

Surface and Subsurface Structural Mapping via Airborne Magnetic and Remote Sensing Data: A Study of Kachia (Sheet 166), North-Central Nigeria

¹Mam Daniel Tawey, ²Ayamezimi Oziofu Ehinlaiye and ²Joseph Odion Odia-Oseghale

¹Groundwater Department, National Water Resources Institute, Mando Road, Kaduna. ²Department of Geology, University of Benin, Ugbowo, Benin City, Edo State.

Corresponding author: taweymam@gmail.com

Abstract

The present study utilizes airborne magnetic and Shuttle Radar Topographic Mission (SRTM) data of Kachia (Sheet 166), north-central Nigeria to elucidate the relationship between the surface and subsurface structures within the study area with the objectives of mapping the structures, ascertaining the structural density of the area and expound the areas of subsurface and surface structural overlaps that are points of structural continuation between the surface and subsurface structures. To achieve these objectives, SRTM data was processed into hillshade maps at four distinct solar elevations and merged after which the surface structures were delineated using Geomatica software. Also, the two methods used in magnetic structural delineation were the first vertical derivative (FVD) and 3D Euler deconvolution using structural index of one ($SI = 1$) in Oasis Montaj environment. The combined structural density map of the area revealed high structural density around the northcentral portion of the area, northeast, in the west of Gidan Bawa, around the southwest in Kazaze and the west and south of Janjala. The combine structural statistical trend analysis revealed that the area has been affected by several tectonic activities that produce structural imprints with predominant trend being the ENE-WSW direction, followed by WNW-ESE, NE-SW, NW-SE, NNE-SSW and NNW-SSE respectively. The combined structural map also revealed areas of structural continuation between surface and subsurface structures. These are points whereby fluid (water or hydrothermal fluids) can find their way from the subsurface to the surface and were observed in areas around Kazaze and Janjala in the southwest and Gidan Bako in the North-central portion of the study area.

Keywords: Aeromagnetic, SRTM, Structural Density, Hillshade, 3D Euler Deconvolution.

Introduction

Airborne magnetic surveys are the most used initial step in a geophysical exploration process, allowing detection of ambient magnetic fields caused by magnetic minerals present in the subsurface (Gaafar, 2015). Magnetic maps are frequently used in conjunction with other geophysical survey methods such as radiometric to provide a more complete geophysical and geological picture of a survey area (Gaafar, 2012). Airborne magnetic and radiometric surveys have been used widely in the mineral exploration industry, primarily to delineate metalliferous deposits (Airo & Loukola-Ruskeeniemi, 2004). Its applications vary from mineral exploration (Murphy, 2007), structure mapping, and rock characterisation

(Telford *et al.*, 1990). An aeromagnetic survey is effective, fast, affordable, and versatile for identifying rock structures underneath the earth based on the variations in the geomagnetic field, which are caused by variations in the magnetite concentration of the related lithological units (Ge *et al.*, 2020; Olasunkanmi *et al.*, 2020).

Geological structure mapping is a necessary step in the search for natural resources like water and mineral ore. A structural lineament is a linear feature of a landscape that expresses a fault or other subsurface geological structure. A lineament typically consists of a faulted valley, a sequence of fault or fold-aligned hills, a straight shoreline, or a combination of these features (Attoh and Brown 2008). Lineaments can be easily seen on aerial or satellite images and are frequently seen on geological or topographic maps. Several research works have been published using remote sensing data for lineament delineations (Dauda *et al.*, 2018; Errami *et al.*, 2022; Fajri *et al.* 2019; Kassou *et al.*, 2012; Mohammed *et al.*, 2020; Nugroho & Tjahjaningsih, 2016; Oluwaseun *et al.*, 2022; Sadia *et al.*, 2016; Sichugova *et al.*, 2020).

With advancement in technology and the advent of remote sensing and GIS, airborne magnetic data it is now being integrated with remote sensing and GIS for structures, structural densities, and hydrothermal alteration zones delineation. In order to pinpoint the geological structures and their characteristics for probable mineral occurrence, Ayuba and Nur (2018), analyzed airborne magnetic and remote sensing datasets in Nasarawa and its surroundings and to connect the effects of the structures to the data, they included fieldwork. Their findings point to anomalous patterns in the NE-SW, NW-SE, E-W, and NNE-SSW trends, with a potential genetic connection. Key markers of the presence of minerals include magnetic lineaments such as pegmatites, fractures, faults, joints, veins, and folds. Also, using reduced to magnetic equator and digital image enhancement techniques, Ogunmola *et al.* (2015) performed an integrated study of airborne magnetic and Nigeria Sat-X image data of Wamba in a GIS setting. The study was able to reveal the geological map of the region to displays basement layouts with NE-SW and NW-SE structures that may be connected to the Pan-African Orogeny. A revised geological map was produced because of the investigation, which also enhanced the contact between the basement and sediments. Faruwa *et al.*, (2021) used SRTM and airborne magnetic dataset analysis for the evaluation of basement structural elements that affect iron mineral deposits and other occurrences across Kabba and its surroundings. They concluded that the Pan-African dominant structural lineament patterns discovered through the examination of topography and airborne magnetic data tended to be regionally prominent in the mineral deposits within the Kabba and its surroundings. A lot of research works have been published within Northcentral Nigeria region where the study area is located mostly on structural and mineralization studies employing airborne magnetic datasets or integration of airborne magnetic and aeroradiometric data sets some which are (Ebele and Nur, 2020; Sanusi and Amigun, 2020; Tawey *et al.*, 2020b).

Statement of the Problem

Nigeria is a country with a wealth of solid mineral resources that are hidden beneath the surface of the earth (Obaje, 2009; NGSA, 2006), but the country's economy has been overly dependent on petroleum resources for decades and has not been able to fully use these resources to the economic advantage of its populace. Determining and looking for areas with significant mineral deposits is thus important to advance the economy of the country. Sometimes mineralisations can make geophysical surveys challenging since they don't always contrast with the host geology. However, to locate these types of deposits, geophysical data (such as the use of airborne magnetic data) and remote sensing data (SRTM data) are required. These data can directly identify weak anomalies brought on by alteration and deposition processes as well as subtle structures that control solid mineral deposition.

Objectives of the Study

The objectives of the study are:

- to identify and map surface and subsurface structures (faults, folds, and shear zones) in the research area,
- create a map showing the area's combined surface and subsurface structural density.
- map and identify locations or regions where the surface and subsurface structures intersect (Points of structural continuation).

