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Magnetic Modeling and Potential Hydrocarbon Trap Over Yola and Environs Upper Benue Trough Northeastern Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Authors MH and NEB designed the study, performed the modeling exercise and wrote the first draft of the manuscript, while author BR carried out the analysis on hydrocarbon potentials and also managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

With a renewed interest to search for hydrocarbons in the hinter land of Nigeria's inland basin climaxed after the discovery of a rewarding oil prospects around the Kolmani river II as recently announced by the National Oil Company, the Nigeria National Petroleum Corporation (NNPC). This research was based on analyzing the high-resolution aeromagnetic data over the study area using the *Oasis Montaj* ^{TM} software, in order to get the total magnetic intensity map as well as the residual map, band pass filter map was used to generate magnetic aureoles. GM-SYS module of the *Oasis montaj* was used for the modeling exercise, the models reveal the horst and graben architecture of the basement with the grabens serving as depocentres, hydrocarbon potentials of the area were highlighted using magnetic aureoles mapping.

Keywords: Depocentres; hydrocarbon potentials; magnetic aureoles; Oasis montaj; sedimentary basin.

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1. INTRODUCTION

This work attempts to analyze high-resolution aeromagnetic data over Yola and environs for potential hydrocarbon traps, magnetic aureoles mapping and modeling. The area is situated between longitude 12°00'-13°00'E and Latitude 9°00'–10°00'N, which is the Yola Trough, a division of the Upper Benue Trough which is also a subset of the Benue trough, a Cretaceous sedimentary basin, trending in E-W direction. The Benue trough is generally said to have formed from a ridge- ridge-ridge structure which existed at the site of the present day Niger Delta in the early Cretaceous times [1,2] with arms as the Gulf of Guinea (R), the South Atlantic (R) and the Benue Arm (R). The Benue Trough was formed by several sub basins of which evolution and distribution were closely controlled by a fracture system where the N55°E Benue trend has been dominant in the entire Trough and the surrounding basement. A compressive phase of late Maestrichtian age is responsible for the fracturing and folding of the Cretaceous cover. The style and direction of folds are greatly influenced by the basement structures. Evidence of tensional movement are also known in the Yola trough, this is why [1] stated that the major rivers in the area exhibit a "V" shape channel due to control by the NE-SW and NW-SE fracture system.

The drainage feature of this region is the Benue River which takes it source eastward from the Cameroons and for the other part by its main affluent the Gongola River which rises from the North Central highlands composed of crystalline rocks. Major towns in the area are Yola, Numan Shelleng and Guyuk.

1.1 Geology of the Study Area

The study area is the Yola Trough, a division of the Upper Benue Trough which is also a subset of the Benue Trough, It is a linear Cretaceous sedimentary basin which extends deep into the African continent and was closely associated with the separation of Africa from South Atlantic, it extends north easterly to attain an approximate length of 1000 km long and 100-700 km wide and houses a thick succession of shales, sandstones, limestones, coal, evaporates, volcanic and intrusive whose age range from Aptian to Maestrichtian. According to [2,3] the Benue Trough was subjected to several depositional cycle characterized by the deposition of sedimentary rocks of varied composition and closely related to the structural evolution of gulf of Guinea as shown in Fig. 1.

1.2 Previous Studies

Working on the high-resolution aeromagnetic data of the triple junction structure of the Upper Benue Trough, Northeastern Nigeria, [4] demonstrated that there was tectonic activity that resulted to uplift of the mantle, thinning of the crust and a later mantle activity which caused a basaltic lava flow or basic igneous intrusions along transform fault, the area was also characterized by NE-SW trending lineaments.

Investigation of $2^{1/2}$ dimensional modeling of the significant structures underlying Dong and Shelleng regions of the Upper Benue Trough, by [5] using GM - SYS computer modeling. Their discoveries revealed that sediments thickness is in the region of 0.9 km to 2.9 km. Analysis by [6] on the two and half dimensional modeling of the major structure underlying the Nupe basin Nigeria, using aeromagnetic data concluded that the basin had considerable sediment thickness and these areas can be further studied using seismic reflection for hydrocarbon accumulation.

Studies carried out by [7] on the high resolution aeromagnetic data for magnetic basement depth using spectral technique and slope techniques revealed areas of high and low frequency anomalies which were related to shallow and deep seated bodies. Geomagnetic modeling of potential hydrocarbon traps in the lower Niger delta off shore West Africa by [8] concluded that the structural low areas were recommended for detail prospecting in the new frontiers using seismic method.

Working in the upper Benue trough using aeromagnetic data [9] concluded that the magnetic anomalies over the area can best be interpreted in terms of combined effects of intrusive bodies and a crystalline basement of variable topography. Studies on 2-D modeling of subsurface structure over Upper Benue Trough and Borno basin in northeastern Nigeria, [10] concluded that there was likely presence of hydrocarbon in the area which was enhance by the presence of thick sediments and also by the kind of geologic structures existing.

