

Mapping of Potential Lithium Mineral Deposits in Some Parts of Northwestern Nigeria Using Magnetic and Gamma-Ray Spectrometry Data

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Abstract

Mapping of potential lithium mineral deposits in some parts of northwestern Nigeria has been carried out in this study using magnetic and gamma-ray spectrometry datasets. Lithium mineral deposits have been known to be controlled by the geologic structures and degree of hydrothermal alterations resulting from enriched potassium (K) in a mineralised pegmatite environment. Consequently, the airborne magnetic and radiometric dataset were analysed by producing the first vertical derivative (FVD), total horizontal derivative (THD), analytic signal, and radioelement ratio, F-parameters, and thorium normalization maps to intensify the interpretations of the spatial distributions and variabilities of the subtle geologic structures and radioelements for probable lithium mineral deposits in the study area. The FVD, THD and analytic signal maps revealed and characterized the distribution of litho-structural features that host solid mineral deposits. The radioelements (K, eTh, and eU), radioelement ratios and the total count (TC) revealed geochemical alteration zones arising from the radiometric signatures of the rocks. They show varying degrees of concentration and distribution across the study area, with values ranging from -0.5 to 8.5 %, 4.0 to 158 ppm, 0.5 to 26.4 ppm, and -2.4 to 64.9 μRh^{-1} for K, eTh, eU, and Tc, respectively. Results from the FVD, THD, analytic signal, ratio maps, F-parameter and thorium normalisation (KD%) shows hydrothermally altered structures in parts of the northeastern, eastern, southeastern, and extreme northwestern flanks of the study area, indicating potential areas of lithium deposits. The maxima on K/eTh (ratio map) and KD% produced, emphasized the favourable structures for lithium deposits and other mineral deposits in the studied area.

Keywords: Geologic structures, pegmatite, Lithium mineral, radiometric signatures, mineralised environment.

Introduction

The northwestern part of Nigeria is considered one of the richest mineral resources, with more than 120 known lithium field deposits and other mineral occurrences identified by unofficial artisan miners in the country (Obaje, 2009; Salau *et al.*, 2016; Dzukogi *et al.*, 2020; Dzukogi *et al.*, 2022). The lithium ore deposits can be categorized into spodumene, amblygonite, white cast and lapidolite. These deposits are non-stratabound deposits and are found in vein-type mineralization (pegmatite veins) or as disseminated mineralization hosted by different types of rocks ranging from schist, gneiss and granite intrusions (Ekwueme and Matheins, 1995; Solomon, 2004; Dzukogi *et al.*, 2022). Abu-Adam *et*

al. (2013) tectonic model stated that; solid minerals were deposited from the hydrothermal solution, which was produced in a deeper crustal level (upper mantle) due to magmatic processes.

In exploring for ore deposits in a mineralized environment such as lithium, gold, copper and other metal deposits on a reconnaissance basis, geophysical methods (magnetic, gravity and gamma-ray spectrometry) play a vital role (Elkahteb and Abdellatif, 2018). This study employs magnetic and gamma-ray spectrometry methods using airborne magnetic and gamma-ray spectrometric dataset to evaluate lithium mineralization potential of the study area via mapping of lithology, structural features and hydrothermal alteration zones.

Magnetic method is used to investigate the subsurface geologic structures based on magnetic anomalies in the earth's magnetic field, resulting from the magnetic properties of the underlying rocks and structures. The aeromagnetic survey has been applied in mapping the magnetic anomalies in the earth's magnetic field and correlated with the surface and underground geologic structures (Anudu *et al.*, 2014).

The gamma-ray spectrometric (GRS) survey, measures the decay of unstable, naturally occurring radionuclides in rocks and soils, attributable to the naturally occurring radioactive minerals (NORMs). GRS is effective in measuring the naturally occurring radionuclides such as potassium (K), thorium (eTh), and uranium (eU) with their daughter isotopes in all crustal formations (IAEA, 2003). The naturally occurring radionuclides are effective geochemical indicators in crustal formations (Wang *et al.*, 2020) because they vary measurably and significantly with lithologies (Darnely and Ford 1989; Elawadi *et al.*, 2004). GRS has proven useful globally for mapping geological formations (lithologies and structures) (Patra *et al.*, 2016; El Qassas *et al.*, 2020), distinguishing regions of hydrothermal alteration zones for mineralization (Elkhateeb *et al.*, 2019; Mamouch *et al.*, 2022; El-sadelk, 2019), nuclear accident fallout (Unno *et al.*, 2013), location of lost radioactive sources (Bukartas *et al.*, 2019; Khan *et al.*, 2020), environmental hazards (Elsadek *et al.*, 2019; Farag *et al.*, 2020; Adabanija *et al.*, 2020; Akingboye *et al.*, 2021), geothermal fields (Hafeez *et al.*, 2019; Adewumi *et al.*, 2021), and hydrocarbon potential zones (Saunders *et al.*, 1993; Al-Alfy *et al.*, 2013; Walker *et al.*, 2018; Adewumi *et al.*, 2021). Compared to other geophysical methods, GRS has proven useful and helpful in mapping surface geology (Darnley *et al.*, 1989). Also, it has been found useful in identifying structures that may be difficult to delineate using other geophysical methods (gravity and magnetic) Elkahteb and Abdellatif, 2018). The successes and significance of GRS methods result from the unique signatures that are produced by the mineralization zones, which distinguish them from the host rocks.

Hence, the current study attempts to explore and evaluate the lithium mineralization potentials of the study area by analysing airborne magnetic and GRS dataset, such as derivative maps (FVD and THD), analytic signal map, ratio maps (K/eTh and eTh/K), F-parameters ($F = K \cdot eU / eTh$), and thorium normalization techniques (KD%), to map the lithologies, structures, and hydrothermal alteration zones.

Statement and economic important of the study

In the advancement of new technology producing chargeable electronics and mobile machines, using battery as source of powering electronics and mobile machines. Lithium mineral is used as raw material in producing lithium batteries. The world technology is focusing on mining and beneficiation of lithium to be used as source of energy in powering electronics. This study revealed the unknown existing lithium ore deposits identified by unofficial artisanal miners and new potential areas of lithium ore deposits. Commercial quantity of lithium ore deposits was identified through hydrothermally altered structures. Undoubtedly, this study will add value and improve the economy Nigeria. Further, the study will yield a better result that will serve as template for lithium mining program.

