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GEOPHYSICS

An integrated approach of advanced methods for mapping geologic structures and sedimentary thickness in Ukelle and adjoining region (Southeast Nigeria)

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ABSTRACT

High-resolution aeromagnetic data were enhanced using recent and advanced filters to map the geologic structures of the Ukelle and adjoin region (Southeast Nigeria). Aeromagnetic data were reduced to the equator (RTE) and upward continued to 100 m. Subsequently, enhancement operations like the tilt angle of the horizontal gradient (TAHG), logistic function of the horizontal gradient (LTHG), and fast sigmoid function (FSED) operations were carried out. The results from these filters indicated that the ENE-WSW, NE-SW, NNE-SSW, and NNW-SSE orientations dominate the structural pattern of the Ukelle region. In addition, the edge filters delineated NE-SW trending synclinal structures that match the location of thick (500-1400 m) sedimentation obtained by the tilt-depth (TD) method. Furthermore, the structural map obtained from remote sensing data validated the lineament orientations and position of the NE-SW trending synclinal structure. The results also showed that the study location's southeastern and northwestern flanking portions, controlled by extensive Santonian igneous intrusions and metamorphisms, are characterized by high lineaments and thin (0-500 m) sedimentation. The observed thin sedimentation is believed to be caused by widespread Santonian tectonic events in the area. At the same time, related geologic structures served as migration pathways and accumulation zones for rift mineralization.

Keywords: Edge detection; Tilt-depth; Geologic structures; Ukelle; Southeast Nigeria.

Acercamiento integrado de métodos avanzados para el mapeo de estructuras geológicas y espesor sedimentario en Ukelle y regiones adyacentes, en el sudeste de Nigeria

RESUMEN

En este trabajo se usaron filtros recientes y avanzados para mejorar la información aeromágnetica de alta resolución que permitiera mapear las estructuras geológicas de Ukelle y las regiones con las cuales limita (en el sudeste de Nigeria). A la información aeromagnética se le aplicó la Reducción al Ecuador y continuó hasta los 100 metros. Luego se realizaron operaciones de mejoría como el ángulo de inclinación del gradiente horizontal, función logística del gradiente horizontal, y la función rápida sigmoide. Los resultados obtenidos con estos filtros indicaron que las orientaciones ENE-OSO, NE-SO, NNE-SSO y NNO-SSE dominan el patrón estructural de la región Ukelle. Adicionalmente, los filtros de borde delinearon que la tendencia NE-SO de las estructuras sinclinales coinciden con la ubicación de la densa masa sedimentaria (entre 500 y 1400 metros) obtenida con el método de inclinación y profundidad. Además, el mapa structural obtenido con la información de teledetección validó las orientaciones de lineamiento y la tendencia en la posición de NE-SO de la estructura sinclinal. Los resultados también muestran que las áreas del sureste y del noroeste que flanquean la zona de estudio están controladas por grandes intrusiones y metaformismo ígneo del Santoniano y se caracterizan por grandes lineamientos y sedimentación delgada (0-500 metros). Se estima que la sedimentación delgada que se observó fue causada por los extendidos eventos tectónicos durante el Santoniano en el área. Simultáneamente, las estructuras geológicas relacionadas sirvieron como caminos de migración y zonas de acumulación para la mineralización en zanjas de hundimiento.

Palabras clave: detección de bordes; método de inclinación y profundidad; estructuras geológicas; Ukelle; Sudeste de Nigeria.

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1. Introduction

Airborne magnetic method is one of the most suitable procedures for mapping near surface and underlying basement geologic structures (Ben et al., 2022a; 2022b). Analysis involving high resolution airborne magnetic data can be used to resolve the challenges involved in delineating subtle geologic features (Eldosouky, 2019; Almasi et al., 2014), detecting regional geological borders (Cooper and Cowan, 2008; Pham et al., 2019), delineation of depo-centres and basement framework (Ekwok et al., 2021a; 2021b; 2021c) as well as mapping of zones of mineralization and hydrothermal modifications (Ekwok et al., 2020a). The evaluation of linear edges and borders of magnetic sources which commonly reveal subsurface faults, fractures, contacts, as well as associated tectonic bodies, are useful in the interpretations of geological structures. Previous research has shown that the magnetic techniques are extremely useful as an investigative delineating tool when there are disparities between the different rock units (Dentith et al., 2000). Tectono-magnetic events of the area control development and expression of the geologic features of the region (Eldosouky et al., 2022). The tectonic settings, the structural framework, occurrence of rift minerals as well as the discovery of oil and gas in commercial quantity triggered extensive geoscience studies in the Benue Trough (Ekwok et al., 2022a; 2019).