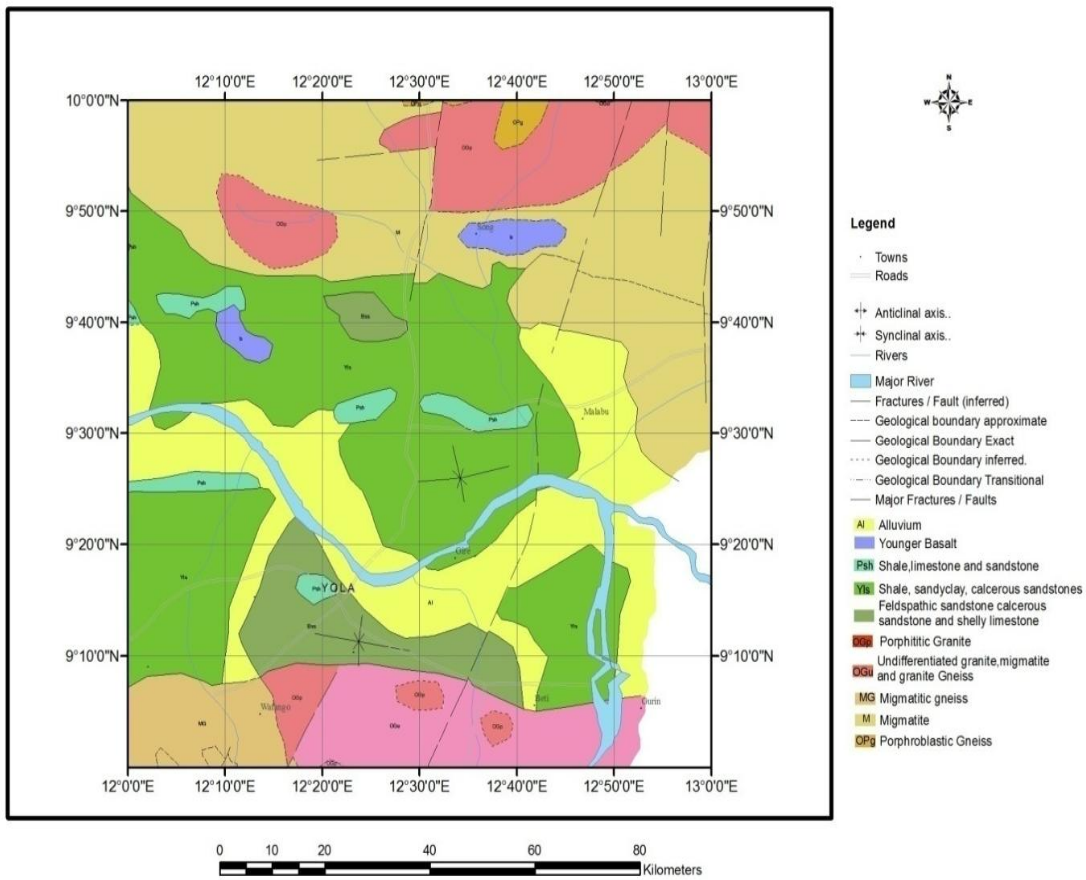

Fig. 1. Geologic map of the study area

2. MATERIALS AND METHODS

2.1 Materials

The high resolution aeromagnetic data used in this study were acquired for Nigeria Geological Survey Agency in 2010 as part of country wide geological survey, the data used for this study has the following specification: terrain clearance of 80 m, flight line spacing of 500 m and tie line spacing of 5000 m. The following sheets with the index numbers 175,176,196 and 197 were used for this study, data was processed to generate the total magnetic intensity map, residual map and the band pass filter map which were used to generate magnetic aureoles, on these maps with potential areas for hydrocarbon prospects delineated. In this work, band pass filter was used to pass or reject a range of wave numbers from the data while band-pass filtering was used to isolate and enhance the anomaly wavelengths associated with the shallow (or deep) sources. For optimal separation of the signals, the band-pass filters specially designed for each survey was a filtering technique used to separate magnetic anomalies produced at different source depths. Optimum anomaly separation is realizable by treating shallow sources and noise as if they were produced by equivalent dipole layers and deeper sources as if they were produced by magnetic half-spaces. This filtering method involved comparing the power spectrum of the aeromagnetic map to the power spectrum of a model of several equivalent magnetic layers at different depths using the United State Geological Survey Potential Field programs by [11].

Oasis Montaj ^{TM} software was used for the modeling study. GM-SYS module of the *Oasis montaj* software was used for this study which made use of the algorithm describe by [12] the program compares a theoretical anomaly with successive fits improvement until best possible fit was obtained. Each separate part of the model (basement/sedimentary) was assigned a susceptibility value. The anomaly along the entire profile was the sum of the contributions of each separate blocks, the modeling involved four pieces of information, top surface, bottom surface, susceptibility and magnitude. If any three of the above is known or assumed the fourth item can be calculated.

According to [13] high resolution aeromagnetic data has a better chance of direct hydrocarbon detection. The data revealed more information on the geology and structures of the area, because of reduction in tie line spacing structures of economic important that are not more than 500 m apart will be revealed, this will help in delineating the economic potentials of the area. Changes in the subsurface geologic structures are usually reflected by magnetic susceptibility and this property of rocks varies from place to place below the earth's surface. This variation in the magnetic susceptibility can cause small magnetic variation in the magnetic fields of rocks measured on the surface. The presence of a local relief on the basement surface or the presence of oil traps in some cases can be analyzed quantitatively, as they are reflected on the residual map as weak or low magnetic anomalies.

In hydrocarbon exploration, residual maps play a key role in identifying the presence of intrusives, lava flows and igneous plugs, which are areas to be avoided in the course of an exploratory exercise, in this case the Lunguda basalt and various volcanic plugs that doted the area may serve as examples. The geothermal energy needed for the maturation of petroleum source rocks may be provided by the intrusives, as they are not completely detrimental to the hydrocarbons per se, problem will only arise as their presence in large quantity may lead to over-maturation of source rocks where more geothermal energy will be released.

It is at this point that the temperature window for hydrocarbon generation could be exceeded, thus, affecting the quantity to be generated. As presented by [8], intrusives may provide suitable hydrocarbon traps or reservoir rocks in some cases. According to [14] sedimentary magnetization contrasts have been observed to be related to anomalies with amplitude of 1 nT. Also [15] concluded that many of these small amplitude anomalies were sourced in the sedimentary section. The trend of these low amplitude anomalies was in some places roughly parallel to major mapped fractures and faults. Based on the observed amplitude (<10 nT), spatial scale, orientation, correlation across flight lines, the low-level magnetic anomalies appear to be of natural origin. Since hydrocarbon exploration has much relied on the generally expensive seismic method with the magnetic method confined to the traditional and conventional role of analysis of prospective sedimentary basins in terms of overall basin architecture. Less frequently has magnetic data been used for "pin pointing" hydrocarbon concentration and determining the genetic association of basement fault pattern with the sedimentary structural pattern. However, the efficacy of high resolution aeromagnetic data for the direct detection of hydrocarbon had been severally documented. Observations by [16,17] showed that the short wavelength, low amplitude magnetic anomalies found over some oil fields result from microseepage of hydrocarbon into iron rich sedimentary rocks which precipitates digenetic magnetic minerals such as magnetite, pyrrotite near the water table. The reduction plumes thus formed above the hydrocarbon deposit is well known from the observed geochemical alteration of the overlying sediment. According to [16], if the magnetic minerals were deposited in sufficient quantities, they would produce a characteristic high frequency, low amplitude magnetic anomalies which will be a direct indicator of the presence of hydrocarbon at depth and which can be detected by aeromagnetic surveys. This was described by [18] as modern magnetic survey. Whereas conventional aeromagnetic anomalies yield information about the basement structure, sediment thickness and distribution of faults and volcanics, the modern magnetics detect the weak signature that may be developed along areas of hydrocarbon seepages due to authigenic mineralization. Thus the modern magnetics is a form that captures and utilizes the full spectrum of the earth's magnetic field, all frequencies of anomalies sourced throughout the geology section, near surface to magnetic basement [19].

