temperature. According to Ross *et al*. (2006) this recorded temperature is at 580ºC for magnetite. At this temperature, ferromagnetic rocks become paramagnetic, and their ability to produce detectable magnetic disorder which disappears under increasing temperature (Nagata, 1961). The depth at this temperature, when contoured for the entire area, provides a picture of the spatial variation of the Curie isotherm level. The Curie point depth is related to either heat flow or geothermal gradient, or to the thermal properties of the lithosphere. Hence, this method is considered the best method for geothermal exploration. To obtain measurement of larger anomalies such as mapping of deeper intrusions, outlining the thickness of sedimentary basins and variations in the Earth magnetic field using high precision magnetometer, aeromagnetic survey is required where the height and spacing of the profiles determines the resolution of the data.

Aeromagnetic survey is a geophysical method carried out by using a magnetometer towed behind an aircraft. This method is similar to magnetic survey carried out with a handheld magnetometer, but it allows a larger surface area of the Earth to be covered at the quickest possible time. As the aircraft flies in a grid like manner with height and line spacing determining the resolution of the data, the magnetometer measures and records the strength of the local Earth's field that is measured. This measurement is called the Total Magnetic Intensity (TMI). The total magnetic intensity of the magnetic field at the sensor is a combination of the magnetic field generated in the earth as well as the little variation due to varying solar wind and the magnetic survey of the aircraft. Aeromagnetic map showing the spartial distribution and relative abundance of magnetic minerals in the upper levels of the earth's crust is obtained and interpreted by the Spectral analysis method in order to estimate the Curie Point Depth, spatial distribution and results used to explore for geothermal resources.

2.5 Spectral Analysis method

Spectral analysis is a depth estimating method first pioneered by Bhattacharryya (1966) and later developed by Spector and Grant (1970). The method is used to determine the Curie point depth and to separate influences of the different body parameters in the observed magnetic anomaly field (Salako et al., 2019). Fundamentally, the method of Spector and Grant (1970) estimates the average depth to the top boundary of the magnetized layer from the slope of the log power spectrum while the method of Bhattacharryya and Leu (1975) obtains the de pth to the centroid, Zo, (effects from the bottom) of the causative body using a single anomaly interpretation. Okubo et al. (1985) effectively combined and expanded both methods to propose an algorithm for regional geomagnetic interpretation oriented to the purposes of geothermal exploration. According to Spector and Grant (1970) they illustrated that the thickness depth and width of a magnetic source ensemble could affect the shape of energy spectrum. The strong term that shapes this energy spectrum is the depth factor. They demonstrated that the depth could be estimated using Equation (3.6).

$$E(r) = e^{-2zr} \tag{3.6}$$

where, E(r) = spectral energy Normalised

r = frequency

If "h" is the mean depth of a layer and the depth factor for the ensemble of anomalies is

$$E(r) = e^{-2rh}$$

Therefore, a plot of the energy spectrum of a single ensemble of prism against angular frequency r would give a straight line graph whose slope is directly proportional to the average source depth, h of that ensemble (Spector and Grant, 1970). That is, the logarithm plot of the radial frequency would yield a straight line whose slope is:

$$m = -2h$$

$$h = -\frac{m}{2} \tag{3.7}$$

Equation (3.7) can be applied if the frequency unit is in radian per unit kilometer. From the slopes of the plot, the first and the second magnetic source depth was respectively estimated.

2.5.1 Curie point depth Estimation

The bottom of a magnetic source shows the thermal boundary at which magnetic mineral in the crust move from ferromagnetic state to paramagnetics as a result of the increase in temperature as depth increases down the crust (Nagata, 1961; Ross et al., 2006). This thermal boundary is referred to as Curie point depth and it is the outermost part of the crust that has material which develops recognisable mark in a magnetic anomaly map (Bhattacharryya and Leu, 1975). Curie point depth is assumed to be the depth for the geothermal source (magmatic chamber), where most geothermal reservoir tap their heat from a geothermal area (Eleta and Udensi, 2012). This Curie point has a temperature of 580 °C. For temperature above Curie-point, magnetic materials lose their magnetic ordering and both induced and remnant magnetisation disappear, thus for temperatures above 580°C, those materials will begin to encounter ductile deformation. The methods of Curie Point Depth determination utilize spectrum analysis techniques to separate influences of the different body parameters in the observed magnetic anomaly field (Hisarli, 1995). The Curie point depth is evaluated in two stages as proposed by Bhattacharyya and Leu (1975); the first stage is the estimation of depth to centroid (Zo), of magnetic source from the slope of the longest wavelength part of the spectrum and the second stage is the estimation of the depth to the top boundary (Zt) from the slope of the second longest wavelength part of the spectrum (Okubo *et al.*, 1985) and finally Bhattacharyya and Leu (1977) developed the method to determine the bottom depth of magnetised bodies (Zb).

2.5.2 Depth to the Top (Z_t), Centroid (Z_o) and Bottom (Z_b) of Magnetic Sources

From the first stage, the centroid depth of magnetic sources can be calculated from slope of the longest wave length part of the power spectrum (Okubo et al., 1985)

$$\text{In}\left[\frac{\sqrt{\text{P(k)}}}{|\text{k}|}\right] = \text{InA} - 2\pi|\text{k}|\text{Z}_\text{o} \tag{3.8}$$

where,

P(k) is the radially averaged power spectrum of anomaly,

|k| is the wave number,

A is a constant.

The second stage is 3the estimation of depth to the top, (Z_t) of the magnetic source is derived from the slope of the second longest wavelength part of the spectrum:

$$\text{In}\sqrt{[\text{P(k)}]} = \text{InB} - 2\pi|\text{k}|\text{Z}_\text{t} \tag{3.9}$$

where B, is the sum of constant independent of |k|

The depth to the bottom of the magnetic source (Z_b) can subsequently be obtained from the relation (Okubo et al., 1985)

$$Z_b = 2Z_o - Z_t \tag{3.10}$$

2.4.3 Geothermal Gradient and Heat Flow

Using the depth to the bottom of magnetic sources (Z_b), the geothermal gradient $\left(\frac{dT}{dZ}\right)$ can be estimated as

$$\left(\frac{\text{dT}}{\text{dZ}}\right) = \left(\frac{\theta_\text{c}}{\text{Z}_\text{b}}\right) \tag{3.11}$$

Here, θ_c is the Curie temperature.

