Integration of Magnetic, Gravity and Geologic Data in Mapping Geologic Structures: A Case Study of a part of Lafiagi [Sheet 203], Southwestern Nigeria*

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Search and Discovery Article #41737 (2015)
Posted November 30, 2015

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG/SEG International Conference & Exhibition, Melbourne, Australia, September 13-16, 2015, AAPG/SEG © 2015.

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Abstract

Structural evaluation of the pegmatite-rich zones in a part of the Lafiagi (Sheet 203), southwestern Nigeria was carried out. It was aimed at the identification of the structures responsible for both the hydrogeology and rich mineralization of the area. This work involved the qualitative and quantitative analysis of aeromagnetic, pseudo-gravity, and geological data using Oasis Montaj™ and Rockwork15™ software. The 3-D Euler Deconvolution and 2-D Forward modeling and inversion of the acquired aero-magnetic and pseudo-gravity data augmented with geological information obtained from reliable sources were employed in the lineaments extraction and other structural interpretation works. The results have shown that the identified faults and lineament features obtained from geophysical data generally coincide with the river channels on the geologic and drainage maps. This indicates a structural control of the drainage system while the abundance of 2D and 3D structures that are commonly associated with gemstones and precious minerals explain why the study area is rich in mineral deposits.

Introduction

The study area covers a part of the Lafiagi (Sheet 203) in the Nigerian topographical map. It is situated at the transition environment between the Nupe Basin and the Southwestern Nigerian Basement Complex. It is bounded by latitudes 8°40’ and 8°51’ N and longitude 5°00’ and 5°23’ E, covering an area of 896.6 km^2. The Nupe Basin is a NW-SE trending embayment (Figure 1) perpendicular to the main axis of the Benue Trough and the Niger Delta Basin of Nigeria. It is frequently regarded as the Northwestern extension of the Anambra Basin, both of which were major depocentres during the transgressive cycle of Southern Nigeria in the Late Cretaceous times (Murat, 1972). It has rocks of sedimentary basin flanked by both the Basement Complex rocks of southwestern and northcentral Nigeria. Evidence from the eastern and northern margins of the West African craton indicates that the Pan-African belt evolved by plate tectonic processes which involved the collision between the passive continental margins of the West African craton and the active continental margin (Pharusian Belt) of the Tuareg Shield about 600 Ma ago (Leblanc, 1981; Black et al., 1979; Caby et al., 1981). The collision at the plate margin is believed to have led to the reactivation of the internal region of the belt. The Nigerian Basement Complex lies at the reactivated part of the belt. The Pan African in

Nigeria was followed by conjugate strike slip fault systems which trends in the NE-SW and NW-SE direction and show dextral and sinistral sense of displacement which cut across the earlier Pan African structures (Wright, 1976 and Ball, 1980).

A contact or transition zone exists between the basement and sedimentary environments in the study area (Figure 2) and the area is also rich in mineral deposits and has generated a lot of interests because of the considerable mining activities that is taking place. The mining of rare metals and gemstones bearing pegmatite is well known in the Gbugbu, Lema, and Bishewa communities (Okunlola et al., 2007). A central positive gravity anomalies flanked by negative anomalies have been confirmed for this basin as shown for the adjacent Benue Trough and typical of rift structures (Ojo, 1984; Ojo and Ajakaiye, 1989). The basin has also been confirmed to be bounded by a system of linear faults trending NW-SE, using geophysical data (Kogbe et al., 1983). In this research, a part of the Lafiagi (Sheet 203) which includes the transition zone between a part of the Nupe Basin area and the adjacent southwestern Nigeria Basement Complex has been mapped, its subsurface structures elucidated, the depth to the basement surface, and an updated geological map of the study area has been produced.

Materials and Methods

Data Source and Analysis

The soft copy of digital aeromagnetic data (i.e. Lafiagi aeromagnetic grid map, Sheet 203), was procured from the Nigeria Geological Survey Agency (NGSA), Abuja, Nigeria. The survey which was aimed at mineral and ground water development through improved geological mapping was collected at Flight Height of 80 m, Flight Line spacing of 500 m, and Tie Line spacing of 2000 m. The Flight Line direction was NW-SE whereas the Tie Lines were NE-SW. For ease of processing, the data was stripped of a common value of 32,000 nT. This value may therefore be added to every data point to get the exact regional field. However, doing this will not change the Grid in any way since the value is common to all the data points.

Data collection for this area was done in 2006, so a 2005 epoch International Geomagnetic Reference Field (IGRF) was used to calculate Inclination and Declination as follows:

Field Strength = 33129.9632nT; Inclination = -6.87339275; Declination = -2.51357917.

Figure 3a is the Total Magnetic Intensity (TMI) map of the study area. The map emphasizes the intensities and the wavelengths of the local anomalies that reveal information on the geometry, strike, contacts between rocks, and intensities of magnetization within the study area. Several anomalies can be referred to distinct magnetic zones. Figure 3b and Figure 3c are the total field aeromagnetic (REDE) and pseudogravity maps respectively being superimposed on their contours.

The 3D Euler Deconvolution Method

The 3D Euler deconvolution technique is an equivalent method based on the Euler's homogeneity equation as developed by Reid et al. (1990) following Thompson's (1973) suggestion and operating on gridded magnetic data. The method is based on the concept that anomalous

magnetic fields of localized structures are homogeneous function of the source coordinate and, therefore, satisfies Euler's homogeneity equation. The method operates on the data directly and provides a mathematical solution without recourse to any geological constraints. The application of Euler deconvolution has emerged as a powerful tool for direct determination of depth and probable source geometry in magnetic data interpretation (Barbosa et al., 1999). The Euler derived interpretation requires only a little a priori knowledge about the magnetic source geometry and information about the magnetization vector (Barbosa et al., 2000).

The 3-D Euler Deconvolution processing routine is an automatic location and depth determination software package for gridded magnetic and gravity data. The depths are displayed as a grid and are based on source parameters of the following source models: contacts (faults), thin sheets (dykes), or horizontal cylinders.

Theory of Euler Deconvolution Method

Any three-dimensional function *f (x,y,z)* is said to be *homogeneous* of degree *n* if the function obeys the expression (Whitehead and Musselman, 2005):

$$f(tx, ty, tz) = t^n f(x, y, z) \qquad (1)$$

From this it can be shown that the following (known as *Euler's equation*) is also satisfied (Whitehead and Musselman, 2005):

$$x\frac{\partial f}{\partial x} + y\frac{\partial f}{\partial y} + z\frac{\partial f}{\partial z} = nf \qquad (2)$$

Thompson (1982) has shown that simple magnetic and gravity models conform to Euler's equation. The degree of homogeneity, *n*, can be interpreted as a *structural index* (SI), which is a measure of the rate of change with distance of a potential field. A magnetic point dipole corresponds to n = 3, while a gravity point mass, a magnetic pole (theoretical), and a line of magnetic dipoles corresponds to n = 1. Reid et al. (1990) have shown that a magnetic contact will yield an index of 0.5 provided that an offset A is introduced to incorporate an anomaly amplitude, strike and dip factors (Whitehead and Musselman, 2005):

$$A = (x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} \qquad (3)$$

Given a set of observed total field data, we can determine an optimum source location (x_0, y_0, z_0) by solving Euler's equations for a given index *n* by least-squares inversion of the data.