To achieve the objectives mentioned, we used airborne magnetic data of Kachia (sheet 166) and Shuttle Radar Topography Mission (SRTM) datasets to map the surface and subsurface geological structures such as faults and fractures, within the study area, encompassing a 55 x 55 km² area (Figure 1).

The study area is bounded by Latitude 9° 30' N to Latitude 10° N and Longitude 7° 30' E to Longitude 8° E (Figure 1), and spans from the northwestern side of Gidan Jatau in the northeast through the north of Gamachua to the northeastern side of Antai in the northeast and southwestern side of Kazaze in the southwest through the south of Akote and Kushi in the south to the southeastern side of Kanyi in the southeast.

The topography of the land surface within the study area varies from 52 m low to 926 m high above the sea level. Areas of low elevation above sea level are observed within the west, northwest, and southwestern part of the study area (Figure 2).

These low-elevated areas are areas around Gidan Jatau, Garkuwa, Danbeki, Amfu, Shigbolu, Gidan Akwaja, Kintaru, Kazaze, Janjala and Kuchi. Areas with high relief or elevation above sea level are within the central part of the study area to the west, northeast and southeast. Towns within these areas are Wake, Antal, Pesa, Arko, east of Gimba, Kanyi, Panga Jere and Kasaru. Geologically, the study area is within the central Nigerian basement complex and the complex dates from Precambrian to the Lower Palaeozoic (Obaje, 2009).

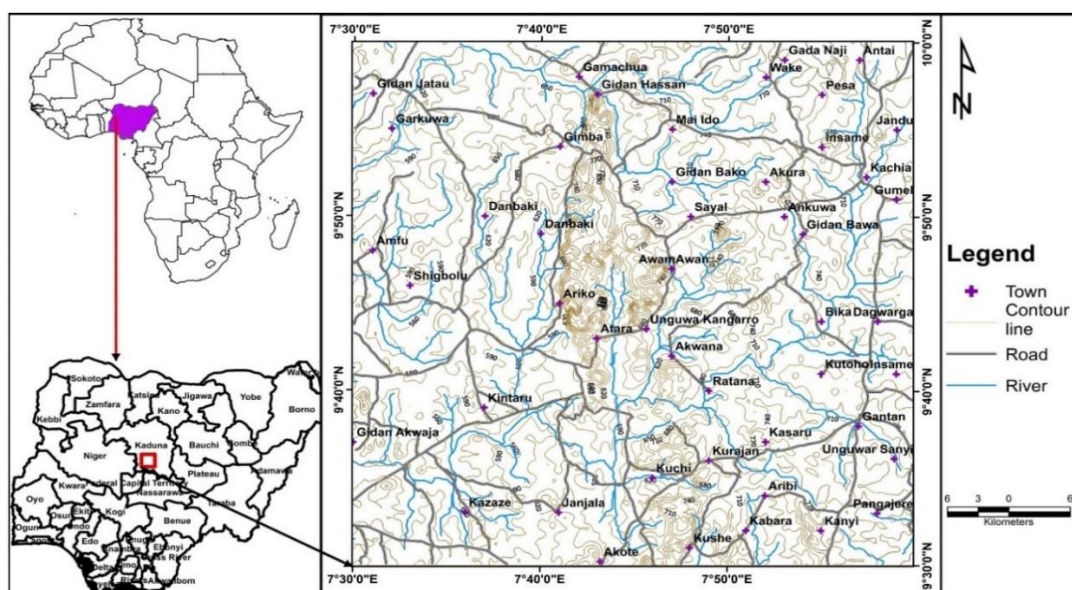


Figure 1: Location of the study area (produced using ArcMap 10.8 and Surfer 15)

Tectonically, the area falls within the Pan-African mobile belt (Figure 3), which was deformed by various pre-Cambrian thermo-tectonic events that were accompanied by gradual regional metamorphism, according to Grant (1978) and Ekwueme (1987). It is located between the West African craton, the Congo craton, and south of the Tuareg shield (Figure 3).

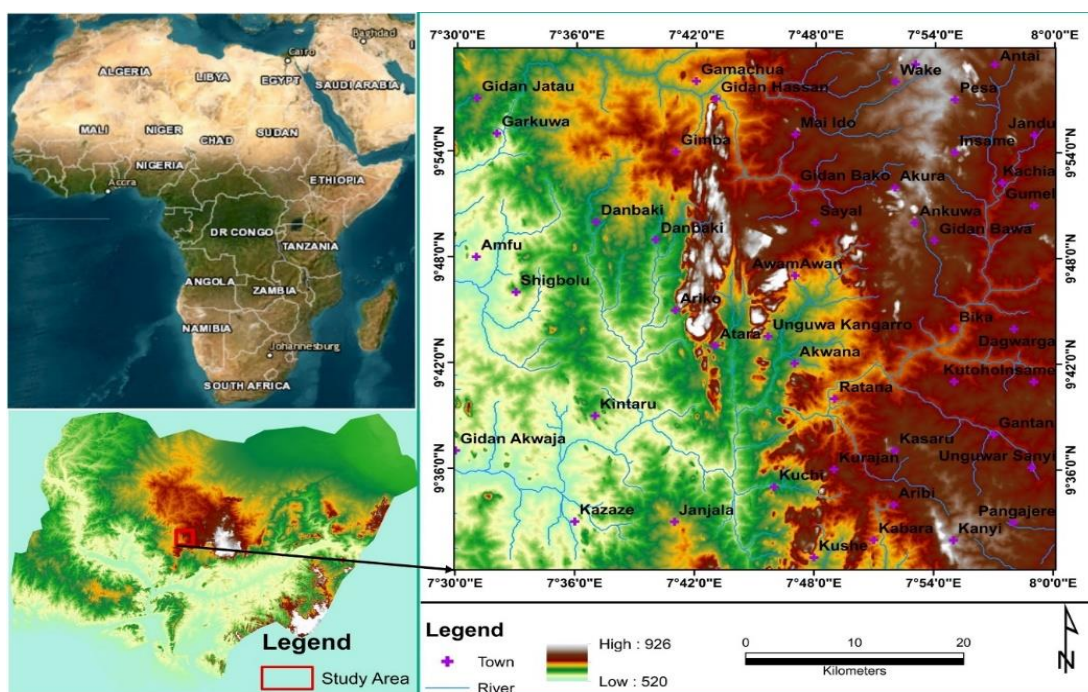


Figure 2: DEM data showing the elevation of the study area in meters, Source (Modified from USGS: <https://earthexplorer.usgs.gov/>)

