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Structural-Depth Interpretation of the Cretaceous Gongola Basin in the Upper Benue Trough, Nigeria: Insights from New High Resolution Aeromagnetic and SPOT 5 Data

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Abstract
The Benue Trough is north-south trending and has been described as a linear depression that is about 1000 km long and filled with Cretaceous sedimentary pile of about 6000 m thickness. The Trough is further subdivided into the Lower, Middle and Upper Benue Trough. The Gongola basin is the northernmost part of the Upper Benue Trough. This present work is an attempt to understand the structural framework and geometry of the basin with the aid of remote sensing and high resolution aeromagnetic data which can enhance further exploratory effort within the basin. SPOT 5 data was passed through edge enhancement image processing method so as to boost the appearance of surface geological features. Several topographic attributes such as shaded relief, curvature, slope, flow direction and stream network were derived from the digital elevation model (DEM). The vertical derivative (VDR) enhanced the high frequency and short wavelength components of the data which could indicate the presence of volcanics. The Total Horizontal Derivative (THDR) and the Tilt Derivative (TDR) were computed to enhance anomalies that could represent faults in the underlying basement. The source parameter imaging (SPI) technique which works well at all magnetic latitudes was applied to the data to estimate the sediment thickness within the basin. The major structural trend within the sediments observed is NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W trends. This may indicate the impact of multiple paleostress regimes in the basin. Structural trends within the host basement rocks is however dominated by NE-SW and minor E-W directions. The basin is deepest at its central parts where its Cretaceous sediments are up to 3 km in thickness, which may not be adequate for hydrocarbon generation.

Keyword: *Aeromagnetic data, SPOT 5, GIS, Geology, Lineaments, Faults*

Introduction

The Gongola Basin is the north-south trending arm of the Upper Benue Trough (Fig 1). The Benue trough has been described as a linear depression that is about 1000 km long and filled with Cretaceous sediments that are about 6000 m thick which have been folded by compressional forces in a non-orogenic setting (Wright, 1981). This present work is an attempt to understand the structural framework and the geometry of the basin with the aid of remote sensing and aeromagnetic data, which can be an aid to further exploratory effort. 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. Two exploration wells, the Kolmani River and Nasara-1 have been drilled in the Gongola basin. The Nasara-1 well (about 1920 meters deep) is located at longitude 10° 54' E and latitude 9° 50' N. The well has penetrated all the Cretaceous Formations of the basin, except the upper Maastrichtian Gombe Formation. Kolmani River 1 Well (about 2773 meters deep) was drilled in the Gongola Basin, northern Benue Trough, Nigeria on Latitude 10°07'03.9” N and Longitude 10°42' 43.8”E in the present Gombe State of Nigeria. Abubakar et al, (2010) used spectral analysis to derive average depths of 1.25 km, 4.03 km and 5.39 km for three magnetic levels in the basin and also concluded a block faulting model as the basin shows a graben-like structure. Shemang et al, (2001) observed a dominant NE-SW magnetic low anomaly that is about 100km in length and 20 km wide which they attributed to predominantly mafic rocks at depths of between 6 and 10 km well below the base of the sediments. They concluded that the area is an old rift that has been affected by the activity of a mantle plume that resulted in mafic intrusions . Gravity surveys by Shemang et al, (2005) also showed that the area is marked by negative bouguer anomalies with an average value of -42 mGal. Interpretations from 2.5-D modeling also suggested that the area is a horst and graben structure filled with sediments up to 4.5 km thick. These results also suggested the existence of high-density rocks of basic composition at depth. Zaborski et al, (1997) suggested that the structural disposition of the Gongola basin was controlled by NE-SW (strike-slip), N-S (strike-slip) and NW-SW (normal) trending faults. 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). Result 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). 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. This study is aimed at showing the effectiveness of integrating remote sensing, magnetic and other ancillary data within a GIS for geological and structural studies.

Background

Magnetic data interpretation can be used to establish the relationship between basement tectonics and the overlying structures within the sediments. The first 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. Total horizontal derivative is a good edge detector because it computes the maxima over the edges of the structures. Remote sensing involves the collection and interpretation of information about an object without physical contact with the object; eg, satellite imaging, aerial photography, and open path measurements. Remote sensing is not limited to direct geology applications. It is also used to support logistics, such as route planning for access into a mining area, reclamation monitoring, and generating basemaps upon which geological data can be referenced or superimposed. It has become a widely accepted research tool by almost all Geological Surveys the world over. A synoptic view of regional scale is a much different perspective than point ground observations when trying to map structural elements. It also allows a geologist to examine other reference ancillary data simultaneously and synergistically, in this case , high resolution aeromagnetic data and geological data. Digital terrain analysis using a Dital elevation model (DEM) is useful in geological/structural mapping and natural resource exploration. A DEM is continuous representation of the earth's topography in a digital format. Geological structures and boundaries of rock units that show strong correlation with relief can be mapped using digital terrain analysis. Topographic attributes such as slope, aspect, curvature, elevation etc can be computed and displayed as DEM derived surfaces through which the relationship between topography and geology can be studied. The drainage network of a basin can also be derived using a digital terrain analysis as was done for the Gongola basin (Ogunmola et al, 2014). One mapping technique that has gained acceptance among water explorationists is the use of fracture trace analysis (Feter, 2001). Fracture traces are located by the study of linear features on aerial or satellite photographs. Natural linear features consist of tonal variation in soils, alignment of vegetative patterns, straight stream segments or valleys, aligned surface depression, gaps in ridges or other features showing a linear orientation. Fracture traces may be related to regional tectonic activity. They tend to be oriented at a constant angle to the regional structural trend; however, the orientation may be independent of local folds. In this study, SPOT 5 image with a 5 meter resolution was used to identify and map out the lineaments.

