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Structural-depth analysis of the Yola Arm of the Upper Benue Trough of Nigeria using high resolution aeromagnetic data

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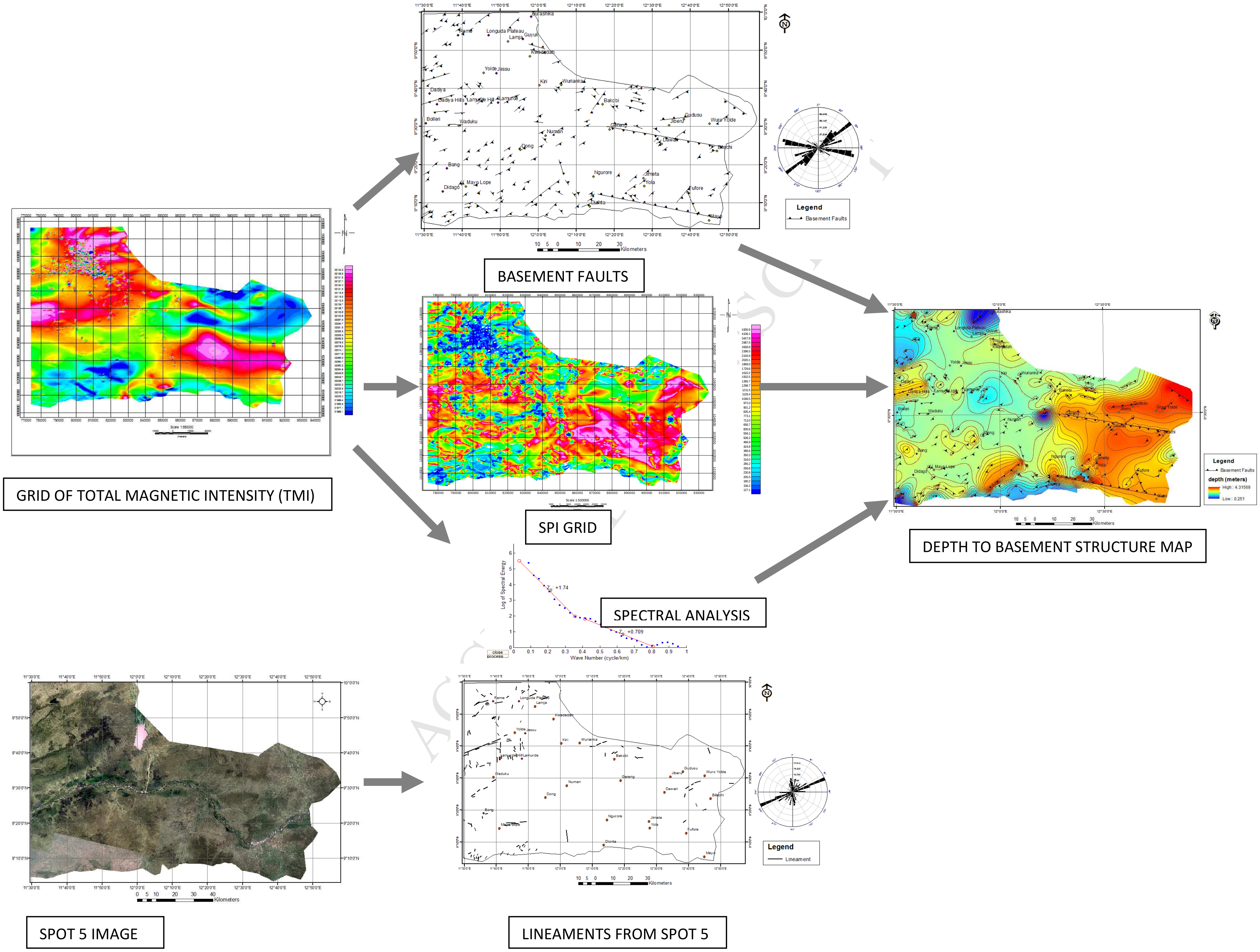
GRID OF TOTAL MAGNETIC INTENSITY (TMI)
BASEMENT FAULTS
SPI GRID
SPECTRAL ANALYSIS
DEPTH TO BASEMENT STRUCTURE MAP
SPOT 5 IMAGE
LINEAMENTS FROM SPOT 5
Legend
Basement Faults
depth (meters)
High : 4.31569
Low : 0.251
Lineament
Log of Spectral Energy
Wave Number (cycle/km)
Kilometers

Structural-Depth Analysis of the Yola Arm of the Upper Benue Trough of Nigeria Using High Resolution Aeromagnetic Data

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ABSTRACT

The Yola Arm is the east-west trending part of the Upper Benue Trough made up of Cretaceous sediments that are Albian to Maastrichtian in age. This work involves interpreting satellite imagery and aeromagnetic data to map out structures within the basin and estimate the depth to the magnetic basement which could be an aid to further exploratory work in the basin. The SPOT 5 imagery covering the basin was processed and interpreted and lineaments extracted from it. The digital elevation model (DEM) of the area was also used to extract the drainage pattern of the area and as an aid in mapping the lineaments that are visible on the surface. The geomagnetic field of the earth was removed from the aeromagnetic data using the IGRF-12 model. The vertical derivative (VDR) enhanced the high frequency and short wavelength components of the data which could be volcanics. The source parameter imaging (SPI) technique which works well at all magnetic latitudes and the spectral analysis were applied to the data to estimate the sediment thickness within the basin. A low pass filter with a cut-off wavelength of 1000 meters was applied to the data to remove the high frequency short wavelength component of the data after which the tilt derivative (TDR) was computed to enhance anomalies that may be faults on the underlying basement. The lineaments from the SPOT 5 data show a predominant NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W trends and the TDR of the aeromagnetic data show a predominantly NE-SW trend which is the predominant trend in the Benue Trough while a few strike in the N-S,NW-SE, and WNW-ESE direction. This suggests that the basin was subjected to several stress regimes. Differential uplift of the basement fault blocks may have given rise to drape folds observed in the overlying sediments. The depths to the magnetic basement range from about 1 km to about 4.3 km with the deepest part in the eastern part of the Basin. The depth analysis indicates that the Cretaceous sediments are thick enough to generate hydrocarbons.

Keywords:- SPOT 5, GIS, Aeromagnetic data, Faults/Lineaments, Geology

1.0 Introduction

The Upper Benue Trough (Fig 1) of Nigeria is comprised of three basins: the east–west trending Yola Basin (Yola Arm), the north-south trending Gongola Basin (Gongola Arm) and the northeast-southwest trending Lau Basin (Main Arm). The Benue Trough is itself a product of the West and Central African Rift System in which it opened as a broad strike-slip fault system. The continents (South America, Africa, Arabia, Madagascar, India, Australia and Antarctica) are thought to have been one super continent called Gondwanaland and the relative movement of the continental plates resulted in the formation of a triple junction where only two arms of the junction opened into the ocean and the third arm did not. The Benue trough is thought to be the failed arm of the triple junction which also led to the separation of the African and the South American plates (Burke et al 1970). This present work is an attempt to understand the structural framework and the geometry of the basin which can be an aid to further exploratory efforts in the basin. It involves processing and interpreting high resolution magnetic data collected at 400 meters flight line spacing by Fugro Airborne surveys which is an improvement on past interpretations that were done with the old data that was collected in 1972 at 2 km flight line spacing. This improvement in data quality will give a better understanding of the basin and also give more accurate depth to basement values. This study is aimed at showing the effectiveness of integrating remote sensing, magnetic and other ancillary data within a GIS for geological/structural studies. When interpreting aeromagnetic data, it is necessary to compare structures or magnetic anomalies delineated from the derivatives with the surface features as can be seen from aerial photographs or satellite images. Remote sensing has become a widely accepted research tool by geologists the world over. It gives the overview required to construct regional unit maps, useful for small scale analyses, and planning field traverses to sample and verify various units for detailed mapping. It is also used to understand the spatial distribution and surface relationships between rock units. For this study SPOT 5 image with a spatial resolution of 5 meters was used. Satellite imagery can give us a picture of the surface where outcrops and features such as dykes can be observed. Also rock units and geological structures often show a strong correlation with relief and can be mapped with a detailed topographic analysis. Digital Elevation Models (DEM) are used for such analysis to derive topographic attributes such as elevation, slope, aspect, shaded relief, drainage network, etc with the aid of a Geographic Information System (GIS).

