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GRAVITY AND MAGNETIC TECHNIQUES FOR THE DELINEATION OF SUBTERRANEAN STRUCTURAL FEATURES OF THE BASEMENT COMPLEX, IMO RIVER BASIN, SOUTHEASTERN NIGERIA.

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ABSTRACT
Gravity and magnetic techniques were applied to delineate the subterranean structural features of the basement complex of the Imo River Basin situated in the southeastern part of Nigeria, aimed at evaluating the subsurface tectonic pattern of the basement rocks. The gravity and aeromagnetic methods of exploration give an effective presentation of the subterranean structures. The corrected gravity data is represented by Bouguer anomaly map. The aeromagnetic data was corrected and represented by total aeromagnetic intensity map and then reduced to the north magnetic pole. The filtering techniques were applied to the corrected gravity and aeromagnetic maps to acquire the residual component produced by local structures and anomalies bodies. The combination of radially power spectrum was applied on both gravity and magnetic to estimate the depths of the deep and shallow sources. The equivalent depths of the isolated short wavelength anomalies are 500 m and 400 m, and the depths of the long wavelength anomalies are 2.8 km and 3.8 km for the gravity and magnetic data, respectively. The Euler deconvolution and 3-D modeling were applied to gravity and magnetic data. The 3-D Euler deconvolution is used not only to delineate major subterranean structures but also to figure out the structural indices of them as well as the mean depth of the gravity and magnetic sources. The computed structural indices show that the study area is mainly affected by contacts/thin sheet and the estimated depth of gravity and magnetic sources ranged between 500 m and 2000 m, also the 3-D Euler deconvolution showed that the area was affected by different fault trends such as E-W, NW-SE, and NE-SW trends. The results of 3-D gravity and magnetic interpretation revealed that the depth of basement was ranging from 2590 m to 3010 m. The main tectonic deformations of the area of study have NE-SW, NW-SE, and E-W trends. The obtained result from this geophysical examination could contribute for the understanding of the subterranean structural settings and the basement relief and tectonics of the Imo River Basin.

Keywords: Gravity, magnetic, subterranean, structural, potential-field, Euler deconvolution, filtering

INTRODUCTION
The Imo River basin like every other sedimentary basin, has its peculiar characteristics, which can be attributed to its geographic location (Opara, 2011). Both gravity and magnetic methods have a great deal in common and an interface for geological interpretation can be established between them (Opara *et al*., 2011). They are both extensively used as reconnaissance tools in oil exploration, mineral exploration as well as deep crustal studies. For the past twenty years, there have been new revolution in the use of gravity and aeromagnetic surveys from the interpretation

of solely basement structures to detailed examination of structure and lithologic variations in the sedimentary sections. In many sedimentary basins, gravity and magnetic anomalies result from secondary mineralization along fault planes, which are often revealed on aeromagnetic maps as surface linear features (Opara, 2001).

The project area lies within the Upper Imo River Basin, Nigeria and is located within latitudes $5^{0}35^{1}$N and $5^{0}56^{1}$N and Longitudes 7^{0}03'E and 7^{0} 38'E. The Study area of gravity data is in Okigwe between latitudes 5^{0} 45' and 5^{0} 50'N and longitudes 7^{0} 03' and 7^{0} 48'E, covering a land area of about 1,216 km^{2} (Ekwe et al., 2006). The study area of the gravity and magnetic data is situated in Okigwe between latitudes 5^{0} 45' and 5^{0} 50'N and longitudes 7^{0} 03' and 7^{0} 48'E. Integrated geophysical tools, gravity, and aeromagnetic techniques, are generally used in detecting the subsurface structures, the depth of the basement and the sedimentary cover thickness.

The word "geophysics" in oil and gas exploration is often used synonymously with "seismic", overlooking many other fruitful techniques. In mineral exploration and engineering projects, applicability of seismic imaging is often limited, and other geophysical methods take the front of seat.

Gravity and magnetic methods, which are applied in this study, are extremely useful in both mineral and petroleum exploration. Unfortunately, among oil-industry geophysicists and managers of the knowledge and appreciation of these techniques tend to be comparatively thin. Rooted in over specialized college training, a too-narrow focus on only some geophysical methods impoverishes oil exploration if potential-field surveys are underutilized. By limiting "geophysicists" ability to switch between oil and mining industries, it restricts their employment flexibility and career choices.

The multi-faceted exploration market calls for many different types of geophysical work. Professional associations and alumni groups need to put pressure on academic instructions to diversify and round out their curricula. Fluctuating economic conditions, and future well-being of new graduates, demand nothing less.

The gravity method is useful whenever the object of investigation has a contrast in density of the subsurface and the magnetic method is useful whenever the object of investigation has a contrast in the magnetic susceptibility. The traditional role of gravity and aeromagnetic studies over continental areas has been in establishing geologic and tectonic framework sand in exploring for mineral and other commodities. Gravity and magnetic anomalies can be defined by gravity and aeromagnetic surveys respectively and interpreted in terms of the depth to the basement rock surface and consequently the thickness of overlying sedimentary rocks. The gravity and magnetic data can also be used to determine relief on the basement surface that may be directly related to structures favorable for accumulation of gas and oil in overlying sedimentary rocks. Thus, with gravity and magnetic data, it is possible to identify areas with potential for occurrence of petroleum and to provide information on thickness of sedimentary rocks plus some information on possible structures in sedimentary rocks. Basement structures and depth can be delineated and mapped using gravity and magnetic data. Trends in gravity and magnetic features often have related trend in the overlying sediments. Systematic offset of magnetic anomalies may indicate strike-slip faults; which have displaced basement rocks; possibly affected the sediment section. Gravity and magnetic basement interpretations can, to a certain extent, lead to a better understanding of the structures of the overlying sedimentary rocks (Ibim et al., 2022). The elucidation of the subsurface structure of the upper crust is the most valuable contribution of the gravity and aeromagnetic data. Magnetic surveys are effective in determining geometry of sedimentary basins and in defining major masses of extrusive and intrusive igneous rocks.

The gravity method depends on the measurement of variations in the gravity field caused by horizontal variations of density in the subsurface. In order words, the method can be used for mineral exploration through the interpretation of gravity data that depend on the density contrast between the ore bodies and contrary rock. It is an essential method in number of specific geological studies, as in mapping near surface voids, quantitative studies of metallic ore bodies, characterizing salt structures, and monitoring changes of fluid/gas content in volcanoes. The gravity method has also been used in regional characterization of the earth to determine the structures of the crust, identifying potentially favorable regions for resource exploration, and developing conceptual exploration models (Hinze et al., 2013). The main targets for gravity survey are mainly used for delineating subsurface structures which control the configuration of oil reservoirs and groundwater aquifers. The gravity method is particularly effective at accurately spotting oil deposits. Many authors used the gravity data interpretation for groundwater exploration (Sultan et al., 2009; Araffa et al., 2015). Araffa and Fernando (2014) used gravity data to delineate structures and tectonic on northern part of Greater Cairo.