Location and geology settings of the study area

The research area covers the northern part of Bida basin and the surrounding basement rocks bounded by longitude 5° 00' E - 7° 00' E and latitude 9° 00' N - 10° 30' N. The study area is accessible through Abuja, the Federal Capital Territory (FCT), via Minna – Kontogora. The study area, fall within the central part of the Northwestern Nigeria (Fig. 1). Further, the study area can be viewed in terms of two principal lithologic units, the oldest unit consist of Precambrian Basement rocks in the northeastern, southeastern, and northwestern parts of the study area and the second unit consist of Cretaceous to recent sedimentary formation of Bida basin which overlies the Precambrian basement unconformable in the southwestern part of the study area (Fig. 2). The Cretaceous sediments were dipping to the southwest reaching a thickness of 1.72 km to 3.24 km (Udensi and Osazuwa, 2002; Maigwara and Udensi, 2014; Usman *et al.*, 2018; Dzukogi *et al.*, 2020). The Cretaceous to recent sediment of the study area consist of Sakpe iron stone formation, Enagi silt stone, Batati iron stone and Bida formation.

According to Wright *et al.* (1985), the geology of northwest Nigeria is distinguished by mild deformation and metamorphism of sediments, and volcanics that correspond to the Tarkwaian rocks of the West African Craton (WAC). The lithology consists of conglomerates, sandstones, and siltstones, as well as acid volcanics and intrusives. However, the conglomerates contain fragments of phyllite, boulders of quartzite, and blocks of granite (Wright *et al.*, 1985). Eduvie *et al.*, (2011) acknowledged that the rocks in part of the northwestern (Gwashi and Bukkuyum) area within the schist belt consist basically of quartz grains and a few feldspars, with all the minerals showing alteration. The field research report reveals that lithium and gold in placers and primary veins of pegmatite, quartzites, phyllite, and schists are pronounced in the northwestern part of Nigeria (Obaje, 2009; Dzukogi *et al.*, 2022). The lithium and gold mineralisation in the pegmatite and schist belt (Anka) were structurally controlled, and the gold migration and deposition mechanisms are related to regional metamorphic processes (Garba, 2000). The delineation of quartz from the field research indicates phyllic alteration (Abubakar *et al.*, 2019). The hydrothermal alteration resulting from the migration of deep-occurring hydrothermal

mineralized fluids or metasomatism are aided by the permeability of rocks (Heasler *et al.*, 2009). The geologic structures within the crust serve as a conduit for the mineralized fluids that are composed of silica, water, sulphide and chlorine compounds, carbonates, and ions of potassium, sodium, calcium, magnesium, lithium, and iron (Almasi *et al.*, 2014) to precipitate and localise precious metals such as gold.