2D Forward Modeling and Inversion of the Aeromagnetic and Gravity Data

To quantitatively interpret the magnetic and pseudo-gravity data (Figure 3b and Figure 3c), the GM-SYS profile of Oasis Montaj software was used. The GM-SYS profile is a program for calculating the gravity and magnetic response from a geologic cross-section model. GM-SYS provides an easy-to-use interface for interactively creating and manipulating models to fit observed gravity and/or magnetic data. Forward modeling involves creating a hypothetical geologic model and calculating the geophysical response to that earth model while inversion, optimization, or inverse modeling involves the reverse procedure. Starting with the observed geophysical response, an earth model that will provide the best fit to that data is calculated. Because gravity and magnetic calculations are non-linear, the calculations use an iterative process. Two-Dimensional (2-D) models assume the earth is two-dimensional; i.e. it changes with depth (the Z direction) and in the direction of the profile (X direction; perpendicular to strike). 2-D models do not change in the strike direction (Y direction). The a priori information obtained from geologic and 3D Euler inversions of the magnetic and pseudo-gravity data were used in GM-SYS to create a hypothetical geological model of the subsurface area of the Lafiagi study area, which was subsequently employed in the 2-D Forward and inversion, optimization, or inverse modeling.

The aeromagnetic and gravity anomalies are trending mainly in the NE-SW direction with occasional NW-SE (e.g. around Bankole) direction at the northern edge of the study area. The first three profiles (Figure 2; AB, CD, and EF) were therefore chosen perpendicular to the predominant strike for maximum information on the causative structures and the geology of the area while other profiles were chosen to cut across the two main lithologies (i.e. Basement and Sedimentary) and suspected structures.

Theoretical Basis for 2D Forward Modeling and Inversion of the Aeromagnetic and Gravity Data

The methods used to calculate the gravity and magnetic model response are based on the methods of Talwani et al. (1959) and Talwani and Heirtzler (1964), and make use of the algorithms described by Won and Bevis (1987). Two-and-a-half dimensional calculations are based on Rasmussen and Pedersen (1979). The GM-SYS inversion routine utilizes a Marguardt inversion algorithm (Marguardt, 1963) and the USGS computer program, SAKI (Webring, 1985) to linearize and invert the calculations (Tom et al., 2009).

Results and Discussions

Pattern Interpretation of the Aeromagnetic and Gravity Data

The aeromagnetic and pseudogravity anomalies maps (Figure 3b and Figure 3c) have been divided into four distinct zones and subzones of various magnetic and gravimetric characteristics. These include:

(i) Zone A which is characterized by low to intermediate magnetic relieves (i.e. subzones A1 to A3; Figure 3b) with corresponding high density relieves (i.e. subzones A1 to A5; Figure 3c) in the northern part of the study area has amplitudes varying mostly from < 23 nT to 58 nT and -00136 to 0.01230 mGal for magnetic and gravity data respectively.

(ii) Zone B is characterized by anomalies with broad and wide extent having moderately high to very high and occasional low magnetic relieves (i.e. subzones B1 to B5; Figure 3b) with corresponding low density relieves (i.e. subzones B1 to B4; Figure 3c) in the central part of the study area. Their amplitudes vary mostly from < 52 to > 93 nT and from < -0.00991 mGal to approx. 0.00112 mGal for magnetic and gravity data respectively. The rock here is composed mainly of Cretaceous sediments and a few other rocks like Biotite gneiss, Mica schist, Quartzite/Quartz schist and Amphibolite.

(iii) Zone C is characterized by ring strake and speckled mixture of high and low magnetic relieves (i.e. subzones C1 to C6; Figure 3b) with corresponding moderately high to very high density relieves with mostly concentric patterns (i.e. subzones C1 to C5; Figure 3c). These anomalies have amplitudes of < 23 to > 93 nT and approx. -0.00336 to > 0.01230 mGal for the magnetic and gravity data respectively. This zone is associated on the geological map with Biotite gneiss, Mica schist, and Amphibolite.

(iv) Zone D is characterized by a relatively low to intermediate magnetic (Figure 3b) and gravity (Figure 3c) relieves that are wedged to the extreme corner of the southwestern part of the study area (D1). The amplitudes range from approximately 35 to 52 nT (magnetic) and -00136 to -00580 mGal (gravity).

Superimposition of Zone Colored Euler Solutions for Lineaments on Drainage Map

Figure 4a and Figure 4b show the superimposition of zone colored Euler solutions for near surface lineaments (i.e. magnetic S.I = 0.5 and gravity S.I = 0.0) on the drainage map of the study area. Both maps show the preponderance of the NE-SW trends and coincidence of the faults/lineament features with the river channels thereby confirming the fact that the drainage in the study area is structurally controlled (Garba, 2011).

Superimposition of Inferred Fault/Lineaments Obtained from 2D Forward Modeling on Drainage Map

Figure 5a and Figure 5b show typical aeromagnetic and pseudogravity anomalies and their corresponding subsurface model while Figure 6 shows the superimposition of inferred fault/lineaments obtained from 2D Forward Modeling on the drainage map and the coincidence of faults/lineament features with the river channels thereby confirming the fact that the drainage in the study area is structurally controlled (Garba, 2011). Figure 7 is the rose plot of faults/lineament features showing the preponderance of the N-S, followed by the NE-SW trends thereby confirming the fact that the Pan African in Nigeria was followed by conjugate strike slip fault systems which averaged in the NE-SW and NW-SE directions and showed dextral (e.g. Q in Figure 6) and sinistral sense of displacement which cut across the earlier Pan African structures (Wright, 1976 and Ball, 1980).

