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Investigation of magnetic anomalies of Abakaliki area, Southeastern Nigeria, using high resolution aeromagnetic data

Daniel N. Obiora^{1*}, Julius I. Idike¹, Andrew I. Oha², Chijioke G. Soronnadi-Ononiwu³, Ngozi A. Okwesili¹ and Mirianrita N. Ossai¹

¹Department of Physics and Astronomy, University of Nigeria, Nsukka, Enugu State, Nigeria.

²Department of Geology, University of Nigeria, Nsukka, Enugu State, Nigeria.

³Department of Geology, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria.

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Aeromagnetic data over Abakaliki area of lower Benue trough, Nigeria was interpreted qualitatively and quantitatively using Oasis montaj software. The qualitative interpretation unveiled basic intrusive bodies like dykes, laccolites and batholithic bodies in the area. It also revealed fault zone which trends southeastern part of the study area. Quantitative interpretation was carried out by forward and inverse modeling, source parameter imaging and Euler deconvolution methods. Depth obtained by source parameter imaging (SPI) ranged from 99.50 to 5930.78 m. Results from this study indicate that deep seated bodies are predominant in the southwestern part of the area, while shallow bodies are predominant in the southeastern part of the area. The anomalies over the area were modeled by bodies in the form of sphere and ellipsoid by varying the total magnetic intensity parameters. Depth obtained by model A is 546 m with susceptibility value of 0.0180 signifying limestone. The height of Model B is 50 m signifying outcrop, likely to be the outcrop near college of Agricultural Sciences of Ebonyi State University, Abakaliki, with susceptibility value of -0.0017 signifying calcite. Depth obtained for models C, D and E are 956, 6366 and 477 m respectively, with respective susceptibility values of -0.0134, -0.009 and -0.006 signifying rock salt, quartz and Calcite. Maximum depth obtained by forward and inverse modeling is 6366m while that obtained by source parameter imaging is 5930.78 m.

Key words: Abakaliki area, aeromagnetic anomalies, qualitative and quantitative interpretation, intrusive bodies, hydrocarbon accumulation.

INTRODUCTION

The study of geophysics has helped man to locate buried materials usually of geophysical interest in the earth's

sub-surface. These materials usually manifest as anomalies which could be sensed by different geophysical

*Corresponding author. E-mail: daniel.obiora@unn.edu.ng.

survey methods. The subsurface which is based on the variation of the magnetic field of the earth that results from the magnetic properties of the underlying rocks is studied using magnetic survey. Magnetic survey may be carried out in air (aeromagnetic), land and sea. The magnetic field of the earth acts on the magnetic minerals in the crust, inducing a secondary field which reflects the distribution of the minerals. The main magnetic field induces a field which varies slowly from one place to another while the crustal field which is the portion of the magnetic field associated with the magnetism induced by the earth's main magnetic field varies more rapidly (Reford, 1962).

The major role of aeromagnetic investigations over continental zones is to establish geologic and tectonic frame works and to explore for minerals. The magnetic technique is a relatively cheap method of learning about geologic threats such as seismically dynamic faults, trivial magma cavities and volcanic cores. Petroleum industry has mapped structures and enhanced depth to magnetic basement using aeromagnetic data (Steenland, 1965).

Aeromagnetic survey is the exploration method of the intensity of the magnetic field of the earth with magnetometers installed in airplanes or helicopters. The process is to operate the magnetometer continuously along equally spaced parallel flight lines covering the survey area. The principle of the aeromagnetic survey is related to a magnetic technique performed with a magnetometer held with hand but it permits more surface areas of the earth to be covered more quickly. The aircraft flies in a grid-like pattern with height and line spacing determining the resolution of the data. The magnetometer registers minute differences in the intensity of the ambient magnetic field due to the temporal effects of the frequently fluctuating solar wind and spatial differences in the magnetic field of the earth, as the aircraft flies. The spatial variation of the earth's field is due to the regional magnetic field and the local effect of magnetic minerals in the earth crust. Subtraction of the solar and regional effects reveals the spatial distribution and relative abundance of magnetic minerals.

Magnetic method is used in many areas such as locating intra-sedimentary faults, defining subtle lithological contacts, mapping salt domes in weakly magnetic sediments. The major aim of aeromagnetic geophysical technique is to spot rocks and minerals with uncommon magnetic properties that disclose themselves by producing anomalies in the intensity of the magnetic field of the earth (USGS, 1997). The anomalies may be due to subsurface structures that have bearing on the site of oil deposits (Lowrie, 2004). Residual magnetic anomaly charts are valuable for hydrocarbon investigation, since they detect the presence of intrusive, lava flows or igneous plugs which are parts that need to be evaded in hydrocarbon exploration (Selley, 1998). Ground and aeromagnetic data are employed to study the existence of a mineral deposit in conjunction with gravity survey for

the exploration purposes. Both magnetic and gravity techniques are broadly employed in mining industry as investigation tools to map subsurface geology and evaluate ore reserves for some enormous ore bodies (Biswas and Sharma, 2016; Mandal et al., 2015; Biswas et al., 2014a, b).

The region of mineralization emanating from the tectonic events in the Benue Valley seems to run in the narrow tract spreading from the southeast in the Abakaliki Trough axis to the northeast. The Benue Trough is mostly recognized to have many mafic and felsic intrusives, sub-basinal structures combined with a positive prospect for hydrocarbon accumulation (Ugbor and Okeke, 2010). Abakaliki area is considered to have a quantity of economic mineral deposits which have created a lot of attention on the commercial significance of this mineral region. The area has a lot of possibilities for hydrocarbon and minerals like lead, zinc, silver, salt, limestone and dolerite which form quarry that provide commercial influence to the people of Abakaliki (Ezema et al., 2014). The major component units of the Lower Benue Trough are the Abakaliki anticlinorium, Afikpo syncline and Anambra basin (Obaje, 2009). By way of increasing the nationwide exploration and production base and thus enhance the proven reserves strength, several investigation operations have been embarked on, in the inland basins of Nigeria. The Bida basin, southeastern sector of Bornu basin (Chad basin), Benue Trough, Sokoto basin and Anambra basin encompass the inland basins of Nigeria. The inadequate information on the geology of these inland basins and the distant from existing structure (finding should be sufficiently great to permit production investments) have frustrated the efforts of many explorers. These made many international companies to turn their attention from frontier onshore to frontier deep-water and ultra-deep water offshore of the Niger Delta zone. The inland basins of Nigeria institute a set of sequences of Cretaceous and later rift basins in Central and West Africa whose source is linked to the opening of the South Atlantic (Obaje, 2009).

The purpose of this study is to interpret magnetic anomalies of Abakaliki area with the intention of providing information on: (i) nature of intrusive in the area and mineral deposits associated with it, (ii) hydrocarbon potentials of the area and (iii) depths to the magnetic anomalous bodies. The results from this study will be compared with results from land gravity survey and results from previous studies in the area and within Lower Benue Trough generally.

Geology of the study area

Abakaliki area falls within the lower Benue Trough and it is located between latitude 6° 35' N and 6° 45' N and Longitude 8° 42'E and 8° 47'E, with average elevation of 117 m. Separation of South American plate from the

African plate is assumed to form the Benue Trough (Petters, 1978). The separation of the continents led to an aborted rift (Aulacogen) which was later filled with transgressive and regressive sedimentary deposits. Aside Abakaliki anticlinorium towards the Anambra basin, the Afikpo syncline is also part of the Lower Benue Trough. The order of actions that led to the development of the Benue Trough and its constituent components are fairly well written (Burke et al., 1971; Nwachukwu, 1972; Olade, 1975; Benkheilil, 1982; Ofoegbu, 1985a). Sedimentation in the Lower Benue Trough began with the marine Albian Asu River Group, though certain pyroclastics of Aptian-Early Albian ages were sparingly stated (Ojoh, 1992). Shales, limestones and sandstone lenses of the Abakaliki Formation in the Abakaliki area constitute the Asu River Group in the Lower Benue Trough and the Mfamosing Limestone in the Calabar Flank (Petters, 1982). A series of tectonic activities characterize the formation of block faulting.

The Lower Benue Trough underlain by thick sedimentary sequences deposited in the Cretaceous and the Precambrian basement complex is essentially made up of granitic and magnetic rocks which are predominant in the eastern part of the study area (Ofoegbu and Onuoha, 1990). The development of Abakaliki anticlinorium was adversely affected by the folding episode which occurred during the Santonian; hence, the main compressional nature of the fold that took place over the time was exposed by their asymmetry and reversed faults. Asu-River Group (Albian), Awgu shale (Cenozoic), Nkporo shale, and Ezeaku shale (Turonian) are four geologic formations in which the sediments that arise in the Abakaliki anticlinorium belonged.