Geological Setting and Stratigraphy

The study area forms part of the Upper Benue Trough of Nigeria (fig. 1) which is part of the West and Central African Rift System that opened as a broad strike-slip fault system (Binks and Fairhead, 1992). The area falls within latitude 9° 29' N to 11° 35' N and longitude 10° 8' E to 12° 13' E and covers a landmass of about 30,322 km^2. The sedimentary sequence in the Gongola basin begins with the continental Bima Sandstone (fig. 2) which unconformably overlies the Precambrian Basement Complex. The top of the Formation is between Upper Cenomanian and Lower Turonian in age while the base could be Upper Albian (Carter et al, 1963). The Yolde Formation conformably overlies the Bima sandstone and is mainly composed of sandstones and shales that represent a transition from continental to marine sedimentation. The first appearance of marine shales defines the base while the top marks the disappearance

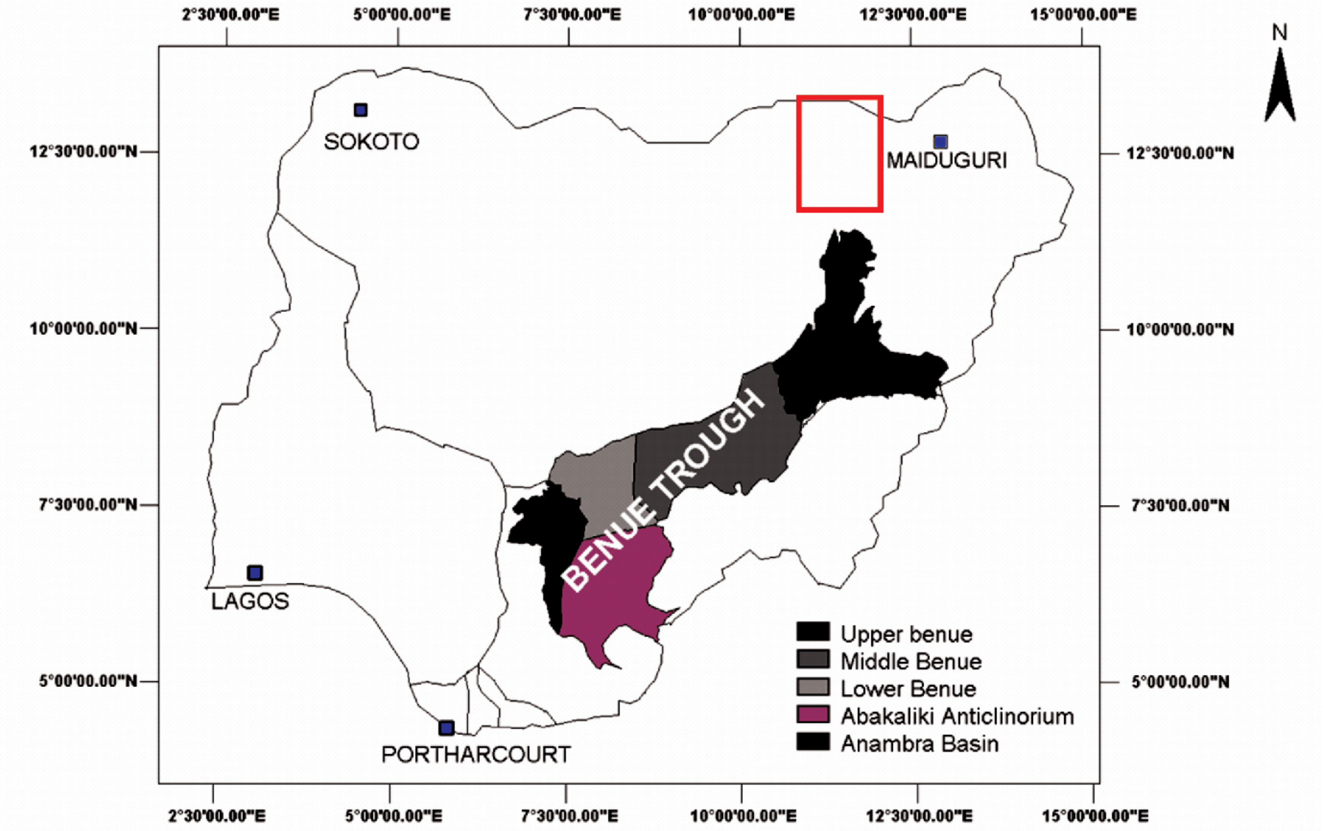

Fig. 1: Map of Nigeria showing the major subdivisions of the Benue Trough and the Gongola basin (red box) (after Ologun *et al*, 2008)

of sandstones and the beginning of limestone-shale deposition. The Yolde Formation is overlain with the Pindiga Formation which is a marine shale facies with basal limestone. Overlying the Pindiga Formation is the Maastrichtian Gombe Formation which consists of sandstones, siltstone, claystone, silty shales and ironstone in the Gombe axis (Akande et al,1998). Overlying the Gombe sandstone is the Tertiary Kerri-Kerri Formation which is made up of whitish grey sandstones, siltstones and claystones.

Materials and Methods

Data Available

Magnetic data- The data set used for this study is an aeromagnetic survey data 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 (fig 3). 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 (fig 4) with a ground resolution of 5 meters was used. This coverage offered by SPOT-5 is a key asset for applications in medium-scale mapping such as 1:25 000 and 1:10 000.

Digital Elevation Model (DEM)- The DEM data set (fig 5) for this study is from the SRTM (shuttle Radar Topography mission) flown by NASA that derived digital elevation models of the earth's surface. The SRTM data of the Gongola basin was acquired from the Global Land Cover Facility (GLCF).

Reduction to the Equator (RTE)

The shape of a total magnetic intensity anomaly is affected by the direction (inclination and declination) of the magnetization and the earth's magnetic field effects. When the inclinations of the vectors are either 90 or 0, the magnetic anomaly is not centered over the source. A reduction to the pole (RTP) or reduction to the equator (RTE) is normally used to remove this effect of inclination and declination and hence centre the anomaly over the source. The RTE transformation was applied to the magnetic data using Geosoft's magmap with an amplitude correction of 14 degrees, declination of -2.011, and inclination of -3.413 (from the IGRF 12 Model).

