Full Length Research

2D modelling of high resolution aeromagnetic data over northern sector of Bida basin north-central Nigeria

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ABSTRACT: The study was carried out in the northern sector of Bida basin. The study focuses on mapping depths to magnetic basement and basement structural framework that may assist in delineating overlying sedimentary sections that have prospect for hydrocarbon exploration. High resolution aeromagnetic data of the study area was subjected to regional residual separation, analytic signal and 2D modeling using Oasis Montaj geo-software. Results of the analytic signal demarcated the basement/sedimentary contact, interpretation of 2D geologic models revealed a horst and graben structures underlying the sedimentary formations in the northern sector of Bida basin. The graben structures having sedimentary fills to a depth greater than 2 km were viewed as favourable sites for source rock development. In view of the aforementioned areas around Bakoni, northeast of Tshipo, Enagi and southwest of Wuya with thick sedimentary piles were recommended for further application of other geophysical methods of better resolving power to explore the area for hydrocarbon; since the basin has potentials for hydrocarbon generation.

Keywords: 2D modeling, analytical signal, graben structure, high resolution aeromagnetic, hydrocarbon exploration.

INTRODUCTION

In hydrocarbon prospecting, geomagnetic surveys are of greatest value in reconnaissance work. Often, such magnetic studies are useful in evaluating large areas, such as geologic basins, to determine the best places for the application of other geophysical methods of better resolving power.

In view of the ongoing interest of the Federal Government of Nigeria in testing petroleum potential of the inland basins, this research work was carried out in contribution to national development. The research focuses at interpreting high resolution aeromagnetic data over northern Bida basin with the sole aim of unraveling the basement topography underlying the sedimentary basin. This study is necessitating because it has filled in an aspect of a missing link in the much needed geophysical studies over northern Bida basin north-central Nigeria in respect to hydrocarbon exploration.
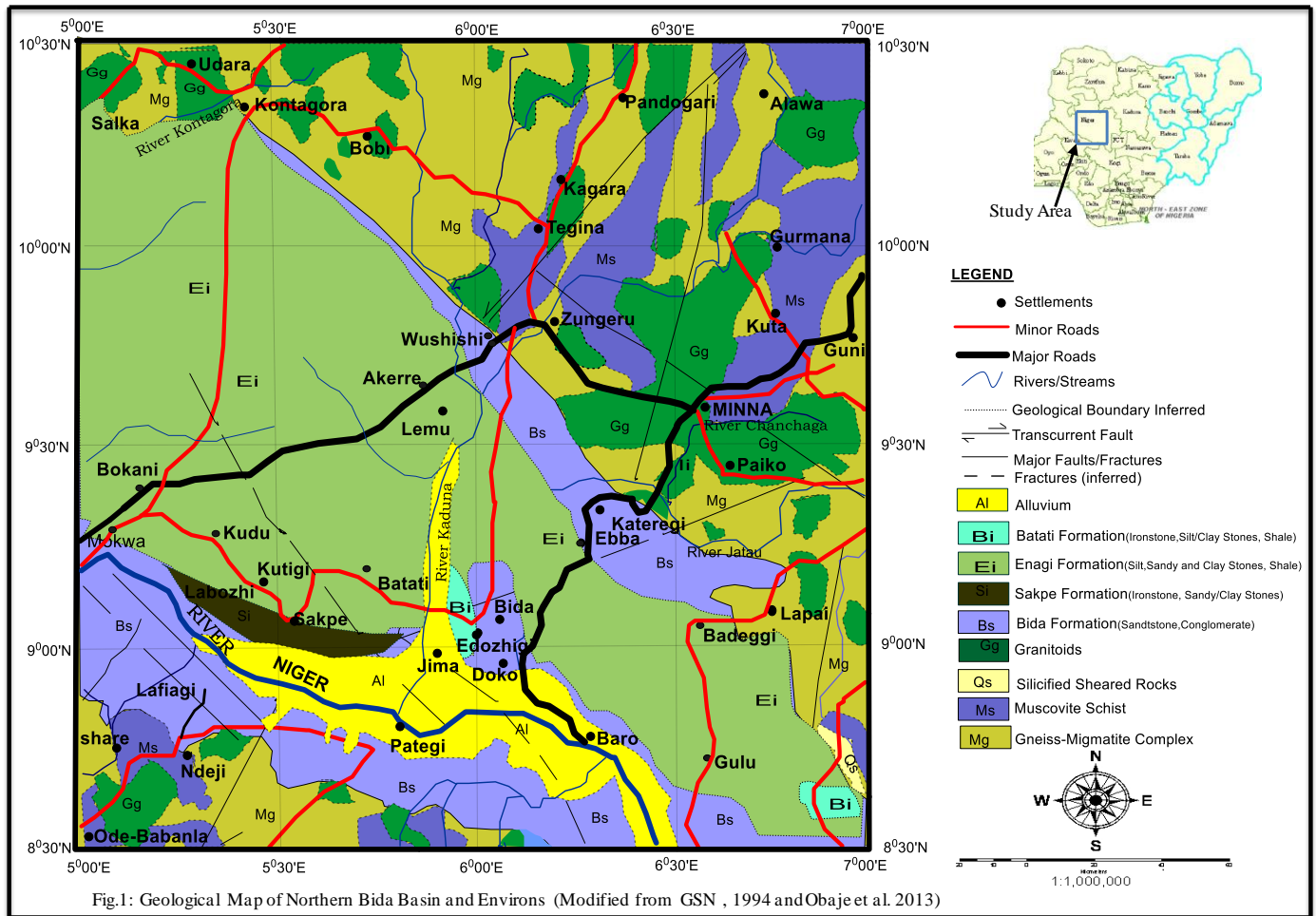
Regional geology of northern Bida basin and environs

The study area is the northern sector of Bida basin and environs located in the north-central part of Nigeria, defined by the following coordinates: longitudes $5^0 00'$ – $7^0 00'$E and latitudes $8^0 30'$ – $10^0 30'$N (Figure 1).