Magnetic data interpretation can be used to establish the relationship between basement tectonics and the overlying structures within the sediments. The 1st vertical derivative is a vertical gradient method that uses a Fast Fourier Transform (FFT) to enhance the high frequency component of a magnetic field made up of intrusives and volcanics while suppressing the low frequency content which is due to the regional field. The tilt-derivative (TDR) is a powerful method because of its peculiar characteristics and it was used to enhance the basement faults. It attempts to equalize the amplitude output of TM anomalies across a grid. All other derivatives have an amplitude response that is closely linked to the amplitude of the TMI anomaly but the TDR is independent of amplitude of the anomaly and are instead controlled by the reciprocal of the depths of the magnetic sources. It is also a good signal discriminator in the presence of noise. The Source Parameter Imaging (SPI) technique so called because all the parameters that make up the source which include depth, dip and susceptibility contrast are computed from the complex analytical signal was used for this study because the technique assumes only induced magnetization and works well at all magnetic latitudes which makes it a good choice for the Yola basin that is at low magnetic latitude. The spectral analysis method was also used for this study in order to compare with the estimates from the SPI because it has the advantage of being able to filter out noise from data without losing information during the process.

In the Northern Gulf of Mexico, Alexander (1999) integrated magnetic, gravity, seismic and refraction data to map out the geometry of the basement and was able to map out grabens and the horst structures within the basin and also identified the primary faults within the basement and the secondary faults in the overlying sediments. In the past, interpretations of magnetic data was done using data with a 2 km flight line spacing that can only resolve structures of > 4 km resolution but recent data acquired can resolve structures as low as 400 meters which will give a better interpretation of the basin. Understanding the deformation that occurred within the basement can help understand the resultant deformation and stratigraphy of the basin. This present work attempts to interpret aeromagnetic data with the aid of ancillary data such as satellite imagery and digital elevation model (DEM) to map out the basement geometry and structures within the basin which can be an aid for further detailed exploratory work.

2.0 Geological setting

The area of study forms part of the Upper Benue Trough of Nigeria (fig 1) which is a product of the West and Central African Rift System where it opened as a broad strike-slip fault system (Binks and Fairhead 1992).

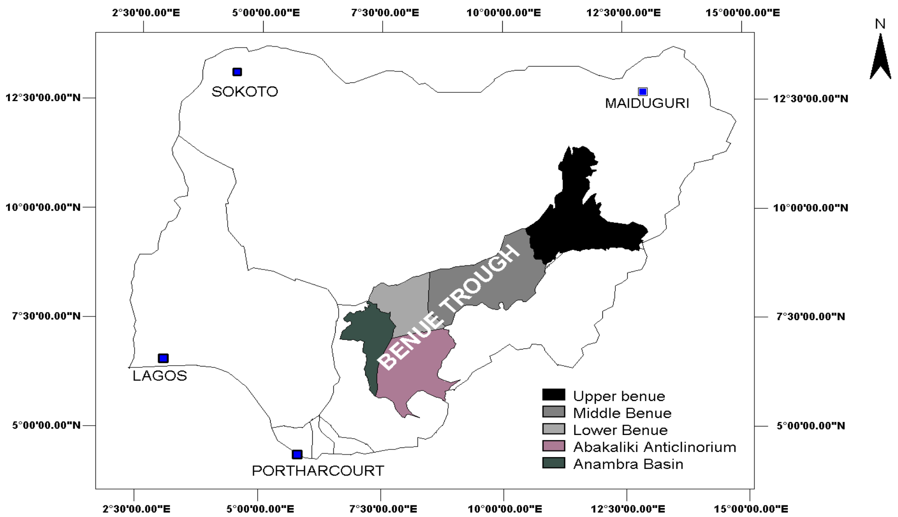


Figure 1. Map of Nigeria showing the major subdivisions of the Benue Trough (after Ologun et al,2008)

The area falls within latitude 9^{o} $03^{'}$ N to 10^{o} $00^{'}$ N and longitude 11^{o} $30^{'}$E to 13^{o} $00^{'}$ E. It covers an area of about 12000 km^2. The geology consists of crystalline basement, Cretaceous sediments and volcanics (fig2).

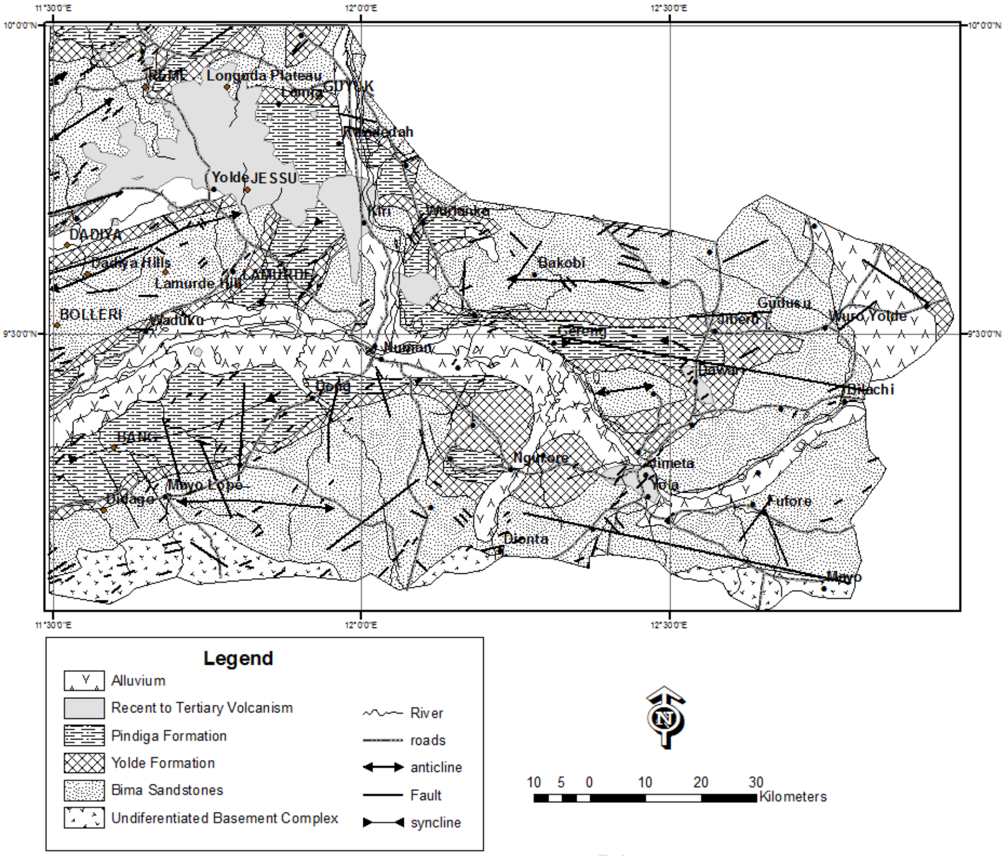


Figure 2. Geological Map of the Yola Basin (modified from Benkhelil, 1989, NGSA map,2004)

A horst and graben structure which resulted in variation in sedimentary thickness of between 2-3 km was deduced from interpretation of aeromagnetic data of the lower Benue (2 km flight line spacing). It also revealed a major lineament trend of NE-SW (Obi et al, 2008). Okereke et al, (2012) observed a major NE-SW lineament trend from Landsat data which is similar to the NE-SW trend of linear structures interpreted from magnetic data. A sedimentary thickness of about 4 km was also deduced for the sub-basin. The depth to basement in the Garoua basin (also known as the Yola rift) which is an eastward extension of the Benue trough in North Cameroon was found to vary from 4.4 km to 8.9 km (Mouzong et al, 2014) from spectral analysis of residual gravity data. Horizontal gradient method also revealed deep faults that trend in a major NW-SE direction within the basin. The spectral analysis and horizontal gradient method of aeromagnetic data of the Upper Benue Trough revealed a maximum sedimentary thickness of 3.45 km, a depth to shallow sources of about 1.5 km and a major structural trend of NE- SE, ENE- WSW and WNW- ESE in order of abundance (Alagbe and Sunmonu, 2014). Results from spectral analysis of the aeromagnetic data of the area around the Longuda Plateau (Upper Benue Trough) indicate a maximum sedimentary thickness of about 2620m and shallow magnetic sources of about 670 m (Kasidi and Ndatuwong, 2008). Fairhead and Okereke (1987) determined the crustal thickness of the Benue Trough and the Yola basin as about 24 km and 19 km respectively from gravity profiles while Stuart et al (1985) determined a crustal thickness of 23 km for the Cameroon extension of the Yola basin. Salako and Udensi (2013) determined sedimentary thickness to vary between 0.268 km and 3.35 km for parts of the Upper Benue Trough from spectral analysis of magnetic data. Ogunmola et al (2015) observed from high resolution magnetic data that the dominant structural trend in the underlying basement of the Middle Benue Trough is NE-SW.

