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Analysis of High Resolution Airborne Magnetic Studies for Curie Depth, Heat Flow and Geothermal Energy Potentials over Parts of Southeastern Nigeria.

[1]Nwokeabia, Charity Nkiru;[2]Ibe, Kalu Kalu;[3]Ibeneme, Sabinus Ikechukwu; [4]Orji, Chikwendu Emenike; [5]Adikwu, Stephen Onum.
[1] Nnamdi Azikwe University Awka. Department of Applied Geophysics. Nigeria.
[2,3,4,5] Federal University of Technology Owerri, Department of Geology, Nigeria

Abstract
Airborne magnetic dataset Studies were carried out in parts of Southeastern Nigeria. The study area is bounded by latitudes $5^o00^{'}$ N and $6^o30^{'}$ N and longitudes $7^o00^{'}$ E and $8^o30^{'}$ E, covering an area extent of about 27,225km^2. Airborne magnetic data covering the study area was acquired, processed, and interpreted with the aim of appraising geothermal potential in the study area. Various data enhancement techniques were carried out on the magnetic data in order to filter unwanted signals. Analysis such as sediment thickness, Curie point Depth, Geothermal gradient and heat flow of the study area were carried out. The Curie Point Depth obtained in the study area ranges from 5699.183 to 20156.59km with the shallow depth at Ugep, Afikpo, and Ezeagu. Geothermal gradient within the study area ranges from 28.757 and 83.098^{0}ckm^{-1}. Heat flow ranges from 71.936m wm^{-2} to 207.746mwm^{-2}. The result reveals that, the Curie Point Depth varies inversely with heat flow. This shows that heat flow in the study area decreases with increases in curie depth.
Airborne Magnetic, Curie Point Depth, Geothermal Gradient, Heat flow, Southeastern Nigeria.

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I. Background Information

Aeromagnetic survey is one of the most frequently used type of airborne geophysical survey and has been recognized as a principal mapping tool for materials that are strongly magnetised (Murphy, 2007). The essence of the magnetic survey is to investigate subsurface geology on the basis of the anomalies in the earth's magnetic field resulting from the magnetic properties of the underlying rocks. The physical principle of aeromagnetic method is based on taking the ambient magnetic susceptibility of the subsurface geology and using the data to determine the distribution of the magnetic minerals and hence changes in the lithology (Telford et al., 1990). The susceptibility (magnetic content) is dependent on the type of rock and its environment (Mariita, 2013). Soil magnetic susceptibility can be related to different terrain topography attributes such as the slope, elevation and concavity – convexity of the surface terrain to explain the distribution of magnetic minerals within soil (Appiah, 2015). Common causes of magnetic anomaly include dykes, faults and lava flows. In a geothermal environment, susceptibility decrease due to high temperature (Mariita, 2013) magnetic basement interpretation can lead to better understanding of the structures of the structures of the overlying sedimentary rocks.

The application of aeromagnetic method range from mineral exploration (Murphy 2007), structural mapping and rocks characterization (Telford et al., 1990) and these provide useful information on lithology and geologic structures.

The objective is to interpret the study area using high resolution aeromagnetic data in order to estimate the Curie point depth, heat flow and geothermal gradient of the area.

1.1 Location of the Study Area

The study area lies between longitudes 7°00'E and 8°30'E and latitudes 5°00'N and 6°30'N (fig. 1). It extends from Enugu in the north to Uyo in the south and Orsu and Ikot Ekpene communities in the east and west respectively covering a total area of about 27,225Km^2.

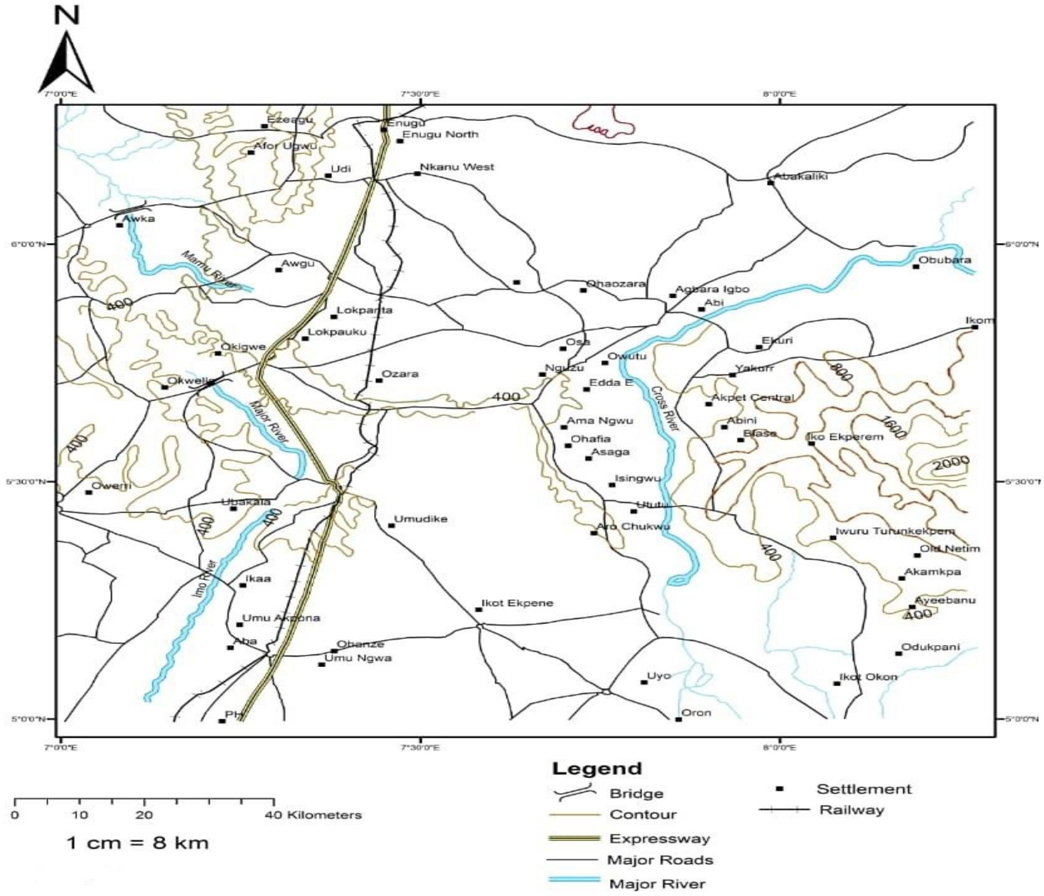

Figure 1. Location /Topographic Map of Study Area

II. Materials And Methods

The aeromagnetic data for this study was obtained from Nigerian Geological Survey Agency. The nominal flight height of 80m along N-S flight lines spaced at 500m interval using advanced equipment with higher resolution. The geomagnetic gradient was removed from the data using the International Geomagnetic Reference Field (IGRF).

The data was further processed, enhanced and interpreted with Geosoft (Oasis Montaj), Arc GIS, and Global mapper. Firstly, on a Geosoft platform the two datasets were projected to Universal Transverse Mercator (UTM) coordinate system Zone 30 N using World Geodetic System (WGS) 84 as the datum. The data was then gridded with the minimum curvature method of gridding.

III. Result And Discussions

The Total Magnetic Intensity (TMI) is the magnetic field that is observed in a particular location, it is a combination of the Earth's magnetic field and the field produced by magnetic bodies located at the subsurface of the study area. Figure 3.1 is the Total Magnetic Intensity (TMI) map of the study area.

