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Analysis of high-resolution aeromagnetic (HRAM) data of Lower Benue Trough, Southeastern Nigeria, for hydrocarbon potential evaluation

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ABSTRACT

The analyses of high-resolution aeromagnetic (HRAM) data of lower Benue Trough in southeastern Nigeria have delineated sections of the basin with requisite sedimentary thickness that could support the generation of oil and gas from right-type organic-matter rich source rock as well as identified intra-sedimentary structural framework that could aid hydrocarbon migration and restrain generated hydrocarbon within available reservoirs. The susceptibility and Analytic Signal (AS) maps derived from processed Gaussian-filtered and Reduced to Pole at Low Latitude (RTPLL) aeromagnetic data discriminate crystalline basement rocks from the sedimentary units. Likewise, many relatively shallow, short (900–1600 m) intra-geologic terrain linear structures and fewer long, deeper (>1.5–43 km) inter-geologic terrains crustal linear structures which reduce in population but increase in lateral extent and depth with increasing continuation distances were delineated from the processed Tilt Derivative (TDR) and the Horizontal components of the Tilt Derivatives grids at different Upward Continuation distances. Euler Deconvolution depth-weighting analyses determined depth to magnetic sources which ranges in value from 120 m above to 5 km below the Minna reference datum. Regions having sedimentary thickness in excess of 3 km with active intra-sedimentary structural elements qualify for further petroleum exploration campaign using other detailed geological and geophysical tools.

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Analytic signal; Euler Deconvolution; hydrocarbon prospect evaluation; Lower Benue Trough; magnetic susceptibility

1. Introduction

Research into frontier inland basins for hydrocarbon prospect has been of necessity. New discoveries in the Dahomey basin have motivated recent research in other basins such as the Benue Trough, Chad Basin and Sokoto Basin. Potential geophysical methods have proved very effective for providing useful information known to guide various exploration campaigns, be it regional hydrogeological studies (Batista-Rodríguez et al. 2017), economic mineral or oil and gas exploration (Mohamed et al. 2016; Di Massa et al. 2018). Meaningful reconnaissance and detailed geological information have been generated by the analyses of aeromagnetic data for defining basin's tectonic framework (Rankin and Newton 2002), subsurface structures as well as delineate favourable regions of hydrocarbon prospect for further evaluation (Airo & Wennerström, 2010; Osinowo et al. 2014; An and Di 2016; Mohamed et al. 2016). Application of magnetic method in evaluating basement configuration is based on the fact that sedimentary rocks are weakly magnetic; therefore, it is assumed that the magnetic sources lie within the basement rocks that underlie the sedimentary units. Wavelength and frequency of a magnetic anomaly increase and decrease respectively, with increasing depth to the anomaly source. Thus, the approximate thickness of the sediments cover over a basin can be estimated by determining the depth to magnetic basement, with the exception of volcanic or pyroclastic sequences and some metallic mineral deposits within the basin. Structures can be mapped since some of the structures within the basins might have been tectonically controlled. This study aimed to provide information necessary to evaluate the hydrocarbon prospect of the Lower Benue Trough, with the desire to delineate the geological boundaries, define structural features within the sedimentary units as well as deep crustal structures that defined the structural architecture of the study area. The study likewise determined the depth to magnetic basement and thus estimates the thickness of sedimentary units in order to evaluate the petroleum prospect of parts of the study area. The study area is the Lower Benue Trough and it spans about 36,300 km^2, situated between latitudes 05° 00′ N and 07° 00′ N and longitudes 07° 30′ E and 09° 00′ E (Figure 1).

2. Geology of the study area

The Benue Trough is a NE-SW trending extensive sediment-filled sedimentary basin which runs

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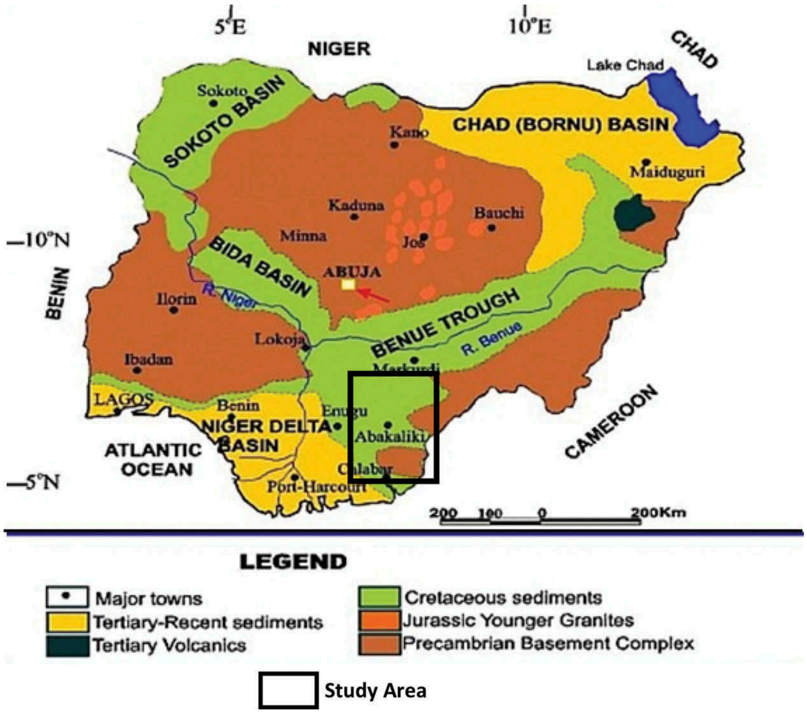


Figure 1. Geological map of Nigeria showing the study area (Modified after Obaje 2009).

approximately 1050 km long and 250 km wide in the Gulf of Guinea on the West Coast of Africa, situated almost exclusively in Nigeria except for the extreme tip of the Yola Branch, which extends to Cameroon. (Cratchley and Jones 1965; Burke et al. 1970; Agagu and Adighije 1983). The basin is partitioned into the Lower, Middle and Upper Benue regions based on stratigraphic and tectonic considerations. The sequence of events that led to the formation of the Benue Trough have been documented by Nwachukwu (1972); Burke et al. (1970); Olade (1975); Offodile (1976) and (Benkhelil 1986, 1989) among other authors. The Lower Benue Trough examined in this study is underlain by both the crystalline basement and sedimentary rocks. The basement rocks are Precambrian in age while the stratigraphic sequences of the Lower Benue Trough range in age from the Aptian to Maastrichtian. The Precambrian Basement Complex is made up essentially of granitic and magmatic rocks which outcrop in the eastern portion of the study area (Ofoegbu and Onuoha 1990), while the sedimentary basin comprises thick sequences of alternating bluish black shale and siltstone with occurrences of sandstone deposited in the Cretaceous (Simpson 1954) (Figure 2).