Nonetheless, due to the low degree of resolution, the boundaries cannot be directly mapped from the observed potential field data (Fedi and Florio, 2001). Several enhancement procedures have been developed by various researchers to properly delineate the geologic structures caused by tectonic events (Eldosouky et al., 2020; Jorge et al., 2023). The gradient amplitude technique (Cordell and Grauch, 1985) is commonly used for improving geologic borders. Hansen and deRidder (2006) used the curvature of the gradient amplitude in identifying linear structures. However, the gradient amplitude filter detects the borders of shallow sources better than deeper bodies (Arısoy and Dikmen, 2015). This is due to the inability of gradient amplitude to provide steady indicators from the borders of low and high amplitude magnetic signatures simultaneously (Eldosouky et al., 2020; Pham et al., 2022a, b). The analytic signal filter developed by Roest et al. (1992), which is also well known, is often used to locate the flank borders of magnetic anomalies (Pham et al., 2021a). Just like the gradient amplitude filter, the analytic signal filter performs defectively in the enhancement of magnetic anomalies created by joint deep and shallow sources (Pham et al., 2018; 2019; 2021b). Other enhancement operators like tilt derivative and theta are often used in mapping lineaments, and describing geologic structures of the bodies (Miller and Singh, 1994; Wijns et al., 2005). Pham et al. (2020, 2021c) introduced the improved logistic function and softsign function to increase the resolution of the edges. Eldosouky et al. (2020), Pham and Prasad (2023) reviewed the effectiveness of the filters in terms of their precision on the detection of borders of magnetic sources on both observed and theoretical data. Other improved enhancement operations like the spectral moments (Sun et al., 2016), TAHG (Ferreira et al., 2013), LTHG (Pham et al., 2019), and FSED (Oksum et al., 2021), can reveal lineaments of different anomalies.

Previous studies in the Lower Benue Trough using magnetic data with low resolution obtained by Geological Survey of Nigeria (GSN) in 1974, were centered on the mapping of major intrusive structures, fault systems, stratigraphy, sediment thickness, spatial distribution of igneous intrusions, and delineation of depo-centres (Oha et al., 2016; Ofoegbu, 1984; Ofoegbu and Mohan, 1990). Later, increased interest amongst researchers were later generated on the geologic structural complexity caused by igneous intrusions, and associated rift-minerals in the area (Oha et al., 2016; Ofoegbu, 1984; Ofoegbu and Mohan, 1990). These geologic structural studies were investigated involving derivatives, analytic signal, low pass filtering, upward continuation, source edge detection, etc (Ekwok et al. 2019; 2020a). However, some local and subtle geologic structures were suppressed by these filters. The availability of improved filters (like the TAHG, LTHG, FSED, etc.) has made it easier to determine subtler anomalies and generate more detailed geologic structural information. These filters generate peak responses directly over source borders, and produce better resolution and distinctive lineament maps (Eldosouky et al., 2020; Pham et al., 2022b; Oksum et al., 2021; Kamto et al., 2023).

This research involved the application of some recent filters such as the TAHG, LTHG and FSED to airborne magnetic data from the Ukelle and adjacent area (Southeast Nigeria) to map geologic boundaries. The mapping of these boundaries is expected to help determine lead-zinc, brine conduit, barite and ironstones accumulation zones within the Ukelle and environs. These minerals are reported in commercial quantity in other geologic units within the Abakiliki Anticlinorium (Uma and Lohnert, 1992; Uma, 1998). Moreover, the TD method was also applied to the magnetic dataset to determine the depth to the geologic structures, as well as sedimentary cover of the basement rocks. The findings from this research are expected to improve the existing knowledge on the geological structures and patterns, as well as thickness of the sediments in Southeast Nigeria.

2. Geologic setting

The Ukelle region is sited in the Lower Benue Trough, on the northeastern flank of the Santonian Abakaliki Anticlinorium (Fig. 1). The investigated region is positioned between longitude 8^{0}00' and 8^{0}30'E and latitude 6^{0}30' and 7^{0}00'N.

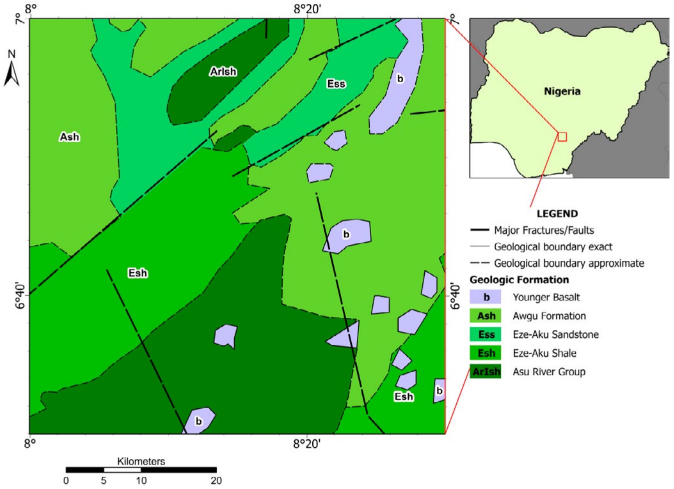

Figure 1. Geological map of the Ukelle and adjacent area.

The series of events which resulted to the development of the Benue Trough and its constituent parts have been well documented (Onuoha and Ofoegbu, 1988). A thick sedimentary successions of the Cretaceous age occupy the Lower Benue Trough, and overlies the Precambrian basement mainly of composed of migmatic and granitic rocks. The Precambrian basement is overlain by the Albian Asu-River Group (ARG), which is composed of bluish black sandstone. The Eze-Aku Formation (EAF), which sits directly on the Asu-River Group, is made up of calcareous siltstone and shale, calcareous sandstones, and shelly and sandy limestone (Reyment, 1965).