The TMI shows the effects of the underlying basement as well as effects of near surface structures within the study area. In the TMI map, areas coloured blue indicate low magnetic intensity, green indicates intermediate magnetic intensity, and red-pink areas indicate high magnetic intensity. The total intensity map therefore shows a very complex pattern of magnetic anomalies. In all the study area the anomalies have a regional gradient with an increasing field intensity from southwest to northeast, with values ranging from -72.3 to 172.5 nT. The study area is characterised by low magnetic amplitude ranging from -72.3to 13.3 nT, intermediate magnetic amplitude ranging from 13.4 to 85.3 nT, and high magnetic amplitude with ranging >85.3 nT. The magnetic variations within the study area trend majorly in the northeast southwest direction with long wavelength bodies occurring within the central, northern, western and southern parts of the study area, these areas correspond to the sedimentary basins (Southern Benue Trough, Anambra Basin and Southern Niger Delta Basin). The eastern part of the study area is occupied by short wavelength (high frequency) magnetic bodies, it is indicative of magnetic bodies at shallow depth, this area corresponds to the Southeastern Basement Complex around Ugep, Obubra, AgoiIbani, Biase, Ikot Ekperem, and EsukAkpai.

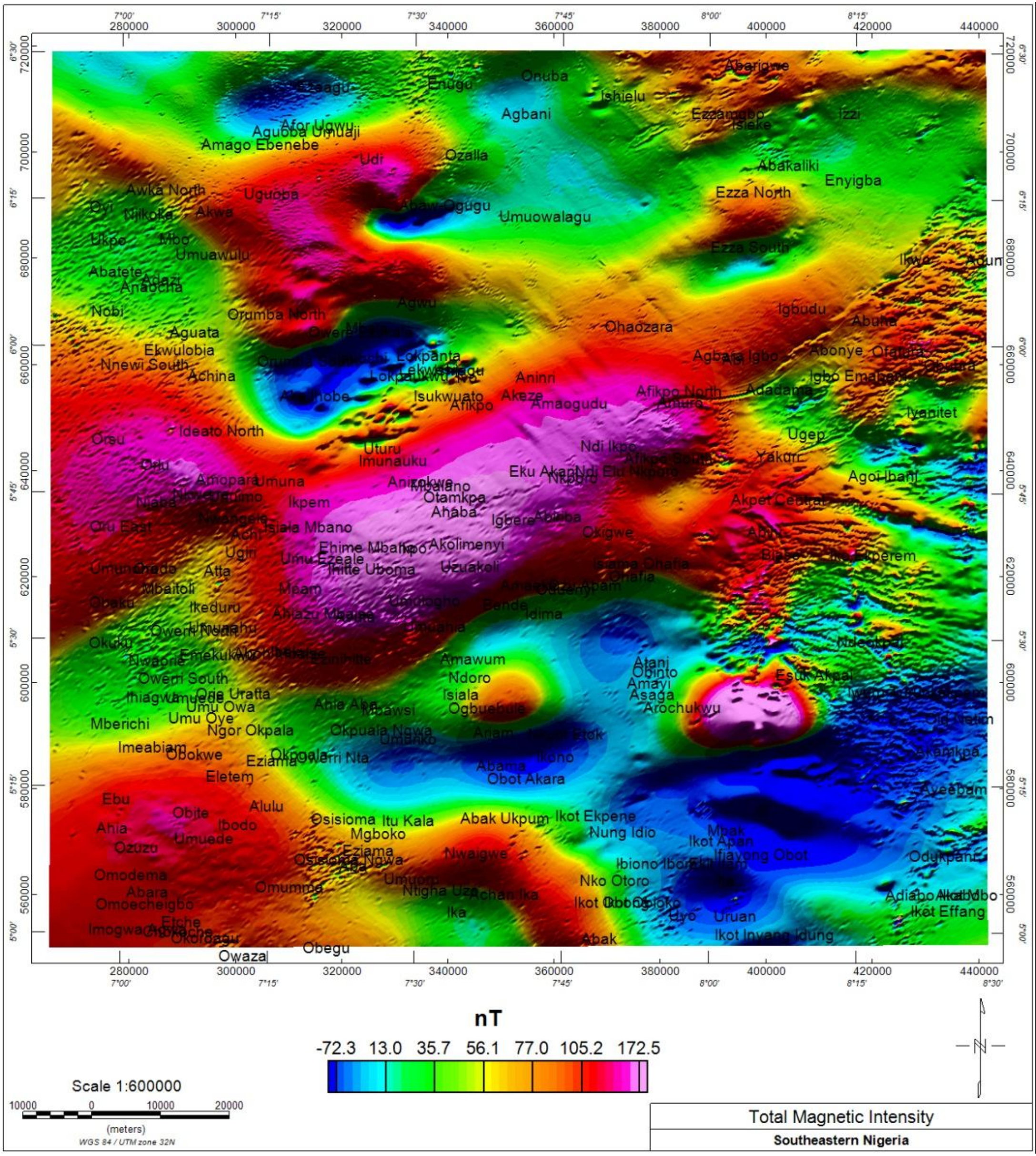

Figure 3.1. Total Magnetic Intensity (TMI) map of the Study Area

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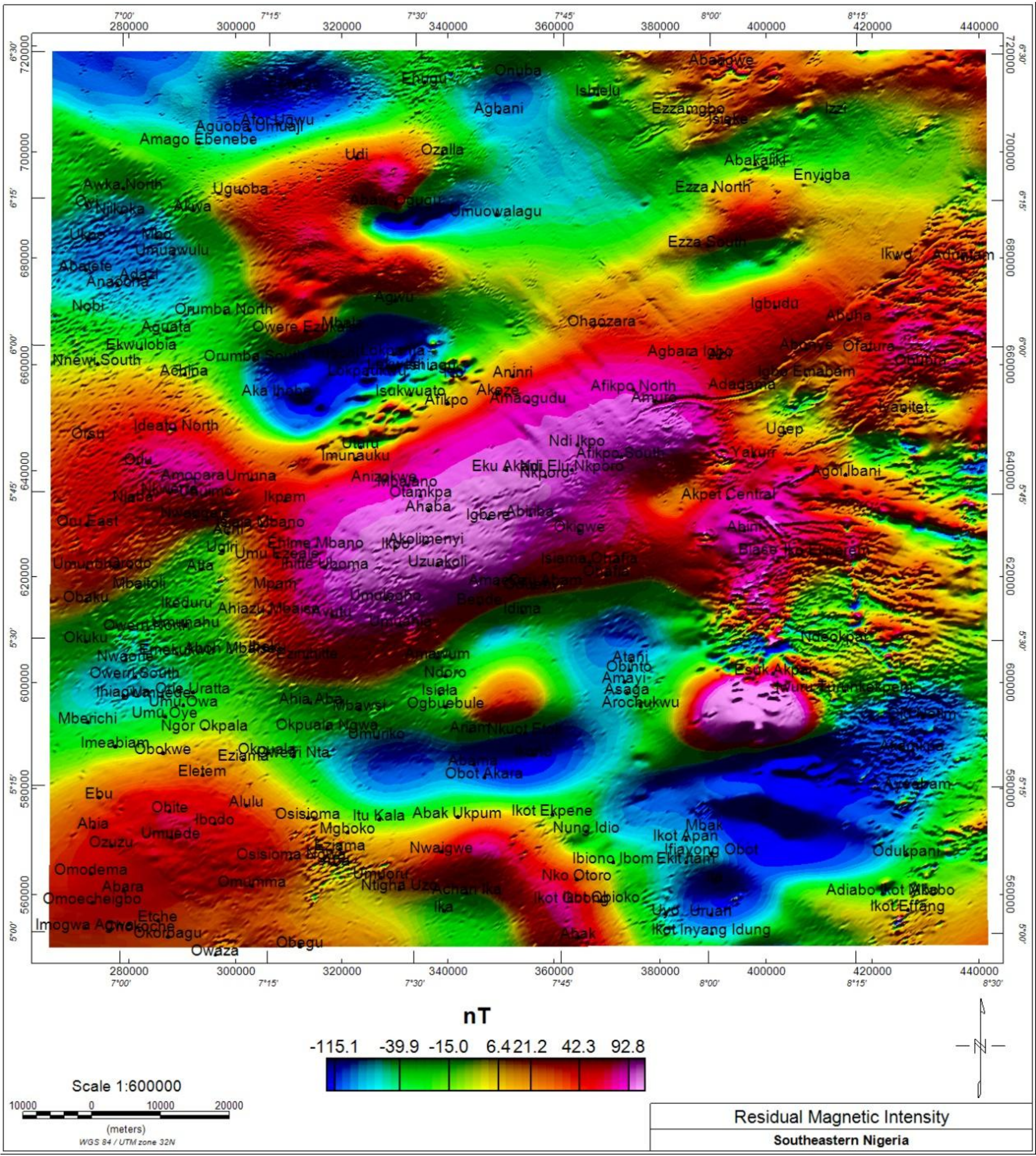