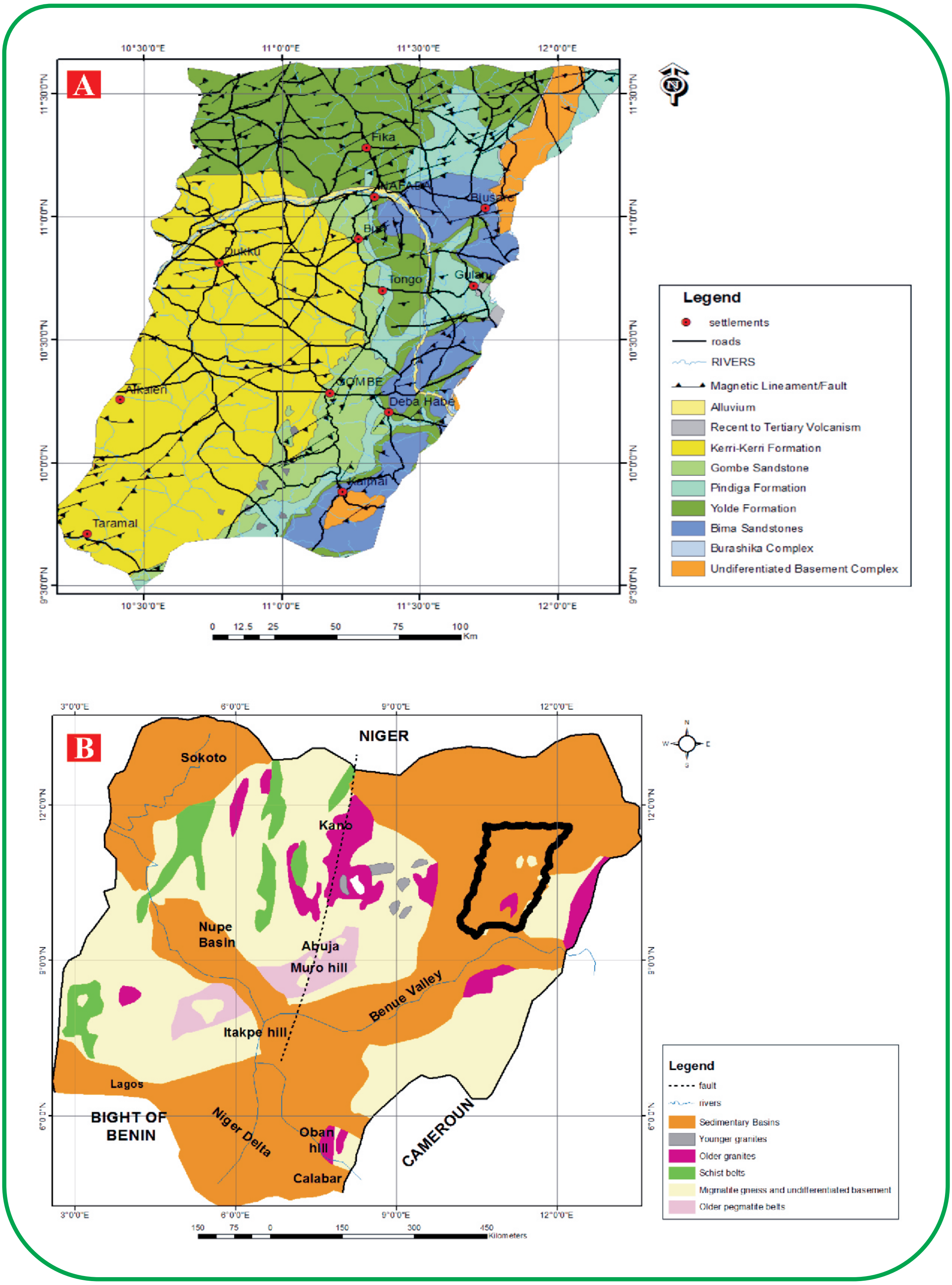

Fig. 2: ***(a)*** Geological Map of the Gongola Basin. ***(b)*** Geological map of Nigeria showing study area in black polygon)