2.1 Crystalline Basement

The crystalline basement is made up of scattered remains of well metamorphosed sedimentary rocks and diverse, mostly granitic, plutonic masses that are collectively called older Granites (Carter et al, 1963). They are seen to occur extensively south of the Benue where they emerge from beneath the Bima sandstone. Three phases of the Older granites have been distinguished; basic and intermediate plutonic rocks, fine grained granites and syntectonic granites. The earlier rocks have also gone through granitization that emplaced tracts of granitic migmatites and hybrid rocks.

2.2 Cretaceous Sediments

The Cretaceous sediments in the Upper Benue Trough are sandwiched between the Precambrian-Late Paleozoic basement gneisses and granites that occur as inliers in some places such as the Kaltungo Inlier. Overlying the Precambrian basement rocks is the Albian Bima sandstone which is the oldest Cretaceous sediment in the Upper Benue. It is overlain by the transitional Cenomanian-Turonian Yolde Formation which is succeeded by the Pindiga Formation (Turonian-Coniacian) with the Gongila Formation in the Gongola Basin and the Dukul, Jessu, Sekuleye and Numaha Formations as its lateral equivalents in the Yola Basin (Table 1).These successions are succeeded by the Gombe sandstone (Campanian-Maastrichtian) in the Gongola Basin and the Lamja sandstone as its lateral equivalent in the Yola Basin. The succession is capped by the Tertiary Kerri-Kerri Formation west of Gombe in the Gongola Basin.

2.2.1 Lithostratigraphic units of the Yola basin

A generalized stratigraphic chart of the Cretaceous Formation of the Yola basin is shown in table 1.

Table 1. Generalized Stratigraphic Chart of the Cretaceous Formation of the Yola basin (modified from Zaborski et al., 1997; Obaje et al., 2004).

AGE	YOLA BASIN
MAASTRICHTIAN	
CAMPANIAN	LAMJA SANDSTONE
SANTONIAN	
CONIACIAN	NUMANHA FORMATION
TURONIAN	SEKULEYE FORMATION
	JESU FORMATION
CENOMANIAN	DUKUL FORMATION
	YOLDE FORMATION
ALBIAN	BIMA SANDSTONE
PRE-CAMBRIAN	BASEMENT COMPLEX

2.3 Cretaceous Volcanics

Most of the minor volcanic activity that occurred during the Upper Cretaceous is within the Benue Trough (Carter et al, 1963). In the Yola arm, they can be seen in a stream 5.5 km NW of Chikala within the Lamja sandstone. They are also present at about 2 km west of Lamja and in the Numanha river within the Numanha shales. In the Jessu Formation, they are seen in a stream near Chikila and in the southern part of Dukul and Kunini. Within the Dukul Formation, they occur about 1.6 km North of Dadiya and at about 5 km east of Reme on the Talasse road. Within the Bima, they are seen at the Lamurde anticline where the basalts have been weathered to greyish green clays. Most of the volcanics consist of thin lavas and tuffs.

2.4 Tertiary to Recent Volcanics

The Late Tertiary and Quaternary witnessed a major epoch of volcanic activity during which numerous volcanic plugs were emplaced and also saw the building of the great lava Plateau of Biu and Longuda. Majority of the plugs consist of fine-grained olivine basalts with a few being trachytic and phonolitic in composition. They are found within all the Cretaceous Formation. The Longuda lavas are mostly fine grained olivine basalts and reach their maximum thickness of 240, 275 and 305 meters at Dukul, Jou and Kola respectively.

3.0 Materials and Methods

3.1 Data Available

Magnetic data- The data set used for this study is an aeromagnetic survey that was acquired at a flight line spacing of 400 meters and a terrain clearance of 80 meters surveyed by Fugro Airborne surveys for the Federal Government of Nigeria. The data study is in grid format only. The earth’s geomagnetic field was removed from the data using the IGRF 12 Model.

SPOT 5 Data- For this study, SPOT 5 data with a ground resolution of 5 meters was used. This coverage offered by SPOT-5 is a key asset for applications such as medium-scale mapping (at 1:25 000 and 1:10 000).

Digital Elevation Model (DEM)- The DEM data set for this study is from the SRTM (shuttle Radar Topography mission) flown by NASA that obtained digital elevation models of the earth's surface. The SRTM data of the Yola basin was downloaded from the Global Land Cover Facility (GLCF).

3.2 Reduction to the Pole (RTP) or Reduction to the Equator (RTE)

The RTP method of reducing maps made anywhere, with exception of those at low latitudes, into what they would appear like if the inclination of the magnetic field were 90 degrees described by Baranov (1957) is a standard method used when interpreting magnetic data because at the poles, magnetic anomalies are true reflections of the geologic bodies causing them. It has however been observed that amplitude correction at very low latitudes (± 10°) for north-south trending features distorts magnetic anomalies and unreasonable amplifies noise/artefacts (McLeod et al, 1993). The magnetic data can also be reduced to the equator (RTE) such that the magnetic bodies will appear horizontal at the equator (Leu ,1982) . The structure will show the same anomaly shape as those at the poles. His approach recalculates the total magnetic intensity assuming the magnetic body is lying in a horizontal position and anomaly lows are converted to magnetic highs by reversing the phase by 180 at the same location over the middle of the bodies. At very low latitudes, it is also unlikely for a RTE to make any significant change in the data as was observed in the Yola basin with a declination of -2.011, and inclination of -3.413 (from the IGRF 12 Model) which showed a resultant grid that is similar to the TMI grid. In the light of all the above, the original TMI grid of the Yola basin was used for data enhancement and interpretation.

3.3 1st Vertical Derivative

The 1st vertical derivative, dT/dz is a vertical gradient method that uses a Fast Fourier Transform (FFT) to enhance the high frequency component of a magnetic field made up of intrusives and volcanics while suppressing the low frequency content which is due to the regional field (Paine, 1986). The transformation takes place in the spectral phase therefore the accuracy cannot be determined but the frequency domain can show the level of accuracy of the method. The first vertical derivative (VDR) can be viewed as taking measurements of the total magnetic intensity (TMI) at two locations that are a small distance above each other at the same time and dividing the difference in the TMI values with the vertical distance between them (Milligan and Gunn 1997). A first vertical derivative transform was applied to the TMI grid of the study area.

3.4 Tilt derivative

The TDR was used in this study to enhance anomalies that could be basement faults. The tilt-derivative (TDR) is useful because of some of its peculiar characteristics. It tends to equalize the amplitude output of TMI anomalies across a grid. While other conventional derivatives show amplitude response that is closely linked to the amplitude of the TMI anomaly, the TDR is independent of amplitude of the TMI anomaly but controlled by the reciprocal of the depths of the sources (Verduzco et al., 2004). The TDR also shows a maximum that peaks over the anomaly. Because the $\tan^{-1}$ component of the TDR is restricted to + 1.57 and – 1.57, it acts like an automatic gain control (AGC) filter that amplifies the amplitude of signals that are low which makes the Tilt derivative a powerful method. Since an average depth of 1 km depth to shallow magnetic sources for the Upper Benue has been estimated by several authors (Alagbe and Sunmonu 2014, Okereke et al, 2012, Kasidi and Ndatuwong 2008), a low pass filter with a cut-off wavelength of 1000 meters was applied to the data to reduce the high frequency short wavelength component of the data after which this transform was applied to the TMI data of the study area.