Figure 3.2. Residual Magnetic Intensity map of the Study Area

3.1.1 STRUCTURAL INTERPRETATION

The first vertical derivative map (figure 3.3), reveals a cluster of dipolar magnetic structure all over the eastern part of the study area, this area interpreted as the southeastern Basement complex of Nigeria, is characterized by rocks such as granite gneiss, biotite granite, porphyritic granite, schist and granodiorites, these rocks are known to be highly faulted and fractured resulting in the almost linear structures observed in the first vertical derivative map. The structures trend majorly in the NW – SE, and EW direction with minor NE – SW directions. Three major folds (FD4, FD5 and FD6) with an average length of about 43.2 Km is observed at the southeastern part of the study area, extending from Odukpani through Ayeebam, Akamkpa, Old Netim to Ndeokpa. The fold is interpreted to have resulted from the second phase of the Santonian event that deformed the Southern Benue Trough.

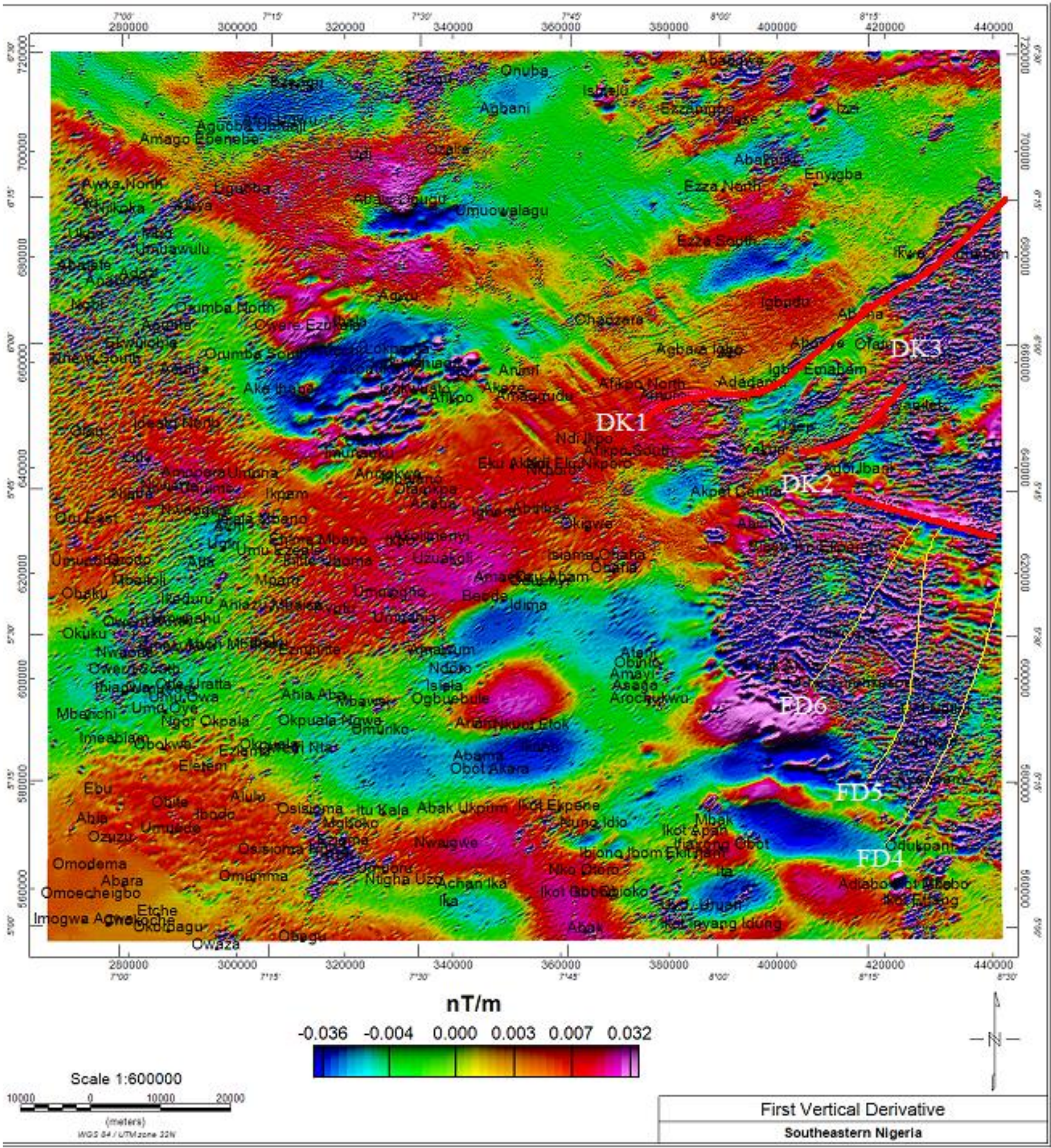

Figure 3.3. First Vertical Derivative Map of the Study Area

Abakaliki, Enyigba, Ezza North and South, Ezzamgbo, Ishielu, Abauwgu and Izzi area has small weak magnetic signatures with high occurance of dipolar structures accumulated around, Ezzamgbo, Ishielu and Abauwgu area. The structures have a major NE – SW trend. These bodies are interpreted as the diorite rock currently being quarried around Ezzamgbo, Ishielu and Abauwgu area. A high intensity of structures occurs around Enugu, Onuba, Agbani, Udi, and AbawOgugu area, the structures trend majorly NE – SW, with a major fold with axial plane trending westward, stretches from Ozalla to Agbani extending for about 14.9 Km. This area is interpreted as the boundary between Abakaliki Anticlinorium (Southern Benue Trough) and the Anambra Basin. Lesser structural occurrence is observed within Ezeagu, Aguoba, AforUgwu, AmagoEbenebe, Uguoba and Awka North, the structures also trend NE – SW, the area is interpreted to fall within the Anambra Basin, with AforUgwu, Aguoba area having weak magnetic signature which indicates probable high depth to basement.

At the central part of the study area, around Lokpaukwu, Ishiagu, Isukwuato, Afikpo, Uturu and Imunauku area shows high intensity of structures trending NE – SW, this area is notably characterized by low magnetic structures. The high structural occurrence indicates good traps for this fluid, expecially around

Isukwuato, Ishiagu and Lokpanta axis. Geologically, these areas (Lokpaukwu, Ishiagu, Isukwuato, Afikpo, Uturu and Imunauku) are also interpreted to be the eastern boundary between the Southern Benue Trough and Afikpo Basin.

Numerous NE – SW trending structures are enhanced in the first vertical derivative maps, around the western part of the study area. The area includes Awka, Ukpe, Mbo, Adazi, Nobi, Orumba North and South, Achina, Nnewi, Orsu, Orlu, AmoparaUmuna, Ikpem, Oru, Atta, Mbano, Mpan, Mbaisa, Ikeduru, Obaku, Okuku, Owerria and Umuahia. The structures within these areas are interpreted to have formed during the breaking of Gondwana supercontinent and the opening up of the southern Atlantic and Indian Oceans in the Jurassic which led to a sinistral strike-slip displacement inherited from pre-existing transcurrent fault zones in the Pan African mobile belt then forming the Benue Trough.

The area around Omodema, Abara, Omoecheigbo, Etche, Imogwa, Okoroagu all at the southwestern part of the study area, reflect clear signature with no notable structural deformation, the area is interpreted to geologically fall within the Niger Delta Basin which has no notable tectonic event post basin formation. The structural displacement in other part of the Niger Delta Basin geographically around Ikot Ekpene, Nungdio, Abak, Ika, Nwaigwe, Itu ala, Achan, Ngwa, Eziama, Osisioma, Omumma, Owerri, Alulu, Obite, Umuede, Ibodo, Obite, ObotAkara, Ogbuebule, Ndoro, Ahia, Aba, Okpuala, Ngwa, Mberichi all show displacement in form of dipolar magnetic structures, these were interpreted to have resulted from the tectonic activities occurring within the Benue Trough.