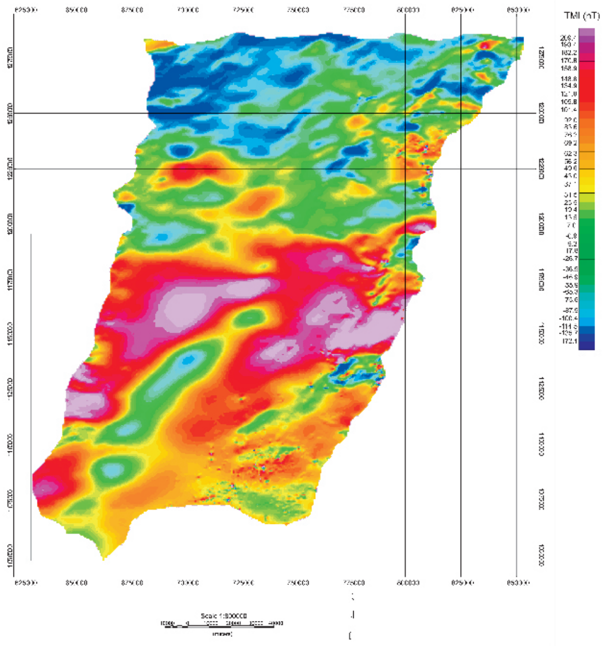

Fig. 3: TMI Grid of the Gongola Basin

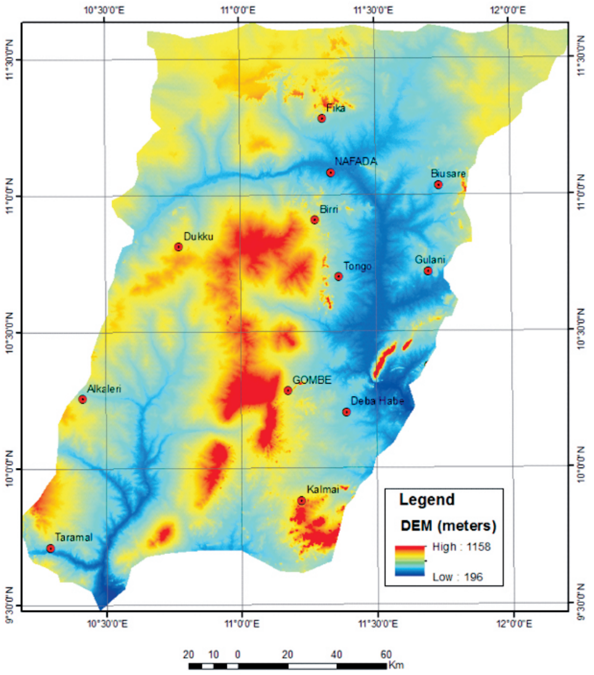

Fig. 5: Digital Elevation Model (DEM) of the Gongola Basin

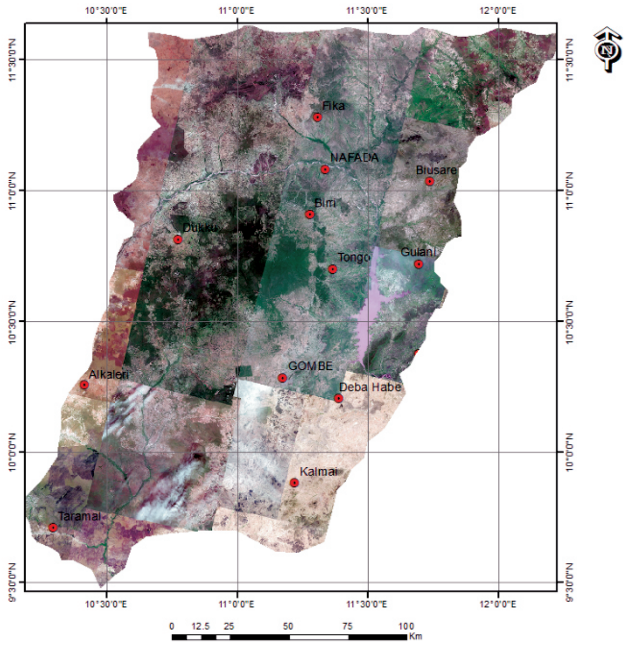

Fig. 4: SPOT5 image of the Gongola Basin

First Vertical Derivative

The first 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 reduced to the equator (RTE) aeromagnetic data of the study area and the output is shown in fig 7.

Regional-Residual Separation and Filtering

Magnetic anomalies as seen on aeromagnetic data are made up of variations in the regional field, the residual field and noise (Reeves, 2005). The regional field in the case of the Gongola basin is the Basement Complex mainly gneisses and migmatite gneiss that underlies the sediments. The residual field is made up of high frequency components that could be intrusives or volcanics and the noise is mainly cultural noise from settlements within the basin. This implies that the total magnetic intensity (TMI) grid data is composed of a wide range of wavelengths. One of the objectives of this research is to derive depth to the basement and map out basement faults, so high frequency component of the data which constitute the residual field should be