3.5 Topographic Analysis- Using the spatial analyst in ArcMap, several topographic attributes such as shaded relief, curvature, slope, flow direction and stream network were derived from the digital elevation model (DEM).

3.6 Structural Mapping

The first stage of the structural mapping was to distinguish which of the high frequency components of the data derived from the first vertical derivative are due to surface/subsurface geology or due to cultural noise from the environment. This was carried out with the aid of SPOT 5 image and the SRTM data of the study area. The SPOT 5 data was passed through edge enhancement image processing method using the ERDAS Imagine software so as to sharpen the surface geological features and give a good contrast between the settlements which appear as cyan colour and the surrounding pixels due to vegetation or water. The next stage of structural mapping involved mapping out on-screen lineaments observed from the SPOT 5 image. It also involved mapping out magnetic lineaments that could be due to the contacts between two rock types of contrasting magnetic susceptibility or edges of structures that could be faults or intrusives within the sediments. To achieve this, all the various data sets were displayed in ArcMap and by studying one layer at a time and comparing with other layers in the GIS environment. The geological map was useful because it showed the location where the basement occurs as surface exposure. The SRTM data was able to show the outline of surface geological features such as dikes which was also evident on the SPOT 5 image. One of the advantages of working in a GIS environment using several data sets is the opportunity to examine features that are spatially referenced. A feature that is less pronounced in one data set can be more pronounced in another data. A shapefile was created in ArcCatalog after which the magnetic lineaments were digitized on-screen.

3.7 Depth to Basement Inversion from Magnetic data

One of the objectives of this research is to derive estimates of depth to causative bodies in parts of the Yola Basin which will also give us the thickness of the overlying sediments. The methods used include the Local wavenumber/source parameter imaging (SPI) and spectral analysis.

3.8 Local wavenumber

This method developed by Thurston and Smith (1997) also known as the Source Parameter Imaging (SPI) technique is so called because all the parameters that make up the source which include depth, dip and susceptibility contrast are computed from the complex analytical signal. Fairhead et al (2004) related the source depth to the local wavenumber (k) of the magnetic field which can be derived from the calculated total horizontal and vertical gradients of the RTP grid. The technique works well at all magnetic latitudes which makes it a good choice for the Yola Basin that is at low magnetic latitude. One other advantage of this method is that the depth estimates can be gridded and exported from geosoft to ArcGIS where it can be overlain on the geological and structural maps derived from the magnetic derivatives. Using the SPI method in geosoft, the depth estimates were derived from the TMI data of the Yola basin that was upward continued a distance of 1km to minimize signals from the high frequency and short wavelength component of the data. The number of peaks to be detected was set at 3 or 4 directions and the maximum depth of solutions was set at 6000m meters based on well data and earlier depth estimates derived from the basin by other authors. The depth solutions were saved in a database and the terrain clearance of 80 meters and 1 km upward continued distance was deducted after which it was gridded using the minimum curvature method.

3.9 Spectral Analysis

When gravity or magnetic sources occur in cluster at a certain depth, the sources will be shown as a straight line that has a gradient of -4π in a power spectrum which is the plot of the logarithm of the amplitude of the source against the wavenumber (Spector and Grant, 1970). Therefore different straight-line branches in a power spectrum show the existence of clusters of gravity or magnetic sources at the different depths. This process of identifying signals from different sources known as Spectral Analysis was carried out in geosofts magmap by first carrying out a Fast Fourier Transform on the data before computing the radially averaged power spectrum. The area was divided into 19 spectral blocks. Block 1-15 about 27.5km by 27.5km while block 16-19 are about 35km by 27.5 km each and block 19 is 20km by 27.5km. From the SPOT 5 data folds such as the Lamurde Anticline are seen to be more than 10 km wide and about 20 km in length. The anomalies in the magnetic data also range from a few kilometers wide to about 24 km wide in the south-eastern part of the basin. It is in the light of the aforementioned that a size of 27.5 km x 27.5 km was deemed suitable for most of the spectral blocks. The .* SPC energy files were imported into Microsoft excel. A matlab code was compiled which plots the power spectrum after which the linear segments were then drawn. The program determines the slope of the linear segments and hence depth for the two sources.

3.10 Depth to Basement Map

A depth to basement map of the Yola basin was produced from the depth estimates that were derived from the Local wavenumber and spectral analysis and the structures extracted from the structural mapping using the Tilt derivative. The basement faults were displayed in ArcMap and the following data sets were overlain on them-

- depth solutions from the SPI method

- depths from the spectral analysis

A shapefile was created and using the editor tool, polylines were drawn beside and within the structures without any overlaps and were given depth values based on geologically reasonable depths from the various depth estimate methods.

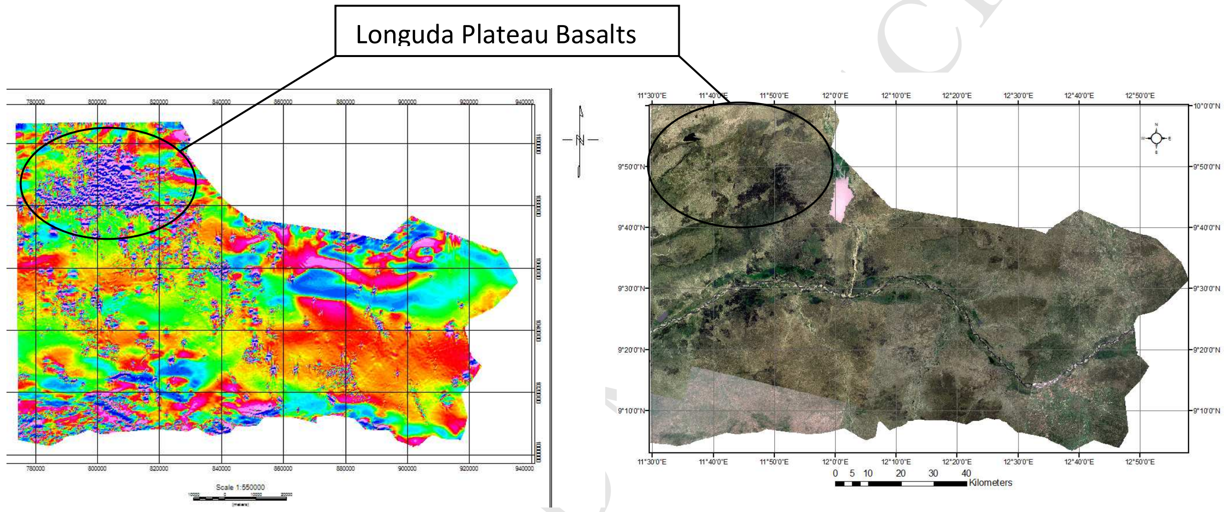
The polylines were then converted to points using the ET Geowizard in ArcGIS and stored as a point data set which contains all the attributes of the polyline. The points were then interpolated using the Spatial Analyst extension that performed a spline with barriers on the point data using a minimum curvature spline method. The barriers in this case are the basement faults represented as polyline features. The interpolated output was exported to Geosoft Oasis Montaj where it was displayed as database table and gridded using the minimum curvature method to produce the depth to basement map of the study area. The depth to basement map was displayed in ArcMap and the faults overlaid on it. Contours of the depth to basement map were also extracted and overlain on the depth to basement structure map for better visualization of the basement configuration.

4.0 Results and Discussion

The integration of the tilt derivative and vertical derivative was very useful in understanding the geology of the basin. The VDR showed that some of the high frequency and low wavelength components are due to surface/subsurface geology most likely volcanics. A good example can be seen in the north-eastern part of the basin (fig 3) where the VDR clearly defined the outline of the Longuda Plateau which is basaltic. There was a strong correlation between the south-western edges of the Longuda Plateau (olivine basalts) observed from the SPOT 5 image and the outline of the high frequency and short wavelength components observed from the VDR grid. There was also a strong correlation with some of the surface exposures of tertiary basalts observed during field work. These include those on the western part of Waduku and the southern part of Kwadedah. It was therefore possible properly map out the outline of the Plateau and other volcanics within the basin as shown in the geological map (fig 2). The root of the Longuda basalts may also extend farther southwards below the sandstones of the Lamurde hill.