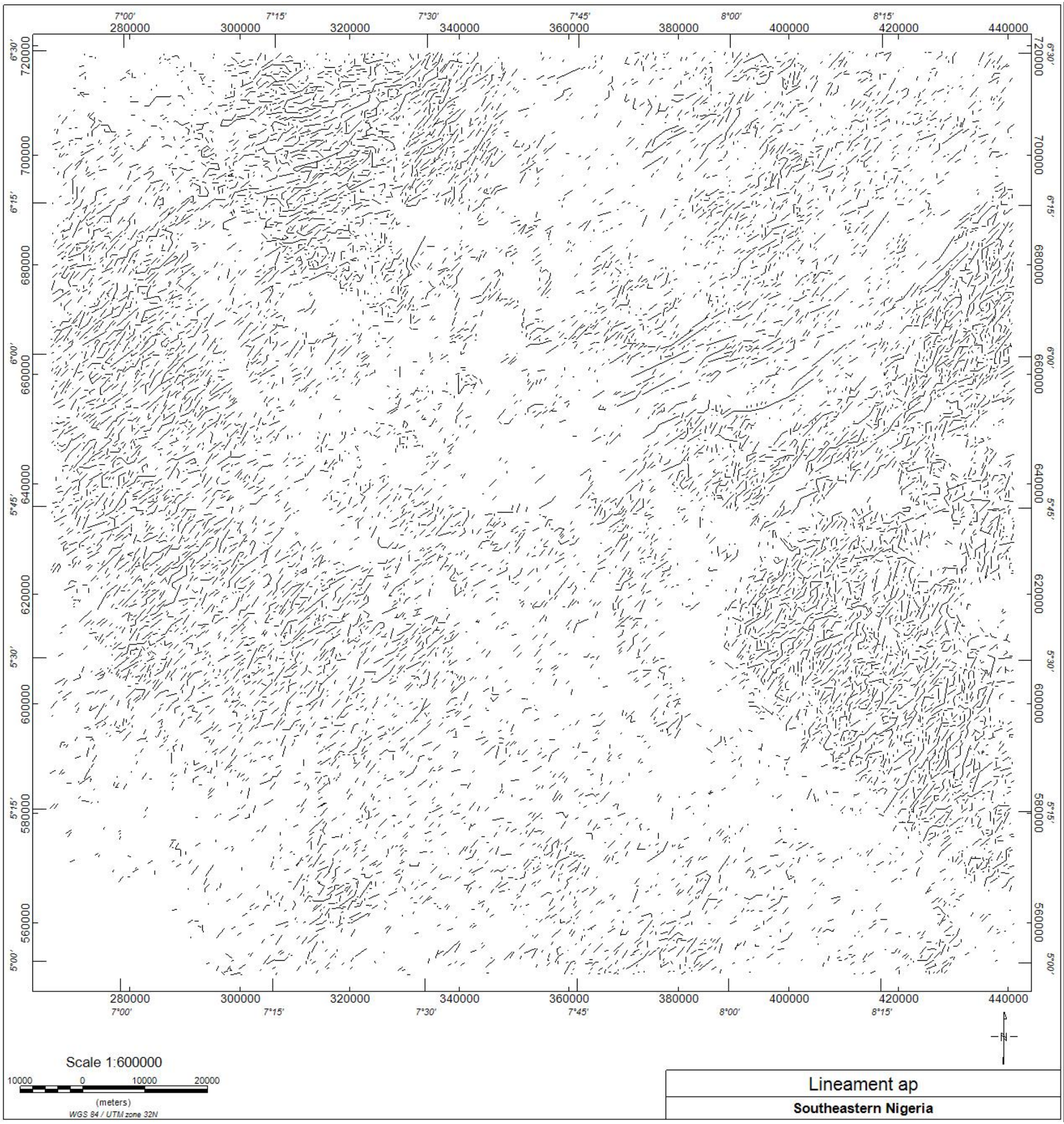

Figure 3.4. Lineament Map of the Study Area

Lineament extraction was done using Center for Exploration Targeting (CET) grid analysis which is a set of algorithms that enhances, locates and vectorizes discontinuity structures within the potential field data. Lineaments maps (Figure 3.4) are linear features which express the underlying geological structures in an area, these lineaments result from faults, joints, folds, contacts or other geological reasons, found in igneous, sedimentary and metamorphic rocks. The lineaments (faults/fractures) are marked in black ticks while dykes and sills are marked in arched curves. The orientation and length of the lineament extracted from the lineament map were displayed in a rose diagram to analyze the spatial distribution of lineaments. The rose diagram (Figure 3.5) shows trends majorly in the NE-SW, EW with minor NW-SE, N-S directions. From the extracted lineaments, those at Ugep, Obubra, Adu, Agoibani, Barase, IkoEkperem, and EsukAkpaigeologically representing the Basement Complex within the study area, trends in the NW-SE direction with minority striking in the EW and NE-SW direction.

The structures within the sedimentary basin trend majorly in the NE-SW with minor NW-SE and NS trends.

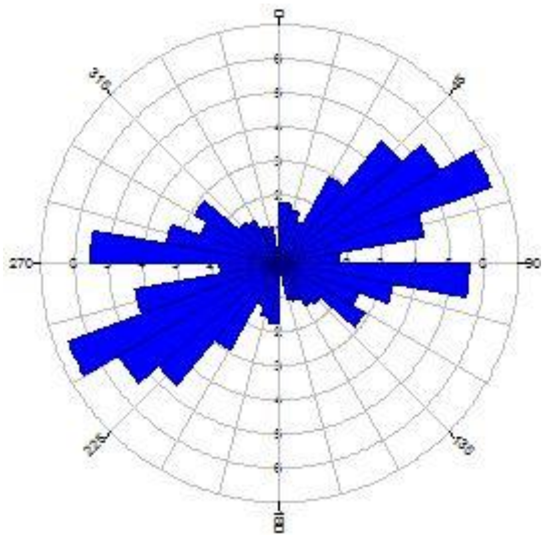

Figure 3.5. Rose Diagram of the Study Area

The intensity of deformation within the study area was evaluated using the lineament density map (Figure 3.6). The orientation of the structures within the basin is also evaluated. Areas that have high lineament density indicates high deformation and closeness of the basement rocks to the earth surface, while areas with less lineament density indicates low deformation with plane grounds mainly composed of sediments. Interpreted lineament density indicates intense deformation at the eastern part of the study area, which represent the intense deformation of the Southeastern Basement Complex. The western part of the study area, around is moderately deformed while the area around Enugu, Udi, Agwu, Uguoba, Amego, Ebenebe, Ozalla, Ezeagu and Aguoba show high deformation, this deformation resulted from the uplift of the Abakaliki Anticlinorium. The Southern Benue Trough shows moderate to low deformation but the centre of the Abakaliki Anticlinorium shows higher deformation around Abakaliki, Ezza North and South, Izzi, Enyigba, Abarigwe, Ohaozara and Ezzamgbo. The map also shows that Osisoma, Eziama, Aba and Ngwa areas are highly deformed due to plutonic rock mapped, around Arochukwu, Asaga, EsukAkpani area shows low deformation. Lokpanta, Isukwuato, Ishiagu and Uturu reflect moderate deformation owing to the occurrence of intrusive rocks within the area.

The areas of high deformation are interpreted to be zones of high emplacement of intrusive rocks, this area is of great interest, as the area closely mapped during the ground radiometric survey, in other to define their radioactive counts and dose within the environment.