3. Materials and methods

The data used for this study were acquired by Fugro Airborne Survey Limited for the Nigerian Geological Survey Agency (NGSA) using digital acquisition system. The data acquisition system digitally records all geophysical, navigation, altitude, temperature and pressure data collected during the survey. Aeromagnetic data were collected using Scintrex CS3 Cesium Vapour magnetometer which samples at 0.1 seconds and records Total Magnetic Intensity (TMI) data at 0.001 nT resolution. The airborne surveys were flown between December 2006 and May 2007 at 80 m terrain clearance along series of equally spaced parallel flight lines which trend 135 degrees. The acquired aeromagnetic data were pre-processed and subsequently reduced to a format that bears simple and direct relationship with the subsurface geology. Data preprocessing carried out by the data acquisition company immediately after acquisition includes matching acquired aeromagnetic data with Global Positioning System (GPS) acquired location data. Other preprocessing activities include levelling, micro-levelling and decuturing to minimise mis-tie and eliminate cultural (man-made) magnetic effects resulting from artificial features such as wirelines, railways, steel tower, pipelines and many others (Mauring et al. 2002).

Data processing started with the removal of regional magnetic effect caused by the magnetic core inducing field by subtracting the IGRF field through the application of Gaussian low pass filter, and in this way the residual magnetic effect which reflects the terrain's induced magnetic field is obtained (Blakely 1995; Xu et al. 2009). The residual magnetic data were further Reduced to Pole at Low Latitude (RTPLL) in order to simplify the magnetic anomalies acquired at mid magnetic latitude (7°) where magnetic anomalies are asymmetrically located over the causative geologic bodies as against at the poles and the equator where magnetic anomalies are symmetrical over responsible

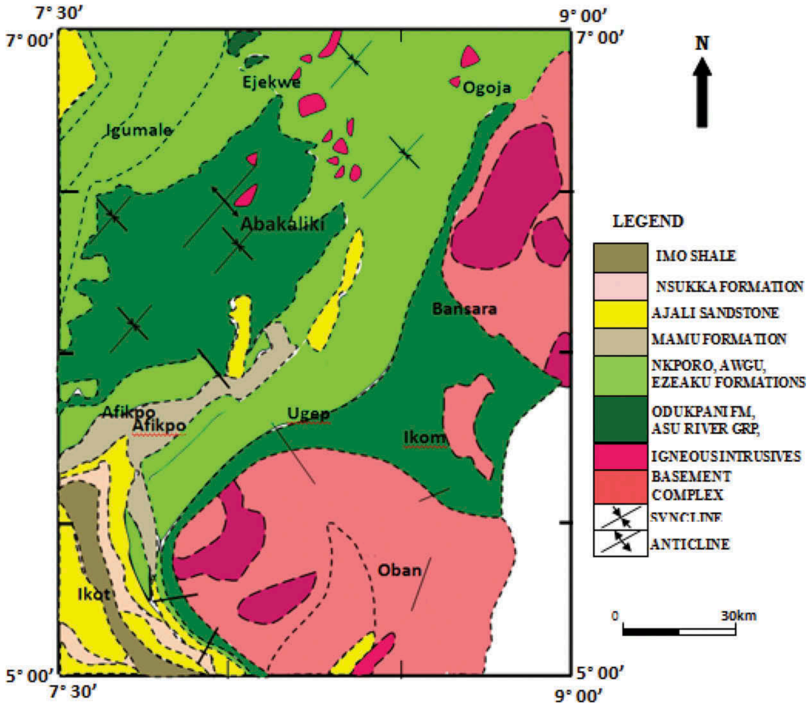


Figure 2. Geologic map of the Lower Benue Trough (Modified from the Geologic map of Nigeria, NGSA 2013).

sources (Baranov 1957). Reduction to Pole (RTP) filter simplifies the interpretation of anomalies by removing the asymmetry introduced due to the inclined main field. However, at very low latitude such as at around 7° around the Lower Benue Trough in the southeastern part of Nigeria, RTP solution is unstable (Zhang et al. 2014); thus, the result would be dominated by N-S trending artefacts. The alternative solution is to simplify the anomaly using the Reduction to the Equator (RTE) filter. However, since magnetic anomalies are inverted at the equator, RTE generates negative symmetric anomalies equivalent of the RTP which present inverted data that may be difficult to interpret. Hence, RTPLL filter, a modified RTP filter that attempts to correct stability error due to very low angle of magnetic inclination (<20°) at low magnetic latitude was adopted in order to obtain positively symmetrical magnetic anomalies over corresponding sources (Keating and Zerbo 1996; Li 2008). Upward Continuation filter, apt at smoothening original data by attenuating short wavelength anomalies relative to regional long wavelength anomalies was applied to enhance deep-seated regional structures that are relevant to achieve the study's objectives (Kellogg 1953; Blakely 1995). The aeromagnetic data were upwardly continued to a distance of 1000 m, 4000 m, 6000 m and 9000 m.

3.1. Susceptibility mapping

The magnetic data of Lower Benue Trough were also subjected to apparent susceptibility filtering in order to define the magnetisation domains within the study area. The filter is a compound filter that first reduces the data to pole, downwardly continued anomaly to the source depth, correct for geometric effect of a vertical square-ended prism in order to generate magnetic field susceptibility distribution across the study area. The generated anomaly will closely reflect the geologic map of the study area and hence very useful for mapping geologic features. The function for the apparent susceptibility filter is as expressed in Equation 1.

$$L(r,\theta) = \frac{1}{2\pi \mathrm{F.H(r).\Gamma.K(r,)}} \tag{1}$$

where H(r) = Downward Continuation to h, Γ (θ) = Reduction to Pole, K(r, θ) = Geometric factor of a vertical prism, F = Total geomagnetic field strength, r = Wavenumber (radian/ground unit), θ = Wave number direction.