The Albian Asu-River Group contains of bluish black shales with slight sandstone components. The shales are fissile, fractured and are related with Pyroclastic rocks. Calcareous sandstones of Cenozoic age, limestone and marine fossiliferous grey bluish shales make-up the Awgu shales, which are overlain by Nkporo shales that are mostly marine in character. The Eze-Aku Formation consists of black shale and siltstones which sits unconformably at the Precambrian gneiss to the north of Ugep (Ukaegbu and Akpabio, 2009). Reporting on the geology of Abakaliki, Benkheilil (1988) accredited its geological development to what happens in a comprehensive Orogenic cycle which involves sedimentation, magmatism, compressive tectonics and metamorphism. Injection of numerous intrusive bodies into the shales of Eze-Aku and Asu-River groups resulted from magmatism. Intrusive occurs mainly in sills in the study area. The sills could be lacolith, batholiths or dyke (Ofoegbu, 1985b; Mamah et al., 2000). The Eze-Aku Formation at the Afikpo basin forms the Amasiri sandstones. This unit is conformably overlain by the Senonian Sandstones and Upper-coal beds along Afikpo, Udi and Ugep. The coal seams are the Mamu Formations which are Maastrichtian. Figure 1 shows the geologic

map of Abakaliki.

METHODOLOGY

Source of data

The digitized aeromagnetic data used in this study were gotten from the Nigerian Geological Survey Agency (NGSA). The aeromagnetic data were acquired in 2008 through the airborne geomagnetic survey conducted by Fugro Surveys Limited for the NGSA, as part of the nationwide aeromagnetic survey in 2008. The data were digitized along flight lines and plotted with a contour interval of 2.5 nT with an average flight height of about 80 m and across tie of 2 km which assisted in smoothing the data. The nominal flight line spacing was 500 m. -13.9° and -6.6° were, respectively the average magnetic inclination and declination across the survey area. The digital form of the data (sheet 303) was made available on a scale of 1:50,000.

Method of data analysis

The data passed through different processing stages (removal of geomagnetic gradient, filtering and depth estimation) to get it ready for interpretation. Two methods of interpretation were employed in this study: qualitative and quantitative. Qualitative interpretation involves the extraction of geologic information from maps and grids. This information is geared towards mapping surface and subsurface structures such as intrusive. The first step in qualitative interpretation was the preparation of magnetic maps or grids on which the intensity values at different stations were plotted and on which contours were drawn at suitable intervals. The contouring was done using Oasis Montaj software by interpolation. The contour was observed in this work in the form of coloured maps and grids, where the colour gradations represent areas enclosed between successive contours.

Quantitative interpretation was carried out by employing forward and inverse modeling, source parameter imaging (SPI) and Euler-3D methods. Quantitative interpretation includes making numerical approximations of the depth and dimensions of the causes of anomalies and this frequently takes the method of modeling of sources which could, in theory, reproduce the anomalies noted in the survey (Reeves, 2005; Biswas et al., 2017; Biswas, 2016). The first stage of quantitative aeromagnetic data interpretation involved the application of mathematical filters. Filtering encompasses the use of low pass or high pass in the removal of either high frequency or low frequency from the data. But in this work, low pass was used to filter off high frequency signal from the data. The different filtering methods employed include: first vertical derivative (FVD), second vertical derivative (SVD), horizontal derivative (HD), reduction to pole (RTP) and upward continuation (UP).

The form of a magnetic anomaly relies on the nature of the causative body, inclination and declination of the magnetization of the body, inclination and declination of the local magnetic field of the earth and the orientation of the body with regards to magnetic north. The observed magnetic anomaly is transformed into the anomaly that would be measured if the magnetization and ambient field were both vertical by reduction to pole. Reduction to pole removed the effect of the earth's magnetic field by way of a gross shift of the observed magnetic readings. The procedure was nothing more than a correction factor applied across the study area to remove the non-vertical magnetic component, leaving only the causative body in its correct spatial position. This process helped to define the boundaries between different basement lithology with different magnetic susceptibilities. Interpretation of magnetic survey is best done on the pole. The vertical alignment enhanced

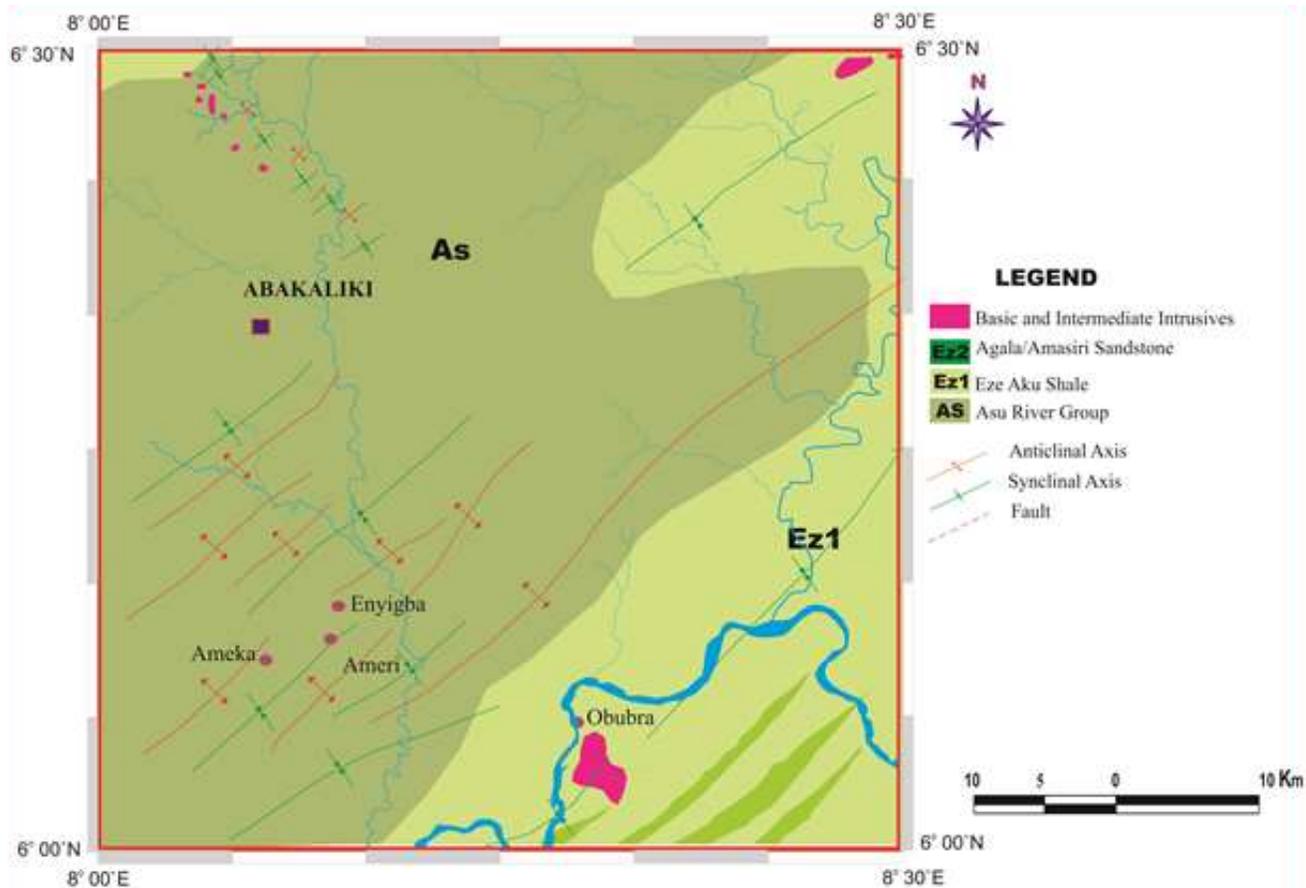


Figure 1. Geologic map of Abakaliki.

overview and interpretation of the anomalous magnetic anomalies.

First and second vertical derivatives emphasized shallower anomalies and can be calculated either in the space or frequency domains. These derivatives were employed to sharpen the edges of the anomalous bodies. The effect of these derivatives was to suppress regional anomalies and enhance local anomalies. The FVD portrays the rate of change of the anomaly with elevation or the variation of the anomaly with height. This enhanced knowledge of the shallow depth of the magnetic anomalies. SVD explains the rate of change of gradient with depth. It sharpened the edges of the anomalous bodies or the boundary between the anomalies. Many modern methods for edge detection and depth to source estimation rely on horizontal and vertical derivatives. In this work, the horizontal gradient was filtered in the x and y directions. Upward continuation is the process of transforming measured data on a given plane to data measured at a higher elevation, hence, smoothing the anomalies and projecting the surfaces upward above the original datum. The upward continuation enhanced knowledge of deeper depth of the anomalous bodies.

Depths estimation to anomalous bodies was carried out using three different methods: forward and inverse modeling, SPI and Euler deconvolution. Modeling is a method used to determine depth to the buried magnetic anomalies, susceptibilities of rocks in the modeled area, angle of dip of anomalous body, plunge and strike angles of the bodies, length, width and height of the bodies (shape).

