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# Structural interpretation of the Afikpo sub-basin: evidences from airborne magnetic and Landsat ETM data

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**ABSTRACT**

This paper presents the structural analysis of Afikpo sub-basin using aeromagnetic and Landsat imagery. It was carried out to determine depth to the magnetic basement, delineate the basement morphology and relief, delineate the structural features associated with the basin and to infer the effects of such structures to the general tectonic history and basin geodynamics of the study area. The aeromagnetic and Landsat data were subjected to various image and data enhancement and transformation routines. Results of the study revealed that the dominant structural trend direction of the study area is in the NE-SW direction. Other lineament trend directions are in the N-S and E-W directions. The lineament density map revealed the presence of high density fracture zone around Afikpo and Ezi-Alayi, 8km SW of Afikpo. Results of the 2-D spectral analysis revealed a two layer depth model. The shallower magnetic source ($d_1$) has an average depth of 1.195km while the deeper magnetic source bodies ($d_2$) have an average depth of 2.660km.The shallower magnetic anomalies is as a result of basement rocks which intruded into the sedimentary rocks while, the deeper magnetic anomalies is associated with intra-basement discontinuities like faults. Finally, the average sedimentary thickness of 2.660km estimated in the study area is unfavourable for hydrocarbon generation. The study area is rather favourable for quarrying and Pb/Zn exploration based on the presence of Dolerite Sill which has galena as an associated ore.



## Introduction

The contributions of airborne surveys including aeromagnetic and remote sensing in the interpretation of linear features and other geological structures have been tremendous; especially within the last decade. This past decade has witnessed a paradigm shift from the interpretation of basement structures to detailed studies with respect to both lithologic and morphologic variations. Magnetic anomalies are major precursor of mineralization, especially along fault planes. The magnetic anomaly signature characteristics are results of one or more physical parameters such as the configuration of the anomalous zone, magnetic susceptibility contrasts as well as the depth to the anomalous body. The broad magnetic closures seen on the total magnetic intensity anomaly maps are often due to changes in the rock composition within the basement. If the magnetic units in the basement occur at the basement surface, then depth determinations will map the basin floor morphology. Depth to basement, faults in the basement surface, and the relief of the basement surface have direct relevance to the depositional and structural history of the area (Gunn, 1997). The trend of basement faults and structure is frequently the main determinant of the primary fractures that develop to accommodate basin extension. In many sedimentary basins, magnetic anomalies arise from secondary mineralization along fault planes, which are often revealed on aeromagnetic maps as surface linear features. Most mineral deposits are therefore related to some type of deformation of the lithosphere, and most theories of ore formation and concentration embody tectonic or deformational concepts (O'Leary et al., 1976; Ananaba and Ajakaiye1987). Some lineament patterns have been defined to be the most favourable structural conditions in control of various mineral deposits. They include the traces of major regional lineaments, the intersection of major lineaments or both major (regional) and local lineaments, lineaments of tensional nature, local highest concentration (or density) of lineament, between echelon lineaments, and lineaments associated with circular features. Linear features are clearly discernible on aeromagnetic maps and often indicate the form and position of individual folds, faults, joints, veins, lithologic contacts, and other geologic features that may lead to the location of individual mineral deposits. They often indicate the general geometry of subsurface structures of an area thereby providing a regional structural pattern. On the other hand, the use of satellite imagery for regional mapping of geologic units and structures has long been demonstrated as a vital tool for regional geologic mapping. This is as result of its ease of operation, speed, accuracy, low cost and coverage. Interpretation of satellite imagery has found application in producing new geologic maps as well as revision of old ones. Also, in the area of hydrogeology, the importance of satellite imagery is heavily felt in the search for potable water especially within areas underlain by the basement complex.

This research work presents an aeromagnetic and Landsat based geological interpretation of the Afikpo sub-basin. The objectives are to determine the basement depth, establish the

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basement topography and relief; determine the structural and tectonic features associated with the basin and to infer the effect of such structures on basin geodynamics.

**Background geology**

The Afikpo Basin (fig.1), like other southern Nigerian sedimentary basins, was consequent to the evolution of the Southern Benue Trough (Murat, 1972; Nwachukwu, 1972; Olade, 1975; Burke et al., 1972). The Benue-Abakaliki Trough originated as an arm of the triple junction rift-ridge system that initiated the separation of South America from Africa in the Aptian/Albian (Burke et al., 1972; Weber and Daukoru, 1975; Obi et al., 2008). The separation of the South Atlantic had reached the Gulf of Guinea and extended north-east to form the Benue-Abakaliki Trough (aulacogen) in the early Albian (Stoneley, 1966).

The development of the mega-tectonic framework of the Cretaceous Southern Benue Trough is sub-divided into two main phases separated by the Santonian orogeny (Murat, 1972; Burke et al., 1972). Prior to the latter event, sedimentation occurred along a narrow NE-SW trending fault-bound “Abakaliki Trough” with its south-eastern and north-western boundaries co-incident with the extensions of the oceanic Charcot and Chain Fracture Zones, respectively (Benkhelil et al., 1982, 1989; Popoff, 1988). The Chain Fracture Zone also coincided with the Benin Hinge Line (Zarborski, 1998). A broad stable area, the Anambra Platform, lay west of the “Abakaliki Trough” and was bounded by the Benin Hinge Line to the west (Murat, 1972). A corresponding stable area, the Ikpe Platform, lay east of the “trough” and separated the latter from both the Oban Massif and the calabar flank (Zarboski, 1998; Nwajide, 2004).