Zone Colored Euler Solutions for 2D and 3D Structures

The results obtained for structural indices 1.1 to 3.0 (i.e. thin prisms with large depth to sphere; magnetic) and 0.5 to 2 (i.e. ribbon to sphere; gravity) represents 2D and 3D structures. Figure 8a shows the result obtained for structural index of 2.0 (i.e. vertical or horizontal cylinder; magnetic) with depths ranging from 45 – 250 m. Some of these solutions which represent deep-seated dykes/ribbons and sills (intra-

sedimentary or intrusives) have been shown and labeled on the map while Figure 8b shows the result obtained for structural index of 1.1 (i.e. pipe and dyke; gravity) with depths ranging from 139 – 297 m. The structural indices 2.0 (magnetic) and 1.1 (gravity) of the 3D Euler Deconvolution have been used worldwide to detect or explore for Kimberlite pipes which are well known for hosting large quantity of minerals (diamonds and garnet) and rocks (peridotite and xenoliths) (Paterson et al., 1991 and Yaghoobian et al., 1992). While the structural indices 3.0 (magnetic) and 2.0 (gravity) have been used worldwide to detect tanks and drums (or metalliferous bodies) (Yaghoobian et al., 1992 and Marchetti and Settimi, 2011). The known rare metals and gemstones bearing pegmatite rich zones (i.e. Gbugbu, Lema, and Bishewa communities) were therefore demarcated on these maps for correlation purposes. Many of these pipe-like and spherical features correlate with the known pegmatite rich zones thereby confirming the association of structural indices 2.0 and 3.0 (magnetic) and 1.1 and 2.0 (gravity) with mineral rich areas. However, other undifferentiated areas which are also rich in pegmatite are shown in Figure 8 where mining activity is less organized (e.g. west of Bishewa and south of Gbugbu communities).

Modified Geologic Map of the Study Area

A modified geologic map based on the results obtained from the interpretation of geologic, aeromagnetic, and gravity maps has been produced (Figure 9). A geological survey conducted prior to this work revealed the existence of the few faults illustrated as solid lines. It failed however to show the whole length of some of these faults (e.g. W2), the lateral shift (e.g. Q), and there were many other faults in the study area (e.g. H, I, P1- P3 etc.). The geophysical measurements yielded more information on the known faults and exposed the hidden ones. The results of geophysical measurements were confirmed by the photo-lineaments information from the satellite imagery, 3D Euler deconvolution and the 2D models. The newly identified faults and lineament features obtained from geophysical data (dashed lines) and the existing faults in the existing geologic map (solid lines) are displayed on the modified geologic map. Generally, they coincide with the river channels on the geologic map (Figure 9) just like the existing faults on the existing geologic map thereby further strengthening the assertion that the drainage in the study area is structurally controlled (Garba, 2011). They are also oriented generally in the NE-SW or NW-SE directions corroborating the fact that the Pan African in Nigeria was followed by conjugate strike slip fault systems which trended in the NE-SW and NW-SE direction and show dextral and sinistral sense of displacement which cut across the earlier Pan African structures (Wright, 1976 and Ball, 1980).

The magnetic and gravity anomalies patterns (Figure 3b and Figure 3c) have shown that Zone B (Figure 3b; represented by subzones B1-B5 in the central part of the study area) with prominent magnetic high that coincides with the position of gravity low and wide area extent (Figure 3c; represented by subzones B1-B3) is assumed to be produced by bodies with low densities and low magnetic susceptibilities since the inclination of the ambient magnetic field in the area is close to 0°. The effect of the sedimentary rocks (mostly conglomeratic sandstones, siltstones, and claystones) is relatively more here compared to that of other rocks, therefore the sedimentary environment was restricted to this area on the modified geologic map.

Conclusions

This research has evaluated the structures within the Lafiagi Study area using geological, aeromagnetic, and gravity data. The newly identified faults and lineament features obtained from geophysical data as well as the existing ones from the geologic map (e.g. Figure 4 and Figure 6) generally coincide with the river channels on the drainage map which indicate a structural control of the drainage system in the study area.

These set of structures which might have resulted from the reactivation or reworking of the crystalline basement complex region of the West African craton after the Pan African orogeny (Black et al., 1979; Caby et al., 1981; and Leblanc, 1981) and which are generally oriented in the NE-SW direction (Figure 6 and Figure 7) correlates with the general geologic strike and corroborate the fact that the Pan African in Nigeria was followed by conjugate strike slip fault systems which trends in the NE-SW and NW-SE directions and showed dextral and sinistral sense of displacement which cut across the earlier Pan African structures (Wright, 1976 and Ball, 1980).

The 2D and 3D structures which are represented by thin prisms with large depth to sphere (magnetic) and ribbon to sphere (gravity) are found in large quantity in the study area. The structural indices of 2.0 (i.e. vertical or horizontal cylinder; magnetic) and 1.1 (i.e. pipe and dyke; gravity) of 3D Euler Deconvolution have been used worldwide to detect or explore for kimberlite pipes which are well known for hosting large quantity of minerals (diamonds and garnet) and rocks (peridotite and xenoliths) (Paterson et al., 1991 and Yaghoobian et al., 1992) while the structural indices 3.0 and 2.0 (i.e. sphere or dipole) in magnetic and gravity respectively have been used worldwide to detect tanks and drums (or metalliferous bodies) (Yaghoobian et al., 1992 and Marchetti and Settimi, 2011). Many of these pipe-like (e.g. Figure 8) and spherical features correlate with the known pegmatite rich zones thereby confirming the association of structural indices 2.0 and 3.0 (magnetic) and 1.1 and 2.0 (gravity) with mineral rich areas. However, other undifferentiated areas which are also rich in pegmatite are found in the study area (Figure 8) where mining activity is less organized (e.g. west of Bishewa and south of Gbugbu communities). These have not been discovered because the local miners were mainly operating on a hit and loss manner and most of the times there are more losses than hits whereas the application of technology was able to show a picture of the subsurface better.