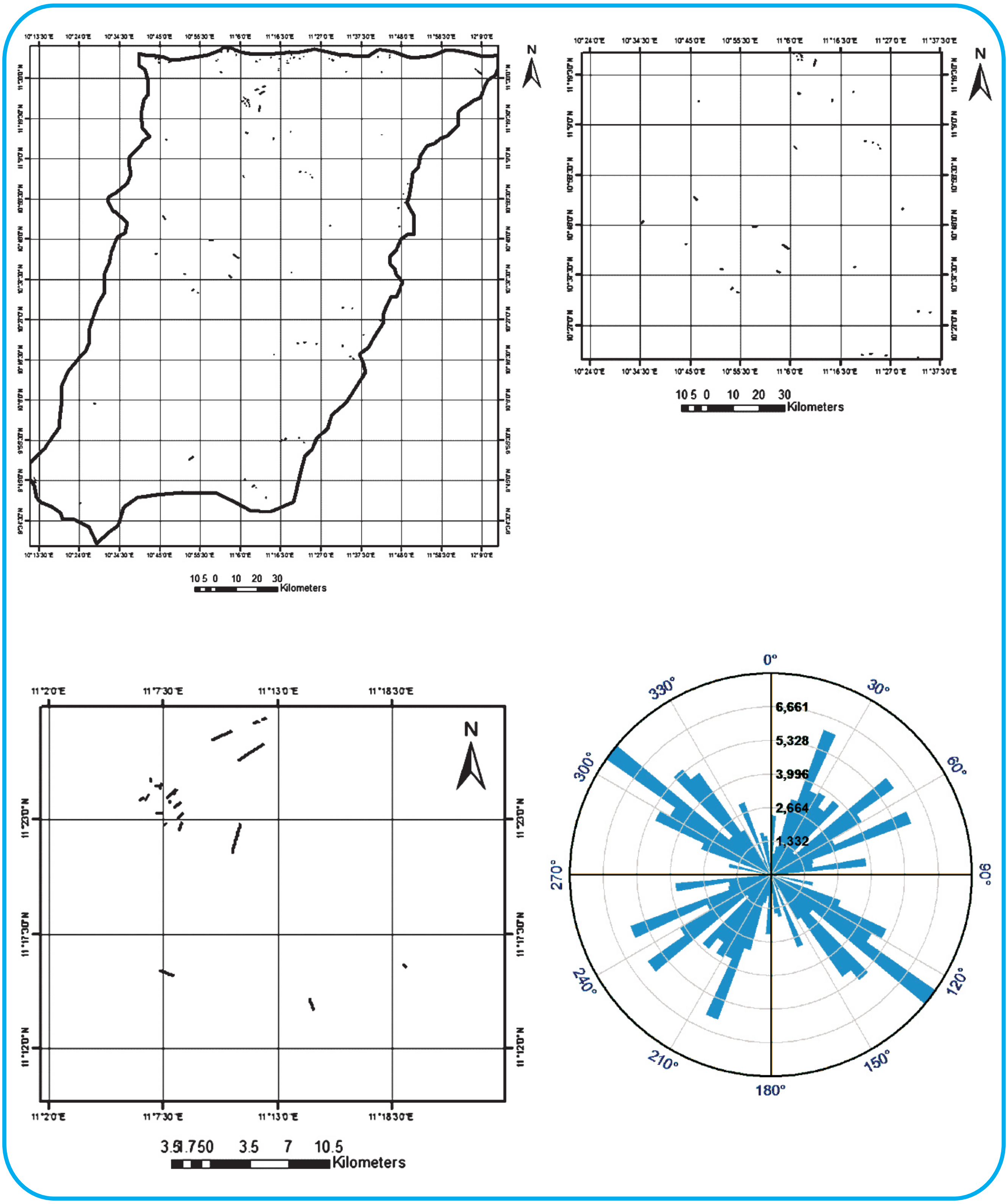

Fig. 6: ***(A)*** Lineaments extracted from the SPOT5 data of the Gongola Basin ***(B)*** Upper part of the basin **(C)** Middle part of the basin **(D)** Rose diagram showing the distribution of lineaments by direction and length

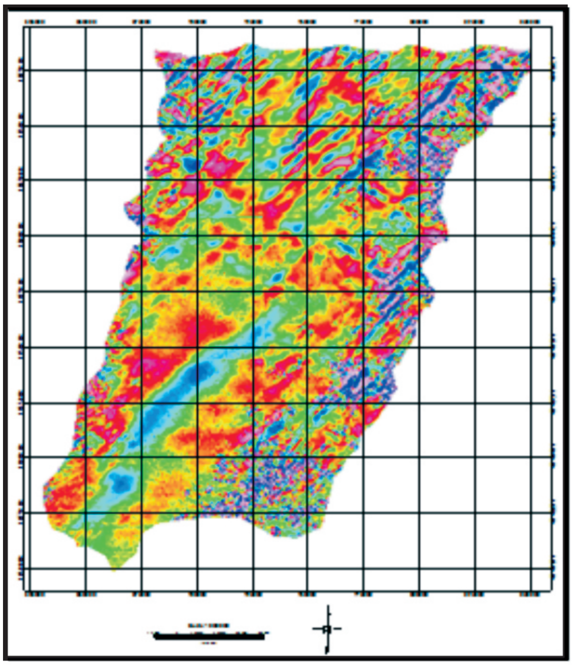

Fig. 7: First Vertical derivative grid

removed. To separate the regional field from the residual field, a low pass filter was applied to the data where low wavenumbers (long wavelengths from the regional field) are passed and high wavenumbers (short wavelengths) rejected. A cut-off wavelength of 3 km was selected with a Gaussian roll-off to minimize ringing. The choice of 3km as cut-off wavelength was based on results of previous studies that suggested maximum sedimentary thickness of about 3.5 km *(Alagbe and Sunmonu, 2014*;Salako and Udensi, 2013). Exploration wells were also drilled in the basin and the deepest well (about 2773 m deep) did not encounter the basement.

Total horizontal derivative of the RTE data

Total horizontal derivative is a good edge detector because it computes the maxima over the edges of the structures.

Full (or Total) Horizontal derivative THDR = $\sqrt{\left[\frac{\partial T}{\partial x}\right]^2 + \left[\frac{\partial T}{\partial y}\right]^2}$ ....(I)

The horizontal gradient method measures the rate of change in magnetic susceptibility in the x and y directions and produces a resultant grid. There is no change in the frequency content of the TMI and the total gradient but the spectral phase of the gradient changes (Cordell and Grauch, 1985). This makes it insensitive to noise and aliasing. The gradients are all positive making this derivative easy to map. This method will show contacts that are linear and very continuous, because it requires only horizontal derivatives. Strike direction of the contacts can be estimated accurately within small windows. This derivative was applied to the RTE data of the Gongola basin using Geosoft's oasis montaj and the output is shown in fig 8.

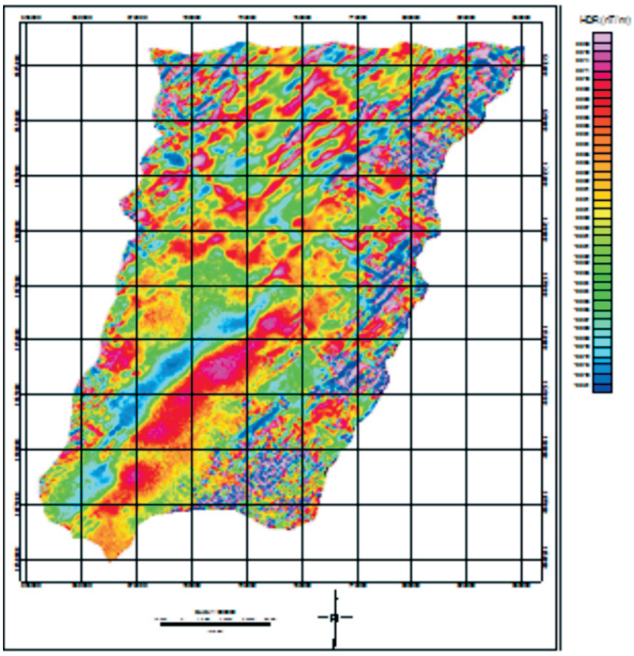

Fig. 8: Horizontal derivative grid

Tilt derivative of RTE

The ratio of the vertical gradient to the total horizontal derivative which is always positive has been defined as the tilt angle (Miller and Singh, 1994). The Tilt derivative (TDR) is defined as-

Tilt derivative $\mathbf{TDR} = \tan^{-1}\left[\frac{\mathbf{VDR}}{\mathbf{THDR}}\right]$ ....(II)

The TDR was used in this study to enhance anomalies that could be basement faults (fig 9). The tilt-derivative (TDR) is useful because of some of its peculiar characteristics. It tends to equalize the amplitude output of TM 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

