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Aeromagnetic and remote sensing evidence for structural framework of the middle Niger and Sokoto basins, Nigeria

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ABSTRACT

High resolution aeromagnetic and Shuttle Radar Topography Mission data from parts of the N-S axis of the western half of Nigeria that covers the Middle Niger and Sokoto Basins provide a coherent picture for the surface expression of the linear and curvilinear features and the topography of the zone. It equally identifies the boundaries of the sedimentary basins with depths up to 950 m, thereby establishing the controlling architectural framework of the two basins. The relationship between observed structural features and lateral continuity of the Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones and their implication on the mineral deposits in the region has been reinforced. The three-dimensional analytic signal applied to the aeromagnetic data unveiled magnetic structures and depths to magnetic basement were estimated using the source parameter imaging technique. The results identified several *E*-W, NW-SE, NNE-SSW and ENE-WSW trending structural features, two of which correspond to the NNE-SSW trending Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones formed during the Pan-African orogeny. Additionally, we unravel a sedimentary pile, here called Libata-Auna sub-basin, connecting the Middle Niger and Sokoto Basins. The shred of evidence derived from both methods reveal the potential of the faults system through the crystalline and the sedimentary parts of the studied area for future minerals exploration projects.

1. Introduction

High resolution magnetic datasets are currently widely used as a preliminary tool in hydrocarbon programs and as a major geophysical tool in mineral exploration projects. These datasets are commonly presented in gridded maps and are rapidly interpreted for magnetic source locations and depths (Salawu et al., 2019a, 2019b). Consequently, various processing techniques have been established to aid these estimations. Location of source boundaries and depths to magnetic sources are estimated by unequivocal techniques such as 3D analytic signal (MacLeod et al., 1993; Nabighian, 1972; Roest et al., 1992) and source parameter imaging (Thurston and Smith, 1997) respectively. The Nigerian basement is characterized by many shear zones that are favourable pathways for fluid-transported mineral deposits associated with quartz veins and pegmatite dikes along these linear structures, making them prime targets in mineral exploration.

The area around the Middle Niger and Sokoto Basins, which constitute the study area, has not been mapped in detail and there are no detailed geological and structural assessments of the sedimentary basins in the area due to thick vegetation cover and diverse physiographic terrain features that reduce accessibility. The study area has long been known for artisanal mining activities with original target mineral deposits associated with placers. However, the greatest challenge in the development of large scale mining is the paucity of structural data on primary targets and in their bid to locate primary deposits; the artisanal miners resulted to random excavation of gold–quartz reefs. This predisposed many non-mineralized locations to large scale land degradation with obvious loss of land for agricultural production. Any significant and economical mining activities will therefore, be at depth hitherto unreached by artisanal miners and requires a detailed

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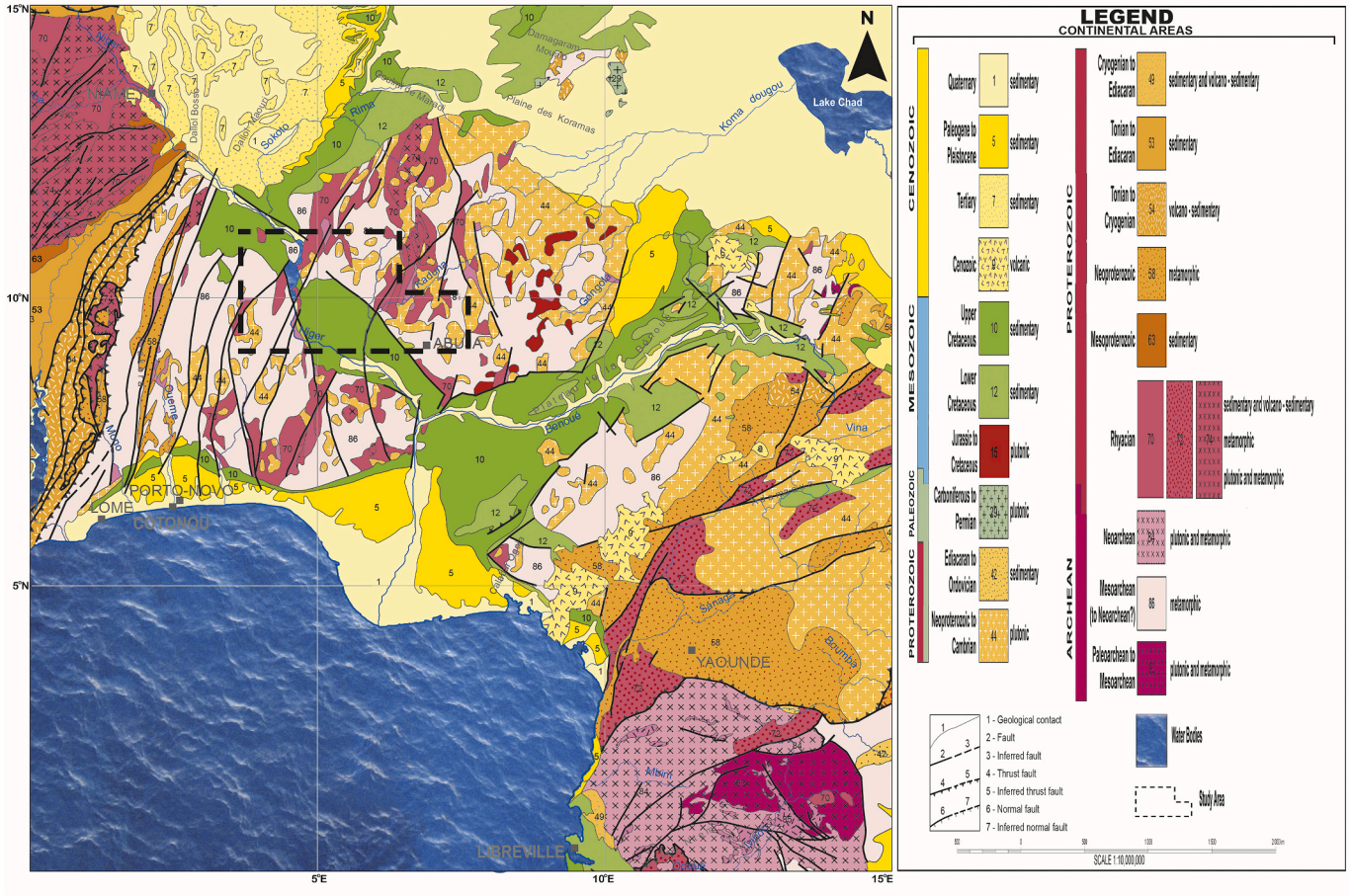


Fig. 1. Generalized geologic map of Nigeria and its environ showing the location of the study area which is indicated as dashed black lines on the map. (Thieblemont, 2016).

structural map of the region. This makes high resolution aeromagnetic and satellite imaging techniques more appropriate for the region.

The present study focuses on delineating surface and subsurface geologic structures for mapping structurally controlled mineral deposits and to estimate depth to magnetic sources of the Middle Niger and Sokoto Basins based on aeromagnetic and Shuttle Radar Topography Mission data. Finally, the integration of this information with ground truthing within the study area constitutes a multidisciplinary approach which provides significant information for future mineral projects.

2. Regional geology

The area studied extends from 4° E to 8° E and 9° N to 11° N and is located within the western half of central Nigeria (Fig. 1). The Sokoto and Middle Niger Basins are underlain and encompassed by the crystalline basement of a reworked Archaean-Proterozoic sequence as discussed below.

2.1. The crystalline basement

The basement in the area is part of the Precambrian terrain that lies within the Pan-African mobile belt as a southern prolongation of the Hoggar-Tuareg shield and northern extension of the Borborema province (NE Brazil) within the context of the Proterozoic Gondwana amalgamation (Ajibade et al., 1987; Dada, 2008). The terrain exhibits a poly-orogenic sequence of reworked Archaean migmatite gneisses, Palaeoproterozoic metasediments of uncertain age which include the prominent Ifewara-Zungeru quartzite/mylonite that grade into Neoproterozoic (Pan African 600 Ma) granitoids. The latter thermotectonic event developed dominant NE-SW and N-S trending shears which define major structural features (such as foliations, lineation, folds etc.) of the whole region (Dada, 2008). The entire crystalline basement of Nigeria is cut-across by two regional scale NNE-trending transcurrent shear systems (Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones) which separate geologic units and/or crustal domains. These shear zone systems has long been acknowledged as probable crustal sutures of Pan-African orogeny and locality for economic mineral deposits (Wright, 1976; Mccurry and Wright, 1977; Ajibade and Wright, 1988; Garba, 2000; Dada, 2008).

2.2. Middle Niger Basin

The Middle Niger Basin (Fig. 2) is a NW-SE trending intra-cratonic basin which extends NW wards from the confluence of Benue and Niger Rivers at Dekina/Lokoja axis. It is separated by the crystalline basement terrane from the early Cretaceous to Tertiary Illo and Gundumi Formations of the Sokoto Basin at Shegwa around Kainji reservoir (Kogbe, 1989; Rahaman et al., 2018). The basin fill consists of a NW-trending belt of Upper Cretaceous (Campano-Maastrichtian) sedimentary rock units which resulted from rifting, basement fragmentation, block faulting, drifting subsidence, deposition of the latter material and subsequent opening of the South Atlantic (Obaje 2009). The basin is distinctive from other basins of Nigeria because it is characterized by the non-existence of Tertiary age sediments, carbonate and volcanic rocks (Rahaman et al., 2018). Based on geographic perspective, the Middle Niger Basin has been generally divided into the southern and