3.2. Analytic signal

Analytic Signal (AS) analysis was carried out to identify and map the boundaries of different geologic features. Analytic Signal is a complex function computed in three dimensions, as the square roots of the sums of the squares of the first order of Vertical (z) and two Horizontal (x & y) Derivatives (Macleod et al. 1993) (Equation 2).

$$\mathrm{AS(x,y,z)} = \sqrt{\left(\frac{\partial \mathrm{T}}{\partial \mathrm{x}}\right)^2 + \left(\frac{\partial \mathrm{T}}{\partial \mathrm{y}}\right)^2 + \left(\frac{\partial \mathrm{Z}}{\partial \mathrm{z}}\right)^2} \tag{2}$$

3.3. Lineament mapping

The linear structures which often present contrasting magnetic signatures that differ considerably from that of the rocks that host them (may be due to re-crystallisation of existing rock minerals across the fracture or due to infilling of fracture with younger material) were extracted to define the structural framework of the study area using the Centre for Exploration Targeting (CET) structural analyses algorithm developed by the University of Western Australia. CET grid analysis carried out texture analysis, lineament detection, lineation vectorisation and structural complexity in order to delineate and extract linear structures which defined the structural architecture of the Lower Benue Trough. Tilt Derivative (TDR) expressed in Equation 3 and the Horizontal components of the grid of the Tilt Derivatives grid (HD_TDR) (Equation 4) were used as the starting grid for the CET grid analyses (Verduzco et al. 2004).

$$\mathrm{TDR} = \tan^{-1}\left(\frac{VDR}{THDR}\right) \quad (3)$$

where VDR and THDR are first Vertical Derivative and total Horizontal Derivative, respectively, of the Total Magnetic Intensity, T.

$$VDR = \frac{dT}{dz} \ \&\mathrm{THDR} = \sqrt{\left(\frac{\mathrm{dT}}{\mathrm{dx}}\right)^2 + \left(\frac{\mathrm{dT}}{\mathrm{dy}}\right)^2}$$

$$\mathrm{HD\_TDR} = \sqrt{\left(\frac{\mathrm{dTDR}}{\mathrm{dx}}\right)^2 + \left(\frac{\mathrm{dTDR}}{\mathrm{dy}}\right)^2} \quad (4)$$

3.4. Depth weighting

Depth weighting technique which determines depth to basement rocks at different solution points within the study area was employed to determine the configuration and geometry of basement rocks in the south-eastern part of Nigeria and thus define the configuration of the Lower Benue Basin. The depth weighting study was also employed to determine the thickness of the overlying sediments which is a very important determinant factor for hydrocarbon generation through geothermal gradient and thus, valuable for delineating regions to focus further petroleum exploration campaign for hydrocarbon prospect generation. Euler deconvolution depth weighting method for estimating the depth of potential field originating from a magnetic anomalous source, assumed to be the basement rock was adopted in this study (Reid et al. 1990; Nabighian and Hansen 2001). It is a depth weighting technique based on Hilbert transform equations, developed by Mushayandebvu et al. (2001). Euler deconvolution method uses magnetic field (T) and its three orthogonal gradients of the field to compute anomaly source location (Pilkington and Keating 2004). The Euler homogeneity equation (Equation 5) relates the magnetic field (T) and its gradient components ($\frac{dT}{dx}, \frac{dT}{dy} \& \frac{dT}{dz}$) to the location ($x_o$,$y_o$,$z_o$) of the source of an anomaly in order to determine the depth to the anomaly source, using the degree of homogeneity expressed as a structural index (N) that accounts for the rate of change of the field with distance for different types of magnetic sources (Thompson 1982; Reid et al. 1990; Mushayandebvu et al. 2001).

$$(x - x_0)\frac{dT}{dx} + (y - y_0)\frac{dT}{dy} + (z - z_0)\frac{dT}{dz} = N(B - T) \quad (5)$$

B is the regional field.

The located Euler which has advantage over the standard Euler method in that it estimates solutions only over recognised anomalies was adopted in order to generate reliable depth solutions. Depth solutions of the located Euler deconvolution analysis were windowed using depth tolerance of 15% which only considered solutions with error estimate smaller than 15%.

A simplified flow diagram illustrating the different data processing and analysis steps that the aeromagnetic data of the Lower Benue Trough were subjected to generate the various interpretation output employed to evaluate the basin is presented in Figure 3.

4. Results and interpretations

The residual magnetic intensity map of the Lower Benue Trough obtained after the removal of the regional field effect is presented in Figure 4. It shows the variation in the magnetic intensity across the study area which ranges in value from – 78.3 nT to +126.4 nT. The application of RTPLL filter to the residual data transformed the magnetic distribution of the Lower Benue Basin as shown in Figure 5. It presents simplified residual magnetic intensity data whose magnetic anomalies lie positively symmetrical over the corresponding geological sources.

The RTPLL magnetic intensity distribution across the study area ranges from −50 nT to +140 nT. High amplitude magnetic anomalies which range in value from +20 nT and +138 were recorded at Igunmale, Wanakonde and Ogoja in the northeastern area, and Ugep and Oban in the south. Medium amplitude magnetic anomalies (−5 nT and +20 nT) dominate the central part of the study area such as Enugu and Ishiagu while Abakaliki, Nkalagu and Afikpo present low amplitude magnetic anomalies with intensity value ranging from −5 nT to −50 nT. Many of the regions characterised by high amplitude magnetic anomalies coincide with areas having exposed

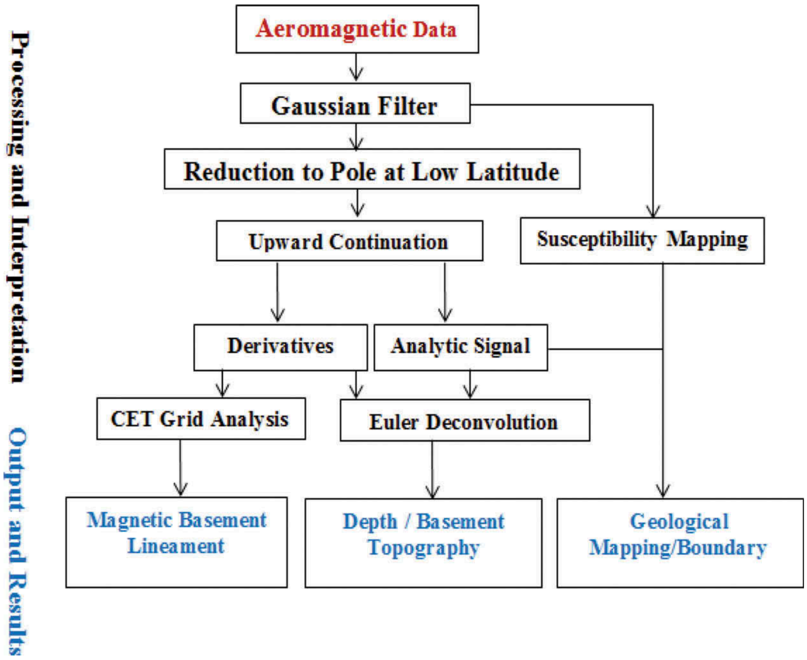


Figure 3. Simplified data correction flowchart.