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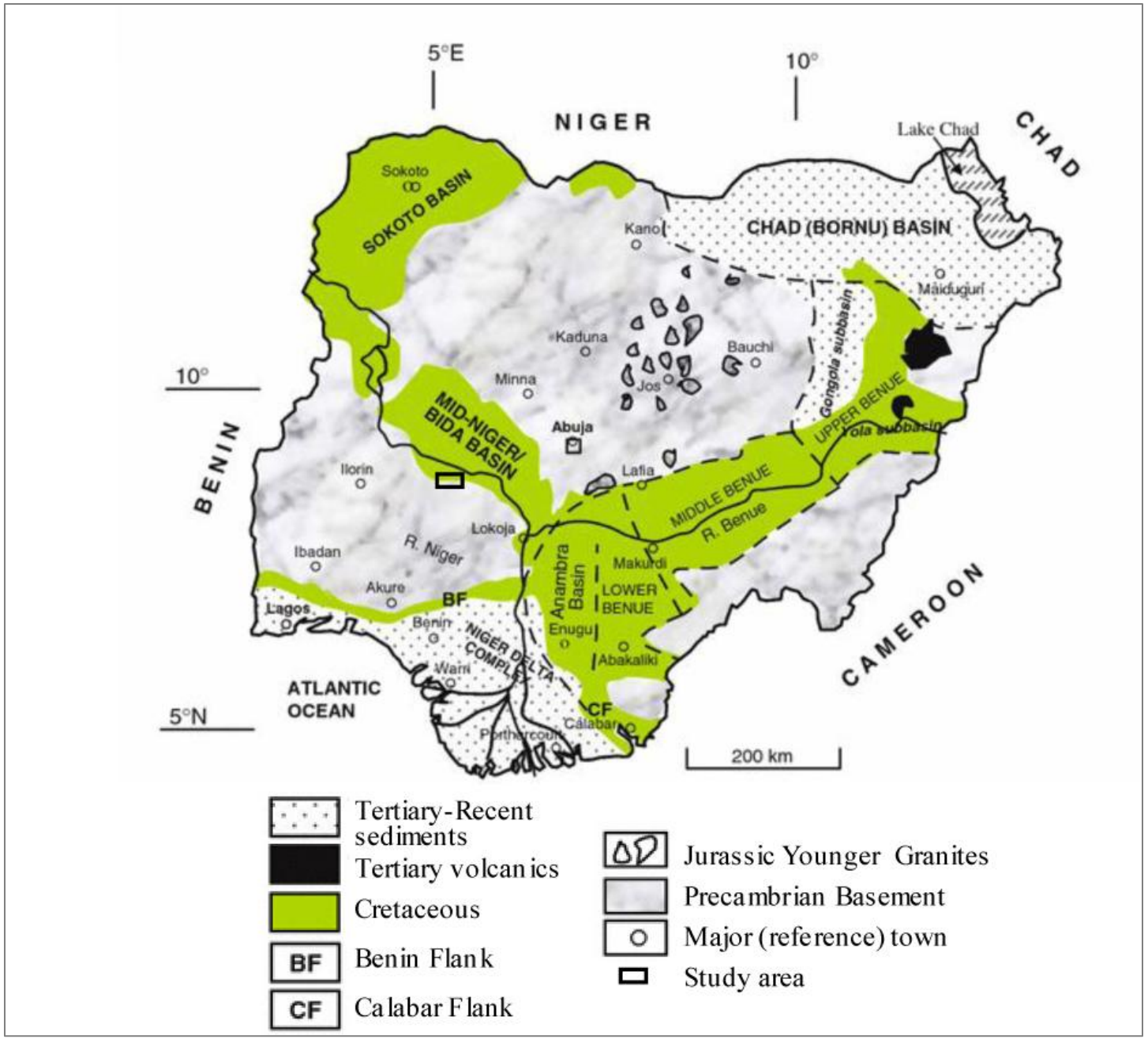


Figure 1. Geological Sketch Map of Nigeria Showing the Major Geological Components (Basement, Younger Granites, and Sedimentary Basins) and the Study Area (after Obaje, 2009).

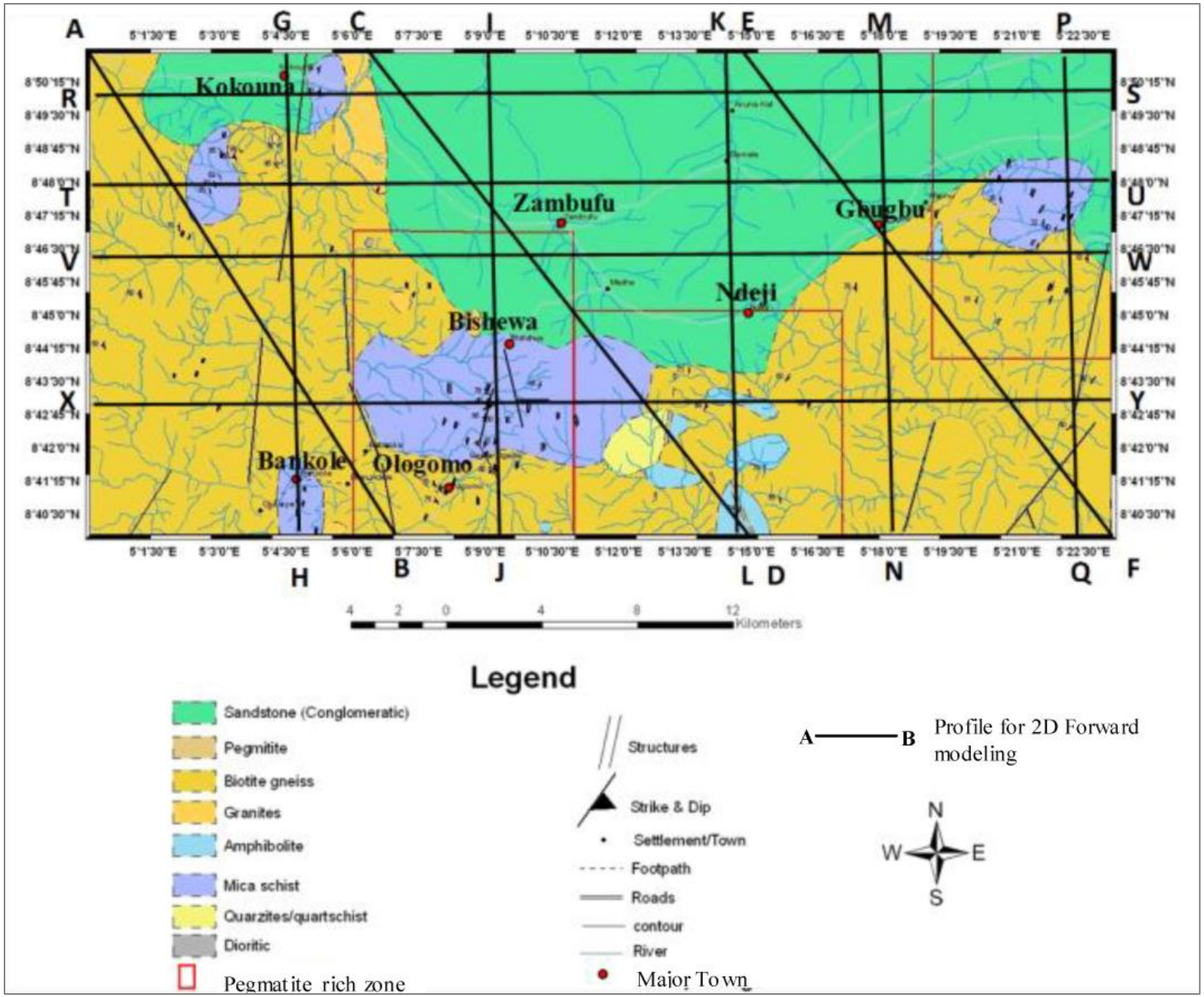


Figure 2. Geological Map of the Study Area (after Garba, 2011).