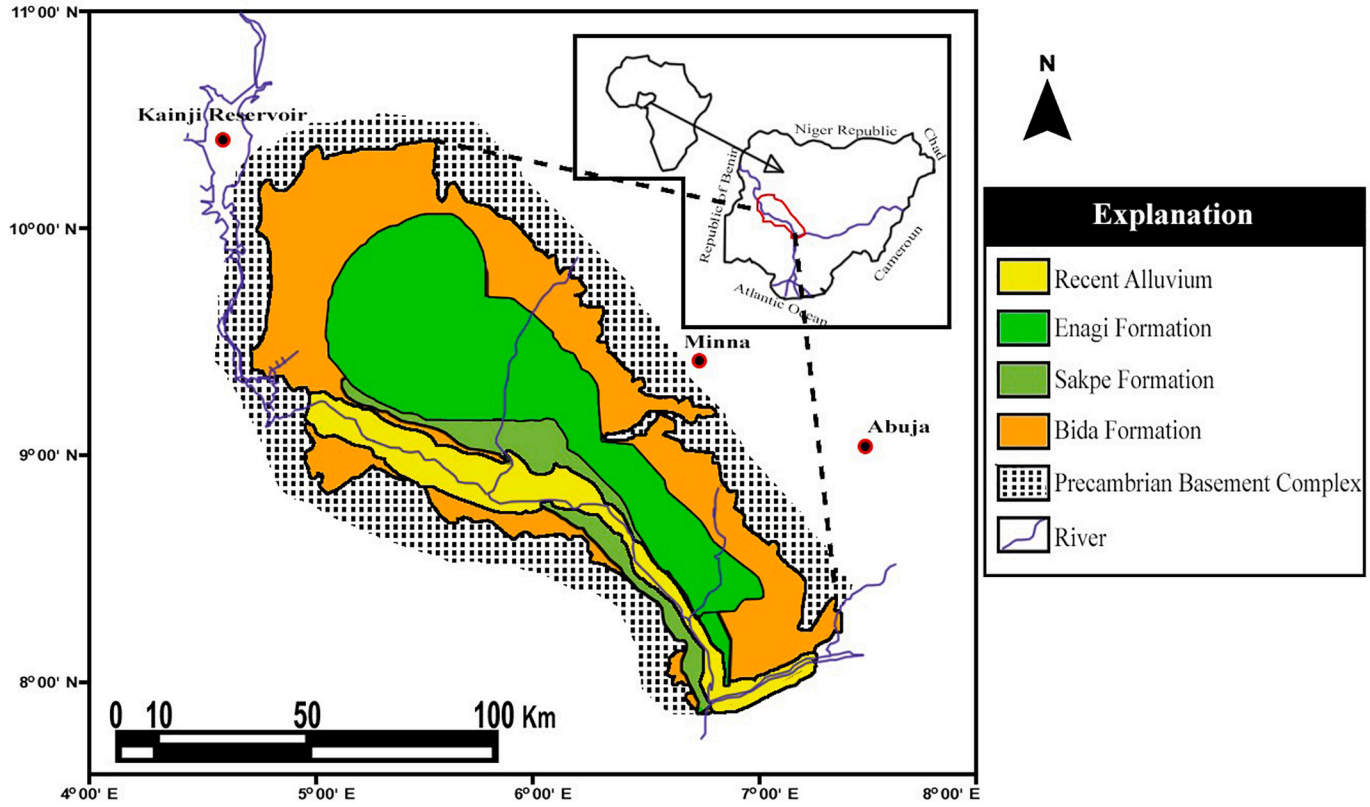


Fig. 2. Generalized geologic map of the Middle Niger Basin in part of the North-central, Nigeria (modified after Rahaman et al., 2018).

northern sub-basins. In the northern segment of the basin (Bida area), the sequence which consists of sandstones unconformably overlies the basement complex. The Bida sandstones range from premature (mineralogically and texturally), clast to matrix supported conglomerate, which fines upward to conglomeratic-sandstones, to medium grained sandstones, subordinated claystone and siltstones. Bida Sandstones are directly overlain by Sakpe Formation which is in turn overlain by Enagi Formation (siltstone, sandstone, claystone) and successively overlain by Batati Formation (Rahaman et al., 2018).

2.3. Sokoto Basin

The Sokoto Basin, which forms part of the Nigeria portion of the Iullemmeden Basin, is underlain by succession of inter-bedded semi-consolidated clay, sand, gravel and limestone. This succession reaches a general thickness of about 1066.8 m which ranges from Cretaceous to Quaternary in age (Anderson and Ogilbee, 1973). Illo and Gundumi Formations which consist of clays and grits are the oldest rock units (Late Jurassic to Earliest Cretaceous) of the succession and overlie the Precambrian basement unconformably (Kogbe, 1981). Directly above the Gundumi and Illo Formations is the Rima Group (Maastrichtian) that consists of a sequence of clay and fine gray sand deposits. Rima Group includes the Taloka and Wurno Formations, which are divided apart in the northern portion of the Sokoto Basin by Calcareous clay shale of Dukamaje Formation and a basal clay member. Rima Group sediments are transitional, from terrestrial sedimentary deposits of Cretaceous Illo and Gundumi Formations to the overlying Tertiary Sokoto Group (marine calcareous sedimentary deposit). Paleocene age sediments of the Sokoto Group include from the base of the Dange Formation which is greenish gray clay, which is overlain by Kalambaina Formation that is a gray clayey limestone which includes a concentration of nodular crystalline limestone. The summary of geological sequence of the Sokoto Basin is shown in Table 1.

3. Data

3.1. Topographic data

We utilized topographic imagery acquired by the Shuttle Radar Topography Mission (SRTM) to examine the impact of major shear zones in the topography of the Sokoto and Middle Niger Basins. The SRTM topographic data were downloaded from the website of the United States Geological Survey (USGS) and have a spatial resolution of 1-ARC (approximately 30 m). These datasets were joined in a mosaic together, and we shade the resulting image utilizing a 45 degrees light angle at azimuths of 45 degrees and 315 degrees to reveal the NW- and NE-trending structures, respectively. Additionally, we produced color digital elevation model to visualize the impact of basement structural features on the topography.

3.2. Aeromagnetic data

Aeromagnetic anomalies constitute great evidence of subsurface geology (materials) when magnetic susceptibility differences are substantial. The aeromagnetic anomaly data analyzed for this study were provided by the Nigerian Geological Survey Agency (NGSA). The data were acquired by Fugro Airborne Surveys for NGSA between 2004 and 2009 as part of the World Bank supported project scheme to foster exploration of mineral resources in Nigeria. The aeromagnetic survey was carried out using 3 × -Scintrex CS3 Cesium Vapour Magnetometer, at 80 m nominal flight height, with NE–SW flight lines perpendicular to the regional structural trends spaced 500 m apart and tie lines of 2000 m interval. The collected data were corrected for transient magnetic variation effects and the International Geomagnetic Reference Field (IGRF 2005 model) was removed from the data. The IGRF corrected aeromagnetic anomaly data (see Fig. 3) forms the basis for all preceding interpretative methods applied to the data. Similarly, it is

Table 1
Stratigraphic sequence of the Sokoto Basin, the Nigerian portion of the Iullemmeden sedimentary basin (adopted from Kogbe, 1981).

Age	Formation	Group	Environment
Quaternary	Sandy drifts, laterites	–	continental
Eocene to Miocene	Gwandu Formation	"Continental Terminal" (*Grès du Niger*)	continental
		Unconformity	
Late Paleocene	Primary oolitic ironstone	Sokoto Group	marine
	Gamba Formation		
	Kalambaina Formation		
	Dange Formation		
		Unconformity	
Maastrichtian	Wurno Formation	Rima Group	Brackish water with brief marine intercalation
	Dukamaje Formation		
	Taloka Formation		
		Unconformity	
Late Jurassic to Earliest Cretaceous	Illo and Gundumi Formations	"Continental Intercalaire"	Continental
		Major Unconformity	
Precambrian		Basement Complex	

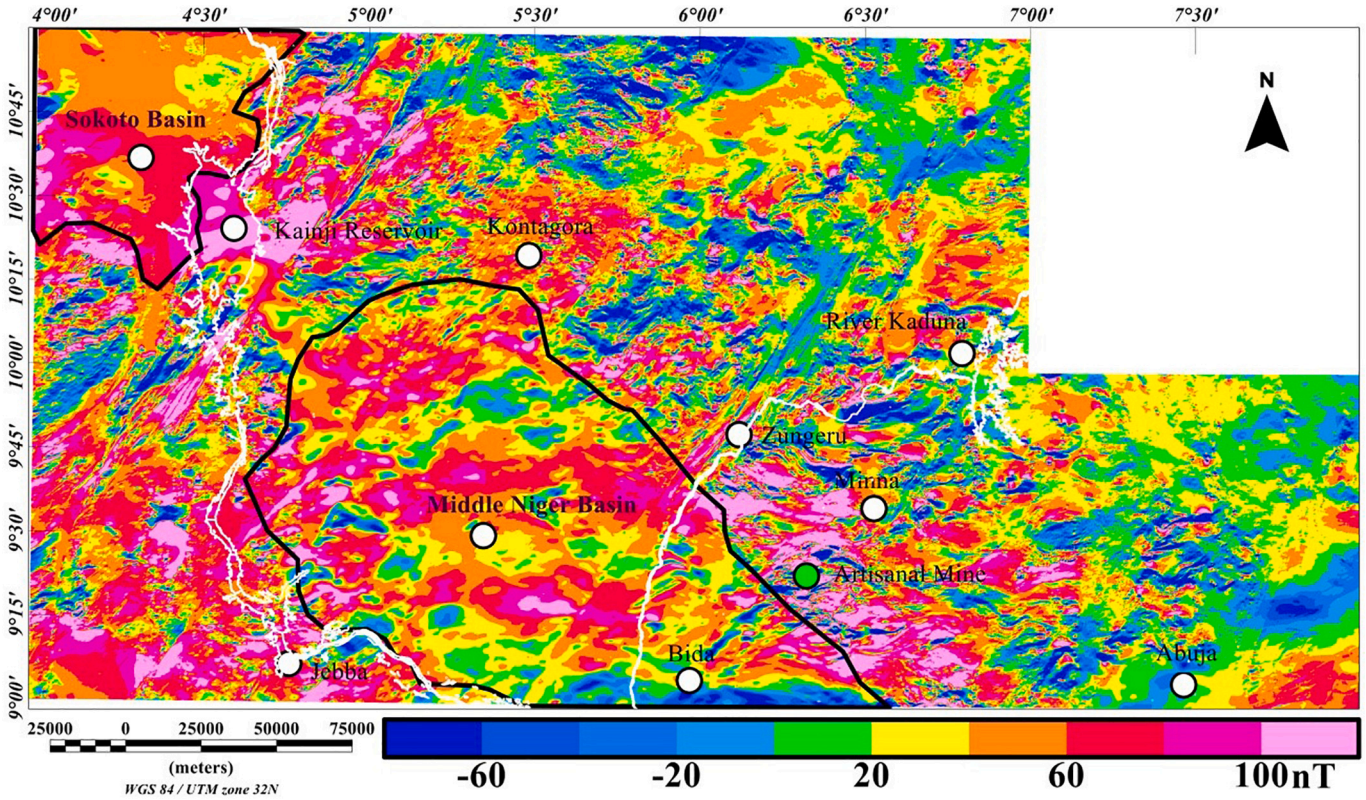


Fig. 3. The total intensity aeromagnetic anomaly map over parts of southern Sokoto Basin, the entire northern segment of Middle Niger Basin and surrounding crystalline basement terrain. The colors reveal large variations in the magnitude of the aeromagnetic anomaly dataset. The white lines represent the river channel and the boundary of sedimentary basin is marked by black polygons.