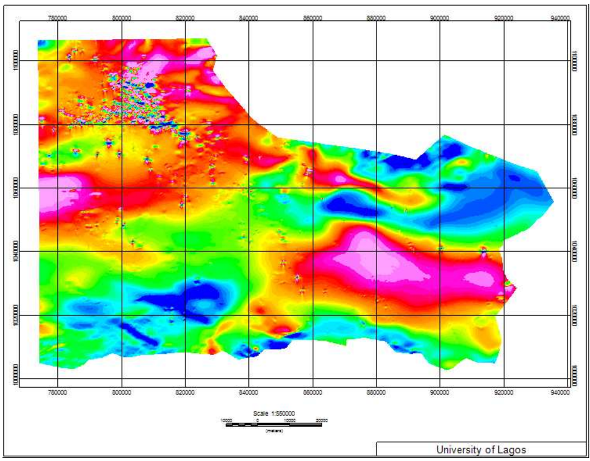
The drainage network derived from the topographic analysis using the digital elevation model (DEM) from the SRTM is dendritic which is indicative of alluvial rocks.

The major structural trend observed from SPOT 5 imagery is also NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W trends (fig 5) and they range in length from 200 m to about 16 km. These trends have also been observed from Landsat study (Ananaba and Ajakaiye, 1987) and interpretation of SPOT 5 imagery (Ogunmola et al, 2014). The straight limbs of the folds in the basin such as the Lamurde anticline as seen from the SPOT 5 image trend in a NE-SW direction.

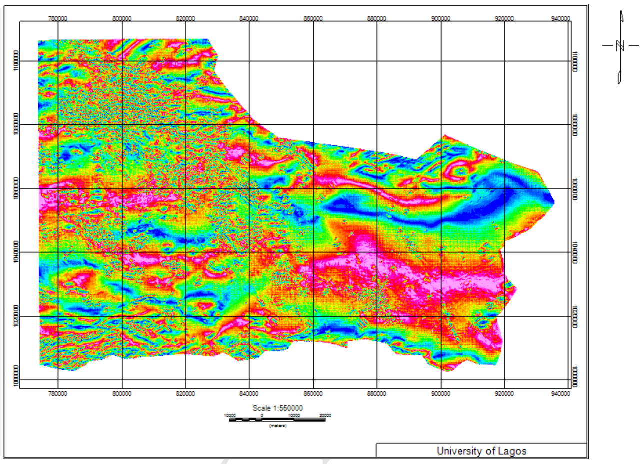


(a) (b)

Figure 3. 1st Vertcal Derivative of the magnetic data (a) and Satellite imagery of the study area (b)



(a)



(b)

Figure 4. The TMI of the magnetic data (a) and the Tilt derivative (b)

The Tilt derivative shown in fig 4 (b) clearly shows that this method is obviously very good at enhancing the basement faults because the zero crossing of the Tilt derivative closely delineate the edges of structures. It was able to enhance structures that were not observed from earlier studies. These structures were also observed not to cut across the tertiary basalts such as on the Longuda Plateau which suggests that the movements within the underlying basement ceased before the Tertiary. The dominant trend of these faults was found to be in the NE-SW with a few N-S, NW-SE, and WNW-ESE direction (fig 6) and range in length from 0.8 km to more than 58 km. These trends have also been observed from surface outcrops (Guiraud, 1990) and from geophysical and remote sensing data (Benkhelil, 1987,1989, Ogunmola et al,2015). These basement faults may be related to fracture zones such as the Romanche fracture zones and the Chain and Charcot fracture zones which are thought to have continental extensions and are likely to control the major NE-SW fracture system along the Benue Trough as suggested by earlier authors (Wright, 1976). A remarkable feature in the western part of the Yola basin are two faults that are about 32 km apart and are parallel to each other. These faults trend WNW-ESE for more than 58km and may well extend into the Garoua Basin in Cameroon and is overlain by the Cretaceous sediments. Sandwiched between these faults is a zone of positive anomaly and corresponds to areas delineated as the deepest part of the study area from the source parameter imaging (SPI) and the spectral analysis (~3.7 km). The rock types on the surface are the limestones, shales and clay of the Yolde Formation, hence this zone can be said to be the area with the thickest Cretaceous deposits. This zone stretches for about 60 km and is about 30 km wide. Gravity surveys by Osazuwa et al (1981) also delineated this zone along a N-S profile. The positive anomaly observed in this zone may be due to basic intrusives with high magnetite content at the surface of the magnetic basement or contributions from high frequency-low wavelength intrusives as amplified around Jimeta and south of Fufore and Dawari. The structures within the sediments may have originated from crustal stresses that were transmitted through incompetent sediments in directions different from the major tectonic trend of the underlying basement. Compressional events such as the one in the Santonian (80ma) that reactivated pre-existing shear zones in the Benue Trough (Benkhelil et al,1989) can lead to the formation of the NNW-SSE, N-S and E-W trends observed within the sediments. These faults are later than the folding that produced the great folds of the Benue Trough such as the Dadiya syncline and the Lamurde anticline which may be related to deep seated movements in the underlying basement. Some of these structures observed from the SPOT 5 image include the straight limbs of the folds around Dadiya that stretch for about 16 km and those around the southern part of Reme but most of the lineaments within the sediments are less than 1.5km in length. The difference in stress directions observed on the overlying sediments and those observed on the underlying basement suggests that they passed through different stress regimes.

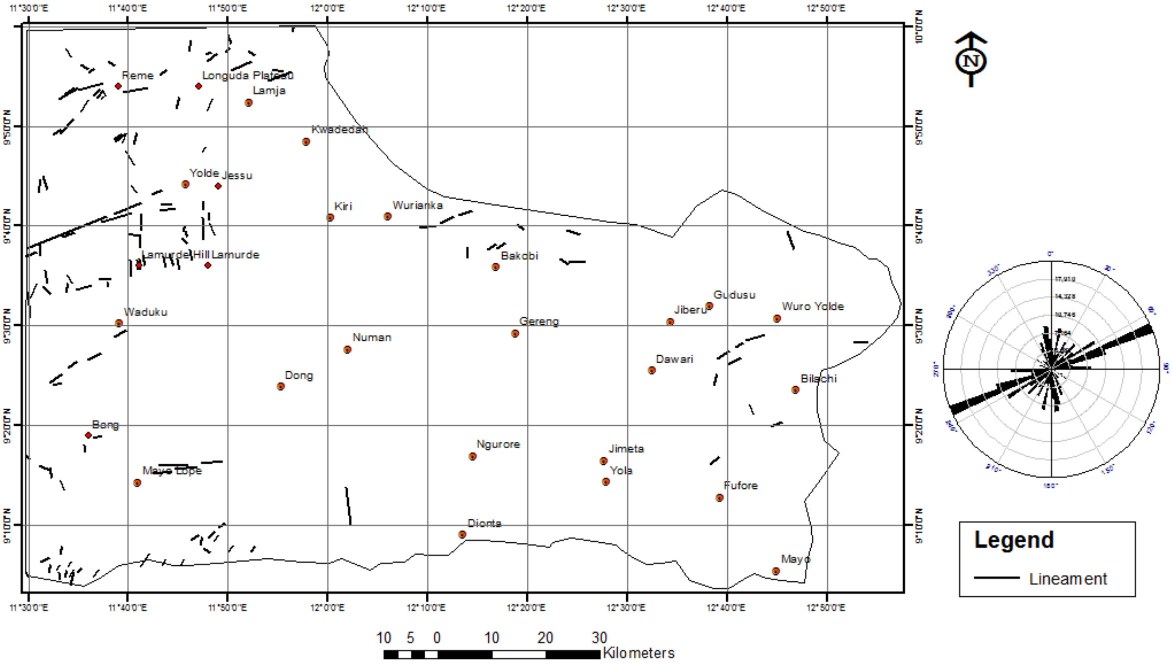


Figure 5. Lineaments extracted from SPOT 5 image of study area and a Rose diagram showing the distribution of lineaments by direction and weighted by length