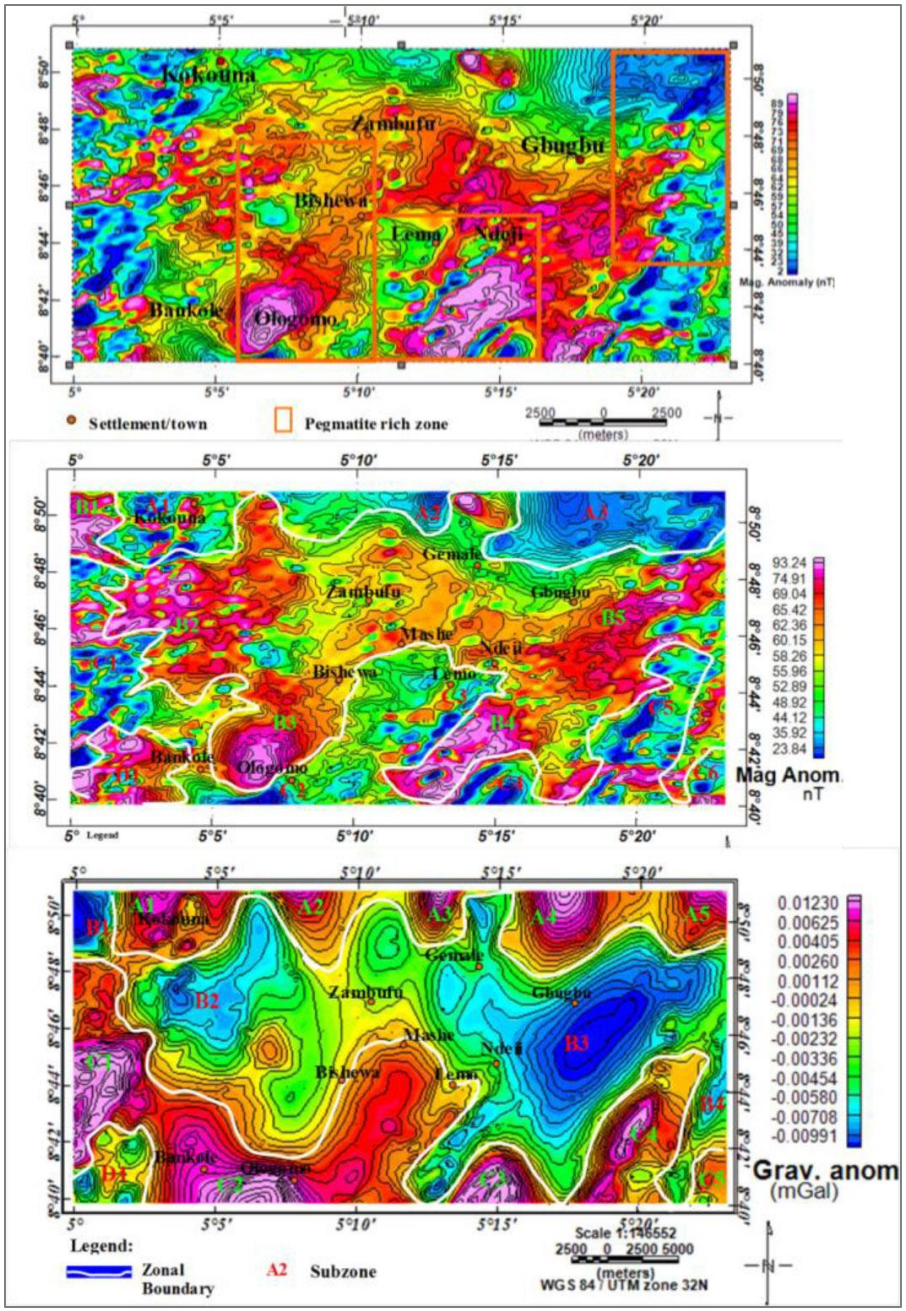


Figure 3. (a) Total Magnetic Intensity (TMI) Map, (b) Superimposition of Total Field Aeromagnetic Map (REDE) and its Contour, and (c) Superimposition of Pseudogravity Map and its Contour.

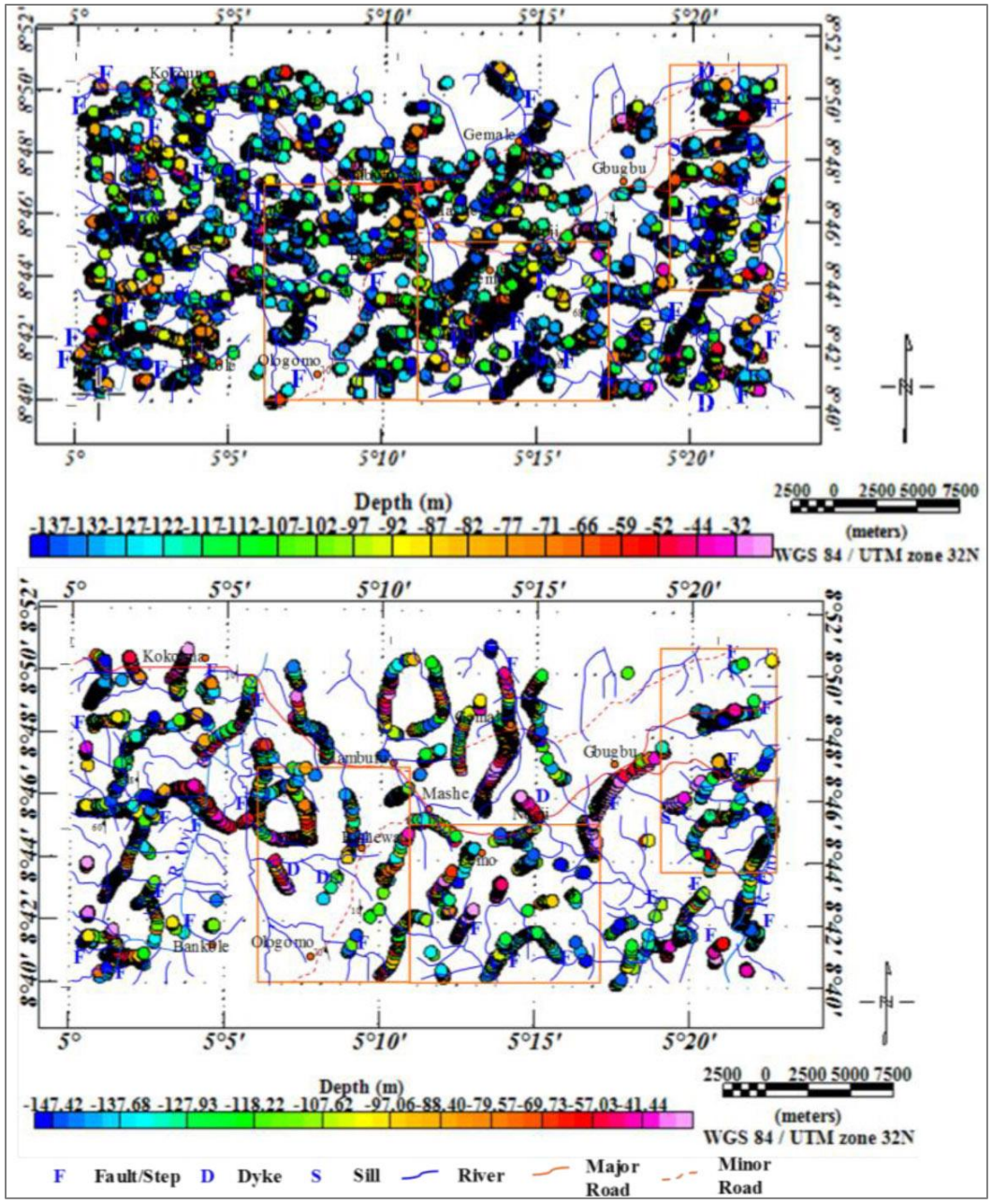


Figure 4. Superimposition of: (a) Magnetic Euler Solutions for Lineaments on Drainage Map and (b) Gravity Euler Solutions for Lineaments on Drainage Map.