Using $Z_b$and $\frac{dT}{dZ}$, the heat flow (q_z) can similarly be estimated as (Okubo et al., 1985)

$$q_z = -\sigma\left(\frac{\theta_c}{Z_b}\right) = -\sigma\left(\frac{dT}{dZ}\right) \tag{3.12}$$

where, σ is thermal Conductivity. Thermal conductivity of 2.5W/m/°C as the average for igneous rocks and a Curie temperature of 580 °C (Stacey, 1977; Trifonova et al., 2009) are used as standard.

CHAPTER THREE

3.0 MATERIALS AND METHODOLOGY

3.1.1 Materials

The material used for this project includes:

i. Aeromagnetic Data

ii. Geospatial Software "Oasis Montaj"

iii. Matlab

iv. Surfer 13

v. Computer

vi. Stationeries (paper, pen, ruler etc).

3.1.2 Data Acquisition

For this research, four aeromagnetic data sheets were obtained from the Nigerian Geological Survey Agency (NGSA), as part of the aeromagnetic survey carried out between 2003 and 2009 by Fugro Airborne Survey. The aeromagnetic sheets used were Warri (309), Kwale (310), Burutu (318) and Patari (319) which corresponds to latitudes 5°00´N and 6°00´N and longitudes 5°50´E and 6°50´E. The Survey was conducted in two phases, Phase 1 by Fugro Airborne Surveys and Phase 2 by Paterson, Grant and Watson Limited (PGW). Each gridded map scale of 1:100,000 cover an area of about $55\ \text{km}^2 \times 55\ \text{km}^2$ while the total area investigated covers $12100\ \text{km}^2$.

3.2 Methods

The methods employed in this research work include:

i. Dividing the residual Total Magnetic Intensity (TMI) map for the area of study into overlapping blocks and interpret the resultant map.

ii. Computing the logarithm of power spectrum for each blocks, to obtain the centroid depth and depth to top of the magnetized body.

iii. Section the grids of the study area into sections and run the spectral energy versus frequency for each section.
iv. Estimating the depth to the top and bottom of magnetic source.
v. Estimating the Curie point depth.
vi. Estimating the geothermal Gradients and heat flow within the study area

CHAPTER FOUR

4.0 RESULTS, INTERPRETATION AND DISCUSSION

4.1 Total Magnetic Intensity (TMI) Map and Residual Magnetic Intensity Anomaly

The four acquired data sheet was assembled, merged and transported into Oasis Montaj software to produce the Total Magnetic Map (TMI) and then performed a residual separation on the TMI map of the study

Figure 4.1 and 4.2 are the Total magnetic intensity and Residual map of the study area (part of Niger Delta). The total magnetic intensity map, TMI and the residual magnetic intensity map show variation of highs and lows magnetic signature. The maps were produced in aggregate colours from deep blue to light blue signifying low magnetic anomalies, the green colour representing the intermediate between high and low anomalies and the red to pink colour shows a high magnetic anomaly. The negative values imply areas that are magnetically quiet while the positive values are magnetically responsive. The magnetically quiet areas are the magnetic low of the study area and this is the typically sedimentary terrain while the magnetic responsive areas are the magnetic highs of the study area which is assumed to be due to the presence of sandstones, ironstones and laterite deposits.

From Figure 4.1, the TMI map reveals that high magnetic anomalies could be found at Northern part of the study area with the highest magnetic signature found at north-western part of Warri. The intermediary signature could be found in north-eastern part of kwale and towards the south western part of Burutu while the low magnetic anomalies are seen at the south-eastern part of Patari.

From the residual map (Fig. 4.2), high anomaly signature could be found at the north-eastern, central part towards the southern part of the study area. The central region was found to have the highest signature, going down the trend shows that the least magnetic signature could be obtained partly in the southern part of Patari while Burutu shows both high and intermediate signatures.

4.2 Spectral Analysis

The residual map (Figure 4.2) of the study area was divided into 16 square overlapping blocks (A – P) which covered 55 km by 55 km. Spectral analysis was performed on each block and a plot of spectral energy against wave number was carried out using Matlab software. Figure 4.3 is the Graph of logarithm of spectral energies against frequencies from block A to D, which generated gradients that were used to estimate depth to the top (Zt,), Centroid (Zo) and bottom of magnetic sources (Zb), in accordance with equation (3.8) and (3.9) respectively. The results of the determined values of Zo, Zt and Zb for the sixteen blocks are shown in Table 4.1.

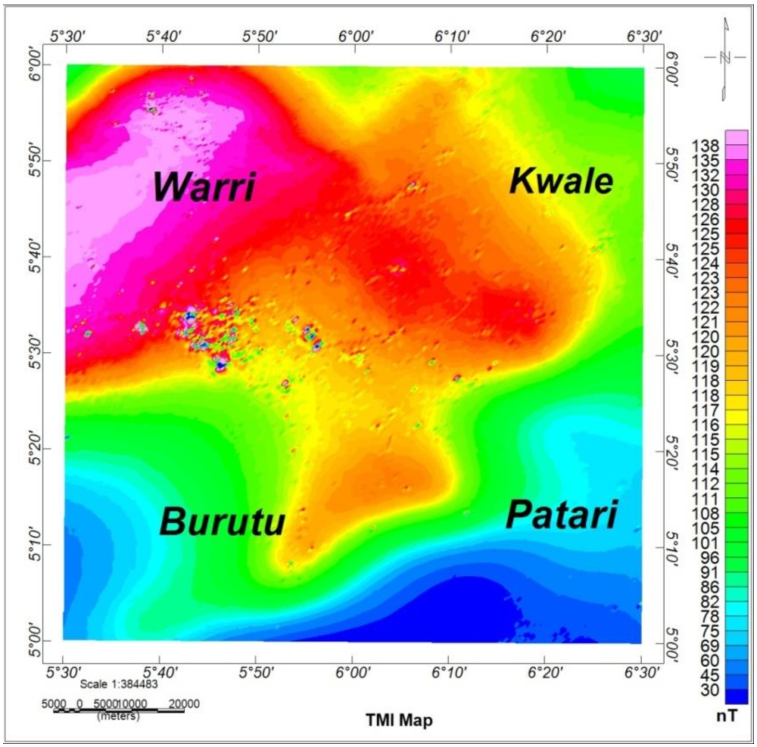

Figure 4.1: Total magnetic intensity map of study area (IGRF value of 33,000 nT must be added to the values in Legend)