The “Abakaliki Trough” was flexurally inverted into the Abakaliki Anticlinorium during the Santonian folding. The anticlinorium forms the southern extension of an axial ridge which runs from the Hawal Massif in the NE southwards through the Kaltungo inliers to Gboko in the middle Benue from where it shifted southwest as the Abakaliki anticlinorium (Zarboski, 1998). The flexural inversion of the “trough” led to the development of the Anambra Basin from the Anambra Platform and the Afikpo Basin from the Ikpe Platform.

The development of the Anambra and the Afikpo Basins coincided with spasmodic basin subsidence in the Cretaceous Southern Benue Trough high in the Pre-Albian, low in the early Cenomanian and very high in Turonian (Ojoh, 1990; Nwajide, 2005). These movements were coincident with the marine transgressive-regressive episodes in the Southern Benue Trough. The Anambra Basin was filled with about 2,000m Campano-Maestrichtian sediments (Murat, 1972; Zarboski, 1998). The Afikpo Basin located south-east of the Abakaliki Anticlinorium, was filled with Cretaceous-Tertiary sediments estimated at between 1,000 and 8,700m (3,500m average) (Reyment, 1965; Agagu et al., 1985; Uzowuru, 2011).

The two basins (Anambra and Afikpo) are not contiguous having been separated by the Hawal-Kaltungo-Gboko-Abakaliki anticlinorial ridge. Each basin had its delimiting basinal boundaries (Benkhelil et al., 1989) and could not be the same as suggested by Nwajide (2006).

**Theory and method**

The data used in this research work are airborne aeromagnetic map obtained from the Geological Survey of Nigeria (GSN) and the seven-band Landsat 5 TM imagery acquired on 29th March 2011. Both systems are used in providing quick, fast, and cost-effective reconnaissance survey of a study area.

The aeromagnetic data used were subjected to a low pass filtering operation. The nature of filtering applied to the aeromagnetic data in this study in the Fourier domain was chosen to eliminate certain wavelengths and to pass longer wavelengths. Several potential field software with different analytical modules were used in the interpretations of the aeromagnetic map. These include Geosoft Oasis Montaj 6.4.2.HJ version, U.S. Geological Survey Potential-Field geophysical software Version 2.0, Surfer 10 and Matlab 7.5. Regional - residual separation was carried out using polynomial fitting. This is a purely analytical method in which matching of the regionals by a polynomial surface of low order exposes the residual features as random errors. For the magnetic data, the regional gradients were removed by fitting a plane surface to the data by using multi- regression least squares analysis. The expression obtained for the regional field T(R) is given as:

$$T(R) = 7612.158 + 0.371x - 0.248y \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 1$$

The regional trend is represented by a straight line, or more generally by a smooth polynomial curve. The fitting of polynomials to observed geophysical data is used to compute the mathematical surface giving the closest fit to the data that can be obtained within a specified degree of details. This surface is considered to approximate the effect of deep seated or regional structures if it is of low degree.

Average depth values to buried magnetic rocks using the power spectrum of total intensity field were achieved using spectral analysis. These depths were 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 an ensemble of magnetized blocks of varying depth, width, thickness and magnetization. Most of the approaches used involve Fourier transformation of the digitized aeromagnetic data to compute the energy (or amplitude) spectrum. This is plotted on a logarithmic scale against frequency. The slopes of the segments yield estimates of average depths to magnetic or gravity sources of anomalies. Given a residual magnetic anomaly map of dimensions l x l, digitized at equal intervals, the residual total intensity anomaly values can be expressed in terms of a double Fourier series expression given as:

$$T(x, y) = \sum_{n=1}^{N} \sum_{m=1}^{M} P_m^n \mathrm{Cos}\left\{\left(\frac{2\pi}{l}\right)(nx + my)\right\} + Q_m^n\, Sin\left\{\left(\frac{2\pi}{l}\right)(nx - my)\right\} \ldots\text{------------}(2)$$

where, l = dimensions of the block, and is the Fourier amplitude and N and M are the number of grid points along the x and y directions respectively. Similarly, using the complex form, the two dimensional Fourier transform pair may be written as:

$$G(u,v) = \iint_{-\infty}^{\infty} g(x,y)\, e^{-j(u_x|+v_y)}\, dx\, dy \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

and

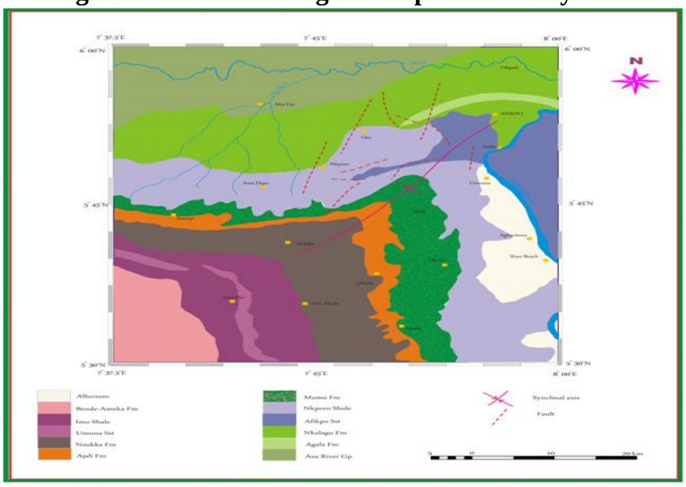
$$g(x,y) = \iint_{-\infty}^{\infty} G(u,v) e^{j(u_x+|v_y)}\, du\, dv \ldots\ldots\ldots\ldots (4)$$

where, u and v are the angular frequencies in the x and y directions respectively.