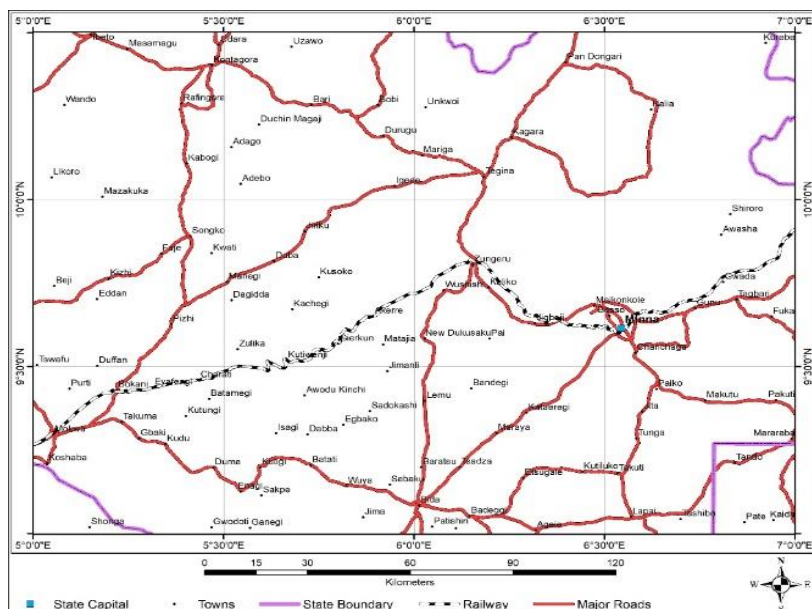


Fig. 1 Location map of the study area

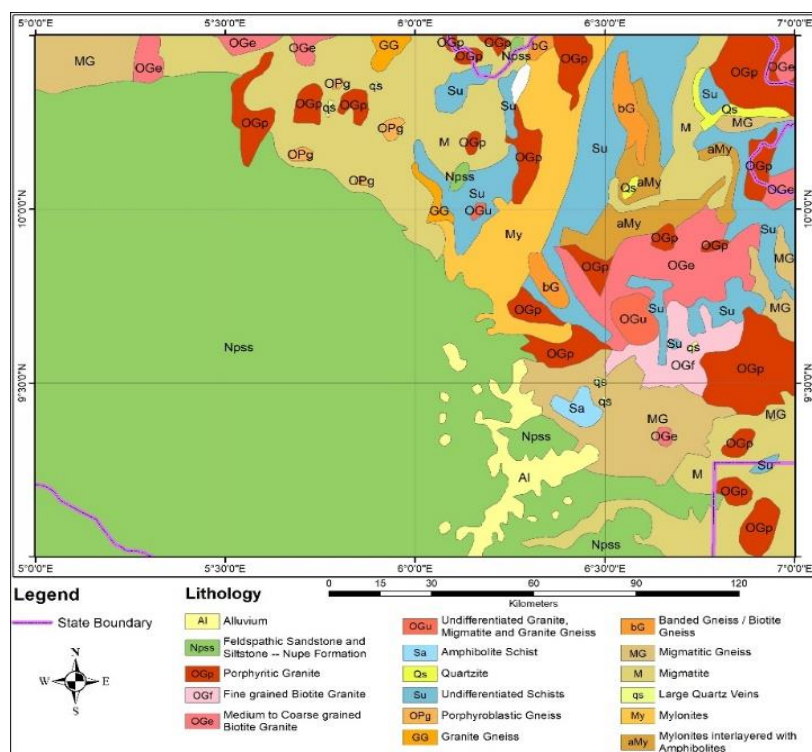


Fig. 2 Geologic map of the study area extracted from the Nigerian geological map

Methodology

Airborne magnetic and gamma-ray spectrometric (GRS) data

The airborne magnetic and gamma-ray spectrometric dataset used in this study was acquired from the Nigerian Geological Survey Agency (NGSA). The datasets, which were available in $1/2^\circ$ by $1/2^\circ$ (55×55 sq.km) grid format, were collected as part of a national airborne survey conducted for the NGSA by Fugro Airborne Survey between 2005 and 2009. The magnetic datasets were collected using a 3X Scintrex CS3 Cesium Vapour Magnetometer using acquisition parameters including an acquisition. The data were collected at an interval of 0.1 sec at an altitude of 100 m along a flight line spacing of 500 m along NW - SE, a sensor mean terrain clearance of 80 m, a tie line spacing of 2 km, and a flight line trend of 125 degrees. For a half-degree sheet, the maps were created on a scale of 1:100,000. Using the International Geomagnetic Reference Field (IGRF) of 2005, the geomagnetic gradient was eliminated from the aeromagnetic data. Since crystallization of the mineralized molten magma from the upper mantle are structurally control (Tawey *et al.*, 20221; Dzukogi *et al.*, 2022). The magnetic data were analyzed to map the subtle geologic structures and delineate regions of possible mineralized zones to indicate probable ore deposits within the study area using a first vertical derivative, total horizontal derivative and analytic signal methods.

A high-sensitivity 256-channel airborne gamma-ray spectrometer system was used for gamma-ray measurements. The flight parameters are as follows: 500-meter flight line spacing, 80 m terrain clearance, NW-SE flight lines, 2 km tie line spacing, and NE-SW tie lines direction. The GRS data was corrected for background radiation resulting from cosmic rays, variations caused by changes in the aircraft altitude relative to the ground and Compton-scattered gamma-rays in potassium and uranium energy windows. The collected airborne GRS data are potassium (K), equivalent thorium (eTh) and equivalent uranium (eU) maps. Each map shows the noticeable surface distribution of these radioelements. The GRS data were analyzed to delineate regions of hydrothermal alteration zones to indicate probable lithium deposits within the study area using a K/eTh ratio map developed by Ostrovskiy (1975) since an increase in K and a decrease in eTh is a pointer for altered zones in various ore deposits. And also, thorium normalization techniques (TNT) (KD%) to distinguish regions of probable lithium deposits within the study area.

Structures mapping from magnetic datasets

First vertical derivative

The first vertical derivative method was applied on the residual magnetic anomalies to enhance shallow and sharpen the edges of anomalies caused by the shallow geologic structures (Gleason *et al.*, 1996). The first vertical derivative filter is more responsive to short wavelength anomalies than long wave length anomalies. Hence the FVD map gives sharper image than the residual magnetic field map. The FVD filter is expressed as (Gleason *et al.*, 1996)

$$FVD = \frac{\partial T}{\partial z} \quad (1)$$

Where, T is the potential field anomaly.

Computing FVD values involves fast Fourier transformation (FFT) of the residual magnetic field intensity values into frequency domain, using FFT method. The fast Fourier transformed data were then multiplied with a first vertical derivative filter (K^n) (Blakely, 1995), where k is the wave number in the frequency domain, and n is the order of the filter which is unity for FVD (Blakely, 1995). The product obtained is transformed back to the space domain to obtain the FVD values.

Total Horizontal Derivative (THD)

The total horizontal derivative (THD) is often applied in locating the edges of the magnetic bodies (Phillips, 1998). This method was used to detect shallow and deep seated anomalies caused by the geologic structures in the study area and can be mathematically expressed as (Cordell and Grauch, 1985).

$$THD = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2} \quad (2)$$

Where T is the potential field anomaly

Computing THD values involves FFT of the residual magnetic field values into frequency domain, using (FFT) method. The fast Fourier transformed data are then multiplied with the THD filter (equation 2) in the frequency domain. The product obtained is transformed back to the space domain to obtain the THD values (Blakely, 1995).

Radioelements ratio maps

The radioelements ratio map (K/eTh) help in delineating alteration zones (Duval, 1983). The three radioelements (K-eTh-eU) in a red-green-blue (RGB) colour model, K for red, eTh for green and eU for blue was produced. This ternary map characterised the typical radiometric response in the ratios of the three radioelements, which was also used to map the lithological units. The ratio maps and the composite image were used to recognise and interpret the radiometric signatures associated with the rocks essential to lithium-bearing mineralization, lithological units, and identification of hydrothermal (such as potassic, phyllic and propylitic) alteration zones within the study area.

Thorium Normalization Techniques (TNT)

The TNT uses eTh values as a lithological control to get the eU and K ideal values (El-sadek, 2019). This technique was established by Saunders *et al.* (1987) and was first used for the delineation of hydrothermal regions in Grixias-Guarinos. Thereafter, several authors such as Adewumi *et al.* (2021), Ghoneim *et al.* (2022), Mamouch *et al.* (2022) and El-Sadek (2017) have also employed this technique for hydrocarbon and mineral prospecting. The concept of this technique arises from the fact that lithology and environment contribute to the concentration and distribution of the naturally occurring radioelements (K, eTh and eU) on

the earth surface (Saunders *et al.*, 1987 and Pires, 1995). As a result, it is stated that data normalization for eTh would suppress the original effects of all undesired variables. Thorium (eTh) is used as a normalizer because of its less geochemical mobility compared to K and eU (Saunders *et al.*, 1987). The TNT is based on the following relation:

$$K_i = \left(\frac{meanK_s}{meanTh_s} \right) * eTh_s \quad (3)$$

Where K_i is the estimated equivalent thorium defined potassium value for the station with a real equivalent thorium value of eTh_s . Variation of the real values from the estimated ideal values for each station were obtained using equation of form (Saunders *et al.*, 1993):

$$KD\% = \frac{(K_s - K_i)}{K_i} \quad (4)$$

Where K_s is the measured value at the station, and $KD\%$ is the relative deviations expressed as a fraction of the station value.