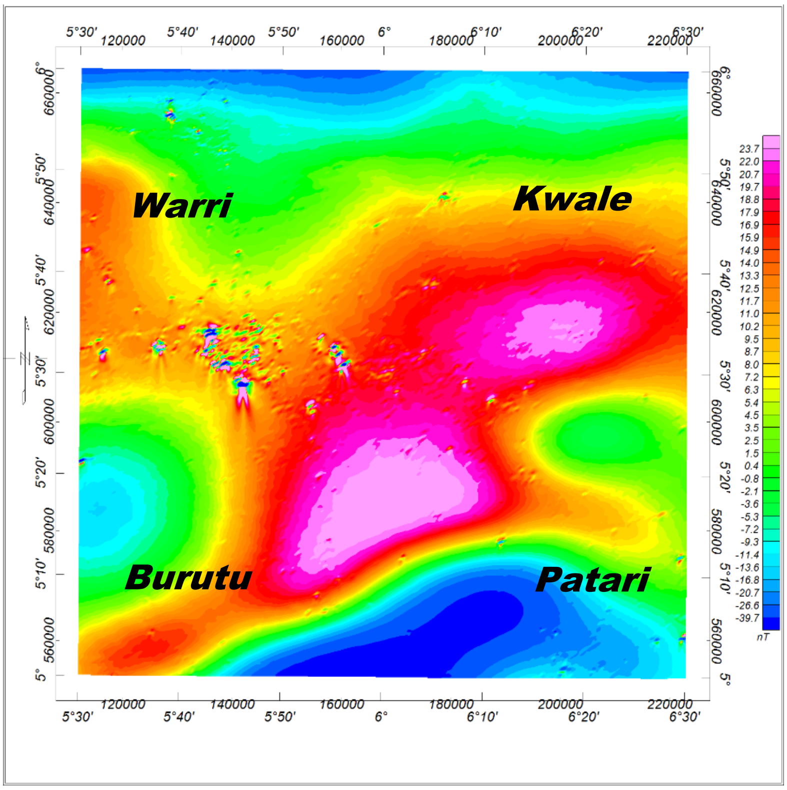

Figure 4.2: Residual map of study area

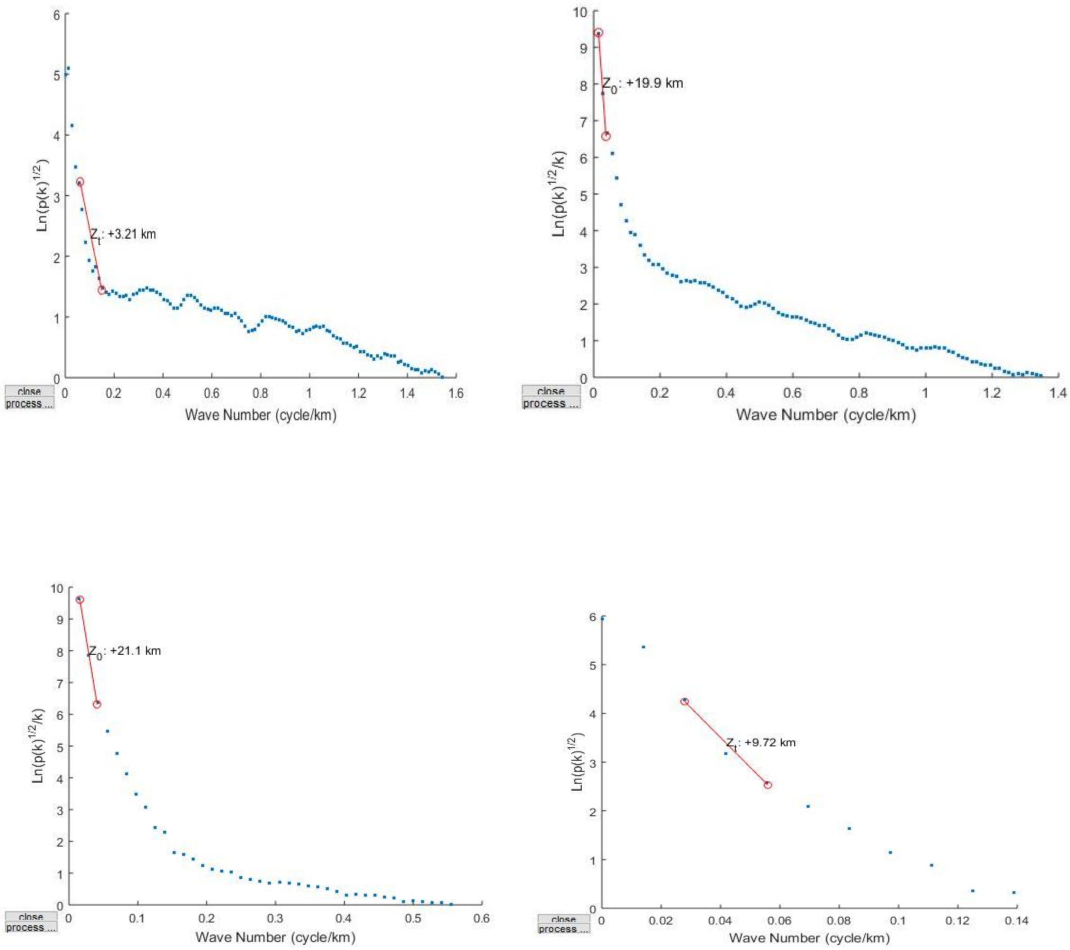

Figure 4.3: Graph of the logarithm of spectral energies against wave number obtained for blocks A - D.

Table 4.1: The results of the determined values of Z_o, Z_t and Z_b for the sixteen blocks

Blocks	Long (°)	Lat (°)	Depth to Centroid (Km)	Depth to Top (Km)	Depth to Bottom (Km)	Geothermal Gradient (°C/km)	Heat Flow (mWm^{-2})
A	5.75	5.75	19.9	3.21	36.59	15.85	39.78
B	5.92	5.75	21.1	9.72	32.48	17.85	44.82
C	6.08	5.75	17.7	10.5	24.9	23.29	58.46
D	6.25	5.75	18.5	8.06	28.94	20.04	50.30
E	5.75	5.58	15.2	10.2	20.2	28.71	72.06
F	5.92	5.58	14.0	11.7	16.3	35.58	89.31
G	6.08	5.58	20.1	11.4	28.8	20.13	50.54
H	6.25	5.58	16.9	12.4	21.4	27.10	68.02
I	5.75	5.42	19.7	13.1	26.3	22.05	55.35
J	5.92	5.42	20.0	12.5	27.5	21.09	52.93
K	6.08	5.42	22.6	9.2	36.0	6.11	40.43
L	6.25	5.42	24.2	12.0	36.4	15.93	39.99
M	5.75	5.25	29.5	9.76	49.24	11.77	29.56
N	5.92	5.25	19.3	7.32	31.28	18.54	46.54
O	6.08	5.25	26.1	11.6	40.6	14.28	35.85
P	6.25	5.25	22.8	8.35	37.25	15.57	39.08

4.3 Depth to magnetic sources

The acquired aeromagnetic data divided into 16 sub-sheets and each sub-sheet was subjected to Fast Fourier Transform (FFT) using Oasis Montaj software, this process decomposed the magnetic data into its energy and wave number components. The energy spectrum was plotted against wave number component using a Matlab graph plotter. The graph generated gradients that were used to estimate depth to the top (sedimentary thickness), Curie point depth, geothermal gradient and heat flow contour maps of the study area using Surfer 13 software.