On the basement rocks, each of the thermos-tectonic events left distinctive imprints. The Pan-African event, however, was so extensive that it destroyed the majority of the prior events' imprints, leaving just their vestiges behind. Pre-existing basement rocks underwent considerable sedimentation, folding, metamorphism, migmatization, and remobilization because of orogenic events, resulting in suites of granitic rocks (McCurry, 1973). The majority of granulitic gneisses are psematic to semi-pelitic gneisses, and because they frequently appear as residual masses that gradually transform into migmatites, it can be difficult to tell them apart from migmatites. Veins, banded gneisses, nebulitic gneisses, porphyroblastic and augen gneisses, as well as Amphibolites, are among the varied group of migmatites (Macleod *et al.*, 1971). Rocks found within this study area are older basalt, Porphyritic granite, Granite-Gneiss, Quartzite and Schists, and undifferentiated Schists including Phyllites and Migmatite (Figure 3).

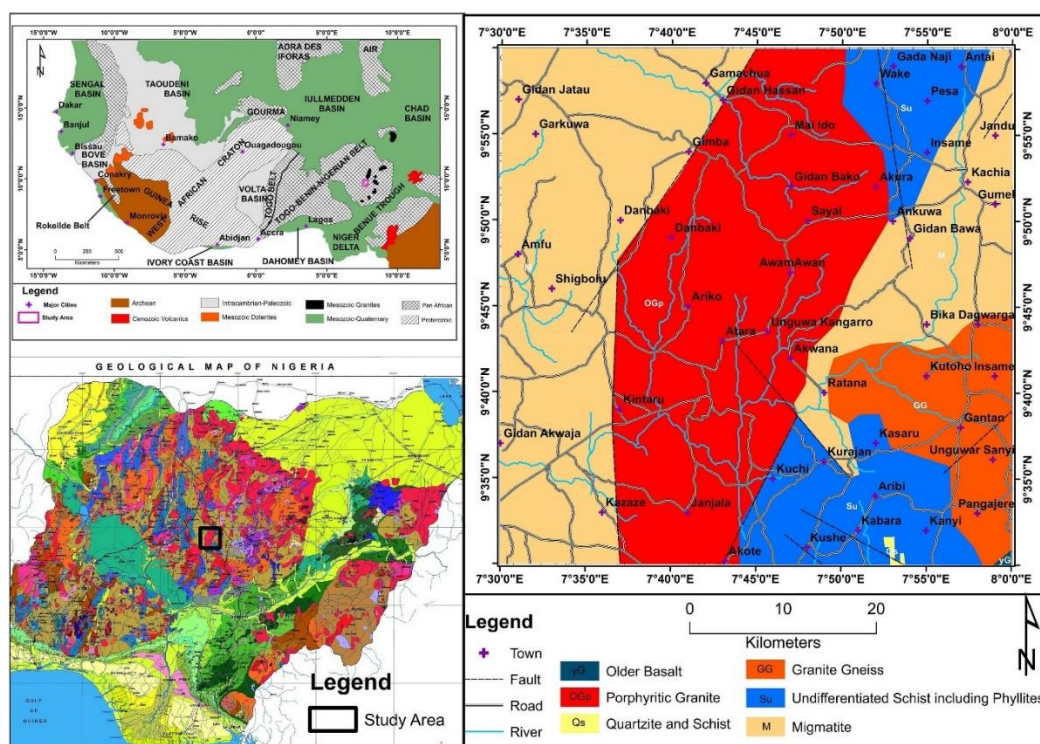


Figure 3: Generalized geological map of Nigeria within the framework of the geology of West Africa and the study area (Modified from Wright, 1985 and NGSA, 2006) and produced using ArcMap version 10.8

Material and Methods

Source SRTM Data

The Shuttle Radar Topographic Mission (SRTM), digital elevation model (DEM) of serial number (nog_e007_1arc_v3.tif) was downloaded from the United State Geological Survey (USGS) website, having a spatial resolution of 30 m.

Source of Aeromagnetic Data

The aeromagnetic data sheet that covers the study area (166 Kachia) was obtained from Nigerian Geological Survey Agency (NGSA) Abuja. This survey took place between 2005 and 2009 and was financed by the Nigerian Federal Government and the World Bank. The survey was conducted in two phases. Phase 1 which covered (Blocks A+C and B) was financed entirely by the Government of Nigeria (Figure 4) by Fugro Airborne Surveys (Reford *et al.*, 2010). Phase 1 where the study area is located was completed in September 2007 and included 826,000 line-km of magnetic and radiometric surveys flown at 500 m line spacing and 80 m terrain clearance; and 24,000 line-km of time-domain.

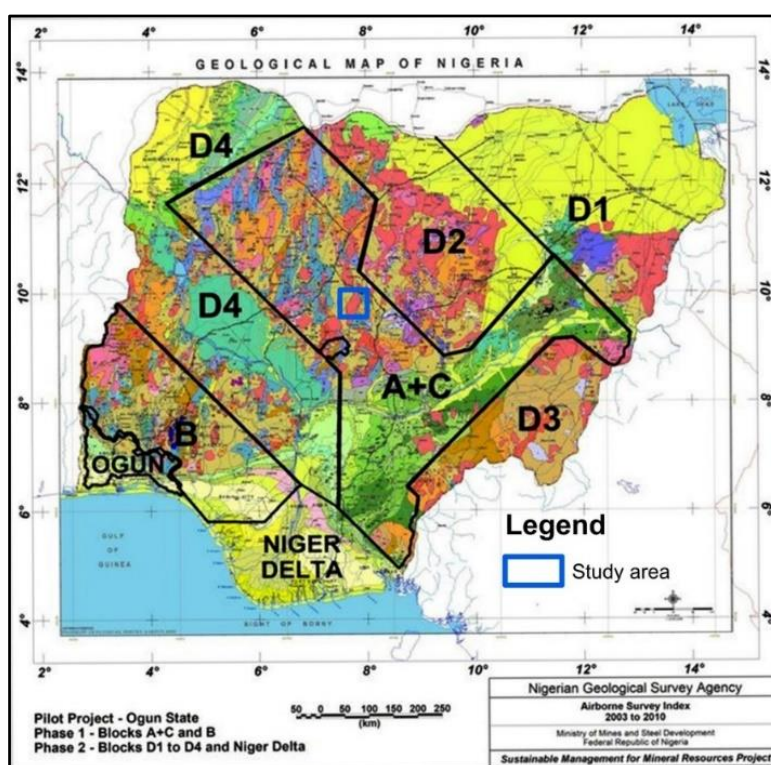


Figure 4: Index map of the airborne survey blocks flown between 2005 and 2009 for the Nigerian Geological Survey Agency (electromagnetic surveys not shown). In the background is the Geological Map of Nigeria (NGSA, 2006), (Adapted from Reford *et al.*, 2010)