The use of this method involved some practical problems, most of which are inherent in the application of the Discrete Fourier Transform (DFT). These include the problems of aliasing, truncation effect or Gibb’s phenomenon and the problems associated with even and odd symmetries of the real and imaginary parts of the Fourier transform. However, in this research, these problems were taken care of by the software used in the analysis.

Other analytical methods used include Reduction-to-Pole, Second vertical derivatives and trend surface analysis 2-D spectral analysis. Reduction-to-pole (RTP) transformation was applied to the aeromagnetic data to minimize polarity effects (Blakely, 1995). The RTP transformation usually involves an assumption that the total magnetizations of most rocks align parallel or anti-parallel to the Earth's main field. Similarly, second vertical derivative filters were used to enhance subtle anomalies while reducing regional trends. These filters are considered most useful for defining the edges of bodies and for amplifying fault trends. Mathematically, a vertical derivative is shown as a measure of the curvature of the potential field, while zero second vertical derivative contours defines the edge of the causative body. Thus, the second vertical derivative is in effect a measure of the curvature, i.e., the rate of change of non- linear magnetic gradients. The zero magnetic contours of the second vertical derivative often coincide with the lithologic boundaries while positive and negative anomalies often match surface exposures of the mafic and felsic rocks respectively.

**Fig.1. GIS-based Geological Map of the Study area**



Finally, Landsat Thematic Mapper (Landsat-TM) imagery acquired on 29/03/2011 from NASRDA, Nigeria was used to map linear structures in the study area. The raw data was geo-referenced using the coordinates of the topographic sheets in the study area. The geo-reference projection was carried out using the Universal Tranverse Marcator (UTM). Image processing, enhancement and analysis were carried out using ILWIS 3.1 Academic software. Image enhancement operations carried out on the imagery include contrast stretching, spatial filtering and edge detection. Also, ArcView 9.3 software was used to extract the lineaments and carry out statistical analysis of the interpreted lineaments in the area.

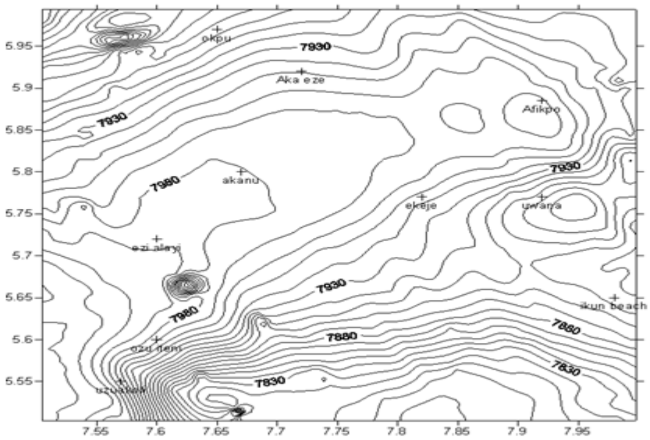



**Fig.2. Total Magnetic Field Intensity Contour Map of the Study area**

## Results and interpretation

The aeromagnetic data used in this work is obtained from the Geological survey of Nigeria being part of the nationwide survey completed in 1976 by Fairey Survey Ltd. Flight line direction was NNW-SSE at station spacing of 2km with flight line spacing of 20km at an altitude of about 150m. Tie lines were flown in an ENE-WSN direction. Regional correction of the magnetic data was based on the IGRF (epoch date1 of January, 1974). For this study, aeromagnetic sheet 313 was used. The aeromagnetic map was digitized along flight lines at 2km intervals. The regional gradients were removed by fitting a plane surface to the data by multi- regression least squares analysis. Fig.2 is the total field aeromagnetic data of the study area as a contour map, while figures 3 and 4 are the shaded relief and 3-D surface maps of the total magnetic field intensity. The total field of the aeromagnetic data is characterized by high magnetic anomalies with intensity range of 7990 to 8030 gammas of NE-SW trending direction. This configuration may be attributed to a tabular concordant plutonic basement structures.