Results

First vertical derivative map of the area

Figure 3 shows the first vertical derivative (FVD) map of the area obtained using the residual magnetic intensity data of the area. The intensity of the FVD anomalies range from -0.1113 nT/m to 0.0632 nT/m. Regions with positive FVD anomalies, depicted in pink and red colours, observed in the southeastern, central, northwestern and northeastern parts, reflects the presence of subtle geologic structures hosting ore deposits (Ekwueme and Matheis, 1995; Okunlola, 2008).

Total horizontal derivative of the area

The THD (Fig. 4) shows the total horizontal derivative (THD) map of the area. The intensity of the THD anomalies range from 0.0027 nT/m to 0.383 nT/m. Regions with high intensity THD anomalies, depicted in pink and red colours, were predominant in the southeastern, central, northwestern and northeastern parts and corresponds with the basement exposed region in the area. These regions highlight the mineralized zones containing geologic structures hosting ore deposits. Regions with low intensity THD anomalies shown in green and blue colours in the southwestern part, highlights subtle sedimentary rocks. The pockets of high intensity THD anomalies in the southwestern, part reflect the effects of lateritic iron stone and ferruginous sand stone and sit stone. (Usman *et al.*, 2018).

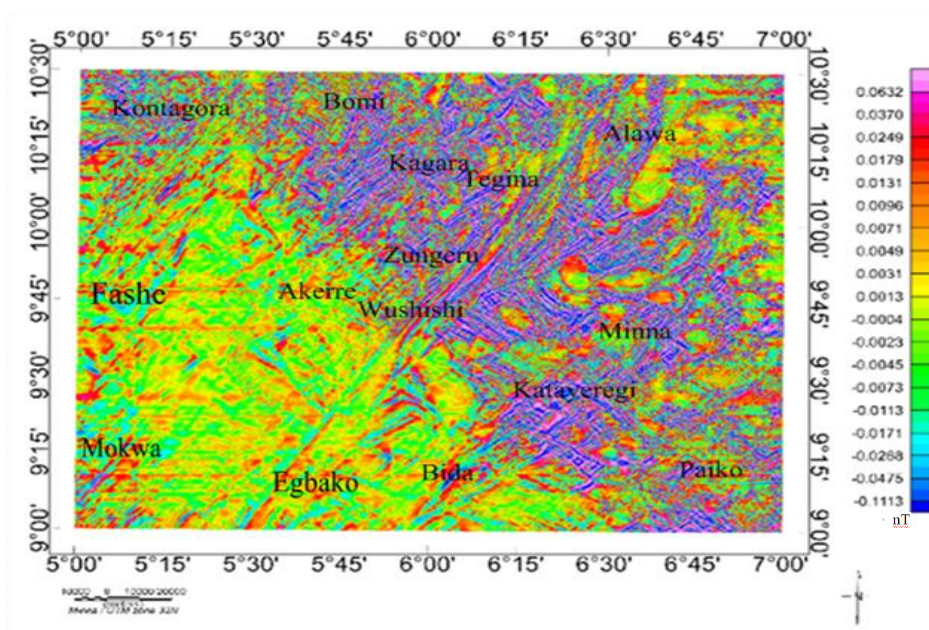


Figure 3: First vertical derivative magnetic anomalies of the study area

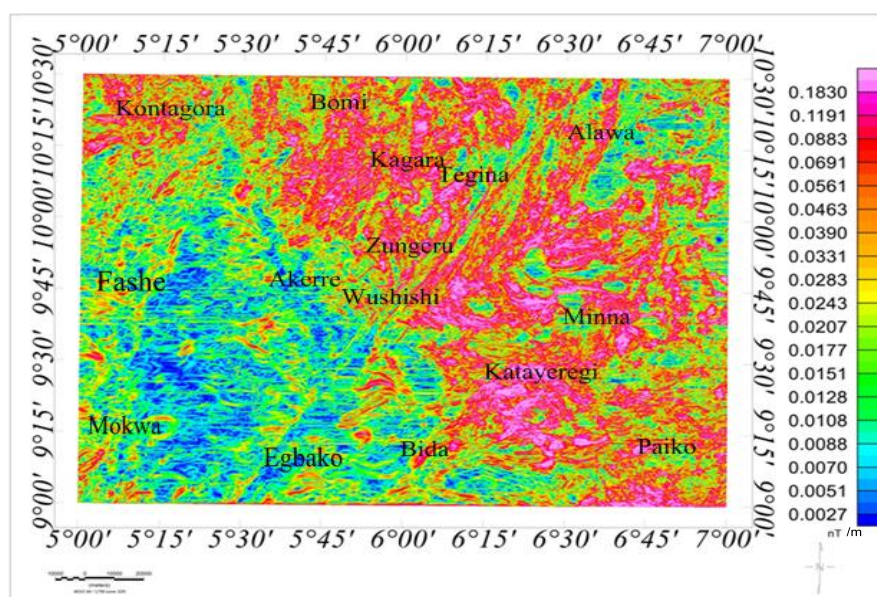


Figure 4: Total horizontal derivative magnetic anomalies of the study area

Analytic signal map

The analytic signal amplitude (ASA) map of the study area (Fig. 5) was obtained from residual magnetic field data. The ASA map shows that the susceptibility contrast of the subtle crustal rocks and structures vary from 0.0022 nT/m to 0.1472 nT/m. Regions of high amplitude ASA anomalies, depicted in pink and red colours, were observed in the southeastern, central, northwestern and northeastern parts of the area, and corresponds with regions of exposed basement rocks associated with high susceptibility contrast. These

regions were interpreted as mineralized zones containing substantial amount of mineral deposits (Tawwey *et al.*, 2020). Similarly, regions of low amplitude ASA anomalies depicted in green and blue colours, observed in the W, SW and S parts, corresponds with sedimentary regions associated with extremely low susceptibility contrast (Okunlola, 2008). However, the low susceptibility contrast in the southeastern, northwestern and central parts reflect the presence of amphibolite schist in the study area.