The magnetic method is one of the most widely used geophysical techniques for investigating the subsurface of the Earth. It can be applied to a wide variety of subsurface exploration problems including horizontal magnetic variations from Earth's crust base anomalies in the Earth's normal magnetic field that are mapped by the magnetic method (Hinze et al., 2013). The magnetic method
depends on variations in the earth magnetic field derived from lateral differences in the magnetization of the subsurface (Hinze et al., 2013). Magnetic data can be used to map large geologic structures, characterize bedrock, and aid high-resolution near-surface engineering, geotechnical, and environmental investigation (Nabighian et al., 2005; Sharma, 2012). The instrument used to meet the objectives of environmental investigations is usually a cesium-vapor magnetometer that measures magnetic-field intensity in nanotesla (nT) (i.e. 1T = 1 newton/amp-meter).

It has become necessary and important to embark on a more articulated study of the subsurface structural features in an area and undertake a detailed geophysical study of the area to enhance an understanding of the subsurface structural status with the aim of reducing the risks associated with oil and gas exploration and management in an area. This work is therefore aimed at delineating the structural features of the basement complex in Imo River Basin using gravity and magnetic methods to delineate the structural features and view the spatial distribution of the subsurface structures in the study area and their possible influences on the regional oil flow. The study could contribute for the understanding of the subsurface structural settings and basement relief and tectonics of the study area. The objectives of this study are to evaluate the subsurface tectonic pattern, and to study the basement relief and its tectonics in the proposed study area. Gravity and magnetic data interpretation will be used to determine the subsurface structures, estimate the depth to basement rocks, define the depth of the basement complex and to ascertain the directional orientation of the structural elements which will be deduced from RTP. Bouguer anomaly map and the filtered magnetic and gravity maps will be integrated with the possible results of Euler deconvolution. Gravity and magnetic basement interpretations which is not common in the study area can, to a certain extent, lead to a better understanding of the structures of the overlying sedimentary rocks, hence the invocation of this research.

Location and Physiography of the Study Area

The study area is part of Imo Basin, southeastern Nigeria, which lies between latitudes 5^0 35ˡN to 5^0 56ˡN and Longitudes 7^0 03'E to 7^0 38'E. The basin is 300 Km NE – SW trending syncline, located at the southwestern dip of the Benue trough in southeastern Nigeria. The study area is characteristically linear in slope and its sedimentary formations are continuous with the Nigerian Coastal Basin. It is characterized by hills and valleys. These hills and ridges were formed due to the resistance of sandstones to agent of denudation such as erosions etc. the plains and the valleys were formed because of the shales that were not resistant to agents of denudation. Therefore, the landform is because of the difference in the degree of resistance to agents of denudation and the bedrock varies from basement complex to shales, marls, and limestone, as well as sandstones and unconsolidated to semi-consolidated sands (Ukaegbu and Akpabio, 2009).

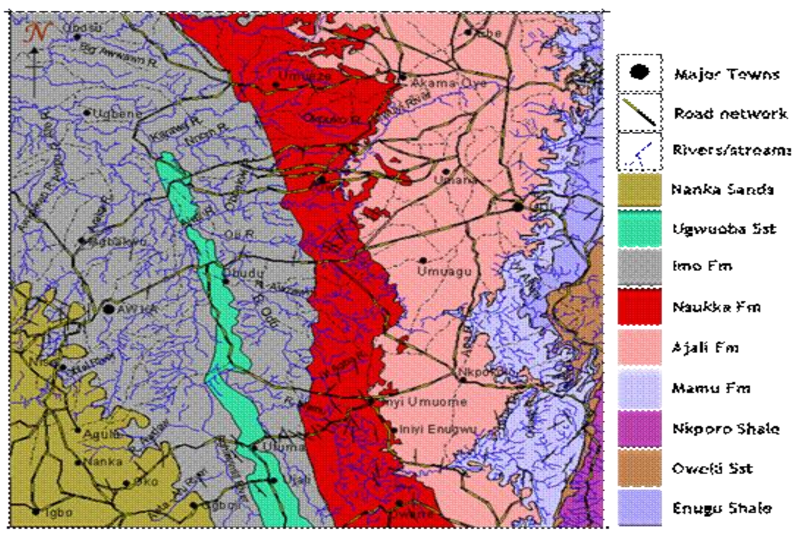

Figure 1: Geological Map of the Study Area
(Source: Opara et al., 2011)

Materials and Methods

In the present study, two geophysical techniques were conducted in the study area including aeromagnetic data and gravity data which covered the area within latitudes $5^0$35ˡN to $5^0$56ˡN and Longitudes $7^0$03'E to 7^0 38'E. Digitized high resolution gravity and aeromagnetic maps of Loko (249), Agana (250), Makurdi (251), Akwana (252), Ankpa (269), Oturkpo (270), Gboko (271) and Katsina-Ala (272) on a scale of 1:100,000 were used in this study. The maps were obtained, analyzed, and interpreted using several potential field software which include Oasis Montaj

Program v.8.4, 2015 version. Fugro Airborne survey acquired high resolution gravity and aeromagnetic data for the Nigerian Geological Survey Agency between 2006 to 2009. The aeromagnetic prospect was aviated along a series of NW-SE flight lines with 500m line spacing, 80m terrain clearance and flight line direction of NW-SE. Data was recorded at very small intervals of 0.5s each with 80 m normal flight elevation. The geomagnetic gradient was extracted from the data using January 2005 IGRF model referenced to the World Geodetic System, 1984 ellipsoid. The aeromagnetic maps were digitally filtered using the nonlinear filter (NLF). The nature of filtering applied to the airborne magnetic data in the present study was chosen to eliminate certain wavelengths and to pass longer wavelengths. Analytical methods used in this study include 2-D spectral inversion, trend surface analyses, Reduction-to-Pole and second vertical derivative. The regional gradients were removed by fitting a plane surface to the data by multi- regression least squares analysis. The regional-residual separation of magnetic anomalies was carried out using the third-degree trend surface analysis method (Mandal et al., 2013). Similarly, in this study, the analytical signal module in Hilbert transform was used as the basis for carrying out reduction-to-pole (RTP) transformation of the HRAM data (Mandal et al., 2013). The voluminous magnetic data sets generally require automatic interpretation techniques like Naudy, Euler, and Werner deconvolution. However, of these techniques, the Euler deconvolution has become a popular choice because the method assumes no geological model. However, the conventional methods to solving Euler equation requires tentative values of the structural index preventing it from being fully automatic and assumes a constant background that can be easily violated if the singular points are close to each other.

