Interpretation of High Resolution Aeromagnetic Data for Hydrocarbon Exploration in Bornu Basin, Northeastern, Nigeria

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Abstract

Hydrocarbon exploration in Bornu basin, Northeastern Nigeria commenced due to the discovery of gigantic hydrocarbon reserves in extended basins in neighboring countries. This study was carried out to map the Mungono and Marte parts of the Bornu basin for geologic structures that could guide in exploring new hydrocarbon fields using aeromagnetic method. Magnetic Intensity grids and their derivatives were used for mapping these structures while depths of magnetic sources (basement) and corresponding sedimentary thickness were estimated using Euler deconvolution and Source Parameter Imaging (SPI) methods. Anomalies show characteristic high positive polarity in the south in contrast to low magnetic signature of northern domain. Features such as faults, folds and intrusive rock bodies were identified as geological structures that could serve as hydrocarbon entrapment. Lineament analysis shows that fractures generally trend NE-SW following the dominant rift system of Bornu basin and Benue Trough. Three basement depressions with thick sediments (more than 3000 m) were also delineated which should be investigated for further petroleum exploration. The outcome of this study would help in delineating promising areas for detail hydrocarbon prospecting in the area.

1. Introduction

Petroleum exploration and production activities in Nigeria have over the years focused on the Niger Delta province, which is the source of the hydrocarbon produced in the country. Recently, the research for hydrocarbon has been extended to Inland petroleum basins to improve the nation's reserve. Bornu Basin is one of the mostly explored inland basins in Nigeria with the early speculation of commercial quantities of hydrocarbon

[Okosun, 1995; Anakwuba and Chinwuko, 2012]. Although this exploration started long ago, results are insufficient to confidently reach conclusion about the hydrocarbon potential in the basin. Aggressive exploration in Bornu Basin commenced more recently due to the discovery of hydrocarbon deposits in commercial quantities in adjacent (Doba, Doseo, Bongor, LogoreBirni and Termit-Agadem) basins in Nigeria's neighboring countries (Chad, Niger and Sudan) with similar structural settings [Nwankwo and Ekine, 2009; Anakwuba et al., 2011; Dieokuma et al., 2013]. New drilling and exploration results have also confirmed that the basin have possible source rocks, reservoir rocks and migration/structural pathway [Dieokuma et al., 2013]. However, the amount of in situ information has not really improved during the time due to security issues. Thus, a more remote method of exploration such as airborne method is required to continue the research and gather useful information about the basin.

Highlighted technical issues in the search for hydrocarbon in the basin are typically related to sediment distribution and variation in the sediment thickness across the basin, structural uncertainty as well as thermal maturation. A regional study is required to focus on basin structure (basin geometry, basement topography, fractures, anticlinal and synclinal structures), and sediment thickness variation across the basin especially around the promising area (Lake chad region). This will be helpful in explaining the results obtained from existing wells and also guide in systematic hydrocarbon exploration.

Geophysical methods have been used previously to investigate sedimentary basin in order to determine the hydrocarbon potential of such basin. These methods provide useful information regarding the basement rocks, geologic fabrics and structural features that could have impact on the overlying sedimentary units [Osinowo et al., 2014; Obiora et al., 2015]. Moreover, magnetic method has been remarkably useful as a result of the relatively high magnetic susceptibility contrasts between basement rocks and sedimentary rocks, which usually play an obscure role on the magnetic signals emerging from the underlying basement rocks [Dobrin and Savit, 1988; Kearey et al., 2002; Osinowo et al., 2014]. Aeromagnetic survey is a geophysical method that has been applied for modern geological mapping. Moreover, its operating principle is similar to that of the magnetic survey but covers larger areas of the Earth's surface mostly as regional reconnaissance. The main objective of aeromagnetic survey is the investigation of the subsurface geology based on anomalous variation of Earth's magnetic field linked to properties of the subsurface rocks [Kearey et al., 2002; Onuba et al. 2008].

Several studies have been done with the use of airborne geophysical survey to delineate the structural patterns of the rocks in Nigeria [e.g., Ajakaiye 1981; Adeniyi, 1985; Yusuf, 1990; Alagbe and Sunmonu, 2014; Anakwuba and Chinwuko, 2012; Aderoju et al., 2016; Oha et al., 2016]. Anakwuba and Chinwuko [2012] also employed aeromagnetic data to evaluate the hydrocarbon deposits in some parts of Chad Basin, Nigeria. The authors identified both shallow and deep depth sources with average depth of 1.5 km and 3.8 km respectively having a thick sedimentary coverage with thickness ranging from 1 km to about 6 km. They also identified three major faults delineating potential areas for exploration of hydrocarbon. Osinowo et al. [2014] employed aeromagnetic data to map Siluko area of the transition zone in the southwestern Nigeria. They identified some structures and thick sedimentary deposits as possible factors responsible for the deposition of tar sand and bitumen/oil shows in the area. Oha et al. [2016] used high resolution aeromagnetic data in parts of the southern Benue Trough for the estimation of the depth of magnetic sources and mapping of the structural features. Their study shows that southern Benue Trough have high potential for large accumulation of base ore mineralization and less suitable for hydrocarbon exploration. The reason attributed to the outcome of their study is the identification of abundant intrusive bodies in the study area. Aderoju et al. [2016] investigated the potential for hydrocarbon in some parts of Chad Basin using high resolution aeromagnetic data. They identified thick sedimentary formation, faults, fractures and magnetic aureoles that could be indications of high prospect for hydrocarbon exploration. Bello et al. [2017] used qualitative and quantitative interpretations of aeromagnetic data in the onshore area of Niger Delta to estimate the depth to basement and to delineate possible areas that could be suitable for hydrocarbon exploration. In their study, they identified thick sedimentary fills, structural lineaments (faults and fractures), and magnetic intrusions. They concluded in their study that the identified features in the study area may suggest possible areas for hydrocarbon exploration.

Therefore, this study was carried out using aeromagnetic data to add value to the understanding of the subsurface geology of the Bornu Basin. This is expected to give valuable information about the the basin structures and its hydrocarbon potential. This study is focused on basin geometry and features, basement topography and fill thickness variation across the study area. The results obtained from this study will help in delineating promising areas for detail hydrocarbon prospecting.