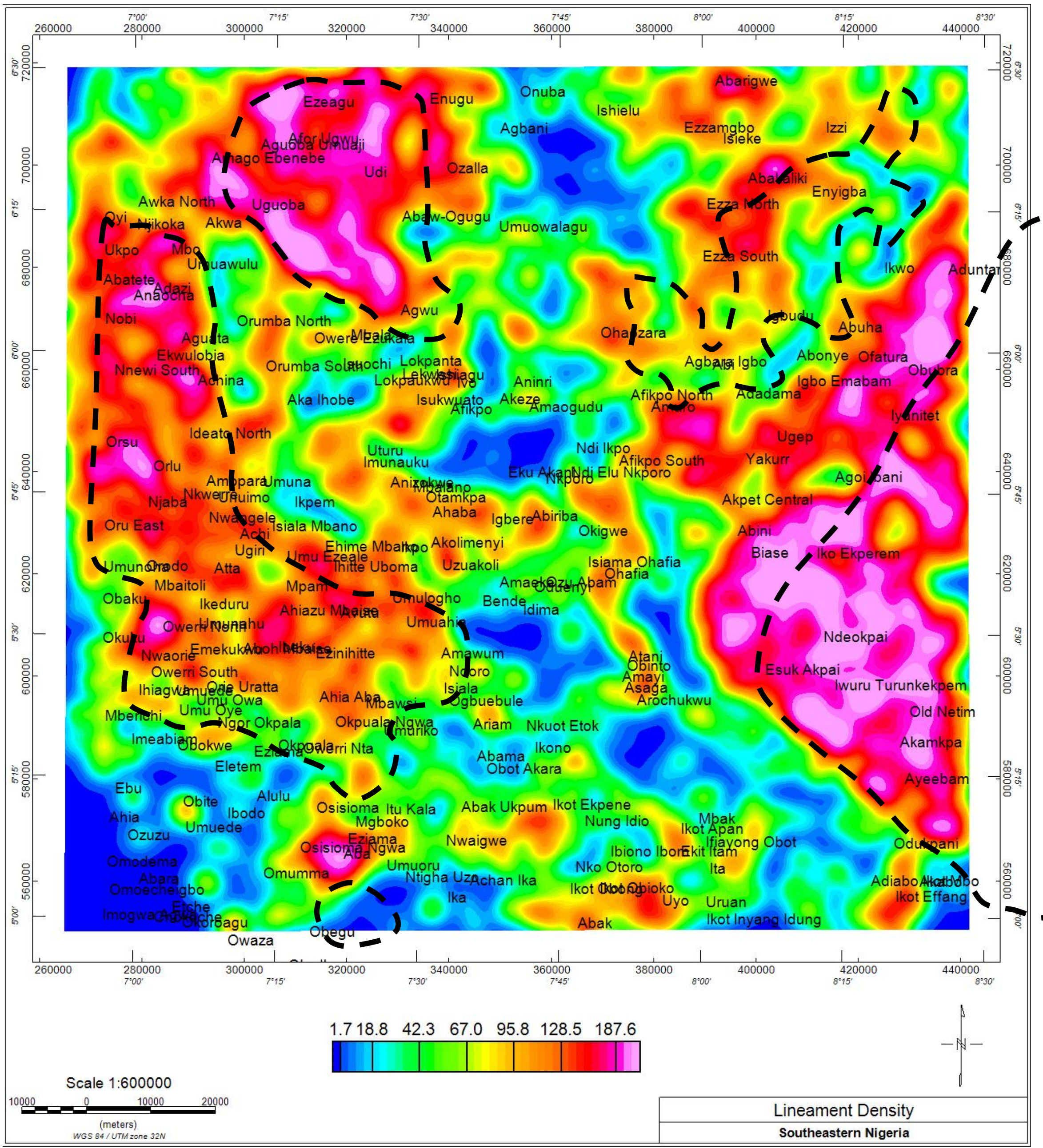

Figure 3.6. Lineament Density Map within the Study Area.

Curie depth, Geothermal Gradient and Heat Flow

Spectral analysis was used to compute the depth to centroid (depth to bottom of magnetic source). The centroid depth was plotted to produce a 2D image of the depth to bottom of magnetic source surface (Figure 3.7). The shallowest depth of <3500 m is observed at Akaeze, Igbere, Abiriba, Okigwe, Amuro, NdiIkpo, Igbudu and Adadema within the Southern Benue Trough and Afikpo Basin; Abak area within Niger Delta Basin; and Awka North, Njikoka, Mbo, Umuawulu, Adazi, Abatete and Nnobi, which geologically falls within Anambra Basin. Shallow depths are also observed within the Southeastern Basement Complex at the eastern part of the study area, at Ugep, Iyanitet, AgoiIbani, BiaseIko, Ekperem, Ndeokpai, EsukAkpai, IwuruTurunkekpem, Akamkpa and Ayeebam. Intermediate depth with range of 3500 to 6500 m, is observed at Enyigba, Ezza South, Ohaozara, Agwu, Afikpo, Isukwuato, Lokpaukwu, Aka Ihobe, Achina, Abarigwe, Ezzamgbo, Isieke, Ishielu, Enugu, Ezeagu, Udi, Ozalla, AmagoEbenebe, Akwa, Orumba, Uturu, Otamkpa, Ahaba, Uzuakoli, Bende, Ohafia, Akpet Central and Yakurr, with the deepest point around Abarigwe, Ezzamgbo, Isieke, Ishielu and Ezeagu. The highest depth to centroid is observed around Ikono, NkuotEtok, Arochukwu, Isiala, Kala Abak, Ikot Ekpene, Osisioma, Omumma, Obite, Umuede, Ozuzu, Omoecheigbo, Etche, Okoroagu, Owaza and OkeIkpe, with depth range >6500 and depth point around Ozuzu, Omoecheigbo, Etche, Okoroagu and Owaza.