Additionally, basement depth estimates within the area was made using 2-D spectral analysis. The fundamental principles and applications of the spectral analysis technique have been disclosed in several key publications (Ofoegbu & Onuoha,1991; Kangoko et al., 1997). The depth estimates are usually established from the slope of the log- power spectrum at the lower end of the total wave number or spatial frequency band. The method allows an estimate of the depth of a set of magnetized blocks of varying depth, width, thickness, and magnetization. The slopes of the segments yield estimates of average depths to magnetic or gravity sources of anomalies. Similarly, second vertical derivative filters were used to enhance subtle anomalies while reducing regional trends (Opara et al., 2012). These filters are considered most useful for defining the edges of bodies and for amplifying fault trends. In mathematical terms, a vertical derivative can be shown to be a measure of the curvature of the potential field, while zero second vertical derivative contours define the edge of the causative body (Opara et al., 2012). Thus, the second vertical derivative is in effect a measure of the curvature, i.e., the rate of change of nonlinear magnetic gradients.

The gravity method depends on the measurement of variations in the gravity field caused by horizontal variations of density in the subsurface. It is the essential method in number of specific geological studies, as in mapping near surface voids, quantitative studies of metallic ore bodies, characterizing salt structures, and monitoring changes of fluid/gas content in volcanoes. The gravity method has also been used in regional characterization of the earth to determine the structures of the crust, identifying potentially favorable regions for resource exploration, and developing conceptual exploration models (Hinze et al., 2013).

The magnetic method is one of the most widely used geophysical techniques for investigating the subsurface of the Earth. It can be applied to a wide variety of subsurface exploration problems including horizontal magnetic variations from Earth's crust base to within the uppermost meter of soil. These variations cause anomalies in the Earth's normal magnetic field that are mapped by the magnetic method (Hinze et al., 2013). The magnetic method depends on variations in the earth magnetic field derived from lateral differences in the magnetization of the subsurface (Hinze et al., 2013).

Radially averaged power spectrum technique

Radially averaged power spectrum technique is applied to find the depths of the shallow depths, basement complex, and the subterranean geological structures. Various authors, such as Muririzio, Tatiana and Angelo (1998), Garcia and Ness (1994), explained the spectral analysis technique. It depends on the analysis of the magnetic data applying the Fourier Transform on the spectral analysis map and its computer conjugate. It is a function of wavelengths in both x and y directions. In this work, the Fast Fourier Transform (FFT) on both RTP aeromagnetic data and gravity data, was used to calculate the energy spectrum.

Filtering techniques

The main purpose of the filtering techniques will be to separate the anomalies of various wavelengths from each other. The local anomalies of shallow sources are corresponding to the anomalies of short wavelengths or high frequencies while the regional anomalies of deep sources are corresponding to long wavelengths or low frequencies. In this work, the 2-D filtering will be carried out on the Bouguer map, and on the RTP aeromagnetic maps to the lineation caused by structural faulting or dislocations in the basement rocks at various depths. In the present study, the filtering technique is performed using the frequency ranging between 0.0170 cycle/ unit and 0.0290 cycle/ unit data.

Euler deconvolution

The Euler deconvolution technique was first applied on the profile data by (Thompson, 1982) which later advanced by (Reid et al., 1990) for the gridded data. Euler deconvolution method will be used to estimate the locations and depths for several linear subsurface features such as (lineaments, geological contacts, faults, dikes, sills). This requires knowledge about the type and nature of the causative body which can be achieved by defining the structural index (Salem et al., 2008). The structural index can be defined as the rate of change of the field depending on the source geometry.

3-D magnetic modeling

The interactive 3-D gravity and magnetic modeling software program is designed for performing layer-earth models. This implies that the GM-SYS 3D is an extension for Oasis Montaj Program v.8.4, 2015 which is applied for the aim of 3-D modeling of subterranean structures and detecting the depth to the top of the basement surface, dominating the studied area.

RESULTS DISCUSSION

From the point of view, the total intensity aeromagnetic map (Figure 2a) and the RTP aeromagnetic map (Figure 2b) we note that the northward shift implied anomalies of the effect of the orientation

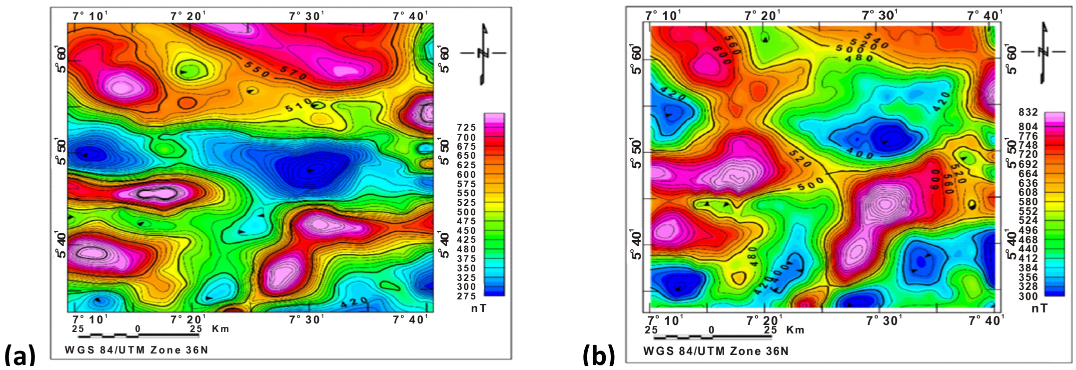

Figure 2: (a) Total Aeromagnetic Anomaly Map of the Study Area (Modified after Folkman and Assael, 1980). (b) RTP Aeromagnetic Anomaly Map of the Study Area

of the magnetic field at the study area. Furthermore, the number of anomalies becomes bigger with approximate decrease of their ariel expansion and the increase of their vertical relief.

From the examination of the RTP aeromagnetic anomaly of the studied area as shown in (Figure 2b), indicates that the magnetic field in the area has a maximum relief of about 776 nT almost in the northern part and minimum relief of about 300 nT in the central part of the map. These anomalies have different shapes, polarities, and reliefs. The general magnetic trends pattern of this field are NW-SE, NE-SW, and E-W. In the northern part of the map, the anomalies consist of three closures, two of them having polarities characterized by its positive polarities, irregular shape, moderate gradient, and trending NW-SE. Between these closures, the area of low anomalies (negative polarity) are located and consists of one closures of irregular shape, and moderate gradient that is trending in NW-SE direction. The southern flank of these anomalies, however, are overlayed by another magnetic anomalies features of negative polarity and high gradient. The extended anomaly zones with high gradient show considerable subterranean faulting trending NW-SE. These anomalies can be explained as due to magnetic basaltic extrusions associated with the NW-SE faulting trend. Closer to the south pole, the anomalies are ellipsoidal of low anomalies (negative polarity). They are characterized by moderate sharpness and moderate gradient, the general magnetic trends pattern along this part are NE-SW, and NW-SE. This anomaly represents a shallow sedimentary basin.