The Coniacian Awgu-Shale (AS) is dominated by marine fossiliferous, grey bluish shale, limestone, and calcareous sandstone. The Campanian Nkporo Shale (NS) which overlies the Agwu-Shale, is characterised by mostly marine arenaceous sandstone members. In general, tectonism has had a significant impact on the sedimentary series, which happened in two stages and resulted in the folding of the overlying sedimentary materials (Nwachukwu, 1972). The folding event that occurred in the Santonian period was the primary cause of the formation of the Abakaliki-Anticlinorium. The asymmetry and reversed faults linking with the folds that were created in this period indicate that they were majorly compressional in pattern. Benkhelil (1987) characterised the Abakaliki Anticlinorium happenings as a whole orogenic cycle encompassing sedimentation, compressive tectonics, magmatism, and metamorphism. The related magmatic happenings caused the introduction of numerous intrusions into the overlying ARG and EAF. The NS sits unconformably over the folded EAF and the ARG (that is, Abakaliki Anticlinorium) (Whiteman, 1982).

The Ukelle area which is part of the Abakaliki Anticlinorium, is a prominent geological structure formed as a result of series of tectonic processes. It is situated within the larger Benue Trough, a major intra-continental rift basin that extends across several countries in West Africa (Benkhelil, 1989). The Abakaliki Anticlinorium is characterized by its distinct folding pattern, where rock layers are bent upwards into an arch-like structure known as an anticline. The primary tectonic process responsible for the formation of the Abakaliki

Anticlinorium is compressional tectonics (Benkhelil, 1989). As a result, the originally horizontal sedimentary strata in the Abakaliki region were folded and uplifted, forming the characteristic anticlinal structure observed today (Benkhelil, 1989). The folding process is believed to have occurred during the Santonian period, as indicated by radiometric dating of the sedimentary rocks in the area (Benkhelil, 1989).

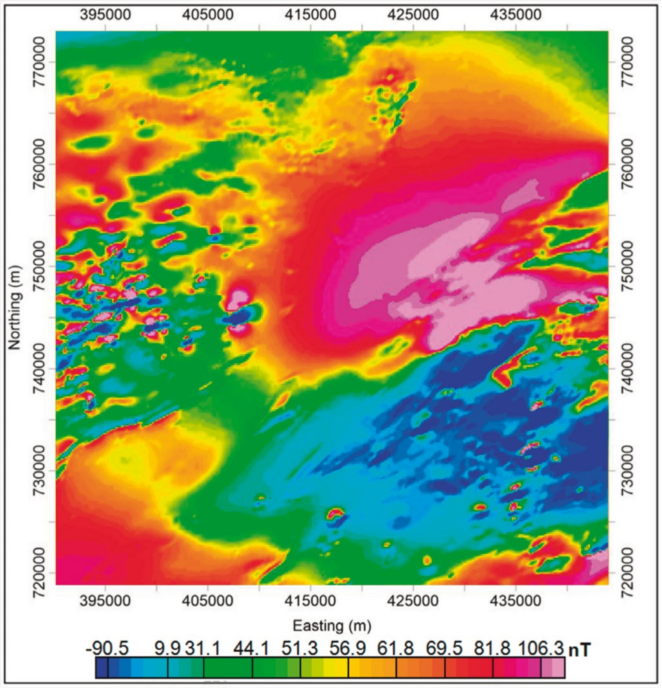

Figure 2. Total magnetic intensity map of the Ukelle and adjacent area.

3. Data and method

Data

The high resolution airborne magnetic data used for this study which covers an area of about 25,000 km^2, were purchased from the Nigerian Geological Survey Agency (NGSA). Fugro Airborne Surveys (FAS), Canada, under contract to the NGSA, acquired aero-geophysical data between the period of 2005 and 2010, covering the whole country. The dataset was acquired using a Flux-Adjusting Surface Data Assimilation System with 100 m of flight-line space, 500 m of tie line space, and terrain-clearance ranging from 80-100 m. Furthermore, Fugro Airborne Surveys, Canada, subtracted the regional field from measured magnetic data engaging the tenth generation of the International Geomagnetic Reference Field. Following the wide acceptance and availability of the IGRF, the main advantage of the IGRF is the reliability it offers in potential field survey practice (Reeves et al., 1997). The dataset used in this paper was converted to total magnetic intensity (Fig. 2) and then reduced to the equator before being upward continued to 100 m. (Fig. 3). Because the data was gathered at a low latitude, the magnetic data was reduced to the equator. Jain (1988) and Leu (1981) reported that RTE generates more reliable results, especially at middle and lower latitudes. Also, the data were upward continued to attenuate the geologic effects associated with very short wavelength anomalies. All the enhancement operations were carried out using the RTE upward continued to 100 m data.