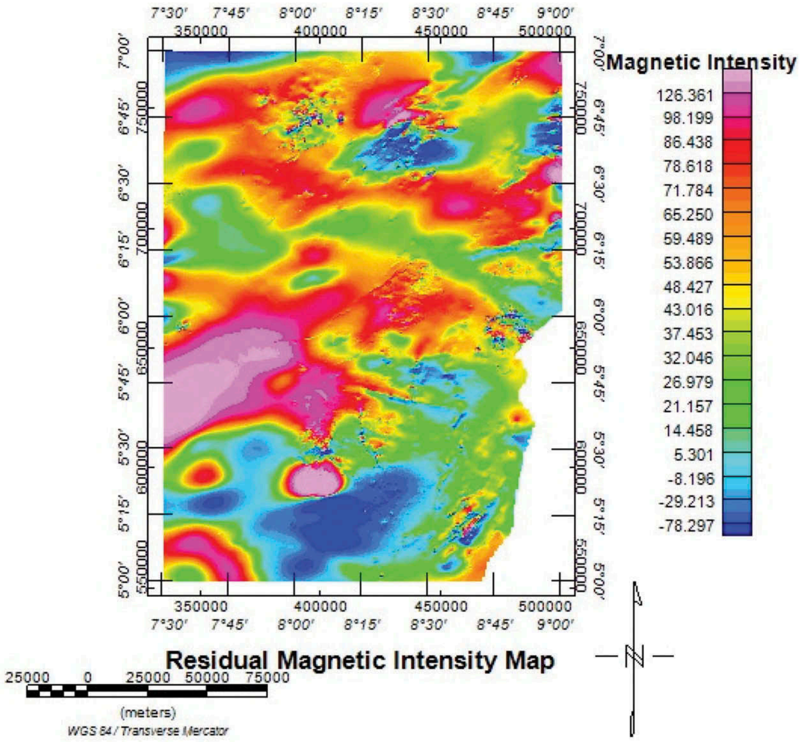


Figure 4. Residual magnetic intensity map of Lower Benue Trough, South Eastern Nigeria.

basement rocks of intrusive and extrusive origins, while areas of low amplitude coincide with portion of the study area having thin to relatively thick sedimentary cover, where the effect of the thick weakly susceptible clastic materials masks the high induced magnetic intensity originating from relatively deep basement rocks.

The application of upward continuation filter at continuation distances of 1000 m, 2000 m and 4000 m smoothens out the magnetic distribution and improved resolution (Figure 6 at upward continuation distance of 1000 m) with deeper magnetic features better enhanced and the shallower signals suppressed.

Susceptibility map (Figure 7) of the study area reflects variation in rock distribution since magnetic susceptibility, a property of rocks based on the constituent magnetic molecules measures the ease with which a rock is induced; thus, the susceptibility derived from magnetic intensity data will directly relate to the geology of the terrain. The map presents susceptibility value which

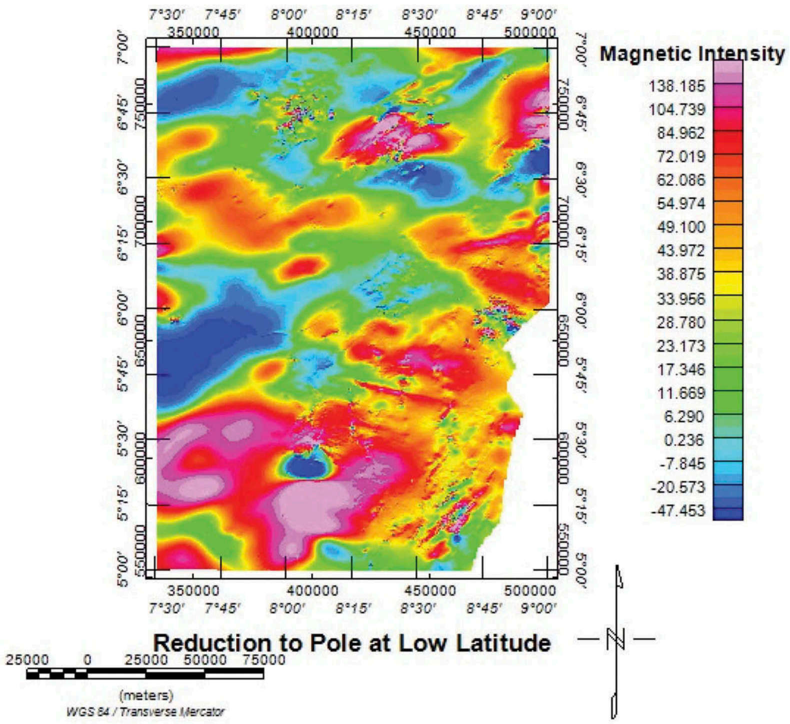


Figure 5. Magnetic Intensity distribution map of Lower Benue Trough after RTPLL.

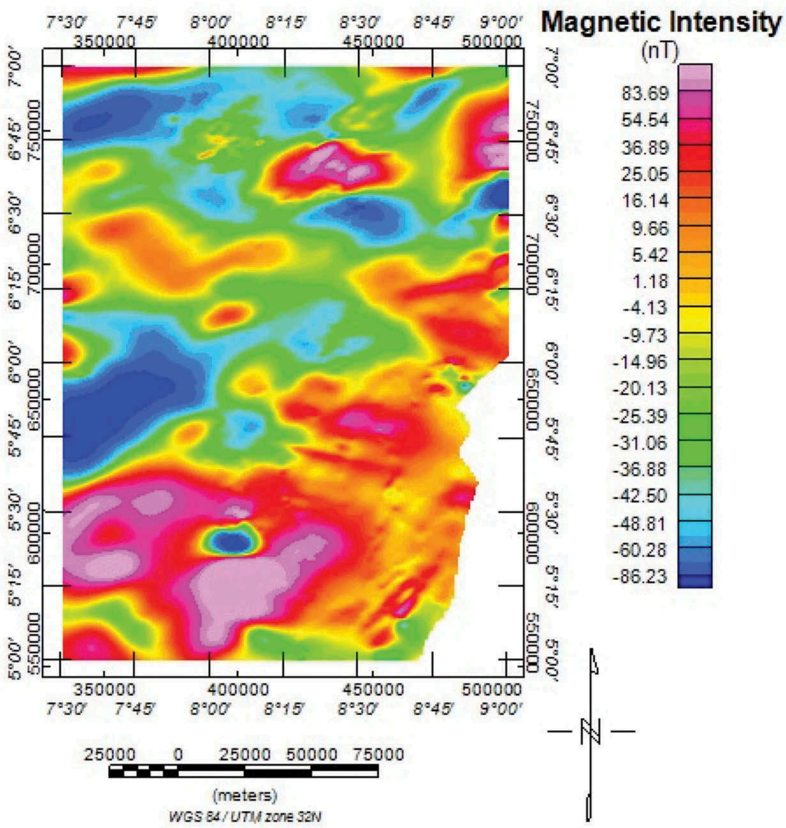


Figure 6. Upwardly continued (1000 m) RTPLL magnetic intensity map of Lower Benue Trough, southeastern Nigeria.

