Journal of Science Research and Reviews
PRINT ISSN: 1595-9074
E-ISSN: 1595-8329
DOI: https://doi.org/10.70882/josrar.2026.v3i5.246
Homepage: https://josrar.esrgngr.org
Original Research Article

Integrated Airborne Magnetic and Gamma-Ray Spectrometric Analysis for Mineral Prospectivity in Pategi, North Central Nigeria

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KEYWORDS
Aeromagnetic,
Aero-radiometric,
Hydrothermal alteration,
Radioelements.

ABSTRACT
Mineralisation assessment within southern parts of Bida basin was carried out employing the analyses of airborne magnetic and radiometric data set. The concept of harmonising geological structures and hydrothermal alterations as dual evidence of inferred mineralisation was put together via detailed data enhancement, qualitative and quantitative interpretations. The total magnetic intensity map (TMI) revealed the distribution of magnetic signatures across the study area. First vertical derivative (FVD), Analytic Signal (AS) and CET analyses were used to delineate underlying geologic structures associated with ore deposits. Main structures inferred as faults, fractures and contacts were mapped trending in the NE – SW directions. Anomalous concentrations of radioactive elements (K, eTh and eU) up to 4.60 %, 54.29 ppm and 10.90 ppm, exceeding crustal average of 2.5 %, 12.0 ppm and 3.0 ppm respectively were mapped across study regions. The variation of eTh and eU against potassium as a trade-off for potassium enrichment was used to delineate regions of hydrothermal alterations. Potassium_thorium ratio (K/eTh), Potassium deviation (K_D) and F_parameter were analysed and interpreted collectively with their high occurrences indicating rock alterations. The regions of hydrothermal alterations corresponding to outlined major structures were designated as zones of potential mineralisation. The mapped areas include: Bankole, Aiyetoro, Babanla, Ndeji on the NW regions, below Ekati, Matokun and danikun, Esanlu-Esa at the central regions and the southern regions includes Omugo, Okunran, Egbe, Eruku, Isanlu, IJagbe, Mopa, and Ogbe. The regions of interest could be focused on using concise ground geophysical methods to ascertain the implied prospect.

CITATION
Sabo, L. M., Salako, K. A., Adetona, A. A., Rafiu, A. A., & Shehu, J. (2026). Integrated Airborne Magnetic and Gamma-Ray Spectrometric Analysis for Mineral Prospectivity in Pategi, North Central Nigeria. *Journal of Science Research and Reviews*, *3*(5), 184-207. https://doi.org/10.70882/josrar.2026.v3i5.246

INTRODUCTION

In recent years, Nigeria has recognised the importance of solid mineral resources in driving economic growth and development (Obaje, 2009). The country has initiated several initiatives to promote mineral exploration and exploitation (Ejepu et al., 2018). The Nigerian government has established policies and programs aimed at attracting investment, providing incentives for exploration, and enhancing the regulatory framework (Saleh et al., 2023). Despite these efforts, the solid mineral sector still faces challenges, including limited geological data, inadequate infrastructure, and insufficient investment.

The adoption of airborne magnetic data has been widely used as an exploration tool in the subsurface mineral resource's exploitation (Shives et al., 1997; Silva et al., 2003; Boadi et al., 2013). Over the years, the improvements in the magnetic data acquisition processes have also increased its capabilities in mapping both shallow and deeper magnetic anomalies (Grauch and Milligan, 1998). The magnetic method has the ability of measuring the variation in the earth magnetic field produced due to remnant and induced magnetic magnetisation between the host rock and the mineralised bodies (Airo, 2007). The mapping of anomalies at the low magnetic latitudes which the current study area falls into, is so tedious because the magnetic field intensity produced at this region is trivial due to the horizontal ambient inducing field in contrast to those produced at higher latitudes (Beard and Goitom, 2000; Rajagopalan, 2003). The anomaly over magnetic susceptible bodies tends to be negative instead of positive and the anomaly pattern perhaps varies with the direction of the structures (Beard and Goitom, 2000).

The corresponding airborne radiometric technique in most cases compliment the finding resulting from the analysis and interpretation of magnetic data. The radiometric method measures the surficial distribution of the uranium (U), thorium (Th) and potassium (K) (Saada, 2016). The disparities that are usually observed in the activity concentration of U, Th and K has been embraced in the characterisation of lithologies and identification of the hydrothermally altered zones. For example, areas of intensive hydrothermal alteration are used in mapping volcanic hosted massive sulphides; volcanic hosted epithermal base and precious metal; granite hosted gold associated through illite alteration; schist hosted gold; metasediments hosted skarn mineralisation (Au-U -W-Mo-Co); porphyry hosted (Au-U); metasediments hosted polymetallic (Bi-Cu-Co-Au) (Jaques et al., 1997; Shives et al., 1997; El-Meliegy et al., 2000; Patra et al., 2016; Boadi et al., 2013; Elkhateeb and Abdellatif, 2018). The deformation of the source rock to form these mineralised deposits mostly have high potassium concentration (Appiah, 2015).

The vast majority of geophysical studies carried over the southern part of Bida basin mainly focused on hydrocarbon prospecting, neglecting solid mineral exploitation. To this day, the Nigeria's mineral potential zones remain underexplored and undeveloped despite the rising global demand. However, the existence of outmoded studies like geochemical and geological for mineralised deposits in parts of the present study area and Nigeria at large, have limitations in characterising subsurface structural geometries and depths extent of the mineralised structures. These outmoded exploration methods used by foregoing studies, cannot effectively provide a comprehensive insight into the complex geological structures, leading to inaccurate assessment of the mineralised zones. In this regard, the study proposes an integration of aero-geophysical methods that can characterise the subsurface structures.

Description of the Study Area

The study region is situated within north-central region of Nigeria as indicated in square (Figure 1). It is bounded by latitude 7° 30' to 8° 30' N and longitude 5° 00' to 6° 00' E covering index map sheets of Lafiagi, Pategi, Osi and Isanlu, with an estimated surface area of 12100 km^2. The study region is covered by four (4) aero-geophysical magnetic and radiometric data namely, Lafiagi, Pategi, Osi and Isanlu with corresponding sheet numbers 203, 204, 224 and 225 respectively. The study area falls within the central part of Nupe sedimentary formation. The study region is accessible by road from the west through Mokwa-Jebba highway. It can also be accessed westward via Ogbomosho-Ilorin highway. The climatic condition varies from arid–dusty, harmattan-dominated dry season starting within November to April and humid, oppressive wet season which begins mostly in May to October every year (Alfa, 2019). The vegetation of the study region is considered as open savannah (Onaolapo, 2015). The major economic activity includes farming, fishing, trading, and sporadic artisanal mining activities.

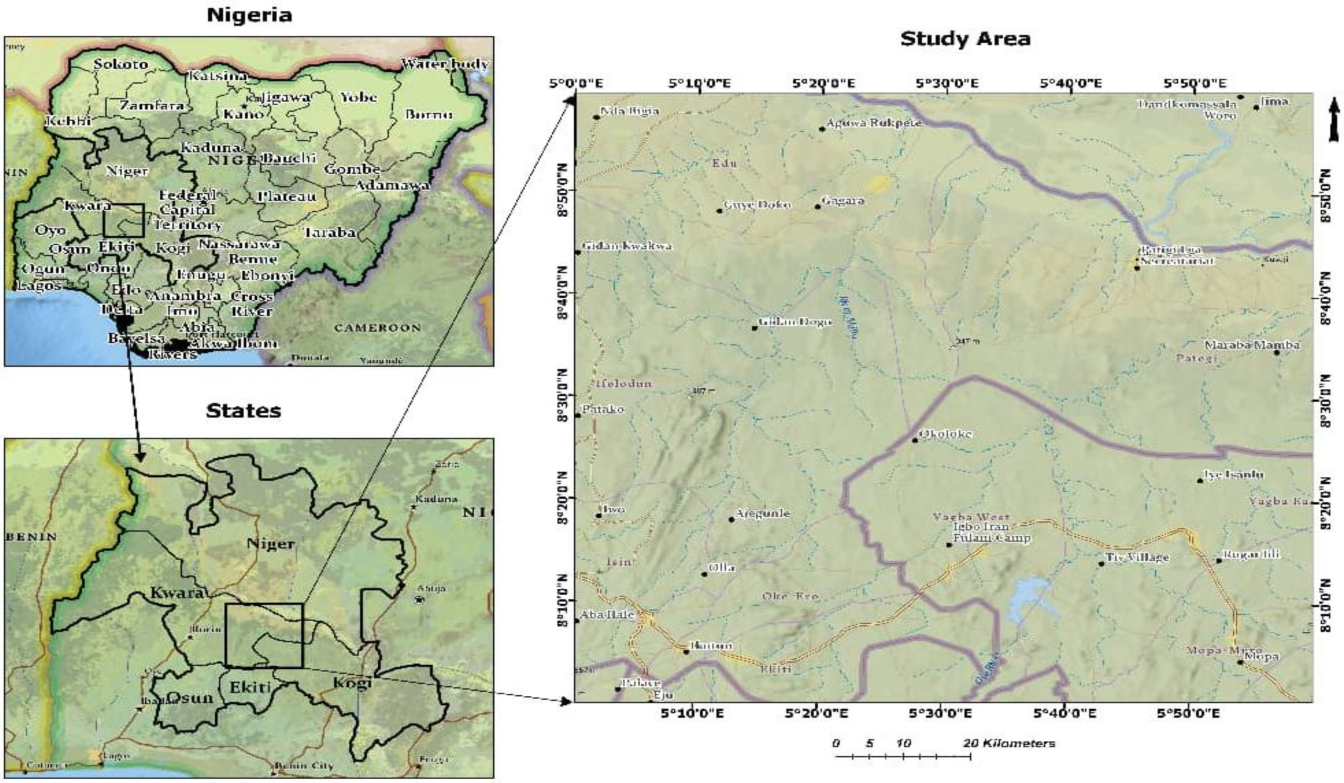

Figure 1: Location map of study area

Geology of the Study Area

The geology of study area is basically Cretaceous sediments (Obaje, 2009; Idris-Nda et al., 2018). The Cretaceous sediment of the basin is made up of conglomerates, sandstones, siltstones, mudstones, and ironstones (Obaje, 2009; Idris-Nda et al., 2018). There are four major lithostratigraphic units: the Bida Formation, Sakpe Formation, Enagi Formation and Batati Formation (Obaje, 2009).

In general, the Mid-Niger Basin also known as the Bida basin or Nupe Basin is a northwestern to southern intra-cratonic sedimentary formation stretching from Kontagora, a segment of Niger State of Nigeria to some extent outside Lokoja (Obaje, 2009). This basin is bounded along the northeast and southwest by the crystalline basement complex. It converges with Anambra and Sokoto basins in sedimentary fill encompassing post orogenic molasse facies and a few thin unfolded marine sediments (Adeleye, 1974). The basin is a slightly down warped trough whose origin could be attributed to the Santonian orogenic movements of southeastern Nigeria alongside neighboring Benue valley. The basin is a northwestern to southeastern trend embayment, perpendicular to the main axis of the Benue Trough and the Niger Delta Basin (Obaje, 2009). This basin is often termed as the northwestern stretch of the Anambra basin, both of which were major depocenters during the third major transgressive cycle of southern Nigeria in Late Cretaceous times (Obaje, 2009).