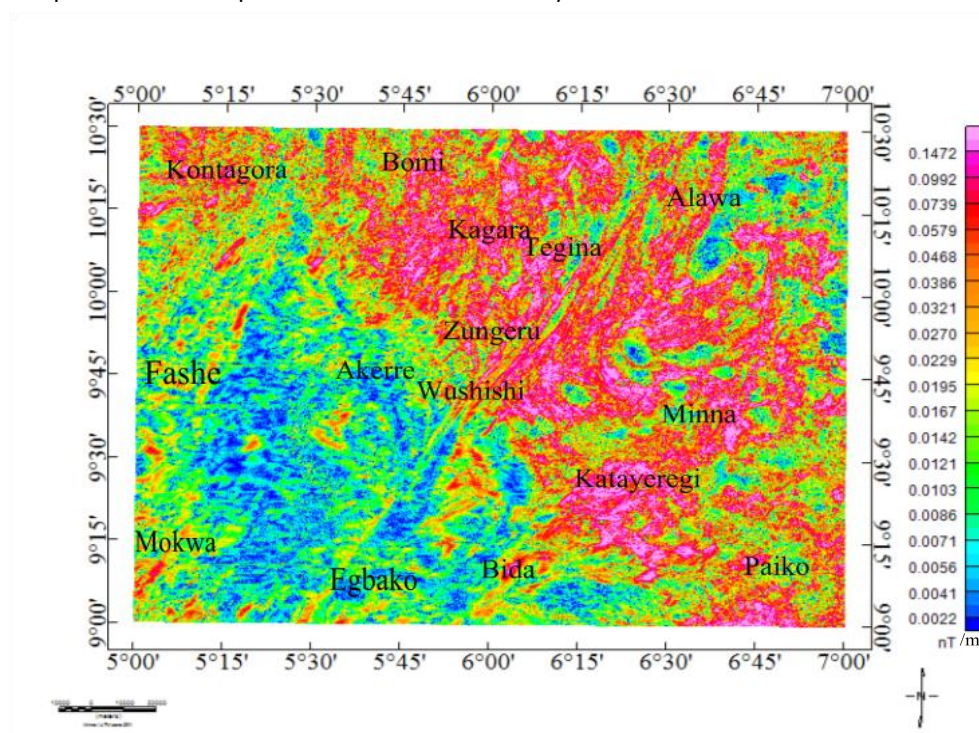


Figure 5: Analytic signal amplitude map of the study area

Structures

Subtle geologic structures are considered very important in exploration as they serve as host to minerals and hydrocarbons (Telford *et al.*, 1990; Dzukogi *et al.*, 2022). The outline of the maxima of the FVD anomalies with amplitudes greater than 0.0179 nT/m were reflected as lineaments on the FVD map (Fig. 3). Similarly, the maxima of THD anomalies with magnitudes greater than 0.0561 nT/m were reflected as lineaments (mineralized veins) on the THD map (Fig. 4). The magnetic peaks (lineaments) were automatically extracted using center for exploration targeting (CET) analysis (Figs. 6 and 7).

Further, the spatial distribution of the inferred lineaments from FVD and THD maps, as highlighted by the structural lineament maps (Figs 6 and 7), commonly shows high density of lineaments in the southeastern, northern, central, northeastern parts and low density of lineaments in the northwestern and southwestern parts, highlighting the occurrence of shallow and deep-seated geologic structures in the study area. Some of these high density lineaments in the southeastern, northern, central, and northeastern parts around Zungeru, Tegna, Kagara, Alawa, and between Katayeregi, and Paiko (Fig. 6 and 7), were observed

along the NE – SW and N – S directions suggesting that the lineaments are Pan-African, and are interpreted as the structural controls to the lithium ore and other related mineral deposits, hither to identify by un-official artisanal miners in the area (Obaje, 2009). Further, the Southwestern and Northwestern parts were characterized with low lineament density. The high density lineaments in the northeast and southeastern parts of the study area, suggest that the exposed basement rocks in the regions were highly deformed perhaps as a result of effects of Pan- African stress regime.

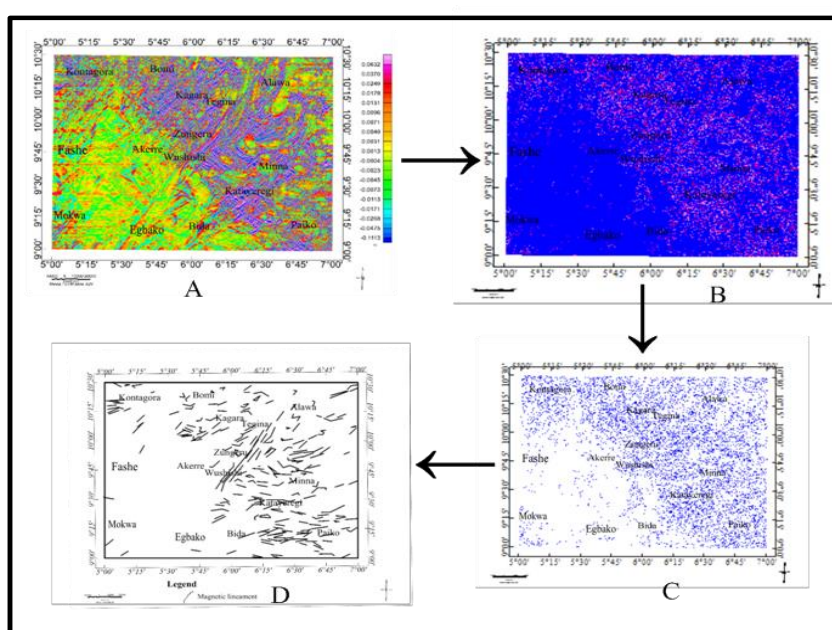


Figure 6: Brief stages among CET analysis. A. FVD grid, B. Phase congruency, C. amplitude threshold and D FVD structural lineament map