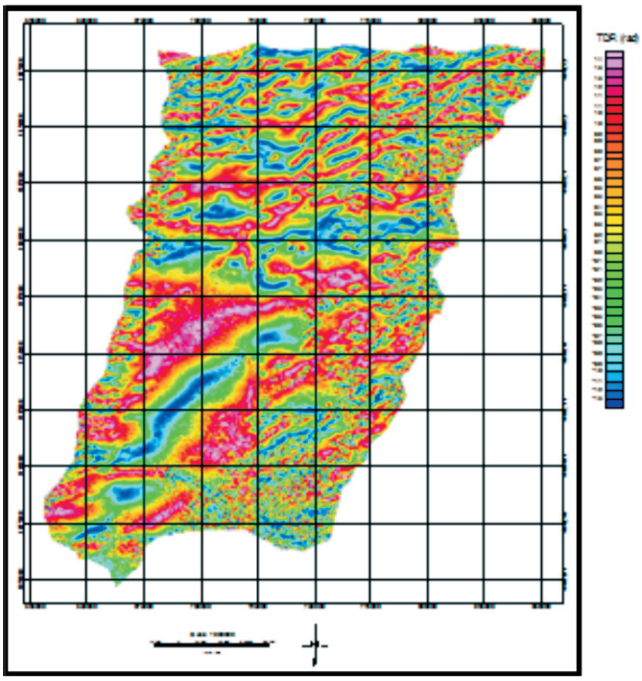

Fig. 9: Tilt derivative grid

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 for RTE and RTP data.

Digital Terrain 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). To derive the drainage network, the Strahler method of stream ordering was used. In the Strahler method, the links without any tributaries are assigned an order of 1 and are referred to as first order. The stream order increases when streams of the same order intersect. Therefore, the intersection of two first-order links will create a second-order link, the intersection of two second-order links will create a third-order link, and so on (Tarboton et al.,1991).

Qualitative Interpretation

To start the qualitative interpretation of the Gongola basin, all the data sets which included all the derivatives produced in Geosoft's oasis were imported into the ArcGIS Software. It was ensured that all the data sets have the same coordinate system (WGS_1984_UTM_Zone_32N) so that they could be overlaid on each other. All the data sets were displayed as layers which were overlaid on each other within the data frame of ArcMap. To view the map below another map, the small box before the map name in the display box can be unchecked. Alternatively the effects tool can be used to swipe the layer above so as to view the map below. The zoom tool also makes it possible to zoom in or out of any of the layers. All these interactive tools were used to study the features in all the data sets to see their similarities or differences as the case may be.

Geological/Structural Mapping in a GIS Environment

One of the applications of remote sensing and GIS is geological and structural mapping. Using satellite data and other ancillary data, in this case derivatives from the magnetic data of the Gongola Basin details of the structural features within the basin were elucidated. The first stage of the on-screen 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 DEM of the study area. The SPOT 5 data was passed through edge enhancement image processing using the ERDAS Imagine software so as to enhance the surface geological features and give

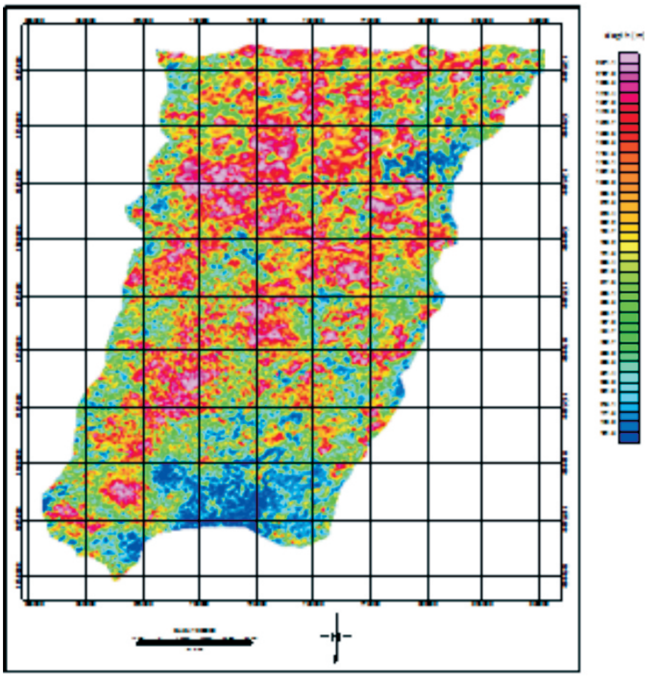

Fig. 10: SPI grid of depth estimates

a good contrast between the settlements which appear as cyan colour and the surrounding pixels due to vegetation or water.

The next stage involved mapping out on-screen lineaments observed from the SPOT 5 image and 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 DEM was able to show the outline of surface geological features such as dikes and ridges which were 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 not well pronounced in one data set can be more pronounced in another data set. Three shapefiles were created in ArcCatalog, for the digitized surface lineaments, magnetic lineaments and the potential volcanics in the Basin.

Depth to Basement Inversion from Magnetic Data

One of the objectives of this research is to derive estimates of depth to magnetic bodies in the Gongola Basin and hence the thickness of the overlying sediments. The Local wavenumber/source parameter imaging (SPI) method was used for this study. 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.

Local wavenumber can be derived using methods described by Verduzco et al (2004) and Fairhead et al (2004) where the Tilt derivative (TDR) and local wavenumber (Total horizontal derivative of the TDR) are written as-

$$TDR = tan^{-1}\left[\frac{VDR}{THDR}\right] \text{..(III)}$$

and

$$THDR\_TDR = \sqrt{\left[\frac{\partial TDR}{\partial x}\right]^2 + \left[\frac{\partial TDR}{\partial y}\right]^2} \text{..(IV)}$$

Where
VDR = First vertical derivative of the TMI data
THDR= Total horizontal derivative which is always positive
X and y = Cartesian coordinates

The technique works well at all magnetic latitudes which makes it a good choice for the Gongola 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 reduced to the equator data of the Gongola basin. 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 Upper Benue Trough by other authors. The depth solutions were saved in a database which was edited to account for the terrain clearance of 80 meters before being exported to ArcGIS.