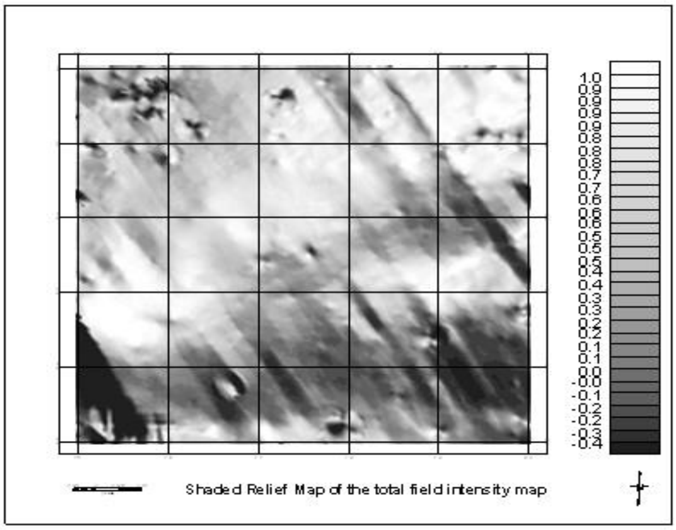



**Fig.3. Shaded Relief Map of the Total Magnetic Field of the study area showing magnetic basement relief**

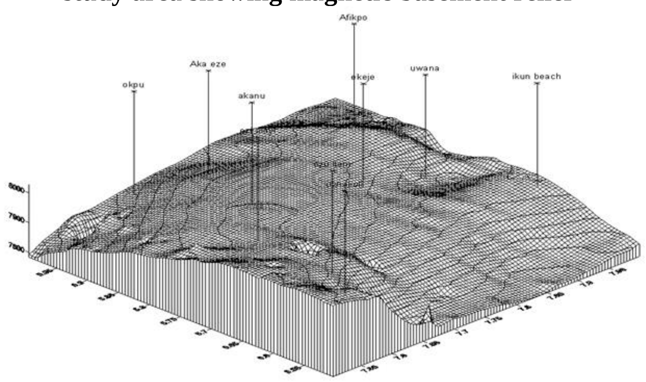



**Fig.4. Total field of the aeromagnetic data presented as 3-D map showing the basement topography**

The wireframe map revealed a quiet, spike-less uplifted topography underlying Afikpo, Akanu, to Ezi Alayi; and downgraded topography seen under Okpu, NW of Afikpo and Ikun beach, south of Afikpo. Both short and long wavelength magnetic anomalies were interpreted on the study area. Areas with high intensity were observed in the central portion of the map, around Afikpo and Ezi Alayi. The absence of spiky topography and high magnetic anomalies within the Afikpo-Akanu to Ezi Alayi area suggest the presence of Dolerite Sill, which must have intruded along the bedding plane of the country rock. The presence of associated ore, galena may be suspected. Galena, which either occurs as metasomatic cavity in limestone or as epigenetic hydrothermal deposits along fault plane may have been deposited following the dolerite intrusion. In the study area the later occurrence may hold because the remobilization of basinal hydrothermal brine has been reported previously (Akande and Mucke,1989 ). The presence of brine springs within the study area may be interpreted from Okpu, south and NW of Afikpo, based on their low magnetic anomalies of intensity range of 7790 to 7820 gammas.

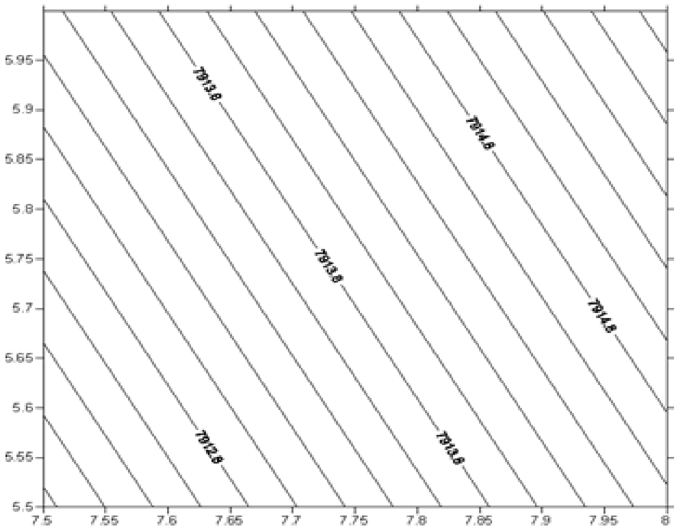



**Fig.5. First (polynomial) surface of the Regional fields of the Aeromagnetic data**

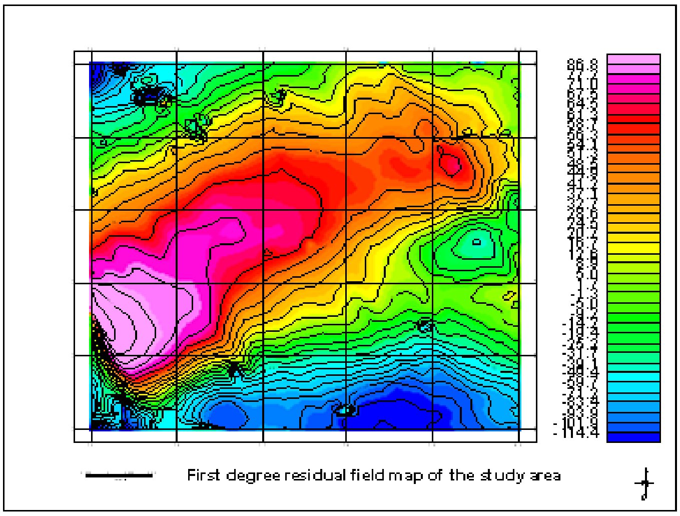



**Fig.6. First Degree (polynomial) surfaces of the Residual fields of the Aeromagnetic data**

Figures 5 and 6 respectively represent the first degree regional and residual maps of the study area. The Analytical signal map and the Reduction-to-Pole (RTP) aeromagnetic data, computed from the grid of total-field magnetic data are shown in Figs.7 and 8. The zero contours of the second vertical derivatives indicated the lithologic boundaries between the different formations, while, the distribution of mafic and felsic rock forming minerals were correlated to the colour-coded positive and negative second vertical derivative anomalies around Afikpo area (Fig.9).

Spectral analysis of the aeromagnetic data was done using software that runs on MATLAB 7.0, developed by Odegard and Berg (1965). For the spectral determination of depths to layers of magnetization, the study area was divided into four (4) blocks containing 14×14 data points. In doing this, adequate care was taken so that essential parts of each anomaly were not cut by the blocks. In order to achieve this, the blocks were made to overlap each other. The estimated depths to magnetic basement are shown as $D_1$ and $D_2$ (table 1). The first layer depth ($D_1$), is the depth to the shallower source represented by the second segment of the spectrum. This layer ($D_1$) varies from 0.235km to 1.848km, with an average of 1.195km. The second layer depth ($D_2$) varies from 0.518km to 4.136km, with an average of 2.660km.The basement depth (sedimentary thickness) contour map of the study area is shown in fig. 10.