Table 2
Utilized parameters for the automatic lineament extraction procedure. Abbreviations: RADI – Filter Radius, GTHR – Edge Gradient Threshold, LTHR – Curve Length Threshold, FTHR – Line Fitting Error Threshold, ATHR– Angular Difference Threshold, DTHR– Linking Distance Threshold,

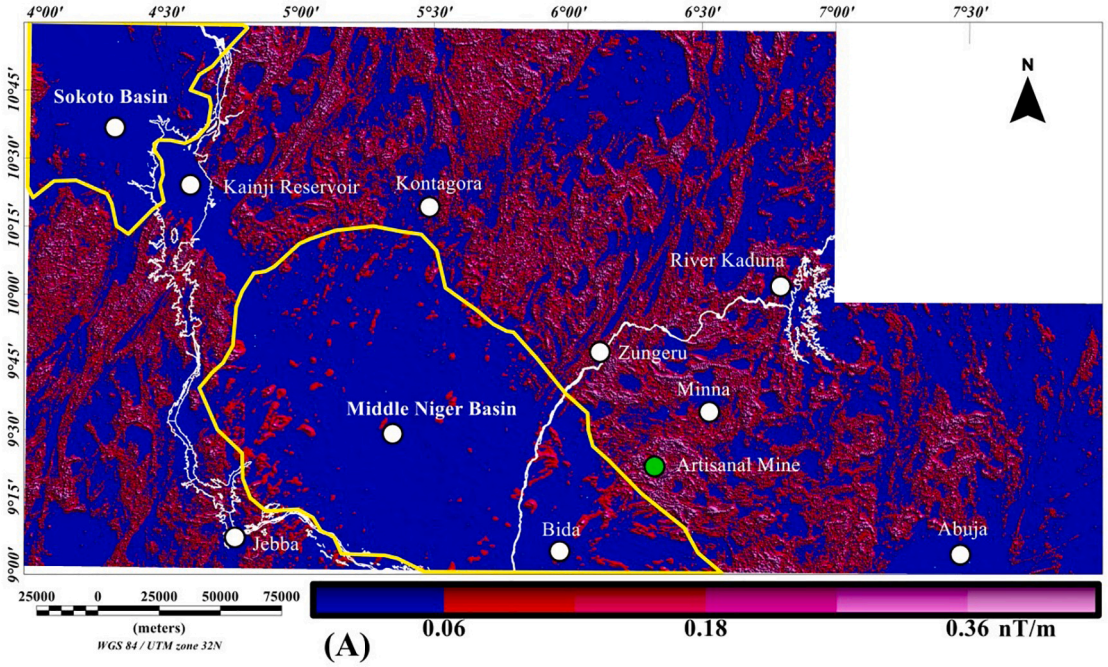
Parameter	RADI	GTHR	LTHR	FTHR	ATHR	DTHR
Values	10	100	100	30	2	5

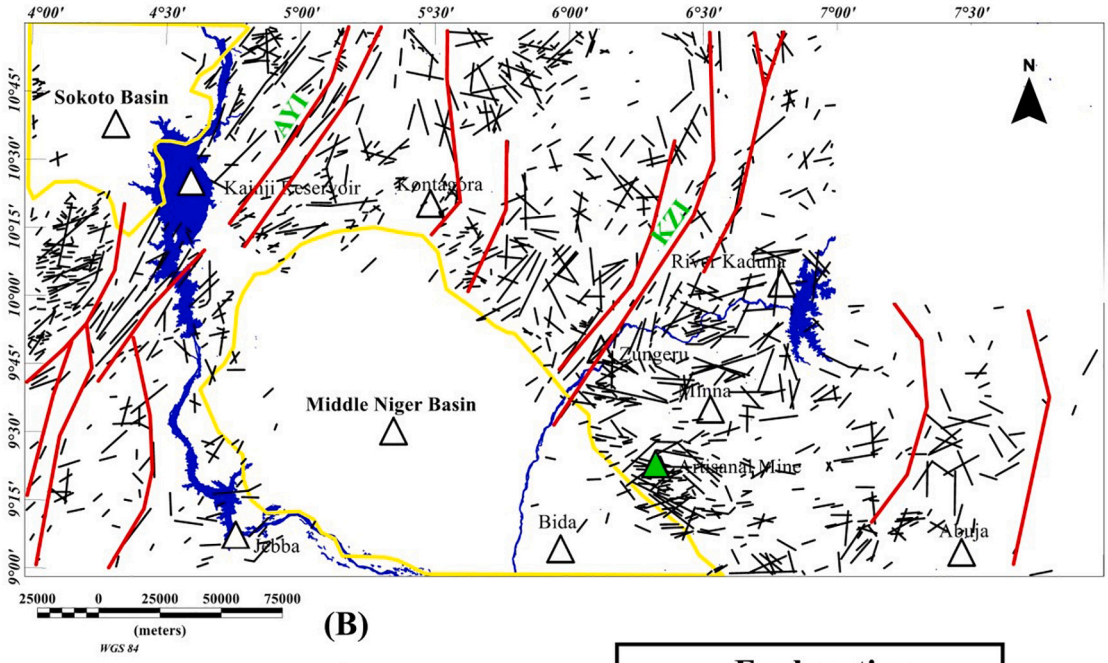
essential to note that good analysis with high resolution data forms part of the requirements for realizing valuable information about the nature of subsurface structural features (Adebiyi et al., 2020).

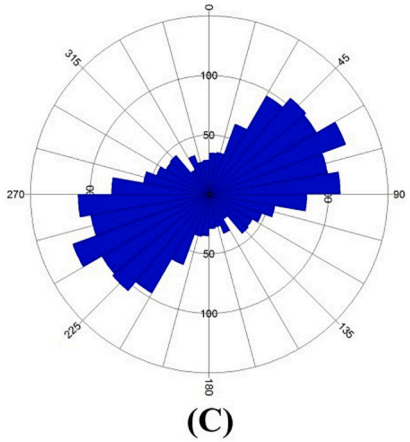
4. Methods

4.1. Remote sensing method

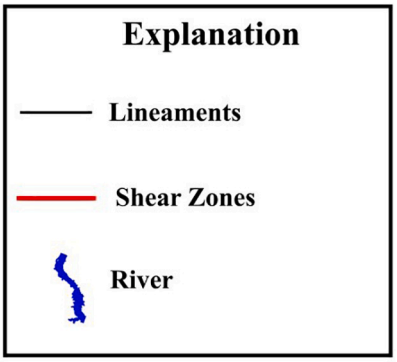
ArcMap software was utilized to produce two illumination hill shade images with a light azimuth of 45° and 135° from the Shuttle Radar Topography Mission digital elevation model data of the study area. The analytical hill-shading technique is commonly used to reveal the topographical relief of the Earth's surface. Surface lineaments (curvilinear and linear features) were subsequently extracted automatically from both hill shade images. This is ensuring that the lineaments produced from the images were comparable and integrated. Integrating multiple light azimuth angles provide valuable understanding of spatial patterns for linear to curvilinear features that cannot







(C)



(caption on next page)

Fig. 4. (a) Color-shaded 3D analytic signal map of the study area, computed from the residual magnetic intensity data. The map shows the entire northern portion of the Middle Niger Basin and southern segment of the Sokoto Basin, which are characterized by low values (blue color). (b) Proposed structural map of the region computed from the identified maxima of the 3D analytic signal. Note the Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones on Fig. 4b specified by thick red lines. (c) Rose diagram computed from the maxima of the 3D analytic signal, showing that the magnetic lineaments are mainly oriented in the NE-SW, NNE-SSW ENE-WSW and E-W directions. Boundary of sedimentary basin is marked by yellow polygons. Abbreviations: AYI – Anka–Yauri–Iseyin shear zone, KZI – Kalangai–Zungeru-Ifewara shear zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 5. Field photo of an active artisanal gold pit dug along N-S and NE-SW trending quartz vein. The location of the site is indicated with green circle in Figs. 4a and b, which matches well with some E-W trending magnetic lineaments within the region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

be observed if a single light hill-shaded image was utilized. The PCI Geomatica LINE module was utilized to extract lineaments from the produced hill-shade images mentioned above. The module extracts linear and curvilinear features from a single input image and stores the resulting polylines in a vector layer using six threshold parameters (Table 2). These parameters were changed until the desired lineaments were achieved; the adopted values are shown in Table 2.

4.2. Magnetic method

The utility of aeromagnetic data measured at non-polar and non-equatorial regions (such as the study area) for direct geological interpretation are complicated by the polarity of the anomalies. Hence, we used a standard edge detection filter (3D analytic signal) and depth estimation technique (source parameter imaging) suitable for low latitude regions. These techniques are designed such that they do not depend on the anomaly polarity and do not require reduction-to-pole/equator transformation as proposed input data. We applied the 3D analytic signal to the total magnetic intensity anomaly data of Fig. 4 to investigate the influence of major shear zones and lineaments beneath the sedimentary cover of Middle Niger and Sokoto Basins. Depth to magnetic sources within the study area were estimated using the source parameter imaging.