Bida basin is located in the north-central part of Nigeria, it is adjacent and nearest to Sokoto and Anambra basins in the northwest and southeast respectively. The basin has a maximum width of about 160 km and is a NW-SE trending intracratonic sedimentary basin stretching about 400 km from Kontagora to areas slightly beyond Lokoja and is bi-furcated into two sectors; the northern and southern Bida basin (Obaje et al., 2011; Nwajide, 2013). Adjoining the northern Bida basin is the north-central and south-western Precambrian Basement Complex rocks. The Basement Complex comprises of migmatite gneiss complex, schist and older granitic rocks.

The stratigraphic sequences within the northern Bida basin is made up of Bida Sandstone, Sakpe Ironstone, Enagi Siltstone and Batati Ironstone Formations (Table 1).

The Bida Formation has an estimated total thickness of over 3000 m from aeromagnetic study (Whiteman, 1982) even though there is uncertainty as to if all this thickness

Fig.1: Geological Map of Northern Bida Basin and Environs (Modified from GSN, 1994 and Obaje et al. 2013)

Figure 1. Geological map of northern Bida basin and environs. Modified from (GSN, 1994; Obaje et al. 2013).

Table 1. Stratigraphic successions in the southern and northern Bida basin (Nwajide. 2013).

Age	Southern Bida Basin (Lokoja Area)	Northern Bida Basin (Bida Area)
Maastrichtian	Agbaja Ironstone	Batati Ironstone (Upper Iron stone)
		Edozighi Member
		Kutugi Member
	Patti Formation	Enagi Siltstone
Campanian	Lokoja Sandstone	Sakpe Ironstone (Lower Ironstone)
		BidaSansstone
		Jima Member
		Doko Member
	Base of Lithic fill (unexposed)	
Precambrian	Crystalline Basement Complex	

belongs to the Bida Formation. The formation aged Campanian – Maastrichtian, consists of basal conglomerate and a successions of cross-bedded white to grey sandstones intercalation with koalinitic clays which were derived from deeply weathered Basement Complex

rocks (Nwajide, 2013). The formation also contains horizons of lateritic crust and concretions and fossiliferous black shales containing arenaceous foraminiferal assemblages (Nwajide, 2013). The Bida Formation is divided into two members namely: the Doko and Jima

members (Adeleye, 1972; Olugbemiro and Nwajide, 1998; Obaje, 2009).

The Sakpe Formation comprises mainly oolitic and pisolitic ironstones with sandy claystones locally, at the base, followed by dominantly oolitic ironstone which exhibits rapid facies changes across the basin (Obaje et al., 2013). This unit according to Nwajide (2013) occurs extensively in west of Bida town with two lateral equivalent members comprising of Wuyo Ironstone member and Baro Ironstone member. The age of Sakpe Formation from the age relation of Faunus specie may indicate Maastrichtian age (Whiteman, 1982).

The Enagi Formation covers more than 50% of the surface area of the northern Bida basin and consists of siltstone and subordinate sandstone, claystone and siltstone/sandstone intermix (Nwajide, 2013). The occurrence of associated shale sequence (Kudu Shale Member), a dark-grey, black shale unit envisaged to be the potential source rock for hydrocarbons that might have been generated in the northern Bida basin was reported by Obaje et al. (2013) as a member of the Enagi Siltstone Formation. The Kudu Shale occurs generally in the sub-surface in the northern Bida basin. Maastrichtian age has been suggested for this formation and the environment of deposition was interpreted by Nwajide (2013) to be continental (lacustrine, ponded, marginal/transitional setting).

The Batati Formation constitutes the uppermost units in the sedimentary sequence of the northern Bida basin. The Batati Formation consists of argillaceous, oolitic and goethitic ironstones with ferruginous claystone and siltstone intercalations and shaley beds occurring in minor proportions; some of which have yielded nearshore shallow marine to fresh water fauna (Obaje et al., 2013). Two members, the Edozhigi member which is overlain uncomformably by Kutugi Ironstone member were established by Adeleye (1972). The Edozhigi member consists of goethitic and oolitic ironstone and the Kutugi member consists of mixed goethitic and kaolinitic oolites. Campanian age was suggested for Batati Formation (Whiteman, 1982).

Hydrocarbons potentials of northern Bida basin

Stratigraphical, paleogeographical and sedimentological interpretations based on field studies by researchers (Obaje et al., 2006; Obaje et al., 2011; Mukhtar and Conjiao, 2012; Obaje et al., 2013) have indicated that petroleum system elements such as source rocks, reservoir facies, trapping mechanisms exist to some limited extent in the Bida basin. From their contributions, they showed that TOC values and liptinite contents are relatively high in the Bida basin samples. The Tmax values and Ts/Tm and moretane/hopane ratios are indicative that hydrocarbons are mainly of gaseous composition and are probably just being generated in the basin and may not yet

have been expelled nor migrated in large quantities. Obaje et al. (2013) reported the occurrence of associated shale sequence in the Enagi Formation, the Kudu Shale Member. This member with dark-grey to black shale unit lithologies is envisaged to be the potential source rock for hydrocarbons generation in the northern Bida basin. Reservoirs were found in the fluvial sandstones of the Lokoja Formation/Bida Fomation and in the well sorted shelf and flood plain sandstones of the Patti Formation. The shales and claystones of the Patti and Agbaja Formations are expected to provide regional seals for the trapping of any generated hydrocarbons in the Southern Bida basin. Different trap configurations are possible in the basin. The presence of unconformities, slump structures and abandoned channels are further indications of potential hydrocarbon traps in the deeper subsurface sections of the basin (Obaje et al., 2013).

Previous works on the Geophysical Investigation of Bida basin for Hydrocarbon Exploration

Obaje et al. (2013) carried out a preliminary integrated hydrocarbon prospectivity evaluation of the Bida basin. Result of geophysical aeromagnetic data evaluation indicates a depth of more than 2 km in some prospective parts of the basin.

Tsepav and Mallam (2017) carried out a spectral analysis of some segments of the Bida basin. Result of the spectral analysis showed that, depth to deeper magnetic source within the basin varies from 1.830 to 4.615 km with an average of depth of 3.063 km.

Okwokwo et al. (2018) determined sedimentary thicknesses over part of the Bida basin from interpretation of high resolution aeromagnetic data. The depths were determined from source parameter imaging (SPI), Euler deconvolution and spectral depth analysis. SPI and Euler deconvolution results revealed a deeper magnetic source of up to 4.2 km while that of the spectral analysis revealed a maximum depth of 3.5 km.