The Bouguer anomaly map (Figure 3) shows lateral changes in the earth gravity field which has a maximum anomaly value of about 12 mGal at the northern and northwestern parts but minimum anomaly value of about 50 mGal at the southern, southeastern and at the southwestern

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parts of the study area. High gravity anomalies are condensed in the northern, northwestern, and closely in the southwestern parts of the area of study. Generally, these high gravity anomaly zones may be because of the presence of subterranean denser rocks or near surface uplifted blocks of basement rocks. Low gravity anomalies are condensed in the eastern, and in the southeastern parts. Generally, the negative gravity anomalies are suggestive of the presence of thick sedimentary sections in these parts of the study area.

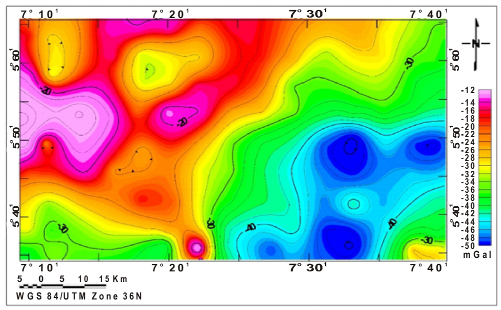

Figure 3: Bouguer Anomaly Map of the Study Area

Two dimensional (2D) radially averaged power spectrum technique has been used to figure out the average depth level to the magnetic and gravity source in the studied area. In this work such technique was used for both the magnetic and gravity data, applying (Oasis Montaj Program v.8.4, 2015). The acquired diagrams of the radially power spectrum Figure 6a and Figure 4b illustrate the estimated average depth levels to the deep and shallow depth segments prevailing the study area. The estimated average depth of the gravity source bodies (Figure 4a) is 2800 m for the deep and 280 m for the shallow source. However, the 2-D power spectrum diagram of the magnetic data. (Figure 6b) indicates, that the deeper source has an average depth of about 3800 m and the shallow is of about 800 m. It is noted that the average depth of the deeper magnetic data is more than gravity, as it somewhat directed to the basement surface as well as intra basement source. In addition, the adoption of this method gives an exact picture of the depth in the two dimensions of the digitized gravity and magnetic data reveals three structural features shown by linear anomalies having their extension in an NE-SW, E-W, and N-S direction. These Linear anomalies lie on several local anomalies of different shapes and polarities (positive and negative). The most important features are the major anomalies of different shape, and polarities which stretch downwards of the basement itself in E-W direction at central, eastern, and northwestern parts. The negative polarities control a zone of uplifting striking faults in north, south, and western blocks having extension N-S and E-W direction. These faults have the main trends NW-SE, E-W, and N-direction and affect the overlain sedimentary section.

Radially Averaged Power Spectrum

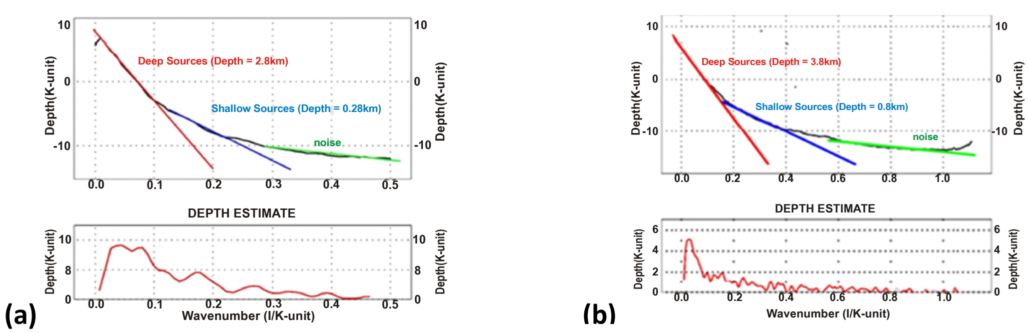

Figure 4: (a) 2-D Radially Averaged Power Spectrum for the Gravity Data. (b) 2-D Radially Averaged Power Spectrum for the Magnetic Data.

By careful analysis of low pass gravity filtered map (Figure 5a) with cutoff at 0.0290 cycle/unit, the outstanding NE-SW, and NW-SE, anomalies trends persist, which reflects the deep extent of the subterranean structures causing these faults anomalies. This displays the depth of textures responsible for the presence of these faults, which interpreted the extension of these faults to great depths. However, some smooth regional anomalies that appear not to be related to a subterranean structure arc most probably a result of regional differences in the density of the rocks at high depth.

High pass gravity filtered map of the study area is shown in (Figure 5b) with an effective cut-off wavelength of 0.0290 cycle/unit, revealing three structural features showed by linear anomalies having their extension in N-S, E-W, and NE-SW direction. These Linear anomalies affect several local anomalies of various shapes and polarities (positive and negative). The most important features are the major anomalies of different shape, and polarities which extend downwards of the basement itself in E-W direction at eastern, central, and north-western parts. The negative polarities control a zone of uplifting striking faults in south, north, and western blocks having extension N-S and E-W direction. These faults have the main trends NW-SE, E-W, and N-direction and impacted on the overlain sedimentary section.

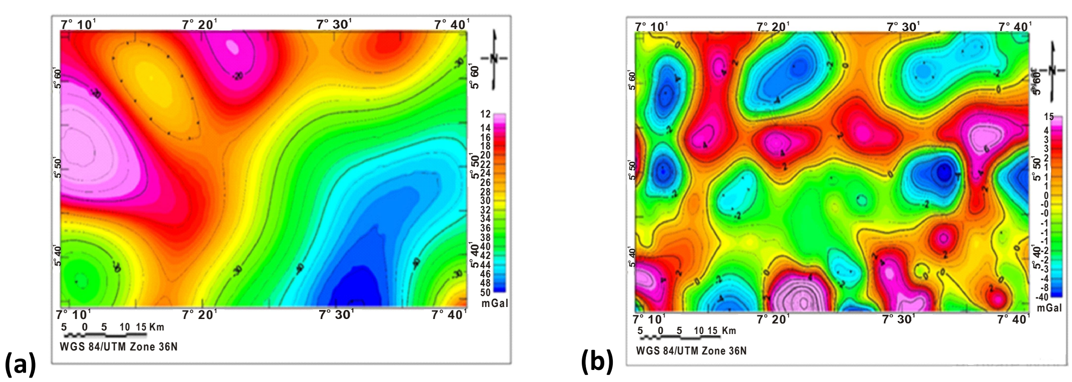

Figure 5: (a) Low Pass Gravity Filter Map with Effective Cutoff Wavelength of 0.0290 Cycle/Unit.
(b) High Pass Gravity Filter Map with Effective Cutoff Wavelength of 0.0290 Cycle/Unit.

Through low pass magnetic filtered map of the study area shown in (Figure 6a) with an effective cutoff wavelength of 0.0170 cycle/unit, we find that the magnetic field increases in the northeastern and southwestern with the prominent trends is NE-SW. and NW-SE. The prominent structure trends in the RTP magnetic map (Figure 2b), is still found in the low pass filtered map and, this reflects the tectonic nature of these faults and subsurface structures which stretch from shallow depths and even large depths.