4.2.1. 3D analytic signal

The independence of the direction of magnetization in the shape of the 3D analytic signal anomalies is an attractive characteristic for the interpretation of aeromagnetic data at non-polar regions (MacLeod et al., 1993). The amplitude of the 3D analytic signal exhibits maxima over magnetic structural features (such as contacts and faults), independent of magnetization direction. It is derived from the vertical and horizontal derivatives of the aeromagnetic anomaly using the following relationship (Roest et al., 1992)

$$|AS| = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2 + \left(\frac{\partial F}{\partial z}\right)^2} \quad (1)$$

where $|AS|$ is the amplitude of the analytic signal, F is the observed aeromagnetic anomaly field, $\left(\frac{\partial F}{\partial x}\right)$, $\left(\frac{\partial F}{\partial y}\right)$are the horizontal derivatives and $\left(\frac{\partial F}{\partial z}\right)$is the vertical derivative of the aeromagnetic anomaly field. The 3D analytic signal enhancement filter was applied to the aeromagnetic anomaly data of the study area to assess structural features within the region.

4.2.2. Source parameter imaging

The source parameter imaging (SPI) technique is routinely used to estimate the depths to the top of magnetic sources. The resulting depth estimates are independent of magnetic declination, inclination, strike, dip and remanent magnetization (Thurston and Smith, 1997). These parameters make the SPI technique highly suitable for low-latitude regions. The SPI technique uses the local wavenumber for depth estimation process given by

$$K = \frac{\frac{\partial^2 F}{\partial x \partial z}\frac{\partial F}{\partial x} + \frac{\partial^2 F}{\partial x \partial z}\frac{\partial F}{\partial y} + \frac{\partial^2 F}{\partial z^2}\frac{\partial F}{\partial z}}{|AS|^2} \quad (2)$$

For dipping magnetic geologic contacts, peaks of K are positioned directly over the edges of isolated contacts. Consequently, depth estimates are computed from the reciprocal of local wavenumber, given as:

$$Depth_{x=0} = \frac{1}{K_{\max}} \quad (3)$$

Where, K_{max} is the maximum value of K (local wavenumber) over the step magnetic source. We applied SPI technique to the aeromagnetic anomaly map of parts of southern Sokoto Basin, the entire northern segment of Middle Niger Basin and surrounding crystalline basement terrain to estimate depth to magnetic sources within the basins.

4.2.3. Upward continuation

The upward continuation of magnetic field anomaly data has been utilized in the analysis and interpretation for over two decades. The further perspective gained from observing an anomaly field at various levels has been extensively acknowledged as valuable in understanding subsurface anomaly sources (Robinson, 1970). The application of upward continuation filter to aeromagnetic anomaly data is used broadly by geophysicists for quality resolution of magnetic signal associated with deep and extended sources, particularly when a considerable effect of shallow sources are present (Ciminale and Loddo, 1989). The filter essentially produces no side effects that may need further processes to correct (Salawu et al., 2020). We applied the upward continuation filter to the aeromagnetic anomaly data to produce the regional magnetic anomaly field of the study area. The structural and depth information deduced from the 3D analytic signal and source parameter imaging (SPI) maps were used to select the height parameter (1200 m) used for the upward continuation filter, which was applied to the aeromagnetic anomaly data. Since the aeromagnetic data (see Fig. 4) includes the

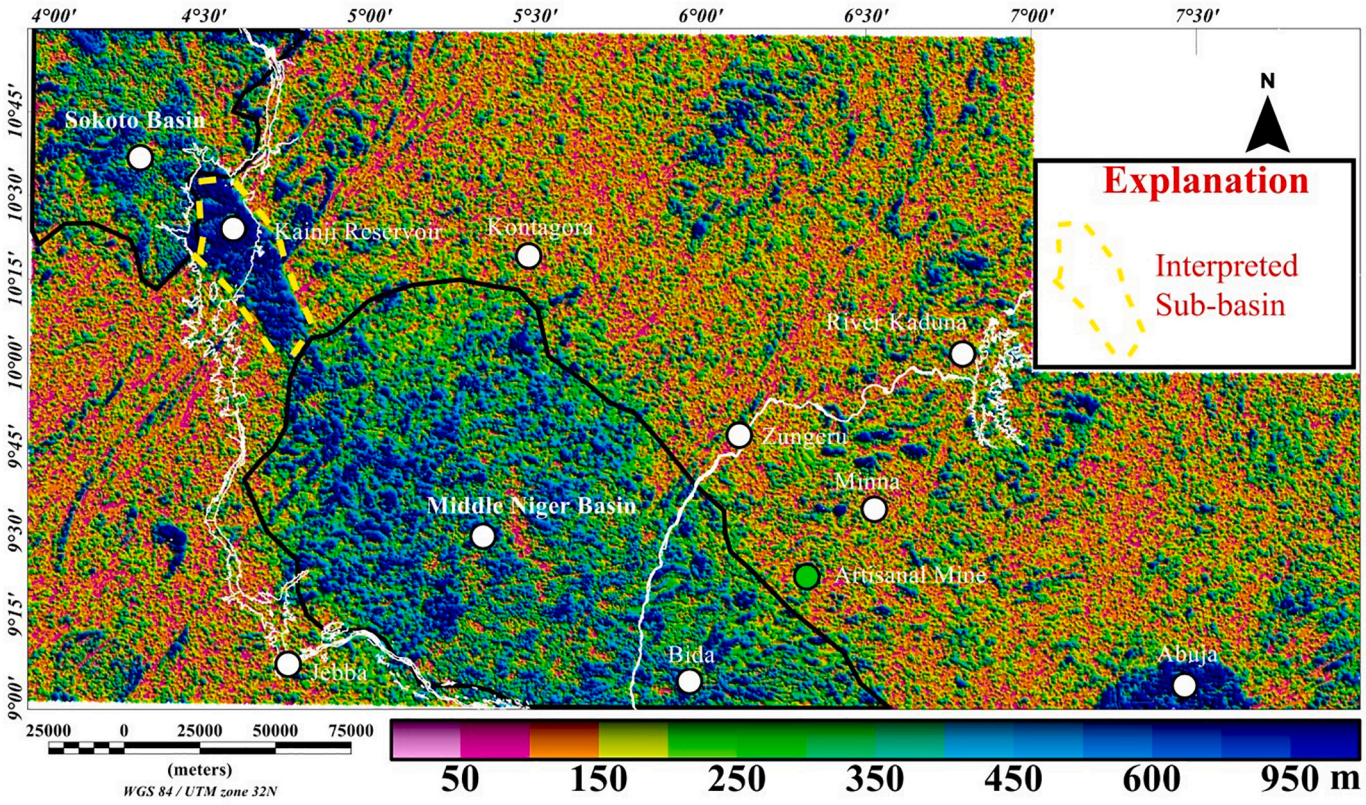


Fig. 6. Color-shaded SPI depth map produced from the aeromagnetic anomaly data of the study area. Note the interpreted sub-basin (here called Libata-Auna sub-basin) enclosed in the dashed thick yellow lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

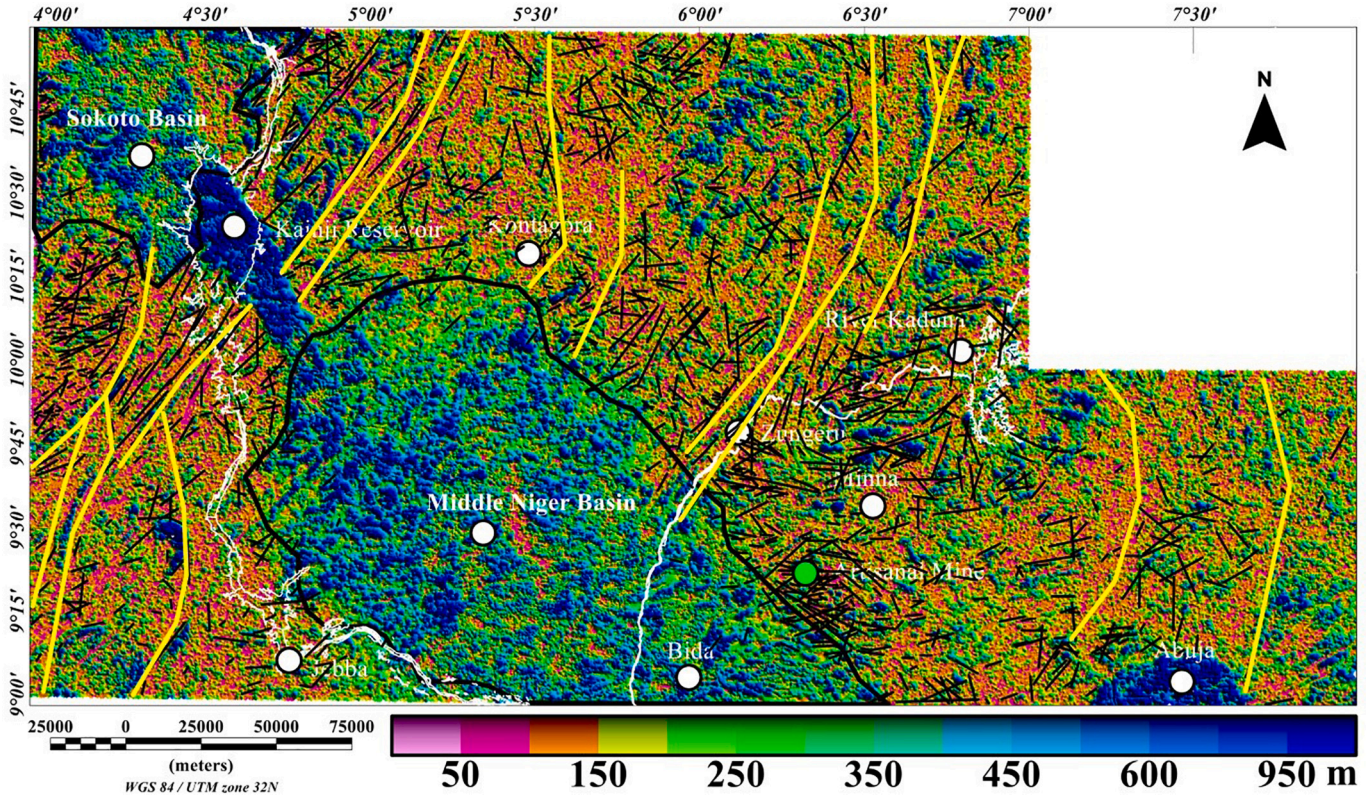


Fig. 7. Color-shaded SPI depth map of the study area with superimposed 3D analytic signal lineaments.