The Bida basin is generally divided into central or northern and southern sub-basins. The present study area cut across the southern part of the Bida basin. This part of the basin consists of sequence of sandstones unconformable that overlain the crystalline basement complex (Salawu et al., 2020a). The Bida sandstones range from premature (mineralogical and textural), clast to matrix supported conglomerate, which fines upward to conglomeratic-sandstones-medium grained sandstones, subordinated claystone and siltstone. There are four major lithostratigraphic units (Figure 2.1) which includes, the Bida sandstone formation, Sakpe formation, Enagi formation and Batati formation (Obaje, 2009).

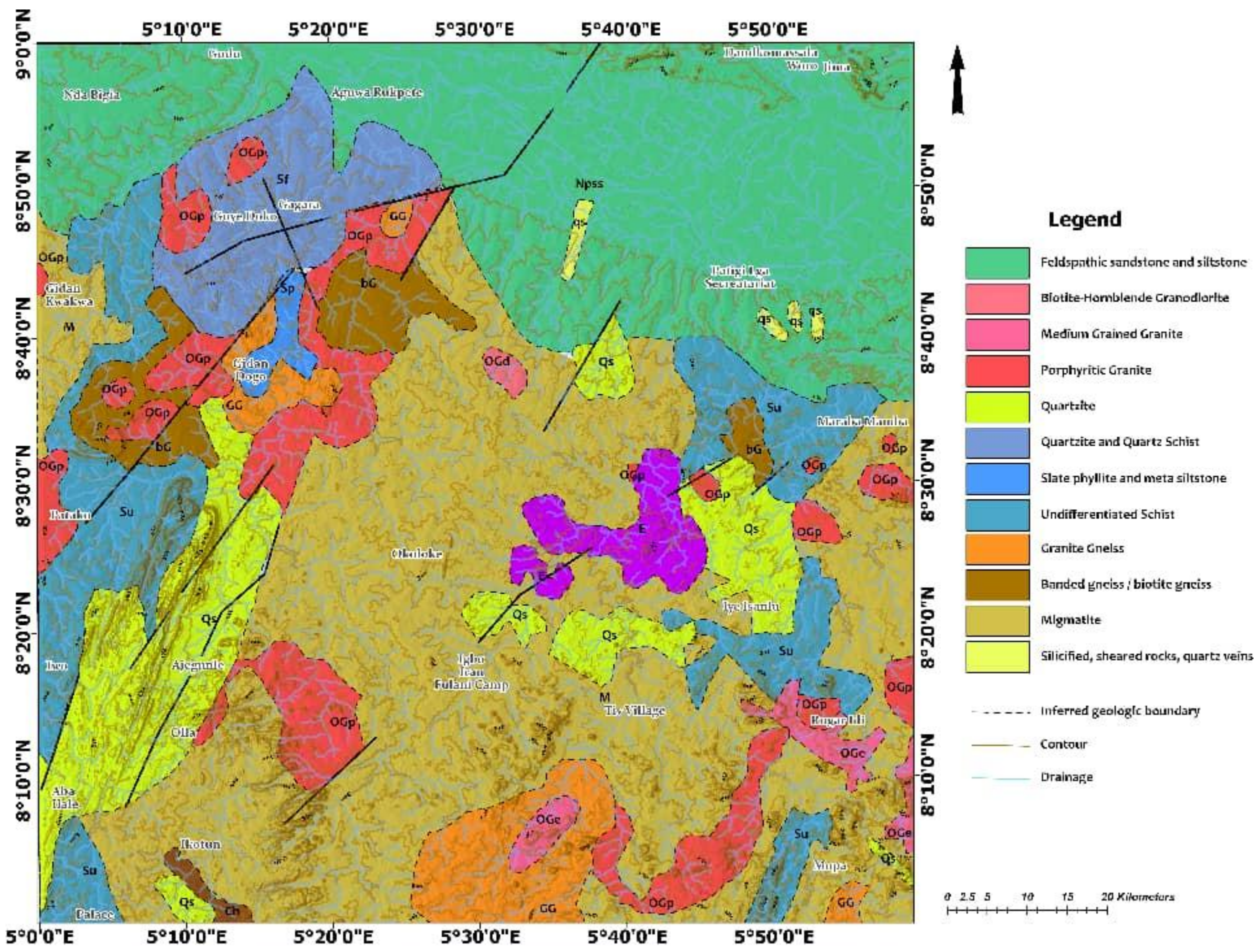

Figure 2: Geology map of study area

MATERIALS AND METHODS

Data source and specifications

The four (4) aeromagnetic and aero-radiometric data covering Lafiagi, Pategi, Osi and Isanlu were procured from the Nigerian Geological Survey Agency (NGSA). In between 2006 and 2010, Fugro airborne surveys in collaboration with the Nigeria Geological Survey Agency (NGSA) carried out magnetic and radiometric geophysical measurements covering all part of the country. The acquisition of the magnetic dataset involves the attachment of the magnetometer sensor on a fixed wing of the aircraft. The raw magnetic susceptibility values and the aircraft variations were corrected. The magnetic data were corrected for diurnal variation and the International Geomagnetic Reference Field (IGRF). The corresponding uranium, thorium and potassium data were micro-levelled.

Research Procedure

Figure 3. shows the different steps and analysis procedures for achieving the mineral prospect mapping of the study area.

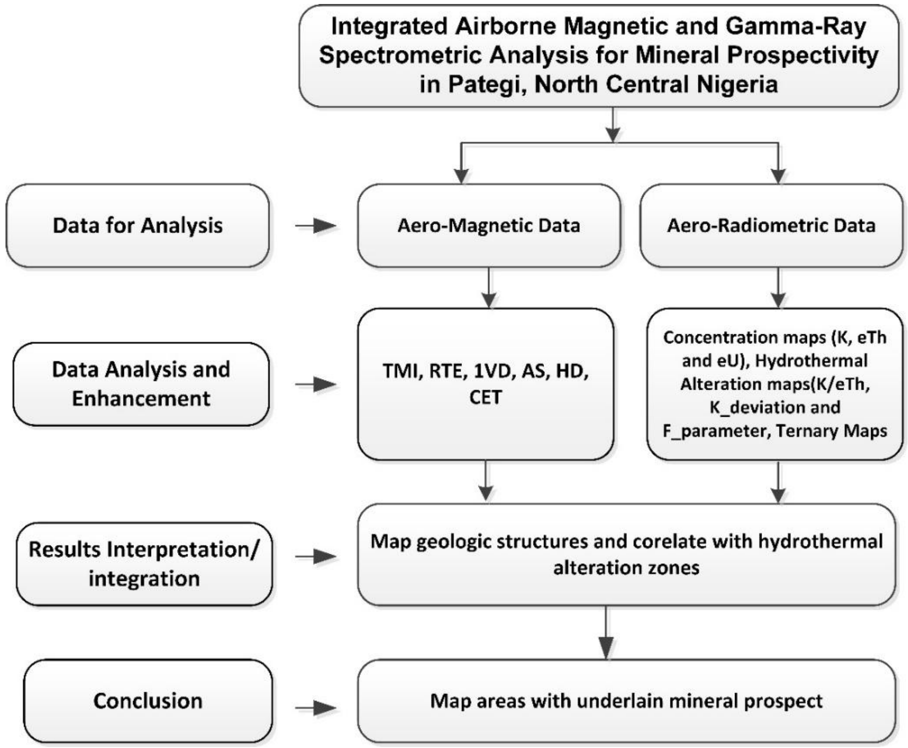

Figure 3: Block diagram of the methodology

Aeromagnetic data enhancement techniques
The total magnetic intensity (TMI) data would be subjected to several data enhancement filter techniques such as reduce to magnetic equator (RTE), regional-residual separation using the upward continuation (UC), first vertical derivative (FVD), second vertical derivative (SVD), Tilt derivative (TDR), Euler Deconvolution (ED), Horizontal gradient magnitude (HGM) and analytic signal (AS) to depict the near surface (shallow) magnetic sources. The data enhancement techniques would be subjected to the CET menu on the Oasis Montaj to generate a lineament map of the study area.

First vertical derivative (FVD)
The first vertical derivative is a high pass filter that is applied to the total magnetic field data to calculate its gradient vertically. The VDR sharpens the effect of high frequency (short wavelength) magnetic features. It is also useful for enhancing the textural variation in the data. Vertical derivatives are also known as vertical gradients is given in equation (1).

$$\mathrm{L(r)} = \mathrm{r}^{\mathrm{n}} \qquad (1)$$

Where, n is the order of differentiation.

Analytic signal (AS)
The AS method is highly useful technique for locating the edge of magnetic geologic structures. The AS filter is the amplitude of the analytic signal (AS) of magnetic anomaly which is defined according to Marwan and Yahia (2017) as the square root of the sum of the vertical and horizontal derivatives of magnetic field given in the equation (2).

$$AS = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \qquad (2)$$

3.3.3 Depth estimate through 3-dimension Euler deconvolution analysis
3-D Euler Deconvolution was applied to the anomaous magnetic intensity grid reduced to equator to estimate the depths to the sill and dyke intrusions. The Euler Deconvolution is based on the Euler homogeneity relation given in equation (3).

$$(x - x_O)\frac{\partial T}{\partial x} + (y - y_O)\frac{\partial T}{\partial y} + (z - z)\frac{\partial T}{\partial z} = N(B - T) \quad (3)$$

Where, x_o, y_o and z_o are the position or coordinate of the top magnetic source, (*x, y, z*) are the location of the field measurement, T is the total magnetic intensity (TMI) anomaly value, B is the background field, $\frac{\partial T}{\partial x}$, $\frac{\partial T}{\partial y}$ and $\frac{\partial T}{\partial z}$ are the derivative of the total field values T. N is the degree of homogeneity also referred to as structural index (SI) (Thompson, 1982). The appropriate use of SI value and window size (grid point) yields tight cluster of solutions whereas inappropriate application of SI value may produce diffuse solutions that are not reliable. However, structural index one (1.0) geological model of silk and dyke intrusions would be chosen to determine the faults with limited throw.

Delineation of Hydrothermal Alteration Zones
Areas of identified with rock alterations are key indicators of vein and disseminated mineral deposit. Hot mineral

fluids circulating within subsurface structures such as fractured, faults and sheared zones influences the chemical processes of mineralisation. Three analyses are combined in this study to map regions alteration within the study area. The potassium and equivalent thorium ratio map, the potassium deviation map and F_parameter map will provide evidence of radioelements variations associated with hydrothermal alteration.

The Potassium_Thorium ratio map (K/eTh)

This ratio is helpful for illustrating how K varies over eTh that have been shown to be geochemically immobile. The ratio highlights a crucial idea: potassium enrichment, which happens concurrently with thorium depletion and serves as a clear sign of hydrothermal changes. In accordance with researchers such as Hoover *et al*. (1992) and Portnov (1987), the values of this ratio in the range of 0.17 to above 0.2 %/ppm is an indication of rocks that have lost their stability and have undergone alteration.

Potassium Deviation

Using eTh as a lithologic control, Saunders et al. (1987), Pires (1995), and de-Quadros et al. (2003) proposed a method called potassium normalisation that determines the ideal value of K. A process that relies on the immobility of eTh is used to derive K_deviation, a measure of hydrothermal changes.

$$K_n = \left(\frac{K_{average}}{eTh_{average}}\right) * eTh \qquad (4)$$

where K_n is normalized K, K_average and eTh_averages are calculated from statistical sampling of the elements concentration values.

$$K_d = (K - K_n)/K_n \qquad (5)$$

Where K is potassium concentration, K_n is normalized potassium values and K_d is potassium deviation. The idea behind using this technique to identify areas of hydrothermal alteration is that high ranges will likely indicate potassium enrichment which is linked with elements mobility and inferentially rock alterations.