The high pass filter used on the magnetic map of the studied area with effective cutoff wavelength of 0.0170 cycle/unit (Figure 6b) shows short wavelength spot and high frequency magnetic anomalies which map are inferred as residual component located in the southeastern and southwestern parts of the studied area. Furthermore, the map contains a great number of smaller anomalies resulting from the filtering process. However, the prominent trend in the magnetic map is NE-SW and NW-SE is still discerned in the high filtered map and this shows that the prevailing faults trends (RTP map, Figure 2b) stretched in the subsurface of the study area up to shallow depths. The random trends of small-scale anomalies indicate that the shallow subterranean section has been separated by various stresses of the new tectonics that may have not impacted.

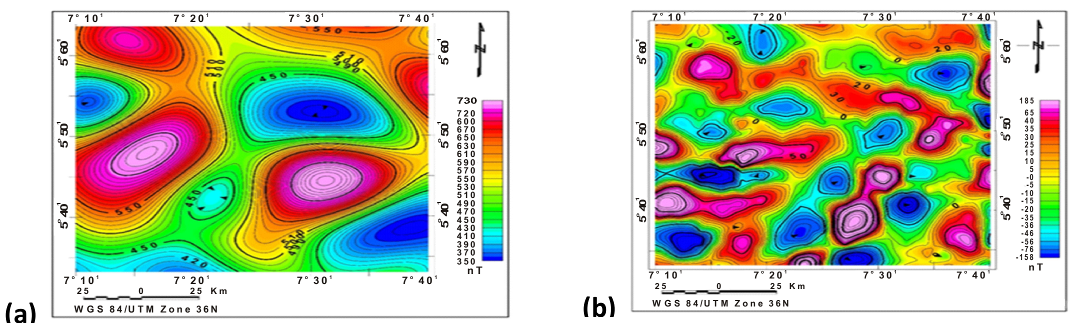

Figure 6: (a) Low Pass Magnetic Filter Map with Effective Cutoff Wavelength of 0.0170 Cycle/Unit. (b) High Pass Magnetic Filter Map with Effective Cutoff Wavelength of 0.0170 Cycle/Unit.

In this study, the 3-D Euler deconvolution technique was applied on both gravity and magnetic field data to find out the locations and depth values of the different lineaments and faults in the study area.

In gravity data, Euler deconvolution solution was used for Bouguer anomaly map for various structure indexes (SI). If the structural index = 0 (Figure 7a), it indicates to dyke, and ribbon. If the structural index = 1 (Figure 7b), it indicates to pipe and cylinder. If the structural index = 2 (Figure 7c), it indicates to sphere (Oasis Montaj Program v.8.4, 2015). Euler deconvolution technic was used on the study area by using Structural Index (SI) = 0, 1, and 2 to achieve different solutions (Figure 7). Figure 7a (SI = 0) indicates the best comparable fault system.

The obtained Euler deconvolution solution of the magnetic map Figure 8. The Euler solutions are applied to the RTP magnetic map of the studied area using the (Oasis Montaj Program v.8.4, 2015). In the present study the structural index that applied to RTP map are 0, 1, 2, and 3 to select the best solution. RTP magnetic map at SI = 0 as in (Figure 8a), SI = 1 as in (Figure 8b), SI = 2 as in (Figure 8c) and SI = 3 as in (Figure 8d). The structural index SI = 0 gives better solutions than structural index 1, 2, and 3 because the data are concentrated at some places in the study area which are not distributed all over the area as SI = 1, SI = 2 and SI = 3.

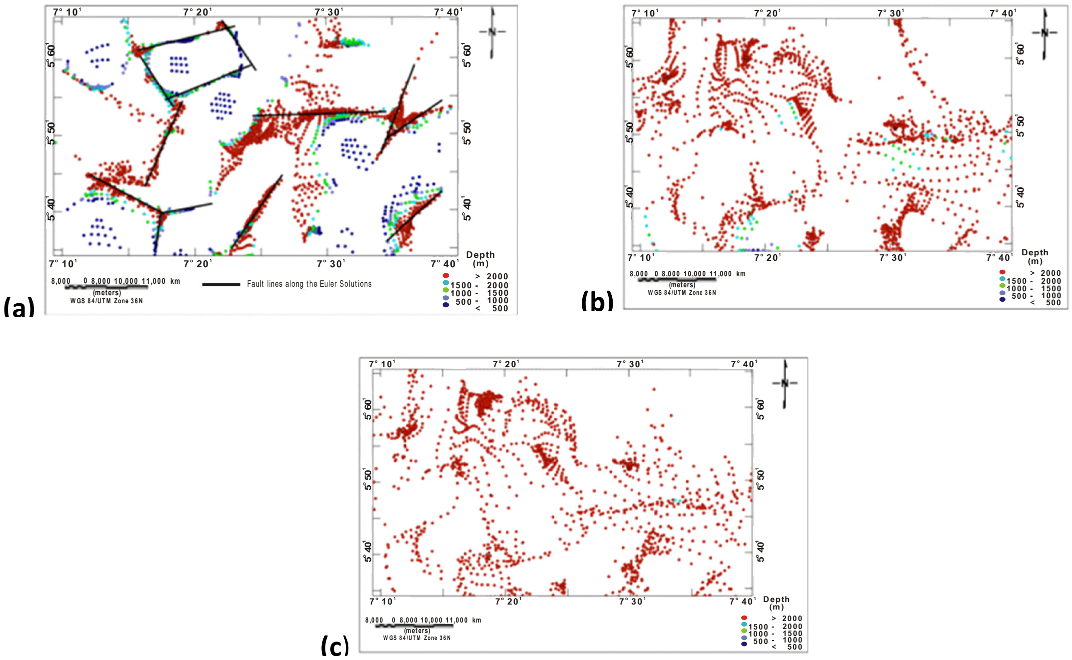

Figure 7: (a) Euler Solutions of the Bouguer Anomaly Map of Structural Index = 0. (b) Euler Solutions of Structural Index = 1. (c) Euler Solutions of Structural Index = 2 for Gravity Data.