2. Description of the study area

The study area is in the northeastern part of Nigeria (Figure 1). It is within the Marte Local Government area of Borno State, Nigeria, on the western coast of Lake Chad. It covers area of about 7,200 km^2 between longitudes 13° 30' 00'' E and 14° 00' 00'' E and latitudes 12° 00' 00'' N and 13° 00' 00'' N. It can be easily accessed through a road about 60 km North of Bama and through another road which is about 20 km South of Baga in Maiduguri area (Figure 1).
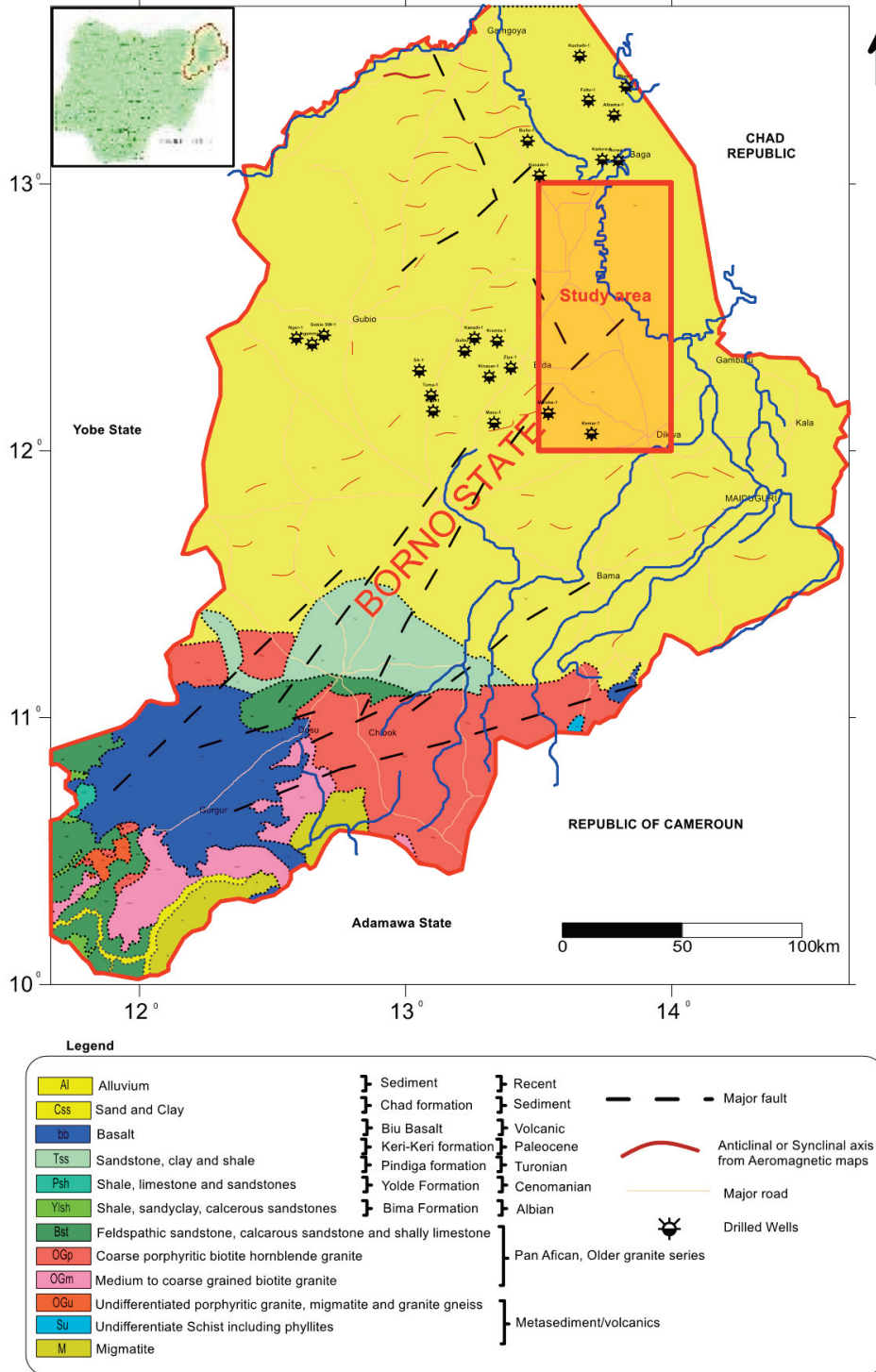

Figure 1. Geological map of Borno state showing the location and geology of the study area (NGSA 2014).