MATERIALS AND METHODS

Materials

The data sets used in this analysis is a 2 by 2 degrees high resolution total magnetic intensity (TMI) aeromagnetic data comprising of sixteen sheets each on a scale of 1:100,000 and was subjected to IGRF (International Geomagnetic Reference Field) correction as at January 2010. The data was acquired by Fugro Airborne Survey Limited in the year 2004-2009 as part of a programme aimed at assisting and promoting mineral exploration in Nigeria using 3X Scintrex CS3 Cesium Vapour Magnetometer. The following flight parameters were utilized: flight line spacing was 500 meters, terrain

clearance was 80 meters, flight direction was in the NW-SE, tie line spacing was 2 kilometres and tie line direction was in the NE-SW direction. The software used for data analysis is the Oasis Montaj Version 7.0.1.

Methods

MAGMAP filter is an application extension within the Oasis montaj environment which has a range of linear and nonlinear mathematical algorithm and was applied to the magnetic grids to enhance data for easy interpretation. The two dimensional Fast Fourier Transform (2D-FFT) in MAGMAP was particularly useful in the transformation of data from the frequency domain to the wave number domain and also for the calculation of derivatives. In this work, the MAGMAP filters that were used in enhancing high resolution aeromagnetic data for better interpretation include:

Regional residual separation

The residual magnetic field data was separated from the regional magnetic field data using the regional residual separation method. Residual magnetic field data was obtained as the deviations of the fitted plane surface from the total magnetic intensity. This method unlike the other methods does not change the amplitude of the shallow features or change the shape apart from the removal of the long wave lengths.

Analytical signal

A better alternative for positioning anomalies vertically over the bodies is to apply analytical signal to the total magnetic field and the vertical integral of the magnetic field. Nabighian (1984) developed the concept of analytical signal |A| of magnetic anomalies which was calculated by taking the square root of the sum of squares of the data derivatives (d) in the x, y, and z directions of magnetic field (T) as follows:

$$|A| = |A(x,y)| = \left((dT/dx)^2 + (dT/dy)^2 + (dT/dz)^2 \right)^{1/2} \quad (1)$$

The resulting shape of the analytic signal which was centered on the causative body is independent of the orientation of the magnetization of the source. This has the effect of transforming the shape of the magnetic anomaly from any magnetic inclination to one positive body centered anomaly. The analytical signal was useful in this work in locating the edges of a magnetic source particularly with the study area located at low magnetic latitude. This filter helped in demarcating a clear boundary between the basement complex rocks and the sedimentary basin.

Analysis of high resolution aeromagnetic data to map basement topography

The basement topography underlying the sedimentary rocks of northern Bida basin was mapped using 2D geophysical modeling. Profiles A-A' to F-F' drawn on the residual and digital elevation maps were imported into the GM-SYS interface in the Oasis montaj environment. The information was used to build a 2D model to help in understanding the subsurface basement topography of the area underlying the sedimentary basin. GM-SYM is an interactive, graphically oriented and modeling program designed for the interpretation of magnetic and gravity data. In order to obtain a calculated model effect as close as possible to the observed, a forward modeling was used. The forward modeling is a modeling approach which transforms the variations reflected by potential field data from the residual magnetic anomaly to a convenient subsurface geological setting (Brimich et al., 2011). The model effect is calculated and compared with the observed anomaly, and model parameters are adjusted in order to improve the fit between the two anomalies. This three-step process of body adjustment, anomaly calculation and anomaly comparison were repeated until calculated and observed anomalies are deemed sufficiently alike. The idea was borrowed from the work of Blakely (1995).

RESULTS

The total magnetic intensity (TMI) data over the study area ranges from 33,110.48 to 32,932.11 nT. The residual magnetic map over the study area (Figure 2) is characterized by positive and negative anomalies scattered in different parts of the map. The positive anomalies with an amplitude ranges between 11.83 to 124.08 nT/m (light blue to magenta colours), are observed in places around Kontagora, Zungeru, Wushishi, Tshipo, Dabba, Batati, Sakpe, Bokaji, Katcha, RogunKpada, Gulu, Baro, Isanlu Esa and Koro. The negative anomalies with amplitude range of -37.75 to -4.55 nT/m (deep blue colours) are observed in areas around Ibeto, Pandogari, Tegina, Kuta, Lemu, Marara, Doko, Agie, Pategi and Agena. The analytic signal map (Figure 3) helped in demarcating the basement-sedimentary contact and it also served as a guide for taking the profiles within the sedimentary basin. The basement complex occupied the north-western, northern, north-eastern and south-western parts of the map, while the central part of the map is mainly the sedimentary basin.