F_parameter

Efimov (1978) suggested this additional hydrothermal alteration indicator study. Two significant changes in radioelements pitched by the F_parameter are: (i) the abundance of K related to Th / U, and (ii) the abundance of U related to Th / K.

$$F = K * \left(\frac{eU}{eTh}\right) = K * \left(\frac{eTh}{eU}\right) = eU * \left(\frac{eTh}{K}\right) \qquad (6)$$

RESULTS AND DISCUSSION

Results of Magnetic Data Analysis

Total magnetic intensity (TMI) and reduced to equator map

The mapping of magnetic signatures across the study area is depicted in colours representing the range of magnetic intensities (Figure 4). Magnetic intensity ranges from -92.32 to 66.86 nT was recorded across the study area. High values are captured in red and pink colours while relatively moderate to low magnetic values are depicted in blue, green and yellow colours. High magnetic signatures are dominant on the eastern flank covering Danikun, Okofushe, Esanlu-Esa, Ofe-Ofi, Okolom, Ijagbe and mamba locations. Spares and isolated high magnetic signatures on the western flank are recorded around Babanla, Oke-ode, Aiyetoro, Ndeji, Omu-Aran and Oyedun locations. The upper northern regions extending from Chita, Lafiagi, Lahagi and Lancika are represented in blue colours signifying little or absence of magnetic minerals.

The reduced to equator (RTE) map (Figure 5) is an enhanced version of the TMI. The analysis is essential for data recorded at low magnetic latitudes. The computation of RTE removes the effect of angles of inclination and declination hence simplifying interpretations by positioning the magnetic anomalies over their sources.

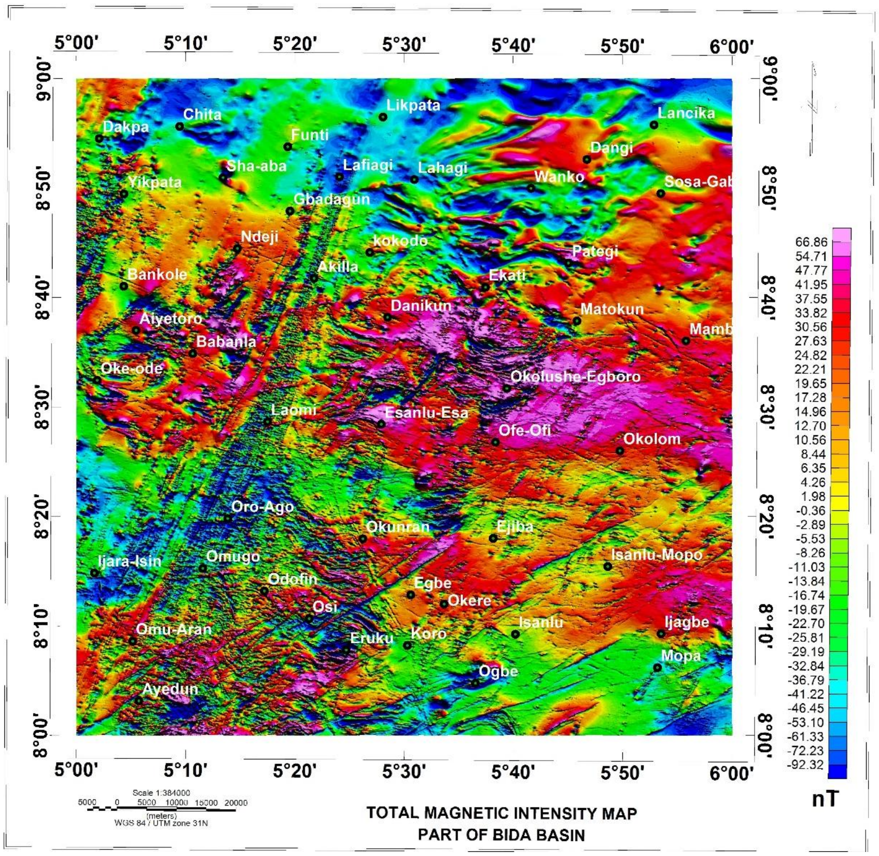

Figure 4: Total Magnetic Intensity Map of Study Area

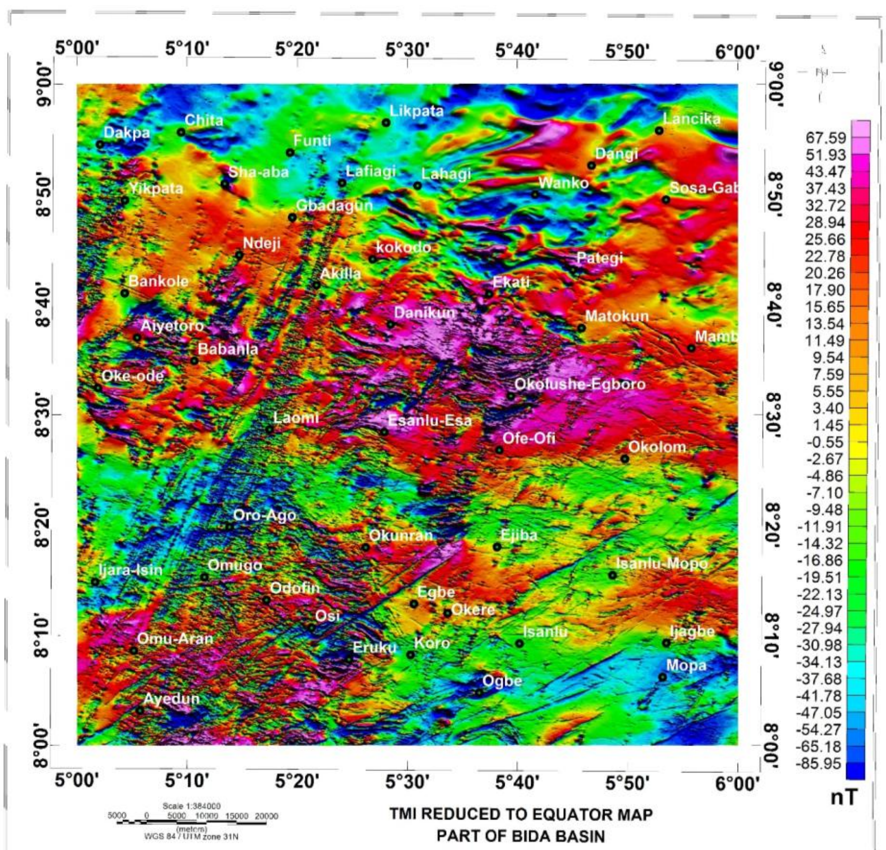

Figure 5: Reduced to Equator Map of Study Area

First vertical derivative (FVD)

The first vertical derivative (FVD) map on (figure 6a) is enhanced for revealing the near surface structures within the study area. The mapping captures major magnetic lineaments and sever distortion to magnetic field. The upper region of study area is apparently devoid of noticeable structures and its demarcated using a dash blue line. Inferentially, this region is dominated by the Bida-basin's thick sediments covering near surface structures. The blue dash line also separates the study area into two regions. The upper northern portion denoting intricate part of Bida sedimentary basin while the downward portion is part of the western Nigeria basement complex geological formation. Two major fault lines extending from the southwestern region towards the northern region terminates at the area surrounding Lafiagi and Likpata locations. Other major magnetic lineation is captured within the southern regions trending in SW-NE directions. Significant distortions to magnetic signatures are recorded at the southwestern region within locations corresponding to Oyedun, Omu-Aran, Omugo, Osi, Eruku, Odofin and Oro-Ago. Other regions showing distortion to magnetic field includes: The central areas and parts of northwestern regions.

The greyscale (figure 6b) is an enhanced view of the first vertical derivative. It clearly portrays the sedimentary regions at the northern part devoid of structures and the downwards regions having structures associated with the western basement complex geological formations.