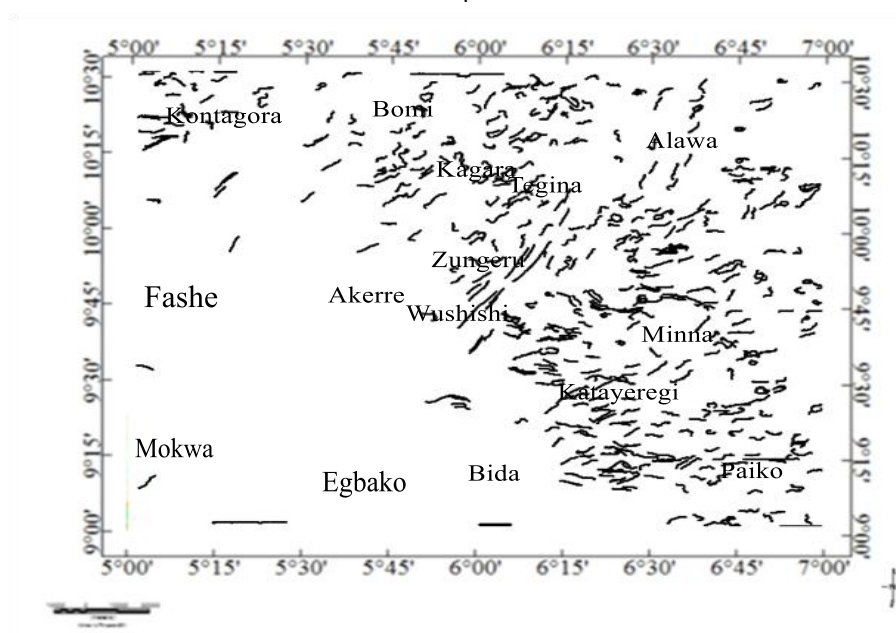
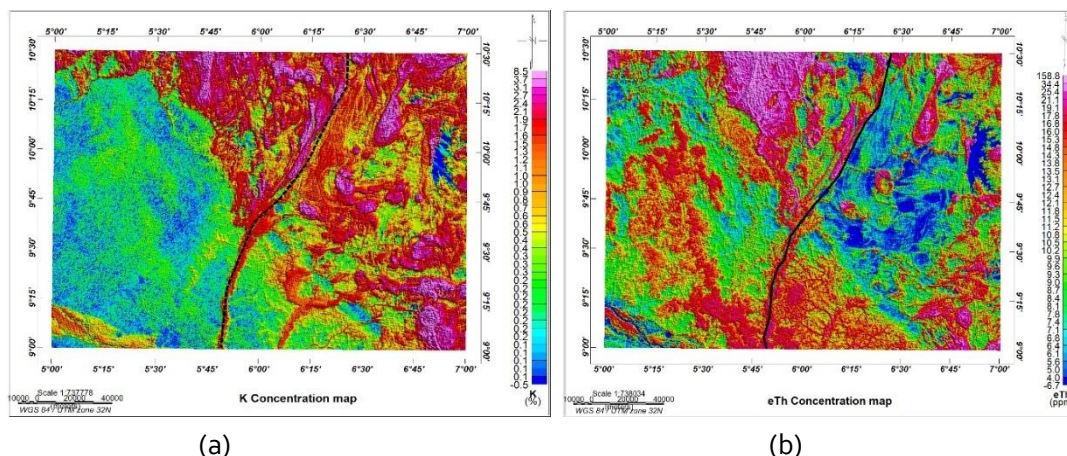


Figure 7: Horizontal derivative magnetic structures from CET analysis

Radioelements concentration and the total count maps of the study area

Figures 8a-d represent the concentration maps of potassium (K), equivalent thorium (eTh), equivalent uranium (eU) and total count (TC) of the study area, respectively. The K, eTh, eU and TC revealed and characterized the hydrothermal litho-structural features and geochemical alteration zones arising from the GRS signatures of the rocks. The maps (Figs. 8a-d) illustrate varying colours, with pink suggesting high concentration, green suggesting moderate concentration, and blue representing low concentration. Figure 8a shows varying degree of K concentrations ranging from 0.5 to 8.5 %, these reflect different lithological units and alterations in the study area. The lower northwestern, western and down to southwestern parts are characterized by low K concentrations ranging from 0.083 to 0.406%, which could reflect the Nupe formation composed of Feldspathic sandstone and siltstone. Also, the southeastern, northeastern, central, and upper northwestern regions of the study area, are characterized by moderate to high K concentration ranging from 0.3 – 1.2% and 1.5 – 8.5% respectively. Likewise, the eTh concentration (Fig. 8b) in the study area is grouped as high concentration (HC) ranging from 13.5 – 158.8 ppm, moderate concentration (MC) ranging from 8.1 – 12.1 ppm, and low concentration (LC) ranging from 4.0 – 7.8 ppm. The HC of eTh, marked by red to pink colorations, are observed in the northern, extreme southwestern, southern, northeastern and west central parts of the study area (Fig. 8b). The Pan African older granitoids (Granite and Granite porphyry, undifferentiated schist including phyllites, Granite gneiss, and migmatite) in the study area are attributed to high concentrations of K and eTh (Dickson and Scott, 1997). The regions of high eTh concentration are sparsely distributed in the study area with low to very low concentration at the southeast and eastern parts.. Also, Figure 8c displays the eU concentration map, showing radiometric signatures with total eU concentrations varying between 0.5 – 26.4 ppm. The map (Fig. 8c) can be grouped as high, moderate, and low concentrations (HC, MC and LC) range from 3.3 – 26.4 ppm, MC ranging from 2.1 – 3.0 ppm and LC ranging from 0.5 – 1.9 ppm. The total count map (TC) (Fig. 8d) has high, moderate, and low values ranging from 7.4 – 64.9 $\mu\text{R}h^{-1}$, 5.1 – 7.0 $\mu\text{R}h^{-1}$, and -2.4–4.9 $\mu\text{R}h^{-1}$, respectively.