The basement topography underlying northern Bida basin and environs which is believed to have a definite relationship to oil bearing structures in the overlying sedimentary rocks was mapped through 2D geophysical modeling. Magnetic data generated from Profiles A-A' to F-F' drawn on the residual magnetic map (Figure 2) and the topography extracted from digital elevation map
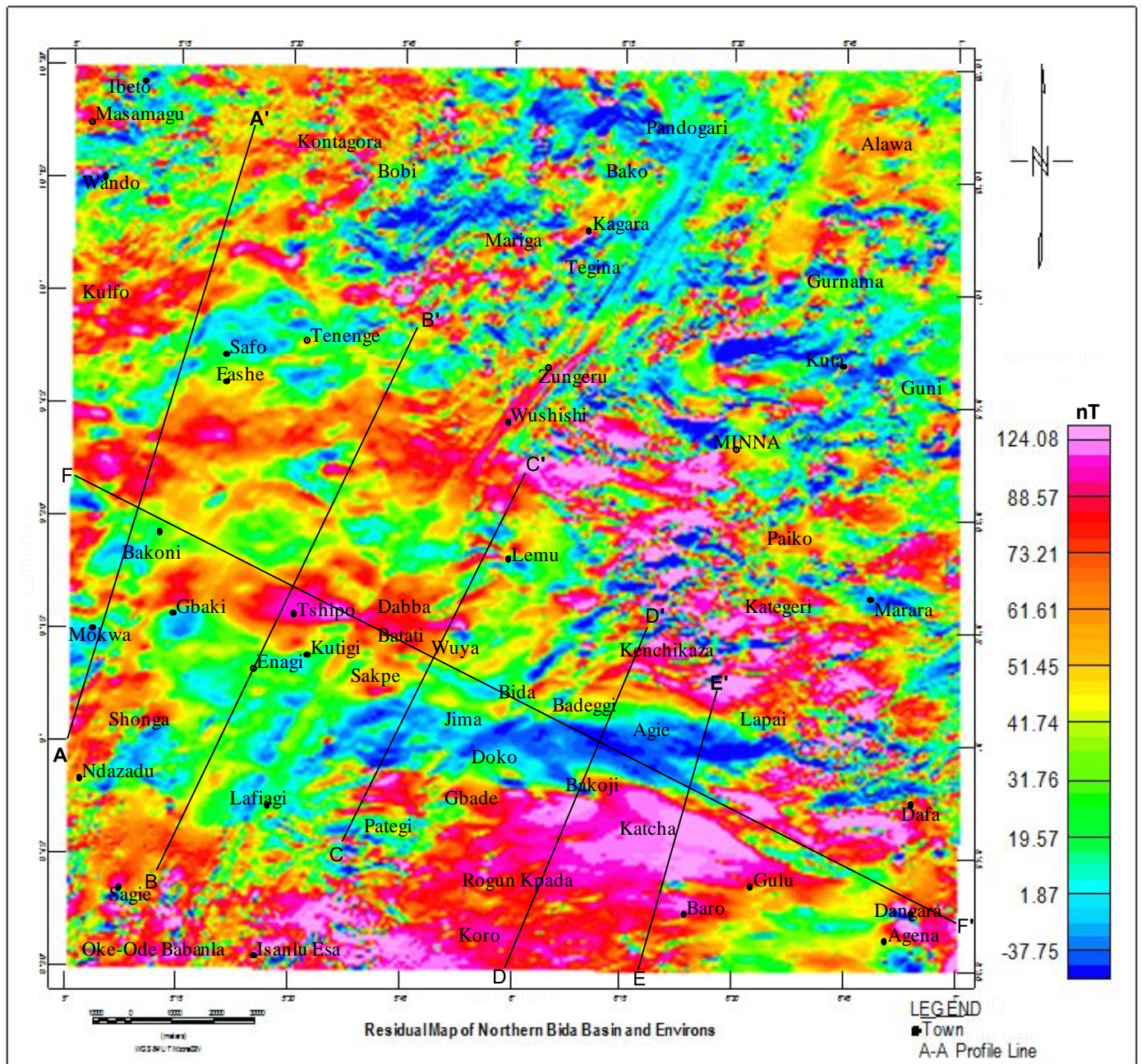
Figure 2. Residual Magnetic Map of Northern Bida basin and Environs with Profiles AA'-FF'.

(Figure 4) are used for the 2D geophysical modeling.

Profile A-A' extends for about 159 km in the SW-NE direction and the profile line passes through Mokwa, Bakoni and west of Fashe towns (Figures 2, 3 and 4). The 2D geologic modeling along this profile line is presented as Figure 5. The interpreted geologic model showed a block-faulted graben and horst structures. The four graben structures on this profile have sediment fill to a depth between 0.8 and 2.8 km. The deepest trough of this graben of slightly below (3 km) is located at a distance of about 55 km along profile line A-A' around Bakoni town. The depocentres (graben structures) are separated by intra-rift horst blocks.

Profile B-B' is about 147 km in length trending in the SW-NE direction. This profile passes through major towns such as Enagi, Tshipo, and east of Tenenge (Figure 2, 3 and 4). The interpreted subsurface geological 2D modeling along this profile (Figure 6) revealed three main graben structures flanked by horst structures. The deepest trough of this graben with sediments fill to a depth greater than 2 km and about 3km occurred at about 51.7 and 70 km along profile line B-B' around Enagi and Tshipo towns respectively.
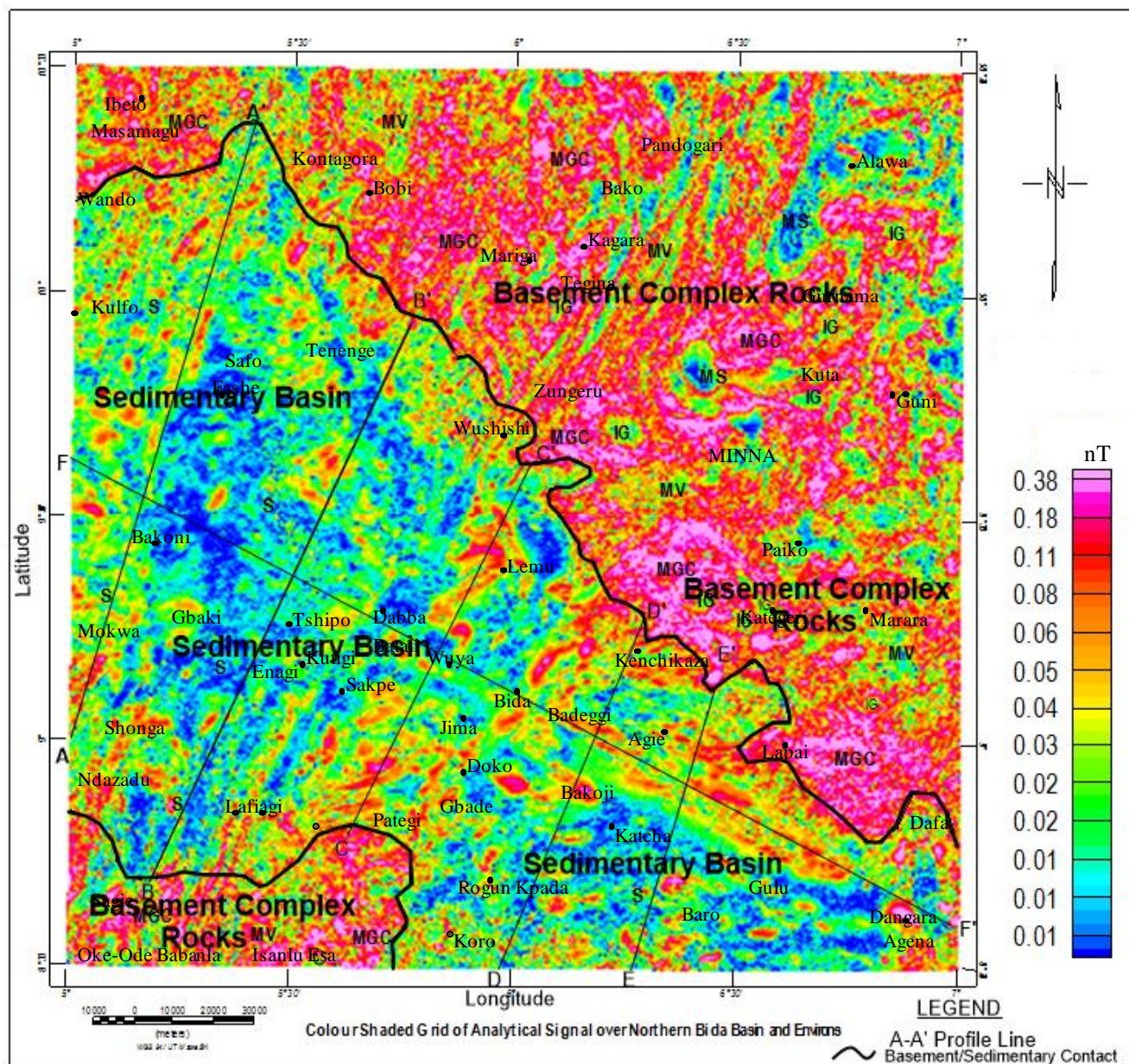
Figure 3. Analytical signal map of northern Bida basin and environs.