**Table 1: Location and Magnitude of First and Second Layer Spectral Depths.**

| Spectral sheets | Longitude | Longitude | Latitude | Latitude | Estimated depths(KM) | |
|---|---|---|---|---|---|---|
| | X1 | X2 | Y1 | Y2 | D1 | D2 |
| SP1 | 7.50 | 7.75 | 5.50 | 5.75 | 1.723 | 4.136 |
| SP2 | 7.50 | 7.75 | 5.75 | 6.00 | 0.973 | 1.849 |
| SP3 | 7.75 | 8.00 | 5.50 | 5.75 | 0.235 | 0.518 |
| SP4 | 7.75 | 8.00 | 5.75 | 6.00 | 1.848 | 4.136 |

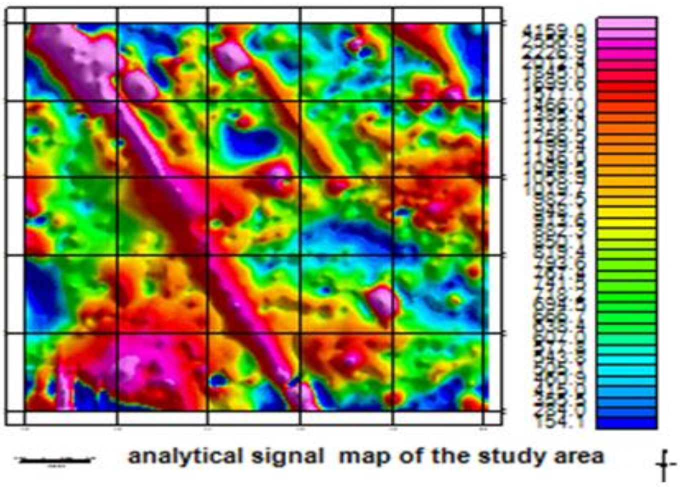



**Fig.7. Analytical Signal map of the Study area**

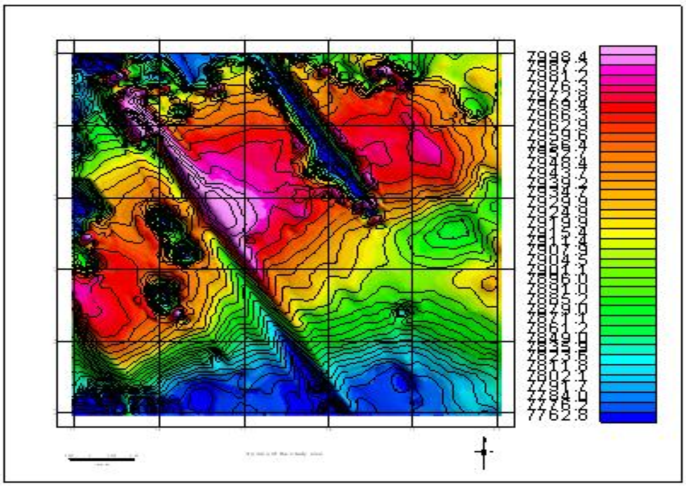


**Fig.8. Reduction to Pole contour map of the aeromagnetic data of the study area**

The local anomalies in the original aeromagnetic field map were modeled in terms of intrusions using non linear optimization techniques built in MATLAB 7.0 software. The method seek to minimize a non linear objective function which represents the difference between the observed and calculated fields through an iterative change of the non linear parameters (location, thickness and depth) by non-linear optimization while at the same time obtaining optimum values for the linear parameters (magnetization components, quadratic regional and composite magnetization angle) by least-square analysis. Graphical methods (Peter's, slope method, Hannel and Tiburg methods) were used in calculating depth estimates (fig.11) to the anomalous bodies.