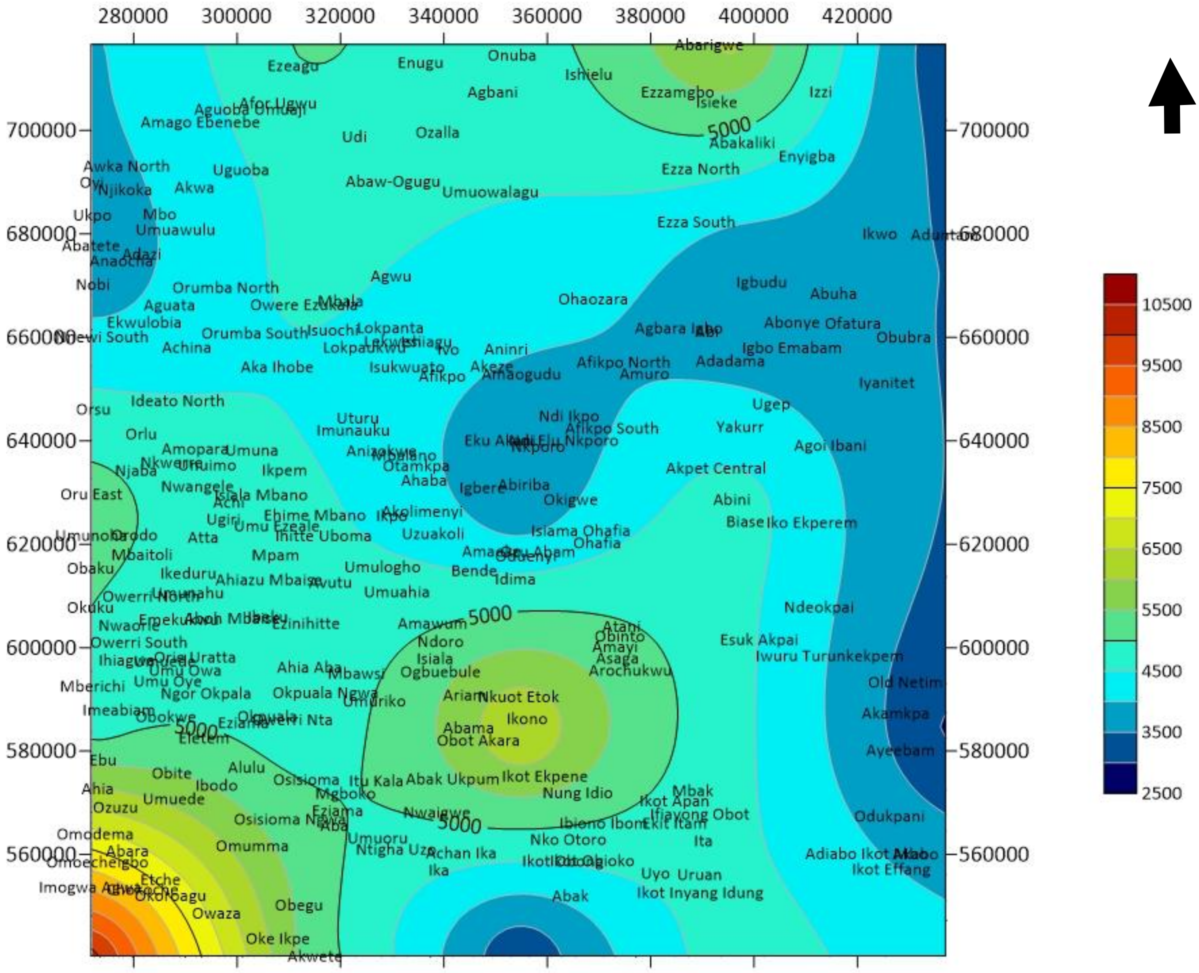

Figure 3.7. 2D Image of the Basement Surface

The curie isotherm depths were computed using the depths of the shallowest and deepest sources which were obtained using the spectral analysis method (Bhattacharyya, 1965). The depths to centroid ranges from 3006.218 to 10223.460 m while the depths to the top of the magnetic bodies range from 154.373 to 368.081 m.

The result reflects Curie isotherm depths map (figure 3.8) vary within the study area with minimum curie depths ranging from 5500 to 13000 m, occurring geologically within Southern Benue Trough and Anambra Afikpo Basin, at Enyigba, Ezza South, Ohaozara, Agwu, Afikpo, Isukwuato, Lokpaukwu, Aka Ihobe, Achina, Abarigwe, Ezzamgbo, Isieke, Ishielu, Enugu, Ezeagu, Udi, Ozalla, AmagoEbenebe, Akwa, Orumba, Uturu, Otamkpa, Ahaba, Uzuakoli, Bende, Ohafia, Akpet Central and YakurrAkaeze, Igbere, Abiriba, Okigwe, Amuro, NdiIkpo, Igbudu and Adadema; within Abak area which geologically falls within Niger Delta Basin. Shallow curie depths are also observed around Ugep, Iyanitet, AgoiIbani, BiaseIko, Ekperem, Ndeokpai, EsukAkpai, IwuruTurunkekpem, Akamkpa and Ayeebam, all which geologically falls within the Southeastern Basement Complex. Curie depth >15500 m is observed at Ozuzu, Omoecheigbo, Etche, Okoroagu and Owaza, while intermediate depth with depth range of 13000 to 15500 m is observed at Ikono, NkuotEtok, Arochukwu, Isiala, Kala Abak, Ikot Ekpene, Osisioma, Omumma, Obite, Umuede and OkeIkpe, The deeper Curie depth point which trends in NE-SW direction within the Niger Delta Basin of the study area could be as a result of isostatic compensation in the region.

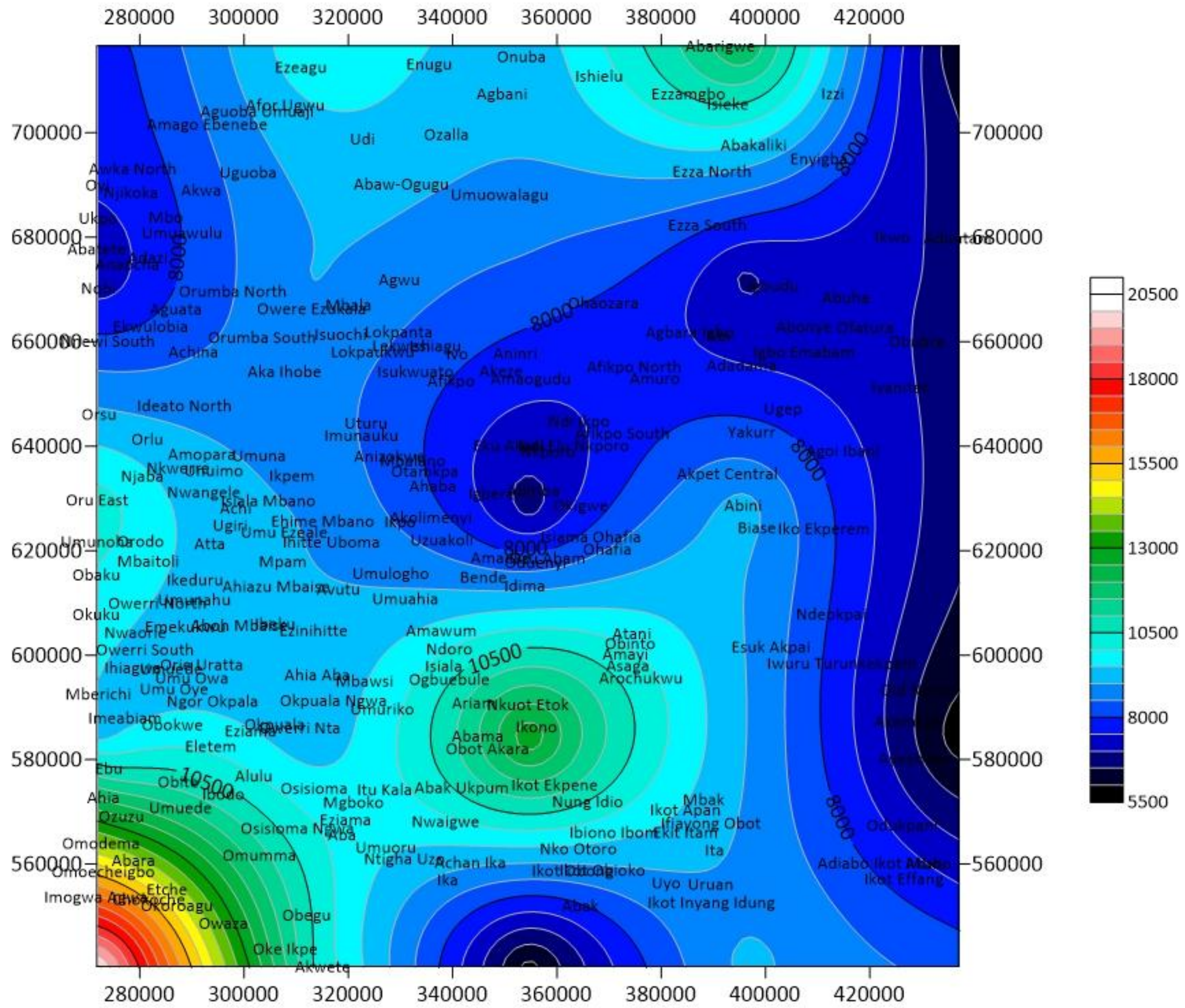

Figure 3.8. Curie Isotherm Depth of the Study Area

Curie-point temperature of 550°C (Curie point temperature of 580°C minus surface temperature of 30°C) and calculated curie isotherm depths were used to compute the geothermal gradient variations within the study area (Ofor and Udensi, 2014) (Figure 3.9). The values of geothermal gradients and thermal conductivity of 2.5 $Wm^{-10}C^{-1}$ (Nwankwo et al. 2009) were subsequently used to calculate the corresponding heat flow anomalies in the study area (Figure 3.10).