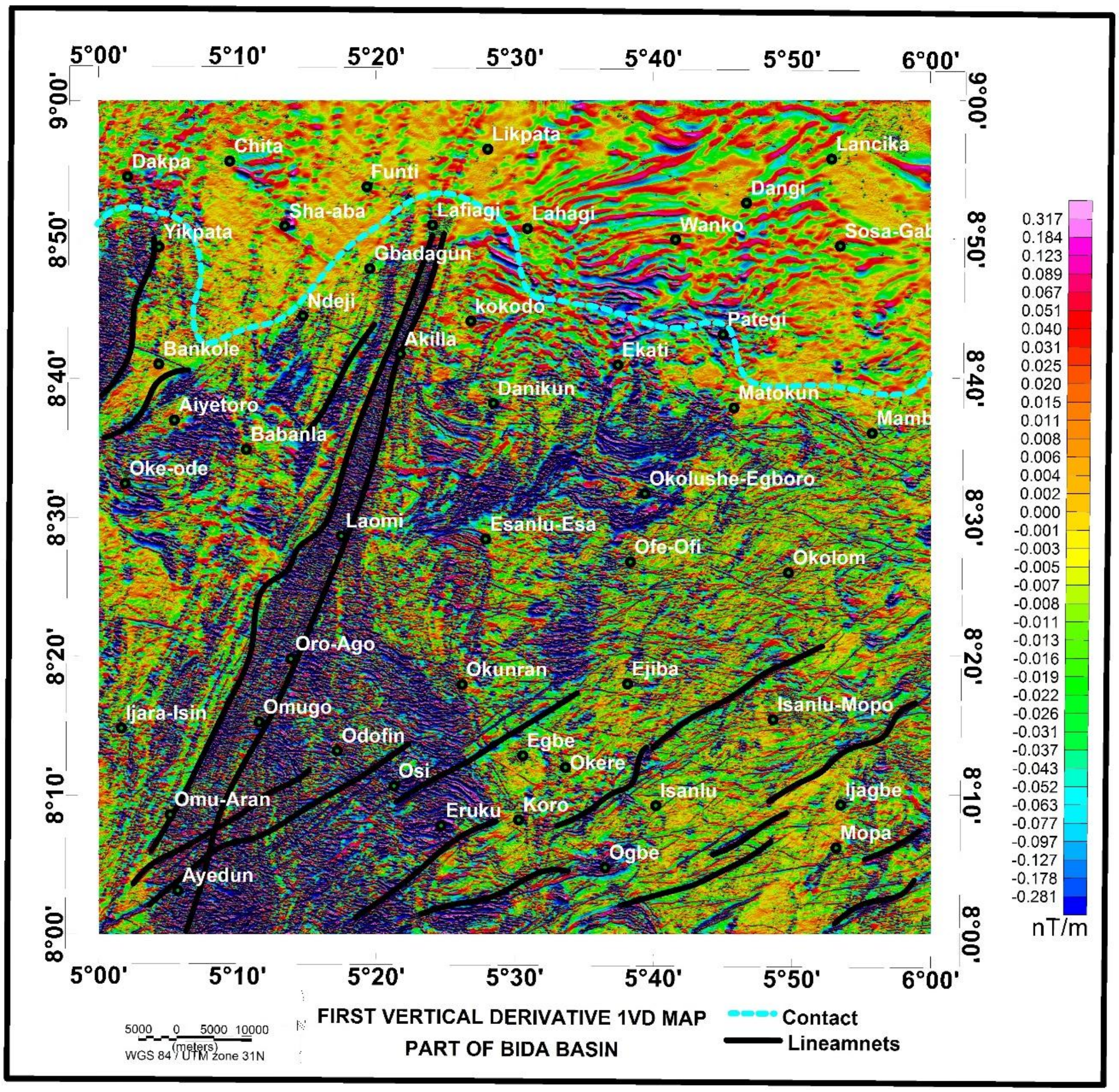

Figure 6a: First Vertical Derivative (1VD) Map of Study Area

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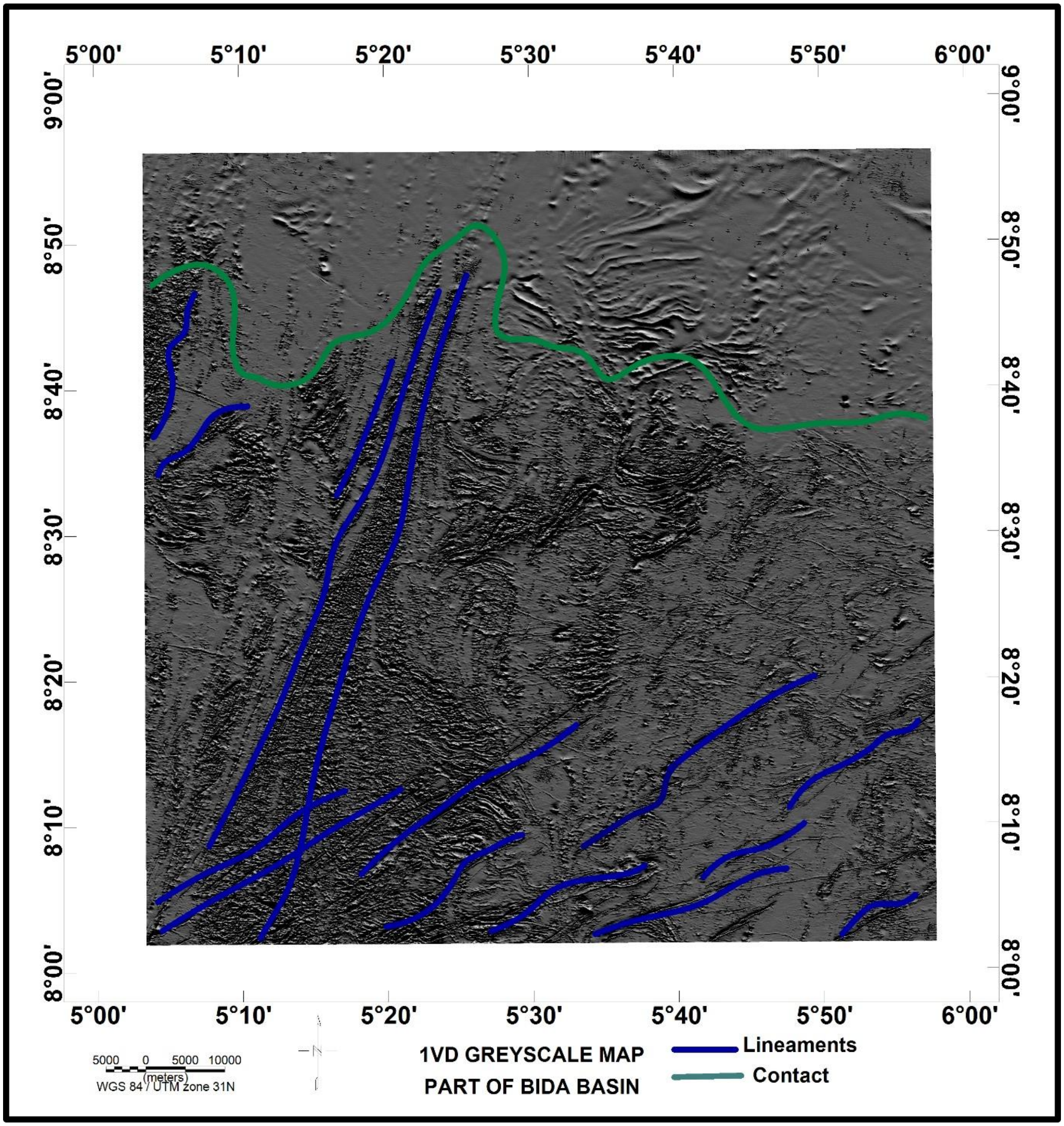

Figure 6b: Greyscale Map of FVD of the Study Area

Total horizontal derivatives (dx, dy and dz)

The horizontal derivative maps (DX, DY and DZ) are presented as figure 7a, 7b and 7c respectively. The analysis is drafted for the purpose of showing the alignment and directional orientations of near surface structures within the study area. It also showcases the edges and boundaries of magnetic anomalies. DX mapping enhances magnetic anomalies aligned in the horizontal direction while DY projects magnetic anomalies that are positioned vertically. DZ represents a balanced orientation and direction of the anomalies.