Forward modeling is a process of creating a shape that could be attributed to the shape of the causative magnetic anomaly buried below the surface by the software. This involves generating a field

which could be compared with the observed field displayed. The process of comparing the field is achieved by inputting the following total magnetic field intensity parameters: susceptibility, inclination, declination and profile azimuth. These parameters were changed until the calculated curve best-fits the observed curve. The depth and dimensional parameters of the body is adjusted by trial and error until a satisfactory agreement is achieved between the calculated and observed values (Parasnis, 1986). Inverse modeling is the reverse procedure of the forward modeling and involves determining the geometry and the physical properties of the source from measurement of the anomalies. Modeling was done using Potent Q software (an extension of Oasis Montaj software). SPI method calculated source parameters (edge locations, depths, dips and susceptibility contrasts) for gridded magnetic data. SPI depth of magnetic data was determined using Oasis Montaj software and employed the first and second vertical derivatives to locate depth to the center of the anomalous bodies. It also enhanced knowledge of the thickness of the source bodies (Smith et al., 1998). Euler 3D deconvolution was used to estimate depth to shallow magnetic bodies. This technique uses first order, x, y and z derivatives to determine location and depths to anomalous targets like sphere, cylinder, thin dyke, etc. Each of the shapes is characterized by specific structural index. Euler deconvolution is not limited to bodies that have known structural indices as Reid et al. (1990) extended the technique to 3D data by applying the Euler operator to windows of gridded data sets. For the purpose of this work, the mathematical calculation and gridding of Euler 3D was performed using Oasis Montaj, wherein images were produced and depth to the suspected

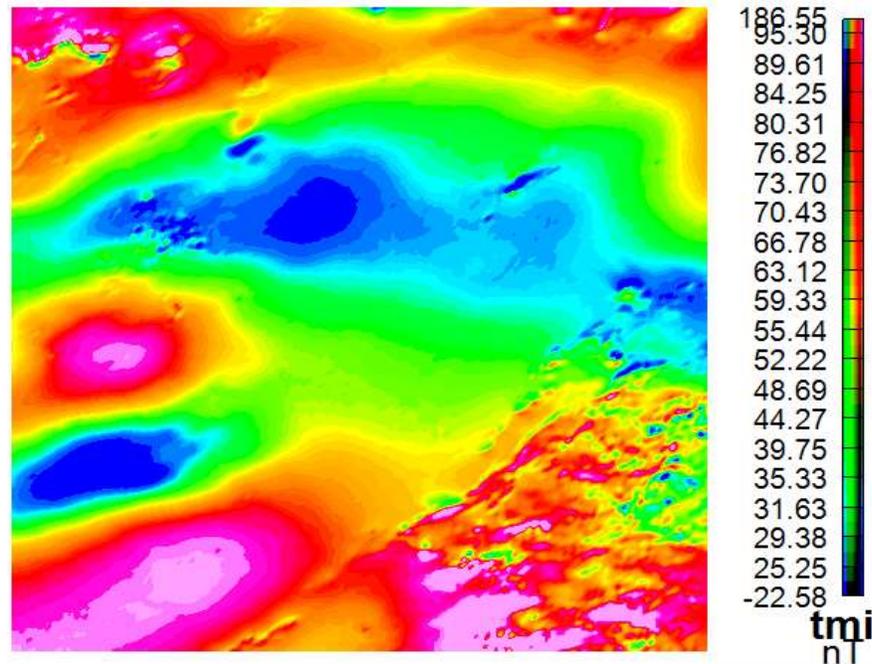


Figure 2. Grid map of the total magnetic intensity of the study area (TMI).

magnetic bodies was estimated. Using three structural indices (SI = 1, 2, 3), three Euler 3D grids were generated.

RESULTS AND DISCUSSION

Figure 2 shows grid map of the total magnetic intensity (TMI) of the study area resulting from qualitative interpretation. The pink colour areas are high intensity areas which have the tendency of producing large gabbro formation with long ore bodies. The circular contours are areas of basic intrusives with ore bodies. The basic intrusives could be lacolyte, batholyte or dyke. The TMI grid also shows fault zone or dislocation zone which is the area where one magnetic anomaly is displaced with respect to another. The fault zone trends northeast to southwestern (NE-SW) part of the area. The green colour areas in the grid are areas with no distinctive contour pattern. These areas are termed quiet areas and have the tendency of limestone, quartzitic rocks and monzonite formation (Parasnis, 1986). The grid shows prominent area of mineralization in the southeastern part of the study area.

When the data used in this work were reduced to pole, the deep seated magnetic bodies represented by the blue colour aligned vertical while the shallow magnetic bodies represented by red, pink and light pink colours tend to align vertical (Figure 3). The vertical alignment enhanced overview and interpretation of the anomalous magnetic anomalies.

The first vertical derivative (FVD) (Figure 4) enhanced

knowledge of the shallow depth of the magnetic anomalies, while the second vertical derivative sharpened the edges of the anomalous bodies or the boundary between the anomalies. The second vertical derivative was associated with noise as a result of the presence of both short wavelength and long wavelength anomalies in the sedimentary area. This effect is noticed in the blurred image of the grid (Figure 5). Figure 6 shows the grid of the horizontal derivative (HD). The upward continuation enhanced knowledge of deeper depth of the anomalous bodies (Figure 7).

Modeling was done using Potent Q software. Figure 8 shows the models used in the interpretation, while the subsets of the modeled portions (A, B, C, D, E) are as shown in Figure 9. From the longitude and latitude of the modeled areas, the modeled areas were delineated as: Obubara, Abakaliki, Enyigba, Ameka and Ameri, respectively. In the model, parameters like position and susceptibility were varied until the calculated curve best fits the observed curve. The observed curve is the blue curve while the calculated is the red curve.

The summary of the modeling results is shown in Table 1. The susceptibility (k) values obtained from profiles A, B, C, D and E are 0.0180, -0.0017, -0.0134, -0.009 and -0.006, respectively which signifies limestone, calcite, rock salt, quartz and calcite (Telford et al., 1990). The height of model B is 50 m which signifies outcrop, likely to be the outcrop near College of Agricultural Sciences of Ebonyi State University, Abakaliki. Depth for model A (Obubara) is 546 m, depth for model C (Enyigba) is 956 m, depth for model D (Ameka) is 6366 m and depth for

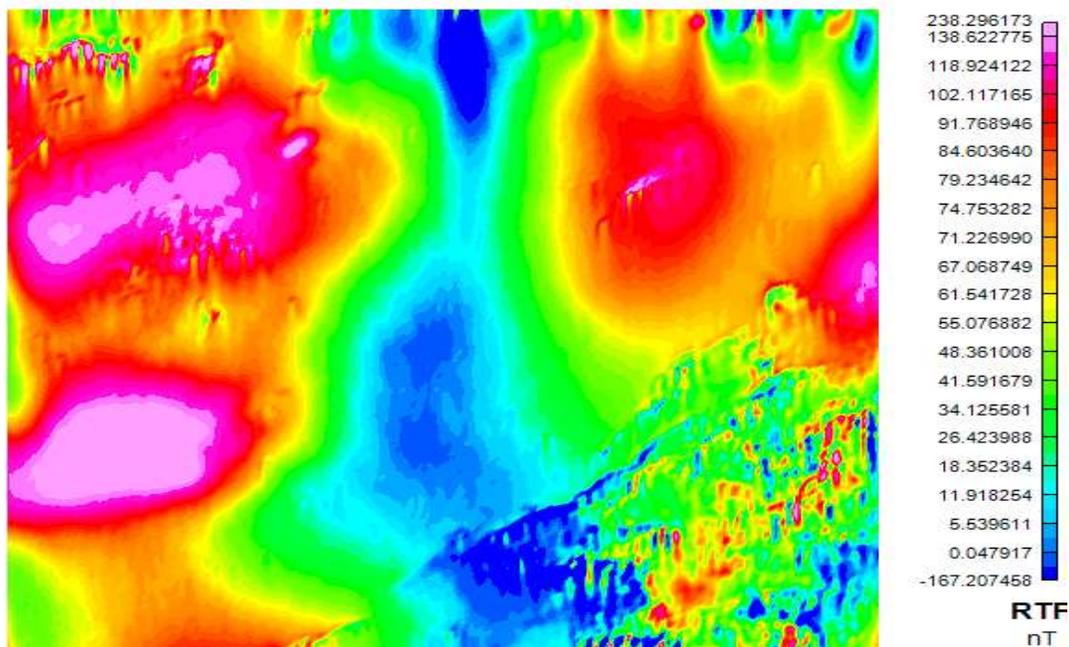


Figure 3. Grid map of reduction to pole.