ranges from 198 to 9879. High magnetic susceptibility values (>5000) characterised crystalline basement terrain at Igunmale, Wanakonde, Ogoja, Ugep and Oban, whereas relatively low magnetic susceptibilities (<500) dominate the sediment covered part of the study area in Enugu, central part of Abakaliki, Nkalagu, Ishiagu and Afikpo in the western region of the study area. These above findings agree with the account of Oha et al. (2017) and Igwe and Okoro (2016) who reported occurrence of crystalline basement rocks and sedimentary rocks in

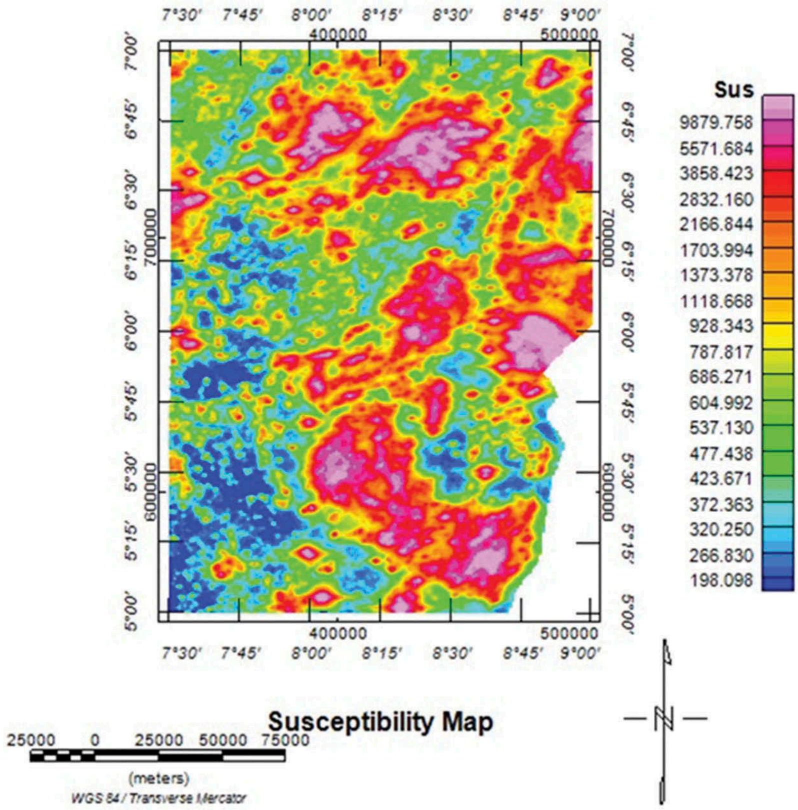


Figure 7. Susceptibility map of Lower Benue Trough, South Eastern Nigeria.

regions characterised by high and low magnetic susceptibilities, respectively.

The AS map of the Lower Benue Trough generated by the application of AS filter to define the boundaries of prominent geological features that characterises the studied magnetic terrain is presented in Figure 8. The boundaries traced out regions having high magnetic intensity contrast which define the crystalline basement rocks and intrusives while the medium to low analytic signal traced out the thick sedimentary units. Seven high amplitude AS anomalies were delineated which coincide with the basement rocks at Oban, Ogoja, basaltic rocks of Ikom as well as the Ezeaku Aku and Asu River Group sedimentary units within the sedimentary terrains.

The CET extracted lineaments from the TDR and HD_TDR grids of the study area at Upward Continuation depths of 1000 m, 4000 m, 6000 m and 9000 m are presented in Figure 9(a–d) with the corresponding rose diagrams which show the orientation, frequency and density of the extracted linear features. Both high frequency local (short length) and low frequency regional (longer length) linear features characterise the study area. The extracted linear features generally trend in the NE-SW direction with few others trending NW-SE direction. Generally, dense concentration of short (limited lateral extent) linear structures (900–1600 m) was acquired at relatively shallow continuation depth of 1000 m (Maurin et al. 1986). However, longer linear structures of regional extent (>1.5–43 km) were extracted at relatively deeper continuation depths (>4000 m). The frequency of the extracted linear structure decreases with continuation depth while the length of individual lineament increases with depth. This indicates that at shallow continuation depth, large number of short length features dominate the near-surface environment while fewer number longer regional features occur at depth.

Depth weighting solutions through the application of Euler deconvolution analysis using Structural Index of 0.5 that gave the best clusters of solutions around anomalies of interest are presented in Figure 10. The depth weighting solutions indicate that depth to basement rocks generally ranges from 120 m above the Minna reference datum to −5000 m below the datum. Deeper solutions (≥3000 m) were obtained in the north-western and south-western part of the study area around Abakaliki, Bansara and Afikpo, while relatively shallower (shallow to averagely deep) depth solutions (1000 m to 2000 m) were obtained in the southeastern part of the study area around Ikom, Boji and Ugep. Very few and shallow (generally close to or above the datum) solutions were obtained in regions underlain by crystalline rocks, such as at Oban, Wanakonde and part of Igunmale, where Euler Deconvolution generate solutions over the Minna datum. The obtained depth solutions were subsequently used to generate depth to basement contour map and 3D basement topography model of the study area, which shows the variation in sedimentary thickness and the magnetic basement topography of the area (Figure 11(a,b)).