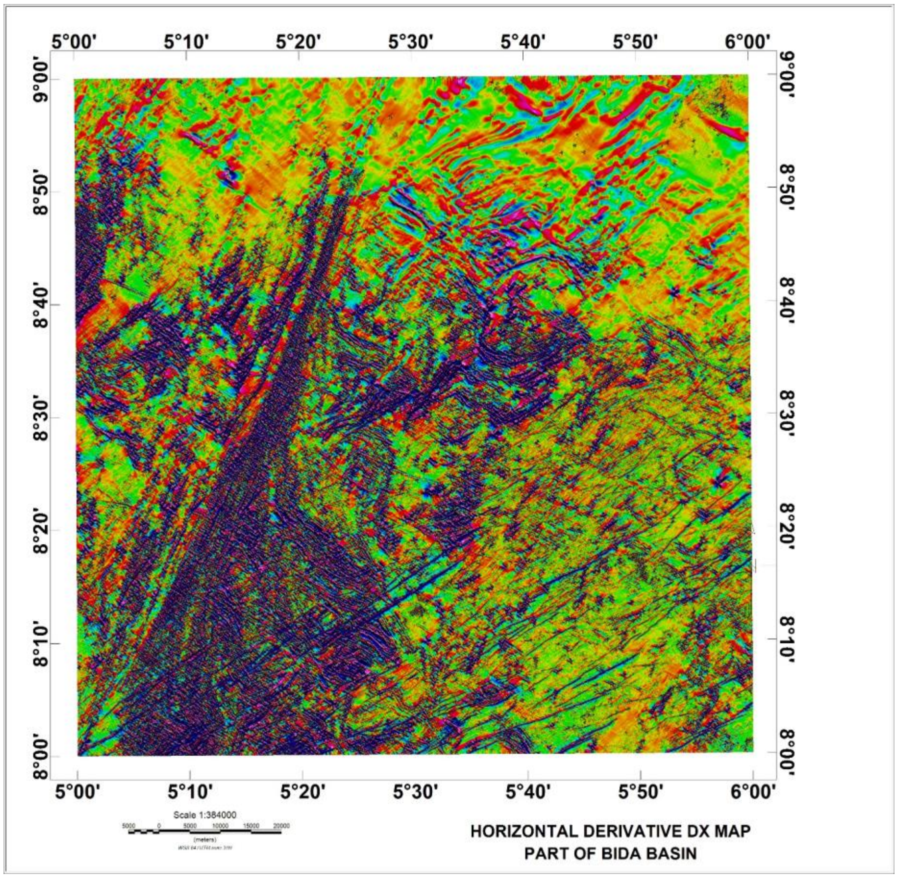

Figure 7a: Horizontal Derivative DX

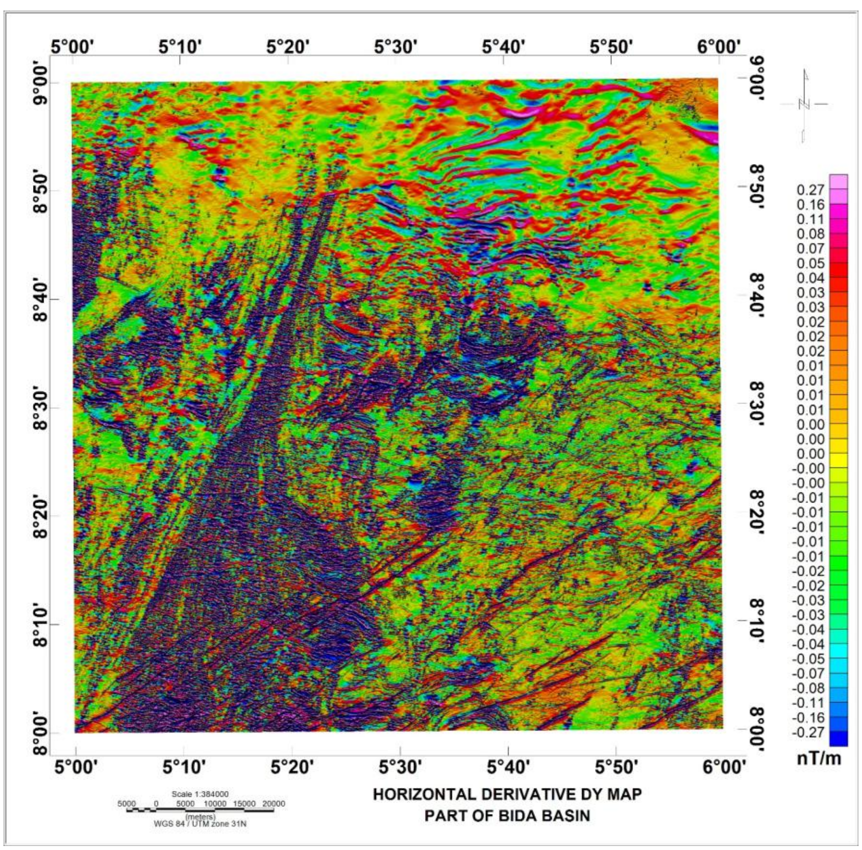

Figure 7b: Horizontal Derivative DY

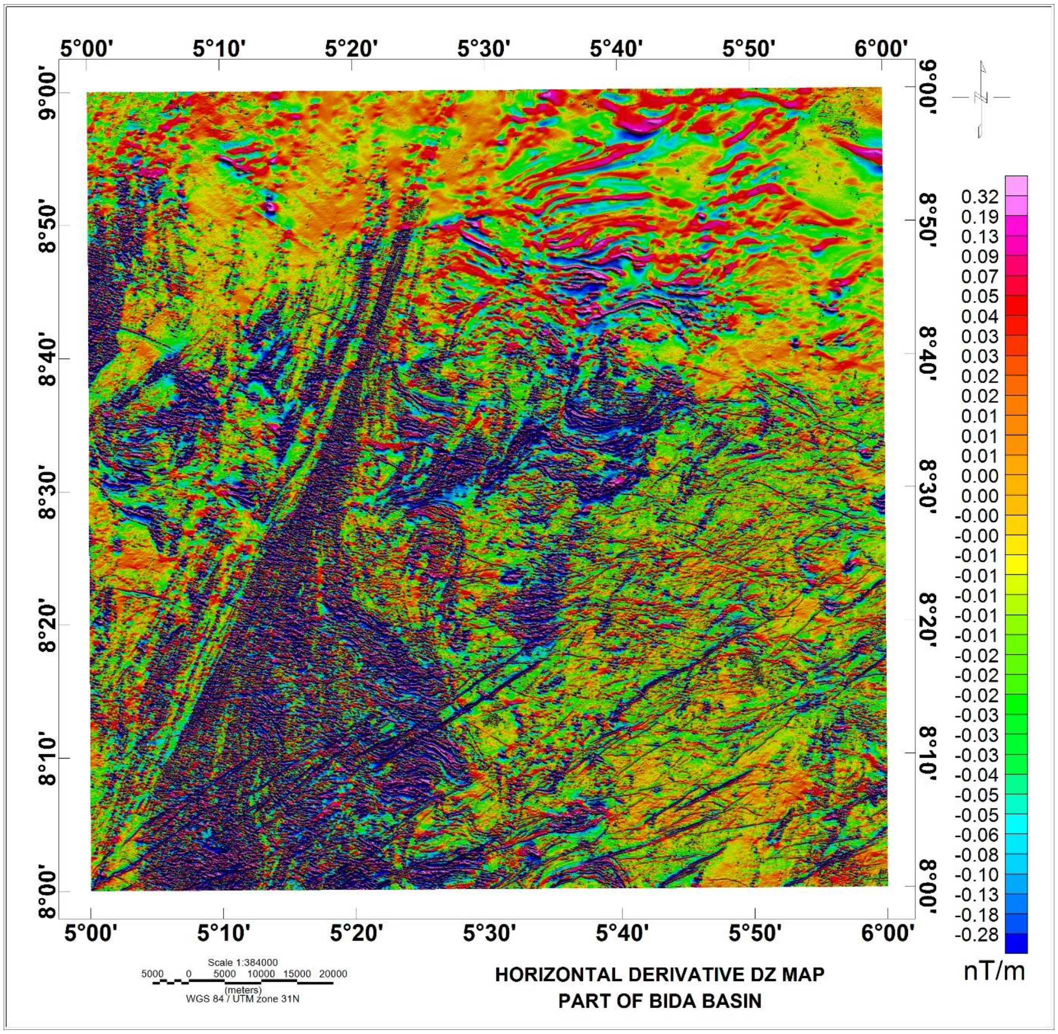

Figure 7c: Horizontal Derivative DZ

Analytic signal and Centre for exploration targeting

The analytic signal (Figure 8) is another analysis for enhancing near surface structural frame work. The 3D analytic signal employed in this study combines the x, y, z orientations of the magnetic anomalies. The values are measured in amplitudes without-cropping and near surface structures having high amplitudes while low amplitudes are linked to deep seated structures. The range of amplitude varies between 0.006 and 0.598. Clusters of structures are mapped at the southwestern, central and north-western regions. The regions extending from Lafiagi and Pategi upwards deficient of structures and are linked to deep sedimentary cover of sand from Bida Basin.

The structural trend and make-up of study area is further expressed in the Centre for Exploration Targeting (CET) map (figure 9). A drawn dashed line separating the upper northern region with the remaining downward region is a contact where the basement complex formation terminates into the sandstones. The region of basement complex which is part of the western Nigeria basement complex geology is well structured while the non-structured region is linked to the Bida sedimentary basin.

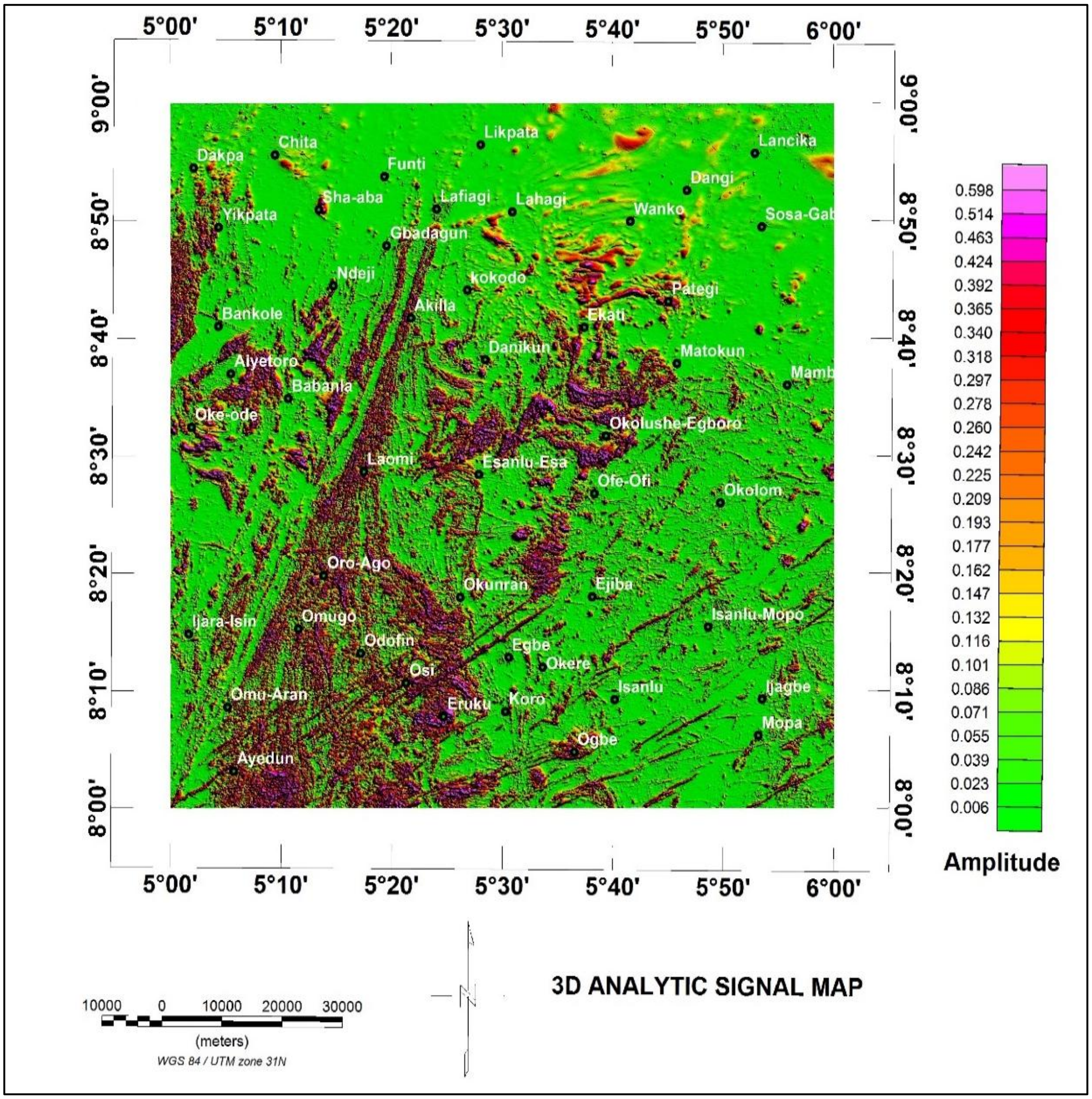

Figure 8: Analytic Signal Map

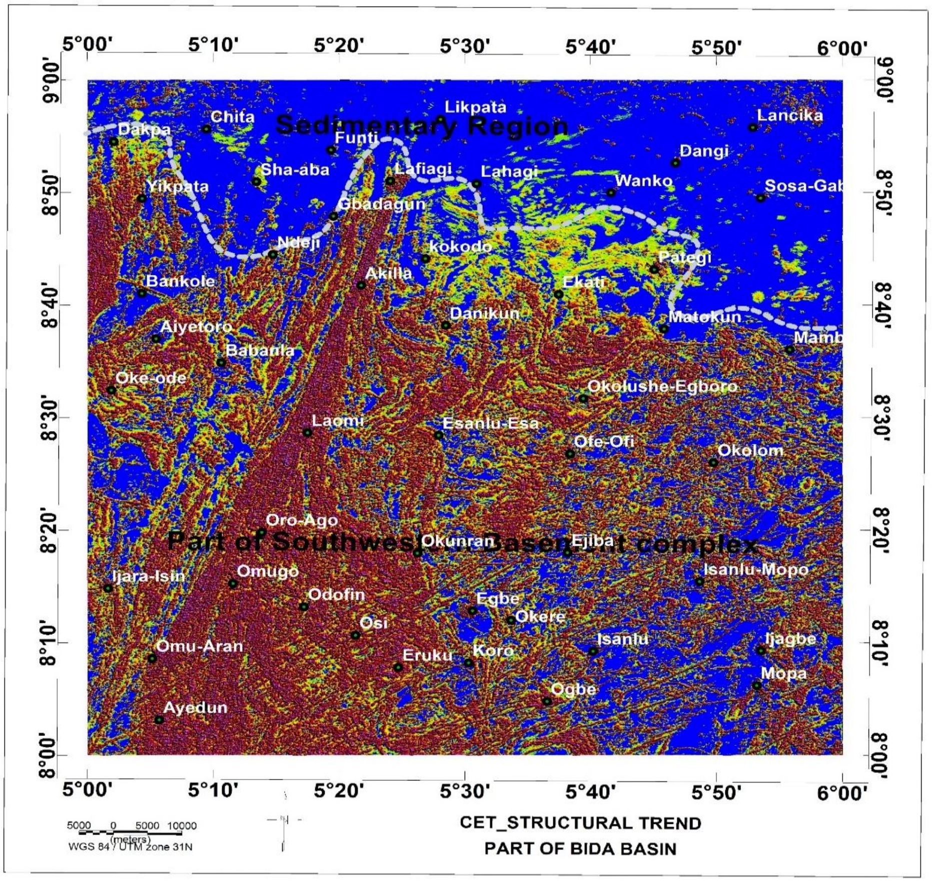

Figure 9: CET Structural Congruence Trend Map

Radiometric Data Analysis Results

Radioelements concentration maps of study area

An analysis of the spatial concentration of radioelements within the study area was computed to map variations of features that are associated with potential mineral deposit. Only radioactive elements detectable via gamma ray spectrometric survey were analysed in this study (Potassium (K), Equivalent Thorium (eTh) and Equivalent Uranium (eU)).

The range of Potassium concentration (figure 10a) varies from 0.16 to 4.60 % across the study area. High concentration denoted (HC) were recorded mainly at the central and southern regions depicted in red and pink colours around Koko-do, Akilla, Danikun, Oro-Ago, Omugo, Odofin, Eruku, Omu-Aran, Isanlu, Ogbe, Isanlu-Mopo, Mopa, Ijagbe, Osi, Egbe, Bankole and Aiyetoro. Moderate concentrations (MC) dominate the north-eastern regions, part of central regions and part of north west captured in green and yellow colours. Low concentrations (LC) depicted in blue colours were mainly at the north western edge corresponding to Dakpa, Chita and Sha-aba. Other isolated areas of LC were recorded at Ijara-Isin in the southwest region and areas below Lahagi at the northern regions.

The spatial measure and distribution of equivalent Thorium (eTh) within the study area is mapped in figure 10b. High concentrations (HC) are captured in red and pink colours, moderate concentrations (MC) are depicted in green and yellow colours while low concentrations (LC) are mapped in blue colours. The values of concentration range from 5.74 to 54.29 ppm. The northwestern regions recorded low concentrations with an exception of HC at Yikpata area. The northeastern region is dominated by moderate concentrations. High concentration is mapped from the southwestern region extending towards the north at locations corresponding to Akilla, Danikun, Laomi, Oro-Ago, Okolushe, Omugo, Odofin, Eruku, Omu-Aran, Isanlu, Ogbe, Isanlu-Mopo, Okolom, Mopa, Osi, Egbe, and Ayedun.

Equivalent Uranium concentration in the study area range from 0.75 to 10.90 ppm. High concentrations (HC) mapped in red and pink colours spans from the southern regions extending upwards towards the north. From the northern regions HC areas includes Likpata, Akilla, Danikun, Laomi, and Esanlu-Isan, from the southern regions: Oro-Ago, Omugo, Odofin, Osi, Eruku, Omu-Aran, Isanlu, Isanlu-mopo, Mopa, Ijagbe, Ogbe and Ayedun. The eastern flanks extending to north eastern regions are covered in moderate concentrations. Low concentrations are mapped at the north western regions.