2.2 Methods

The methods used in the processing of the aeromagnetic data were stated and explain below. The methods include the Euler deconvolution method, the analytic method and the horizontal method.

2.3 Euler Deconvolution Method

The Euler deconvolution method provides estimates of source location and depth.

Delineation of geologic contacts was done using this method. This method was employed as it requires no information about the magnetization vector and requires a little prior knowledge of the magnetic source geometry. The method is based on solving Euler's homogeneity equation:

$$\frac{(x - x_0)\partial M}{\partial x} + \frac{(y - y_0)\partial M}{\partial y} + \frac{(z - z_0)\partial M}{\partial z} = N(B - M) \qquad (1)$$

Where $(x_0, y_0, z_0)$is the position of the magnetic source, which produces the total magnetic field M measured at (x, y, z), B being the regional value of the total magnetic field and N is the structural index.

2.4 The Analytic Method

The analytic method was used to detect the structures responsible for the observed magnetic anomalies over the study area. It helps in the enhancement of magnetic data as its amplification function is always positive and does not need any assumption of magnetization body's direction. The Absolute Analytic Signal Magnitude is defined as:

$$\|ASM(x, y)\| = \sqrt{\left(\frac{\partial f(x, y)}{\partial x}\right)^2 + \left(\frac{\partial f(x, y)}{\partial y}\right)^2 + \left(\frac{\partial f(x, y)}{\partial z}\right)^2} \qquad (2)$$

This is the square root squared sum of the vertical and horizontal derivatives of the magnetic field.

2.5 The Horizontal Gradient

The Horizontal Gradient Magnitude (HGM) was calculated as shown in equation (3), where M is the magnetic field.

$$HGM(x, y) = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2} \qquad (3)$$

This method has low sensitivity to noise in the data as it requires calculations of the two first-order horizontal derivatives of the field.

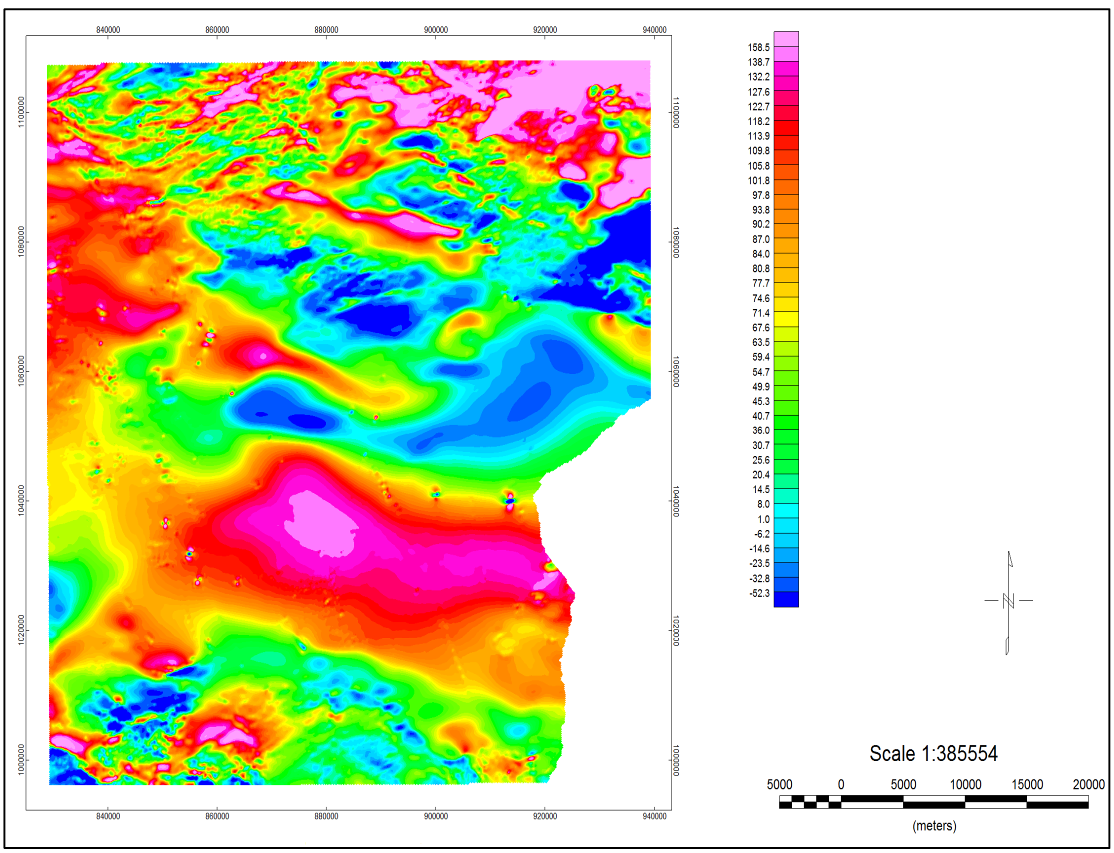

Fig. 2. Total magnetic intensity map of the study area

3. RESULTS AND DISCUSSION

3.1 Residual Map

In this study, data was residualized (i.e. removal of the regional) leaving only the residual so as to obtain a magnetic response from the upper-crust of the earth comprising of the basement and sedimentary unit. Residual components of magnetism are the portion of regional effect, usually the relatively small or local anomaly components of the total or observed magnetic field. The anomalies of 1538 to 57.6 nT were observed partly in the central area and are also scattered in the northern part, these may arise from either near surface intrusives in the basement, susceptibility changes within the basement, or their combined effect, these are the places where the sediment thickness is very low. While anomalies of 53.7 to -46.8 are the lows, which were observed in areas characterized by deeply buried basement rocks, these are the sedimentary areas and are probably having non-magnetic rocks such as sandstones, limestones, shales etc, as shown in points A-F in Fig. 3, since sediments are weakly magnetic.