2.1 Regional Geologic Framework of Chad Basin

Chad basin is the largest intracratonic basin in North-central Africa, and it is characterized by Cretaceous and Tertiary rift covering a very wide land mass area from parts of Algeria, Niger, Chad, Southern Sudan, to northern parts of Cameroon and Nigeria [Matheis, 1975; Avbovbo et al., 1986]. Figure 2 is a regional map showing the location of Chad and neighboring basins.
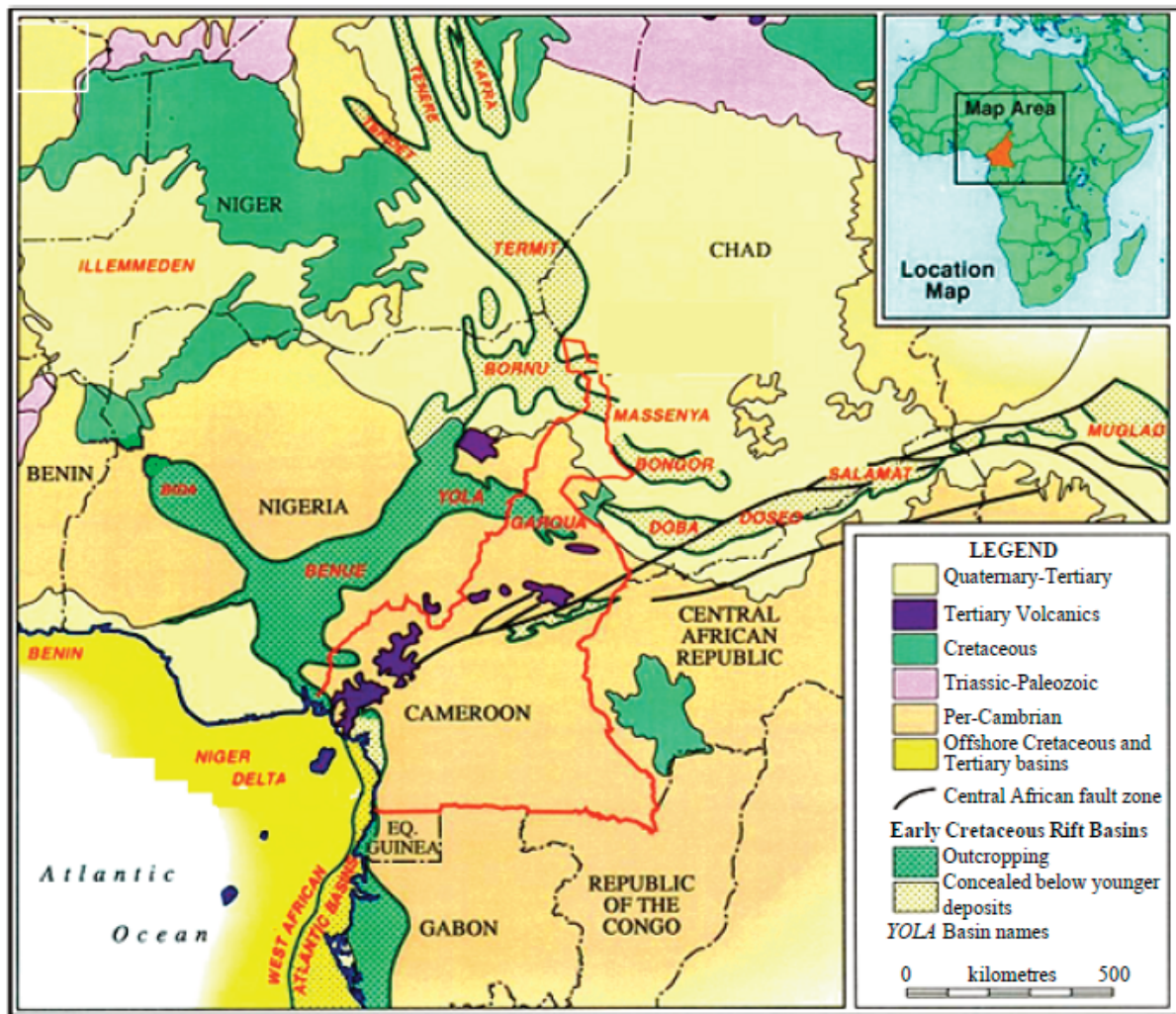

Figure 2. Regional map showing the location of Chad and neighboring basins

The breakup of West Africa and South America was accompanied by rifting in the Early Cretaceous and this led to the formation of the basins, thereby creating depositional sites for the continental and marine rocks that were deposited in the basin [Fairhead and Green, 1989; Genik, 1992, 1993]. These continental rocks were deposited in the northwest to southeast trending Western African Rift System, to a thickness of 2,000 to 5,500 m [Genik, 1993]. Early Cretaceous is marked by the deposition of fluvial and lacustrine rocks in the basin [Genik, 1992; 1993]. A regional sag event in the Late Cretaceous (Cenomanian to Maastrichtian) formed a broad basin leading to a marine transgression where the shallow marine to marginal marine and coastal plain rocks accumulated. During the Late Cretaceous to Oligocene, thick fluvial and lacustrine rocks were deposited which occurred during the last rifting phase in the Chad Basin [Genik, 1993].

The total petroleum system includes Cretaceous and Tertiary lacustrine and marine source rocks, Cretaceous and Tertiary clastic reservoirs, shale seals, and traps that are mostly structural. Hydrocarbons were generated from

Cretaceous and Tertiary lacustrine and marine source rocks and most likely began in the Late Cretaceous. The generated hydrocarbons migrated into Cretaceous and Tertiary reservoirs. Hydrocarbon traps are generally structural and include tilted faulted blocks, drape anticlines, reverse-faulted structures and rollover folds. Some inversion features are recognized [Biswas, 2016; Biswas and Acharya, 2016].

The Nigerian region of Chad basin is known as Bornu Basin which constitutes about 10% of the Chad basin. From the Nigeria context, the separation of the African and South American lithospheric plates and the formation of rift system resulted into subsidence that led to the development of the Benue Trough and the Bornu Basin. Bornu Basin is known to be a broad sediment-filed depression stranding Northeastern Nigeria and adjourning parts of the Chad Republic.

The stratigraphy of the Bornu Basin has been previously described by various researchers [Avbovbo et al., 1986; Obaje, 2009; Nwakwo and Ekine, 2009; Odebode, 2010; Olabode et al., 2015]. The thickness of the sedimentary units is more than 3.6 km and made up of very thick basal continental sequence and transitional Calcareous deposits. The average thickness of Chad, Kerri-kerri and Gombe Formations are 400, 130 and 315 m, respectively (Figure 3).

System	Series	Stage	Formation	Lithology	Average thickness/m	Thickness from seismic data/m	Outcrop Description
Quater-nary			Chad		400	800 (Average)	Variegated clays with sand interbeds
Tertiary			Kerri-Kerri		130		Iron rich sandstone and clay covered by plinth of laterite
Cretaceous	Upper	Maastrichtian	Gombe		315	0–1 000	Sandstone, siltstone and clay with coal beds. Fossils, bivalve impressions and *Cruziana lebana purren*
		Senonian	Fika		430	0–900	Shale, dark gray to black, gypsiferous with limestone beds
		Turonian	Gongila		420	0–800	Alternating sandstone and shale with limestone beds
		Cenomanian	Bima		3 050	2 000	Sandstone, gravelly to medium grained, poorly sorted and highly feldspathic
	Lower	Albian	Unnamed	???		3 600	Seismically transparent sequence, monolithologic sequence inferred
			Unnamed			0–3 000	Piedmont alluvial fans early rift sediments
Pre-cambrian			Basement				

Sandstone · Shale · Unconformilty

Figure 3. Stratigraphic Sequence of Bornu basin, Nigeria (Odebode 2010)

Chad Formation consist of mudstone and traces of sandstone, muddy sandstone and claystone. The sequence of the Formation consists of massive and gritty clays, loose to uncemented sands and silts. These Formations underlain by Fika Shale which is dark grey to black in color and its average thickness is about 430 m. Below the Fika Shale are the Gongila and Bima Formations having average thickness of 320 m and 3 km respectively (Odebode 2010).Bornu Basin is mostly covered by the sediments of the Chad Formation that are Pleistocene to Pliocene age. It consists mostly of massive and gritty clays, silts and loose to uncemented sands (Figure 1). Older sediments are not exposed in the study area but have been penetrated by wells drilled in the area. Most structures in the basin are results of tectonic activities that occurred during Late Cretaceous which reshaped the basin.