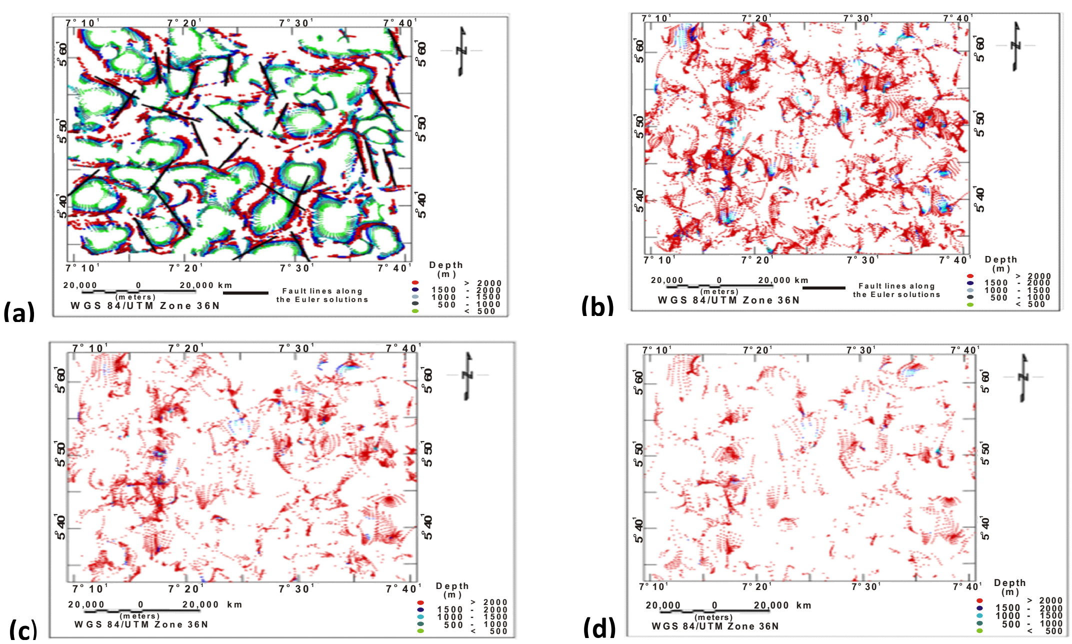

Figure 8: (a) Euler Solutions of the RTP Magnetic Map of Structural Index = 0. (b) Euler Solutions of Structural Index = 1. (c) Euler Solutions of Structural Index = 2. (d) Euler Solutions of

Structural Index = 3 for Magnetic Data.

It is obvious that, the depth values of the fault structures or contacts structures obtained from both Euler deconvolution of gravity and magnetic data in the study area ranging from minimum depth value of less than 500 m to maximum depth value of more than 2000 m, and the subsurface lineaments and fault structures are oriented in different directions such as NE - SW, E – W, and NW – SE, taking the trends of the Anambra Basin.

For the gravity data, the 3-D gravity modeling was embarked upon by using ten iterations until the fitting between the observed and calculated gravity data occurred with error percentage lower than 0.5 percent (Figure 9a–c). The most significant results of the final 3-D gravity model are deliberated here unit-wise in connection with the existing geophysical results of the study area and the adjacent regions. Firstly, the topographic surface is ranging from minimum value of about 310 m in the northeastern parts of the studied area to maximum value of about 610 m in the southern and eastern parts (Figure 10a). Secondly, the upper crust (The depth to the basement surface), is considered here at the bottom of the sedimentary layer. The basement relief of gravity map (Figure 10b) clears that the depth of the basement surface is equal to 2600 m which represents the shallow depth and is in the northeastern part of the studied area and the deeper basement surface with depth values about 3000 m below the sea level toward the southeastern and southwestern parts of the study area.

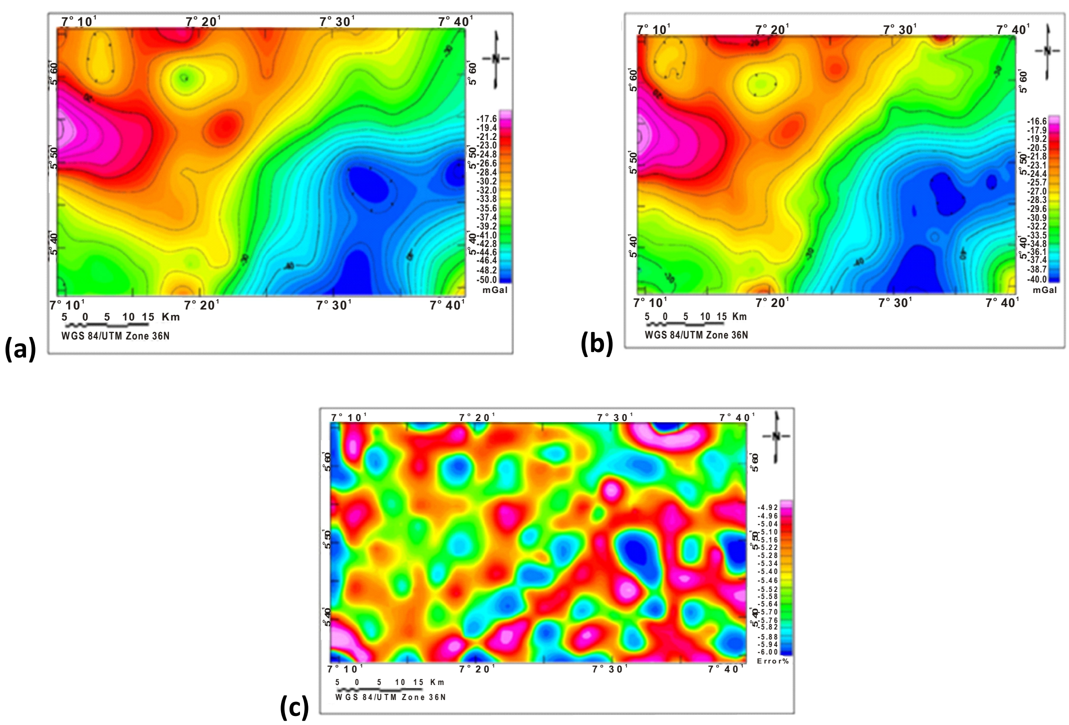

Figure 9: (a) Observed Gravity Anomaly. (b) Calculated Gravity Anomaly. (c): Error Percentage

In general, the thickness of the basement layers increases towards the southern part of the study area. The Figure 11 portrays the 3-D gravity modeling of the basement surface of the study area.

Thirdly, the middle crust (Conrad surface), shows the top of the oceanic crust with relatively depths ranging from 3918 and 5850 m (Figure 10c). Fourthly, the lower crust surface (Moho surface), (Figure 10d) is relatively ranging from 26900 to 32000 m in the study area.