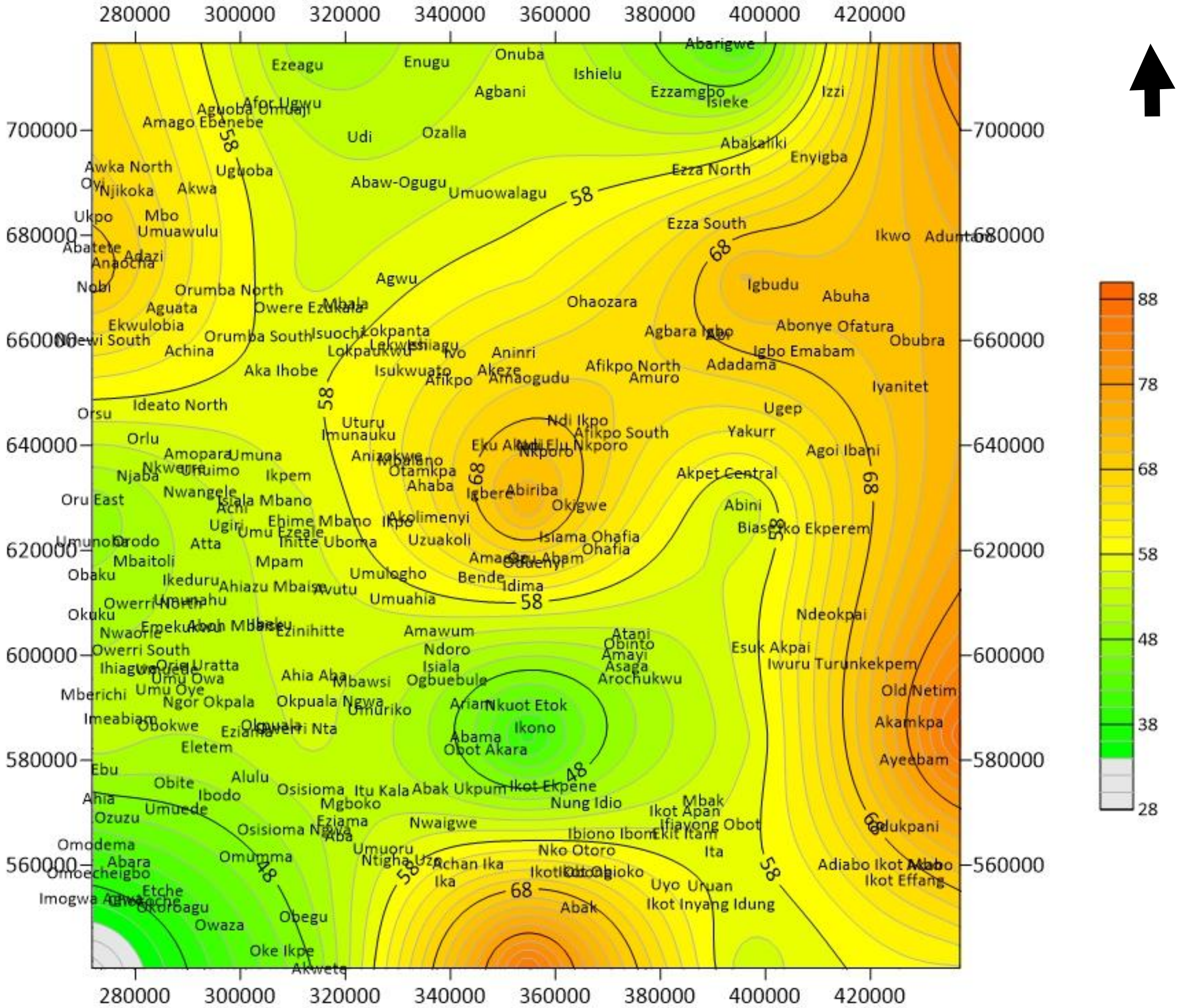

Figure 3.9. Geothermal Gradient Map of the Study Area

The results obtained in the study area shows that geothermal gradient varies between 28.775 to 87.713^{o}C/km. Within the basement complex rock at the eastern part of the study area, geothermal gradient ranges from 58 to 87.713 ^{o}C/km. Southern Benue trough recorded geothermal gradient ranging from 38 to 58 ^{o}C/km, with the highest values observed around Abakaliki, Enyigba, Ohauzara, Ishiagu and Lokpanta and lowest values occurring around Ezzamgbo, Abarigwe and Ishielu areas.

Anambra Afikpo Basin recorded similar geothermal gradient as that of Southern Benue Trough, with Awka, Umuawulu, Aguata, Njikika, Achina, Uturu, Otamkpa, Afikpo, Uzuakoli, Okigwe, Abiriba and Ohafia area; while the lower values within the basin is recorded at Enugu, Ezeagu, Udi, Ozalla, Agbani, Onuba, AbawOgugu and Agwu. Niger Delta Basin recorded variation in geothermal gradient ranging from 28.775 to as high as 78 ^{o}C/km, higher values are recorded at Abak, Ika, AchanIka, NkoOtoro, IbionoUyoUruan and Ikot Inyang Idung and lower values within Ozuzu, Omoecheigbo, Etche, Okoroagu and Owaza, Ikono, NkuotEtok, Arochukwu, Isiala, Kala Abak, Ikot Ekpene, Osisioma, Omumma, Abama, ObotAkara and Eletem.

Heat flow of the study area ranges from 71.937 to 170 mWm^{-2}within Niger Delta Basin, from 95 to 170 mWm^{-2}within Anambra Afikpo Basin and from 170 to 195 mWm^{-2}within Southern Benue Trough, while within the Southeastern Basement Complex, the heat flow is >195 mWm^{-2}. The variation of heat flow within the study area indicates random distribution of magma conduits. The heat flow result obtained is compared favourably with other works on heat flow within Nigeria's inland basins (Onwuemesi, 1997., Nur et al,1999., Nkwankwo, etal 2009., Kasidi and Nur, 2012 and 2013., Akpabio and Ejedawa, 2001 and 2010., Emujakporue and Ekine, 2014., Anakwuba and Chinwuko, 2015.).

The average heat flow obtained within the sedimentary basin in the study area is 107.5 mWm^{2}, this may be considered as typical of continental crust (Jessop *et al.*, 1976). It can be inferred that the geothermal prospect areas in this study may be areas where there is thick layer of thermally insulated sediments cover, basement rocks and volcanic activities as observed around Afikpo, Okigwe, Ndikpo, Amuro, Ivo, Aguata, Ekwulobia, Umuawulu, Mbo, Awka, Anaocha, Adazi, Abak, and NkoOtoro.