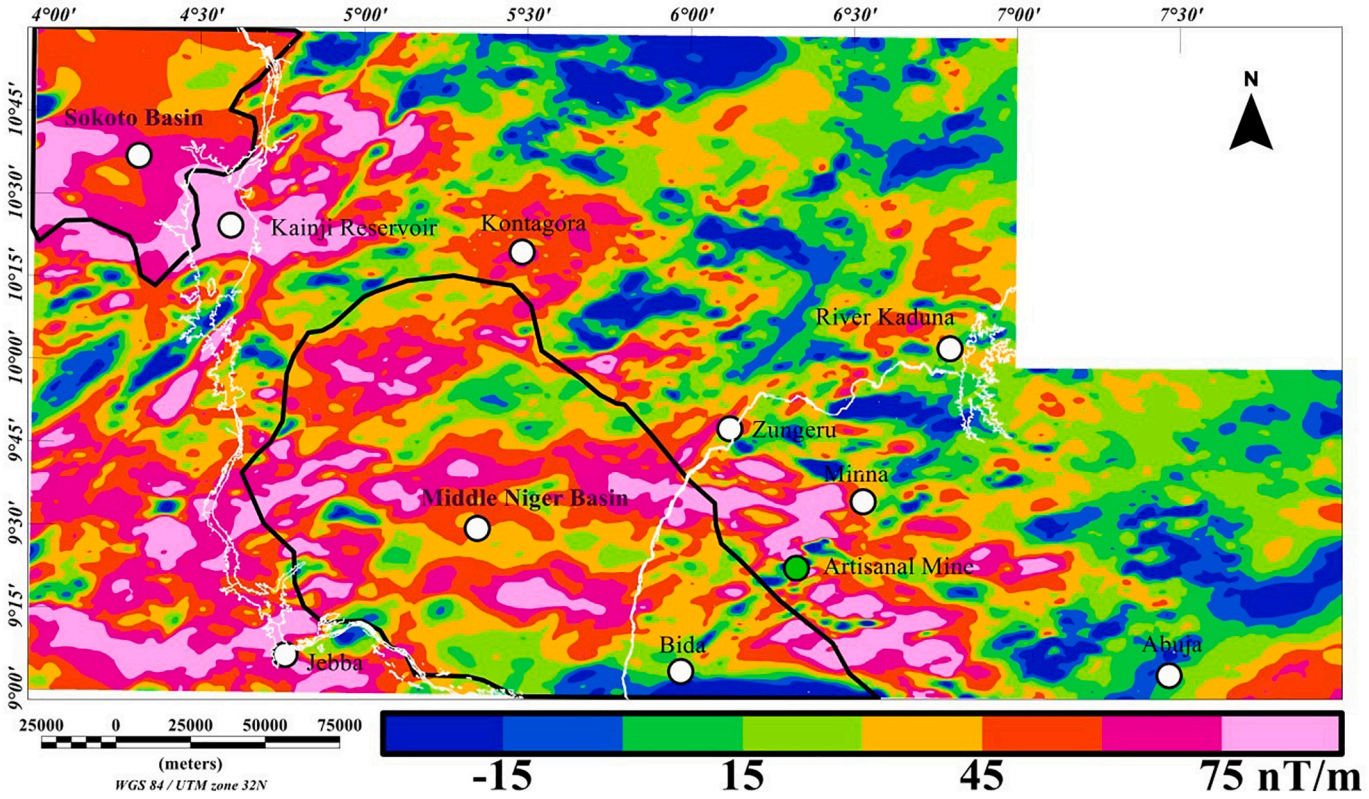


Fig. 8. Regional aeromagnetic anomaly map derived from the upward continued (by 1200 m) aeromagnetic anomaly data (Fig. 3). The white lines represent the river channel and boundary of the sedimentary basin is marked by black polygons.

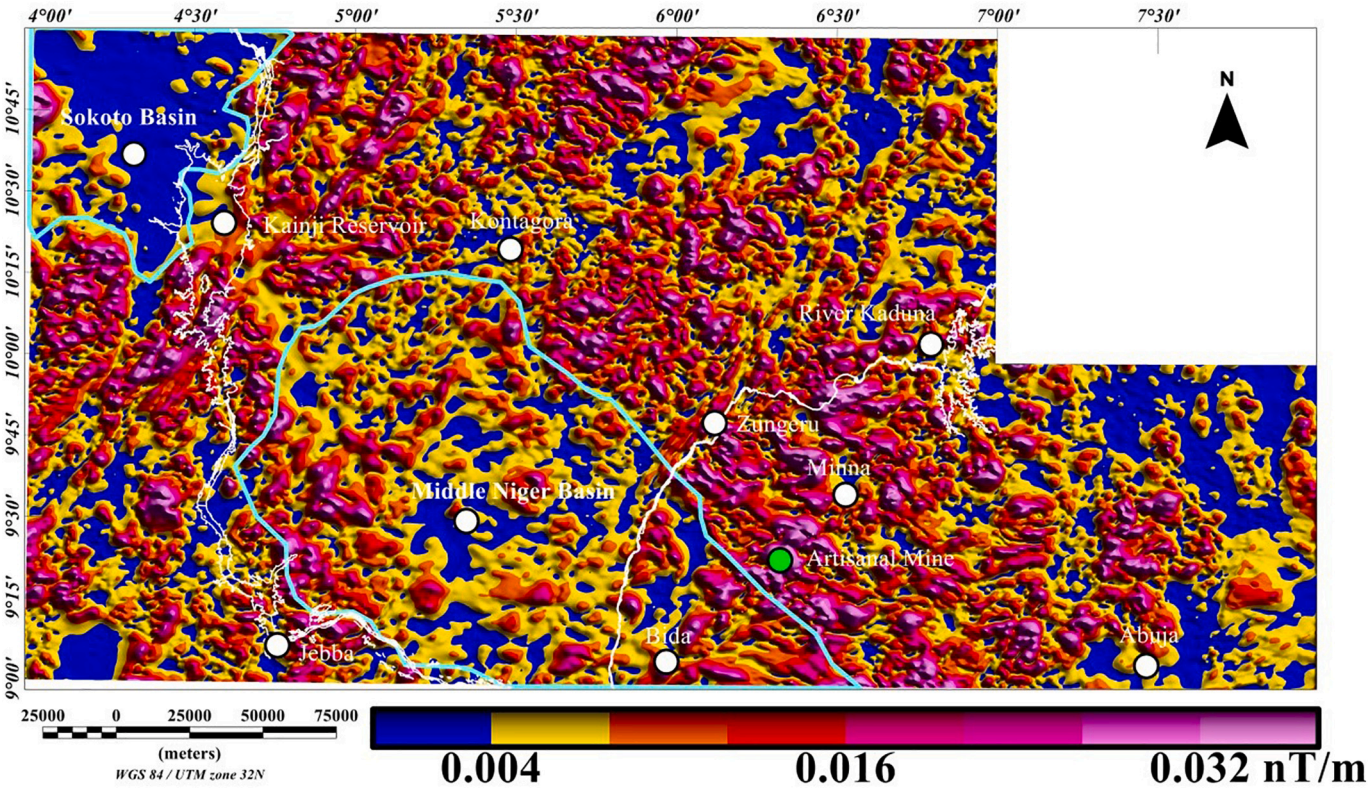


Fig. 9. Color-shaded regional 3D analytic signal map produced from the regional upward continued to 1200 m aeromagnetic anomaly map.

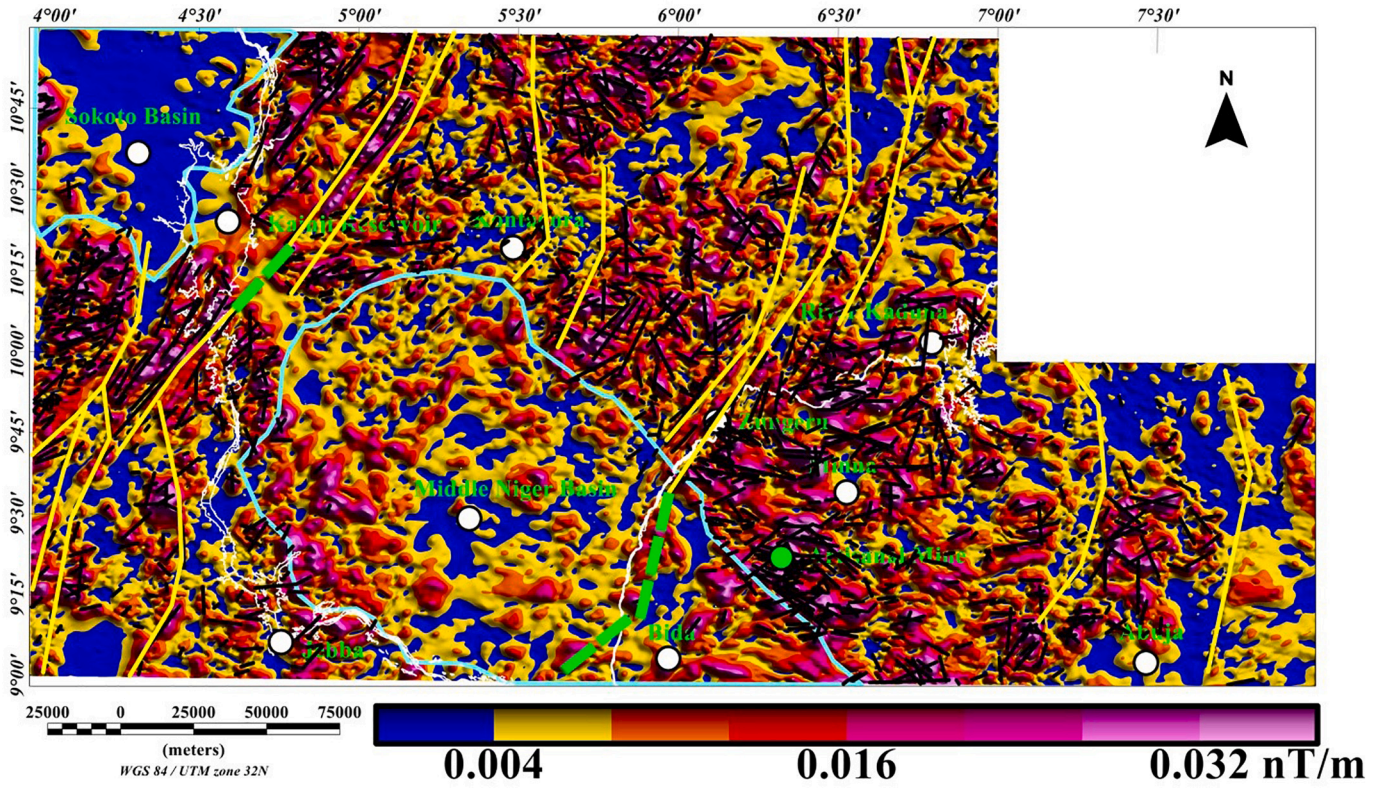


Fig. 10. Color-shaded regional 3D analytic signal map with superimposed analytic signal lineaments from Fig. 5b. Note the extension of the Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones on map is indicated as thick dashed green lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

effects of shallow and deeper magnetic sources, we continued the data upward to a height of 1200 m.