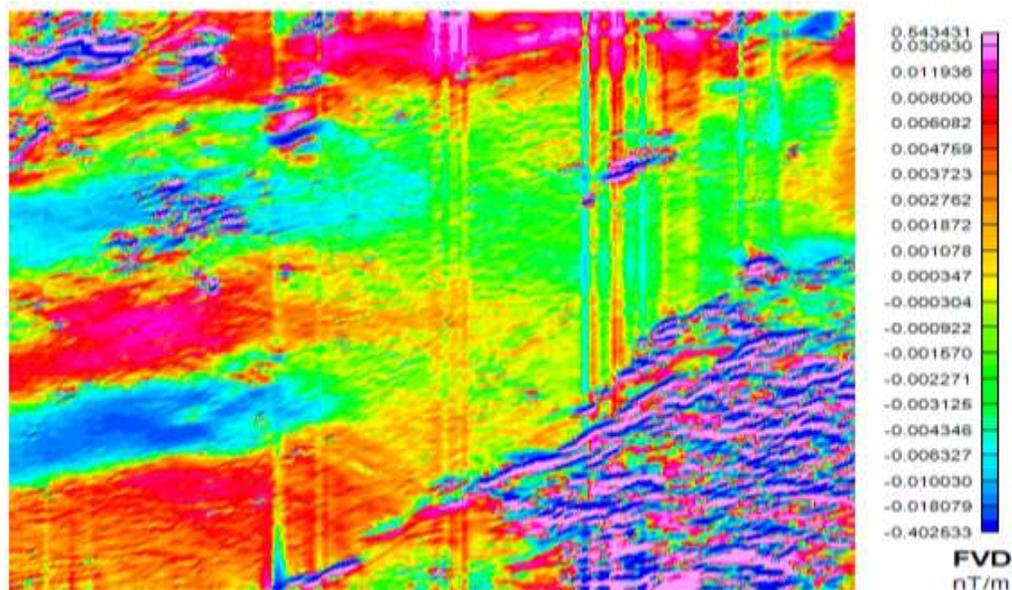


Figure 4. Grid map showing FVD.

model E (Ameri) is 477 m.

Depth to the magnetic anomalous bodies computed by employing SPI (Figure 10) ranged from 99.50 to 5930.78 m. The colour variations indicate different magnetic depths and susceptibility contrasts in the study area. The deep blue to light blue colour which ranged from 99.59 to 143.44 m show depth to shallow magnetic bodies while

the pink to light pink colour ranging from 1070.71 to 5930.78 m signify deep seated bodies. The deep seated bodies are predominant in the southwestern part of the study area.

The mathematical calculation and gridding of Euler 3D was performed using Oasis montaj where images were produced and depth to the suspected magnetic bodies

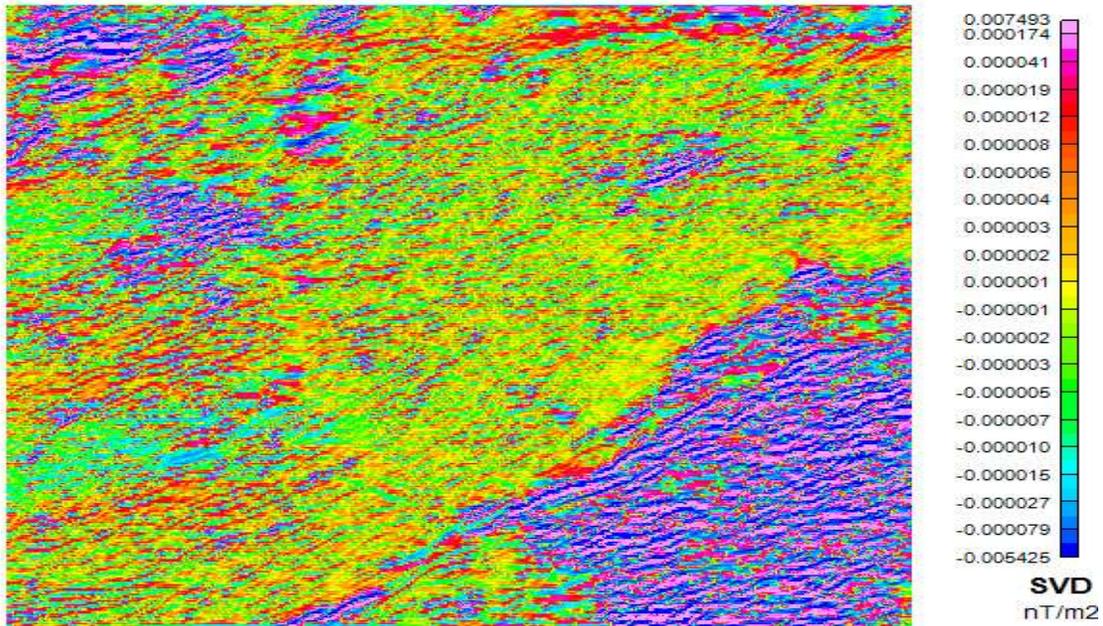


Figure 5. Grid map of SVD.

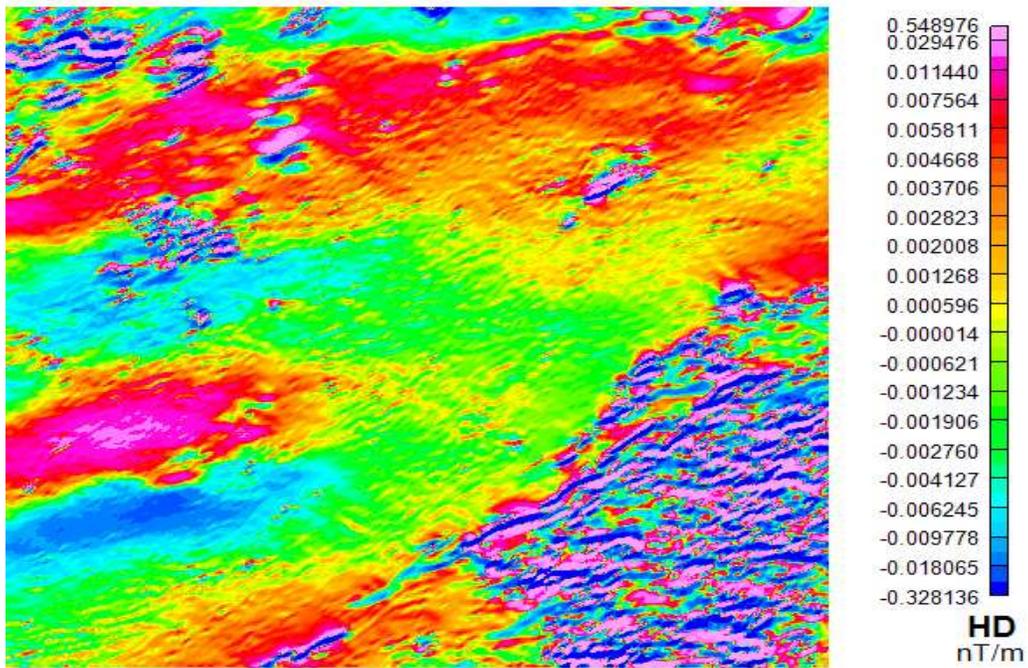


Figure 6. Grid map of HD.

estimated. Using three structural indices, three Euler 3D grids were generated. The legends by the grids showed both positive values and negative values. The positive values signify outcrops in the study area while the negative values signify depth below the surface.

However, there are scattered values or colours in the grid. The light blue to deep blue colour on the grid shows depth below the surface, while the pink colour shows outcrop. The portions in the grids without magnetic signature signify no Euler solutions to the structural index

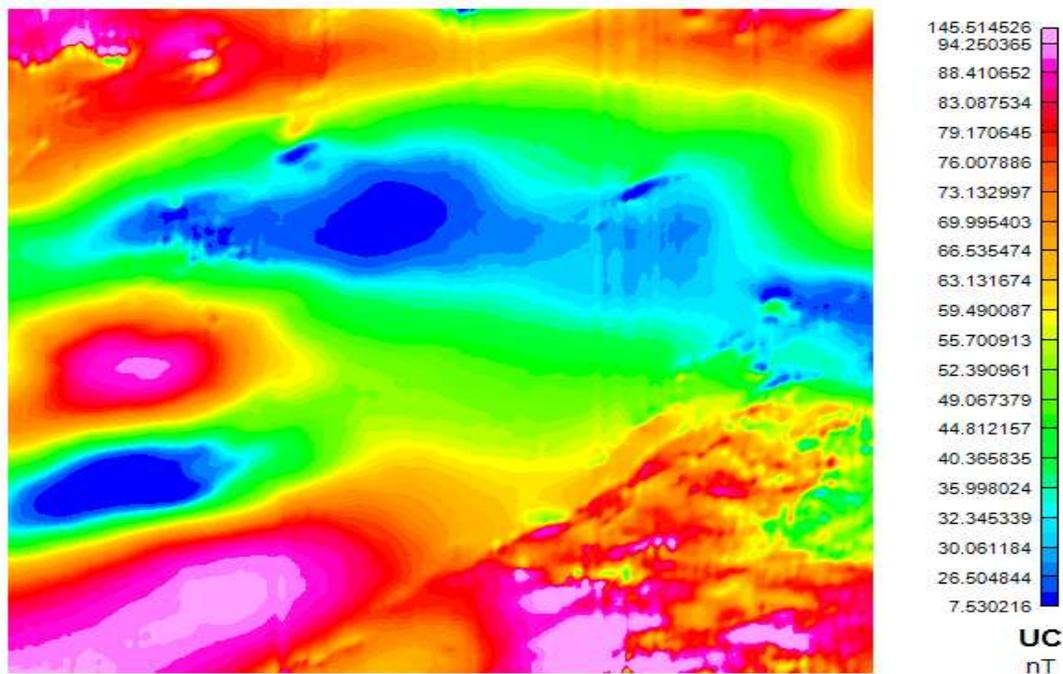


Figure 7. Grid map of upward continuation.