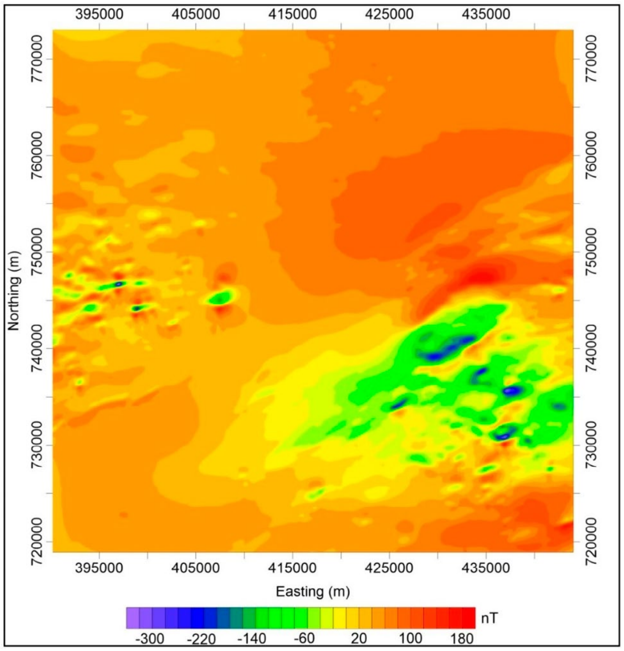

Figure 3. RTE data upward continued to 100 m.

Methods

Edge detection methods

Ferreira et al. (2013) proposed the TAHG operator to outline the lateral boundaries, which is based on the derivatives of the horizontal gradient (THG). The filter is expressed as:

$$\mathrm{TAHG} = \mathrm{atan}\frac{\dfrac{\partial \mathrm{THG}}{\partial Z}}{\sqrt{\left(\dfrac{\partial \mathrm{THG}}{\partial}\right)^2+\left(\dfrac{\partial \mathrm{THG}}{\partial Y}\right)^2}} \quad (1)$$

where ∂THG/∂x, ∂THG/∂y and THG/∂z are the THG derivatives, which is expressed as:

$$\mathrm{THG}=\sqrt{\left(\frac{\partial F}{\partial X}\right)^2+\left(\frac{\partial F}{\partial Y}\right)^2} \quad (2)$$

where (∂F/∂x) and (∂F/∂y) are the derivatives of the field F. Figure 4c shows the TAHG of synthetic magnetic data (Fig. 4b) of the bodies M1 and M2 in Figure 4a. We can see that the TAHG can balance different anomaly amplitudes, but it cannot provide the sharp edges.

The LTHG technique is the enhanced type of the THG, which is centred on the logistic function and given by Pham et al. (2019):

$$LTHG=\left[1+exp\left(\frac{\dfrac{\partial \mathrm{THG}}{\partial Z}}{\sqrt{\left(\dfrac{\partial \mathrm{THG}}{\partial}\right)^2+\left(\dfrac{\partial \mathrm{THG}}{\partial Y}\right)^2}}\right)\right]^{-\alpha} \quad (3)$$

Pham et al. (2019, 2022b) proved that 2 ≤ α ≤ 10 will produce the best solutions. As shown in Figure 4d, the LTHG can equalize different amplitudes, and provides sharper edges than the TAHG.

The fast sigmoid function (FSED) is another detector, developed by Oksum et al. (2021). This technique is centred on the fast sigmoid function of the ratio of the derivatives of the THG. Its maximum values are used to detect the source borders. This technique is given by:

$$\mathrm{FSED} = \frac{\mathrm{R}-1}{1+\left|\mathrm{R}\right|'} \tag{4}$$

where

$$\mathrm{R} = \frac{\dfrac{\partial \mathrm{THG}}{\partial \mathrm{Z}}}{\sqrt{\left(\dfrac{\partial \mathrm{THG}}{\partial \mathrm{X}}\right)^2 + \left(\dfrac{\partial \mathrm{THG}}{\partial \mathrm{Y}}\right)^2}} \tag{5}$$

As displayed in Figure 4e, the FSED also provides balanced anomalies and sharper edges than the TAHG.

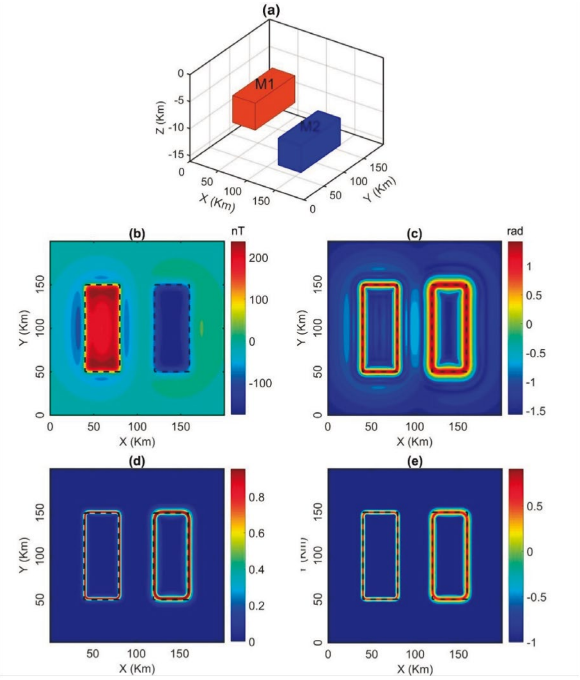

Figure 4. (a) Synthetic model, (b) magnetic anomaly, (c) TAHG, (d) LTHG, (e) FSED.