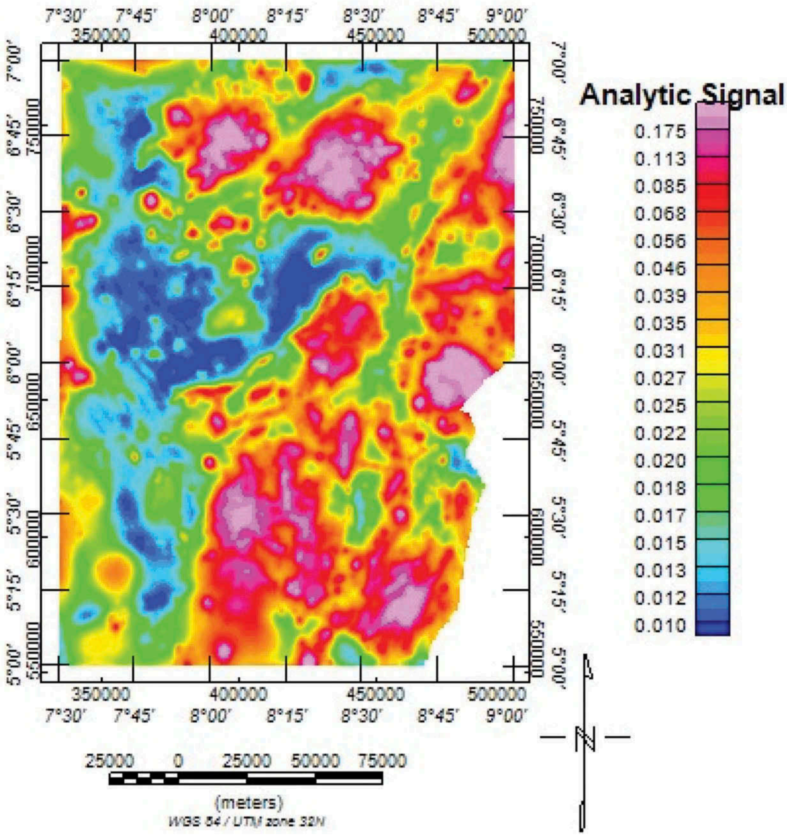
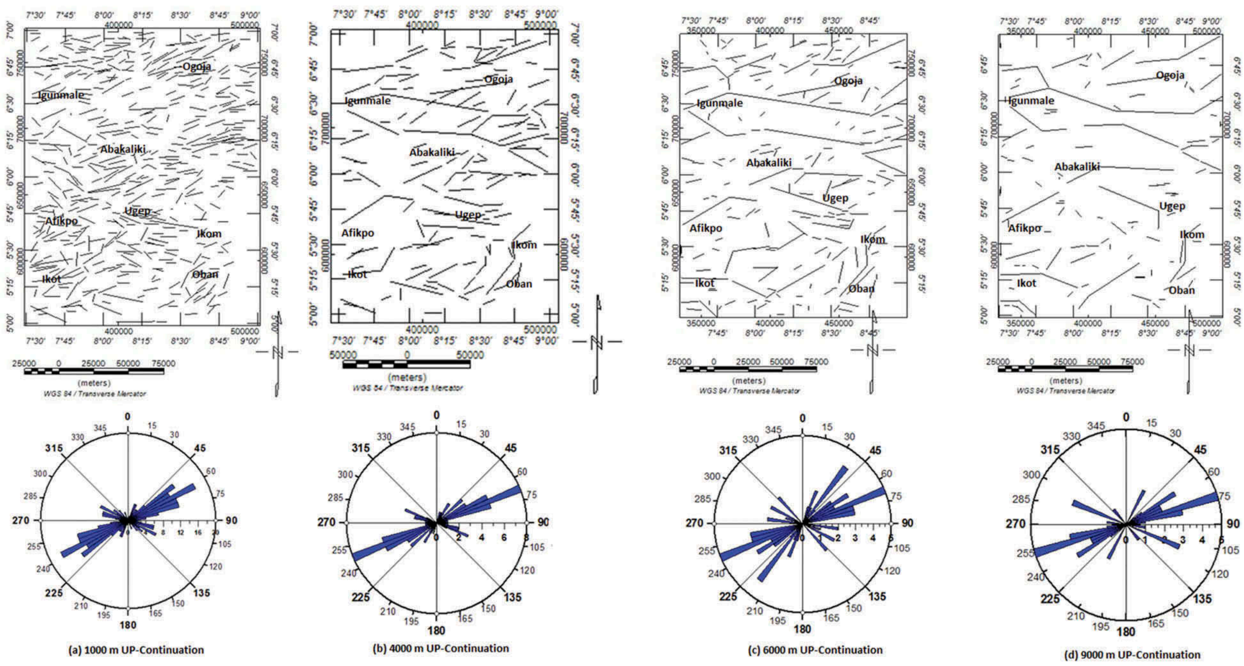


Figure 8. Analytic signal map of the study area.



Figures 9. (a-d) Distribution of extracted lineaments at 1000, 4000, 6000 and 9000 m Upward Continuation distances.

Four (4) cross-section profile generated from the Euler basement depth contour data, purposively selected to run along NE-SW trend present basement topography configuration and sedimentary thicknesses along the profile sections (Figure 12(a)). Profile AA′ traversed Ejekwe, Wanakonde to Abakaliki (Figure 12(a)) and it indicates that the sedimentary thickness generally increases westward with thickness reaching 4000 m at Ejekwe and 3000 m at Abakaliki as the basement dip and get depressed westward. Profile BB′ section imaged basement configuration and sedimentary thickness variation across Ogoja, Bansara, Abakaliki and Afikpo (Figure 12(b)). The section presents two major depressions with a basement high between them and sedimentary thickness up

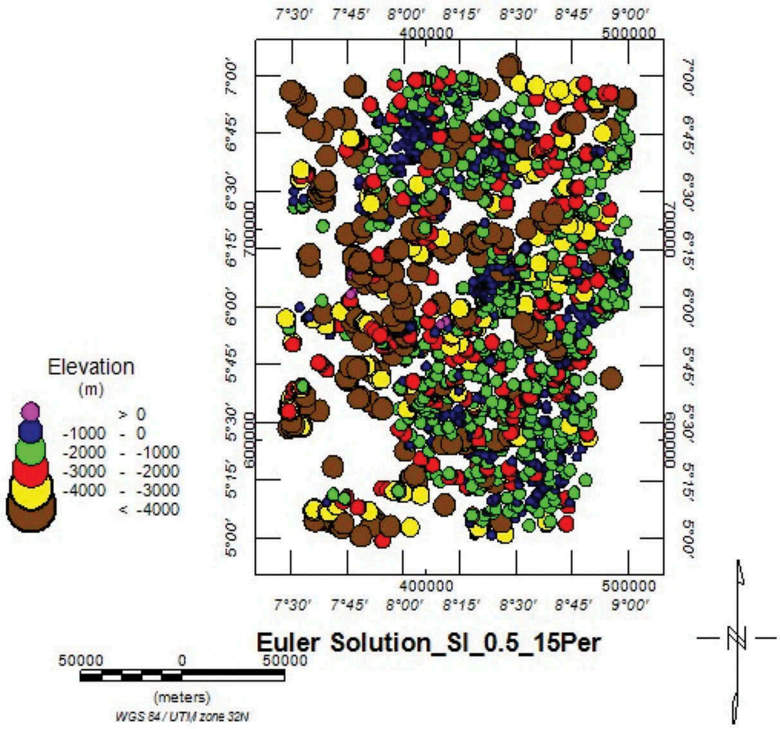


Figure 10. Euler depth solution plot of the study area (Structural Index 0.5, Maximum Depth Tolerance of 15%).