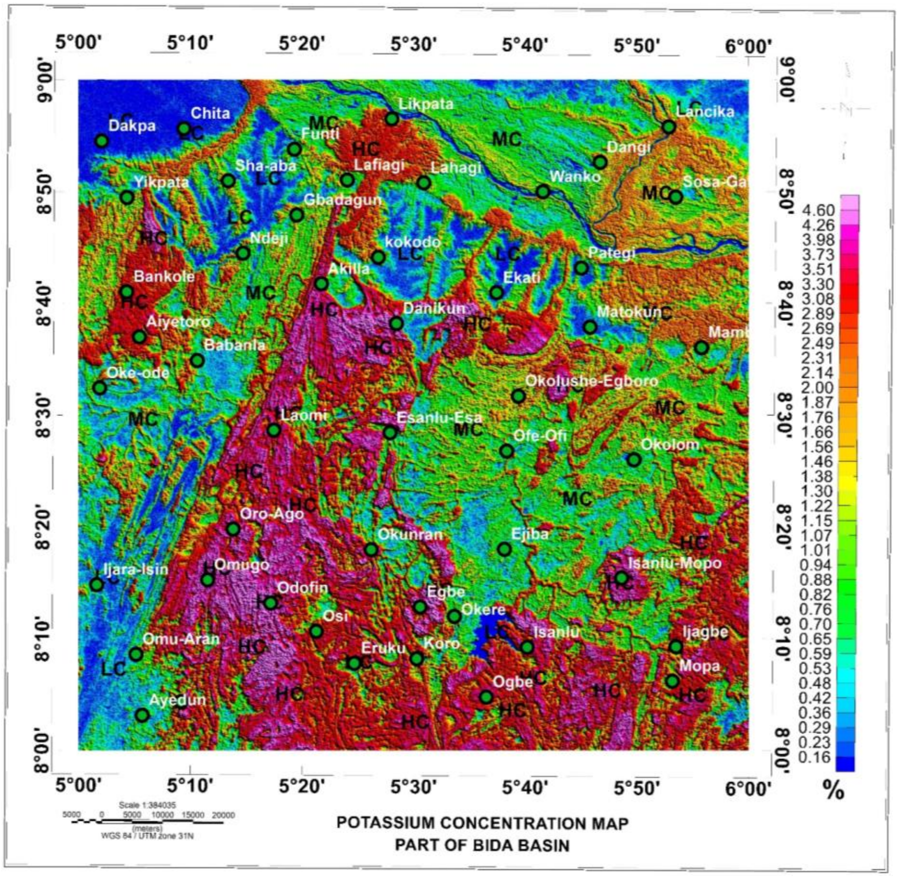

Figure 10a: Potassium Concentration Map of Study Area

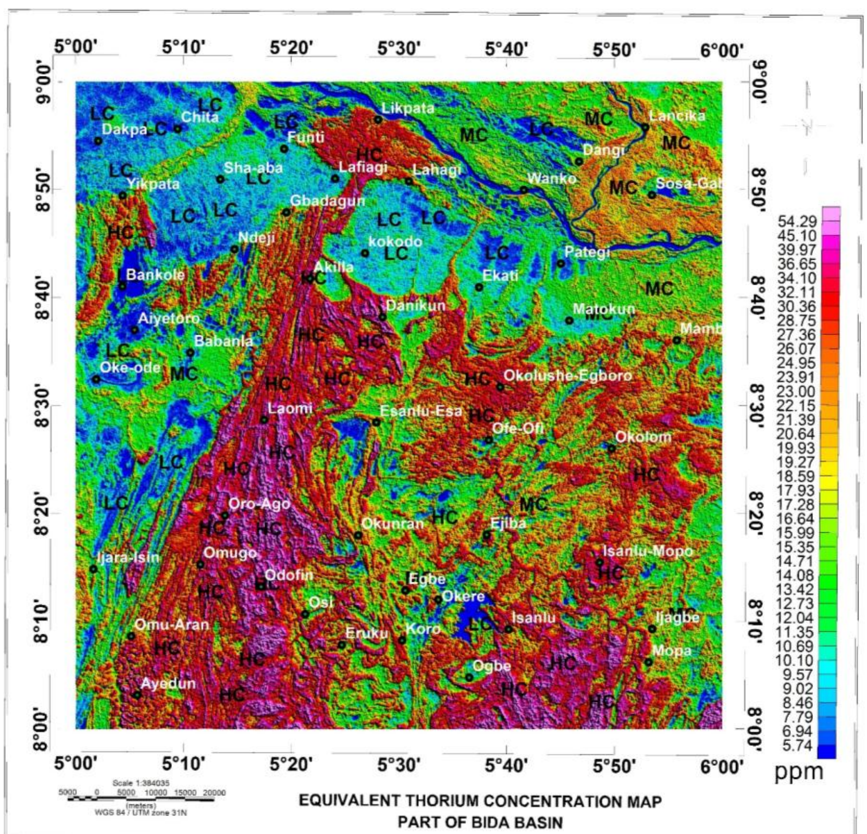

Figure 10b: Equivalent Thorium Concentration Map of Study Area

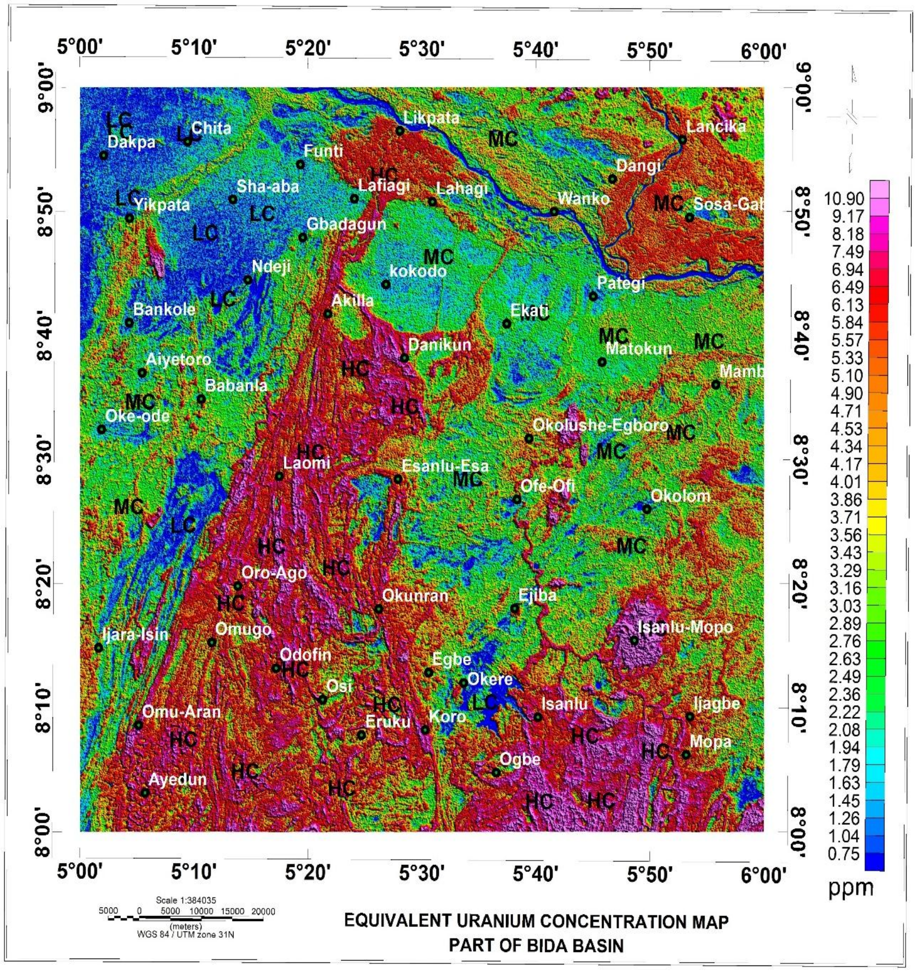

Figure 10c: Equivalent Uranium Concentration Map of Study Area

Ternary Image

The ternary image in figure 11 presents a composite mapping of the three radioelements (K, eTh and eU) within the study area. The colours are an aggregate of three colours representing the radioelements; K is in red, eTh is in green and eU is in blue colours. The map reveals variation of the radioelements where their combined occurrence is high, moderate and low. Regions depicted in white colours indicate high concentration of the three elements while dark regions represent low occurrence of the three elements. Relatively red, green and blue captures regions dominated by K, eth and eU respectively.

Hydrothermal Alteration Mapping (K/eTh, K_D and F_parameter)

The mapping of hydrothermal alteration zones is essential in localising potential mineral deposit. The Potassium_Thorium ratio map (figure 12a), potassium deviation map (figure 12b) and F_parameter map (figure 12c) were generated to achieve this target. The map show case the variation of potassium over equivalent thorium and uranium and it's used to provide evidence of potassium enrichment which is a factor associated with hydrothermal alteration process (Adetona et al., 2025; Akingboye et al., 2021). The regions of high value occurrence of K/eTh, K_D and F_parameter indicated as (HA) and depicted in pink colours are of interest. The corresponding locations mapped with evidence of hydrothermal alteration includes Bankole, Aiyetoro, Babanla, Ndeji on the NW regions. Below Ekati, Matokun and danikun, Esanlu-Esa at the central regions. At the southern regions HA areas includes Omugo, Okunran, Egbe, Eruku, Isanlu, IJagbe, Mopa, and Ogbe.

The structural features mapped on the FVD map was superimposed on the K/eTh map to consolidate of the assertion that geologic structures serves as primary controls for mineralisation in basement complex formations (Ordonez et al., 2024; Eldosouky et al., 2024). The structures cuts across the hydrothermal alteration regions marked in yellow dots. The structures serves as channels for potential mineral deposits.