As shown in Figures 4c and 4d, the depth of the source bodies has no effect on the TAHG and LTHG, and their peak values are near the true boundaries even for deep bodies. This is one of the benefits of the TAHG and LTHG over the horizontal gradient, which cannot delineate boundaries originating from deep magnetic bodies (Pham et al., 2022b; Eldosouky et al., 2020). The FSED also enhances the boundaries of both deep and shallow bodies and its peak values are near the real boundaries (Fig. 4e).

Depth estimation method

The TD technique is based on the relationship between tilt angle derivative (TDR) (Miller and Singh, 1994), horizontal position and depth of a vertical 2-D contact as (Salem et al., 2007):

$$\mathrm{TDR} = atan\frac{\dfrac{\partial \mathrm{F}}{\partial \mathrm{z}}}{\sqrt{\left(\dfrac{\partial \mathrm{F}}{\partial \mathrm{x}}\right)^2 + \left(\dfrac{\partial \mathrm{F}}{\partial \mathrm{y}}\right)^2}} \tag{6}$$

and

$$\mathrm{TDR} = atan\frac{\mathrm{h}}{\mathrm{z_c}} \tag{7}$$

where z_c is the contact depth, and h is the horizontal location. Equation 7 shows that the contact location (h = 0) relates to the zero values of the TDR, and the depth relates to the horizontal distance between TDRs of 0 and and ±π/4.

4. Results

In an attempt to offer better understanding of the location, trend and pattern of geologic structures in the Ukelle and adjoining regions of Southeast Nigeria, enhanced filters like the TAHG, LTHG and FSED were applied on the high resolution RTE magnetic data that were upward continued to 100 m (Fig. 3). Figure 5 signifies the output of the TAHG. The maxima of the method revealed lineaments caused by magnetic bodies. Nevertheless, sharp edges cannot be detected by this filter. The LTHG of upward continued RTE magnetic data is shown in Figure 6. This map displays a clearer delineation of geologic structures, which are much easier to visually interpret qualitatively. Figure 7 shows the output of the FSED. Like other methods, the FSED generates the edges with the same amplitude.

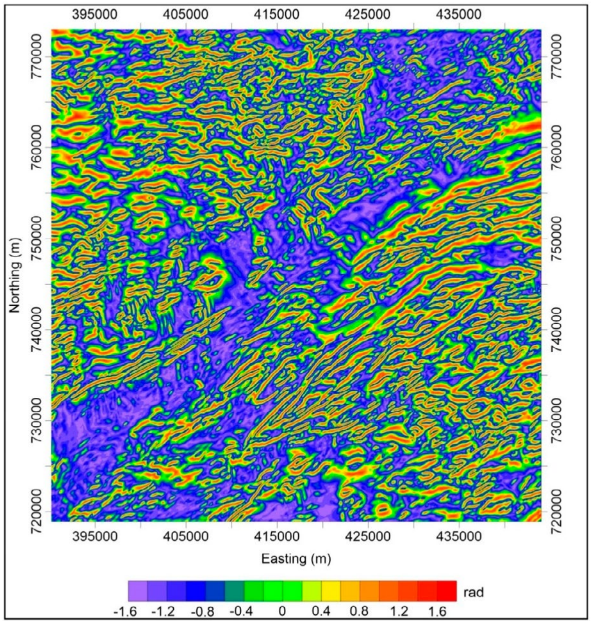

Figure 5. TAHG map of the Ukelle and adjacent area.

As shown in the synthetic model, the peak responses obtained from the TAED (Fig. 5), LTHG (Fig. 6), and FSED (Fig. 7) were positioned directly over magnetic source borders. The filters applied in this study (Figs. 5-7) delineated horizontal geologic structures with ENE-WSW, NE-SW, NNE-SSW, and NNW-SSE orientations. Figure 5 generated more connective linear features that are somewhat diffused. The low resolution of source edges in Figure 5 makes geologic interpretations more difficult. The LTHG and FSED simultaneously balanced the low and high amplitudes (Figs. 6 and 7). These filters also provide greater resolution and distinctiveness compared to the TAHG (Fig. 5). By comparing the results from the methods, we can say that the LTHG and FSED are precise and highly effective in identifying several geologic features associated with the Santonian Abakaliki Anticlinorium (Benkhelil, 1987), which were not clear in Figure 5.

Since the TAED, LTHG, and FSED peaks respond to the source edges, we determined these peaks using the improved crest detection technique (Pham et al., 2023). Magnetic boundaries are then identified from the locations of the peaks. The overlay of the locations of the peaks is presented in Figure 8. Here, the peaks of the TAHG are shown by black dots, the peaks of the LTHG are displayed by cyan dots, while red dots respond to the FSED peaks. By mapping the maxima locations of the filters, the results for the edge locations are similar (Fig. 8).