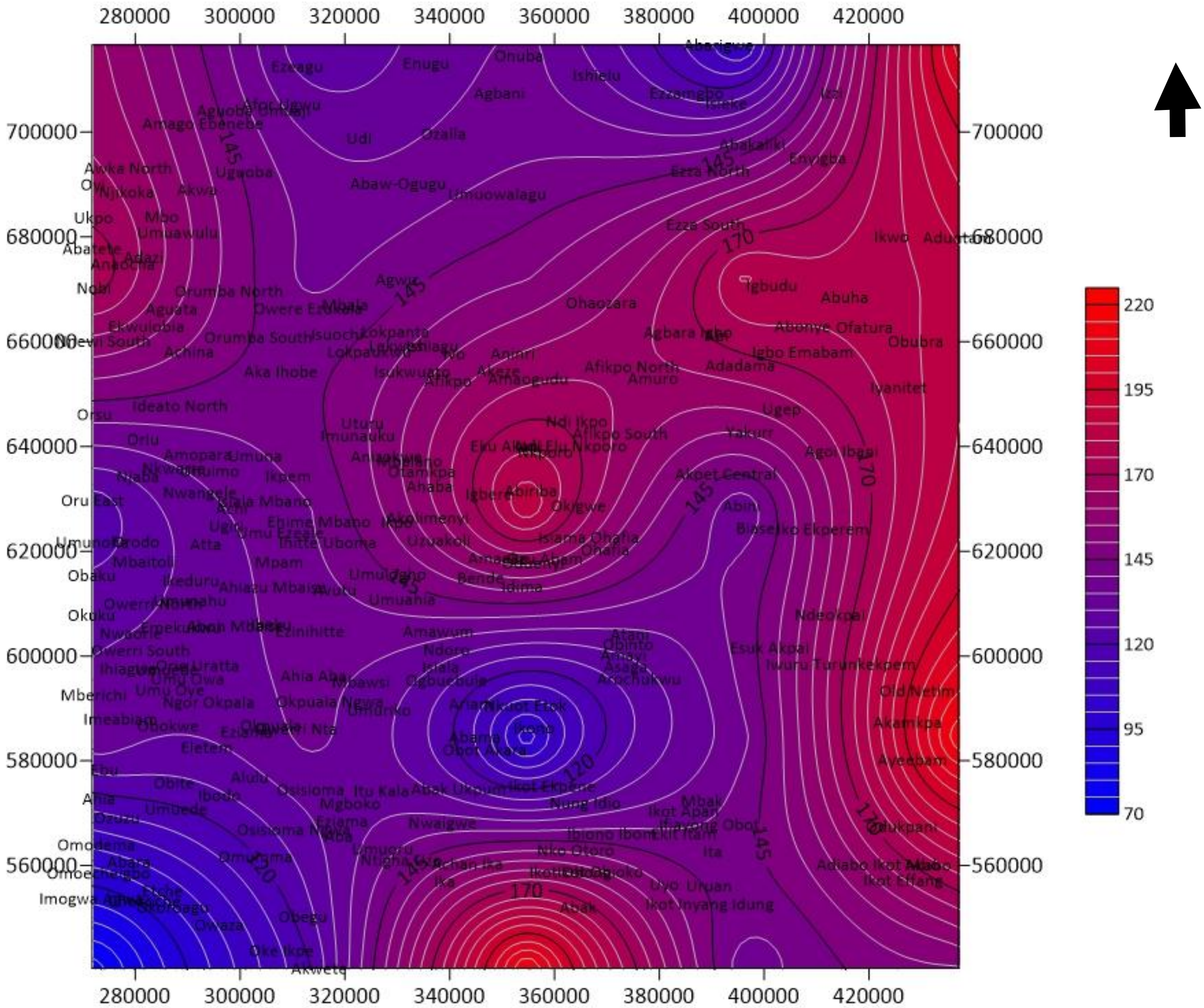

Figure 3.10. Heat Flow Gradient Map of the Study Area

Spectral analysis of the data revealed an almost inversely proportional linear relationship between heat flow and Curie depths (Figure 3.11) meaning a decrease in curie isotherm depth results to an increase in heat flow within the study area.

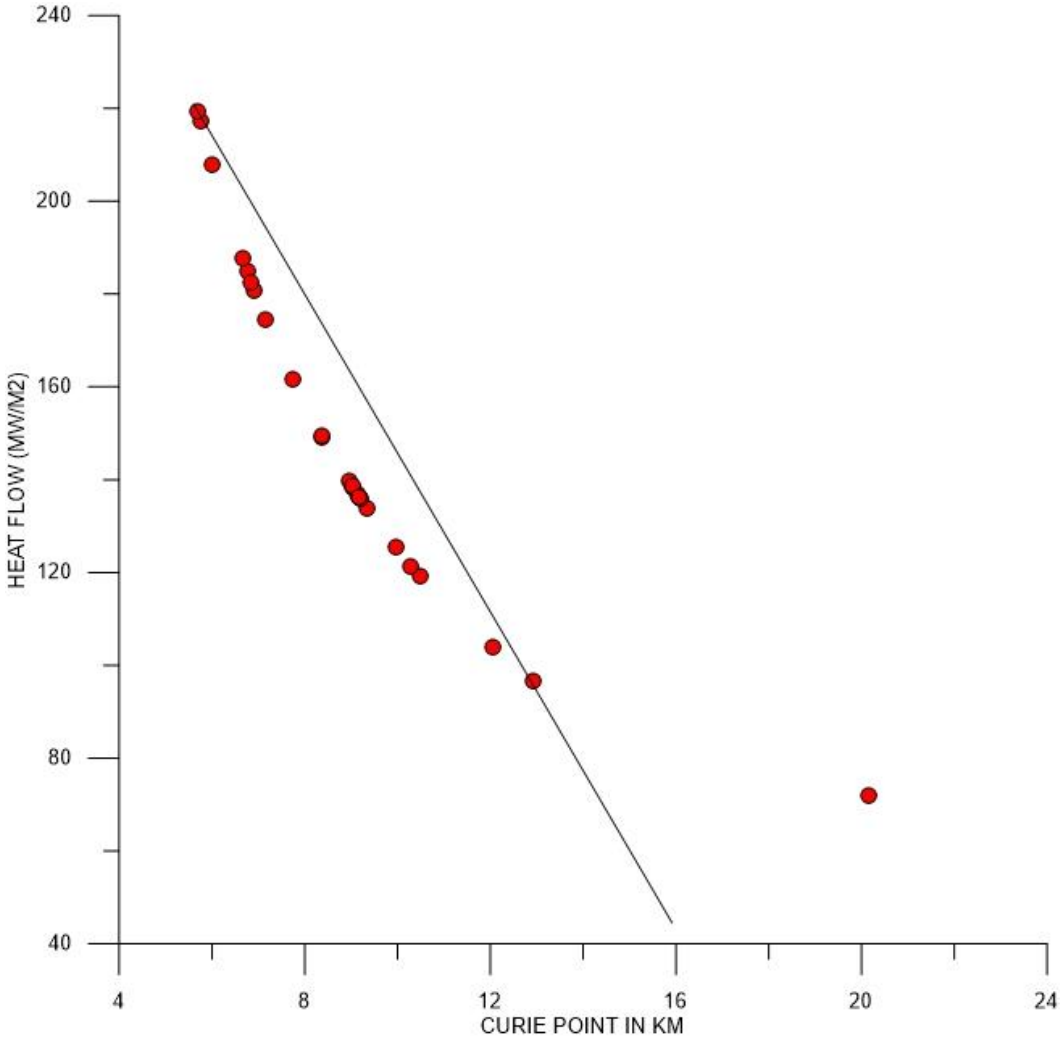

Figure 3.11. Relationship between Curie Depth and Heat Flow within the Study Area

IV. Conclusion

Airborne magnetic dataset covering southeastern Nigeria was acquired, processed and filtered for the interpretation of structures within the study area. The structural interpretation revealed that structures trend majorly in the NE-SE direction, with minor NW-SE and NS trends. The Southern Benue Trough, Anambra and Afikpo Basin and Niger Delta Basin is dominated by NE-SW trending structure while the Southeastern Basement Complex, observed around Ugep, Obubra, Adu, Agoibani, Barase, IkoEkperem, and EsukAkpai host structures trending NW-SE with minor NE-SW and EW structures.

The Curie point depth obtained in the study area ranges from 5699.183 to 20156.59 km, with the shallow depth at Ugep, Iyanitet, AgoiIbani, BiaseIko, Ekperem, Ndeokpai, Enyigba, Ezza South, Ohaozara, Agwu, Afikpo, Isukwuato, Lokpaukwu, Aka Ihobe, Achina, Abarigwe, Ezzamgbo, Isieke, Ishielu, Enugu, Ezeagu, Udi, Ozalla, AmagoEbenebeEsukAkpai, IwuruTurunkekpem, Akamkpa, Ayeebam, Akaeze, Orumba, Uturu, Otamkpa, Ahaba, Uzuakoli, Bende, Ohafia, Igbere, Abiriba, Okigwe, Amuro, NdiIkpo, Igbudu, Adadema, Abak, Awka, Njikoka, Mbo, Umuawulu, Adazi, Abatete and Nobi, while deeper depths were record around Ozuzu, Omoecheigbo, Etche, OkoroaguOwaza, Ikono, NkuotEtok, Arochukwu, Isiala, Kala Abak, Ikot Ekpene, Osisioma, Omumma, Obite, Umuede and OkeIkpe. Geothermal gradient within the study area ranges from 28.775 and 83.098 ^{o}C/km and corresponding mantle heat flow ranges from 71.936 mWm^{-2} to 207.746 mWm^{-2}. The result reveals that, the Curie point depth varies inversely with heat flow; this shows that heat flow in the study area deceases with increase in Curie depth. It confirms that Curie depths are indirect indicator of the thermal structure of an area. Geothermal prospect areas in this study include Afikpo, Okigwe, Ndikpo, Amuro, Ivo, Aguata, Ekwulobia, Umuawulu, Mbo, Awka, Anaocha, Adazi, Abak, and NkoOtoro.

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