5. Results

5.1. Structural features

The 3D analytic signal map (Fig. 4) shows magnetic structural features responses by high values (magenta color). Visual inspection of the 3D analytic signal map reveals that the Sokoto Basin and entire northern segment of the Middle Niger Basin are characterized by low values (blue color). The boundaries of the basins (indicated by yellow polygons) display strong contrast of high (0.36 nT/m) and low (0.06) analytic signal values, which are interpreted as series of faults. The map also revealed narrow analytic signal lows around Kainji Reservoir which separate the Sokoto Basin from the Middle Niger Basin. This suggests a link between the two sedimentary basins. The structural map (Fig. 4b) was extracted from the maxima of the analytic signal map to reveal the locations and lateral extent of the magnetic lineaments already revealed on the 3D analytic signal map. The map (Fig. 4b) underlined significant subsurface structures, characterized by lineaments having different trends and of varying degrees of importance. The map shows structural features within the crystalline basement including two major shear zones within the study area. These major shear zones are known as the Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones indicated with red lines on Fig. 4b. Local subsidiary faults with NW-SE trends are associated with the northern portion of the Anka–Yauri–Iseyin shear zone. The structural trends also marked the boundaries (indicated by yellow polygons) of the entire northern part of the Middle Niger and Sokoto Basins which is indicated by the termination of faults. The sudden termination of the mapped structural features as well as the major shear zones made the mapping of the deeper portion of the studied region possible. The continuity of the shear zone below the basin was assessed by the upward continuation and application of the analytic signal method, to understand the impact of the Pan-African orogeny (ca. 600 Ma) on the basement of the basins. A location at Kataeregi, indicated as green circle in Figs. 4a and b) of primary gold mineralization is an active mine site of artisanal miners. Fig. 5 shows a pit that was excavated along the trend of quartz vein (with vein trending N-S and N*E*-SW). The artisanal gold pits match well with some E-W trending magnetic lineaments within the region. In addition, Rose diagram is produced from the extracted maxima of the analytic signal to determine dominant trend directions of magnetic lineaments. The lineaments within the study area are mainly oriented in the NE-SW, NNE-SSW, ENE-WSW and E-W directions.

5.2. Depth to magnetic basement

The depth analysis of the aeromagnetic anomaly data was performed using the source parameter imaging (SPI) technique. This is to aid the interpretation of structural features within the study area. The resulting SPI map (Fig. 6) shows depth estimates of magnetic sources within the study area between 50 m to 950 m. We interpret a narrow zone (here called Libata-Auna sub-basin) enclosed in the dashed thick yellow lines on the SPI map, as a sub-basin at the Libata-Auna area linking the Middle Niger and Sokoto Basins. A superposition of 3D analytic signal lineaments on the SPI depth map (Fig. 7) reveals shallow depth areas to be fairly characterized by dense lineaments. SPI depth values that correspond to the mapped structural features are estimated mainly to be < 150 m. One interesting feature on the SPI map is the higher average depth values (600 m) of the Sokoto Basin and entire northern portion of the Middle Niger Basin in comparison to the lower average SPI depth value (150 m) of the surrounding crystalline basement complex terrain. This information allowed the direct visual

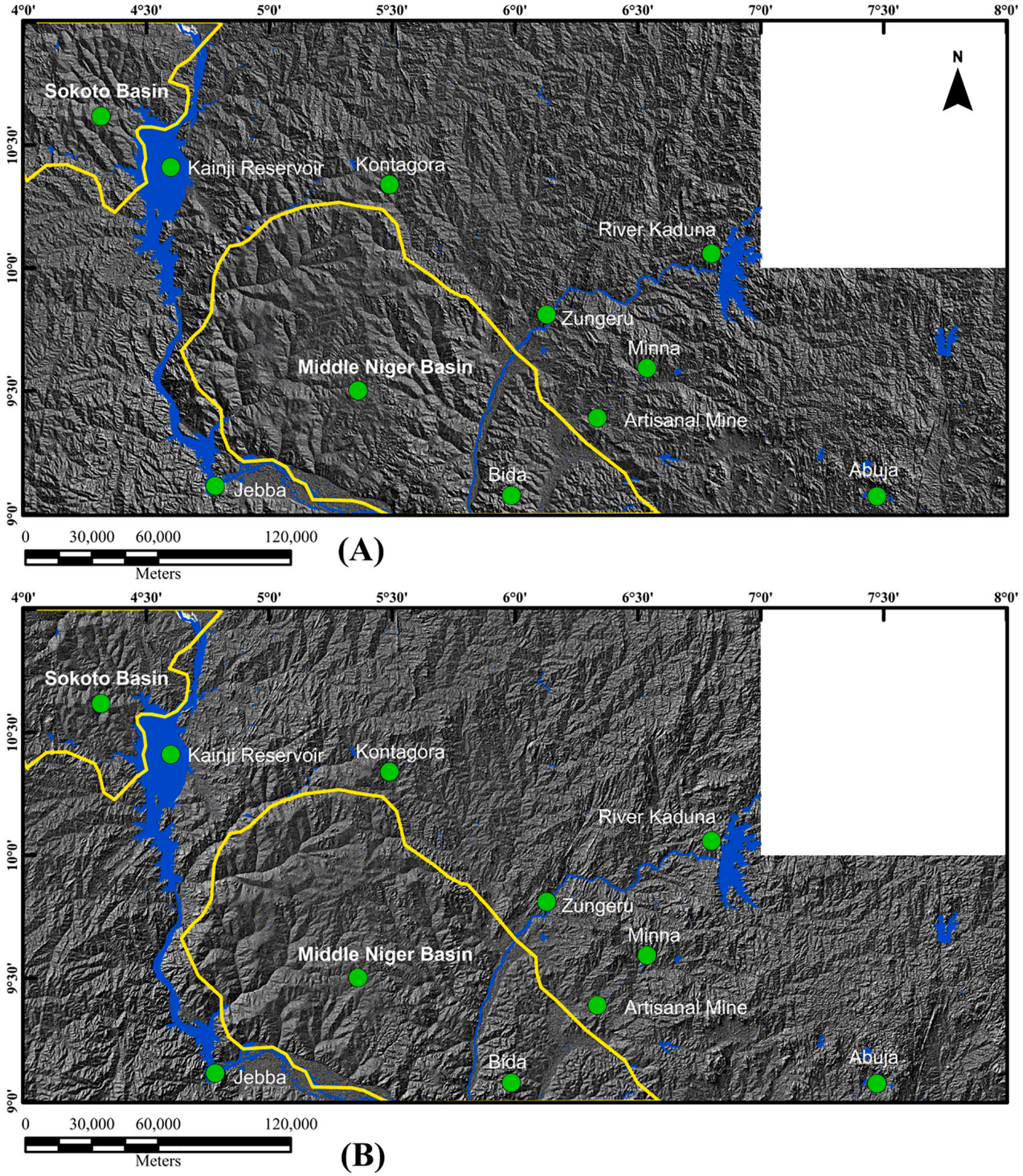


Fig. 11. (A) Shaded-relief map computed from Shuttle Radar Topography Mission data utilizing a 45 degree light angle at azimuths 45 degree and (B) Shaded-relief map computed from Shuttle Radar Topography Mission data utilizing a 45 degree light angle at azimuths 315 degree.

comparison of the mapped boundaries of the basin (indicated by the sudden termination of the analytic signal lineaments interpreted as faults) on the 3D analytic signal map with SPI map. Next we compared the low values (blue color) portion which indicates the two basins on the 3D analytic signal map with the SPI map and observed that the boundaries correlated with the edges of the higher depth value portion on the SPI map. The SPI map also shows consistent and high depth values of 950 m between the boundary (around Kainji Reservoir) of Sokoto and Middle Niger Basins. This reveals that the boundary between the two basins, indicated with dashed yellow lines on Fig. 6 has