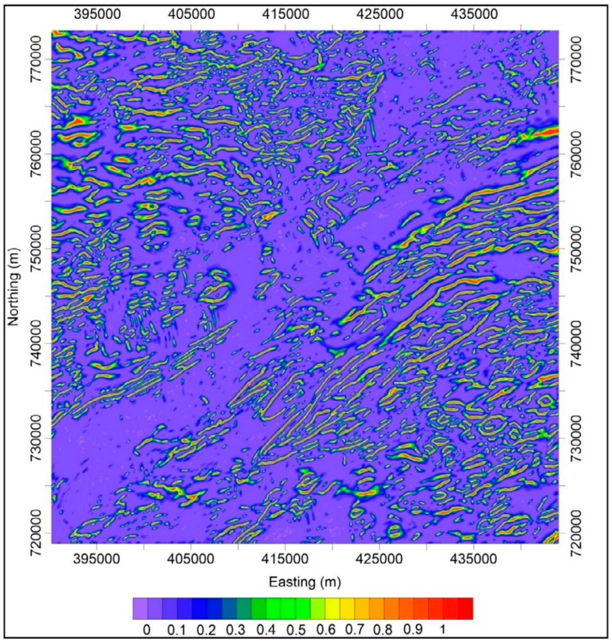

Figure 6. LTHG map of the Ukelle and adjacent area.

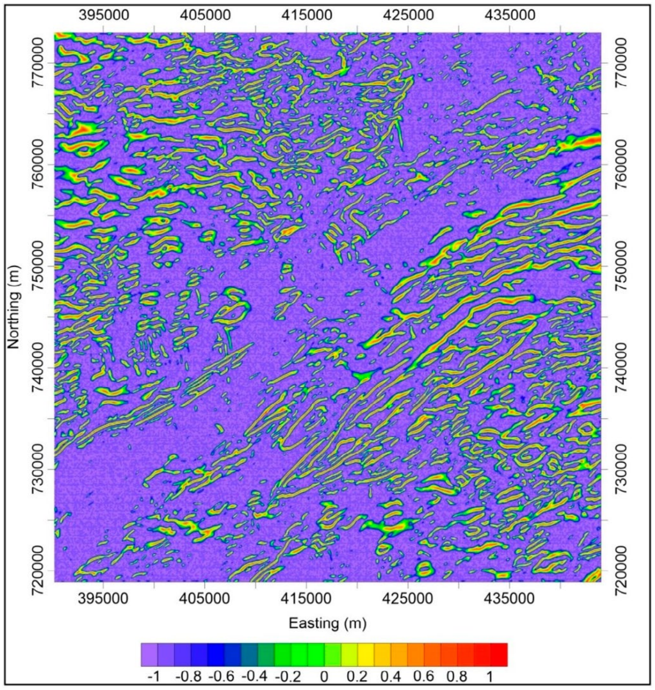

Figure 7. FSED map of the Ukelle and adjacent area.

Furthermore, the TD method (Salem et al., 2007) was applied to assess the depths of geologic structures within the study area. The main advantage of the TD method is that, unlike standard Euler deconvolution, it doesn't require the window size (Ekwok et al., 2022a; 2020a; 2021b). The depth map (Fig. 9) revealed depth range of approximately 0-1400 m. This thin sedimentation is thought to be caused by the extensive invasion of the sediments by the Santonian intermediate-mafic igneous intrusions, as well as tuffs and calc-alkaline lavas intrusions (Benkhelil, 1987; Murat, 1970) in the study area. The tectonic event caused extensive baking of sediments, generation of metamorphosed rocks and creation of geologic structures in the region.

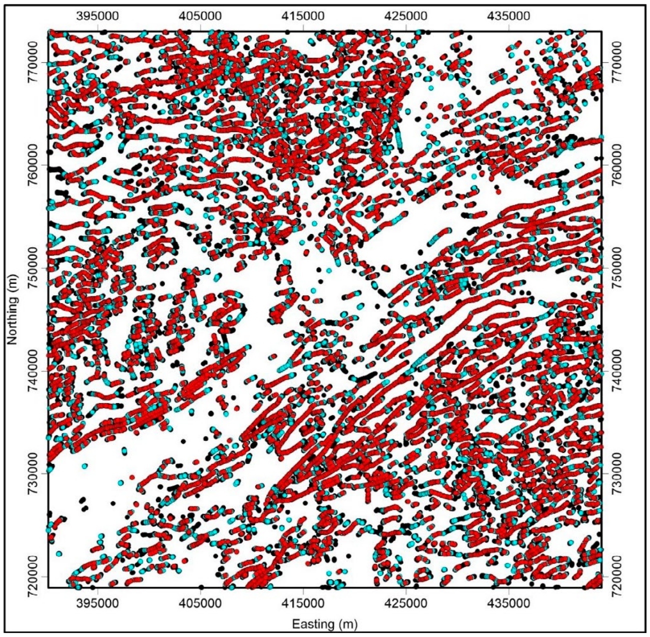

Figure 8. Peaks of the TAHG (black dots), LTHG (cyan dots) and FSED (red dots).