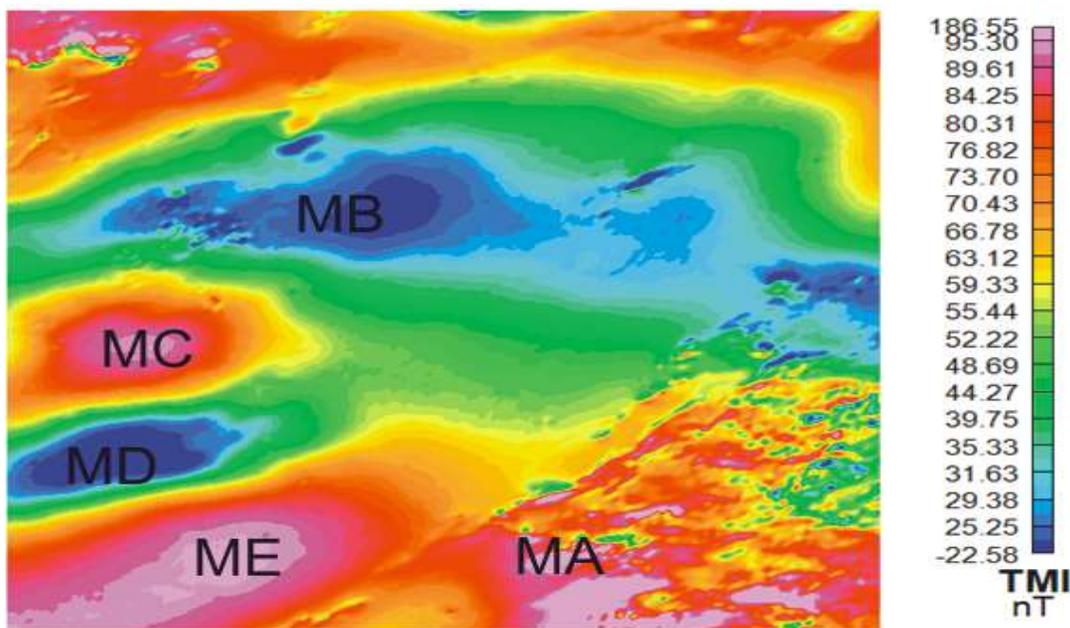


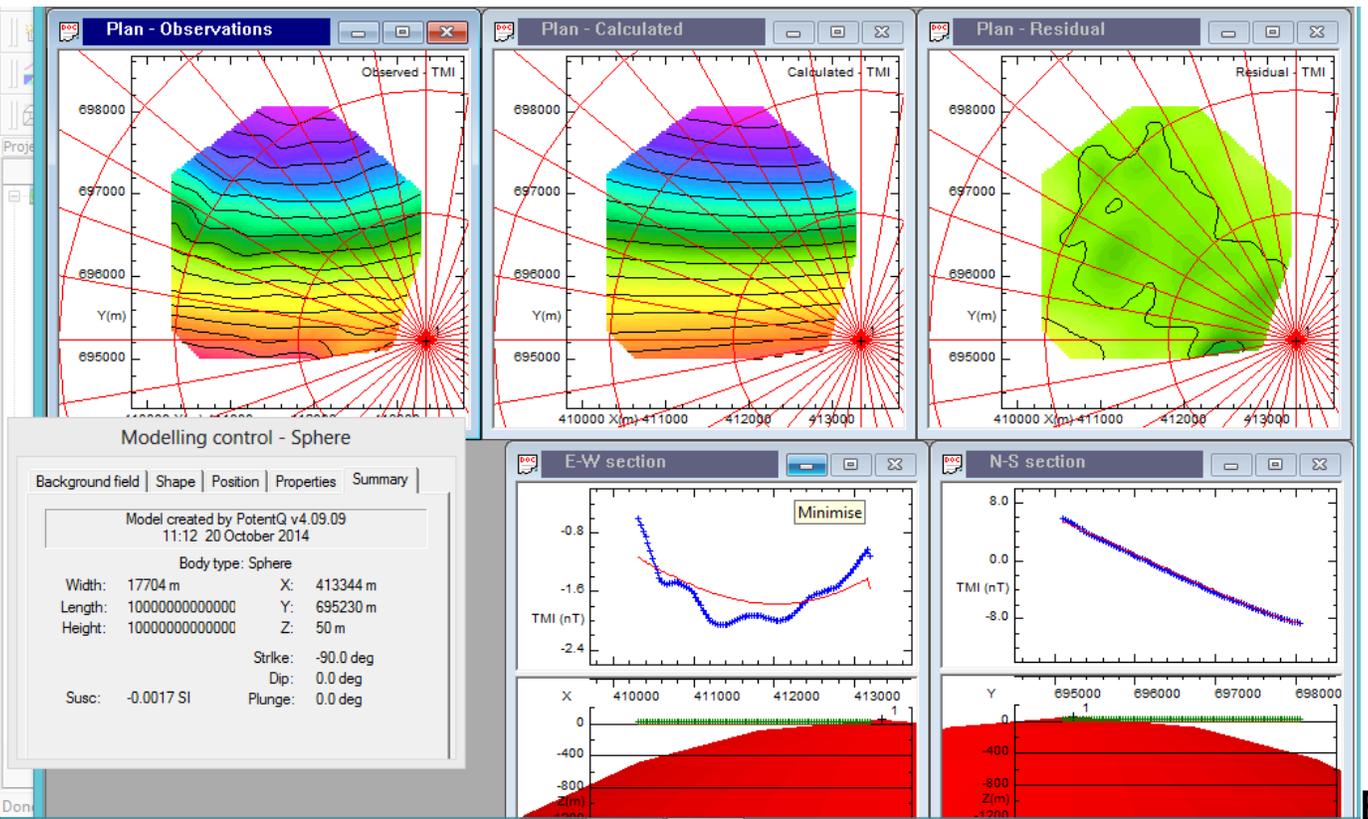
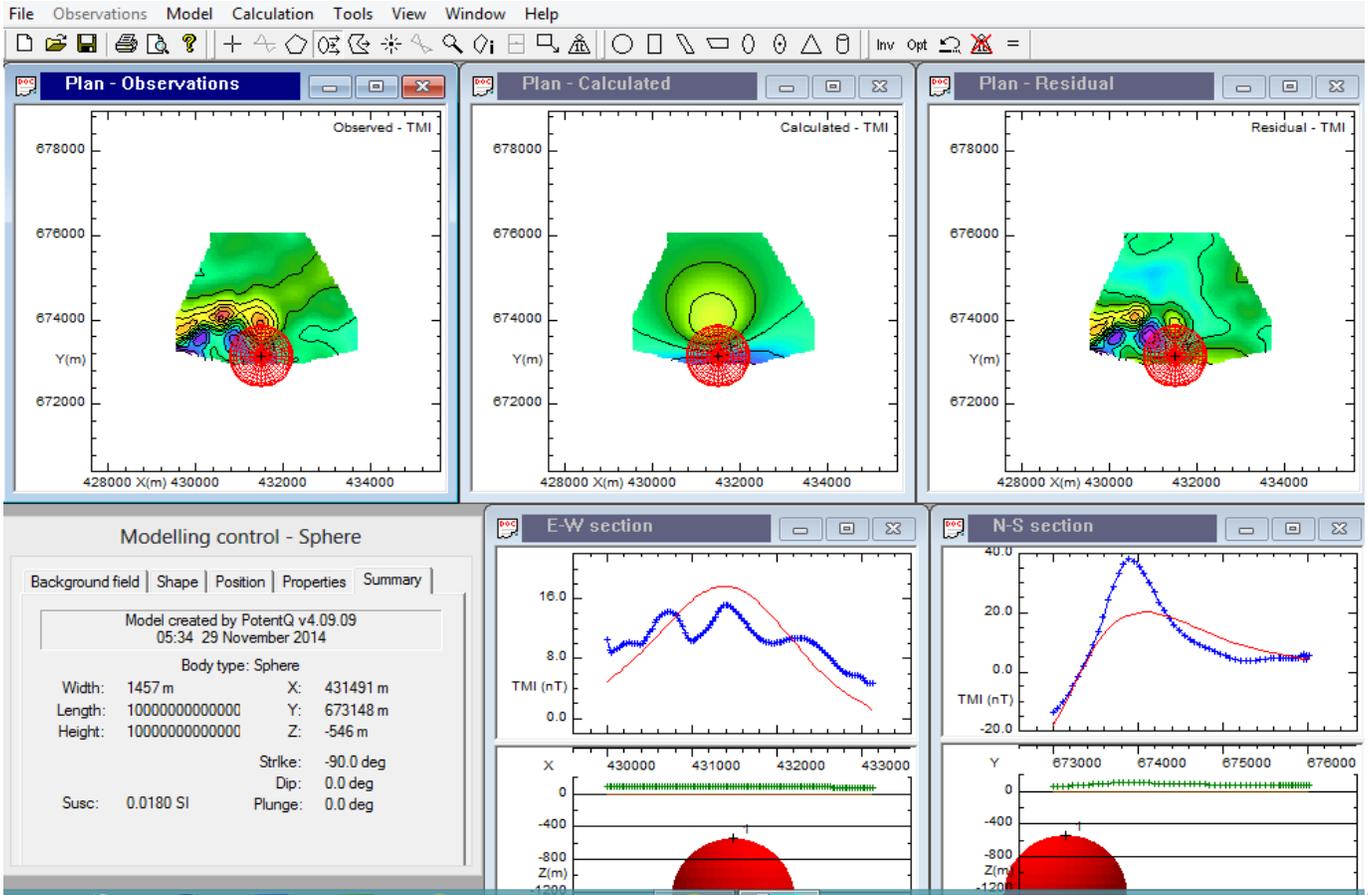
Figure 8. Grid map showing modeled areas (M implies model).