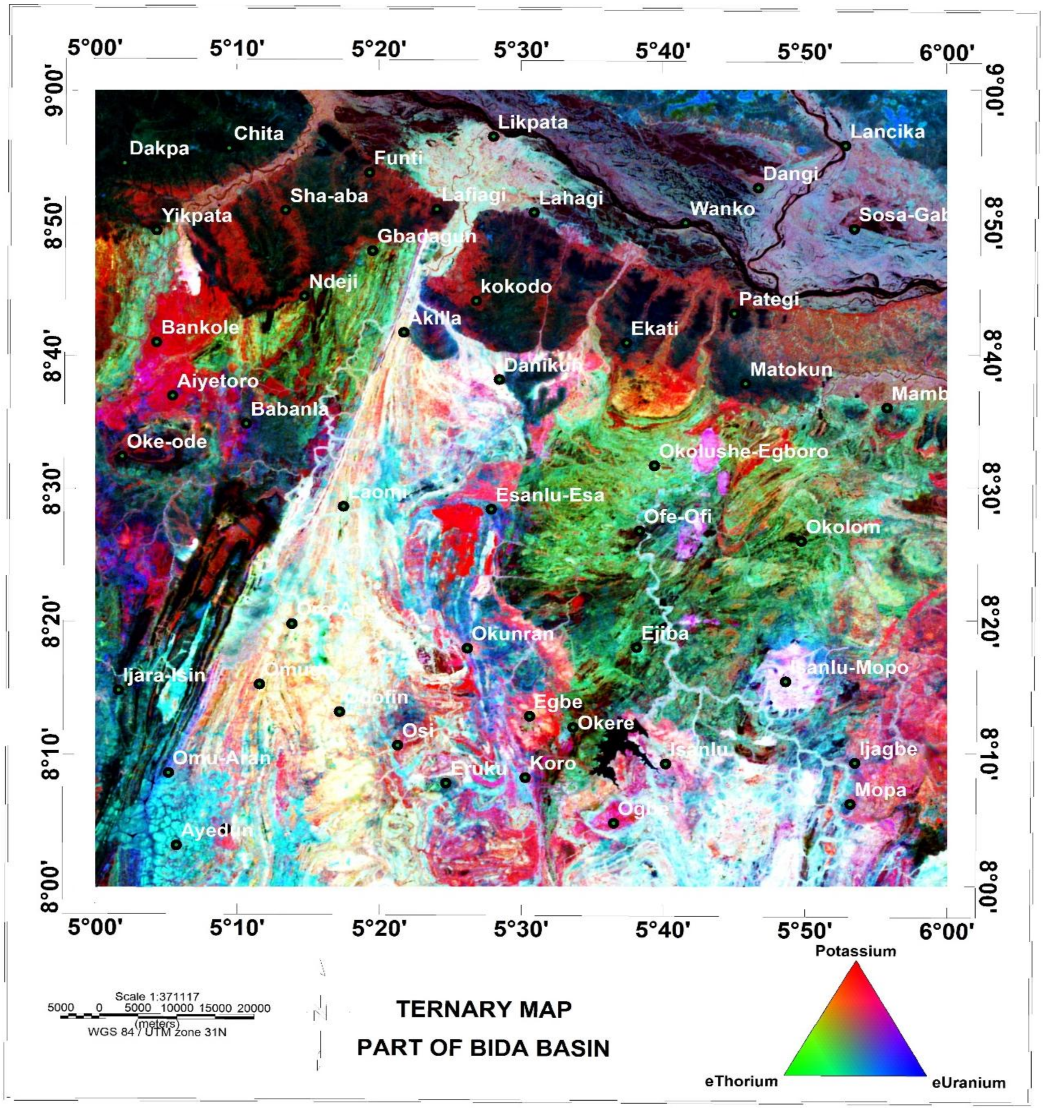

Figure 11: Ternary Map of Study Area

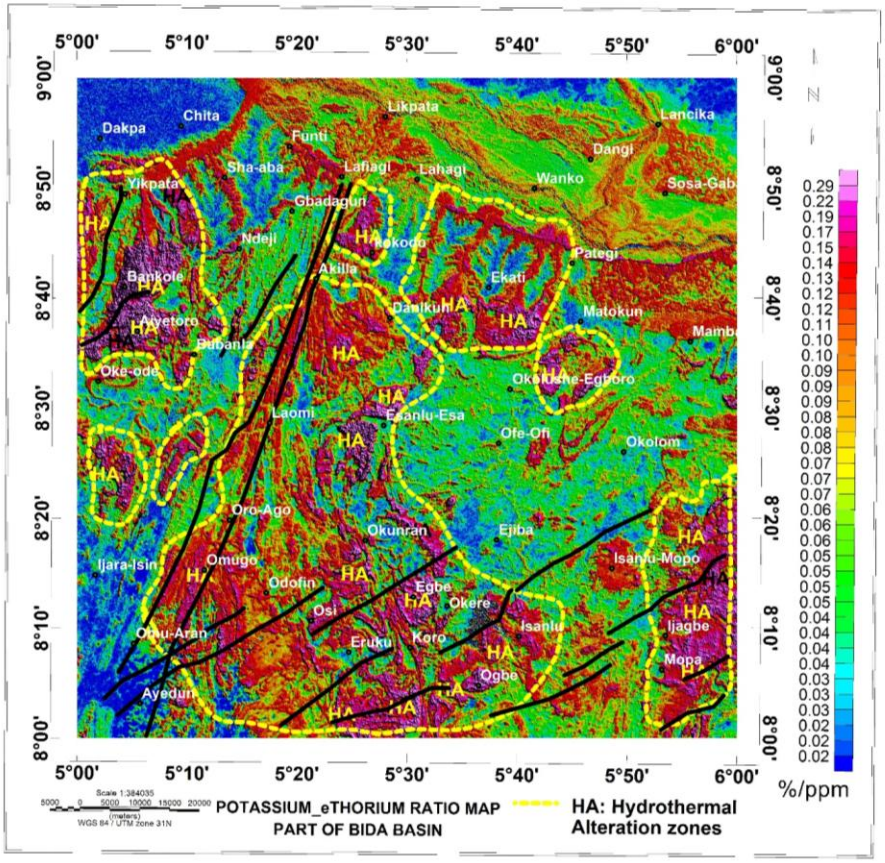

Figure 12a: Potassium_Thorium Ratio Map of the Study Area

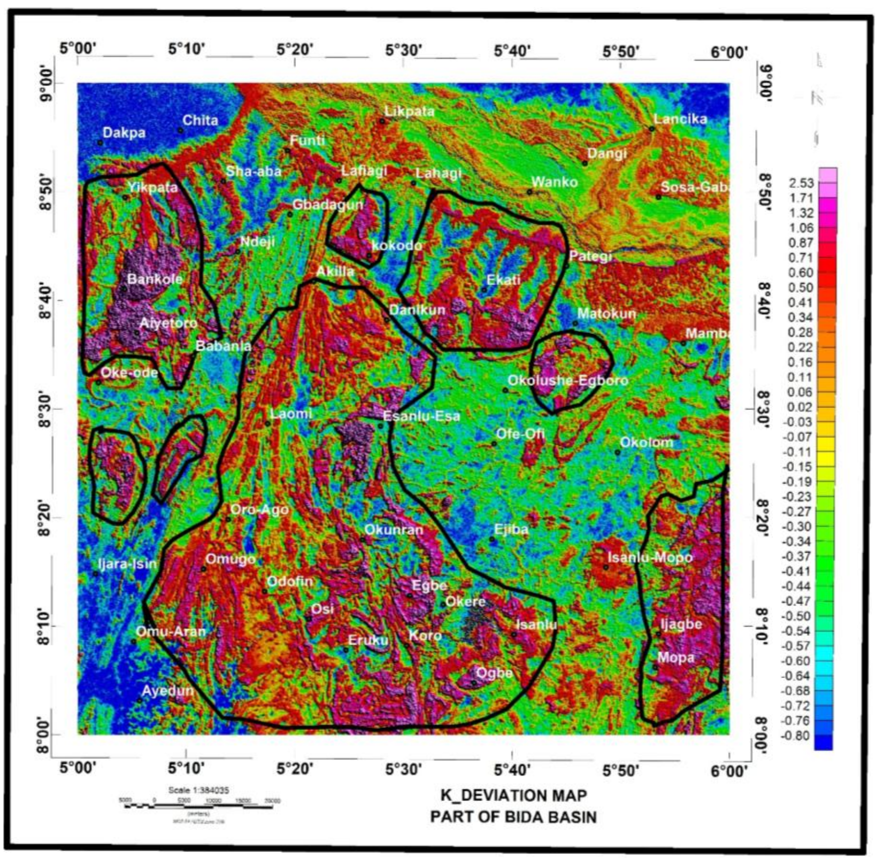

Figure 12b: Potassium Deviation Map of Study Area

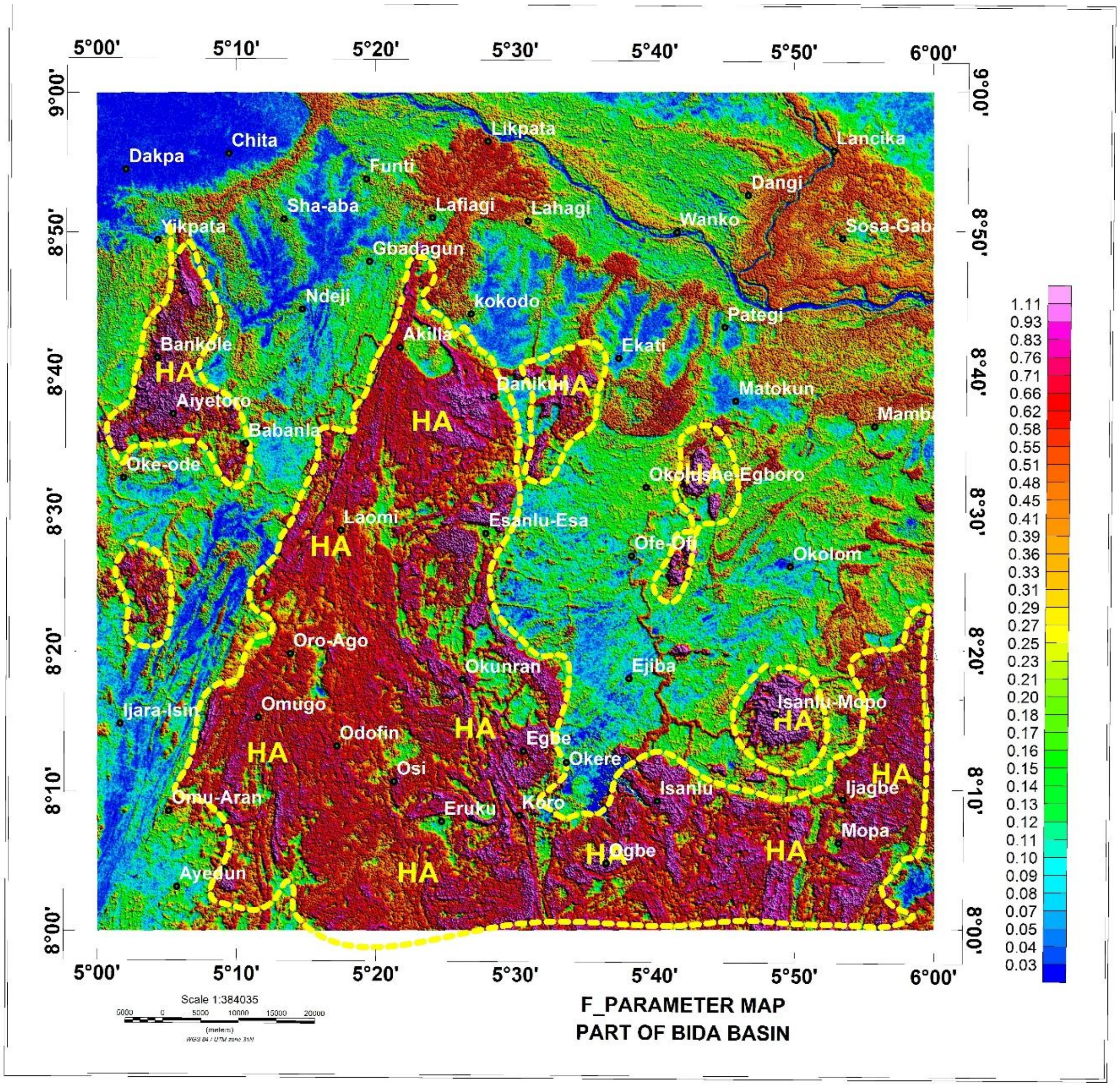

Figure 12c: F_parameter Map of Study Area

A combination of three hydrothermal alteration maps (K/eTh, K_D and F_parameter) were fused to reinforce the zones of alterations and inferably zones of mineralisation. The colours are indicative of the high and low values of the composite maps. White and bright colours depict high occurrence of the fused maps which are also the regions of interest associated with rock alterations. These zones correspond to locations viz: Bankole, Aiyetoro, Babanla, Ndeji on the NW regions. Below Ekati, Matokun and danikun, Esanlu-Esa at the central regions. At the southern regions HA areas includes Omugo, Okunran, Egbe, Eruku, Isanlu, IJagbe, Mopa, and Ogbe. The delineated structures coinciding with regions of alteration are corelative evidence of inferred mineralisation.