4000 m. Profile CC′ and DD traversed Boji, Obubra, Ugep to Ikot, (Figure 12(c)) and Ikom, Oban to Ikot (Figure 12(d)), respectively, with thickest sediments recorded at Obubra and Ikot.

5. Discussion of results

The analyses of aeromagnetic data of the Lower Benue Trough in southeastern Nigeria have generated several maps, profiles, sections and 3D subsurface image which described the rocks distribution and association, structural framework and subsurface basement topography beneath the sedimentary units. The susceptibility map presents variation in the susceptibility values of rocks across the study area. Regions underlain by crystalline basement rocks such as basaltic rocks at Ikom and doleritic rock at Ugep and Obubra have high magnetic mineral content and thus resulted in high magnetic susceptibility values as shown by the susceptibility map. On the other hand, sedimentary terrains which often consist of sandy and shaly rocks as found in Npkoro and Ezeaku Formations and the Asu River group present low magnetic susceptibility due to lack of or low magnetic mineral content. The AS map differentiated and enhanced the boundaries of different rocks corresponding to different geologic terrains; crystalline basement and sedimentary terrains, alike, which positively correlate with the geological map of the Lower Benue Trough (Hsu et al. 1996).

The extracted lineaments at 1000 and 4000 m upward continuation distances superimposed on the analytic signal map of the study area (Figure 13) indicate high frequency shorter local structural features of limited lateral extent (0.9-1.6 km) which are often restricted within the same geological terrain. However, fewer regional linear structures (1.5–43 km) which run across different geological terrains were extracted at deeper continuation depth of 4000 m. This indicates that many of the local, shorter and shallower structural features are intra-geologic terrain while the longer, regional deeper lineaments run across several geological rock boundaries. The occurrence of several structures within the areas underlain by sedimentary rocks indicates active basins which may constitute structural features that could retrain generated hydrocarbon within the reservoir rocks. The structures observed around Abakalilki and Ugep are linked with Lower Senonian tectonism which generated several structural features such as faults and Abakaliki Anticlinorium (Burke et al. 1970; Ofoegbu and Onuoha 1991). The structures within the sedimentary rocks are likely associated with crustal tectonic activities that were transmitted through incompetent sediments to generate structures trending in related direction to that of the major tectonic trend of the underlying basement rocks.

The Euler depth weighting solutions (Figure 10) which presented depth to basement source of ~0–+120 m above the reference Minna datum in the Basement Complex terrain and >0–−5000 m below the reference datum in the sedimentary terrain indicate that the sedimentary terrain around upper Bansara and Ogoja presents depth solutions less than 3 km. However, areas such as part of Abakaliki, Afikpo and Ikot gave solutions in excess of 3 km which is the minimum sedimentary burial depth required for the generation of hydrocarbon

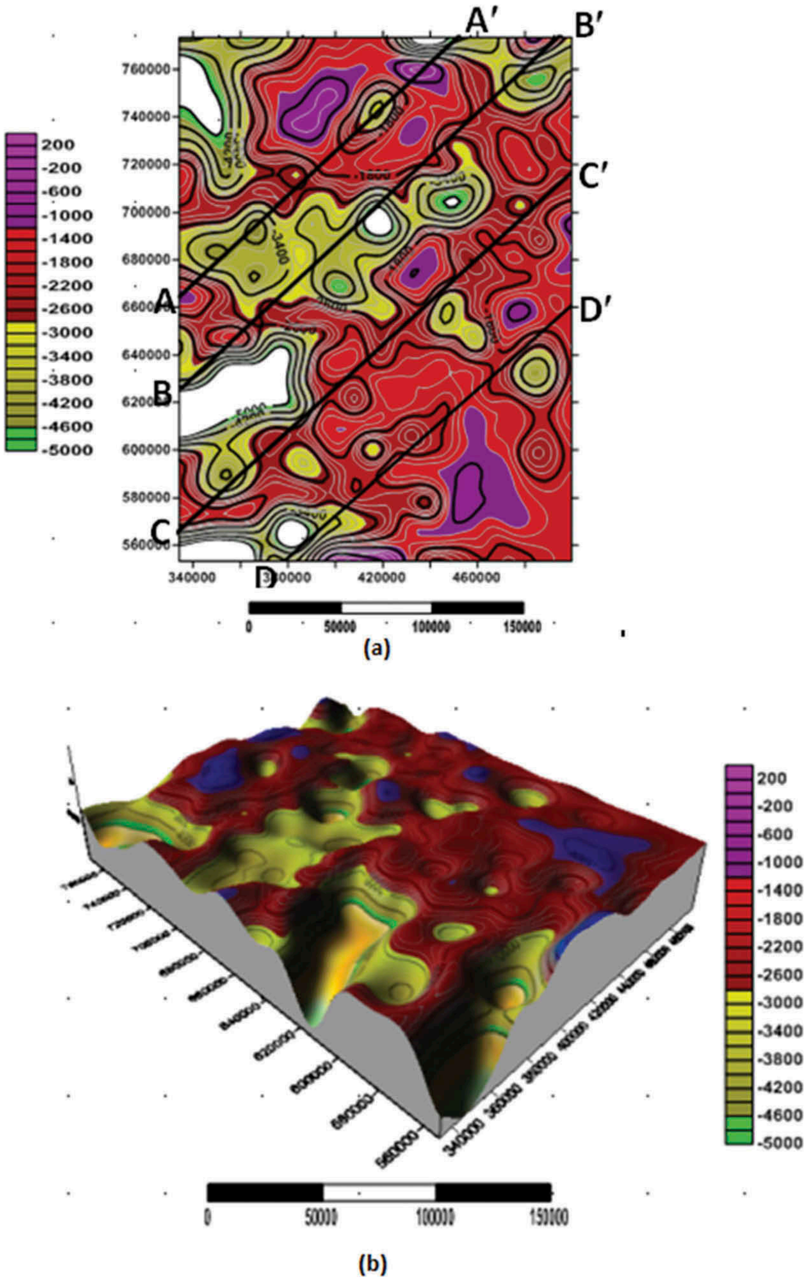


Figure 11. (a) Depth to Basement contour map, (b) 3D depth model of the basement topography of Lower Benue Trough, southeastern Nigeria.

from organic matter based on the geothermal gradient within the basin (Hunt 1996).