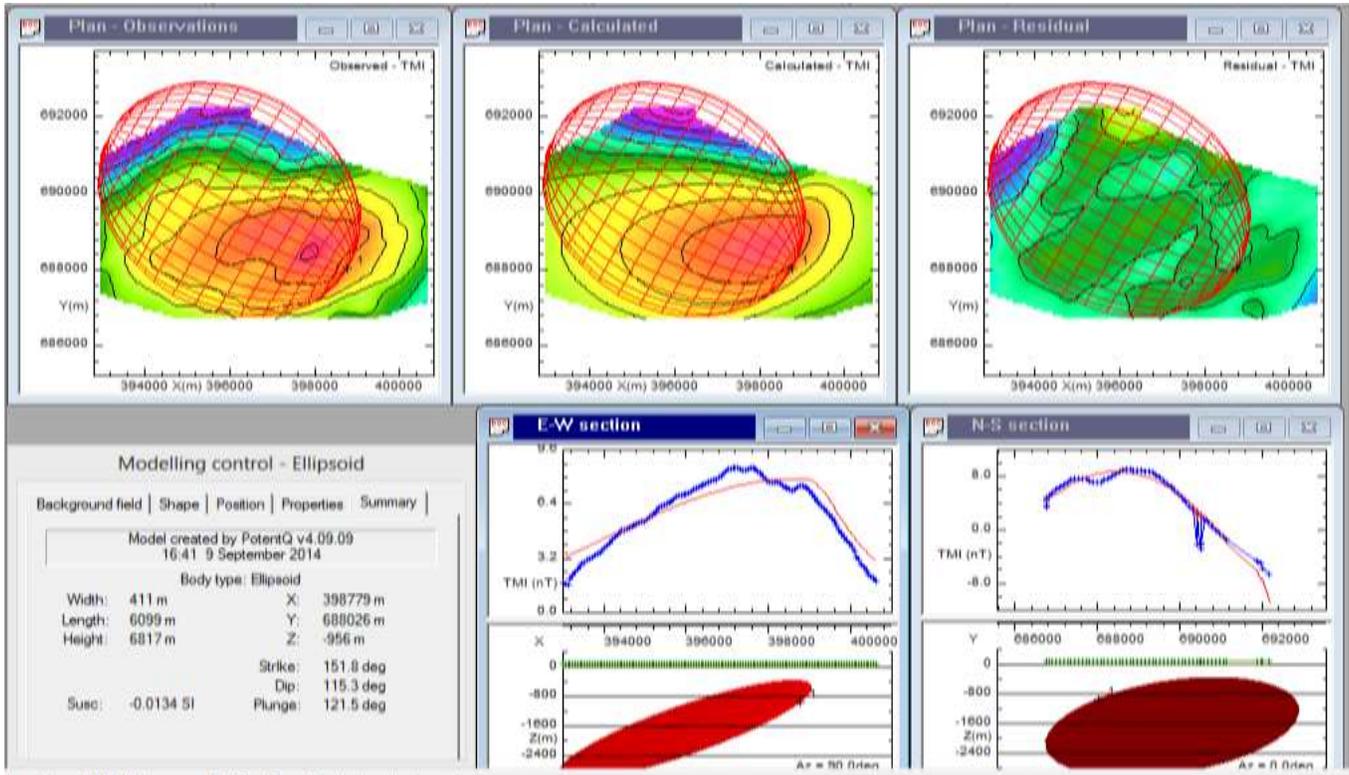
used in the grid. Figure 11a to c shows the Euler solution for the structural indices (1, 2 and 3) used. Table 2 summarizes the result of the Euler depth estimation.

Comparing the results of this study with the results from

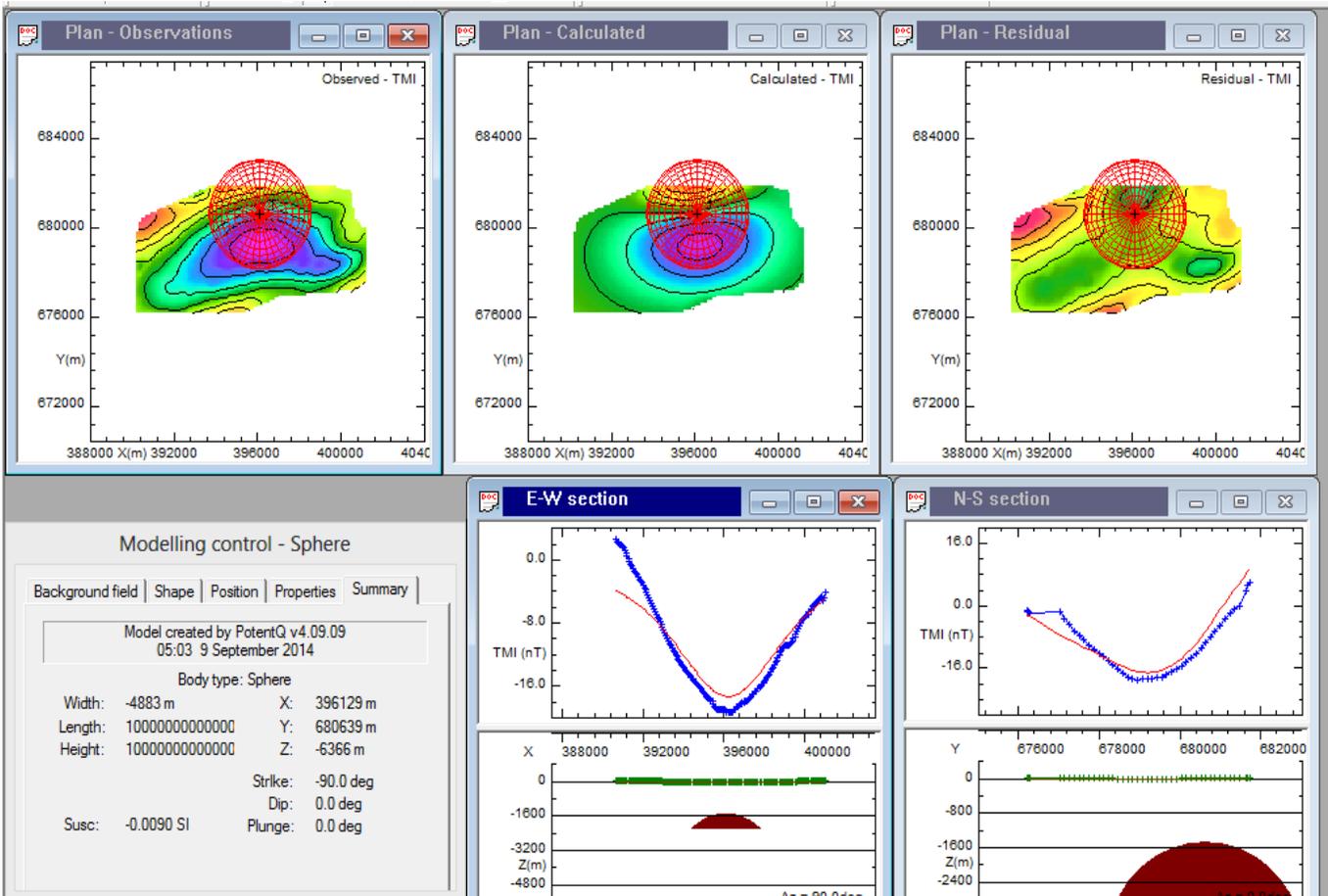
previous studies that employed different methods in the area, Ugbor and Okeke (2010) carried out land gravity survey in Abakaliki area using worden gravimeter.