Electromagnetic surveys were flown at 500 m line spacing and 80 m terrain clearance using Fugro's GENESIS EM system. All the airborne geophysical work-data acquisition, processing, and interpretation was carried out Fugro was also tasked with the interpretation of these data. Phase 2, completed in August 2009, surveyed blocks not covered in Phase 1 which includes (Blocks D1 to D4 and the Niger Delta) as displayed in (Figure 4). It included 1,104,000 line-km of magnetic and radiometric surveys flown at 500 m line spacing and 80 m terrain clearance.

Methodology

The residual magnetic intensity (RMI) data covering the study area was reduced to a magnetic pole (RTP) to centre the anomalies above their respective causative source using Oasis Montaj software, version 8.3. The resultant RTP data was subjected to first vertical derivative and 3D Euler deconvolution with a structural index of one ($SI = 1$) to delineate subsurface structures within the study area and their respective depth. SRTM data from the study area was used to create hillshade maps, this was achieved by using illumination angles of 315° , 200° , 100° , and 50° , with respective azimuth angles of 45° , 50° , 60° and 90° respectively (Figure 5).

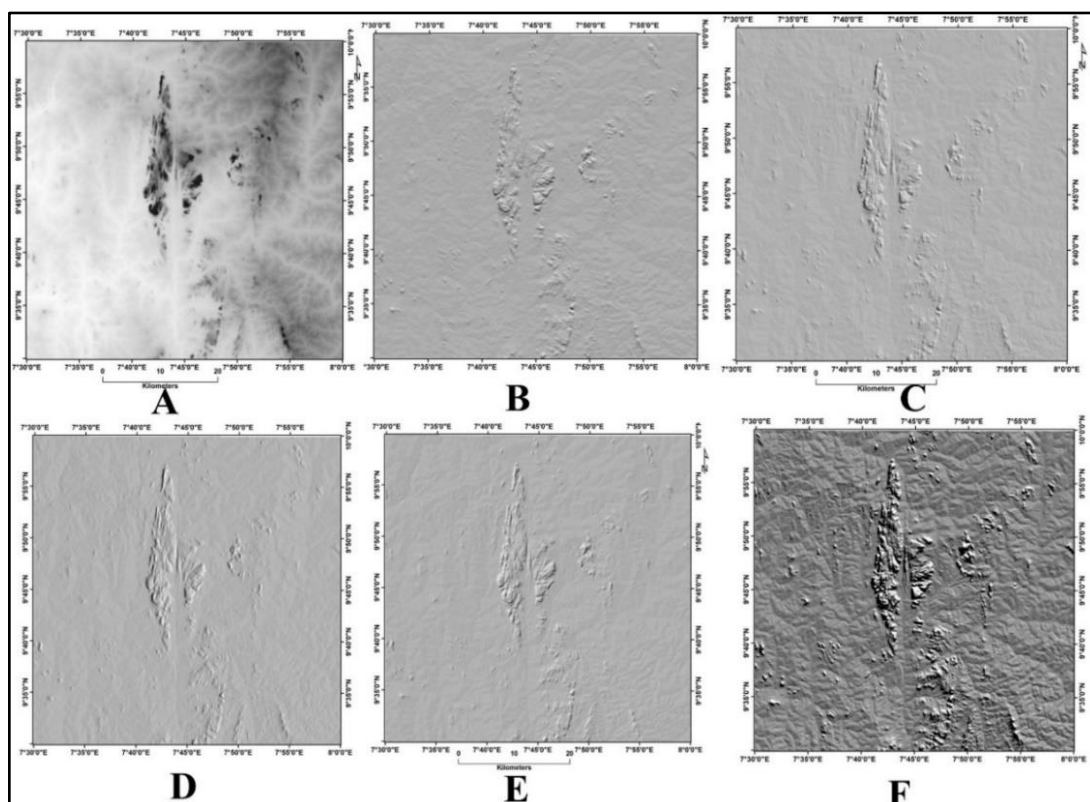


Figure 5: a. SRTM map of the study area invited, b. Hillshade map at a solar elevation of 315° , c. Hillshade map at a solar elevation of 200° d. Hillshade map at a solar elevation of 100° , e. and Hillshade map at a solar elevation of 50° f. Combined Hillshade maps of the study area Source, (produce using ArcMap version 10.8)

The raster calculator in the arithmetic function of ArcGIS 10.8 was used to combine the four hillshade maps that were produced. The combined hillshade map obtained from the SRTM data was also subjected to the PCI Geomatica edge detection technique, and the structural lineaments were delineated after applying the thresholding and filtering operations. The structural map created with PCI Geomatica from the SRTM map, and the structures delineated from magnetic data using the first vertical derivative technique was saved as an ArcView Shapefile with related files, and then each lineament on the maps was given

geometry in the arc Map (GIS) Version 10.8 environment to create a rose diagram of the lineaments or structures outlined for trend analysis. The geometry of the X and Y coordinates of the sites where the lineaments start and terminate was possible to be calculated and assigned by the arc Map (GIS).

To create the Rose diagrams, the Shapefiles with the given geometry were loaded into Rockworks version 16. Additionally, the ArcMap 10.8-line density function was used to determine the density of the structural lineaments.