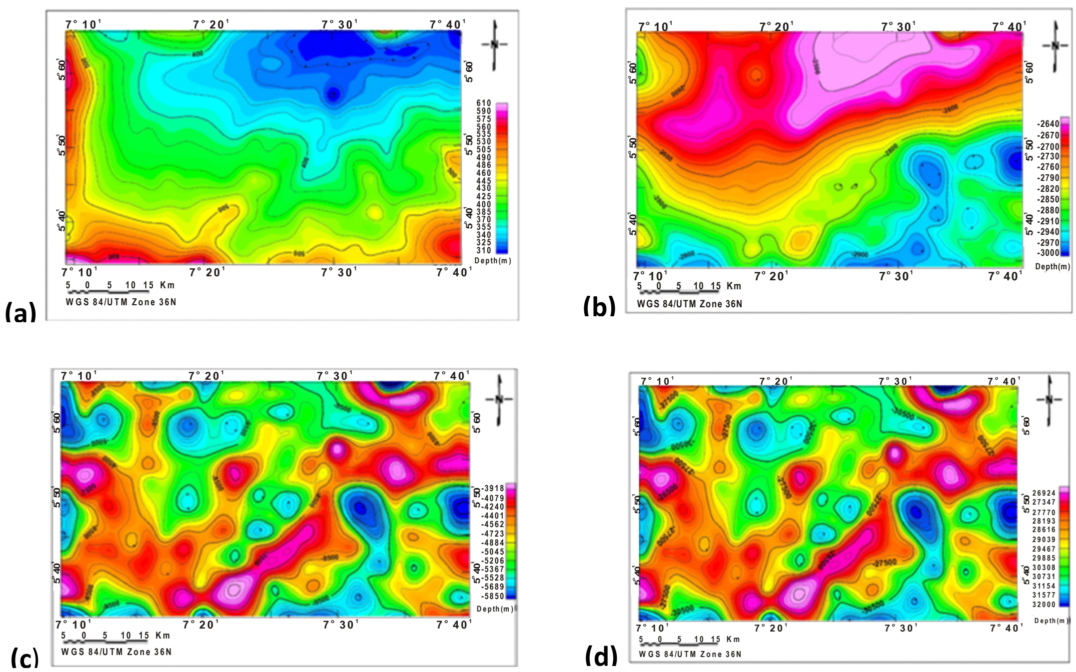

Figure 10: (a) Observed Gravity Anomaly. (b) Calculated Gravity Anomaly. (c): Error Percentage

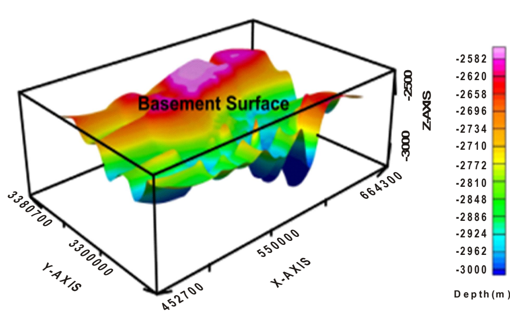

Figure 11: 3-D Gravity Modeling of the Basement Surface of the Study Area.

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In this work, for the magnetic data, the 3-D magnetic modeling was embarked upon by using ten iterations until the fitting between the observed and calculated magnetic data occurred with error percentage lower than 5 percent (Figure 12a–c). The obtained results indicate that the two main parts of the final 3-D magnetic modelling (Figure 14b) are topographic surface as shown in Figure 13a and the upper crust (the depth to the basement rocks) as shown in Fig. 13b. Firstly, the

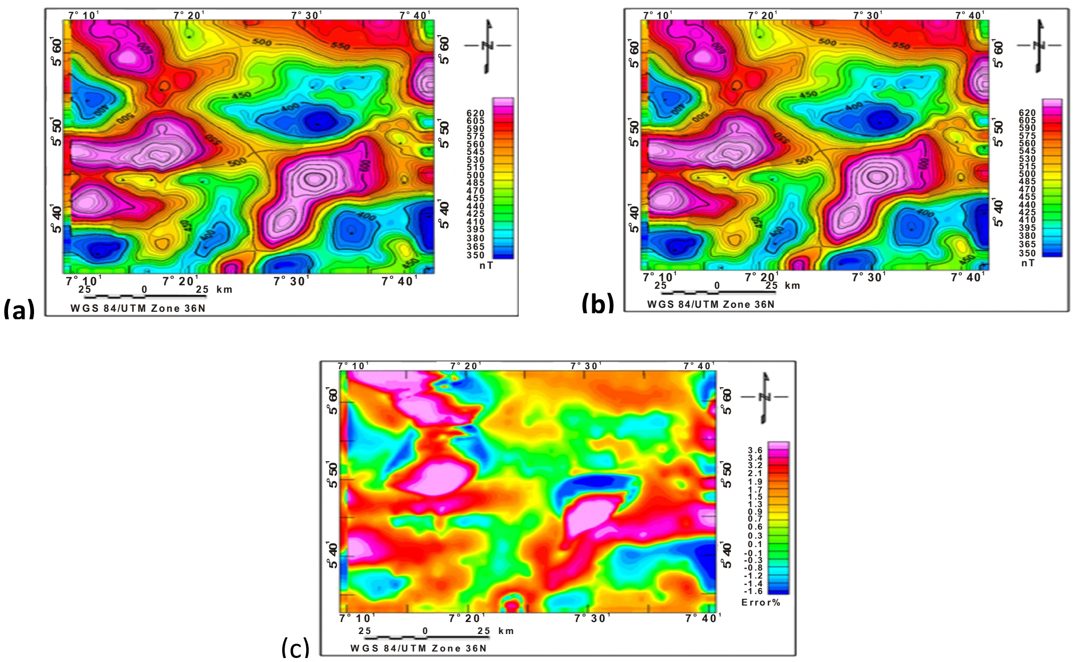

Figure 12: (a) Observed Magnetic Anomaly. (b) Calculated Magnetic Anomaly. (c) Error Percentage.

topographic surface (Figure 13a) ranges between 140 m in the northern and northeastern parts and 950 m in the central, southwestern parts of the study area, forming high topographic features. Secondly, the upper crust (the depth to the basement rocks), from the analysis of the depth to the basement surface map in the studied area (Figure 13b) we can note that the depth of the shallow basement surface located in the northwestern and central parts of the study area approximately equals to 2500 m, below the sea level.

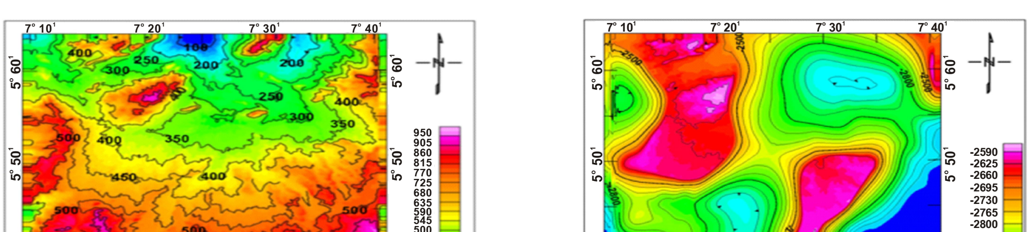

Figure 13: (a) Surface Topographic Map of the Study Area. (b) Basement Relief Magnetic Map, below the Sea Level of the Study Area.

While the deep basement surface is concentrated in the eastern, southwestern, and northeastern parts of the study area relatively equals to 3000 m. From the results of the depth to the basement we can deduce that the thickness of the sedimentary cover ranges from 2500 m in northwestern and central parts and 3000 m in southeastern and southwestern parts. Figure 14a shows the 3-D magnetic modeling of the basement surface of the study area Figure 14b portrays the final 3-D magnetic modeling of the study area.