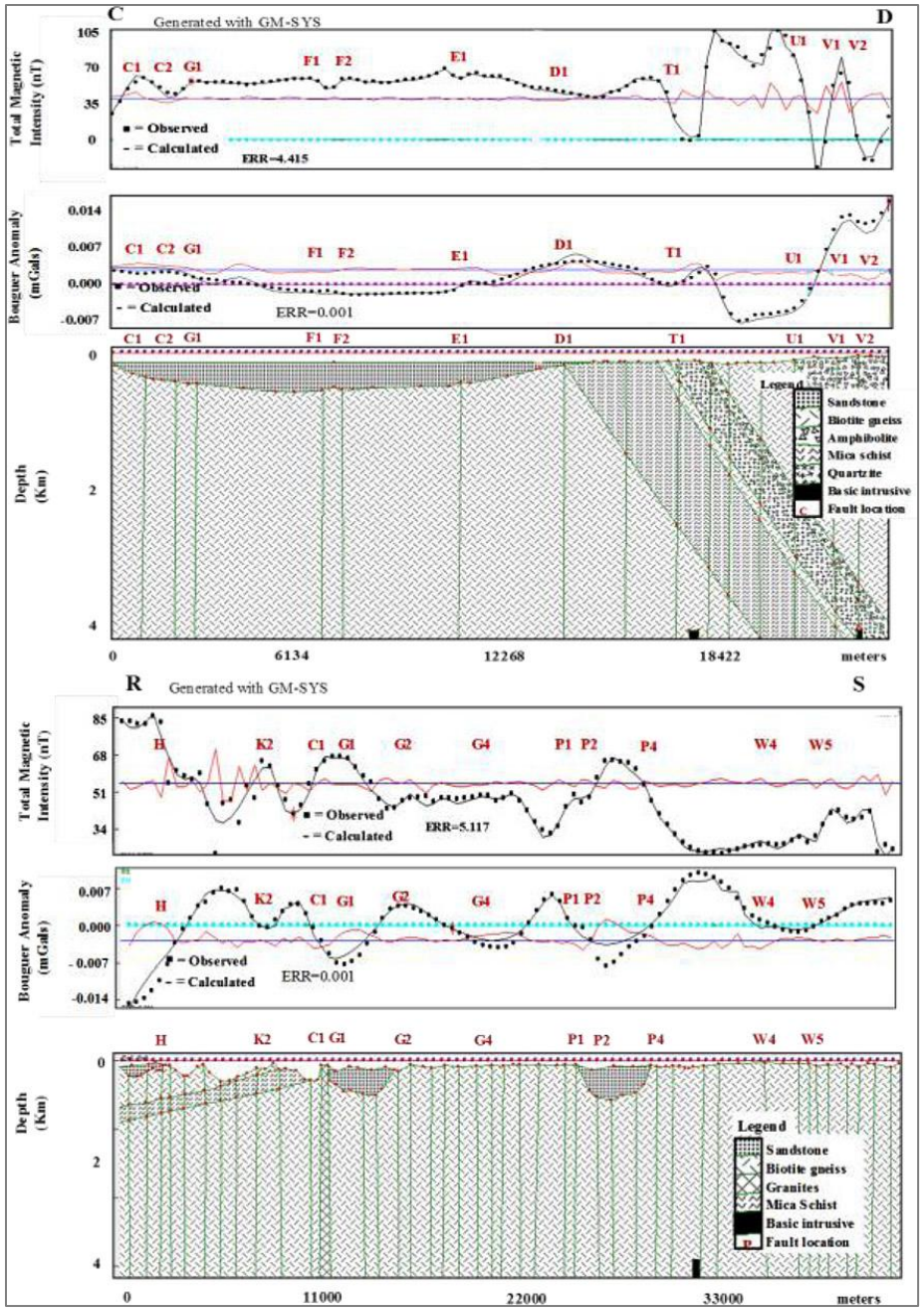


Figure 5. A Typical Aero-Magnetic and Pseudo-Gravity Anomalies and their Corresponding Subsurface Model along Profiles: (a) CD and (b) RS.