3.2 Modeling

Four profiles were drawn on the residual magnetic anomaly map over the area across prominent anomalies as shown in Fig. 4, so as to estimate the geometry and physical character of the cause to an investigated anomaly and also to delineate depocentres.

3.2.1 Modeled magnetic profile A-A'

This model cut across the study area in the NE-SW direction. It shows a good fit between the observed and computed magnetic profile with an error of approximately 11.28%. The profile was modeled as eight (8) basement blocks i.e. rocks 1-8 as shown in Fig. 5. Movement along these blocks may be responsible for the uplifted blocks (horst) and down faulted blocks (graben) given rise to undulation of the basement topography. The green line that separate rocks 1-8 are lithologies or structural contacts. The entire profile has an average depth of 42 km with sediment thickness of less than 10 km on the average. Blocks B, D and F are Horst while A, C and E are graben.

Abroad graben blocks was observed in rocks 1, 2, 4, 6 and 7 which are interpreted to be lithologic contact, joints or faults which have slightly moved relative to the neighboring blocks.

3.2.2 Modeled magnetic profile B-B'

This model cut across the study area in the NE-SW direction. It shows a good fit between the observed and computed magnetic profile with an error of 5.87%. The profile was modeled as thirteen (13) basement block, i.e. rocks 1 – 13 as shown in Fig. 6. The combined effect of the thirteen contacts contributed to the irregular topography of the area. Blocks B, D, F, H, J, L, N, and P are graben while blocks A, C, E, G, I, K, M, O and Q are host. The green lines that separate rocks 1-13 are lithologic or structural contacts. The entire profile has an average depth of 28 km with a sediment thickness of less than 10 km. Two of the blocks, A and Q may be a few metres to the surface.

3.2.3 Modeled magnetic profile C-C'

The model cut the central area in the NE-SW direction with a fifteen (15) basement blocks i.e. rocks 1-15 as shown in Fig. 7. It also has an error of 7.9 % which shows a good fit between the observed and computed magnetic profile. Blocks B, D, F, H and J are graben while the rest are horst. The green lines that separate the rocks (block) represent lithologic or structural contacts. Movement along these blocks gave rise to undulating basement topography which is responsible for the uplifted block (horst) and down faulted block (graben). The entire profile has an average depth of 28 km with sediment thickness of less than 10 km. Three of the blocks, A, I and K may be a few metres to the surface.

3.2.4 Modeled magnetic profile D-D'

This model cut across the study are in the NW-SE direction. It has an error of 2.7% with seven (7) basement blocks, i.e. rocks 1-7 as shown in Fig. 8, which shows a good fit between the observed and computed magnetic profile. Blocks A, D and F are graben while blocks B, C and E are horst. The green lines that separate the rocks (blocks) represent lithologic or structural contact. Movement along these block gave rise to undulating basement topography which is responsible for the uplifted blocks (horst) and down faulted blocks (graben). The model profile has an average depth of 35 km with a sediment thickness of less than 10 km. Grabens observed