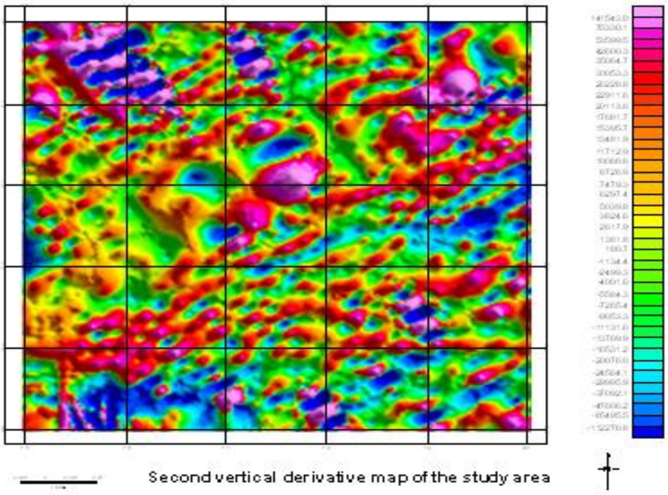



**Fig.9. Second vertical derivative contour map of the aeromagnetic data of study area**

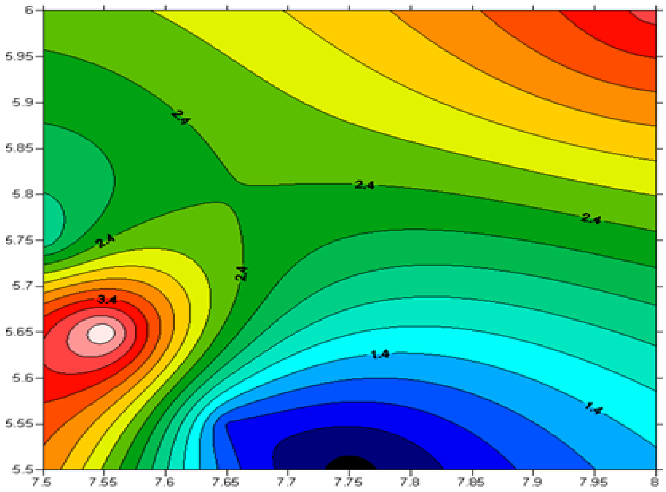



**Fig.10. Depth to basement (sedimentary thickness) map estimated from spectral inversion contoured in metres**

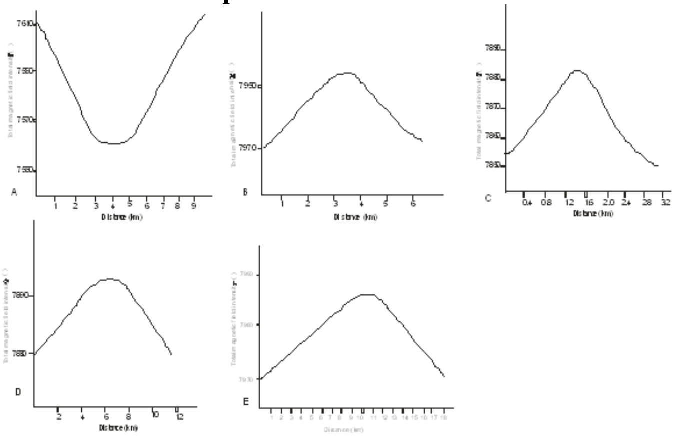



**Fig.11. Interpretation of some linear magnetic anomalies from Afikpo Sheet. Profiles A→E were taken as follows: Profile[A], 6.2Km South of Ehome Lake ; Profile[B], 4Km North-East of Afikpo ; Profile[C], 2Km North-West of Ishiagu. Profile [D], 11Km North-West of Ehome lake. Profile [E], 3Km South-East of Afikpo.**

Similarly, the susceptibility map of the aeromagnetic data was presented in figure 12. Filtering of magnetic data is used to enhance the data and to see features that would be difficult to detect without filtering. High susceptibilities are observed around Aba Omege and Ama Ekpu which could be interpreted as areas where metallic minerals may be found. Other areas with high susceptibility include Afikpo, Akanu and Ezi-Alayi. It will be recalled that rocks and minerals exhibit low magnetic susceptibilities.

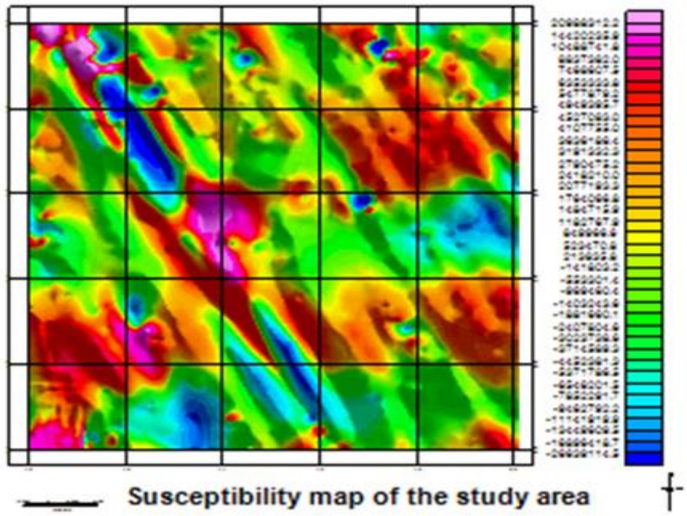



**Fig.12. Susceptibility map of the Study area**

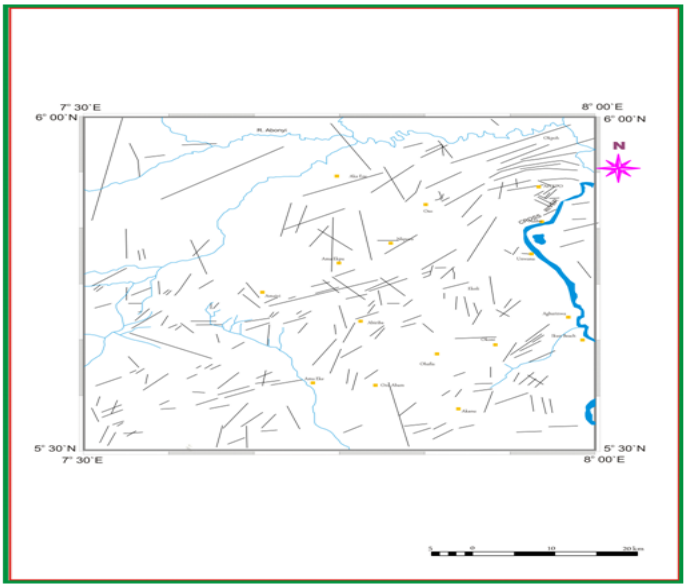



**Fig.13.Lineaments map of the Study area**

The processing of the Landsat TM imagery was done in way to help the image analyst perform the functions of image rectification, enhancement, transformation and classification of the data. For this research work, IDRISI 32 software and other appropriate modules in ILWIS 3.1 academic were used for the image enhancement. Two major filters were applied to the imagery using ILWIS 3.0 filter module: Laplace filter and edge enhancement filter. This was done to increase the spatial frequency of the imagery so as to enhance high frequency features, which would include fractures (lineaments). The edge enhancement filter image was observed to be more appropriate for this work. The interpreted lineaments (fig.13) were superimposed on the edge enhanced map to show the relationship between geological formations and structural features (fig.14).