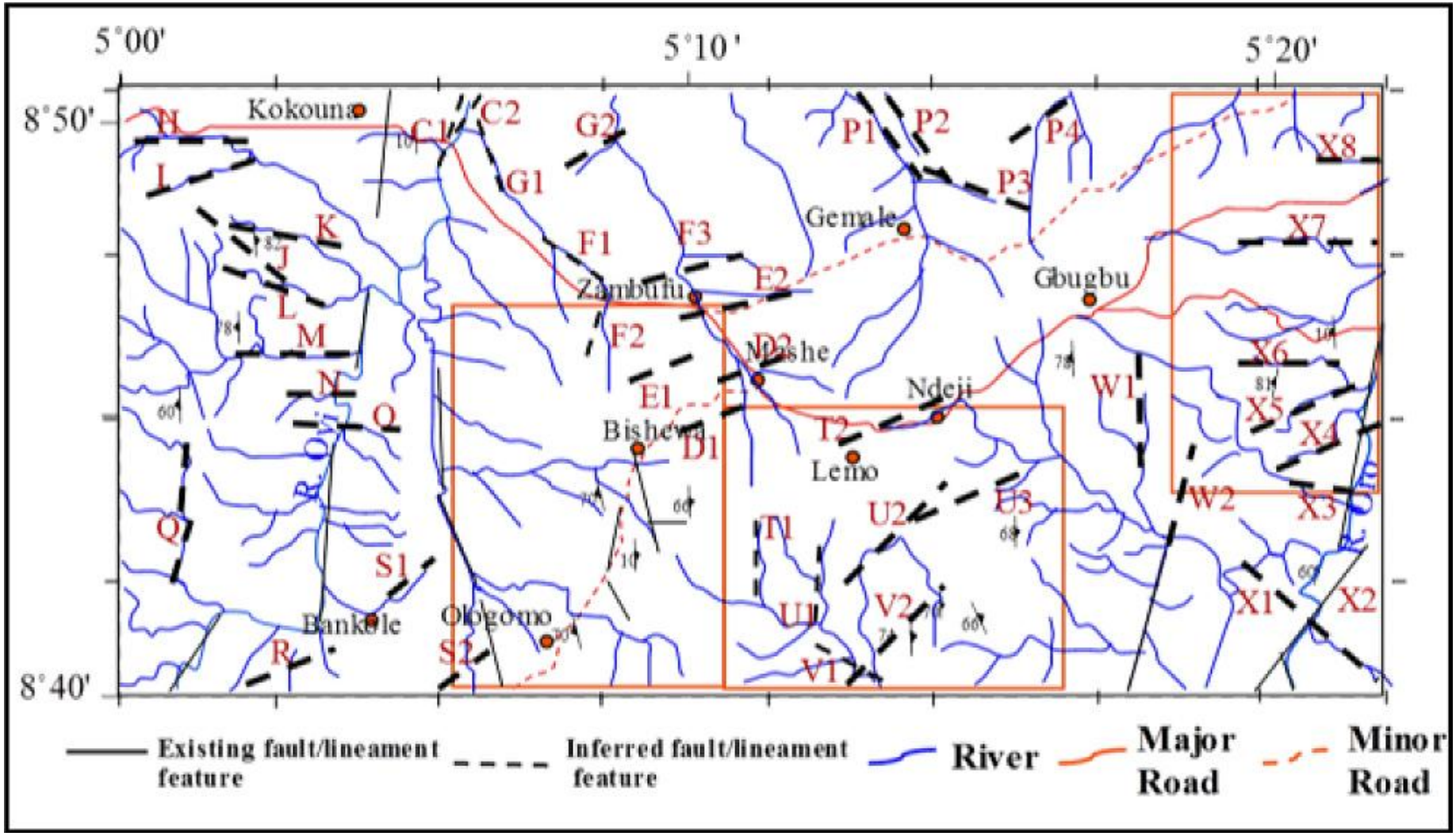


Figure 6. Superimposition of Inferred Fault/Lineaments Obtained from 2D Forward Modeling on Drainage Map.

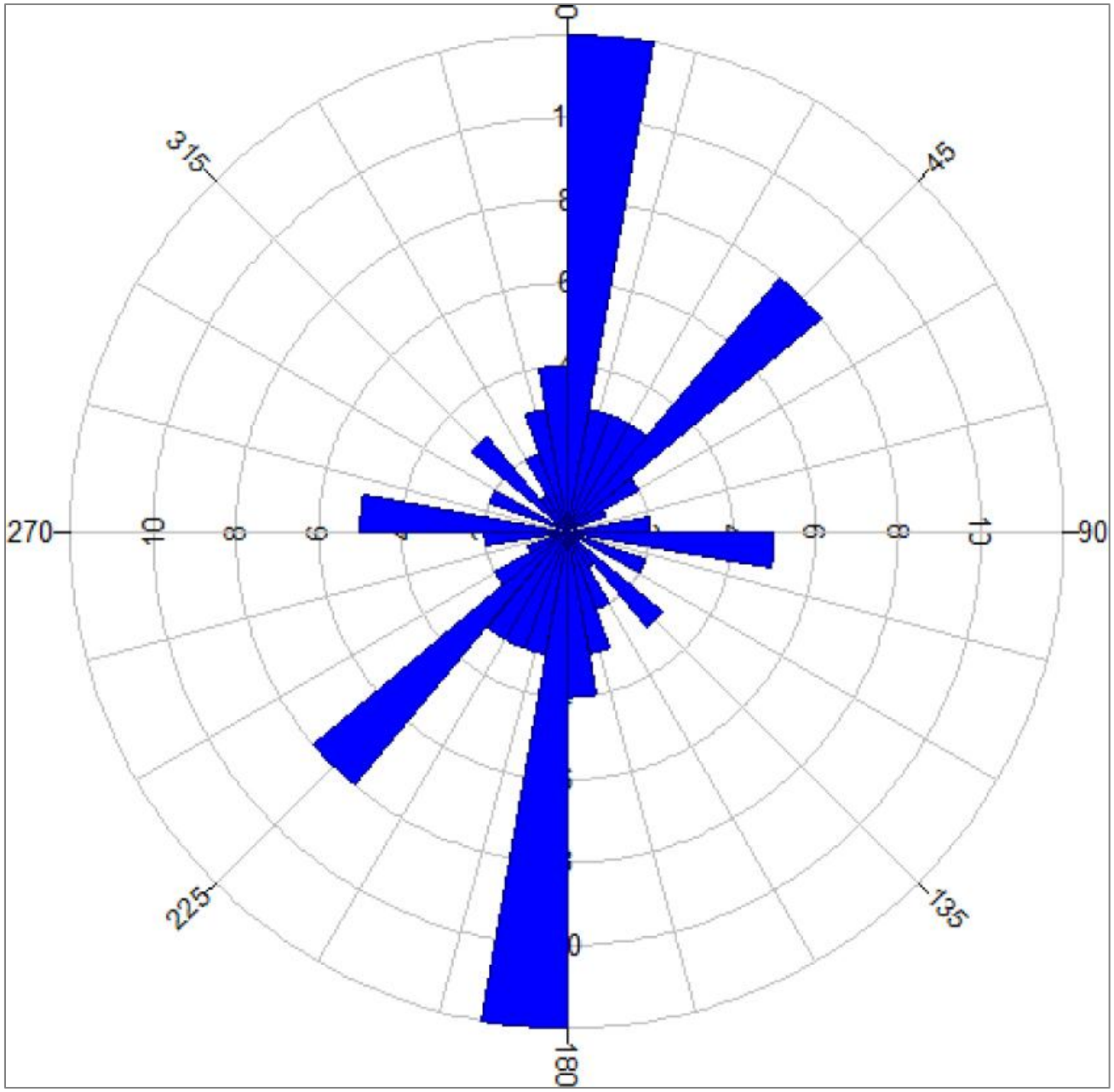


Figure 7. Rose Plot of Faults/Lineament Features in the Study Area.