3. Materials and methods

The total magnetic intensity (TMI) data of Monguno and Marte containing line data, grid data and digital plot files and color map on 250,000 scale was provided by the Nigeria Geological Survey Agency (NGSA). The data is part of the high resolution airborne geophysical surveys of Nigeria that were acquired by Fugro Airborne Survey Limited between 2003 and 2009 using fixed wing aircrafts Cessna caravan 208B 2S-FSA, 208 2S-MSJ and 406 ZS-SSC types with digital tracking and recovery flight path systems (Nigeria Geological Survey Agency, 2014). The flight was flown in draped mode with the use of real time differential GPS at a sensor mean terrain clearance of 80-100 m and at flight and tie line directions of northwest-southeast (NW-SE) and northeast-southwest (NE-SW) respectively having traverse and tie line spacing of 500 and 2000 m.

Pre-processing of the data was done by Fugro Airborne survey which include micro-leveling, cultural effects removal and noise content filtering. Two grids of Marte and Munguno were combined to form a composite grid with 1119 profile lines covering an area extent of about 110 km by 55 km. The data were first checked for isolated spikes and other spurious data which bears no geological significance before further processing; and then International Geomagnetic Reference Field (IGRF) corrected using IGRF model of 2005 with mean magnetic inclination, declination and field value of 3.58, 0.099 and 34,769.2 nT respectively. It was then subjected to various filtering operations to extract useful information related to the geology of the area. All filtering operations were carried out by applying filters (high pass, derivatives, analytical signal, upward continuation etc.) in the Fourier domain.

3.1 Qualitative Interpretation

The study area is within low latitude region where magnetic remanence complicates interpretation as reducing the TMI grid to pole and/or equator produced strong artifacts that are not recognized in the original field. These effects are caused by extremely low magnetic declination (near zero). Analytic signal (AS) was alternatively computed to locate the edges of the major magnetic sources since it is almost independent of magnetization direction. Analytic signal (AS) is given as the square root of the sum of the squares of the derivatives in the x, y and z directions as seen in equation 1.

$$AS = \sqrt{(df/dx)^2 + (df/dy)^2 + (df/dz)^2} \tag{1}$$

where df/dx, df/dy and df/dz are the first derivatives of the total magnetic field.

High pass filtering technique were used to output low frequency anomalies. In this process, high frequency anomalies were cut off and events reflecting local geology of the study area are enhanced. A cut off wavelength of 100 m was observed to be considerable with the geology of the area. First vertical derivative helped to enhance shallow sources as well as magnetic lineaments. Horizontal (x and y) derivatives were also computed with respect to x and y azimuths to enhance location of geological contacts [Phillips, 1999]. Tilt derivative filtering was also carried out to enhance weak magnetic anomalies overshadowed by strong structures.

3.2 Quantitative Interpretation

Two depth estimation techniques, Euler (located) deconvolution [Reid et al., 1990] and Source Parameter Imaging (SPI) [Thurston and Smith, 1997; Fairhead et al., 2004] were used to model the basement topography and subsequently give variation in thickness of basin across the study area.

3.2.1 Source Parameter Imaging (SPI)

SPI technique uses the principle of complex analytic signal to compute source parameters from gridded magnetic data. This method adopts first and second order derivatives and thus susceptible to noise and interference effects [Nabighian et al,, 2005]. SPI grids are used to estimate the edge locations, depths and dips. For vertical contacts, the poles of the local wave number define the inverse of depth (equation 2).

$$depth = 1/ Kmax \qquad (2)$$

where $Kmax$ is the peak value of the local wave number K over the step source given in equation 3.

$$K_{max} = \sqrt{(dTilt \, / \, dx)^2 + (dTilt/ \, dy)^2} \qquad (3)$$

and $Tilt = arctan$ (VDR/HGRAD)

$$Tilt = arctan\left[\frac{(dT \, / \, dz)}{\sqrt{(dT \, / \, dx)^2 + (dT/ \, dy)^2}}\right] \qquad (4)$$

3.2.2 Euler Deconvolution

Euler deconvolution was used to estimate magnetic source distance and depth. This approach calculates solutions to conventional Euler equation [Reid et al., 1990] assuming there is no remnant magnetization. Euler deconvolution uses the total magnetic field, first horizontal derivative in x, y and vertical derivative in z-direction. The method makes use of a structural index (S.I.) to compute depth estimates for a variety of geologic structures such as faults, magnetic contacts, dykes, and sills by varying the S.I. locations and depths (x_0, y_0, z_0) of any sources are calculated using equation 5:

$$\frac{df}{dx}(x - x_0) + \frac{df}{dy}(y - y_0) + \frac{df}{dz}(z - z_0) = SI(B - f) \qquad (5)$$