Theory of the Methods

Vertical derivatives

Vertical derivative vertical gradient filters accentuate short-wavelength components of the field at the expense of longer wavelengths (Foss, 2011). Vertical derivative filters are generally applied to gridded data using FFT (Fast Fourier Transform) filters. Various vertical derivatives of the magnetic field can be computed by multiplying the amplitude spectra of the field by a factor of the form:

$$\frac{1}{n} \left[(U^2 + V^2)^{\frac{1}{2}} \right]^n \quad 1$$

where n is the order of the vertical derivative, and (U, V) is the wavenumber corresponding to the (x, y) directions respectively. The first vertical derivative is physically equivalent to measuring the magnetic field simultaneously at two points vertically above each other, subtracting the data and dividing the result by the vertical spatial separation of the measurement points. First vertical derivative data have become almost a necessity in magnetic interpretation projects. This is a derivative of the anomaly with the respective depth of the source gives a better resolution of the anomaly itself. Computation of the first vertical derivative in an aeromagnetic survey is equivalent to observing the vertical gradient directly with a magnetic gradiometer and has the same advantages, namely enhancing shallow sources, suppressing deeper ones, and giving a better resolution of closely spaced sources.

3D Euler Deconvolution

According to Reid *et al.* (1990), Euler deconvolution is both a border and a depth estimator. It extracts data from grids using the homogeneity relationship shown by Thompson (1982). This relationship can be written in the following form:

$$(x - x_0) \frac{\delta T}{\delta x} + (y - y_0) \frac{\delta T}{\delta y} + (z - z_0) \frac{\delta T}{\delta z} = N(B - T) \quad 2$$

where (x_0, y_0, z_0) is the position of a magnetic source whose total field T is detected at (x, y, z). B is the regional field value, and the degree of homogeneity interpreted as the structural index (SI) which is a measure of the rate of change at field distance is represented by N, and this structural index was chosen based on prior knowledge of the source geometry. Reid *et al.* (1990), also put forward that, structural index (SI) ranges from zero (0)

(short wavelength) signatures at the southwestern portion of the map with a structural trend of east-west (E-W).

Around the eastern portion of the map, there are also observed shallow seated sources that have tectonic trends of both NE-SW and NW-SE. Statistical structural trend analysis has revealed that trend within this area has been brought about by previous tectonic activities, one of whom is the Pan-African have the following trends: the predominant trend being ENE-WSW direction, followed by both WNW-ESE and NE-SW, then, NNE-SSW, NW-SE, and lastly NNW-SSE trends respectively. Figure 7d showcases high subsurface structural densities around southwest at east and

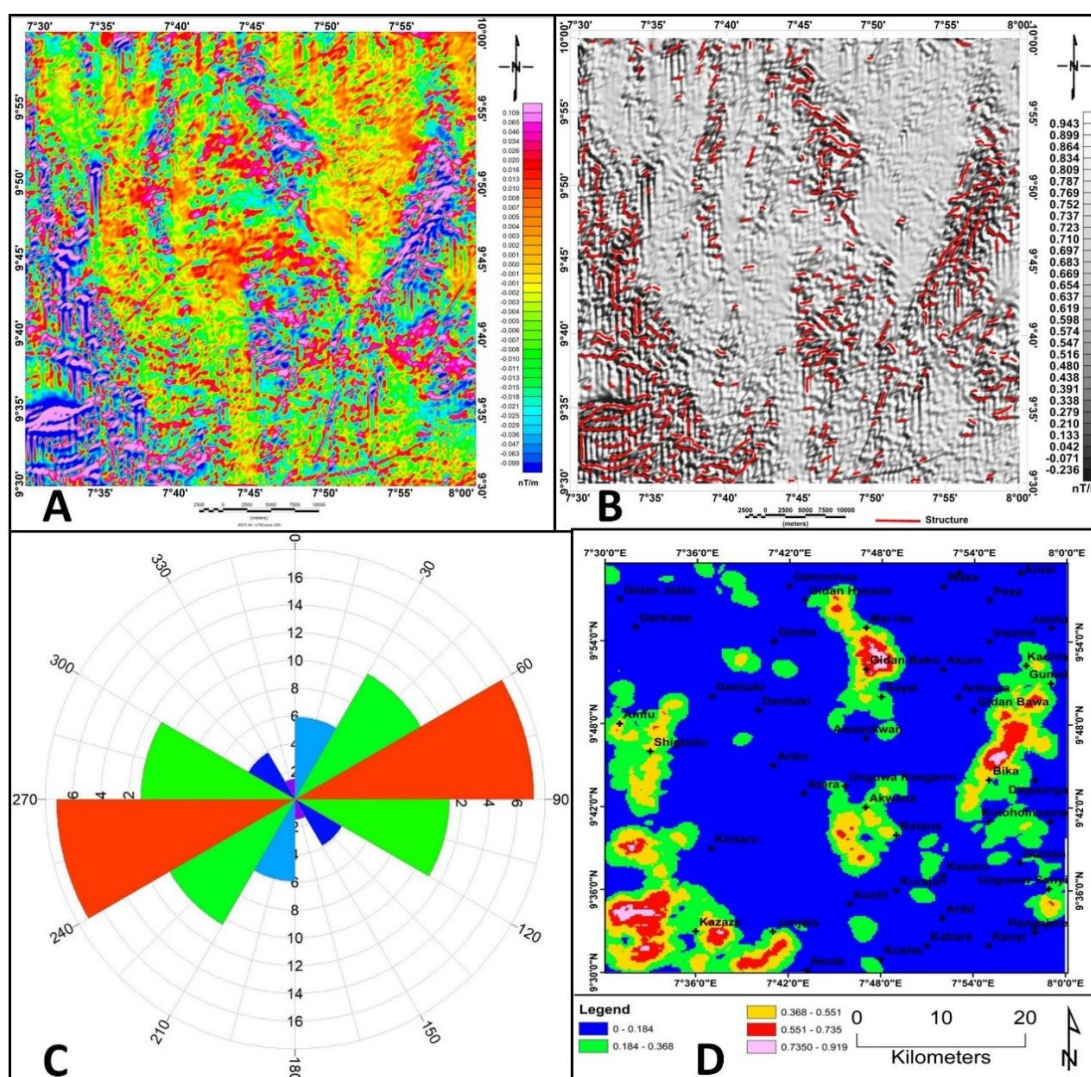


Figure 7: a. First vertical derivative map b. first vertical derivative grayscale map with structures c. Rose diagram showing subsurface structural trend and d. Structural Density map of the study area produced using Oasis montaj (8.3) and ArcMap (10.8)

west of Kazaze, north of Bia and around Gidan Bawa with the north central portion of the study area. Areas of high lineament densities area presumably very viable for hosting ore mineral because they destination mineralisation fluid where they are hosted and solidify within the host rocks (tawey, *et al.*, 2020a).