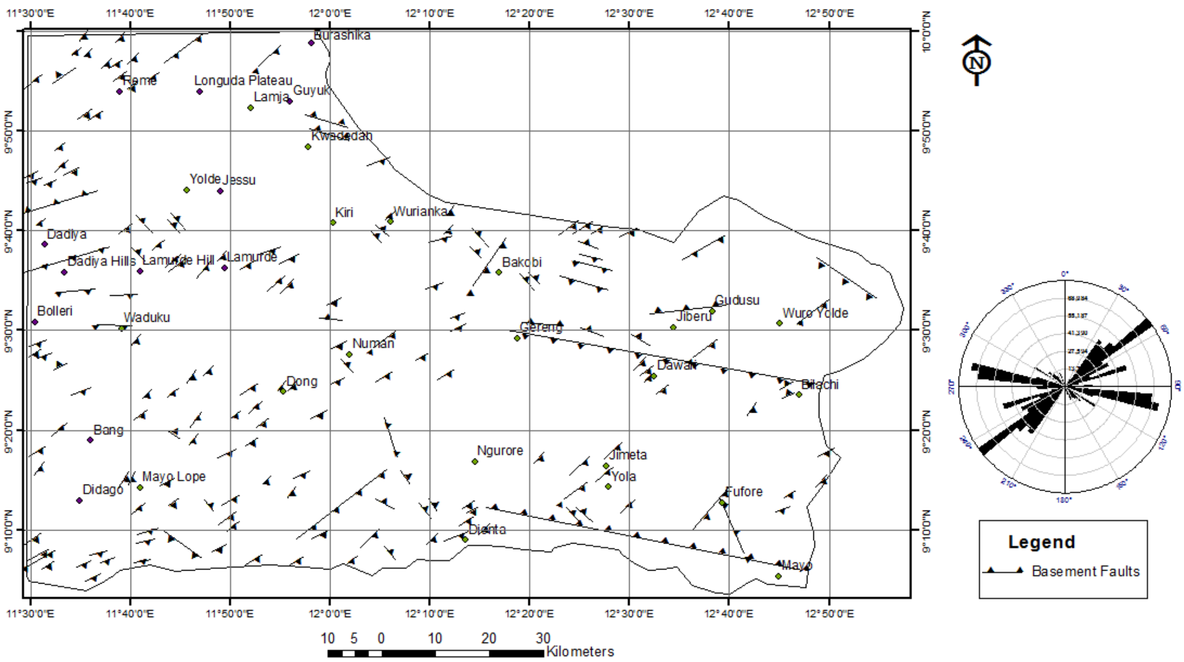


Figure 6. Faults derived from Tilt derivative (TDR) of study area and Rose diagram showing the distribution of faults by direction and weighted by length

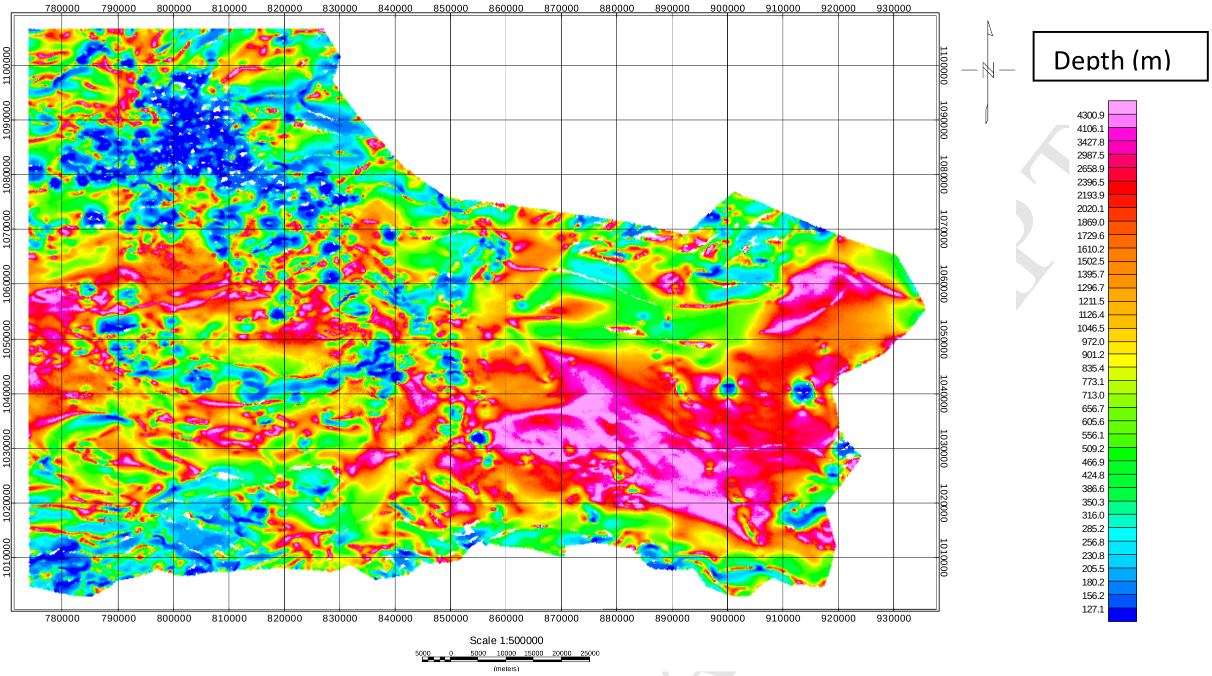


Figure 7. A grid of depth estimates from magnetic sources derived from the SPI method

The grid of the depth solutions derived from the Source Parameter Imaging is shown in fig 7. The depths range from about a 0.127 km to about 4.3 km with the deepest part being in the eastern part of the basin. These depths are from all magnetic sources that include shallow volcanics/intrusives mainly in the northern part of the basin and shallow basement rocks on the southern part. The 19 plots of the log of spectral energy versus the wave number are shown in fig 8 and fig 9 and the depths derived from the spectral analysis are shown in table 2. The shallow depths which could be due to intrusives and volcanics range from about 0.343 km around Bang and Didago to 0.70 km around Yola but are mainly confined to the western part of the basin. The second depths which are most likely mainly from the magnetic basement range from about 1 km southwest of Yola to about 3.66 km around Yolde and Bilachi.