Depth to Basement Structure Map

A depth to basement map of the Gongola basin was produced from the depth estimates that were derived from the Local wavenumber method and the structures extracted from the structural mapping using the Horizontal and Tilt derivative. The basement lineaments/faults were displayed in ArcMap and the depth solutions from the SPI method were overlain on them. 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 grid was displayed in ArcMap and the faults overlaid on it produce the structural-depth map. Contours of the depth to basement grid were also extracted in Geosoft and overlain on the structural-depth map for better visualization of configuration of the basement.

Results and Discussion

The major structural trend observed from SPOT 5 imagery is NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W trends (fig 6) and they range in length from 200 m to about 3 km, but majority of them are less than 1 km in length. These trends have also been observed from Landsat study (Ananaba and Ajakaiye, 1987) and interpretation of SPOT 5 imagery (Ogunmola, et al, 2014). The high frequency and low wavelength part of the data that was derived from the vertical derivative (fig 7), correlates with the location of exposures of undifferentiated basement in the south eastern and northeastern parts of the basin, which made it possible to clearly define the boundaries of the Kaltungo inlier and also map out potential volcanics around the Kaltungo area (fig 3). Qualitative interpretation of the magnetic data, shows that the basin is dominated by several NE-SW trending anomalies, the most prominent one being a magnetic low in the southern part of the basin, that stretches for about 116 km in length and about 20 km wide.

The integration of the tilt derivative, horizontal derivative and vertical derivative was very useful in understanding the geology of the basin. From the horizontal derivative, the major anomaly appears as a continuous stretch as also reported by early workers (Shemang, et al, 2001) but the tilt derivative clearly shows that a magnetic high (about 1.3 rad) which could be another fault cuts across the major anomaly north of Taramal at the southern part. The dominant trend of the magnetic lineaments derived from the derivatives was found to be in the NE-SW with a few E-W direction and range in length from about 3 km to about 100 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 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 workers (Wright, 1981). Structures within the basement trend in a predominantly NE-SW direction while those within the overlying sediments observed from field study and the SPOT 5 image trend in several directions. This may imply the operation of several paleostress regimes on the sediment. The sediment overlying could also have experienced the transmission of residual stress from the underlying basement. The grid of the depth solutions derived from the Source Parameter Imaging is shown in fig 10. The depths range from about 1 km to about 3 km with the shallowest part being in the eastern part of the basin. Basement depths are taken as sediment thickness since sediments are generally non-magnetic. In neighboring Chad Republic, the Balanga well spudded oil at a depth of 3,567 meters in the Cenomanian sediment. Also the Madama-1 well in the Termit basin in Niger Republic spudded oil at a depth of 3810 meters also in a Cenomanian sediment (Abubakar, 2014; Peters and Ekwezor,1982). In this light, the depth of burial of sediment within the Gongola basin may be inadequate for hydrocarbon generation. The structure-depth maps (fig 4 & 7) show that the major anomaly within the basin occurs at a depth of about 3km.

Conclusions

The conclusions drawn from the interpretation of the high resolution magnetic data and SPOT 5 imagery of the Gongola basin include the following:

1. The major structural trends observed in the sediments from SPOT 5 imagery is NNE-SSW, NE-SW followed by the NNW-SSE with a few N-S and E-W. They range in length from 200 m to about 3 km.
2. The dominant trend of the magnetic lineaments derived from the derivatives was found to be in the NE-SW with a few E-W direction and range in length from about 3 km to about 100 km.
3. The major magnetic low in the basin is discontinuous and it alternate with magnetic highs which suggests horst and graben architecture of the basin floor.
4. The structures patterns in the overlying sediments may have partly resulted from the transmission of residual stress from the underlying basement.
5. The deepest parts of the basin are in the central parts where the Cretaceous sediments are up to 3 km thick.
6. The depth of sediment burial may be inadequate for hydrocarbon generation in the Gongola basin.

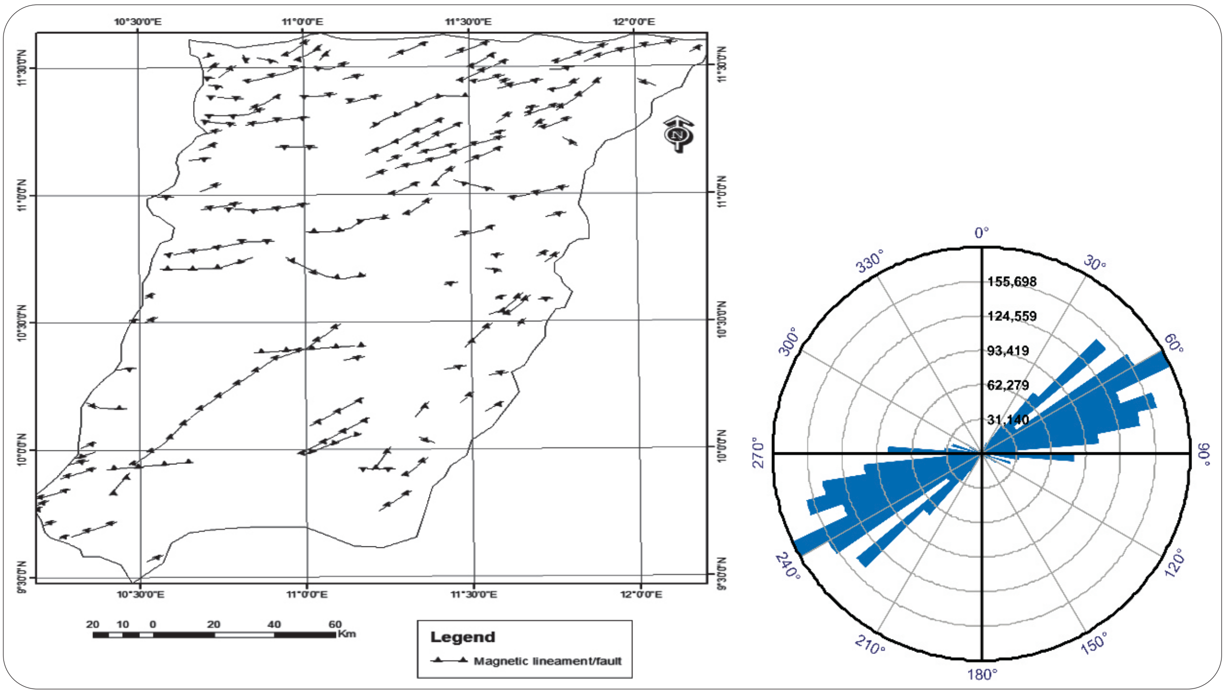

Fig. 11: Faults derived from the magnetic derivatives of the study area and Rose diagram showing the distribution of faults by direction