Likewise, the lineament density map in figure 15 reveals a high density fracture zones at Afikpo and around Ezi-Alayi. The zones are thus interpreted because of the high density of lineaments seen within the area. Lineaments seen at Afikpo have almost the same trend. This implies that there was intense tectonic activity within those areas. A summary of the lineament trend direction was done using Rose diagram (fig. 16).

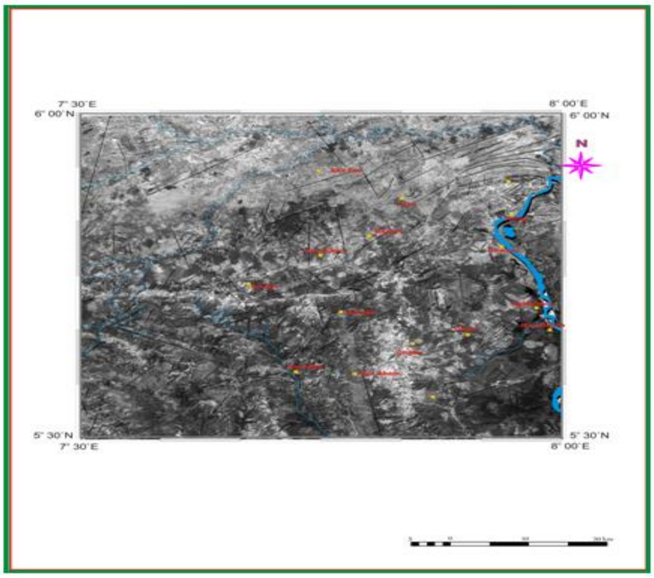



**Fig.14.Lineaments superimposed on Edge Enhanced Filtered Landsat ETM Image**

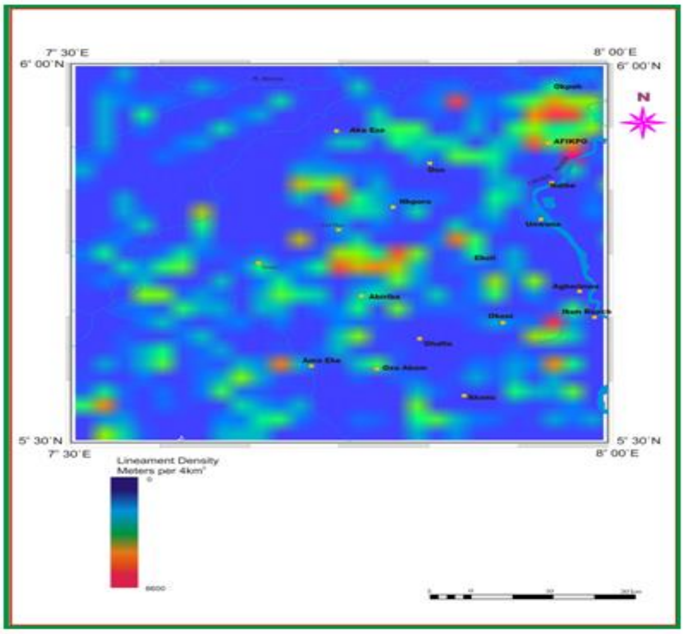



**Fig.15: Lineament Density map of the study area**

The Digital Elevation Model (DEM) (fig.17) was created by performing a colour shaded operation on Shuttle Radar Topographic Mission (SRTM) data. On the DEM, the highest topographic relief is represented by the light green linear feature seen in the central portion of the study area. The feature correlates to Ajali sandstone on the geological map. This is interpreted as a sandstone ridge which forms cap of the Enugu cuesta in some areas like Arochukwu. The slope of the ridge is identified where light green, yellow and red colours are closely packed together; representing a sudden change in topography from 228 to 50 metres. The slope is characterized by numerous streams, gullies and rivers. It will be correct to interpret the high topographic relief areas as characterized by sandstone and the low areas as shale and mudstone. This is justified by dendritic pattern of drainage evident in the low-lying areas (fig. 17), which supports an underlying clayey lithology. The sandstone is the watershed of the area under study. This drainage pattern reflects a marked structural control of drainage by faults. The major drainage, the Cross River channel has many lineaments which run along the channel. The aeromagnetic data and Landsat imagery were processed in such a way as to meet with the objective of this research. Recall, however that the objective of this study is to identify: lineaments and hence structures, trend of the structures, geomorphic changes, depth to anomalous bodies and to infer the effect of such structures on basin geodynamics. Lineaments can be identified with the following indicators: chains of lakes, elongated lakes, promontories or embayments in lake shore-lines that suggest fault location, changes in stream appearance and direction, constant direction for a stream over a kilometer or more and fault scarps. Lineaments quantification and statistical analysis were done regarding the orientation frequency of these lineaments to construct a rose diagram. The rose diagram revealed three major trends: NE-SW, ENE-WSW and E-W. However, several other trends are observed which have low frequency on the diagram. The dominant NE-SW trend reflects the younger tectonic events. Similarly, subsurface linear structures identified in study area from polynomial surfaces (first - fourth degree regional and residual maps) revealed tectonic features with principal trend directions in the NW-SE, NE-SW, E-W, and to a lesser extent N-S directions. The predominant NE-SW, ENE-WSW fault trends would so have played an essential role in the control of the geodynamic evolution of the region.