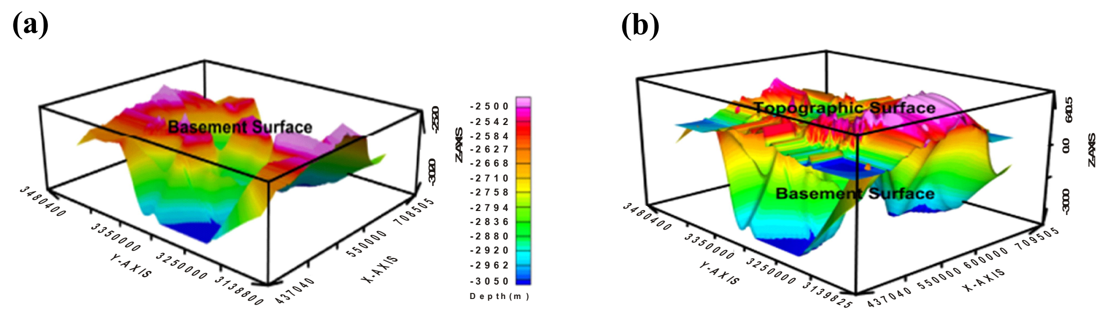

Figure 14: (a) 3-D Magnetic Modeling of the Basement Surface of the Study Area. (b) Final Three-dimensional (3-D) Magnetic Modeling of the Study Area

The RTP aeromagnetic, Bouguer gravity maps and filtered gravity and magnetic anomaly maps, (Figures 2b, 3, 5 and 6) were applied to figure out the general structural trends in the studied area, by using Linsser (1967) technique which state that mapping the structural trends by following lineation in magnetic contour represent the most useful geological applications of magnetic surveys. In some situations, the lineation reflects the strike lines of extended intrusive features, or the surfaces of large faults reflected in the basement topography. Such features are hidden under sedimentary layers and show up only on the magnetic maps.

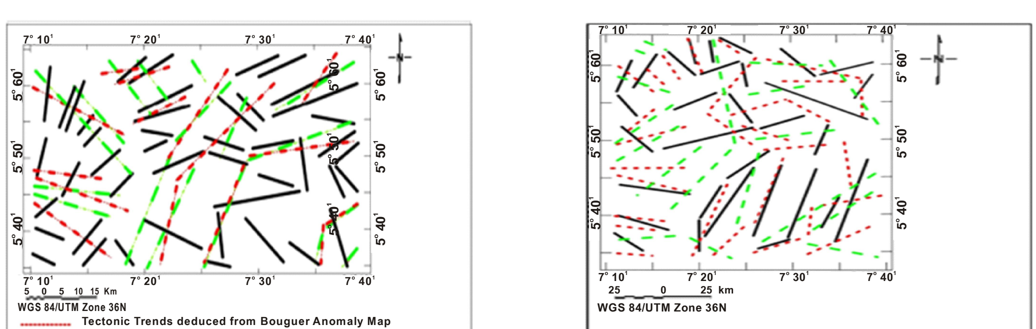

Figure 15: (a) A Map Showing Tectonic Trends Deduced Bouguer Anomaly Map, Residual Gravity Filtered Map and Regional Gravity Filtered Map. (b) A Map Showing Tectonic Trends Deduced RTP Aeromagnetic Map, Residual Magnetic Filtered Map and Regional Magnetic Filtered Map.

The deduced structural maps (Figure 15a and b) represent the fault system dissecting the area. The deduced fault planes of the different directions are grouped every 10 around the north for their length percentage L% and represented by Rose diagrams. The results of fault system deduced from both magnetic map, gravity and filtered magnetic and gravity anomaly maps, were represented in the form of rose diagram as shown in (Figures 16a and 16b).

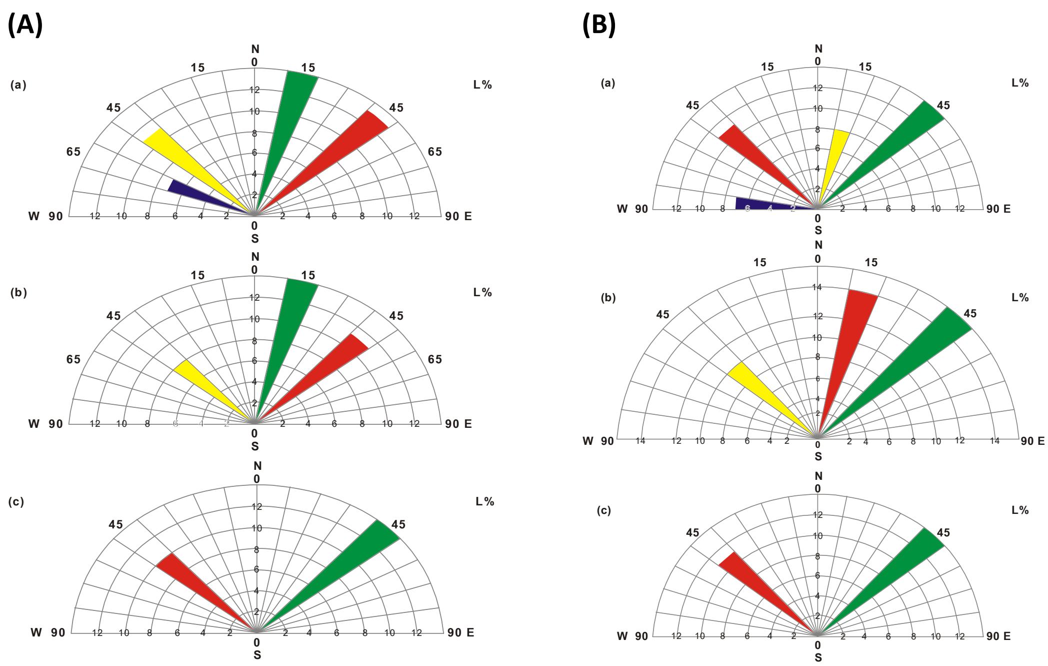

Figure 16: A: (a) Rose Diagrams Deduced from: (a) Bouguer Anomaly Map. (b) High Pass Gravity Filtered Map. (c) Low Pass Gravity Filtered Map. B: (a) Rose Diagrams Deduced from: (a) RTP Aeromagnetic Map. (b) High Pass Magnetic Filtered Map. (c) Low Pass Magnetic Filtered Map.

Results indicate that, most of the prevailing directions are N 45^o E. This trend is the most predominant direction in the studied area according to its characteristics making a mean strike of N 45^o E. This trend has a strong relation to trends deduced from the Bouguer anomaly maps and the RTP magnetic maps. The second prevailing trend is N 45° W with minor variation in the N 15° E, and E-W directions.

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