where f is the observed field at location (x, y, z) and B is the base level of the field (regional value at the point (x, y, z)) and S.I. is the structural index or degree of homogeneity.
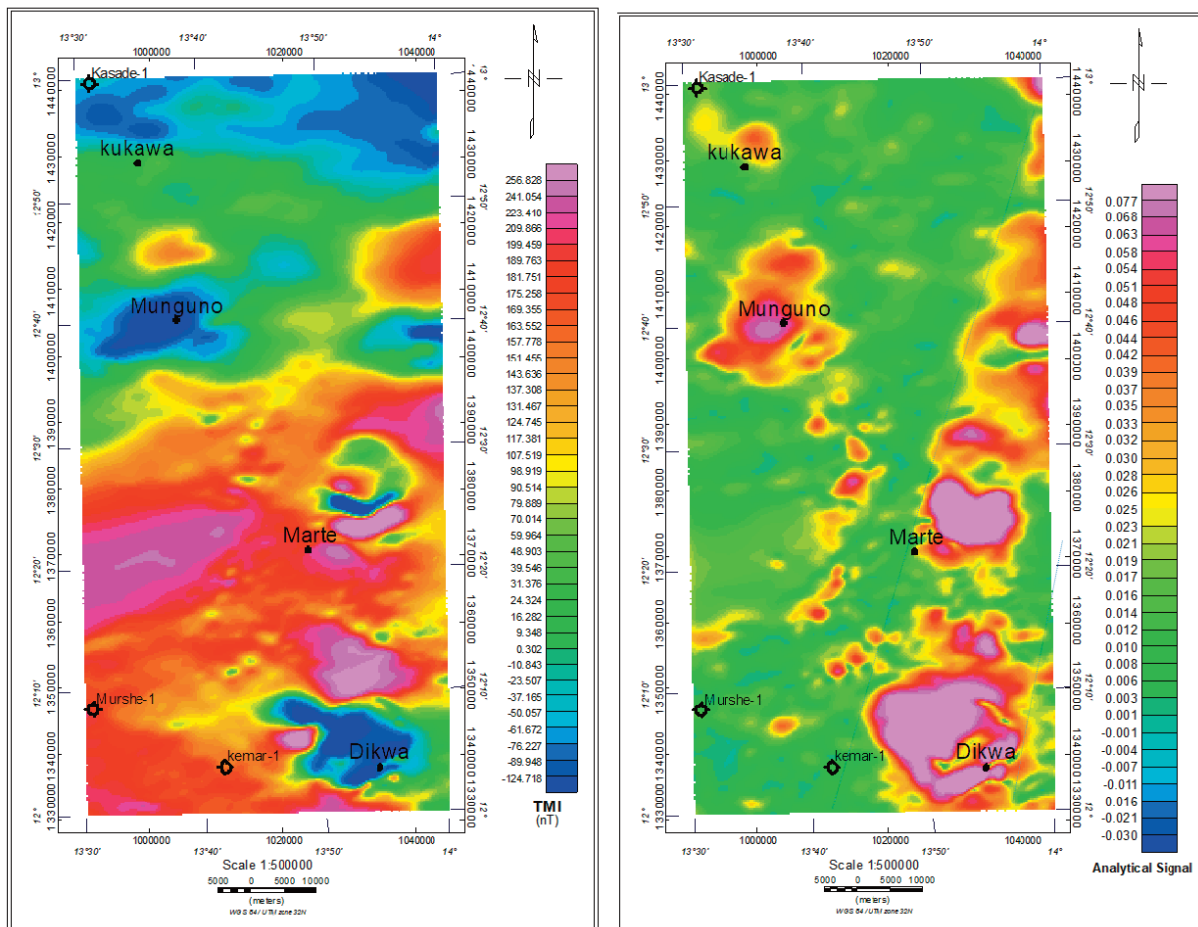
4. Results and interpretation

4.1 Geological Structure Mapping

Total Magnetic Intensity (TMI) grid and its derivatives were used to interpret the aeromagnetic data for identification of geological structures in the area. TMI of the area ranges from -124.7 to 256.8 nT; high intensities dominate the southern part whereas relatively low intensities cover the entire north. These magnetic patterns reflect the general geology of the area. The magnetic highs that characterized the south may be attributed to intrusive, buried bodies, basement horsts or relatively shallow crystalline basement. Notable
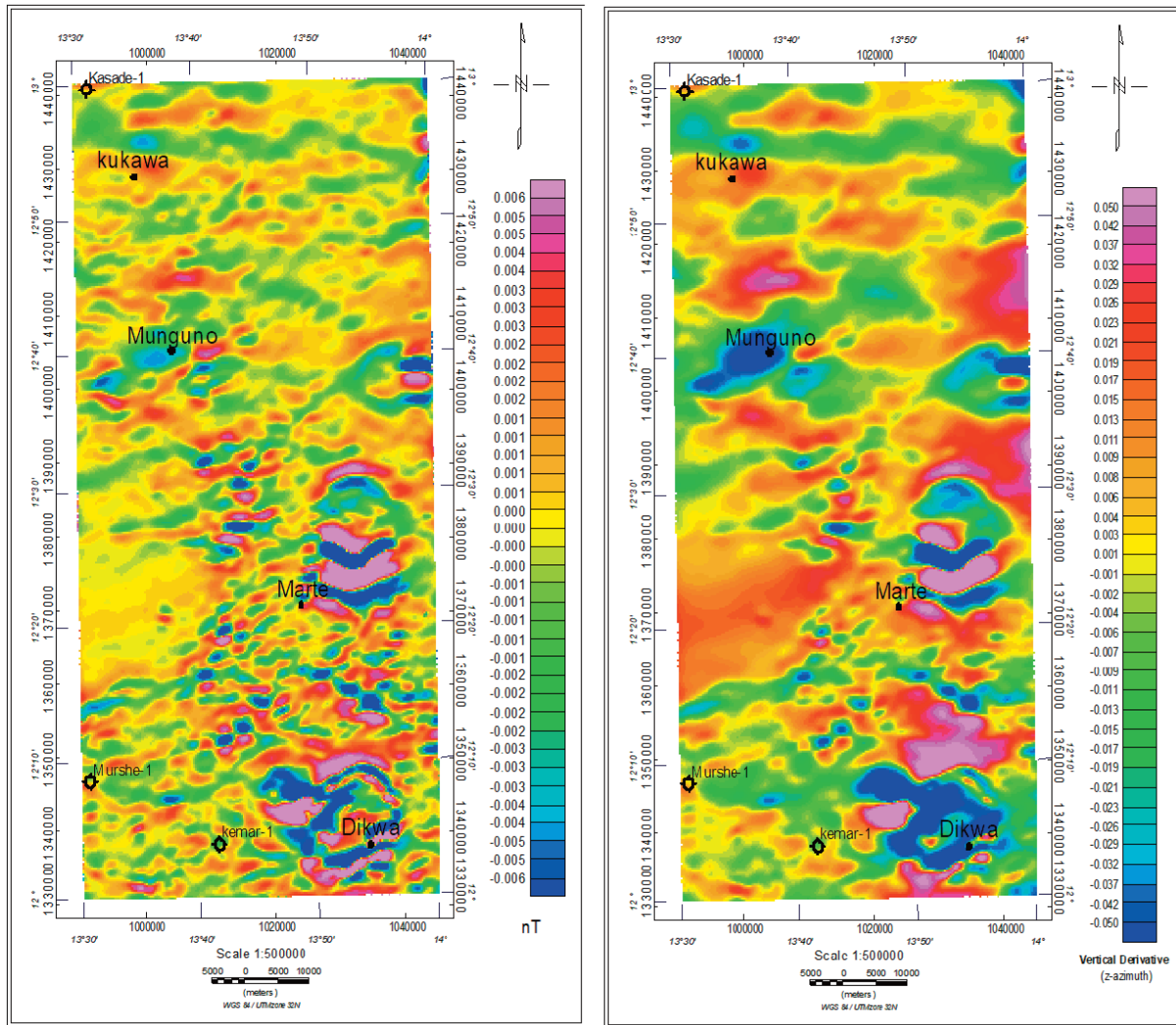
magnetic features identified in the TMI grid (Figure 4a) include an elongated NE-SW trending positive anomaly located west of Marte, and a round shaped negative anomaly around Munguno axis. Other prominent features are ovoid shaped magnetic lows and cover Marte, Dikwa and east of Munguno. The location and edges of these magnetic sources are further delineated using analytic signal grid since the operation is independent of magnetic remanence. There is no remarkable change in the positions of the anomalies seen in both TMI and the analytic signal grids as indicated in Figure 4a & b. However, the analytic signal grid shows that the magnetic bodies around Dikwa and Marte axis form an elongated NE-SW trending mega-structure that extend from southwestern to the northeastern part of the study area as indicated in Figure 4b. This body might represent series of undulating folds in the sedimentary fill.