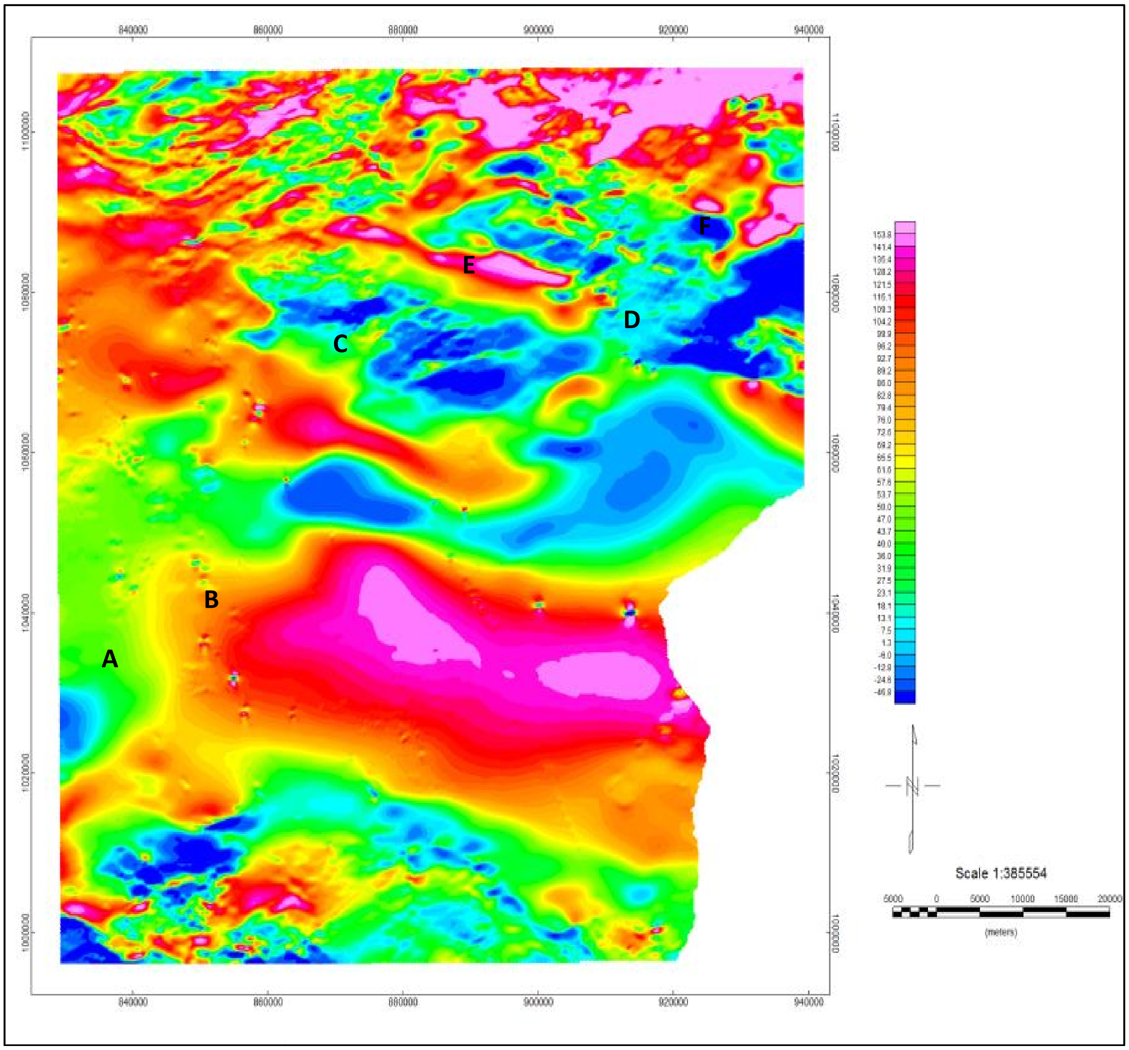

Fig. 3. Residual map of the study area with points A-F

in this profile are interpreted to be lithologic contacts or joint or faults, which has slightly moved relative to the neighboring rocks.

3.3 Magnetic Hydrocarbon Indicator Mapping

The magnetic hydrocarbon indicator (MHI) anomaly search methodology utilized in this study was the annular aureole anomaly procedure described by [20], aureole anomaly is essentially characterized by a central magnetic low surrounded on all sides by a high. The aureole anomaly which is an effective indicator of proximal hydrocarbon reservoir is distinguishable by shape in that it is somewhat circular or elliptical. Aureoles need not be entirely complete to be rated as seepage indicator. Aureole anomaly in hydrocarbon exploration has the ability to distinguish closely coupled anomalous zones from displaced anomalous zones that might exist. Therefore, by employing magnetic aureoles mapping, orphaned (displaced) magnetic anomalous zones are less commonly included. The processes require a subsurface redox zone, as would occur at the interface between the reducing environment within the hydrocarbon seep zone (generated largely by microbial action) and a subsoil oxidizing environment generated by a non-static (thereby promoting oxygenation) present day or paleo-water table [20]. It is within this environment that magnetite appears to concentrate in an enlarging annular fashion through a dynamic cycle of conversion and reconversion (precipitation and dissolution) often forming annular/aureole micromagnetic anomalies (among others) when imaged in plan. Sedimentary magnetization contrast have been associated with low anomalies amplitude of 1 nT in some cases, therefore anomalies as low as -46.8 nT were observed in this research, therefore further exploratory work in the study area is strongly suggested using 2-D and 3-D seismic surveys for possible hydrocarbon traps.

Knowledge of processes leading to precipitation condition and buildup of magnetic aureoles is sparse, [18] observed that the process culminating to ring like magnetic aureoles was rife in the following environmental settings:

(i) Onshore areas with permanent or annually recharged water tables,
(ii) Regularly inundated onshore areas, and
(iii) Offshore regions where upper section water saturation is sustained and littoral areas.

The study area met one of the environmental conditions above and therefore strongly suggests the formation of magnetic aureoles in the area. Based on the method of [18] an attempt was made in this study to map out some magnetic aureoles, this is presented in Fig. 9. These probably are (MHI) in the Yola Rift basin. Areas where aureole mapping had been employed for the search of hydrocarbon traps were the Niger Delta, the Anambra basin, Formby oil-field, Lancashire, U.K, [21], Muglad basin Sudan [18], where some of the results coincided with site of drilled wells.