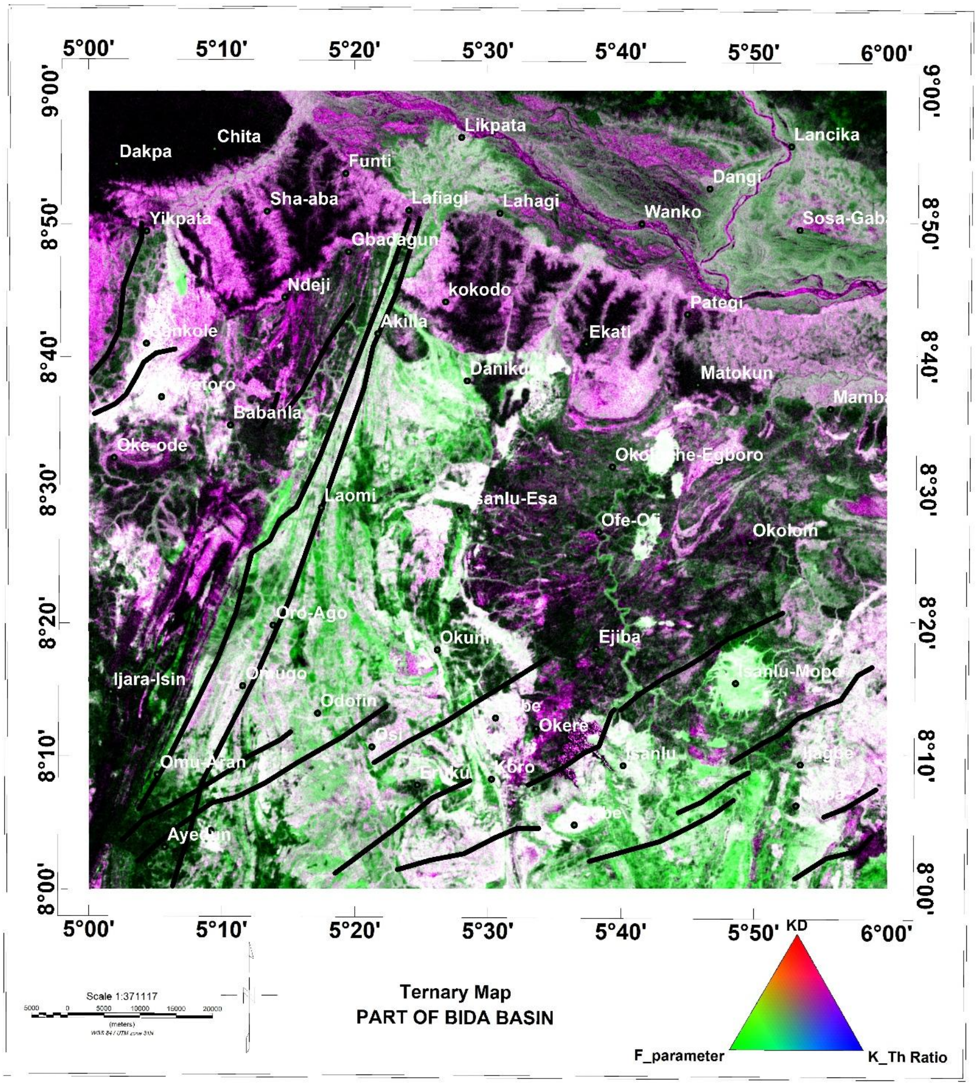

Figure 13: Ternary Map (composite of hydrothermal alteration maps)

Discussions of Results

This study presents an integration of two potential field methods to provide a clearer view and image of the subsurface associated with potential mineral deposit in the study area. Analysis of the airborne magnetic data targeted delineation of mineral bearing geological structures while radiometric data analysis revealed areas affected by hydrothermal alteration, an essential process in mineral deposit.

A perspective of the spatial spread of magnetic minerals occurrence in the study area was mapped using the total magnetic intensity map (TMI). The upper northern region identified as core part of the Bida sedimentary basin recorded low or negligible magnetic signatures. This is because, sand sediments have low magnetic susceptibility (Currie and Bornhold, 1983; Satria et al., 2021; Hatfield, 2014; Costa et al., 2016).

The first vertical derivative map revealed the geological structural network of the study area. The structures which could be faults, fractures, fold, contacts or shear zone serves as conduits and traps for potential mineral deposit during hydrothermal alteration process (Salako et al., 2024; Adetona et al., 2023).

The FVD mapped two major fault lines extending from the south western region and terminate at Lafiagi, northern region of study area. The two fault lines are an extension of the Ifewara and Iweraja fault lines projecting from the southwestern region of Nigeria (Awoyemi et al., 2018; Salawu et al., 2021; Arogundade et al., 2022). The fault lines which appear to terminate at the entrance of the Bida sedimentary basin are inferred to extend under the basin sediment, emerging at Zungeru area (Kolawole and Anifowose, 2011; Adepelumi et al., 2008; Salawu et al., 2021).

Results from analytic signal and CET were helpful in revealing further the two main geological formations dominating the study area (part of Bida basin and southwestern basement omplex geologies). The analytic signal showcased structures within the basement complex regions which could be out-crops or near surface magnetic sources (Adetona and Abu, 2013; Egbelehulu and Osagie, 2021).

Major and minor lineaments were mapped within the basement complex region of study area from CET analysis. The termination of structural complexes and clusters below the Lafiagi and Pategi areas confirms the termination of basement geological formation and beginning of the Bida basin sandstones sedimentation. This makes the Yikpata, Ndeji, Lafiagi, pategi and mamba locations a transitional environment between the basement complex and sedimentary geologies (Rahaman et al., 2019; Olawuyi, 2018; Olusola 2012).

The results of magnetic analysis are validated by other researchers who delineated similar geological veins and structures in concise portions of the study area (Akinlalu et al., 2018; Akinsunmade et al., 2020; Busari, 2021; Usman et al., 2025; Fowowe, 2018; Ohioma et al., 2017; Lawal et al., 2021).

The concentration of radioelements in the study area is relatively high compared to conventional crustal averages. The peak value of potassium within study area was recorded as 4.60 %, this exceeds the crustal average value of 1.23 %. The peak value of equivalent thorium was recorded as 54.29 ppm which surpasses the crustal value of 12.0 ppm. Also, 10.90 ppm peak value recorded for equivalent Uranium is above the crustal average of 3.0 ppm (Lambert and Heier, 1968; UNSCEAR, 2000; Gbenu et al., 2020).

The K/eTh, K_D and F_parameter analyses provided the basis for identifying areas that have undergone hydrothermal alteration process. The concept of potassium enrichment at the expense of equivalent thorium was employed since it can be easily leached from its host rocks while equivalent thorium is immobile and not easily affected by weathering and hydrothermal processes (Dadi et al., 2024; Sanusi and Amigun, 2020; Adetona et al., 2023). It is inferred that, aqueous solution of minerals is mobilised during hydrothermal alteration process with crystallisation and deposition occurring within subsurface structures such as faults, fractures, folds, contacts and shear zones (Giggenbach, 1984; Heinrich, 2007; Mathieu, 2018; Bénézeth et al., 2018). Research findings by Hoover et al., 1995 and Shives et al., 2000 suggested that the K/eTh ratio value of 0.17 – 0.2 %/ppm signifies stable range for most rocks while values above this range is indicative of alteration. In this study, locations mapped with possible alterations on the K/eTh map are in pink colours and corresponds to Bankole, Aiyetoro, Babanla, Ndeji on the northwestern regions. Below Ekati, Matokun and danikun, Esanlu-Esa at the central regions. At the southern regions HA areas includes Omugo, Okunran, Egbe, Eruku, Isanlu, IJagbe, Mopa, and Ogbe. The identified regions are situated within the basement complex regions hosted by metamorphosed rocks which are formed when existing rocks are transformed by heat, pressure or chemical reactions. Some of the metamorphosed rocks mapped within study area include quartzite, phyllite, and schist. The transformed rocks are linked with mineral deposited via crystallisation in veins (Chauvet, 2019; Harlov et al., 2013; Verlaguet et al., 2011). The results of hydrothermal alterations mapped in this study is validated by previous researches carried out in concise locations that are components of the current research area (Afolabi et al., 2024; Lawal, 2020; Bamisaiye, 2024; Ohioma et al., 2017). The corelation of geological structures mapped from airborne magnetic data and hydrothermal alteration zones from radiometric analysis is a proven and suitable integrated analysis for localising mineral deposit (Githenya et al., 2019; Aisabokhae et al., 2023; Courba et al., 2023; Eldosouky et al., 2017). This also suggest or infers that, locations hosting major structures and coinciding with zones affected by hydrothermal alteration process can be inferred to be areas favourable for possible mineralisation within the study area. These locations include Bankole, Aiyetoro, Babanla, Ndeji on the northwestern regions. Below Ekati, Matokun and danikun, Esanlu-Esa at the central regions. At the southern regions HA areas includes Omugo, Okunran, Egbe, Eruku, Isanlu, IJagbe, Mopa, and Ogbe.

CONCLUSION

The assessment of mineral potential within the southern Bida basin was carried out by integrated analysis of airborne magnetic and radiometric data. Analysis of aeromagnetic data was useful in delineating geological structures that could be host to the target minerals. Evidence of structural occurrence within the study area was established from First Vertical Derivative (FVD) and the greyscale, Horizontal Derivatives (DX, DY and DZ), 3D Analytic Signal and Centre for Exploration Targeting (CET). Source Parameter Imaging was used to estimate the depth to the structures and magnetic sources.

Two major fault lines extending from southwestern region of study area and terminating at Lafiagi in the northern region were outlined. The fault lines are associated with the Ifewara and Iweraja fault lines that runs from Ilesha southwestern region of Nigeria and passing under the sediments of Bida basin to emerge at Zungeru area. Other fault lines also exist within the study area alongside areas that showed strong distortion to magnetic signatures. The delineated structures were outlined as possible traps and conduits for mineral deposit during hydrothermal alteration process.

The study also showcased the termination points of the southwestern basement complex geological formation at the regions where deep sedimentations of the Bida basin begins. These regions were mapped at the northern region of study area corresponding to Yikpata, Ndeji, Lafiagi, Lahagi and Pategi locations.

The concentration of radiometric elements (K, eTh and eU) in the study area was mapped to exceed that of conventional crustal averages. The variation of potassium over equivalent thorium was computed as a ratio to map areas of potassium enrichment which is also evidence for hydrothermal alterations. The areas affected by hydrothermal alterations coinciding with the mapped geologic structures are of prime interest relating to the localisation of potential minerals within the study area. The high prospect of mineral potential within study area is also informed by the geological composition of metamorphosed rocks which are linked to vein deposits. Imperatively, locations such as Bankole, Aiyetoro, Ndeji, Koko-do, Mopa and Isanlu-Mopo are mapped as host to undifferentiated Schist and Phyllite on the geology map. The schist and Phyllite rock types are generally associated with deposit of gold and other valuable minerals.

The integrated analysis provided essential information for drawing conclusions on high prospect of mineral potential within the study area. The regions of interest inferred as mineralised are characterised by geologic structures, evidence of hydrothermal alterations and hosted by metamorphosed rocks associated with mineral vein deposit. The favourable areas of mineralisation include Bankole, Aiyetoro, Babanla, Ndeji on the northwestern regions. Below Ekati, Matokun and Danikun, Esanlu-Esa at the central regions. At the southern regions, Omugo, Okunran, Egbe, Eruku, Isanlu, IJagbe, Mopa, and Ogbe.

RECOMMENDATION

The locations delineated with clear evidences of mineralisation (mineral vein structures and hydrothermal alteration occurrence) could be investigated further using grand truth methods to validate economic mineral deposit. The mapping of radioactive elements (K, eTh and eU) in the study area highlighted anomalous concentrations above crustal averages. This calls for details geochemical analysis to assess exposure of local populace to harmful radiations and radiological hazards especially in locations hosting artisanal mining activities.

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