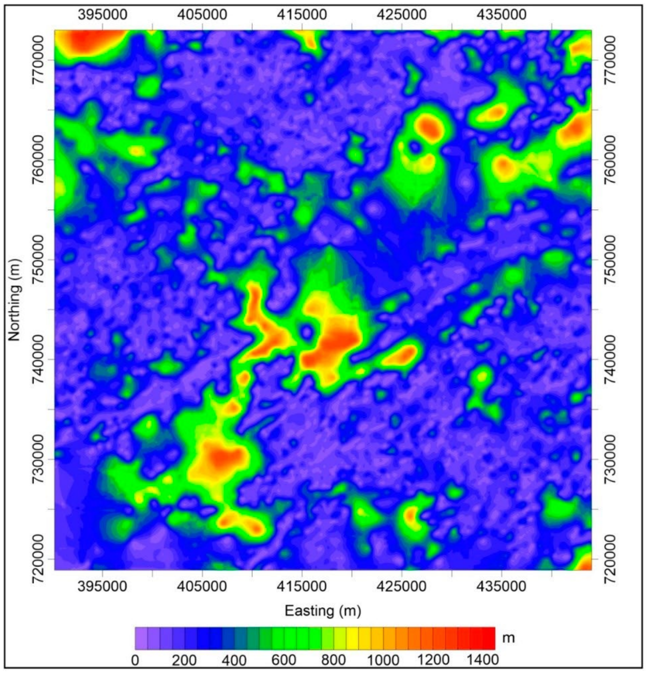

Figure 9. Tilt-depth map of the Ukelle and adjacent area.

5. Discussion

The northeast-southwest structural trend controlled the basement framework and sedimentation pattern in the southeastern part of Nigeria (Benkhelil, 1987; Benkhelil et al., 1975; Burke et al., 1970). The lineaments within the investigated area that trend in NW-SE, NE-WS, NNE-SSW, and E-W directions were easily traced (Figs. 5-7). The LTHG (Fig. 6) and FSED (Fig. 7) filters are additionally efficient in mapping edges of the NE-SW trending synclinal structures associated the Abakaliki Anticlinorium. This NE-SW synclinal structure previously mapped by Ekwok et al. (2020a), partitioned the study area into northwest and southeast flanks (that is, folds/uplifts), that coincide with the zone characterised by relatively thick (500-1400 m) sedimentation (Fig. 7). The northwest and southeast flanks that correlated strongly with zones dominated by thin (0-500 m) Cretaceous sedimentary series, are controlled by widespread near-surface igneous, tuffs and calc-alkaline lavas intrusions (Benkhelil, 1987; Murat, 1972) as well as metamorphosed Albian shales (Ekwok et al., 2022c; 2021b; Benkhelil et al., 1975). The coexistence of uplifts/folds (positive anomalies) and synclines (negative anomalies) in Southeast Nigeria have been reported by previous studies (Benkhelil, 1987; Burke et al., 1970; etc). Generally, the uplifted regions are controlled by high concentration of lineaments (Fig. 8), caused by a series of elongated narrow folds within the ENE-WSW, NE-SW, NNE-SSW and NNW-SSE configurations of the Abakaliki sedimentary area triggered by the invasion of alkaline dolerites, basalts, and syenites (Murat, 1972) into the overlying sediments. The major structural pattern of the Benue Trough and Abakaliki Anticlinorium is NE-SW (Benkhelil, 1987; Murat. 1972; Burke et al., 1970), while some E-W lineaments pattern are described as transverse fractures to the major NE-SW fault along which massive intrusions were placed. Lineament maps (Fig. 10) were generated from magnetic data (Fig. 10a) and remote sensing involving shuttle radar topographic mission (SRTM) data (Fig. 10b). Fig. 10a is characterised by a wide range of geologic structures, while Fig. 10b is dominated by short lineaments and some regional structures. Besides, the NE-SW trending synclinal structure (Fig. 10a) with thick sedimentation was mapped also mapped (Fig. 10b). Generally, it was observed that the trending pattern of Fig. 10b correlates strongly with lineaments determined in Fig. 10a generated from the edge filters. Comparatively, the various results of the enhancement operation applied in this research showed that the LTHG and FSED methods generated sharper and more distinct geologic structures of the Ukelle and adjacent area, than the TAHG. In addition, there is a good correlation between lineaments in Fig. 10a and 10b, and the rose petals (Fig. 11) show trends in the ENE-WSW, NE-SW, NNE-SSW and NNW-SSE orientations. These geologic trends have been previously reported in the Lower Benue Trough (Ekwok et al., 2021a; 2021b; 2021c). The main strike orientation in the Lower Benue Trough and Abakaliki-Anticlinorium is represented by the ENE-WSW, NE-SW and NNE-SSW directions. The ENE, NE and NNE characterise the regional-strike of the lineaments that correspond to region (the Lower Benue Trough) that was tectonically disturbed during the Santonian period (Murat, 1970).