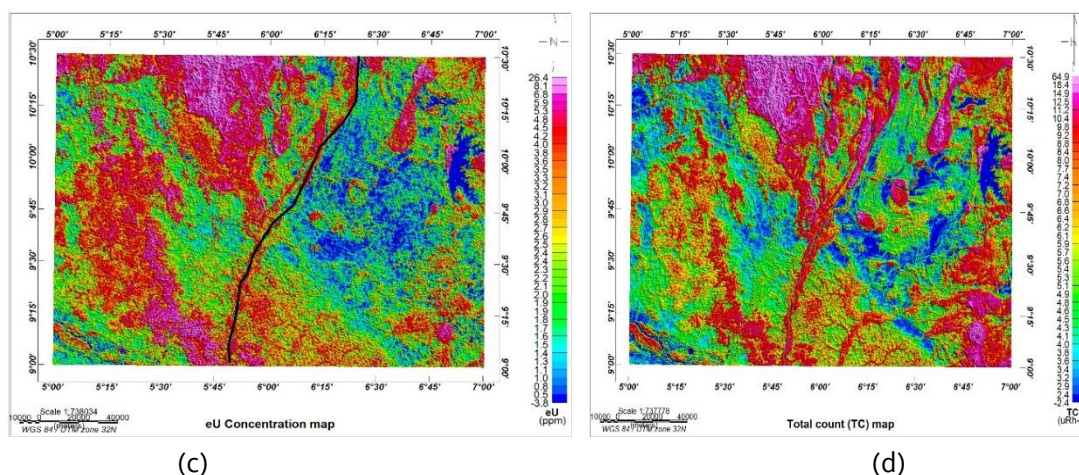


Fig. 8 (a) K concentration map, (b) eTh concentration map, (c) eU concentration map, and (d) TC map of the study area

Discussion

The study area is made up of two major lithologies: the sedimentary part known as the Nupe Formation (feldspathic sandstone and siltstone) occupying the southwestern, western and northwestern parts of the study area, and the crystalline rocks occupying the northeast, eastern and southeastern, regions of the study area. The crystalline rocks in the study area include Porphyritic granite (oGp), fine grain biotite (OGf), Granite gneiss (GG), Mlyonites (My), Quartz vein (qs), Amphibolite Schist (Sa), Undifferentiated schist (Su), Quarzite (Qs), Migmatic gneiss (MG), Migmatite (M), Biotite gneiss (bG), Porphyroblastic gneiss (OPg), Undifferentiated granite, migmatite and granite gneiss (OG), medium to coarse-grained biotite granite (OGe), and Mylonites interlayered with amphibolites (aMy). There are also traces of Alluvium deposits in the southeastern part of the study area. The HC of K reflects the crystalline rocks (Porphyritic granite (oGp), fine grain biotite (OGf), Granite gneiss (GG), Mlyonites (My), Quartz vein (qs), Amphibolite Schist (Sa), Undifferentiated schist (Su), Quarzite (Qs), Migmatic gneiss (MG), Migmatite (M), Biotite gneiss (bG)) in the study area (Fig. 2). Rock types are identified and characterized by their average potassium concentration (Dickson and Scott, 1997). An elongated potassium alteration (anomaly) interpreted as a mineralization zone was observed around longitude $5^{\circ} 45''$ and latitude $9^{\circ} 00''$ and correspond with FVD and THD anomalies (Figs. 3 and 4). This anomaly was Pan Africa trending SW – NE or NE – SW which could reflect the effect of Ifewara – Zungeru fault, which is also an inward reflection of St. Paul's fracture/fault from the Atlantic Ocean passing through Nigeria. Noticeably, the regions with LC of eTh corresponding to high K concentration (Fig. 8a) regions, specifically at the southeast and eastern parts, could be attributed to the characteristic immobile nature of eTh during magmatism and alteration processes, have very little or no effect on the eTh concentration of radioelements (Mam *et al.*, 2021). The Ifewara – Zungeru fault, suggested to host mineral deposit, was also observed in the eTh concentration map (Fig. 8b). The pockets of HC (Fig. 8c) observed in the southwestern to the western part of the study area can be attributable

to feldspathic sandstone and siltstone in the Nupe formation. On the other hand, the LC to MC in the eastern can be attributable to porphyritic granite and other crystalline rocks. Also, the HC observed in the northern part might be attributable to quartzite and other crystalline rock in the study area. The erratic nature of the eU map (Fig. 8c) reveals that it's reactive and capable of migrating into the surroundings as a result of weathering and fluid pathways.

Lithium mineralization potential of the study area

Radioelement ratios, and Thorium normalization maps

The GRS datasets were analysed by producing the radioelement ratios and thorium normalization maps to intensify the interpretations of the spatial distributions and variabilities of the radioelements for probable lithium mineral deposits in the study area. These yield a better understanding of the litho-structural characteristics and hydrothermal alteration processes that support lithium and other economic mineral exploration within the study area. The radioelement ratios reveal the abundance determination of the radioelements relative to one another. The potassium thorium ratio map (K/eTh) (Fig. 9a) revealed the abundance of eTh concentration within the study area relative to K, revealing the geochemical alteration zones that favoured lithium mineralization in the study area. This is a result of the high mobility of K compared to eTh. The K/eTh ratio anomalies can be grouped into regions of hydrothermal alterations, which are characterized by K enrichment. The K/eTh value ranges from 0.0–5.2 %/ppm. Studies have shown that hydrothermal alteration occurs in different rocks with K/eTh ratio ranging from 0.17 to 0.2 %ppm; rocks within this range are considered unaltered rocks and above this range are considered altered rocks and promising for mineralization resulting from metamorphism and crystallization process. High K/eTh ratio values of 0.2 – 5.2 %/ppm observed in the study area's southeastern, eastern, northern and northeastern parts corresponds with the structural density, delineated from FVD and THD structures and were identified as prominent regions (PR) on the maps. These identify the hydrothermal alteration zones, a strong indicator of potential lithium deposits in the study area. Hydrothermal alteration zone plays a vital role in the localization of lithium mineralization as they serve as a source for the formation of gemstones and other mineral deposits (Fig. 9a).