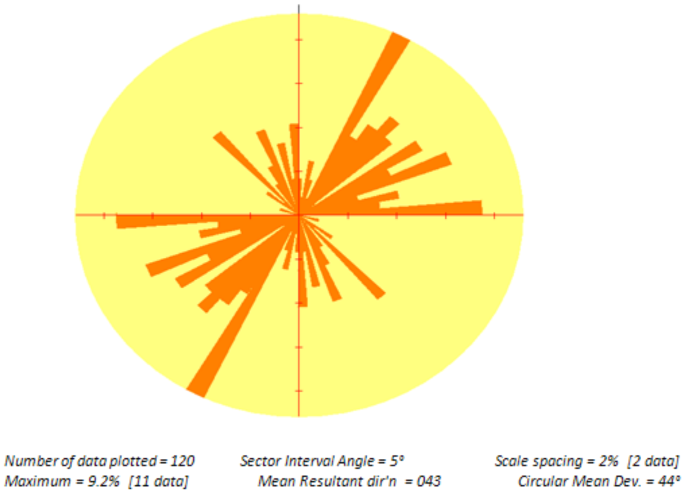



**Fig.16. Azimuth Frequency (Rose) diagram of the study area**

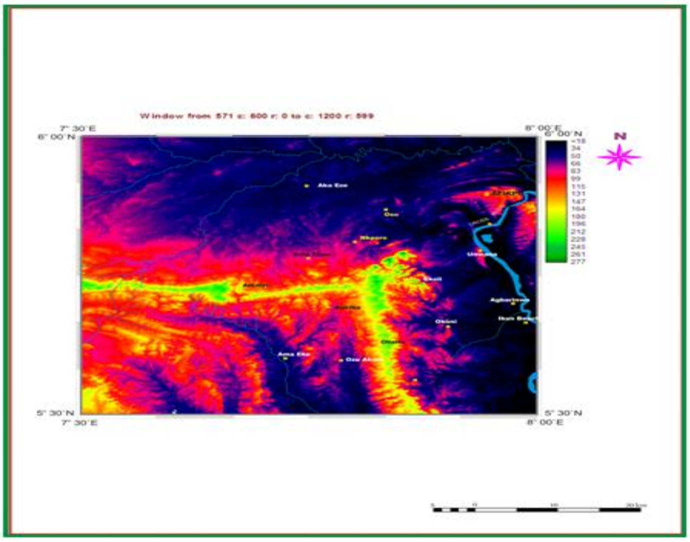



**Fig.17.Digital Elevation Model (DEM) of the study area**

## Discussion and conclusion

The second layer depth ($D_2$), obtained from the spectral plots represent the average depths to the basement complex in the blocks considered. It varies from 0.518km to 4.136km, with an average of 2.660km. This layer may be attributed to magnetic rocks intruded onto the basement surface. Another probable origin of the magnetic anomalies contributing to this layer is the lateral variations in basement susceptibilities, and intrabasement features like faults and fractures (Kangoko et al.,1997). Depth to source interpretation of aeromagnetic field data provides important information on basin architecture for both petroleum and mineral exploration mapping for areas with shallow basement. Magnetic basement is an assemblage of rocks that underlies sedimentary basins and may also outcrop in places. If the magnetic units in the basement occur at the basement surface, then depth determinations for these will map the basin floor morphology, relief and structure (Onyedim et al., 2006).

Economically, the basin has low petroleum potential because the average sedimentary thickness of 2.660km is very thin for entrapment of crude oil. Another reason put up is that high magnetic anomalies may be associated with igneous and/or metamorphic rocks which have high susceptibility than sedimentary rocks. This implies that the temperature accompanying tectonic activity in the area must have cooked the source rock, if any beyond the oil window phase of maturation. Therefore, the study area will be viable for magnetic mineral exploration and quarrying of dolerite for construction industries. Galena which occurs as an associated ore with dolerite may be explored from the plutonic rock present.

The Dolerite Sill intrusion which lays concordantly over the Ezeaku Shale implies that the accompanying tectonic activity or deformation occurred during the Santonian deformation. This obviously marks the end of transgressive –regressive phase of Turonian- Santonian period of deposition (Nwachukwu, 1975; Olade, 1978).

The interpretation of Landsat imagery and aeromagnetic data of the study area reveals that the area has a dominant NE-SW trend which reflects the basin. The high magnetic intensity observed around Afikpo and Ezi-Alayi suggests the existence of a relatively deep-seated basement structure. The presence of the deep-seated structure in the study area confirms that area has been subjected to both regional stress and strain fields. This is evident by the faults and fold axes of the anticlinal fold interpreted from the area, which has dominant NE-SW trend. The edge enhanced map (fig.14) obtained for the area is dissected by many faults, which have different directions indicating a complex tectonic history and several events of deformation.

An updated GIS based geologic map (fig.1) of the study area was developed by using the colour composites and DEM of the area. This map shows a better representation of the formations.

The present study is therefore in agreement with previous studies which suggested that Nigeria has a complex network of fractures and lineaments with dominant trends of NW-SE, NE-SW, N-S and E-W directions. These linear structures running NE-SW observed from the study are suggested as the continental extension of the known pre-Cretaceous oceanic fracture zones viz. Charcot and Chain fracture zones which run along the trough axis beneath the sedimentary cover (Ananaba, 1991). Therefore, the structural and tectonic facts put in were in accordance with those of previous workers.

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