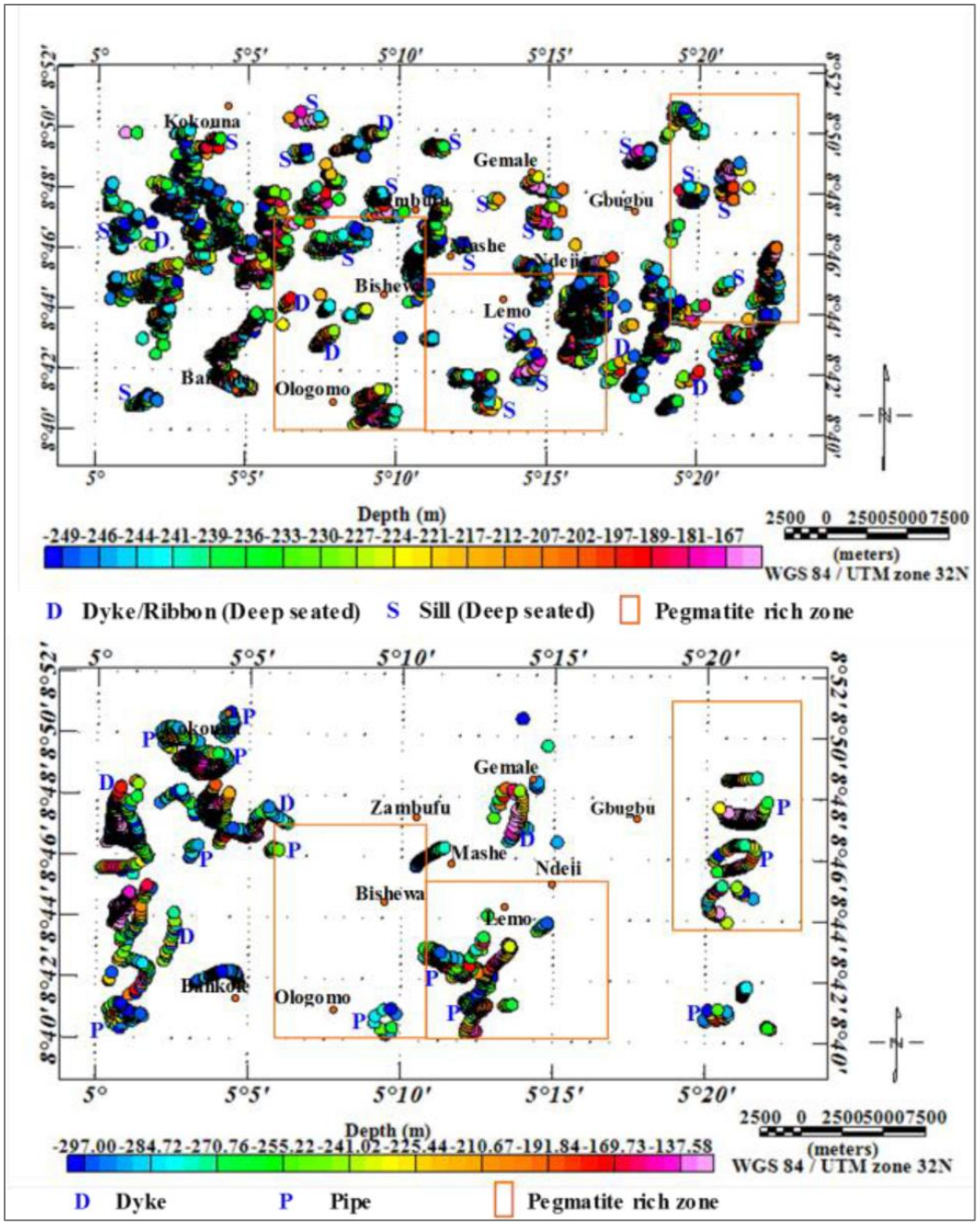


Figure 8. (a) A Typical Aero-Magnetic Euler Solutions Map for Sphere (S.I =2.0) and (b) A Typical Pseudo-Gravity Euler Solutions Map for Sphere (S.I =1.1).

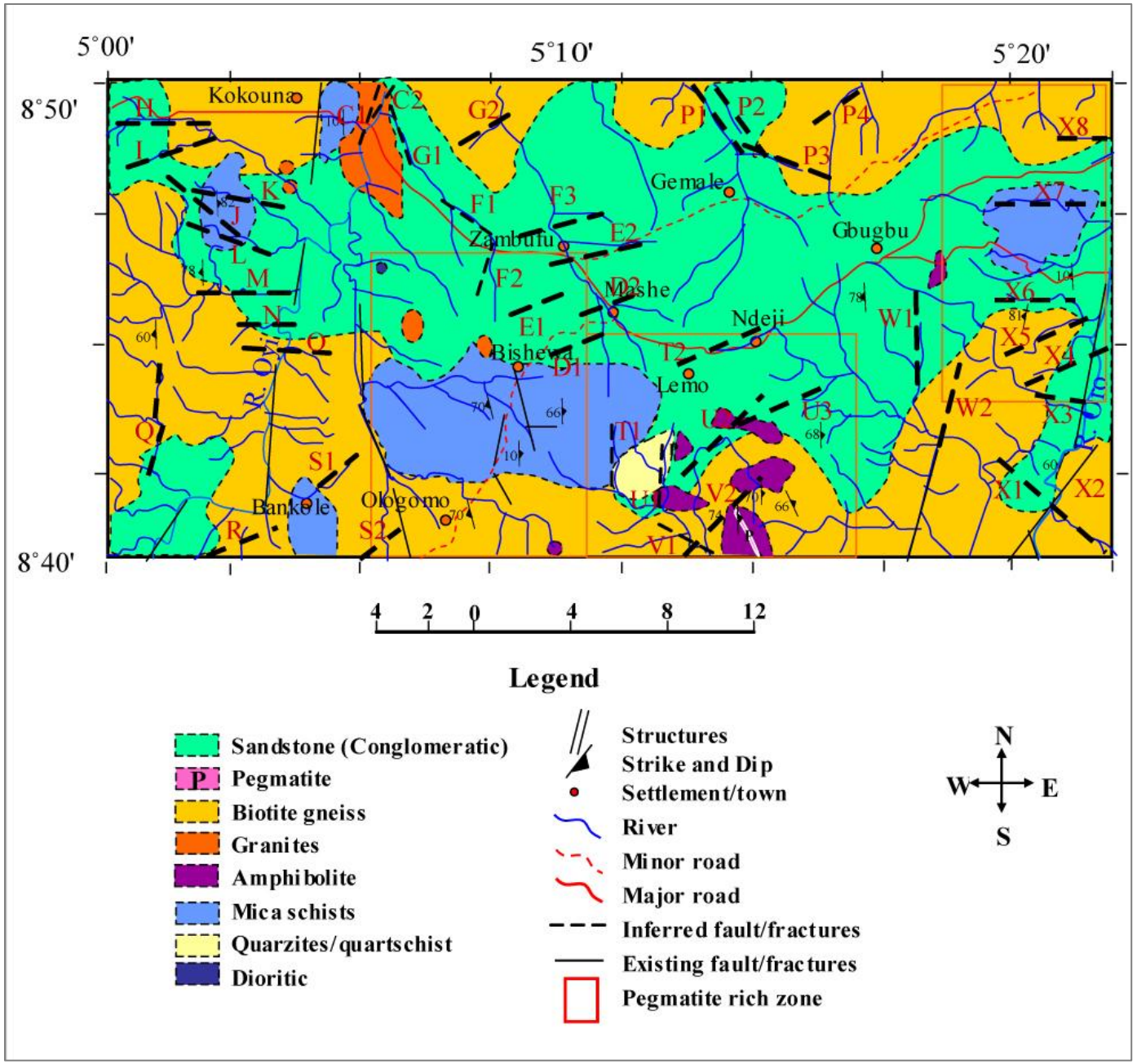


Figure 9. Modified Geologic Map of the Study Area.