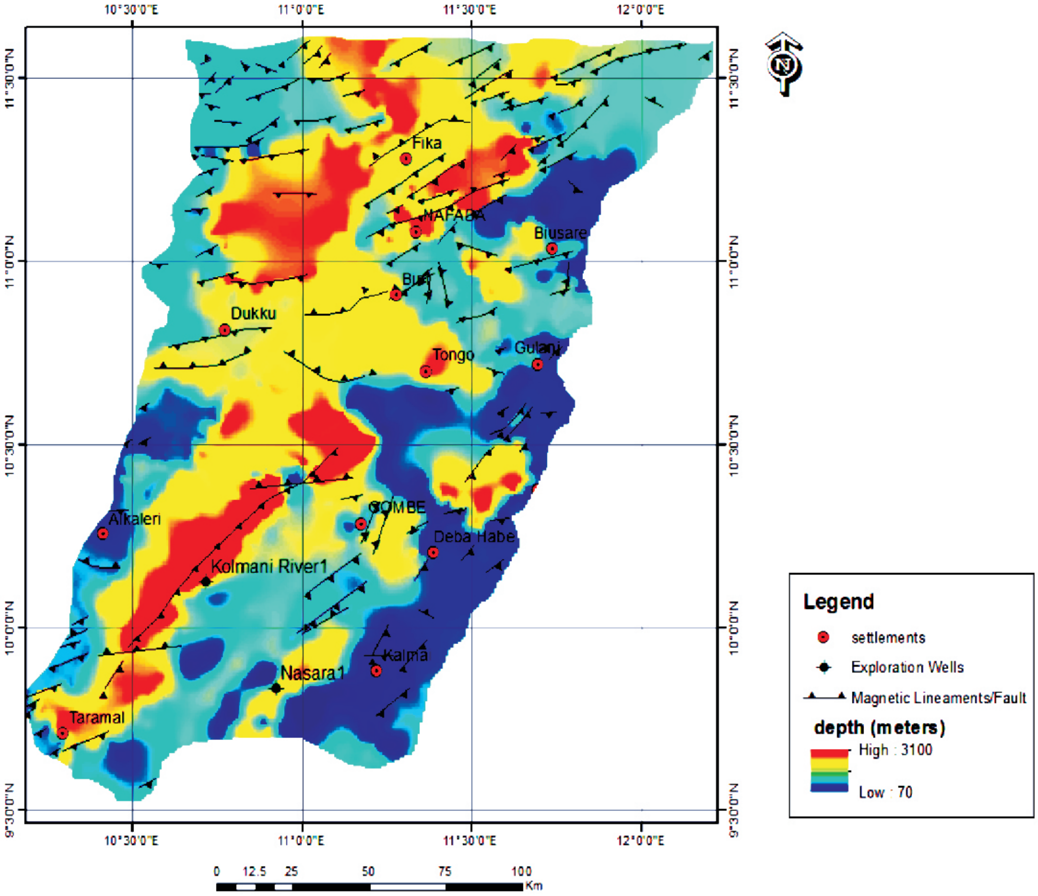

Fig. 12: Depth to Basement structure map of the Gongola Basin

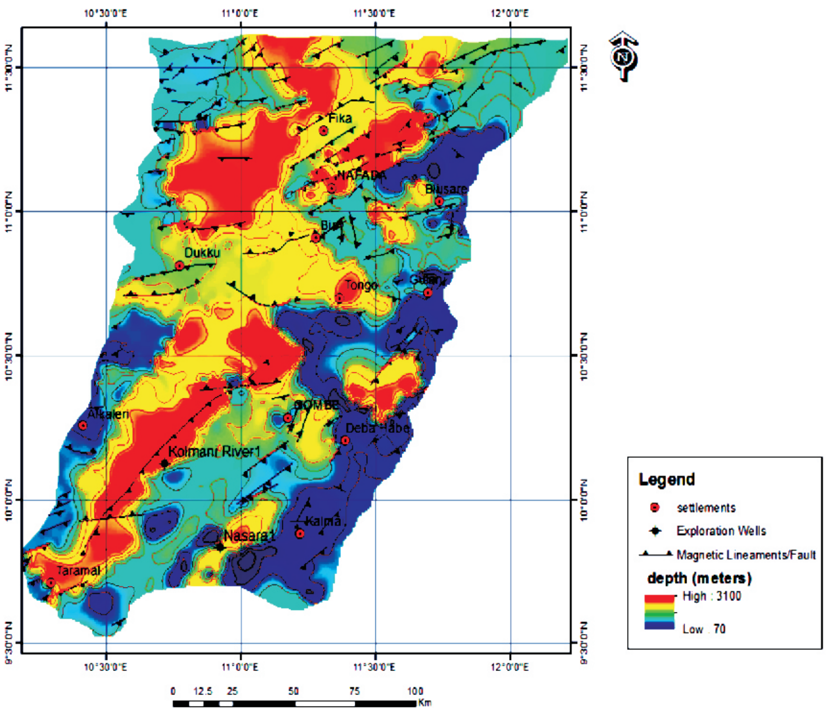

Fig. 13: Depth to Basement structure Map of the Gongola Basin with an overlay of the depth contours

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