4.3.1 Sedimentary thickness

Using the plot of spectrum energy against wavenumber in (Figure 4.3) and the values determined in (Table 4.1), Surfer 13 software was used to obtain the sedimentary thicknesss contour map. The measure of depth to the top of basement rock is a representation of the extent of sedimentation (Figure 4.4). The spectral depth analysis revealed the variation of depth to top of magnetic sources varied between 3 and 13.5 km. The deepest depths in the range of 11 km to 13 km could be found at the central part of the study area; this area corresponds to Uvwie, Ughelli North and Udu. The shallowest depth could be obtained at the North-western part of Warri, with depth range of 3 to 5 km. Medium depth range of 8 to 10 km was found at the north eastern part of Kwale, south eastern part of Patari and the southern western part of Burutu were recorded.

4.3.2 Curie point depth map

The results of the spectral analysis of aeromagnetic anomalies over the area of study shows that that the Curie point depth estimated in accordance with (equation 3.10) range between 16 km to 50 km.

Figure 4.5 is the Curie point depth contour map of the study area. High values of 38 km and 50 km could be seen at the south western region (Burutu). The shallow CPD depth of 16 km to 30 km could be seen at the central part (Uvwie, Udu, Ughelli north and Isoko north) extending towards part of Kwale North-east of the study area and the medium values seen at the north western (Warri) and south eastern (Patari) region.