Figure 8a displays a 3D Euler deconvolution map for a structural index of one (SI=1), while Figure 7b represents a 3D Euler deconvolution map for a structural index of one (SI=1) overlaid with FVD structures. This showcases the trend and depth of structures like faults within the study area.

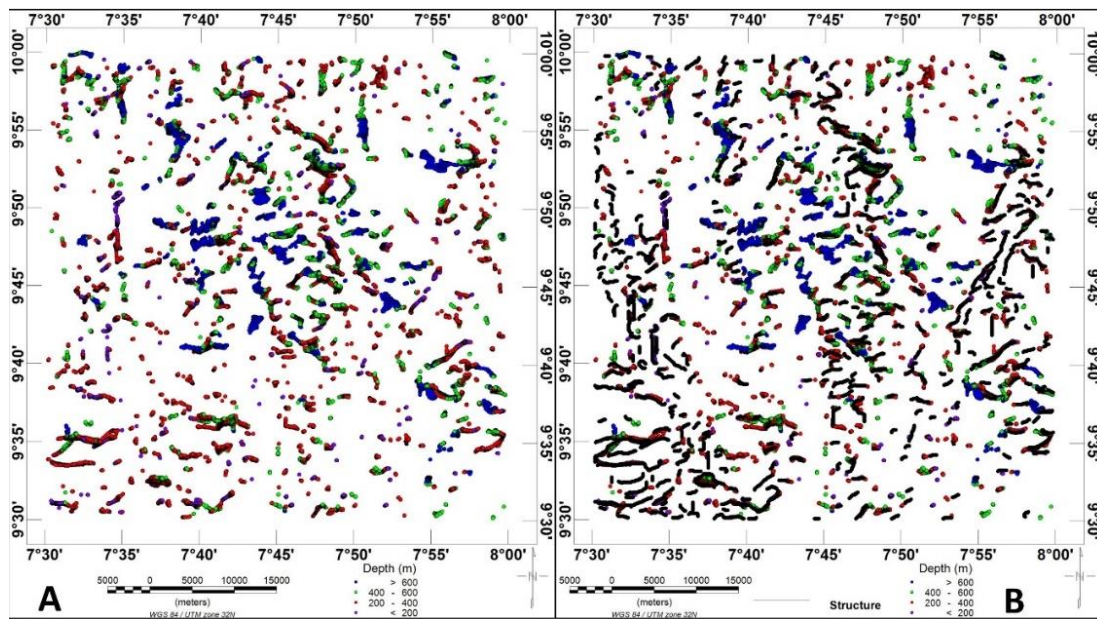


Figure 8: a. 3D Euler deconvolution with a structural index of one (SI=1), b. 3D Euler deconvolution map with 1VDstructures overlaid

The map is like the structural map delineated using FVD, the difference is that the Euler map also displays structural depths and in the present case, the structural depths were classified into four groups: those below 200 m, those between 200 m and 400 m, those between 400 m and 600 m and those above 600 m. This map revealed structures that have similar trends and spatial dispositions as structures revealed by the FVD map (Figure 7b). when the FVD structures are overlaid on the 3D Euler deconvolution map with a structural index of one (SI=1), it coincided with the 3D Euler structures (Figure 8b).

Figure 9a represents the combined hillshade and the delineated surface structures overlaid on it while Figure 9b represents the surface structural density map of the study area. Also, Figure 9c represents the Rose diagram of the surface structures delineated displaying surface tectonic trends within the study area, and Figure 9d represents the summary of the constructed Rose diagram.