Table 3 shows the summary of their results (Z is depth





C



Position cursor over reference point to drag body

D

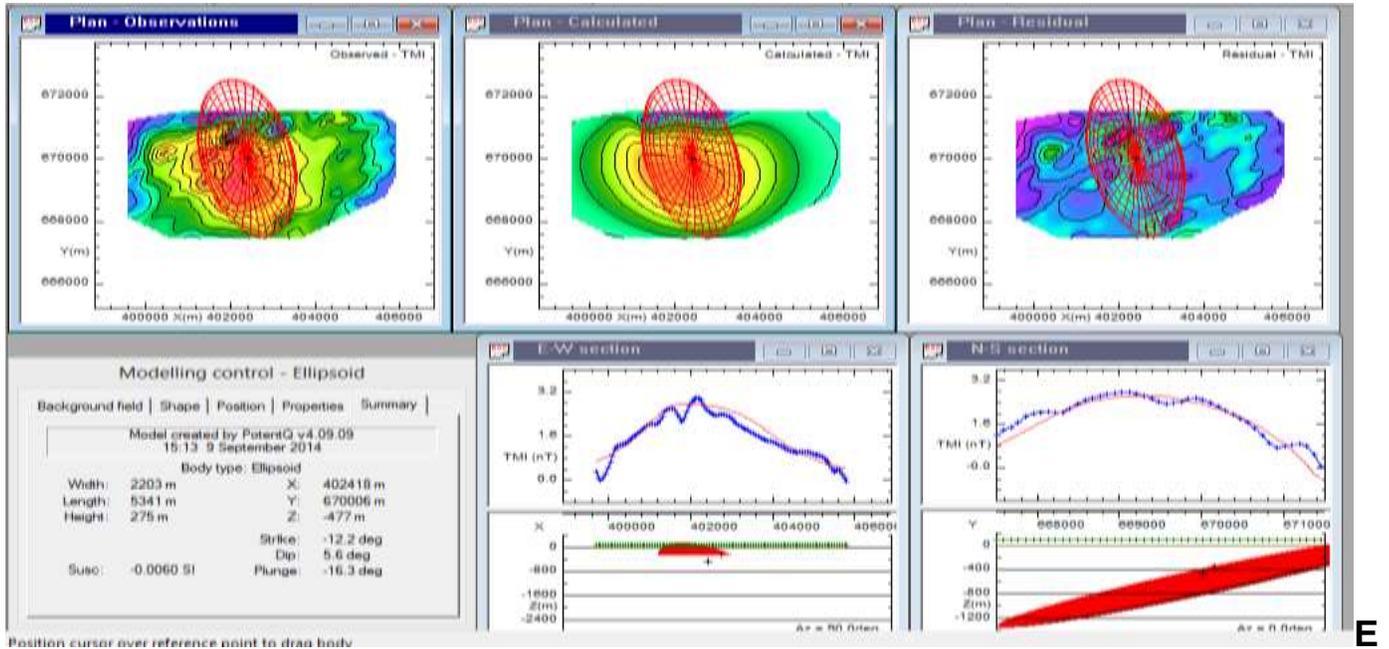


Figure 9. (A) Model A, (B) Model B, (C) Model C, (D) Model D, (E) Model E.

Table 1. Summary of modeling result.

Model	X (m)	Y (m)	Depth (m)	Dip (°)	Plunge (°)	Strike (°)	Body shape	k value (SI)	Probable mineral
A	431491	673148	-546	0.0	0.0	-90.0	Sphere	0.0180	Limestone
B	413344	695230	50	0.0	0.0	-90.0	Sphere	-0.0017	Calcite
C	398779	688026	-956	115.3	121.5	151.8	Ellipsoid	-0.0134	Rock salt
D	396129	680639	-6366	0.0	0.0	-90.0	Sphere	-0.009	Quartz
E	402418	670006	-477	5.6	-16.3	-12.2	Ellipsoid	-0.006	Calcite

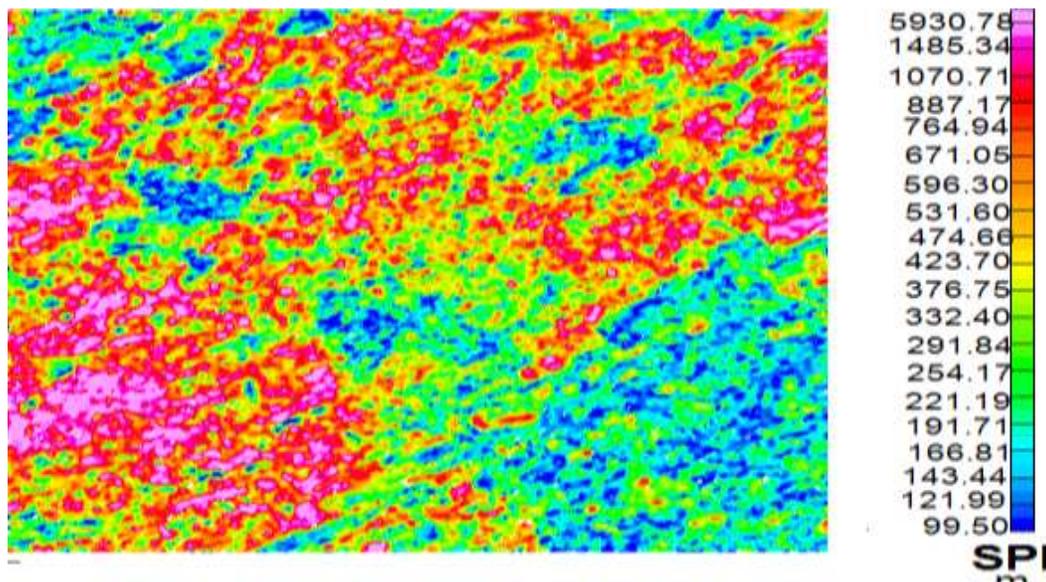


Figure 10. Source parameter imaging (SPI).