The graben structures were separated by minor horst structures, flanking the graben structures to the SW and NE are major horst structures.

Profile C-C' trending in the SW-NE direction is 97 km long. This profile line passes west of Pategi and through Wuya towns (Figures 2, 3 and 4). The interpreted geologic 2D model along this profile is presented as Figure 7. The 2D model revealed a graben structure with sediments fill of 2 km and below.

Passing through east of Bakoji, Badeggi and Kunchikaza towns is profile D-D' (Figures 2, 3 and 4). This profile extends for about 92 km in the SW-NE direction. The interpreted 2D geological model for profile D-D' (Figure 8) revealed a

horst and graben structures. The graben structure occurring around Badeggi is about 70 km along this profile line. The sediments fill in this graben is greater than 2 km. Profile E-E' was taking along the SW-NE direction and extend for about 71 km and it passes east of Katcha town (Figures 2, 3 and 4). Subsurface 2D geological model interpretation (Figure 9) revealed a block faulted graben structure between two horst blocks. The graben structure which is the depocentre for sediments in this location has sediments fill of less than 2 km. To the south-western direction along this profile, the basement complex rock is uplifted to near surface or surface exposure.

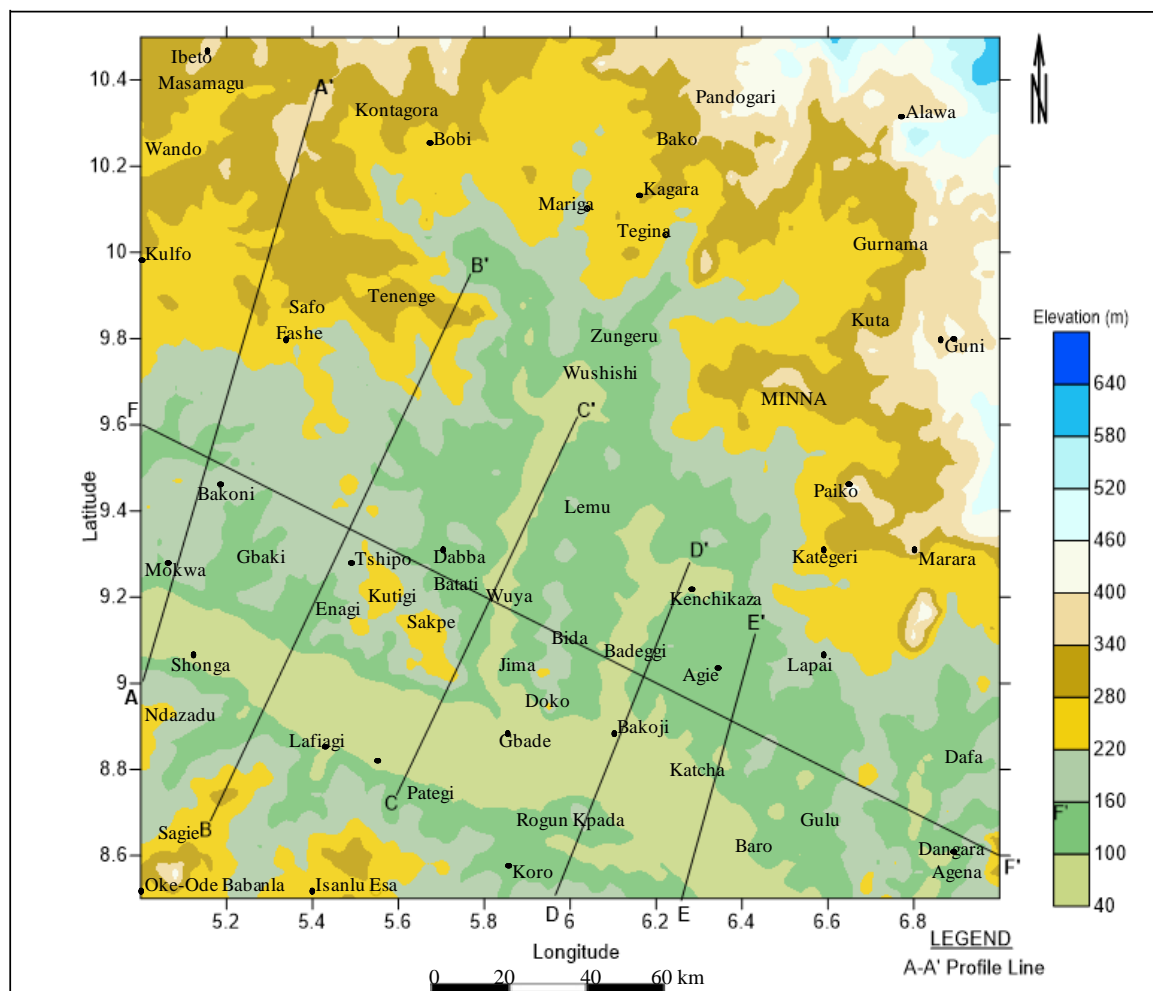Profile F-F' is 243 km of length and was taking along a