Derivatives and high pass filtering techniques were carried out to give more detailed information related to the structural geology of near-surface (sedimentary fill and underlying basement). These grids enhanced features that are not clearly discernible in the Analytic signal and TMI grids. The vertical and tilt derivatives grids show that the major structural trends of the area are generally NE-SW, NW-SE and E-W. A more detail structural outline of the magnetic feature around Dikwa and Marte are displayed in the high pass and derivatives grids (Figures 5 and 6). These operations enhanced some sausage shape (curvilinear) features around the magnetic lows observed in the TMI grid. The patterns and the shapes of these features show that they might represent undulating folds which can serve as structural traps in the area. The maps were grey shaded to enhance these lineaments and produce the lineament map of the area as shown in Figure 7. The southern part typified by magnetic highs also corresponds to region with high fracture density with fractures generally trending NE-SW and NW-SE; these likely represent dikes, sills, faults, joints etc.

Figure 4. (a) TMI (IGRF corrected) map of the Munguno and Marte environs. (b) Analytic Signal map (after upward continuation to 500 m) showing edges of the major magnetic sources in the area.

Figure 5. (a) High pass (100 m) map. (b) First vertical derivative map showing shallow geological structure in the sedimentary fills and underlying crystalline basement.

4.2 Basin Modeling

Figure 8a is the contoured SPI depth to source map of the area. It shows a wide depth range of depth solutions which could be as a result of combination of effects of intrusive within the sedimentary basin (shallow sources) and sedimentary-crystalline contact – deep sources [Obiora et al., 2015; Oha et al., 2016; Olurin et al., 2016]. Marte and Dikwa area are largely populated with depth solution less than 1000 m while the northern part is dominated by clusters of solution greater than 2000 m. SPI estimates are similar to Euler results (Figure 8b) when a contact model is assumed (S.I. = 0) and both estimates agree with the TMI grid. Distribution graph of Euler solution shows that about 45% of the estimates are less than 1000 m and more than 90% of this (<1000 m) are populated within clusters of 1000 m to 2000 m around Dikwa, Marte in the southern part of the study area. This likely indicates influence of intrusive rocks within the sediments using Murshe-1 (TD = 3,927 m) and Kerma-1 (TD = 1,790 m) wells as controls. Oha et al. [2016] have shown that shallow solutions observed within clusters of solution could be due presence of granitic intrusions within the sedimentary fill. About 35% of the Euler results are within 1000 to 2000 m and are distributed around the entire study area, while about 15% are within 2000 to 3000 m and are restricted to Munguno and Kukawa areas (this corresponds to magnetic lows in the TMI grid) in the northern part of the study area. Other solutions greater than 3000 m are localized to few kilometers north of Murte-1 well (T.D = 3927 m) representing basement depressions.
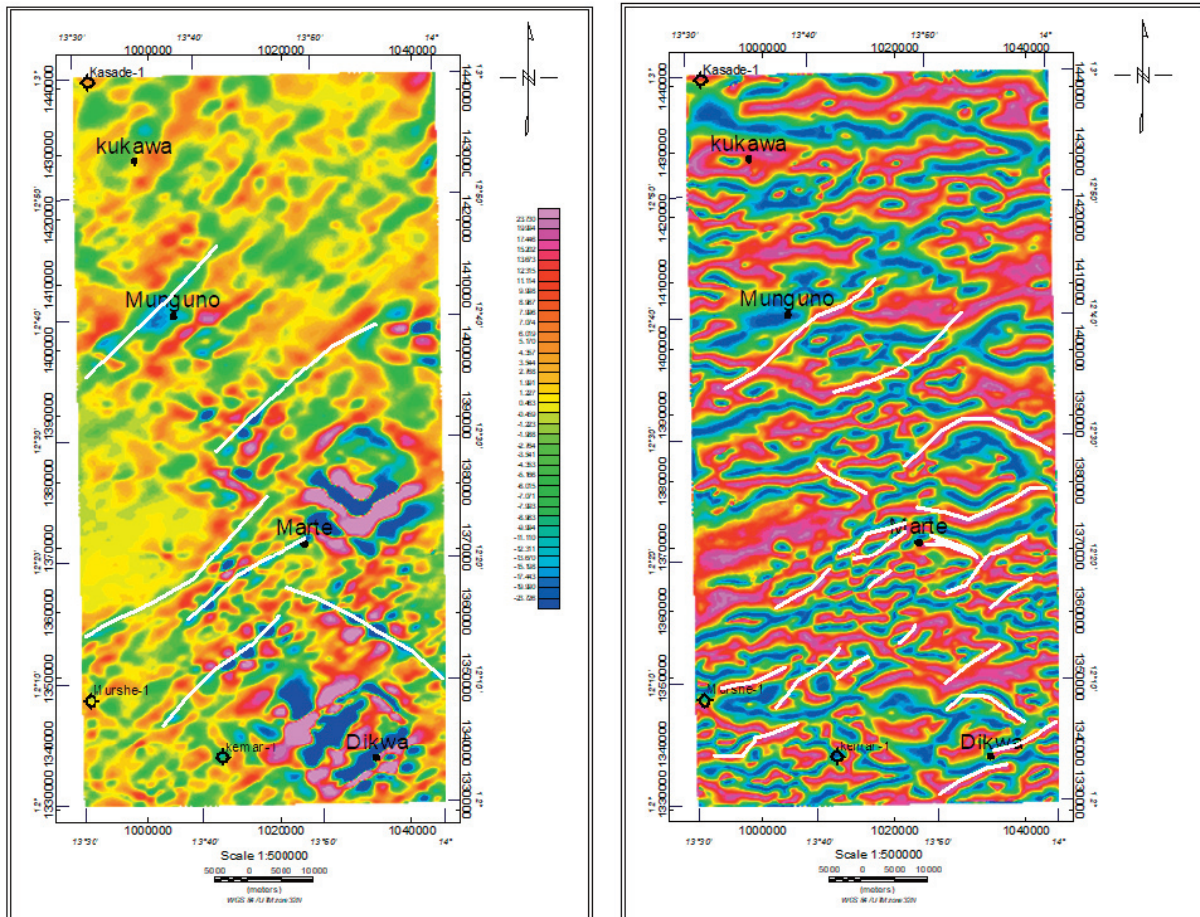
Figure 6. Linear features interpreted from minima and maxima derivatives on (a) high pass map (b) tilt derivative map
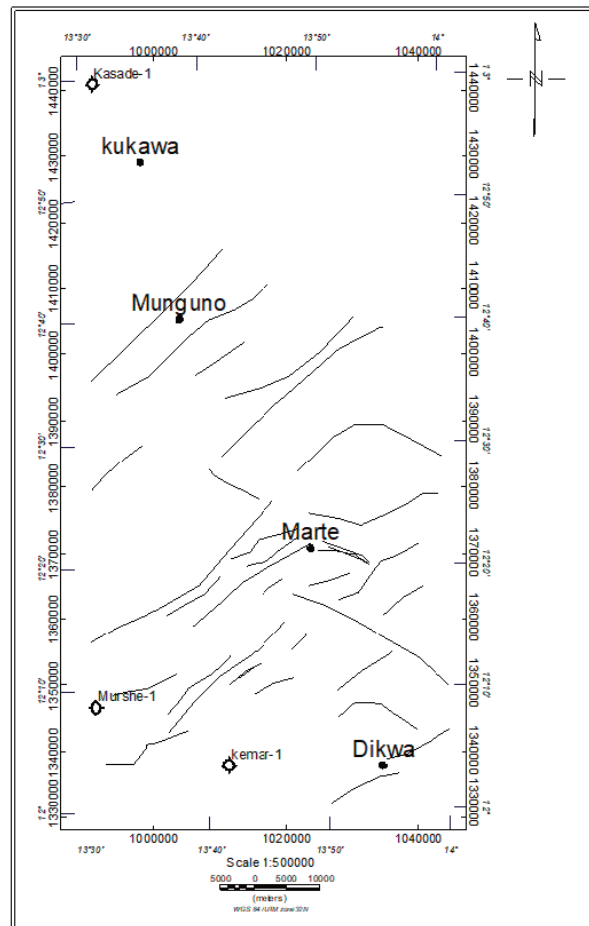
4.3 Basement Topography