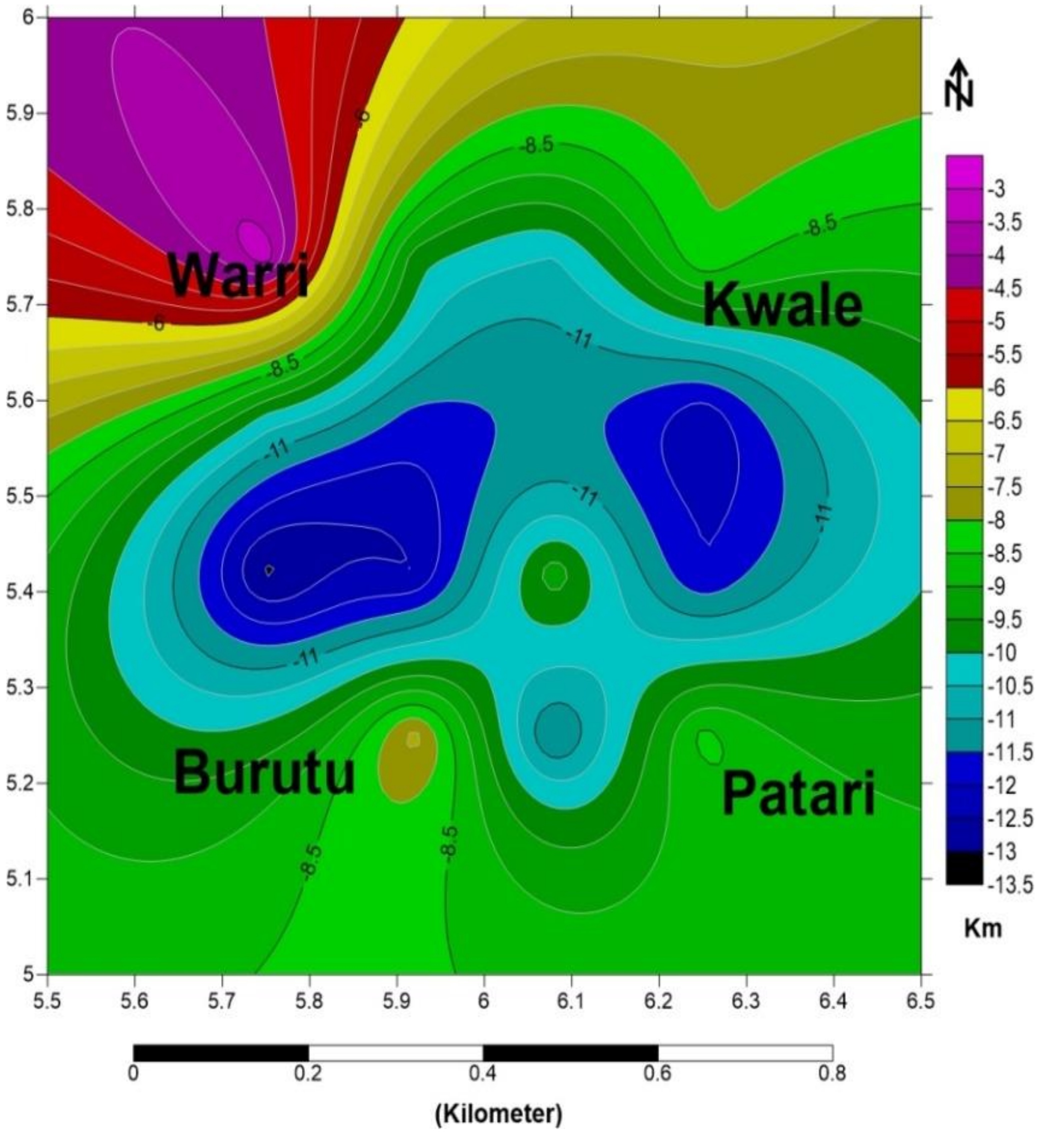

Figure 4.4: Contour map of sedimentary thickness

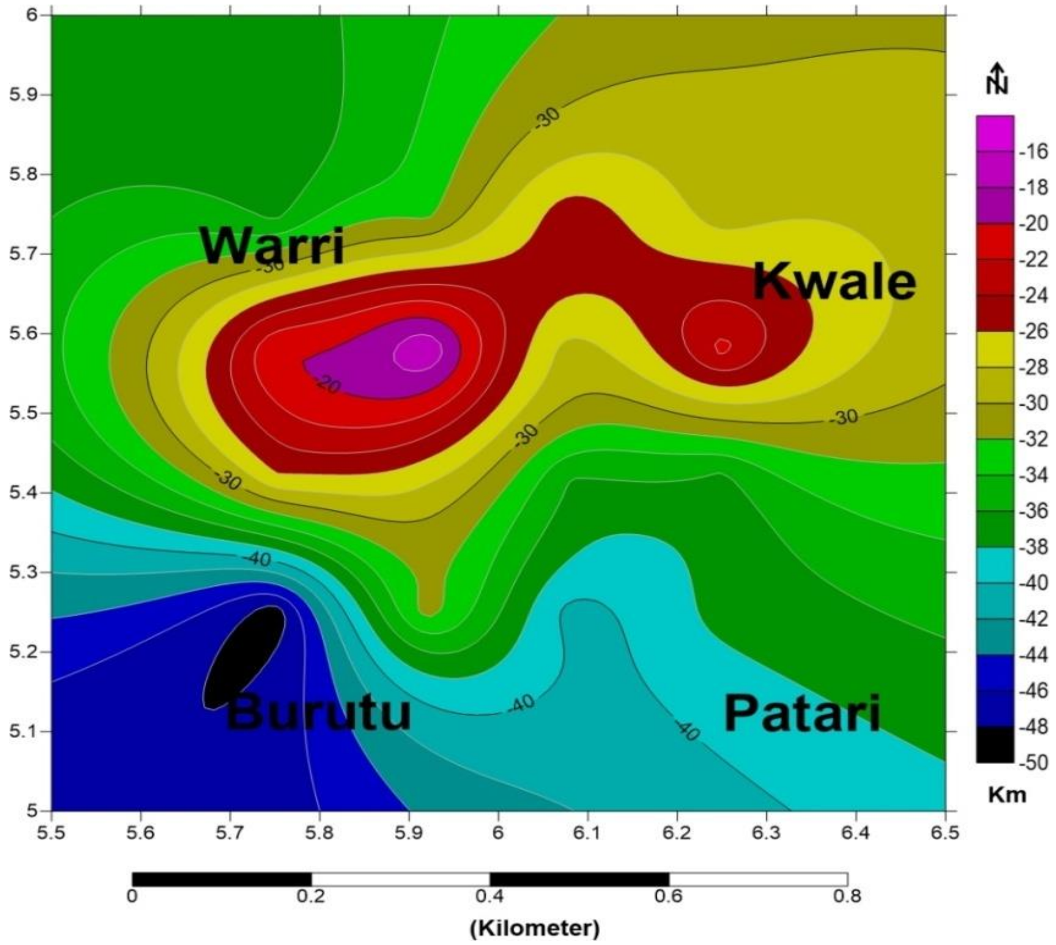

Figure 4.5: Curie point depth contour map of study area

4.3.3 Geothermal gradient map

Using a Curie temperature of 580 ℃ and the estimated Curie point depths from (equation 3.11), the results show that the geothermal gradients (Table 4.1) of the study area vary between 11 to 36 °C/km. Figure 4.6 shows that the maximum gradient values were observed at the central part below Warri and Kwale, between the range of 19 to 36 °C/km. While the medium and low values were recorded at Kwale and Burutu extending around Patari.

4.3.4 Heat flow map

The result (Table 4.1) shows that heat flow values (estimated in accordance with equation 3.12) of the area vary between 28 mW/m^2 and 88 mW/m^2. The heat flow contours plotted in (Figure 4.7) shows that the highest heat flow values, vary between 80 and 88 mW/m^2 throughout the central regions (Uvwie and Ughelli north). The central region when compared to other regions such as Warri, Kwale, Burutu and Patari was found to be probable for geothermal energy exploration.