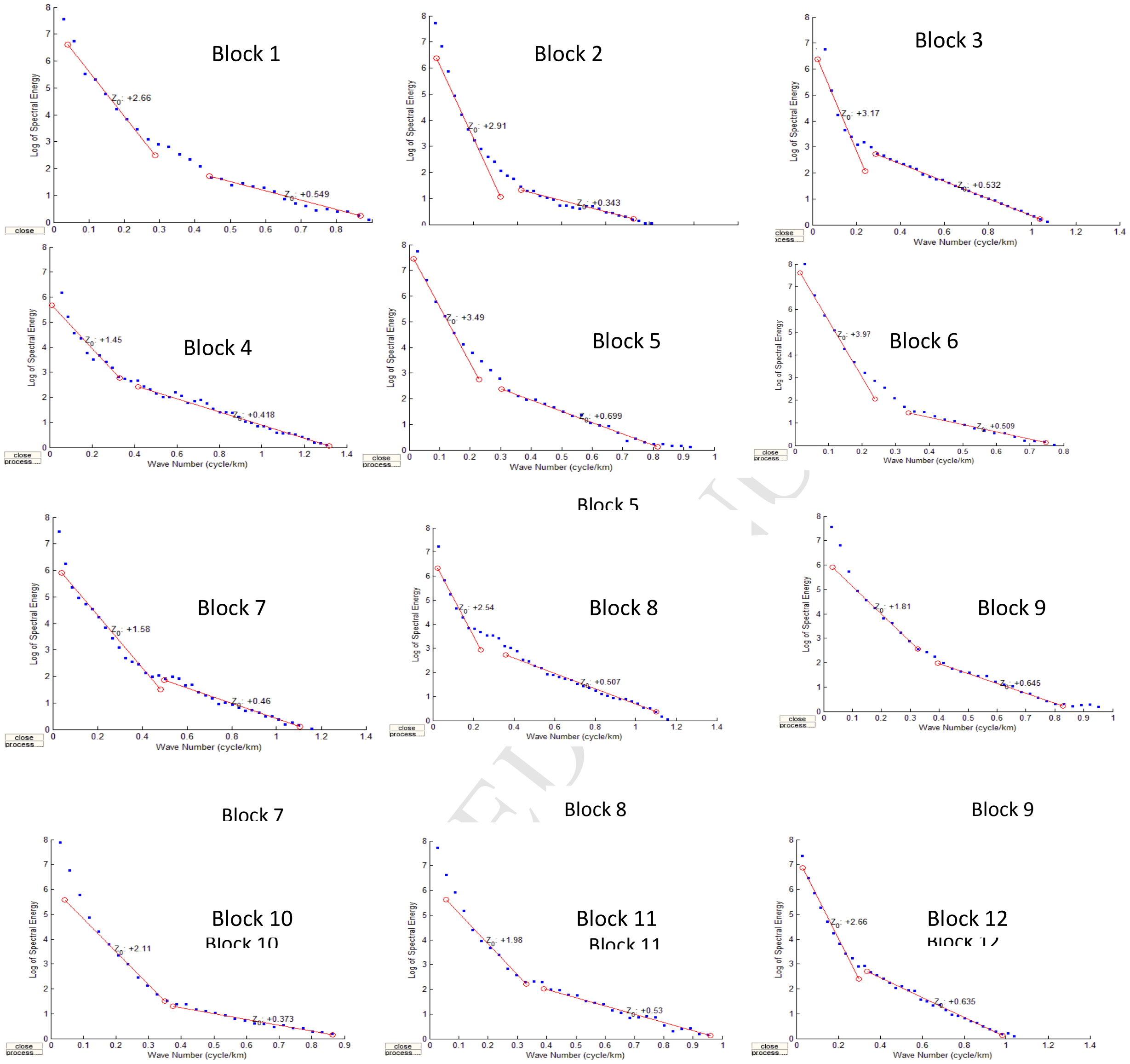


Figure 8. Spectral plots of energy against frequency for spectral blocks 1-12

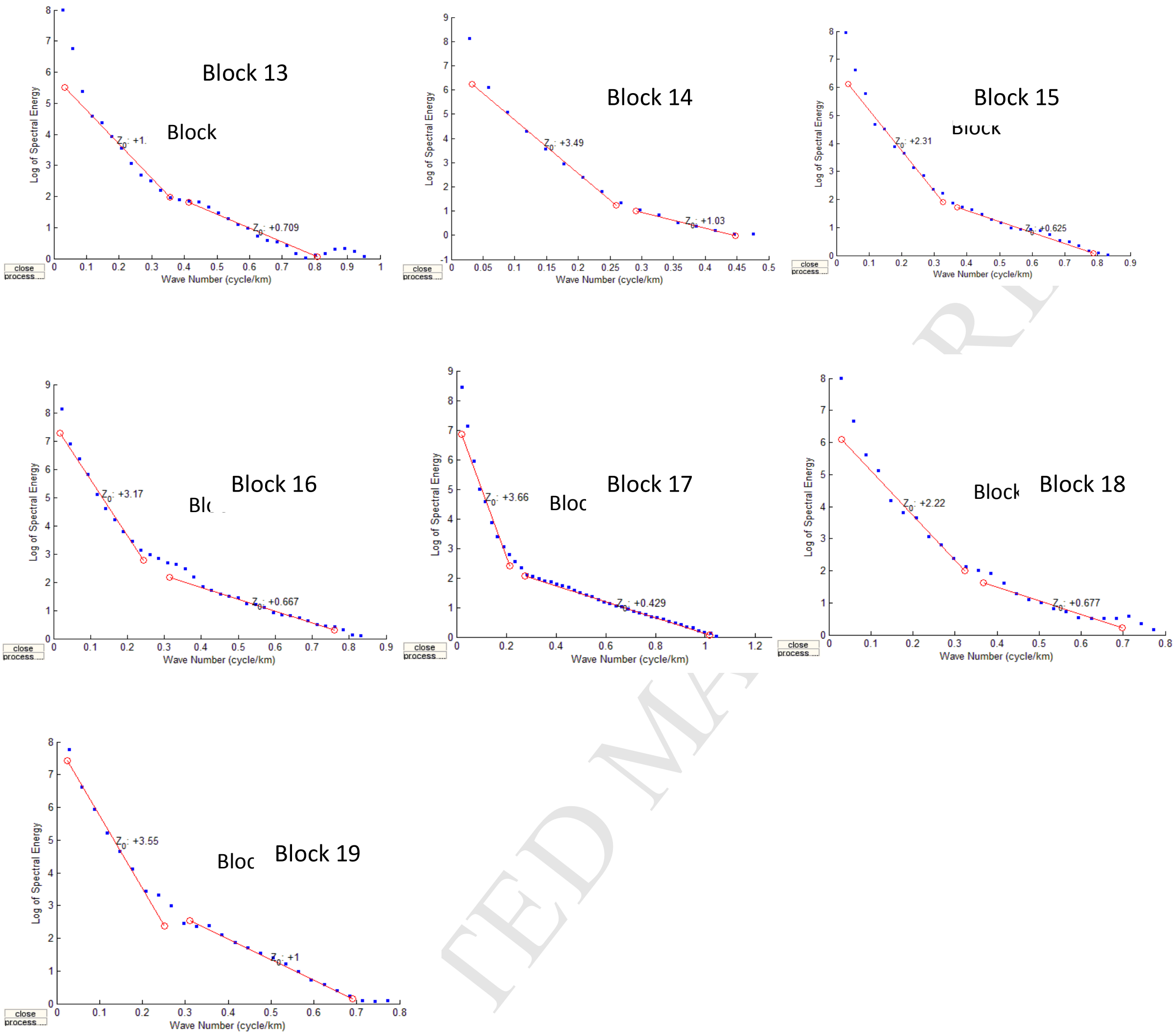


Figure 9. Spectral plots of energy against frequency for spectral blocks 13-19

Table2: Estimated depth to the shallow magnetic sources (depth1) and deep magnetic sources (depth2) in km

Spectral Block	**Longitude**	**Latitude**	**Depth 1 (km)**	**Depth 2 (km)**
Block 1	11.5-11.75	9.0-9.25	0.549	2.66
Block 2	11.5-11.75	9.25-9.5	0.343	2.91
Block 3	11.25-11.75	9.5-9.75	0.532	3.17
Block 4	11.25-11.75	9.75-10	0.418	1.45
Block 5	11.75-12	9.0-9.25	0.699	2.49
Block 6	11.75-12	9.25-9.5	0.509	2.97
Block 7	11.75-12	9.5-9.75	0.460	1.58
Block 8	11.75-12	9.75-10	0.507	2.54
Block 9	12-12.25	9.0-9.25	0.645	1.81
Block 10	12-12.25	9.25-9.5	0.373	2.11
Block 11	12-12.25	9.5-9.75	0.530	1.98
Block 12	12-12.25	9.75-10	0.635	2.66
Block 13	12.25-12.30	9.0-9.25	0.709	1.00
Block 14	12.25-12.30	9.25-9.5	1.03	2.49
Block 15	12.25-12.30	9.5-9.75	0.625	2.31
Block 16	12.5-12.825	9.0-9.25	0.667	3.17
Block 17	12.5-12.825	9.25-9.5	0.429	3.66
Block 18	12.5-12.825	9.5-9.75	0.667	2.22
Block 19	12.825-13.0	9.5-9.75	1.00	3.55

Generally, the depth estimates from the local wavenumber (LWV) or source parameter imaging (SPI) method and those from the spectral analysis show some correlation. Depths are taken as depth to the magnetic sources.

Both estimates show that the eastern half of the Yola basin is the deepest starting from Bakobi to Yolde in the northern part and from Ngurone through Jimeta to Fufore in the south as shown by the depth to basement maps (fig 10 & 11). However the SPI gave the deepest average estimate of about 4.3 km while the spectral analysis gave about 3.66 km. These depths are similar to those derived from recent study of the Yola basin such as about 3.4 km from spectral analysis of aeromagnetic data (Salako and Udensi, 2013), sedimentary thickness of about 4 km (Okereke et al, 2012) and a depth of about 4.4 km in the Garoua basin which is the eastern extension of the Yola basin in Cameroon (Mouzong et al, 2014). The depth to basement structure maps (fig 10 & 11) gives a better visualization of configuration of the basement. Most of the faults are deep seated within the underlying basement while the shallow ones occur where there are surface exposures of the basement.