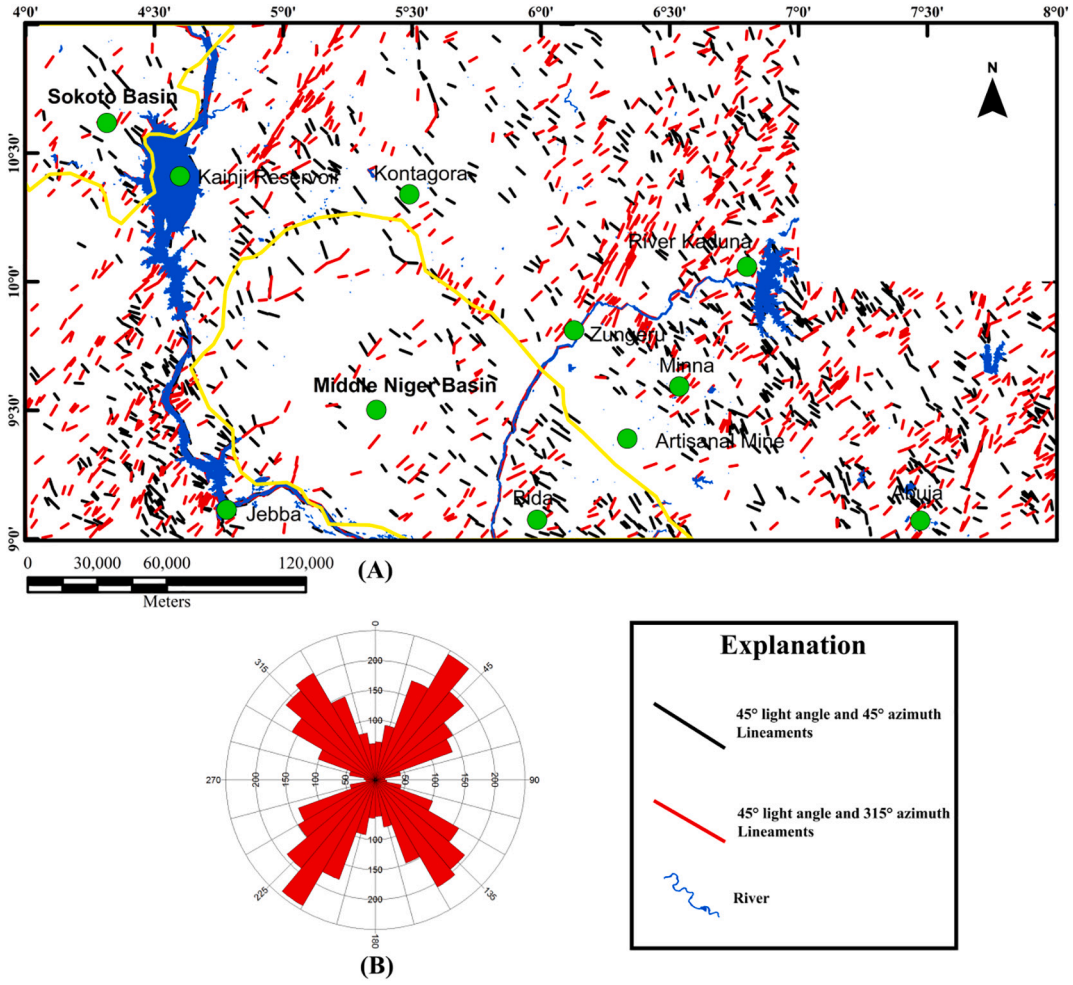


Fig. 12. (a) Surface lineament map, produced from the two enhanced hill-shade images produced at a 45° light angle at azimuths of 0° (Fig. 9) and 315° (Fig. 10). (b) Rose-diagram computed from the automatically extracted surface lineaments, showing that the lineaments are mainly oriented in the NW-SE and NE-SW, directions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

deep magnetic sources which are interpreted as the basement. Additionally, the low value of 0.06 (blue color) observed on the 3D analytic signal map (Fig. 4a) within the same boundary of the two basins indicate the low magnetic susceptibility of the overlying sedimentary formations. We tentatively interpret this zone as a sub-basin linking the two basins together.

5.3. Deep structural features

The upward continued map (Fig. 8) is considered as the regional magnetic anomaly map of the study area. We applied the 3D analytic signal to the regional aeromagnetic anomaly map to further emphasize deeper structural features with greater depth extent. The resulting regional 3D analytic signal map (Fig. 9) shows the deeper structural features of the study area. The superposition of lineaments in Fig. 4b on the regional analytic signal map is shown in Fig. 10. Maxima of the regional analytic signal indicates a good spatial correlation between lineaments (shear zones and the faults) on the produced structural map (Fig. 4b). This allowed us to suggest that the maxima of the regional analytic signal represents the continuities of these lineaments in the basement. The Anka–Yauri–Iseyin shear zone (indicated with yellow dashed lines on Fig. 10) continued from the crystalline basement terrain and linked with faults in the basement of the earlier interpreted sub-basin (around Kainji Reservoir). In other words, the regional 3D analytic signal map (see Fig. 10) shows the full extension of the Anka–Yauri–Iseyin shear zone through the basement rock of sub-basin. This vital information is unknown before this study. Additionally, the regional 3D analytic signal map also revealed the continuity of the Kalangai–Zungeru shear zone (indicated with green dashed lines in Fig. 10) below the Middle Niger basin.

5.4. Subsurface structural features control on landforms

The shaded relief maps (Figs. 11a and b) show enhanced view of topographic features of the study area. Major topographical features might have formed as a fragment of rejuvenated older terrane. As a result of subsequent tectonic events, the terrain may have been fragmented into numerous reliefs with shears surrounding hill ranges. Automatic lineament extraction procedure applied on the hill shade images (Figs. 11a and b) resulted in the delineation of lineaments, presented in the surface lineament map (Fig. 12a). The spatial locations of surface features such as faults, fractures and contacts, indicate complex geologic structures within the study area. Major surface lineaments coincided with the valleys of River Kaduna, with the latter exploiting the zone of weakness, in sub-parallel alignment with the NNE-SSW Kalangai–Zungeru-Ifewara shear zone (see Figs. 4a and b, 6, 7, 9 and 10). The results reveal the sensitivity of fluvial network to the topographic features and remarkably align the valley of River Kaduna with individual widths of the river as determined by the lineaments.

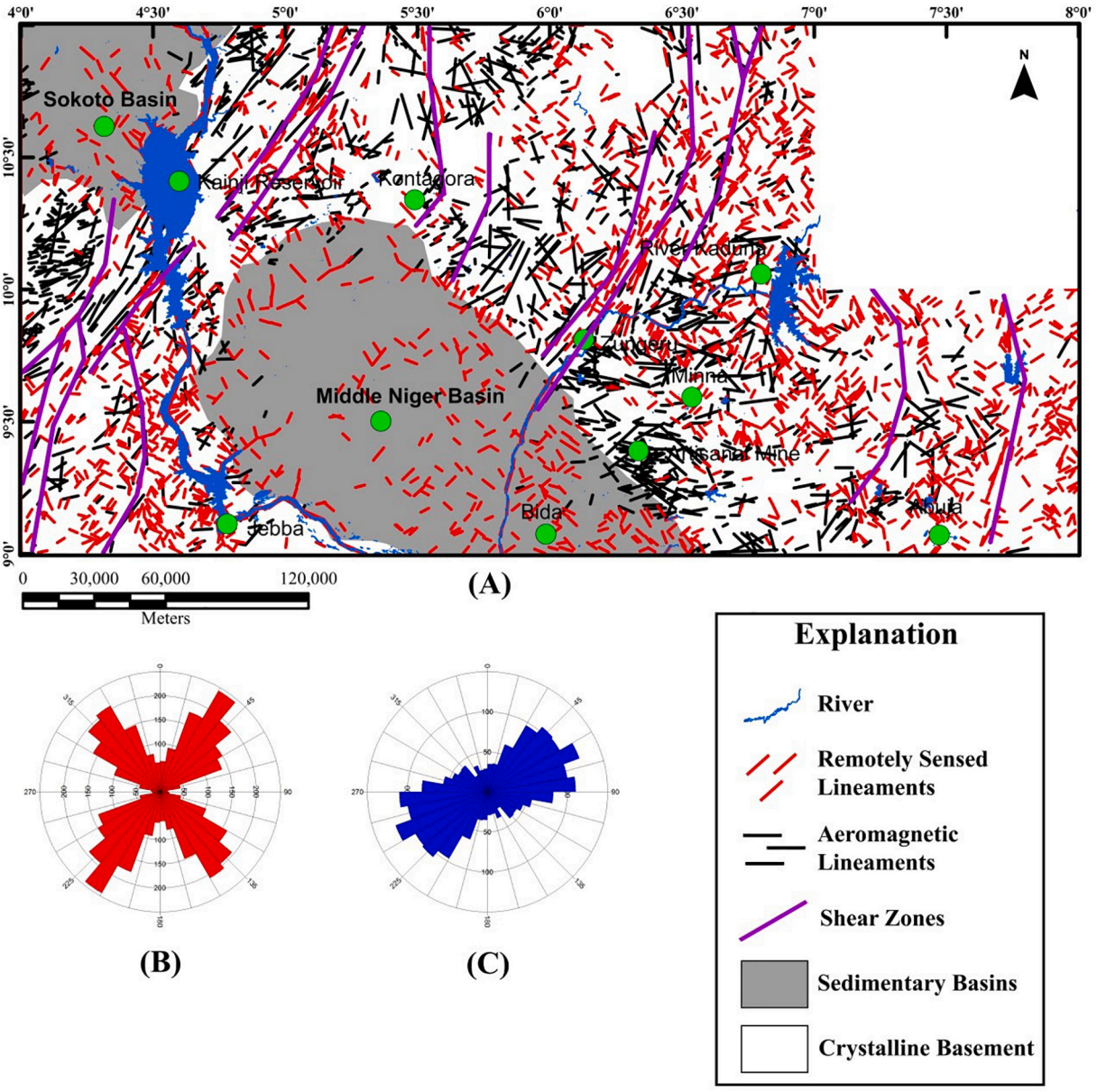


Fig. 13. (a) Structural map of the study area produced from the combined analysis and interpretation of SRTM and high resolution aeromagnetic anomaly data. The map depicts good information about surface and subsurface lineament distribution within the study area. (b) Rose-diagram of remote sensing lineaments which provides trend patterns of surface lineaments. (c) Rose-diagram of aeromagnetic lineaments which provides information about subsurface lineaments trend patterns. Note the extension of the Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones in the basement is indicated as thick purple lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.5. Surface and subsurface structural appraisal

The surface and the subsurface lineaments derived from the interpreted SRTM and aeromagnetic data respectively (Figs. 12a and 4b respectively), were combined within the ArcMap software environment to generate the composite structural map of the southern portion of Sokoto Basin, the entire northern segment of the Middle Niger Basin, and the surrounding crystalline basement terrane (Fig. 13a). The convergence of surface and subsurface lineaments on the resulting structural map indicates that the deduced surface lineaments coincide with some subsurface features and reflect real continuity at depth. The continuities of aeromagnetic structural features, in the basement of the Sokoto and Middle Niger Basins, match with some of the major topographic breaks in the crystalline basement and the basins of the studied region. For instance, the two major shear zones, which were deduced from the analytic signal technique correlate with major topographic features within the crystalline basement terrain of the study area. The visual inspection of the Rose-diagrams for subsurface and surface lineaments (Figs. 13b and c) show major lineament sets with predominance of NW-SE and N*E*-SW trends on Fig. 13b in contrast with the major ENE-WSW and E-W trends on Fig. 13c. This is because the E-W and ENE-WSW structural trends reflect an earlier deformation phase, which has been almost completely obliterated by the later NE-SW deformation. The Rose diagram of remotely sensed lineaments (Fig. 13b) reveals major dominant latter (younger) surface structural trends that have largely obscure the earlier (older) *E*-W and ENE-WSW trending

structural features, which appears to dominate the subsurface of the region (McCurry, 1978). The structural map (Fig.13a) equally substantiated the surface expression of the mega shear system at places, as well as the depth continuity − revealed by some surface lineaments, coincided with the shear zones. Also of central importance is the clustering of these lineaments around the gold mine (artisanal mining site) located 45 Km to the east of the Kalangai–Zungeru-Ifewara shear zone. The coincidence of lineament locations and gold deposit occurrence, especially the E− and NE − trending lineaments, encourages the mapping of new zones of possible economic mineral deposits. Some E − W trending lineaments equally overlie the artisanal gold mine shown in Fig. 13a. Hence detailed geological mapping and other geophysical methods can equally be focused on *E*-trending lineaments within and around the study area for further elucidation.