Further, Figure 9b (eU/K) shows values ranging from 0.2–39.3 ppm/%, showing the depletion of eU relative to K and the relocation and redistribution of eU from the host rocks to the surrounding. The fractures/lineaments are mostly found in the crystalline rocks (Dzukogi *et al.*, 2022), commonly saturated by minerals and hence decreases the sorption capacity of the overlying rocks for mobile radioelements eU and K (Matolín and Stráník, 2006). The high eU/K in the southwest and western parts indicate the radiation effects from feldspathic sandstone and siltstone in the Nupe formation. Delineated on all the radioelement ratio maps is the SW – NE or NE – SW Pan African trending which could reflect the effect of the Ifewara – Zungeru fault, which is also an inward reflection of St. Paul's fracture/fault from the Atlantic Ocean passing through Nigeria and agree with the structure

delineated from FVD and THD anomalies.

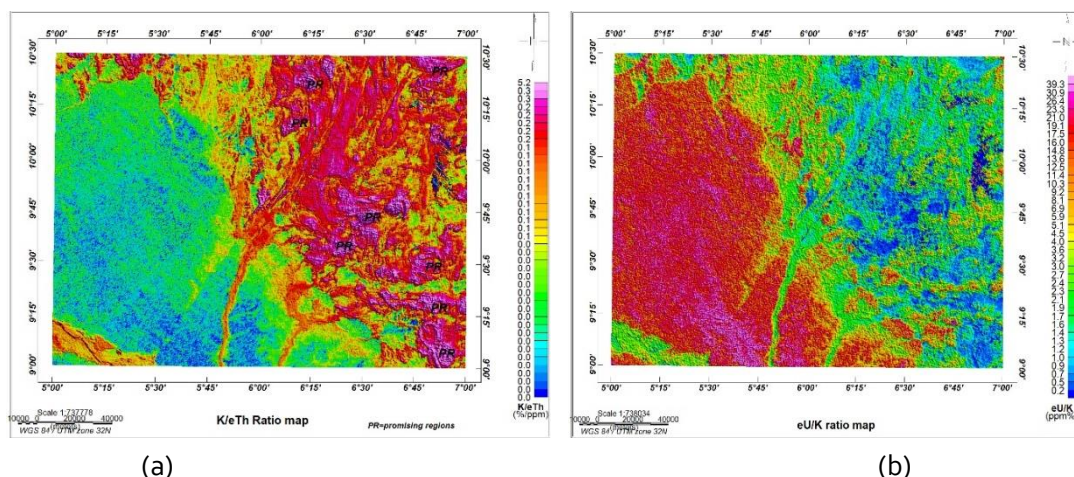


Fig. 9 Radioelement ratio maps of; (a) K/eTh and (b) eU/K,

The KD% map (Fig. 10) is characterized by values ranging from -0.9 to 3.3 %. The regions with more positive values, depicted with pink, in the northeastern, eastern and southeastern parts of the study area are good locations of lithium, gold and other mineral deposits in the region of the study area. The KD% map shares a similar feature with the K/eTh ratio map (Fig. 9a). They show similar regions of hydrothermal alteration in the study area, which is an indicator of pegmatite vein containing lithium, limonitic quartz vein containing gold and other mineral deposits. The regions with negative values are associated with sedimentary rock containing ferruginous sand stone, and feldspertic minerals, corresponding to Nupe formation.

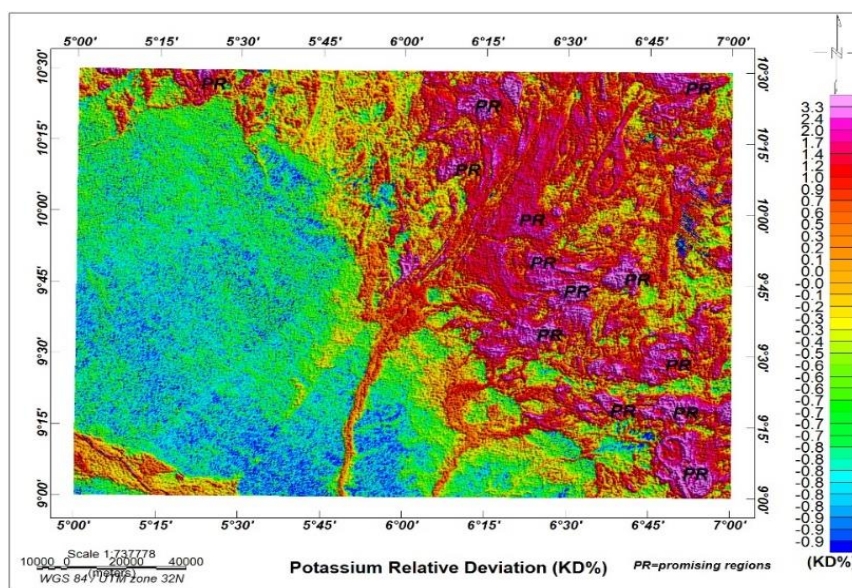


Fig. 10 Potassium relative deviation map (KD%) delineating lithium and gold occurrence prominent region (PR) in the study area

Conclusion

The airborne magnetic and gamma-ray spectrometric datasets of parts of the northwestern part of Nigeria have been analysed and interpreted with the aim of mapping potential lithium mineral deposits and other minerals in the study area. The analyses and interpretation involve first vertical derivative (FVD), total horizontal derivative (THD), analytic signal amplitude (ASA), radioelement ratios and KD% maps. The FVD, THD, ASA anomaly peaks were delineated as mineralised geologic structures. Further, the prominent region (PR) on the (KD% and K/eTh maps were the hydrothermal alteration zones (hydrothermal alternated structures), which are also strong indicators of pegmatite veins containing lithium deposits in the study area. The KD% and K/eTh, maps highlight the hydrothermally altered zones resulting from enriched K in the northeastern, mid-eastern, central, and southeastern parts of the study area. These delineated hydrothermally altered zones with high values of KD% and K/eTh, can be further investigated to exploit lithium minerals and percentage concentration of lithium mineral in the study area.

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