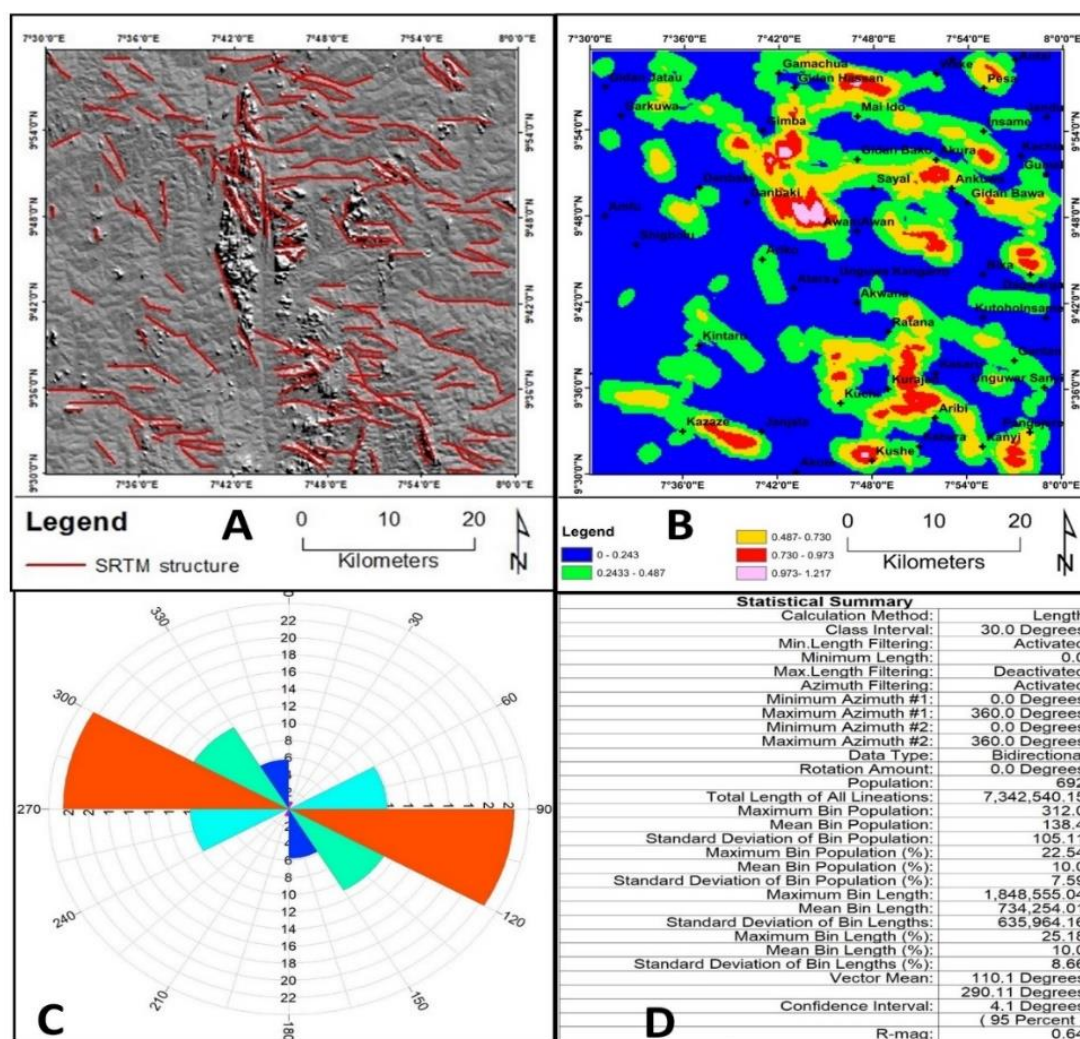


Figure 9: a. Hillshade map with delineated structure overlayed, b. SRTM structural density map, c. SRTM structural rose diagram and d. Statistical summary of the constructed rose diagram, (produced using ArcMap 10.8, rockworks16, and Geomatica 2016)

From the surface structural density map (figure 9b), the northcentral portion around, east of Kazaze, Kushe and north of Aribi are having high lineament densities. The Rose diagram that displays the statistical trends of the surface structures revealed the most dominant surface structural trend within the study area to be WNW-ESE, followed by NW-SE, ENE-WSW and lastly NNW-SSE.

Figure 10a represents combined surface and subsurface structures delineated from SRTM and aeromagnetic data, Figure 10b represents the combined surface and subsurface structural density map, figure 10c represents the structural trend analysis map (Rose diagram), while Figure 10d represents the statistical summary of the constructed Rose diagram of the study area.

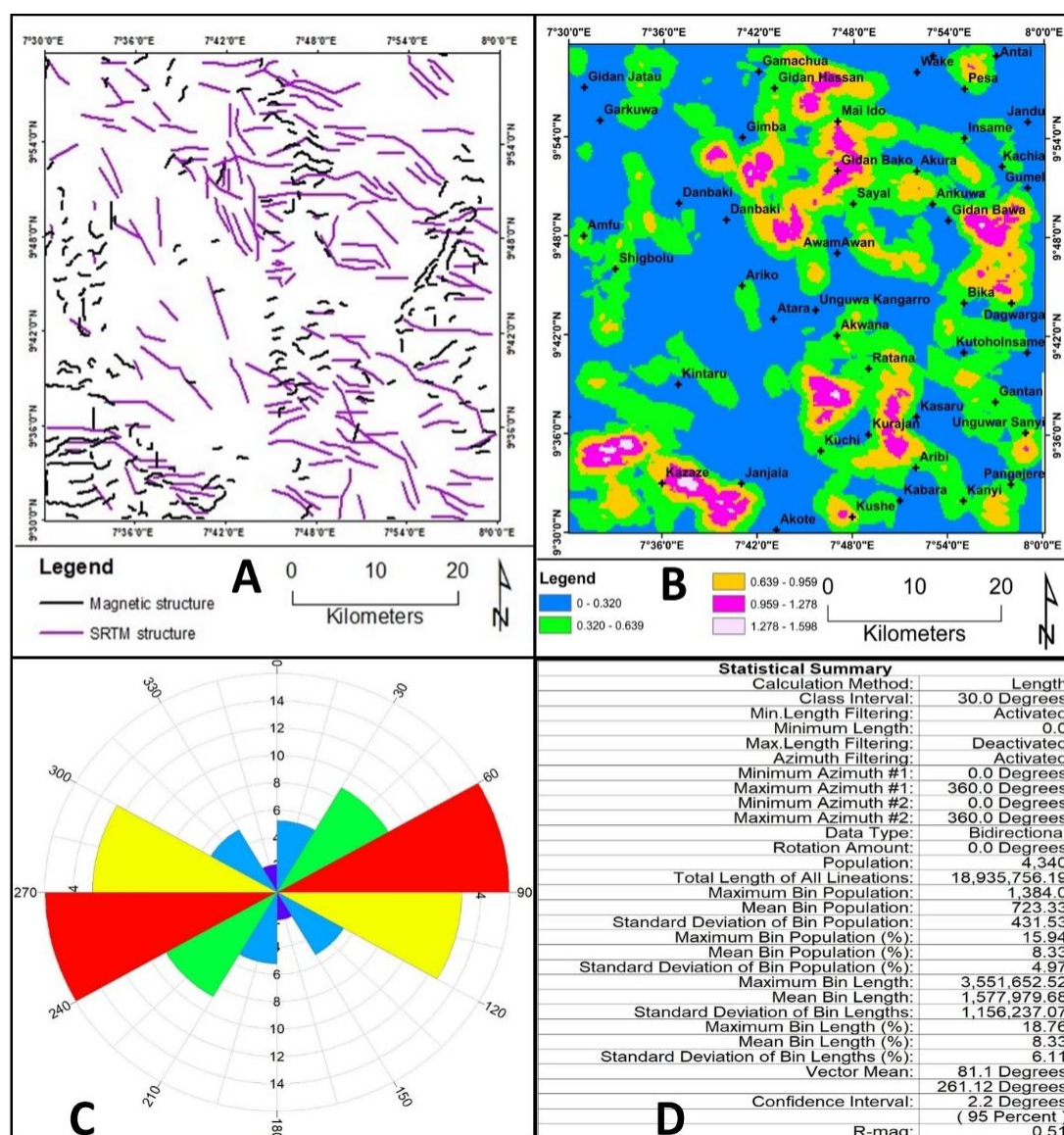


Figure 10: a. combined surface and subsurface structural maps, b. combined surface and subsurface structural density map of the study area, c. Rose diagram of the combined surface and subsurface structures and d. Statistical summary of the rose diagram produced.