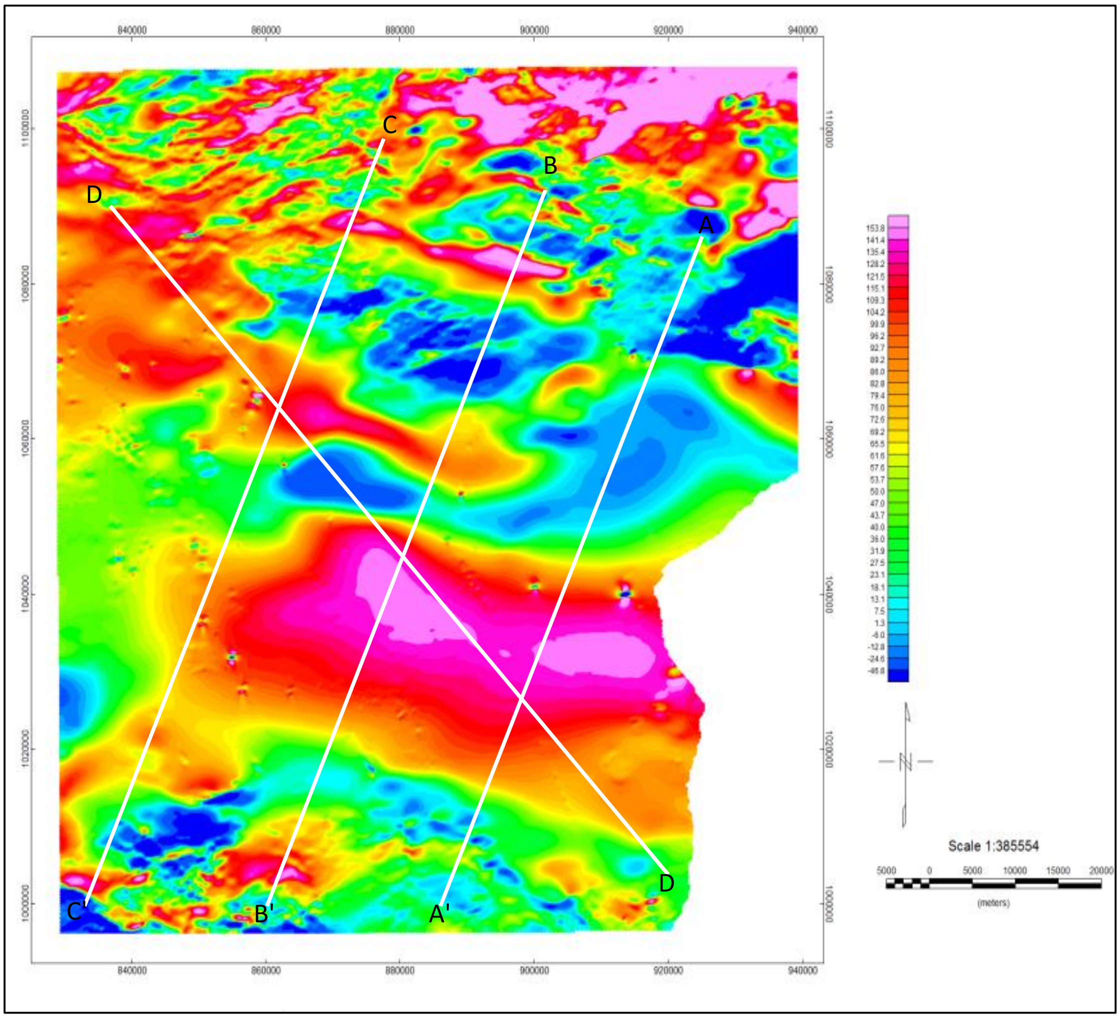

Fig. 4. Residual map of the study area with profiles A-A', B-B', C-C' and D-D' used in modeling

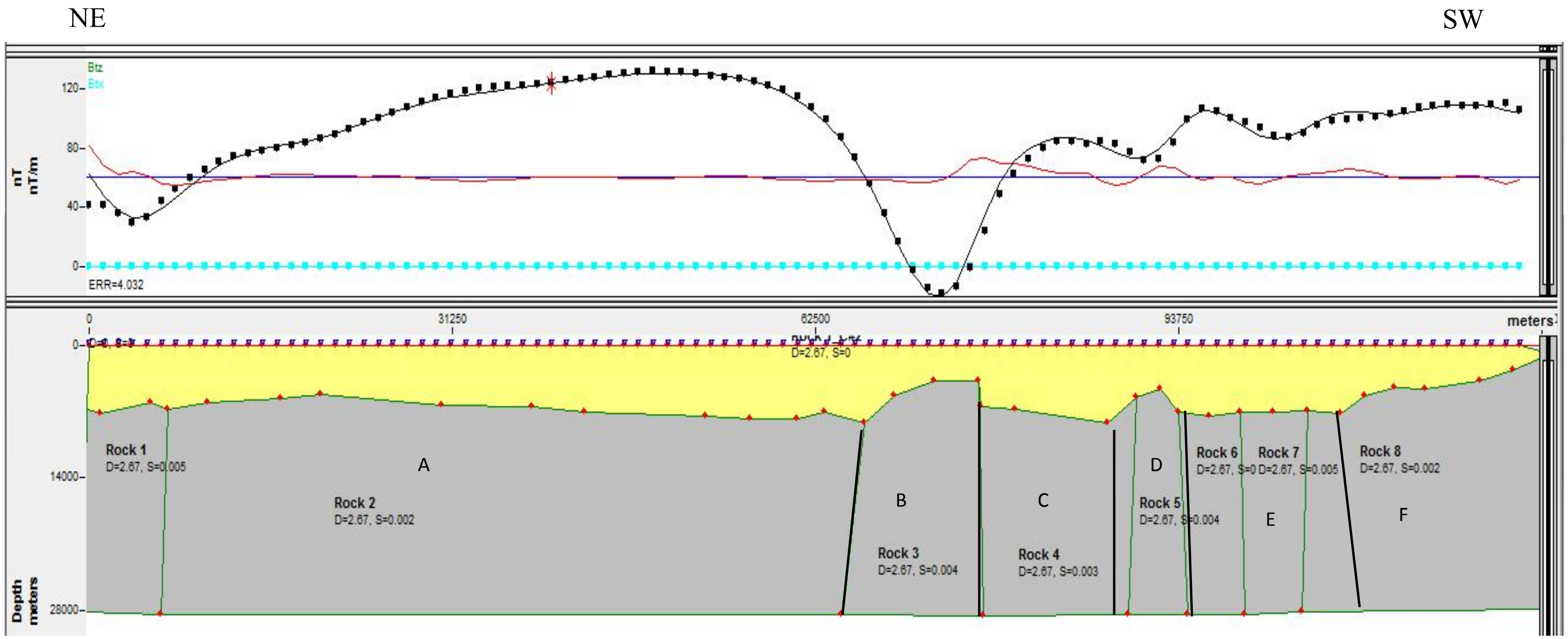

Fig. 5. Model magnetic profile along A-A', top panel magnetic anomaly, bottom panel depth section. (Red line indicates error)

