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Remote Sensing-Based Mapping of Gold Mineralization in the Donko Area, Northwestern Nigeria

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Abstract
Gold mineralization in the Donko area of the Zuru Schist Belt is associated with lithological, hydrothermal alteration and structural features that can be effectively investigated using multispectral remote sensing. This study employed Landsat 9 Operational Land Imager (OLI) data to delineate lithological units, identify hydrothermal alteration signatures and characterize surface lineaments associated with gold-mineralization potential. Cloud-free Level-2 Landsat 9 OLI imagery acquired on 17 February 2024 along Path 190/Row 052 was processed using ENVI 5.3. The processing involved layer stacking, spatial sub-setting, false-colour composite (FCC), band-ratio analysis and selective Crosta principal component analysis (PCA), followed by automated and manual lineament extraction and GIS-based spatial analysis. The 7-4-3 FCC effectively enhanced lithological contrasts and facilitated discrimination of schist, gneiss, quartzite and other basement rock units. Band ratios of 4/2, 6/5 and 6/7 enhanced iron-oxide/hydroxide, ferrous/silicate and hydroxyl/carbonate mineral responses, respectively, with hydroxyl/carbonate signatures notably concentrated around the known gold-mineralized area. Crosta-PCA further enhanced the spectral responses of iron-oxide, hydroxyl/carbonate and ferrous minerals, providing complementary evidence of hydrothermal alteration. Lineament analysis revealed relatively high densities in the northeastern and central parts of the study area, with dominant NE–SW and NW–SE orientations and subordinate N–S trends. Integration of lithological, alteration and structural information identified areas where alteration signatures coincide with concentrated lineaments as the most favourable remote-sensing targets for gold mineralization. The results demonstrate the effectiveness of Landsat 9 OLI for reconnaissance-scale mineral exploration in the Donko area and provide targets for subsequent geological and geochemical validation.

Keywords: Landsat 9; remote sensing; hydrothermal alteration; Crosta-PCA; band ratio; lineaments; gold mineralization.

Introduction
Gold mineralization in Precambrian and metamorphic terrains is commonly associated with hydrothermal alteration and structurally controlled pathways such as faults, fractures, shear zones and lithological contacts, which facilitate fluid migration and ore deposition (Carranza, 2009; Pour et al., 2021; Wang et al., 2023). Hydrothermal alteration therefore provides an important surface indicator of mineralizing systems where alteration minerals exhibit diagnostic spectral responses. Multispectral remote sensing has become an effective tool for regional mineral exploration because it provides spatially continuous information over extensive terrains. Landsat imagery has been successfully applied to lithological and alteration mapping using false-colour composites, band ratios and principal component analysis (PCA), while selective Crosta-PCA enhances spectrally diagnostic mineral responses (Crósta & Moore, 1989; Loughlin, 1991; Pour et al., 2021; Wang et al., 2023). Applications of these techniques in African Precambrian terrains have demonstrated their effectiveness in identifying iron-oxide, ferrous and hydroxyl/carbonate signatures associated with prospective gold-bearing environments. Similar studies in northwestern Nigeria have highlighted the usefulness of multispectral imagery for investigating hydrothermal alteration and structural controls on mineralization. The Zuru Schist Belt (ZSB), which hosts gold and other metallic mineral occurrences, represents an important setting for such investigations; however, extensive weathering and locally limited bedrock exposure can constrain conventional geological mapping. Remote sensing therefore provides a valuable complementary approach for characterizing lithological and alteration variations across the area. Despite previous investigations within the broader ZSB, the Donko area remains insufficiently characterized using an integrated Landsat-based approach. This study applies Landsat 9 OLI imagery, false-colour composites, diagnostic band ratios, Crosta-selective PCA and lineament analysis to delineate lithological units, identify hydrothermal alteration

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signatures and characterize the surface structural framework. The integration of these spectral and structural indicators provides a remote-sensing-based framework for identifying areas where alteration and structural features coincide, thereby defining prospective targets for subsequent geological, geochemical and ground-based exploration.

Location of the Study Area

The study area is located within the Donko (Sheet 74), Gwashi (Sheet 75), Zuru (Sheet 97) and Wasagu (Sheet 98) map sheets in Kebbi State, northwestern Nigeria. It extends approximately from latitude 11°00′N to 12°00′N and longitude 5°00′E to 6°00′E, covering an area of about 12,100 km² (Fig. 1).