From Figure 10a, subsurface structures (Magnetic structures) are represented by black lines while the surface structures (SRTM structures) are represented by purple lines. Structures both surface and surface tend to trend in the same direction at locations such as the southwestern portion of the map, the northcentral portion, and the western portion of the map. At these locations, some of the surface and subsurface structures are observed to coincide and overlap with each other suggesting direct pathways for fluid migration from the subsurface to the surface. The combined structural density map revealed high structural densities around the northcentral portion particularly around Gidan Bako and west of Danbeki, in the southwestern portion of the map around the west and south of Kazaze and

areas around the west and south of Janjala (Figure 10b). These portions of high structural densities area presume areas with high prospect for mineralisation. The combined structural trend as revealed by the Rose diagram (Figure 10c) showed that the predominant combined surface and subsurface structural trends are the ENE-WSW tectonic trend followed by the WNW-ESE, NE-SW, NW-SE, NNE-SSW and NNW-SSE trends respectively.

Possible Structural Continuations

Figure 11 represents a combined map of surface and subsurface structures delineated in purple and black lines respectively. From the map, one can observe the distinct occurrences of coincidence and overlap of surface structures on the subsurface ones. These points or areas of coincidence and overlap are suspected to be direct pathways that connect surface and subsurface structures thus allowing the free movement and migration of fluids from the subsurface to the surface of the earth. This fluid could be water or hydrothermal fluids. For areas where subsurface structures do not continue to the surface, hydrothermal fluids can be hosted in between the structures.

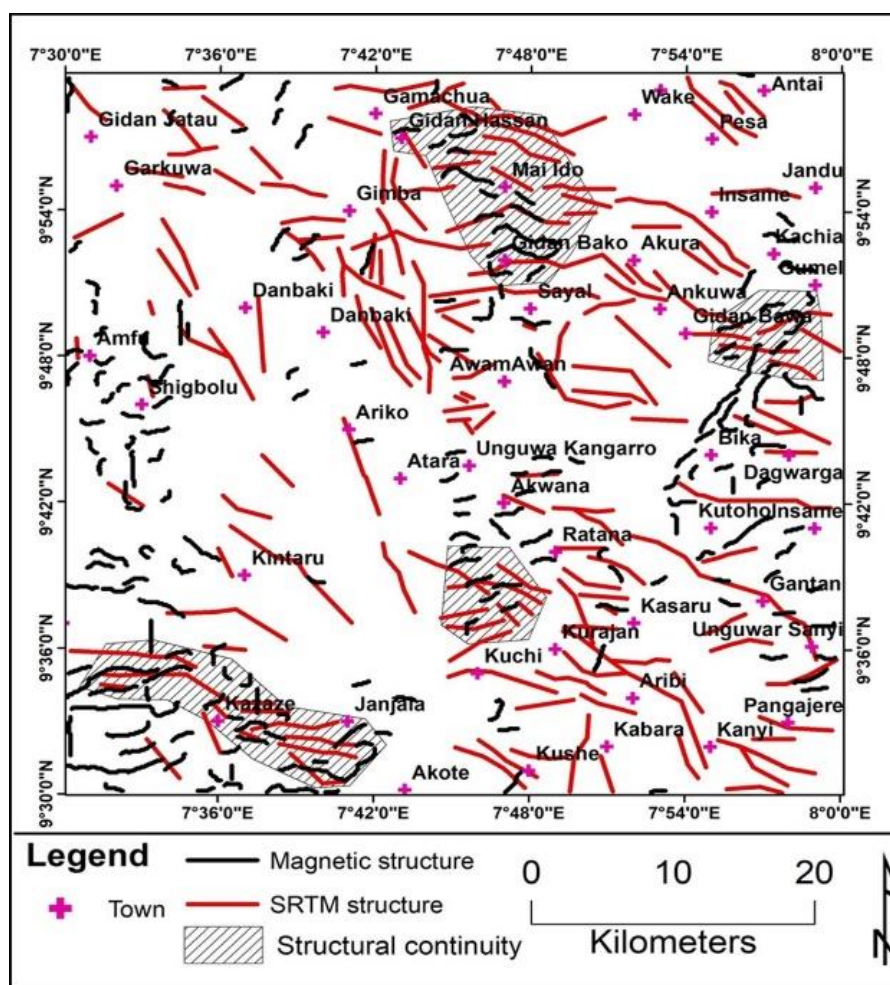


Figure 11: Showing areas of structural continuation between surface and subsurface structures

Conclusion

According to a general structural assessment, the area has been impacted by several tectonic processes. The trend in the study area, which was caused by previous tectonic activity, has been revealed by statistical subsurface structural trend analysis. The Pan-African trend, for example, has a predominant trend of ENE-WSW direction, followed by both WNW-ESE and NE-SW, then NNE-SSW, NW-SE, and NNW-SSE trends, respectively. High subsurface structural densities are also found around the southwest at east and west of Kazaze, Kushe and north of Aribi. Areas of high lineament density were seen on the surface structural density map (figure 9b) around the northcentral part, to the east of Kazaze, Kushe, and the north of Aribi. Surface structural trends within the study area showed that WNW-ESE was the most prevalent, followed by NW-SE, ENE-WSW, and then NNW-SSE.

The combined surface and subsurface structural map (Figure 10a) have revealed these structures to overlap and corresponded with one another, indicating direct channels for fluid movement from the subsurface to the surface. High structure densities were seen on the combined structural density map in the north-central region, particularly around Gidan Bako and west of Danbeki, in the southwestern region around west and south of Kazaze, and in locations around west and south of Janjala (Figure 10b). These areas of high lineament densities are portions presumed to have high prospect for ore mineralisation. Rose diagram analysis of the combined structural trend (Figure 10c) revealed that the ENE-WSW tectonic trend is the major combined surface and subsurface structural trend, followed by the WNW-ESE, NE-SW, NW-SE, NNE-SSW, and NNW-SSE trends, in that order.

In Figure 11, we showed the places where we have seen clear instances of coincidence and overlap between surface and subsurface features. These sites or areas of coincidence and overlap are thought to constitute direct channels linking surface and subsurface structures, allowing fluids to freely travel and migrate from the earth's interior to its surface. Water or hydrothermal fluids may be this fluid. Hydrothermal fluids can be housed between subsurface structures in regions where they do not extend to the surface.

Recommendations

- Gravity method is recommended to confirm the presence of the structures and mineralisation zones already delineated.
- Areas delineated as prospective mineralisations zones and hydrothermal alterations zones need to be followed up in fieldwork (Ground-truthing) using resistivity and other methods to ascertain the types and potentials of minerals present in the respective mineralisation zones delineated.

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