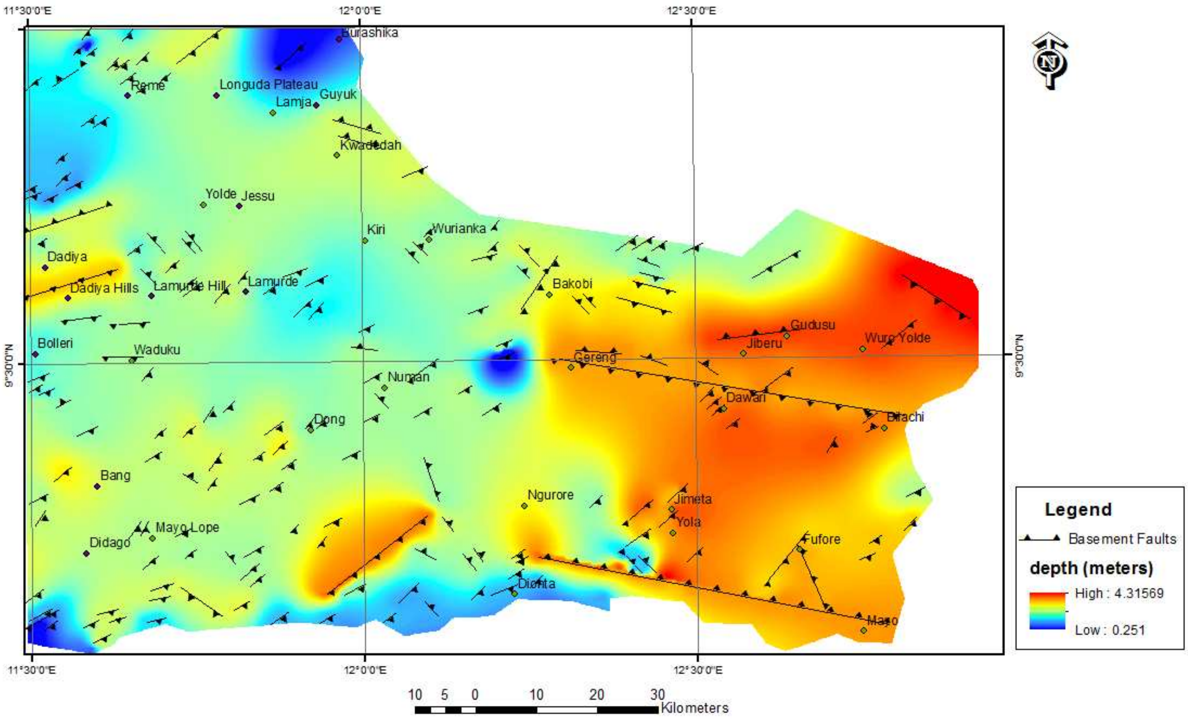


Figure 10. Depth to Basement structure map of the Yola Basin

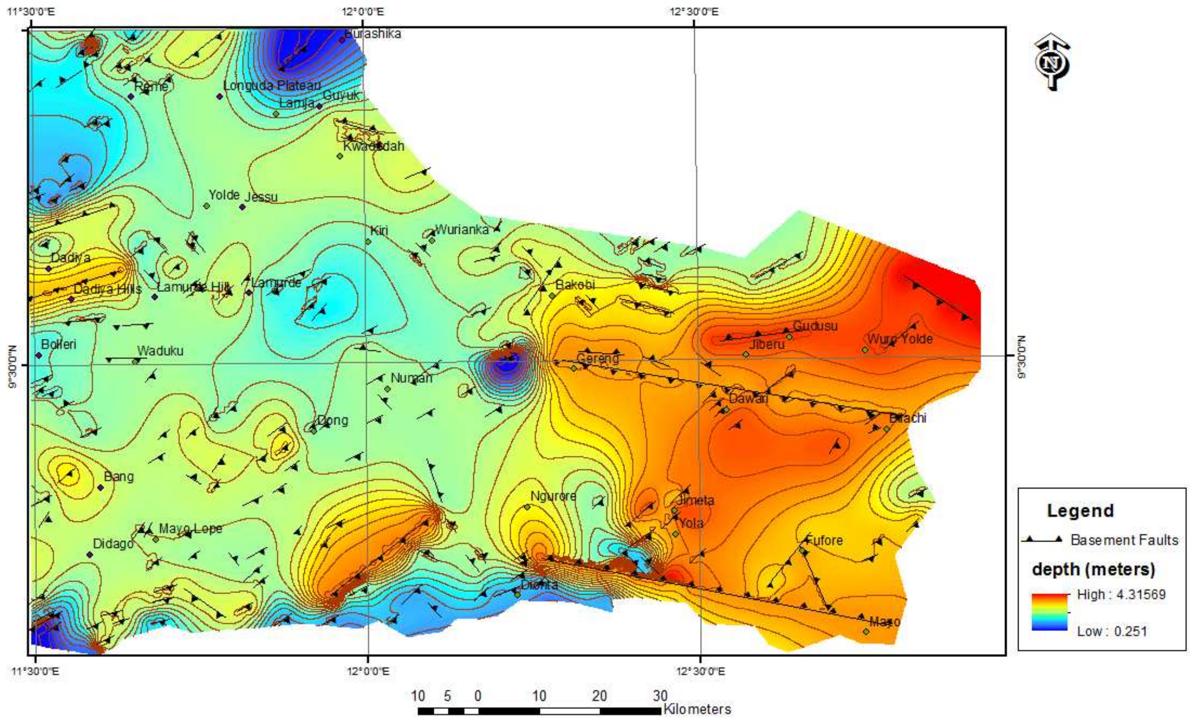


Figure 11. Depth to Basement structure Map of the Yola Basin with an overlay of the depth contours

5.0 Conclusions

This interpretation has shown that the underlying basement in the Yola basin is faulted in a major NE-SW direction and these basement faults may have controlled the fracture system with the Cretaceous sediments that may have been generated in the Precambrian. Wright (1981) suggested that it was differential uplift of the basement fault blocks that gave rise to drape folds in the overlying sediments. He based his conclusion on the evidence from the straight limbs of the Lamurde anticline that trend in a NE-SW direction as observed from ERTS imagery which could be surface expressions of large basement faults. Evidence is now at hand from this study to support his theory because the Tilt derivative was able to show a major basement fault that runs parallel to the straight limbs of the Lamurde anticline. Other conclusions drawn from this interpretation are-

1. The dominant trend of the basement faults was found to be in the NE-SW with a few N-S, NW-SE, and WNW-ESE directions that may have been generated in the Precambrian.
2. These basement faults may be related to fracture zones such as the Romanche fracture zones and the Chain and Charcot fracture zones which are thought to have continental extensions and are likely to control the major NE-SW fracture system along the Benue Trough.
3. The major structural trends within the sediments as observed from SPOT 5 imagery and geological mapping are also NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W trends.
4. The major direction of the great Lamurde fold in the basin are in the NE direction which suggests that some of the folding may be related to the deep seated earth movements of the underlying basement.
5. The presence of some NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W structures in the sediments suggests that they were as a result of stresses that were post Cretaceous.
6. The area may have undergone several stress regimes.
7. The absence of faults that are abundant in the underlying basement in the great Tertiary basalts of the Longuda Plateau suggests that the tectonic regimes ceased before the Tertiary.
8. Apart from the Tertiary basalts of the Longuda Plateau, localised volcanics are present in parts of the study area especially to the west.
9. The deepest part of the basin is found in the south-eastern part of the area where the Cretaceous sediments are about 4 km thick and are flanked by two prominent faults.
10. The Cretaceous Sediments in the eastern part of the basin are thick enough for hydrocarbon generation.

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Highlights

1. The dominant trend of the basement faults was found to be in the NE-SW with a few N-S, NW-SE, and WNW-ESE directions that may have been generated in the Precambrian.
2. The major structural trends within the sediments as observed from SPOT 5 imagery and geological mapping are also NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W trends.
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