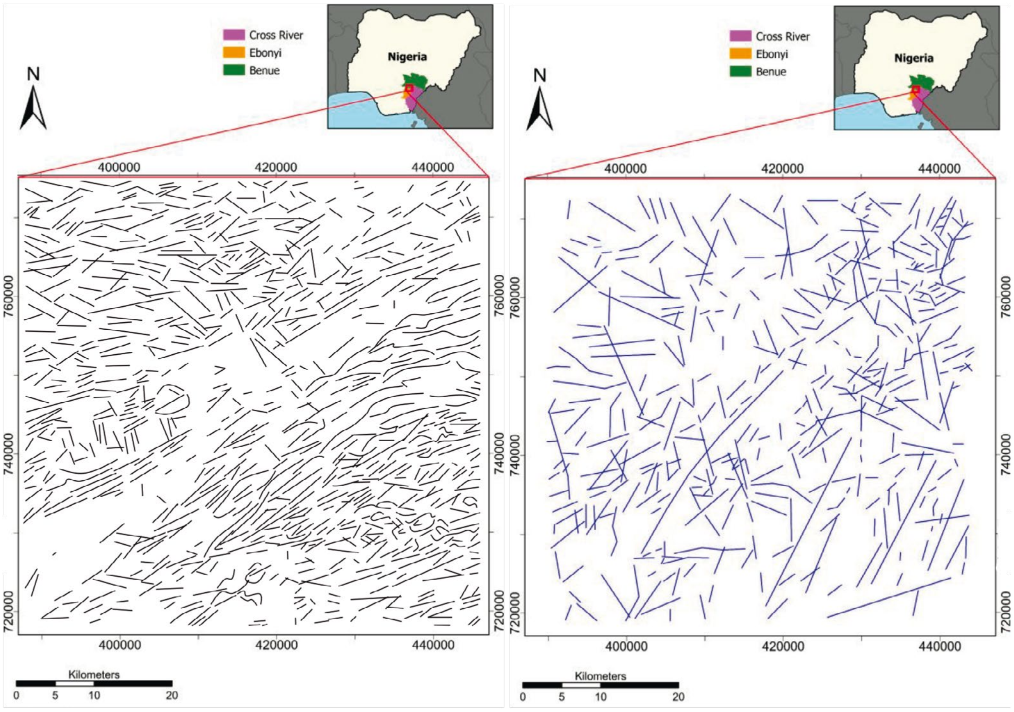

Figure 10. (a) Magnetic lineaments map obtained from the edge filters, (b) GIS generated lineaments map from SRTM of the Ukelle and adjacent area.

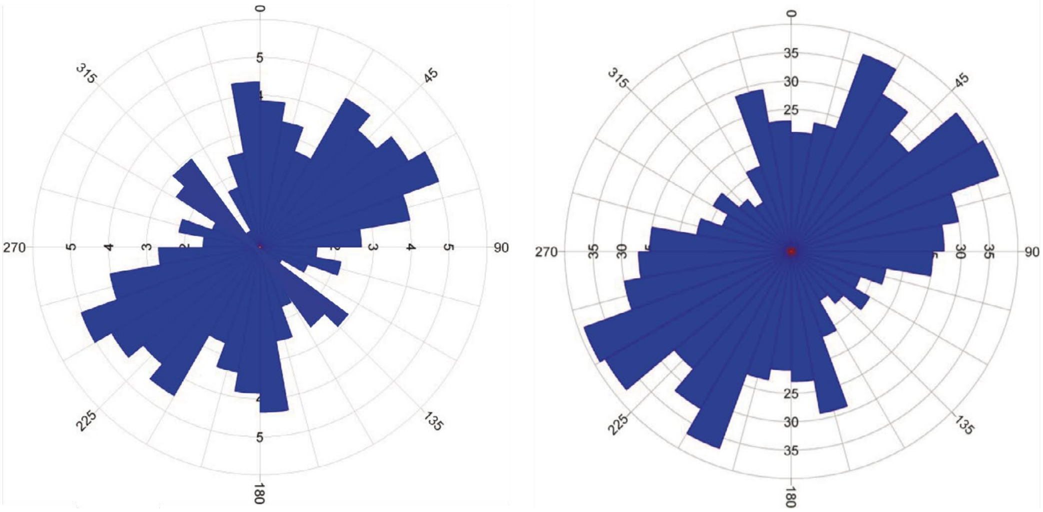

Figure 11. Rose diagrams of magnetic lineaments obtained from the edge filters (a) and (b) GIS lineaments.

Conclusions

Delineation of geologic structures and contacts in the Ukelle and adjoining area (Southeast Nigeria) involved the TAHG, LTHG, FSED, and the RTE total magnetic intensity data that were upward continued to 100 m. The filters generated geologic structures that trend in the ENE-WSW, NE-SW, NNE-SSW, NNW-SSE and NW-SE directions. Remote sensing involving SRTM data generated structural map that validated the structural orientations of lineaments obtained by the enhanced filters. Furthermore, the lineament maps delineated the NE-SW trending synclinal structures that coincide with the zone characterised by relatively thick (500-1400 m) sedimentary series revealed by the TD map. Also, the enhanced filters as well as the TD result mapped folds/uplifts in the northwest and southeast flanks with thin (0-500 m) sedimentation, controlled by widespread Santonian igneous intrusions and metamorphism that caused high concentration of lineaments in these portions.

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