Figure 4. Digital elevation map of northern Bida basin and environs.
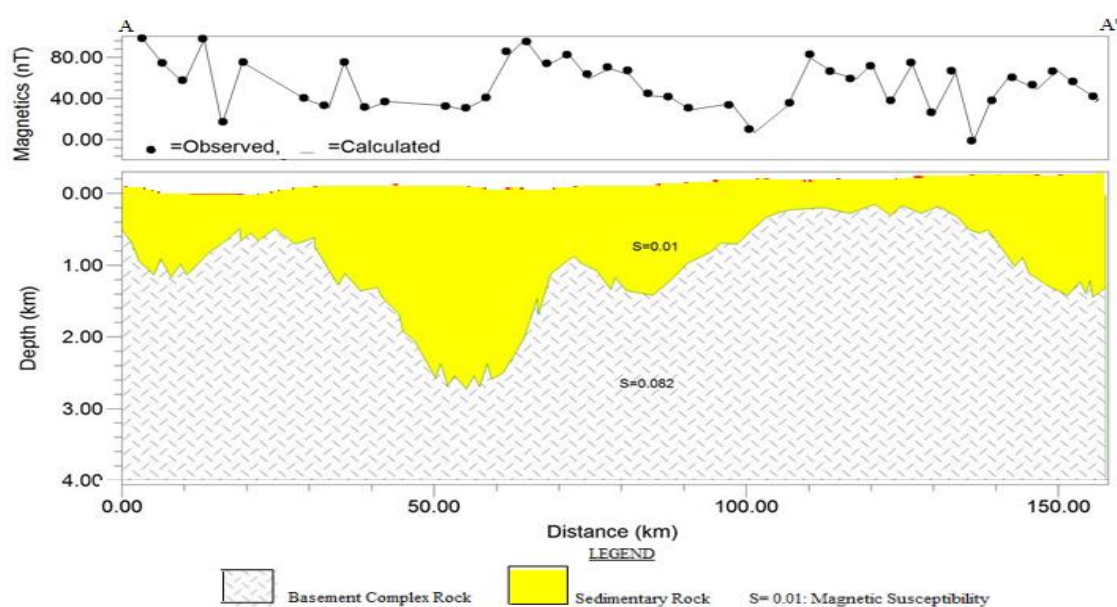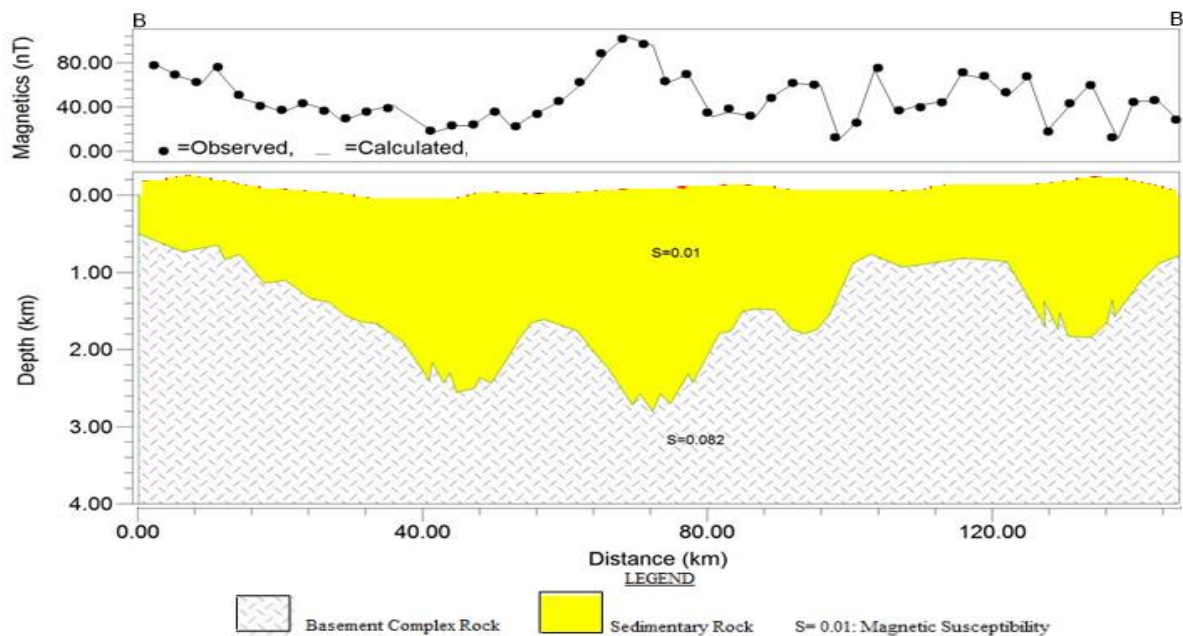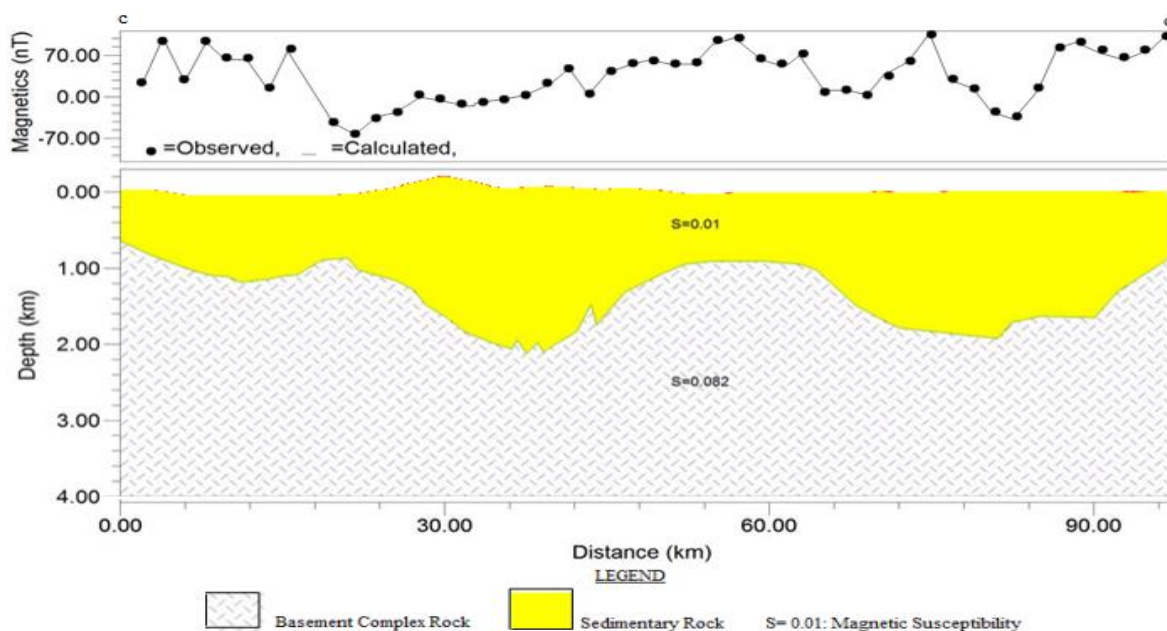