Euler deconvolution result was used to generate the 3D basement topography of the area as shown in Figure 9. Basement elevation relative to main sea level (MSL) was estimated at terrain clearance of 100 m. The ruggedness and undulations of the relief as indicated in the model show that the area has been affected by episodes of tectonic events; thus it is therefore difficult to estimate range of basement elevation in the area. However, results show that the deepest basement is in the range of 4200 m below MSL while the sediments are estimated to vary in thickness up to about 4500 m. The 3D basement topography generally agrees with the TMI grid. However, it is difficult to explain why high depth to basement was obtained over the elongated magnetic high observed west of Marte. The relief highlighted in reds and purple, especially in the southern region, can be attributed to intrusive bodies within the sedimentary units or shallow sources around the sedimentary-basement contact; while prominent blue color signify basement depressions. Three basement depressions with thick sediments (>3000 m) have been delineated at West of Marte (the fridge penetrated by Murshe-1 well-TD=3927 m), East of Munguno and NorthWest of Kukawa (Figure 10) and could be investigated for further petroleum exploration.

5. Conclusions

In this study we identified regions with thick sedimentary deposits which could be featured by the presence of high oil and gas reservoirs. The average thickness of sedimentary formation obtained from SPI and Euler methods (2000 m to about 3000 m) is sufficient enough to generate hydrocarbon from the organic rich shale within the formation. Moreover, three basement depressions have been delineated with sedimentary fill thickness of more