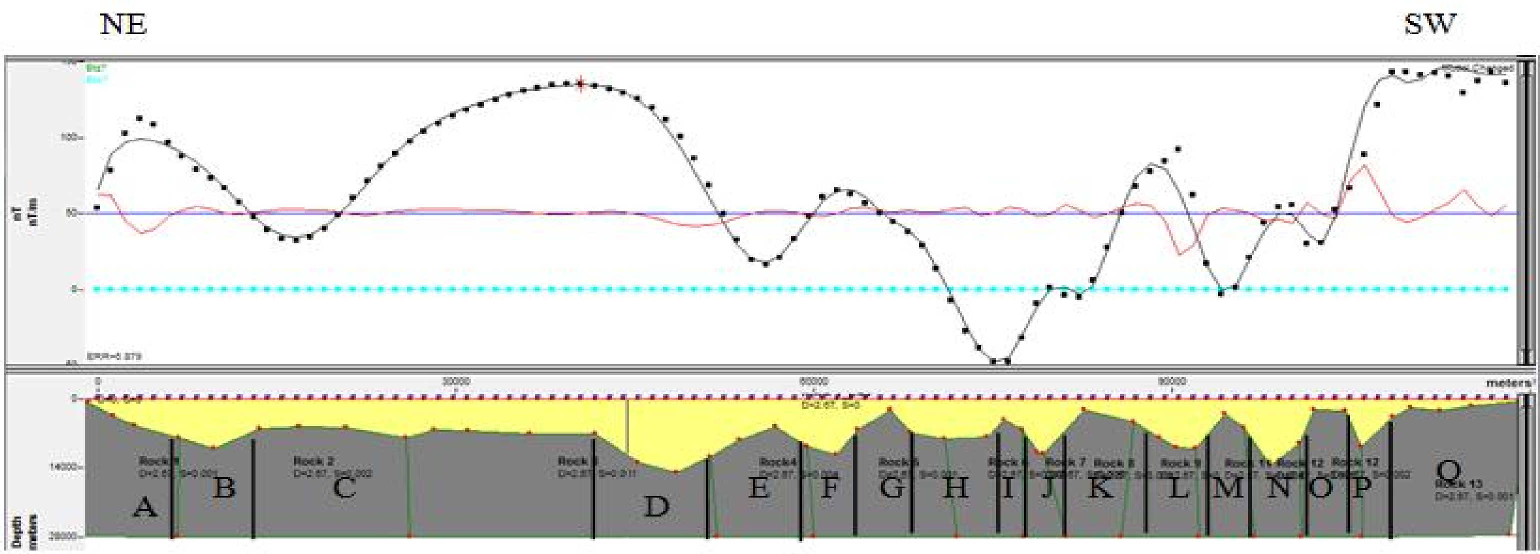

Fig. 6. Model magnetic profile along B-B', top magnetic anomaly, bottom depth section. (Red line indicates error)

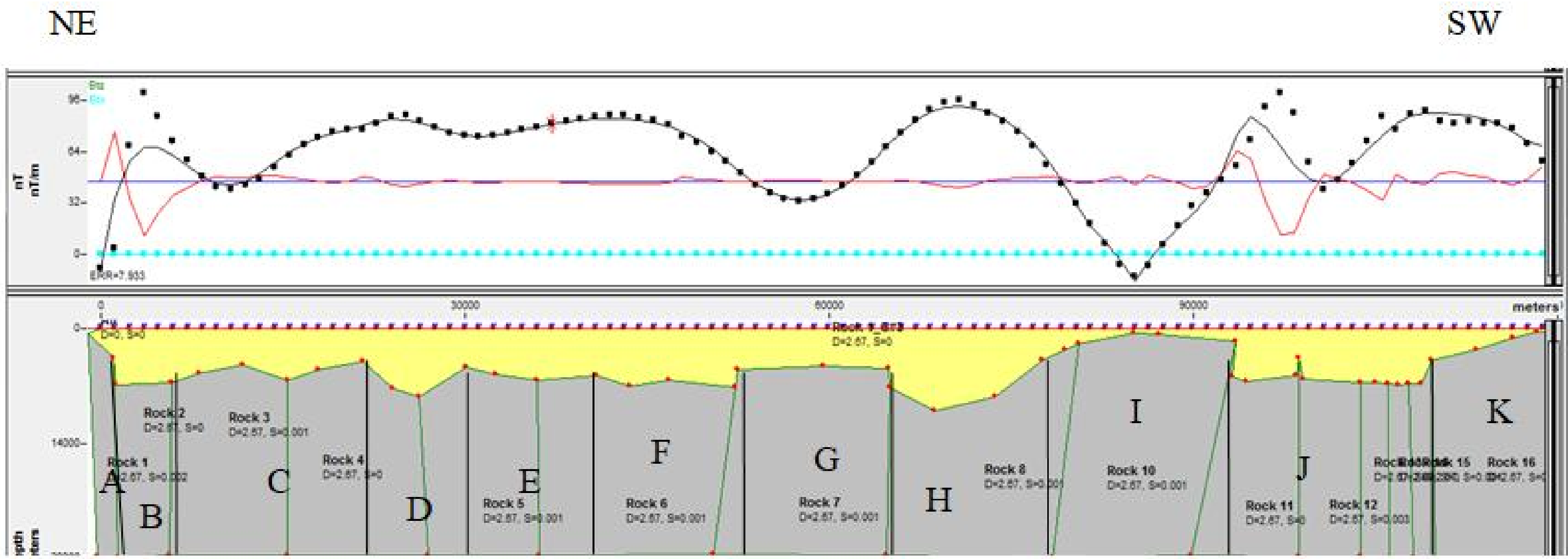

Fig. 7. Model magnetic profile along C-C', top magnetic anomaly, bottom depth section. (Red line indicates error)