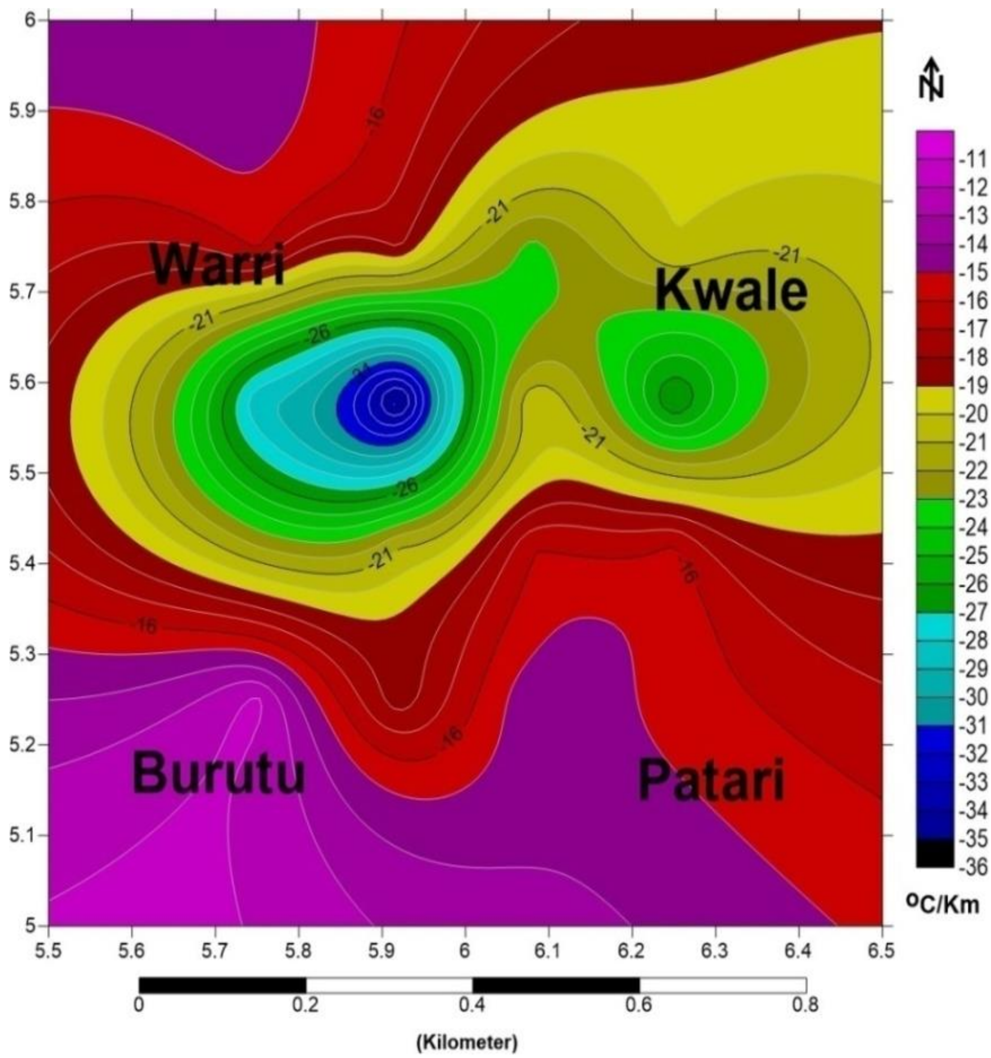

Figure 4.6: Geothermal gradient contour map of study

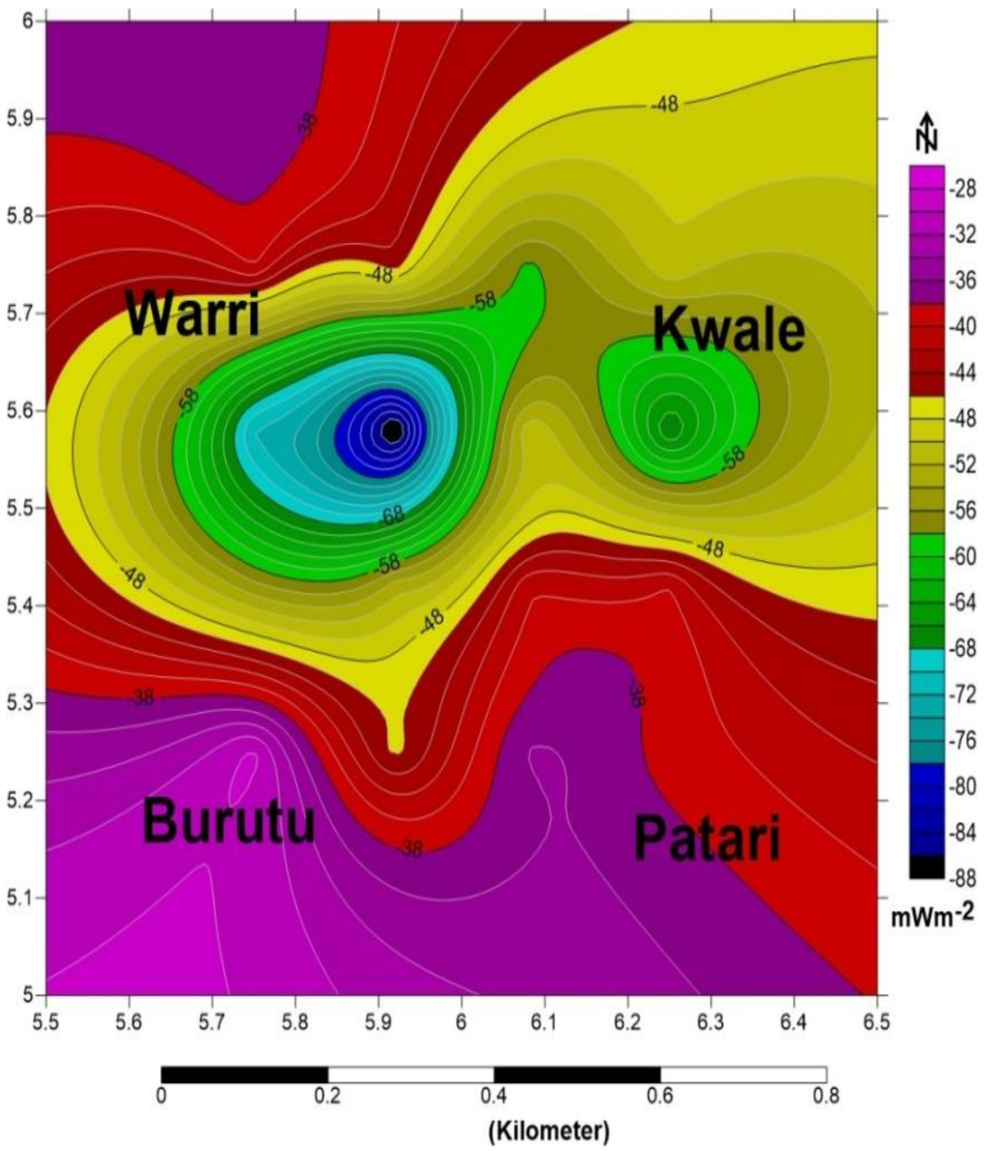

Figure.7: Heat flow contour map of study area.

4.4 Discussion

The result of spectra analysis of the aeromagnetic data of the study area (Table 1) revealed that the centroid depth (Zo) varies from 14.0 km to 29.5 km. Conversely the depth due to the top boundary of magnetic sources (Z(t) ranges between 3.21 km within the North west of Warri and 13.1 km within Ughelli North (central) region while the corresponding Curie point depth ranges from 20.2 km to 49.24 km. The low depth value might be as a result of the dominance of sandstones, ironstones and laterites. Furthermore, the geothermal gradient was found to vary between 6.11 and 28.71˚C/km with the highest seen at the central region (Uvwie, Udu, Ughelli north and Isoko north) while the heat flow parameter varies between 29.56 and 89.31 mW/m2 also at the same region. Both geothermal gradient and heat flow show a linear relationship in both the location and trend as areas of high heat flow correspond to high geothermal gradient and both shows an inverse variation to Curie point depth. These results compare favourably with the result obtained from the other researcher (Chuckwu et al,.2017) who worked on the eastern part and (Ogagarue, D. O. 2007) on the western part of the study area.

Ranging between 12.0676 and 40.1910 oC/km and 25.3419 and 84.4010 mW/m2 respectively

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMEDATIONS

5.1 Conclusion

The results obtained from the Curie point depth at which the thermal boundary of the magnetic material present moved from ferromagnetic state to paramagnetic state was successfully used to estimate the depth to top of magnetized bodies Z_t, from the slope of the log power spectrum. The centriod Z_o and bottom of the magnetic sources Z_b were also obtained using Bhattacharyya and Leu (1975) model.

The assessment of the two stages as proposed provided a detailed information about the study area. It was revealed that the sedimentary thickness varied between 3 km and 13.5 km. The deepest depth in the study area was found between the range of 11 and 13 km at the central part. The shallowest and medium depths were obtained in parts of Warri and Burutu respectively.

The Curie point contour map revealed also, that the shallowest depth was recorded at the central part of the area. It ranged between 16 km and 30 km around Uvwie, Udu, Ughelli and Isoko north. This result corresponds to the values obtained from the sedimentary thickness at the central part of the study area.