6. Discussion

The linking of crystalline basement structural features to the sedimentary basins of the study area has not received much geological attention. This study reveals that magnetic structural features related to Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones and surface lineaments demonstrate a clear geomorphic connection. These NNE-SSW trending shear zones are suggested to have resulted from the Pan-African orogenic event about 600 Ma (Wright, 1976; Mccurry and Wright, 1977; Ajibade and Wright, 1988) and as loci of economic mineral deposits (Garba, 2000; Dada, 2008). The surface lineament map (Fig. 12a) reveals remarkable alignment of the Kalangai–Zungeru-Ifewara shear zone with the valley of River Kaduna. This reveals that the river is structurally controlled and provides the possibility of high concentration of alluvium gold mineralization within the river banks of River Kaduna and its tributaries. The magnetic structural map (Fig. 4b) and its Rose diagram reveal dominant ENE-WSW and E-W trends. These trends are believed to have resulted from the earlier pre-Pan-African orogeny (McCurry, 1978). The structural features with Fig. 4b and 13 reveal obvious match between artisanal gold mine and some E-W trending lineaments. Hence, our result suggests a possible earlier structurally controlled gold mineralization prior to the more prolific Pan-African gold deposits attributed to structural features with NE – SW and NNE – SSW trends (Garba, 2000; Dada, 2008). The result establishes that Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones extend deep into the basement of the region but are not prominent in the sedimentary sequences of the basins. Their absence within the basin corresponds to post-structural/fragmentation formation and evolution of these basins. Surface and subsurface faults along the margin of the Middle Niger Basin indicates rift-related origin of the basins. The 3D analytic signal map also revealed that the Middle Niger Basin is directly linked to the Sokoto Basin as opposed to the sudden termination of the Middle Niger Basin by the crystalline basement around Kainji Reservoir which separated the Sokoto Basin from the Middle Niger Basin as shown on various geological maps of Nigeria (e.g. Obaje, 2009b). We interpret this zone as a sub-basin at the Libata-Auna area linking the two basins. This fact is unknown before this study; hence we suggest that the two basins are linked contrary to the general opinion held hithertofore. This calls for more detailed work in this boundary area.

7. Conclusions

The application of 3D analytic signal and source parameter imaging techniques reveal the lateral extent, trends and depths of structural features including two major shear zones within the surrounding crystalline basement terrain and underlying the Sokoto and Middle Niger Basins. The existence of the major shear zones within crystalline basement and the basins are described by prominent aeromagnetic and SRTM lineaments. The shear zones match with and are suggested to control the locations of various faults and influenced the landform evolution of the study area, thereby causing topographical features. Our data reveal two major aeromagnetic structural features, which correspond to major shear zones established within the studied region, namely, the Anka–Yauri–Iseyin and Kalangai–Zungeru-Ifewara shear zones formed during the Pan-African orogeny. Finally, we have identified a sub-basin linking the Sokoto and Middle Niger Basins around Libata-Auna area, immediately west of the Anka–Yauri–Iseyin shear zone.

Declaration of Competing Interest

None.

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Compliance with Ethical Standards

None

References

Adebiyi, L.S., Fatoba, J.O., Salawu, N.B., Dopamu, K.O., Abdulraheem, T.Y., Obaseki, O.S., Olasunkanmi, N.K., Adediran, S.O., 2020. Analysis of aeromagnetic data: application to early – late cretaceous events in parts of lower Benue trough, Southern Nigeria. J. Appl. Geophys. 178, 104052.

Ajibade, A.C., Wright, J.B., 1988. Structural relationships in the schist belts of northwestern Nigeria. In: Oluyide, P.O. (Ed.), Precambrian Geology of Nigeria. Geological Survey of Nigeria Publication, Kaduna, pp. 103–109.

Ajibade, A.C., Woakes, M., Rahaman, M.A., 1987. Proterozoic crustal development in the Pan-African regime of Nigeria. Geodynamics Ser. 259–271. https://doi.org/10.1029/gd017p0259.

Anderson, H.R., Ogilbee, W., 1973. Aquifers in the Sokoto Basin, Northwestern Nigeria, with a description of the generel hydrogeology of the region. In: Geological Survey Water-Supply Paper 1757-L, https://doi.org/10.3133/wsp1757L.

Ciminale, M., & Loddo, M. (1989). A computer program to perform the upward continuation of potential field data between arbitrary surfaces. Comput. Geosci. 15(6), 889–903. https://doi.org/10.1016/0098-3004(89)90003 -4.

Dada, S.S., 2008. Proterozoic evolution of the Nigeria–Boborema province. In: Pankhurst, R.J., RAJ, Trouw, de Brito Neves, B.B., de Wit, M.J. (Eds.), West Gondwana: precenozoic correlations across the south Atlantic region. 294. Geological Society, London, pp. 121–136. https://doi.org/10.1144/sp294.7. Special Publications.

Garba, I., 2000. Gold prospect of the Nigerian Pan-African terrain of West Africa. J. Min. Geol. 36, 123–156.

Kogbe, C.A., 1981. Cretaceous and tertiary of the Iullemmeden Basin in Nigeria (West Africa). Cretac. Res. 2 (2), 129–186. https://doi.org/10.1016/0195-6671(81)90007-0.

Kogbe, C.A., 1989. Cretaceous and tertiary of the iullemmeden basin in Nigeria. In: Kogbe, C.A. (Ed.), Geology of Nigeria, 2nd edition. pp. 377–421.

MacLeod, I.N., Jones, K., Dai, T.F., 1993. 3-D analytic signal in the interpretation of total magnetic field data at low magnetic latitudes. Explor. Geophys. 24, 679–688.

McCurry, P., 1978. Geology of Degree Sheets 19 (Zuru), 20 (Chafe), and Part of 19 (Katsina). Overseas Geological Mineral Resource, Nigeria, pp. 53.

Mccurry, P., Wright, J.B., 1977. Geochemistry of calc-alkaline volcanics in northwestern Nigeria, and a possible Pan-African suture zone. Earth Planet. Sci. Lett. 37, 90–96.

Nabighian, M.N., 1972. The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: its properties and use for automated anomaly interpretation. Geophysics 37, 507–517 10.1190/1.1440276.

Obaje, N.G., 2009a. Geology and Mineral Resources of Nigeria, Lecture Notes in Earth Sciences. 120https://doi.org/10.1007/978-3-540-92685-6_7.

Obaje, N.G., 2009b. The basement complex. In: Geology and Mineral Resources of Nigeria. Lecture Notes in Earth Sciences 120 Springer, Berlin. https://doi.org/10.1007/978-3-540-92685-6_2.

Rahaman, M.A.O., Fadiya, S.L., Adekola, S.A., Coker, S.J., Bale, R.B., Olawoki, O.A., Omada, I.J., Obaje, N.G., Akinsanpe, O.T., Ojo, G.A., Akande, W.G., 2018. A revised stratigraphy of the Bida Basin, Nigeria. J. Afr. Earth Sci. https://doi.org/10.1016/j.jafrearsci.2018.11.016.

Robinson, E., 1970. Upward continuation of total intensity magnetic fields. Geophysics 35 (5), 920–926.

Roest, W.R., Verhoef, J., Pilkington, M., 1992. Magnetic interpretation using the 3-D analytic signal. Geophysics 57, 116–125.

Salawu, N.B., Olatunji, S., Adebiyi, L.S., Olasunkanmi, N.K., Dada, S.S., 2019a. Edge

detection and magnetic basement depth of Danko area, northwestern Nigeria, from low- latitude aeromagnetic anomaly data. SN Appl. Sci. 1, 1056. https://doi.org/10.1007/s42452-019-1090-3.

Salawu, N.B., Olatunji, S., Orosun, M.M., Abdulraheem, T.Y., 2019b. Geophysical inversion of geologic structures of Oyo Metropolis, southwestern Nigeria from airborne magnetic data. Geomech. Geophys. Geo-energy Geo-Resour. 5, 143–157.

Salawu, N.B., Orosun, M.M., Adebiyi, L.S., Abdulraheem, T.Y., Dada, S.S., 2020. Existence of subsurface structures from aeromagnetic data interpretation of the crustal architecture around Ibi, middle Benue, Nigeria. SN Appl. Sci. 2, 427. https://doi.org/10.1007/s42452-020-2230-5.

Thieblemont, D. (Ed.), 2016. Geological map of African at 1: 10M scale. CGMW-BRGM (edit) et al.

Thurston, J.B., Smith, R.S., 1997. Automatic conversion of magnetic data to depth, dip and susceptibility contrast using the SPI (TM) method. Geophysics 62, 807–813.

Wright, J.S., 1976. Fracture systems in Nigeria and initiation of fracture zones in the South Atlantic. Tectonophysics 34, 43–47.