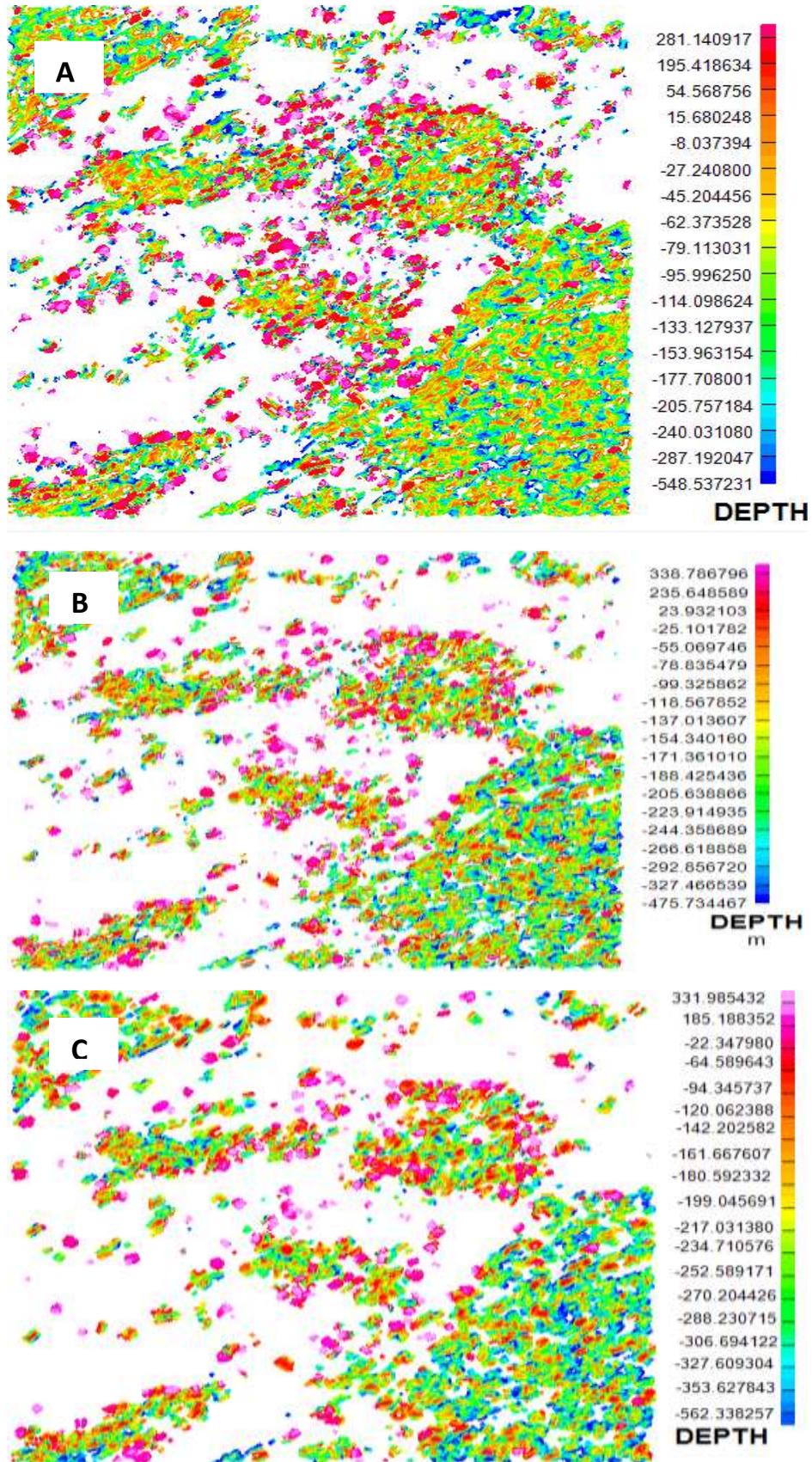


Figure 11. (A) Euler 3D (SI=1), (B) Euler 3D (SI=2), (C) Euler 3D (SI=3).

Table 2. Euler 3D result.

SI	Depth range (m)	
	From	To
1	8.037	548.537
2	25.102	475.734
3	22.348	562.338

Table 3. Interpretation results of land gravity survey (Ugbor and Okeke, 2010).

Profile	Z(m)	R(m)	T(m)	M(kg)
AA'	3132.00	1432.64	1699.36	2.8945×10^{13}
BB'	1931.40	1063.14	868.26	1.1828×10^{13}
CC'	2479.50	1133.88	1345.64	1.4350×10^{13}
DD'	2061.90	1100.13	961.77	1.3107×10^{13}
EE'	4280.40	1661.95	2618.45	4.5187×10^{13}
FF'	2283.75	1188.80	1094.95	1.6538×10^{13}
GG'	1794.38	1012.24	782.14	1.021×10^{13}

from surface to centre of anomaly, R is radius of anomaly, T is depth to surface of anomaly and M is mass of anomaly). They observed low Bouguer gravity anomaly which its cause might be accredited to a big and enormous anomalous low-density material whose depths of intrusion from surface to top range from 782 to 2618 m, with radii and masses ranging from 1012 to 1661 m and $1.02 \times 10^{13} \text{ kg}$ to $4.52 \times 10^{13} \text{ kg}$, respectively.

This proposes a region of basic to intermediate igneous intrusions, deep basement and crustal thinning. The low-density anomalous body which indicated existence of salt dome, concealed at a depth between 868 and 2618 m suggests occurrence of oil or/and Uranium in the area. Its diameter and mass ranged between 2126 and 3322 m and $1.18 \times 10^{13} \text{ kg}$ to $4.52 \times 10^{13} \text{ kg}$, respectively. The depth to anomalous bodies estimated by Ugbor and Okeke (2010) agrees with the depths from this work especially as could be seen from SPI depth results.

The total magnetic intensity grid (TMI) of the study area shows fault zone which trends NE-SW part of the study area. The circular contour pattern is evident of granitic as well as basic intrusives such as dyke, lacolyte or batholyte which agrees with the interpretation of aeromagnetic anomalies over the lower and Upper Benue Trough by Ofoegbu (1985b), where he opined that the anomalies occur mainly as basic intrusives within the cretaceous sediments. The gravity work of Cratchley and Jones (1965) who interpreted the positive anomaly over Amar in terms of zone of basic intrusive also agrees with this result. From the model results, model B signifies outcrop, and gravity work in the lower Benue trough by Cratchley and Jones (1965) suggested that further

positive anomalies flank the elongated negative anomalies on either side. The positive anomalies could be due to additional basic intrusive bodies within either the basement or sedimentary rocks which agree with the present work. The outcrop also conforms to the gravity work of Adighije (1981) on the Benue Trough who explained the central positive gravity anomaly in terms of an intrusive body with density of about 2.90 gcm^{-3} .

Aeromagnetic data of Abakaliki and Nkalagu areas were interpreted by Ugwu and Ezema (2012), using forward and inverse modeling method. The magnetic susceptibility values they got from their modeling results depict that most of the anomalous bodies are igneous rocks. The mineralization in the study area is due to igneous intrusions in the area. Though depth ranges of 10 to 22 km which they obtained for some anomalies could be favourable sites for buildup of hydrocarbons, they held that the existence of huge amount of intrusions makes this portion of the Benue Trough incapable of holding any substantial hydrocarbon potentials, since the existence of a great amount of igneous intrusions in the area designates an exceptionally high temperature history capable of destroying any hydrocarbons that might have been formed in the area. However, the works of Obi et al. (2010) and Igwesi and Umego (2013) did not rule out the possibility of hydrocarbon accumulation in the area. Igwesi and Umego (2013) employed spectral techniques in analyzing aeromagnetic data of some parts of Lower Benue Trough in order to estimate the average depth to magnetic sources in the area. Their results showed deeper magnetic sources situated at depths which fluctuate between 1.16 and 6.13 km, with an average depth of 3.03 km, representing magnetic basement surface. Their shallower magnetic sources

vary from depths of 0.06 to 0.37 km, with an average depth of 0.22 km displaying the presence of magnetic intrusive bodies within the sediments. The profiles taken from the area show that the topography of the basement is undulating with an anticlinal structure over Abakaliki area. The average depth to basement of 3.03 km to the magnetic source recommends sufficient sedimentary thickness for hydrocarbon accumulation. The undulating of the basement surface probably offers traps for hydrocarbon. The work of Igwesi and Umego (2013) agrees with the present work. Ezema et al. (2014) interpreted aeromagnetic data of Abakaliki using forward and inverse modeling method and spectral analysis. Their results disclosed five intrusive bodies comprising granulites, pyrite and basalt. The intrusive depths range from 2.4 to 6.32 km. Their spectral analysis indicates maximum depths of 4.96 to 9.8 km with minimum depths ranging from 0.12 to 0.71 km. Their results also showed availability of mineral (pyrite), granulites and salt at Mfuma which according to them agrees with the work of Ehinola (2010). They observed that the main source of magnetic anomalies in Abakaliki arises from the existence of intrusive and basic igneous in the sedimentary terrain. They agreed with Obi et al. (2010) who believed in the possibility of hydrocarbon potential in Abakaliki. The works of Ezema et al. (2014) and Anyanwu and Mamah (2013) fairly agree with the present work. The results of the 2-D spectral analysis of Anyanwu and Mamah (2013) showed a two depth models: the shallower magnetic source bodies which range in depth from 0.035 to 1.285 km with an average depth of 0.656 km while the deeper magnetic source bodies range in depth from 1.585 to 4.136 km with an average depth of 3.096 km. They believed that their average sedimentary thickness of 3.096 km estimated in their study area may favor hydrocarbon generation which fairly agrees with our work. Ofoegbu and Onuoha (1991) who employed spectral analysis on aeromagnetic data of Abakaliki estimated a shallow sediment thickness that ranges from 1.2 to 2.5 km, which is in fair agreement with this work.

There is a good correlation between the depths estimated by source parameter imaging and depth estimated by forward and inverse modeling in this study. The shallow depths obtained by source parameter imaging, forward and inverse modeling and Euler 3D deconvolution also correlate.

Conclusion

The results of this study suggest that the magnetic anomalies over the study area are caused by intrusive bodies of basic composition with different thicknesses and fault zone in the sedimentary area. The result of qualitative analysis shows that the magnetic anomalies are predominant in the southeastern part of the study area. It also showed the presence of intrusive like dyke,

lacolyte or batholyte. From quantitative interpretation, the presence of mineral deposits was deduced such as limestone, calcite, quartz, and rock salt in the study area. This correlates with the mineralization in the Lower Benue Trough and agrees with the works of Ehinola (2010), Ugwu et al. (2013) and Ezema et al. (2014). The forward and inverse modeling results revealed the presence of out crop in the area which correlates well with the work of Ofoegbu (1985a, b). Depth obtained by source parameter imaging (SPI) ranges from 99.50 to 5930.78 m, while depth obtained by forward and inverse modeling ranges from 477 to 6366 m. The depth range makes the study area good for hydrocarbon accumulation, but the intrusive bodies that dominate the area at variable depths make the chance of hydrocarbon generation and accumulation rare.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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