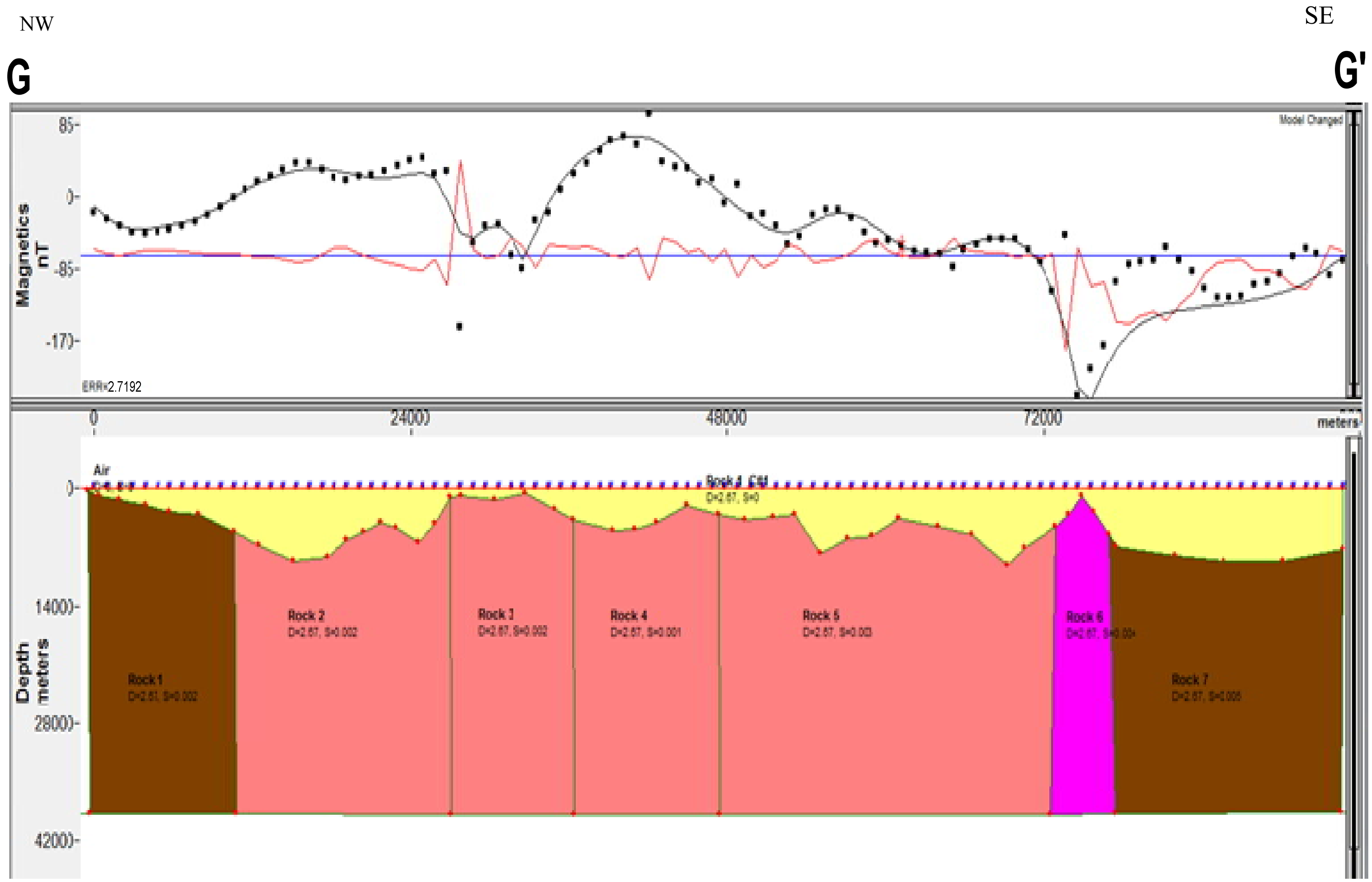

Fig. 8. Model magnetic profile along D-D', top magnetic anomaly, bottom depth section. (Red line indicates error)

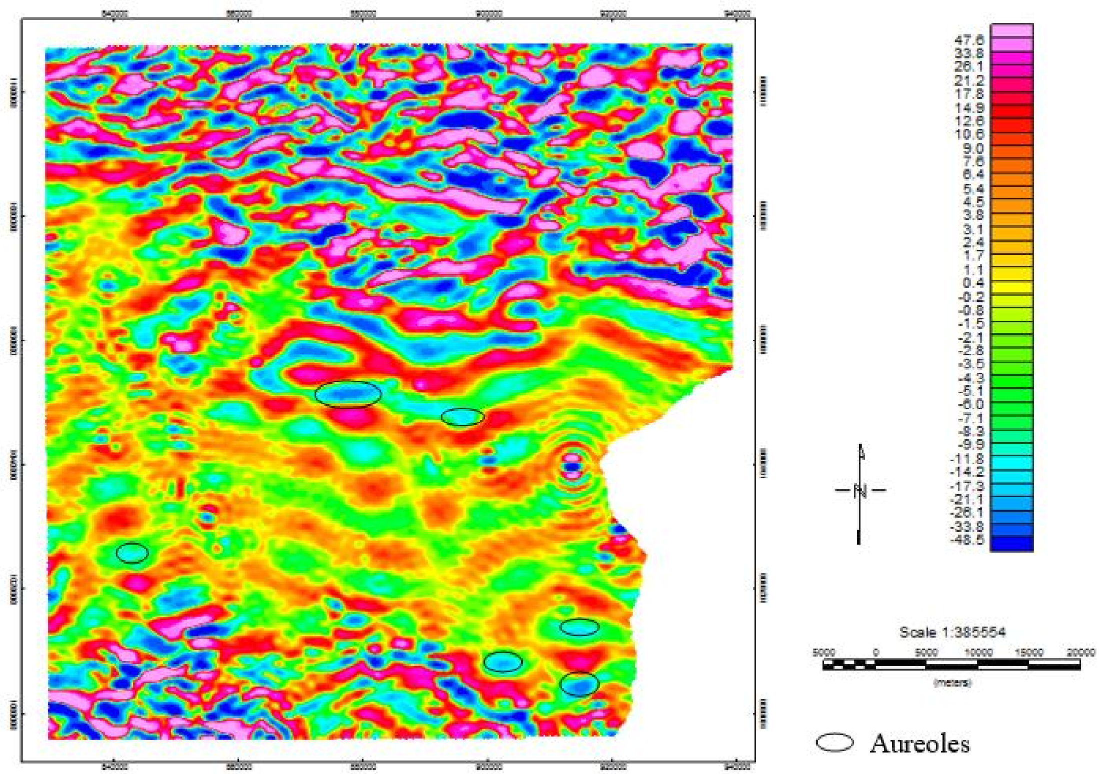

Fig. 9. A band pass filter map of the study area, showing magnetic aureoles

4. CONCLUSION

Hydrocarbon traps from the residual map, depocentres and magnetic aureole anomaly were studied in this work. There are six locations on the residual map, A-F characterized by weak anomalies or magnetic lows they are direct indicators of the presence of hydrocarbon at depth, low amplitude anomalies are in some places roughly parallel to major mapped fractures and faults, these are potentials traps for hydrocarbon or local relief on the basement surface. The models reveal the horst and graben architecture of the area which will serve as depocentres. The annular magnetic aureole mapping shows areas where hydrocarbon traps may be encountered. The study area met one of the environmental conditions that strongly suggests the formation of magnetic aureoles in the area and these areas are similar to what has been obtained in the residual map, aeromagnetic anomalies yield information about the basement structure, sediment thickness and distribution of faults and volcanics. These areas are recommended for detail prospecting using seismic surveys.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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