6. Conclusion

The analyses of HRAM data have proved very effective for geologic mapping, lithological boundary delineation, lineament mapping and modelling of basement rock topography in the structurally complex basin of the Lower Benue Trough, southeastern Nigeria. The study used susceptibility and AS distribution across the study area to delineate and differentiate crystalline basement terrain of intrusive and extrusive origin from sedimentary terrain. CET grid analyses and other structural mapping techniques proved very useful to identify long, deep, regional, inter-terrain linear structural features and separate them from shallow, relatively short local intra-terrain structures which are restricted within a geologic terrain in terms of lateral extent, that dominantly trend NE-SW. Euler deconvolution identified depth to magnetic basement and thus delineate part of Abakaliki, Afikpo and Ikot as having sedimentary thickness in excess of 3 km. The occurrence of Cretaceous sediments having right organic matter source rock in excess of required overburden thickness essential to generate hydrocarbon from organic source rocks through geothermal gradient together with structurally active sedimentary terrain as found in Abakaliki, Afikpo and Ikot axis of the study area identified these regions as candidate for further hydrocarbon prospect evaluation using more detailed oil and gas prospecting techniques.

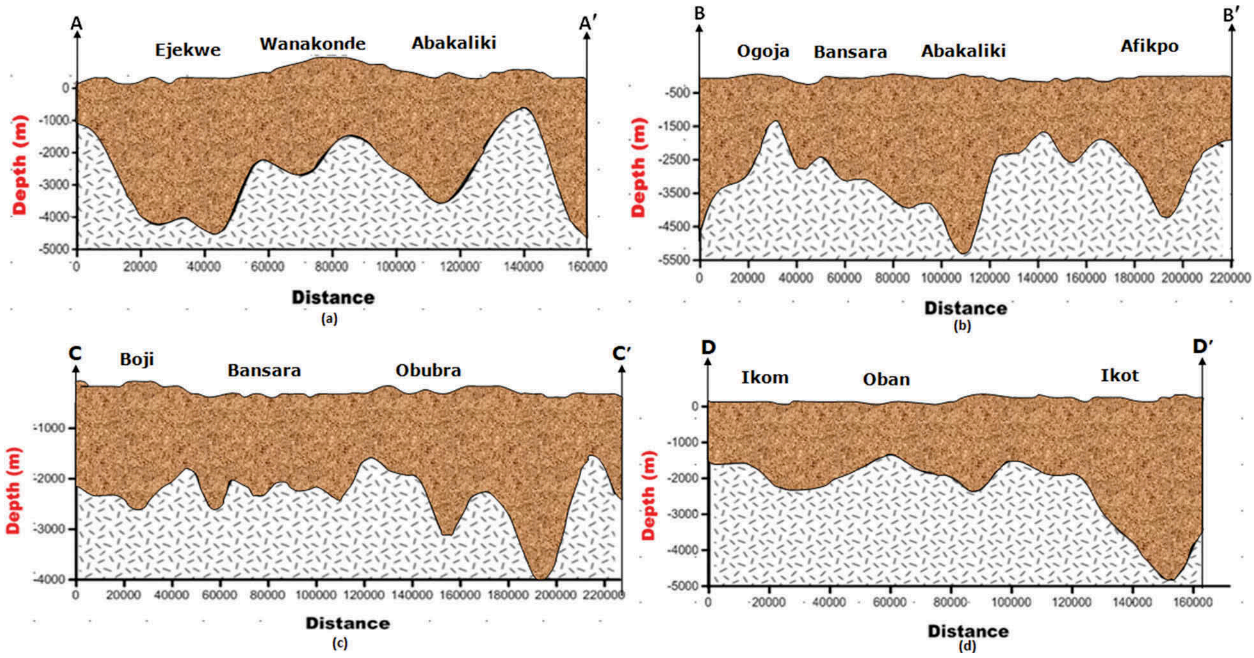


Figure 12. (a-d) Basement topography model of Profiles AA′, BB′, CC′ and DD′.

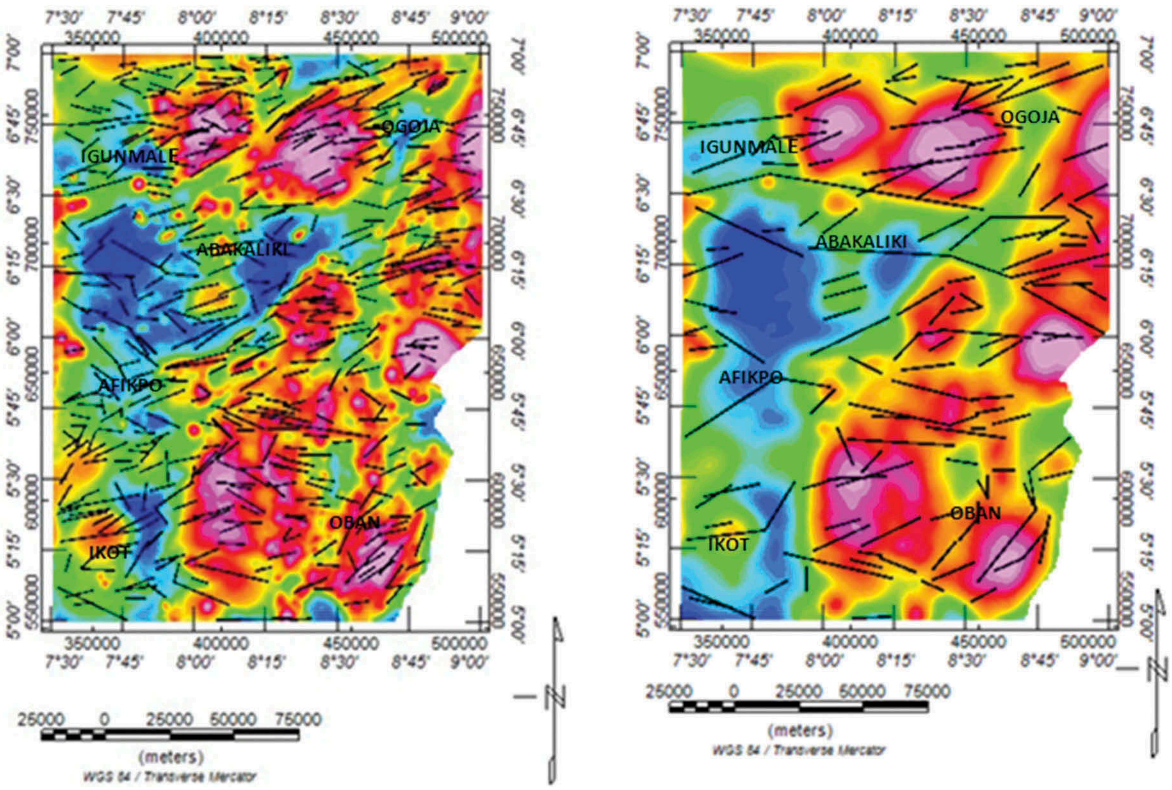


Figure 13. Lineament maps for upward continuation 1000 m and 4000 m showing the distribution of structures in the basement and sedimentary unit.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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