The central regions also recorded high values of geothermal gradient and heat flow between 19 and 36 $^oC/km$ and 80 and 88 mW/m^2 at the central part of the study area. It is shown, that in a thermally continental region, the average heat flow is estimated to be 60 mW/m^2 (Jessop *et al.*, 1976). Values from the result recorded from heat flow are within the range at the central region.

For a good geothermal source, a shallow Curie point depth with higher geothermal gradient and heat flow is necessary for geothermal exploration. The assessment done reveals the indication of a viable geothermal source at the central part of the study area.

5.2 Recommendations

From the result obtained in this research, the at the central region with a shallow Curie point depth of 16 km and 30 km and the high values of the geothermal gradient and heat flow between 19 and 36 ^{o}C/km and 80 and 88 mW/m^2 of the study area, using spectral analysis of Aeromagnetic data should therefore be subjected:

i. To the combination of another geophysical method such as ground aero radiometric survey which is capable of determining the radiogenic heat of the three radioelements (K, Th and U) present in the region for geothermal exploration.
ii. To exploring geothermal energy as an alternative source of generating electricity within the study area and Nigeria at large.

5.3 Contribution to Knowledge

This research work, in no doubt, has contributed to knowledge in the following way by discovering the central region of the Niger Delta area with a shallow Curie point depth of 16 km and 30 km and the high values of the geothermal gradient and heat flow between 19 and 36 ℃/km and 80 and 88 mW/m^2. Therefore, towns with these values such as Uvwie, Udu, Ughelli North and Isoko North can be considered for geothermal exploration.

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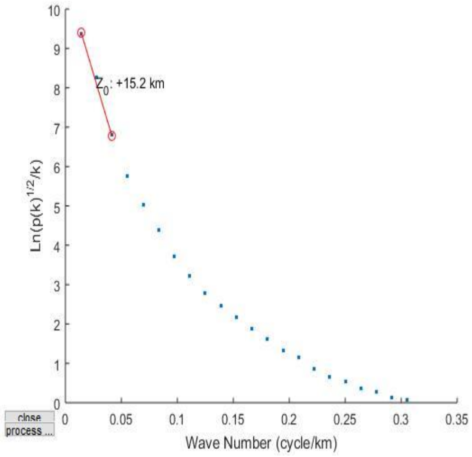
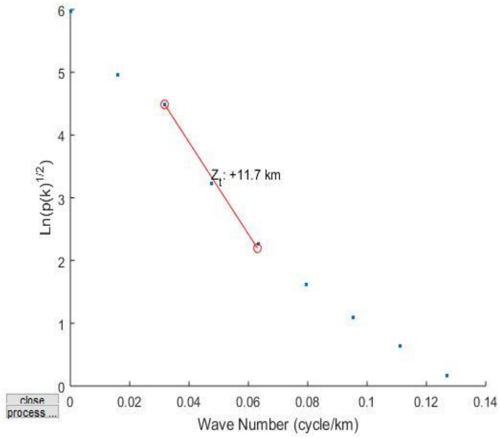
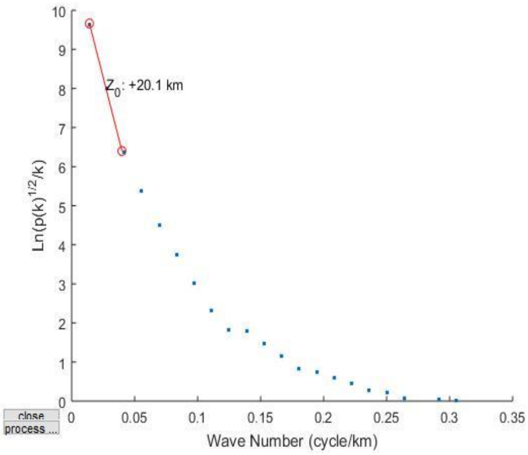
APPENDIX



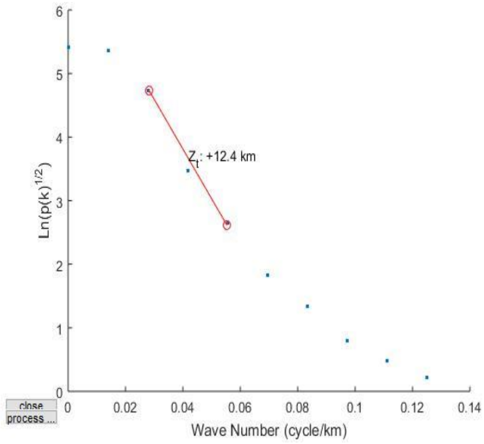
Z_0: +15.2 km
Ln(p(k)^1/2/k)
Wave Number (cycle/km)
close
process ...



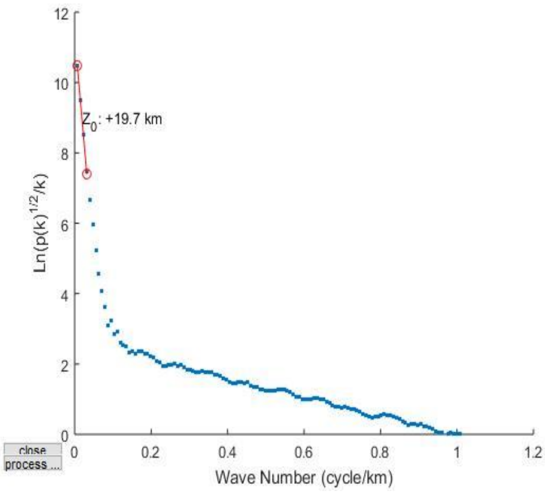
Z_1: +11.7 km
Ln(p(k)^1/2)
Wave Number (cycle/km)
close
process ...



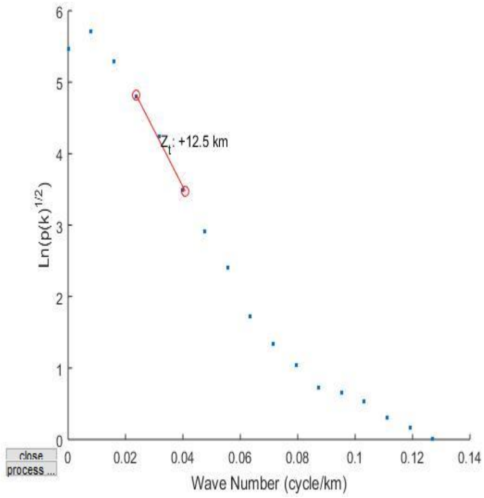
Z_0: +20.1 km
Ln(p(k)^1/2/k)
Wave Number (cycle/km)
close
process ...