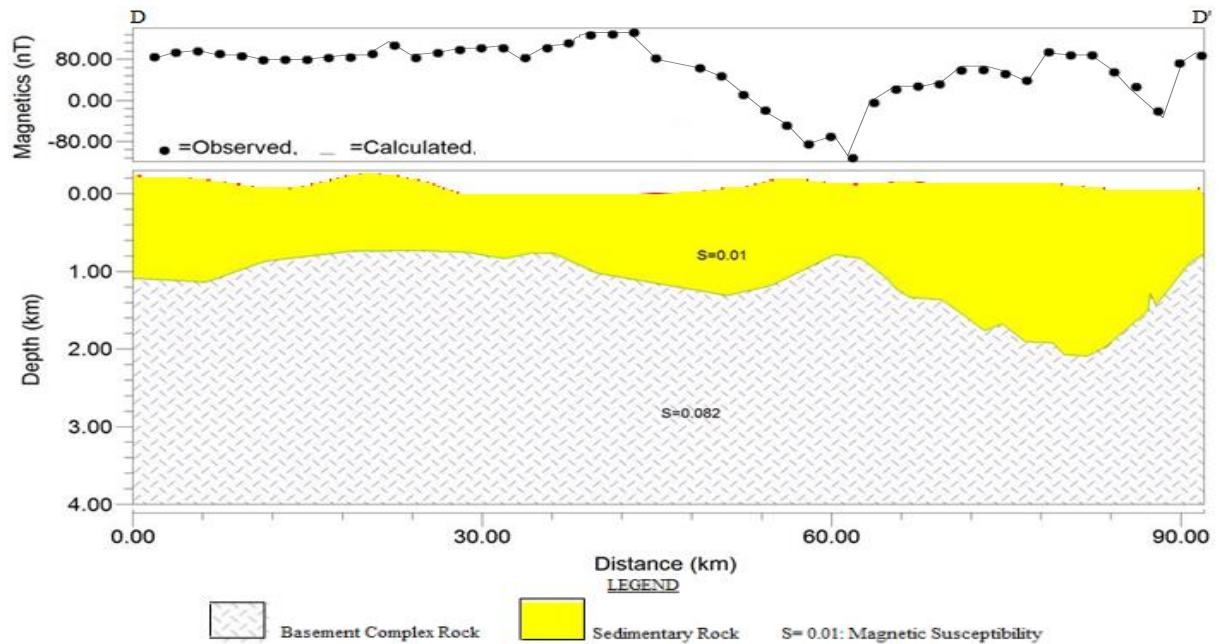**Figure 5.** Interpreted geological model of profile A-A' from residual data.

Figure 6. Interpreted geological model of profile B-B' from residual data.
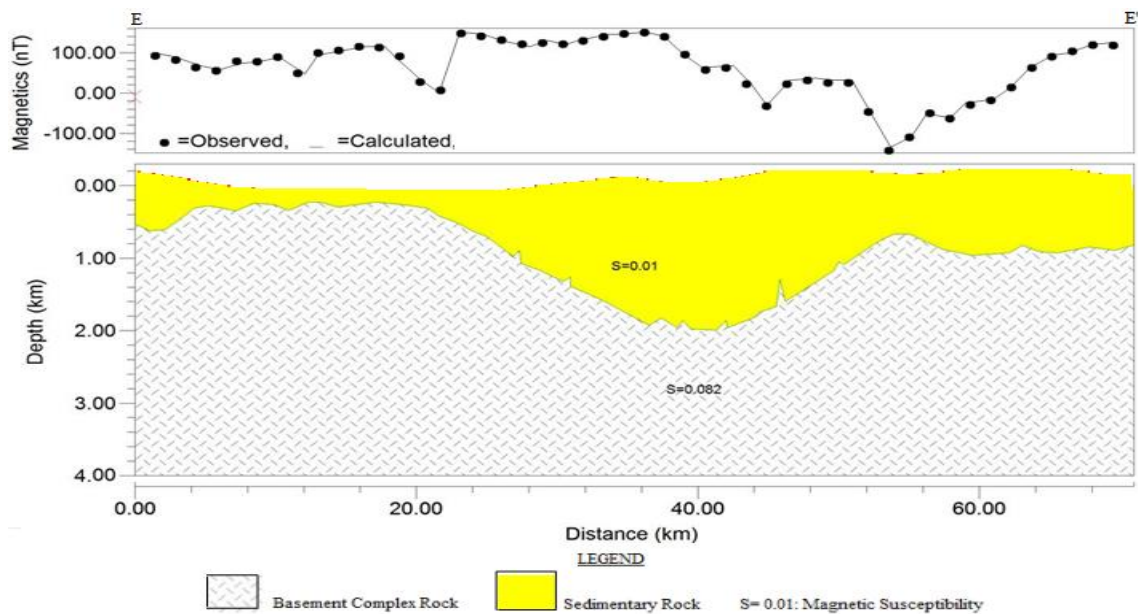

Figure 7. Interpreted geological model of profile C-C' from residual data.