Figure 7. Lineament map of the study area

than 3000 m at West of Marte, East of Munguno and NorthWest of Kukawa as possible targets for further hydrocarbon exploration. These regions have sediments thick enough for hydrocarbon generation and possibly host stratigraphic traps. Qualitative interpretation of TMI and its derivatives have been used to identify geological features that could serve as entrapments for hydrocarbon in the area. These features include faults and intrusive rock bodies which are dominantly found in the southern part of the area. The fractures generally trend NE-SW following the dominant rift system of Bornu Basin and Benue Trough. Furthermore, an elongated NE-SW trending undulating feature that extend from Dikwa to the northeastern part was identified within the sediment. Although the bodies have the characteristics of folds (anticlines or syncline in sediment) which could also serve as good structural trap, the geological description of the magnetic event cannot be clearly ascertained solely from magnetic interpretation as no well has been drilled around it. These identified structures (faults, intrusive and fold) should be further explored using seismic method. This study has shown that the study area has high prospect for hydrocarbon occurrence due to the availability of huge pile of sedimentary fills and presence of petroleum entrapping structures (faults, fold, intrusive). It was also shown that the subsurface modelling of the basin using magnetic method is affected by presence of intrusive within the sedimentary rocks, therefore additional data using other geophysical method is required to reduce the uncertainty in interpreting magnetic anomalies.
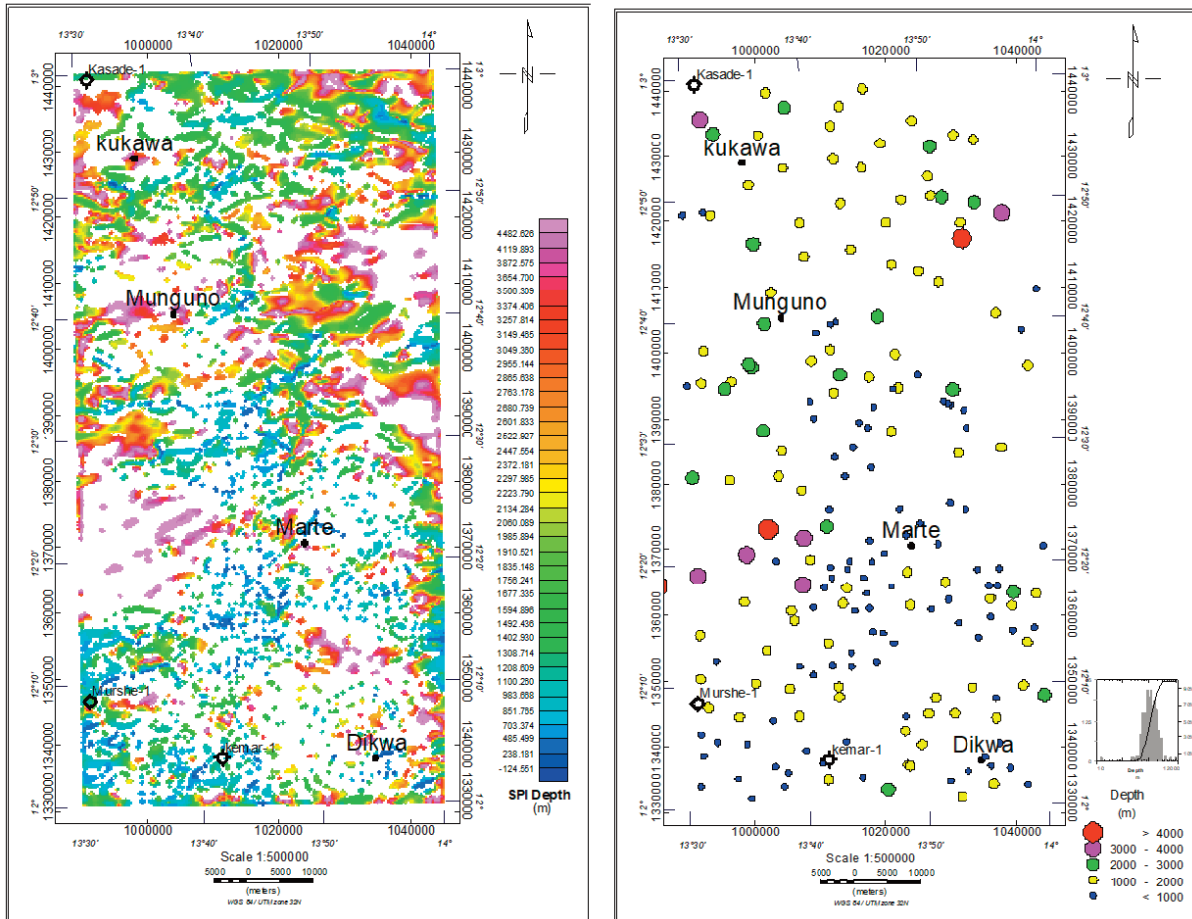
Figure 8. (a) SPI depth to source map (b) Euler depth to source at S.I = 0 (after upward continuation to 500 m) showing depth to magnetic basement in the study area.
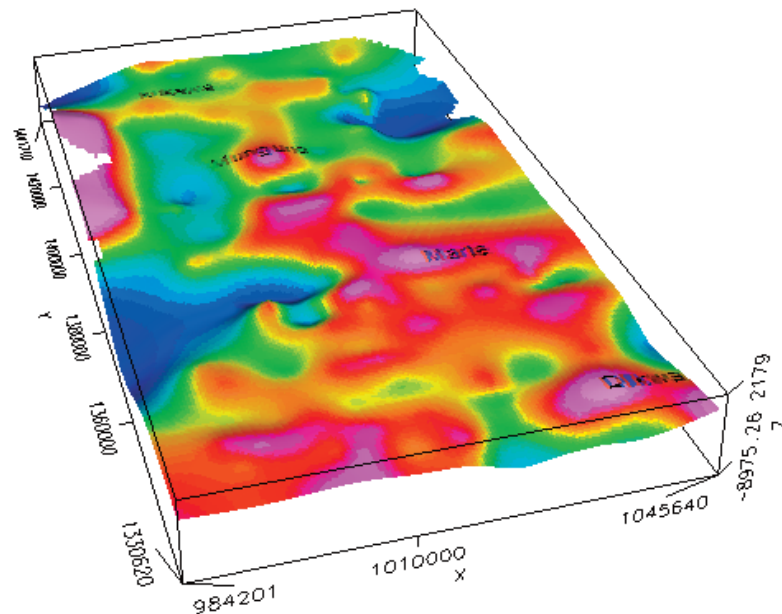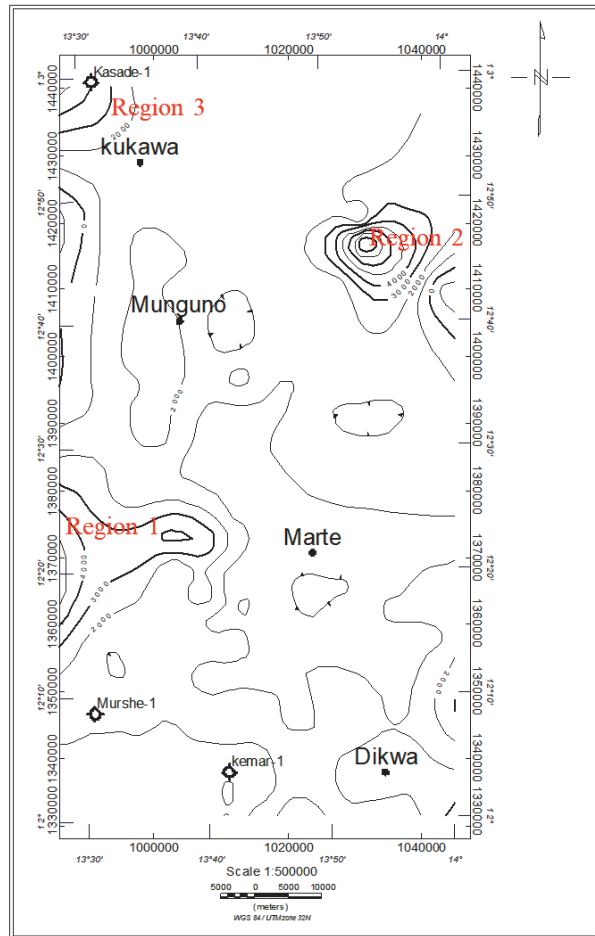

Figure 9. Basement topography generated from Euler depth to source.

Figure 10. Sedimentary basin thickness map showing region with thick sediment delineated for further exploration.

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