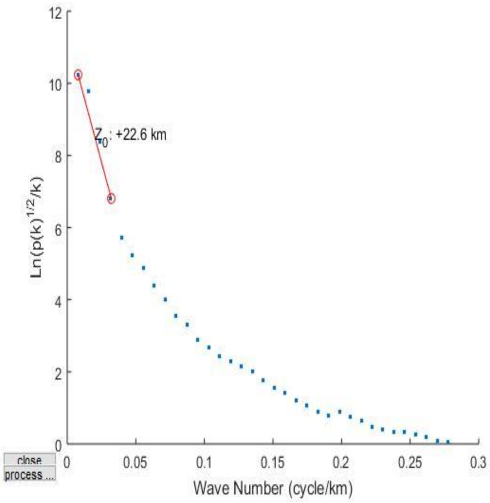
Z_1: +12.4 km
Ln(p(k)^1/2)
Wave Number (cycle/km)
close
process ...



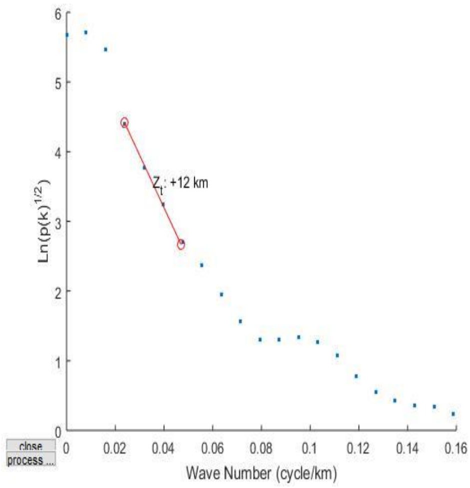
Ln(p(k)^1/2/k)
Z0: +19.7 km
Wave Number (cycle/km)
close
process ...



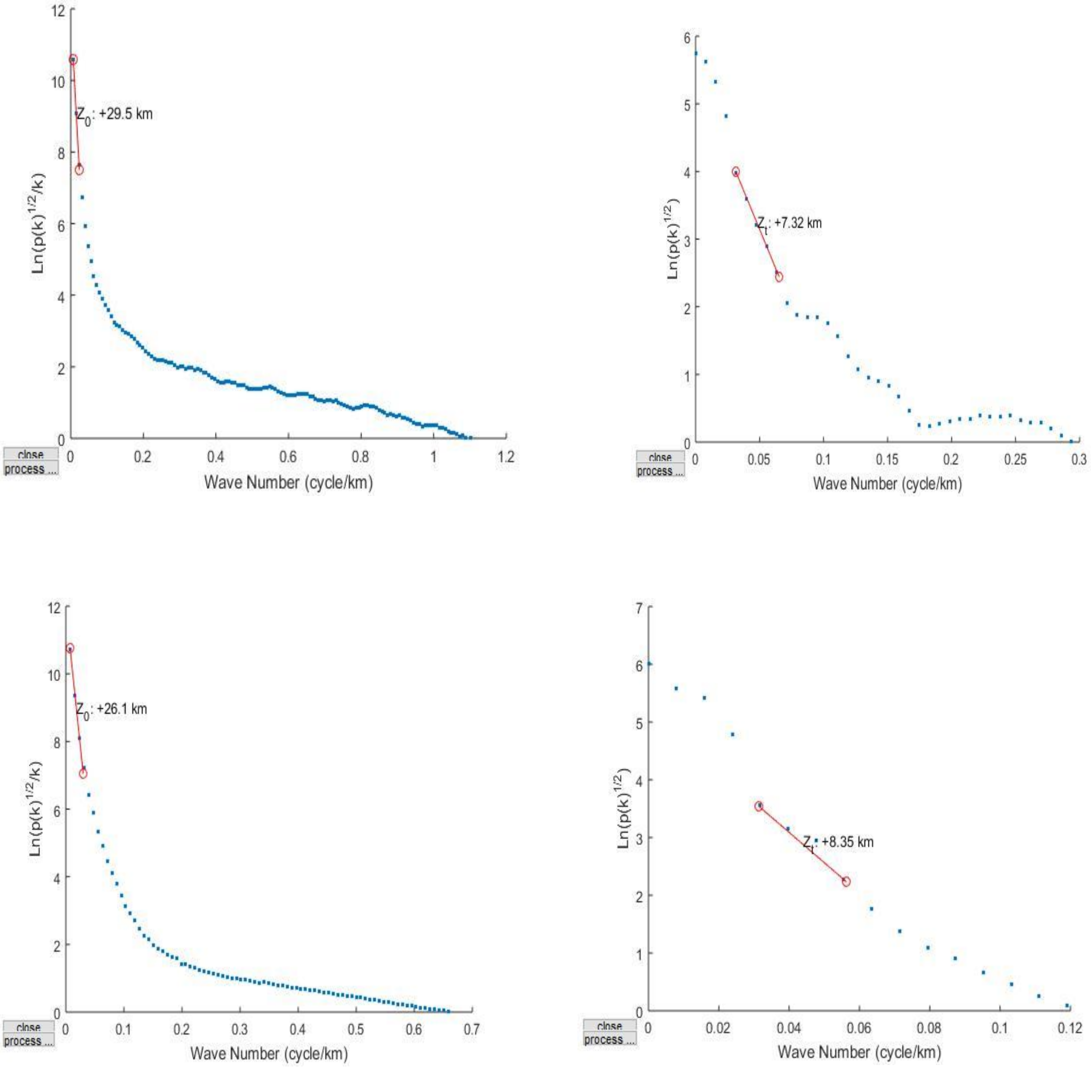
Ln(p(k)^1/2)
Zt: +12.5 km
Wave Number (cycle/km)
close
process ...



Ln(p(k)^1/2/k)
Z0: +22.6 km
Wave Number (cycle/km)
close
process ...



Ln(p(k)^1/2)
Zt: +12 km
Wave Number (cycle/km)
close
process ...


Z0: +29.5 km
Ln(p(k)^1/2/k)
Wave Number (cycle/km)
close
process ...
Z1: +7.32 km
Ln(p(k)^1/2)
Wave Number (cycle/km)
close
process ...
Z0: +26.1 km
Ln(p(k)^1/2/k)
Wave Number (cycle/km)
close
process ...
Z1: +8.35 km
Ln(p(k)^1/2)
Wave Number (cycle/km)
close
process ...