NW-SE direction. The profile line passes through Bakoni, north of Tshipo, Batati, Wuya and Bida Dabba, Wuya, Bida towns (Figures 2, 3 and 4). The 2D geologic model along this profile is presented as Figure 10. The interpreted geologic model revealed three main depocentres (graben structures) separated by intra-rift horst block. Out of the three graben structures on this profile, two are promising.

The first promising depocentre (graben) with sediment fill to a depth of about 3 km has its deepest trough around Bakoni town just about 25 km along the profile line F-F'. The second promising depocentre (graben) with sediments fill to a depth of about 3 km is located 63.3 km along profile line F-F' and its deepest trough occurred around Tshipo town.

Figure 8. Interpreted geological model of profile D-D' from residual data.
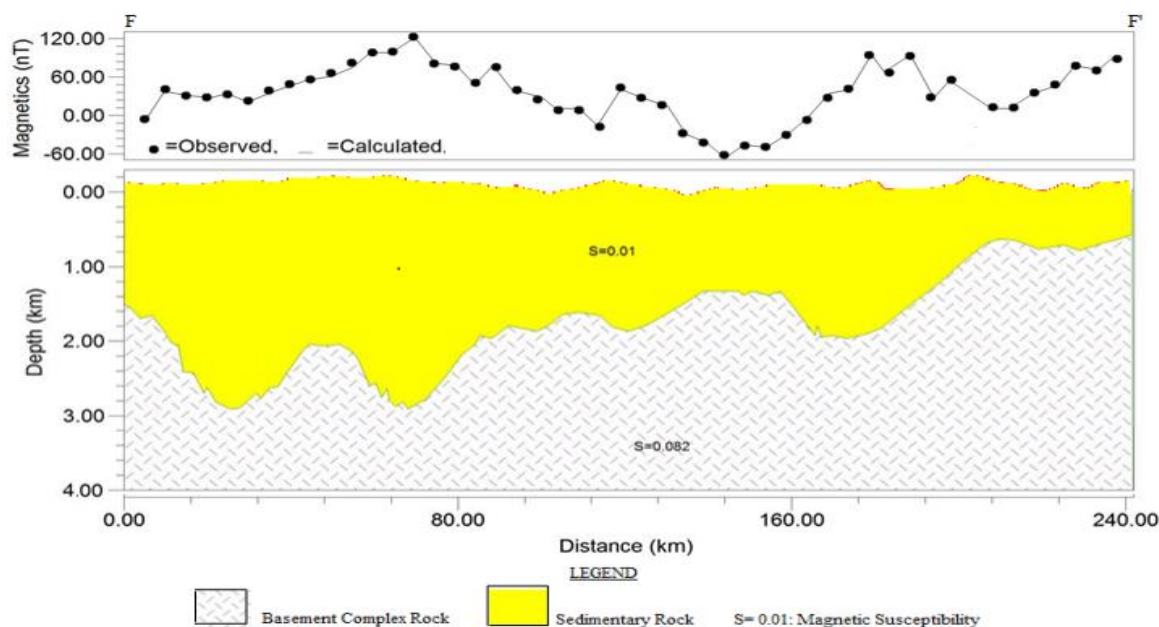

Figure 9. Interpreted geological model of profile E-E' from residual data.

DISCUSSION

The residual magnetic map exhibits both positive and negative magnetic anomalies. The positive anomalies recorded in northern Bida basin and environs have values ranging from 70.06 to 124.08 nT. This positive anomaly is an indication that the lithologies within these areas contain in them some magnetic grains, hence, the positive anomalies. Areas with negative anomalies of the range of -37.75 to -4.55 nT are indications of the absence of ferro- or ferri-magnetic substances in the lithology (Milsom, 2003).

Hydrocarbon trapping structures within the sedimentary basins are sometimes controlled by topographic and structural features on the basement surface thus; basement framework ultimately determines the depocenters

Figure 10. Interpreted geological model of profile F-F' from residual data.

and sedimentary fairways (Okiwelu et al., 2014). Good understandings of the basement topography underlying a sedimentary formation(s) assist in defining areas of the sedimentary section that have promising prospects for hydrocarbon exploration. From this study, the resulting basement faulted block pattern unveiled a horst and graben structures underlying the sedimentary formations in the northern Bida basin. The graben system has served as favourable areas for source rock development in many petroleum and gas provinces in the world (Okiwelu et al., 2014). In the study area, sediment thickness appears to be thicker within the graben structures hence the grabens (basement synclines), areas in this study with depth greater 2 km are viewed as favourable sites for source rock development. Depths of 2 km and beyond in this part of the basin, coincide well with depth interpreted by Obaje et al. (2013). From this study also, it is possible that within the horst and graben structures, the overlying sedimentary formations are folded over tilted fractured basement, therefore, forming favourable structural entrapment conditions for hydrocarbon accumulation. Obaje et al. (2011) suggested four possible different trap configurations in the Bida Basin namely: a) traps within uplifted blocks, b) traps in drapes and/or compacted structures over deep horsts, c) traps in structures developed along major faults and lineaments, and finally d) stratigraphic traps along flanks of uplifted blocks. The presence of horst and graben structures in the study area has proven these possibilities. Perveiz et al. (2014) suggested that the presence of horst and graben structures is the result of extensional tectonic forces in an area and these structures are favourable traps for hydrocarbon accumulation.

Conclusion

The 2D geological models along profile AA'- FF' revealed that the Basement Complex topography underlying the sedimentary formations in the northern sector of the Bida basin is made up of horst and graben structures. The graben systems unveiled from interpretation of geologic models were viewed as favourable sites for source rock development in areas where the sediment thickness is 2 km and beyond. At this depth, it is possible that the source rock may have the needed physical conditions of temperature and pressure required for hydrocarbon generation. The presence of horst and graben structures suggest that the possible structural traps in this basin are traps within uplifted blocks, drapes and/or compacted structures over deep horsts and stratigraphic traps along flanks of uplifted blocks and the basin. In view of the aforementioned, areas around Bakoni, northeast of Tshipo, Enagi and southwest of Wuya towns with sedimentary thicknesses of greater than 2 km are recommended for further prospecting for hydrocarbon using 3D or 4D seismic data acquisition.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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