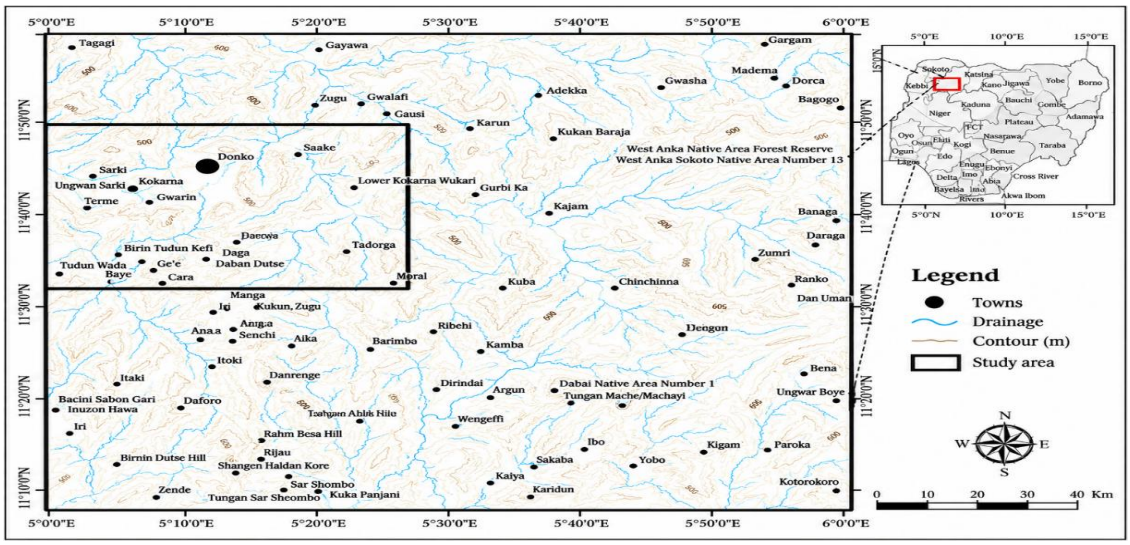


Fig. 1: Map of Nigeria showing location of the study (Adopted from WHO/UNEP, 1997)

Geology of the Study Area

The study area lies within the Zuru Schist Belt of the northern Nigerian Basement Complex and comprises medium-grained granite, quartzite, quartz–mica schist, schist–phyllite, psammitic schist, granite–gneiss, migmatite and migmatite–gneiss (Fig. 2). The basement rocks are Precambrian in age and consist mainly of migmatite–gneiss, Older Granite and schist, with associated quartz veins and pegmatites (Obaje, 2009).

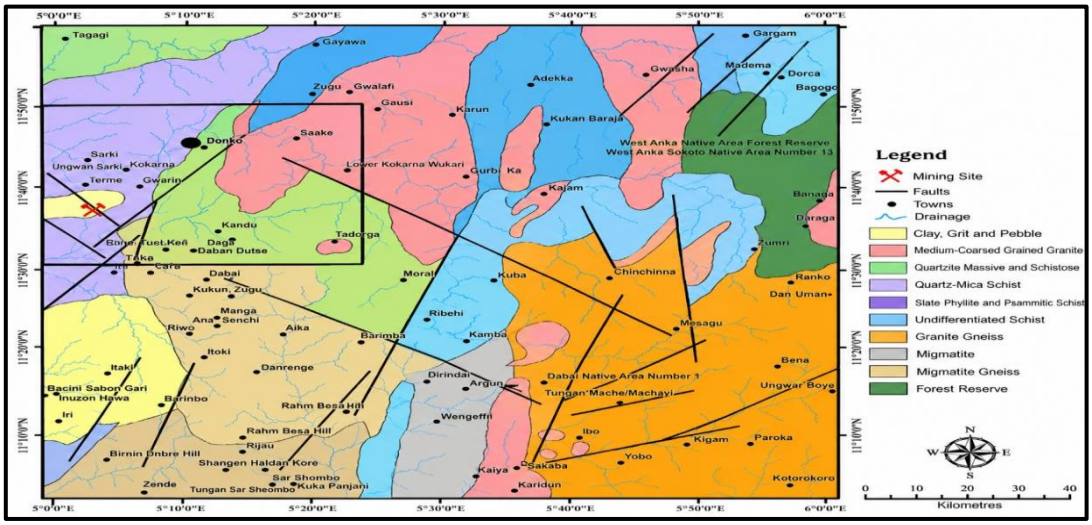


Fig. 2: Geological map of the study area showing Donkoarea (adopted from NGSA 2009).

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Materials and Methods

The remote-sensing workflow involved acquiring cloud-free Level-2 Landsat 9 OLI data for the Donko area, followed by layer stacking and spatial sub-setting in ENVI 5.3. The spectral characteristics of the bands used are presented in Table 3.1. FCC (7-4-3), band ratios (4/2, 6/7 and 6/5) and selective Crosta-PCA were applied to enhance lithological and hydrothermal alteration signatures. Landsat-derived lineaments were then extracted and analysed for density and orientation. Finally, lithological, alteration and structural information were integrated to delineate areas with coincident indicators of gold-mineralization potential (Figure 3.1).

Table 1. Spectral characteristics of Landsat 9 OLI/TIRS bands used in the study.

Band	Wavelength (µm)	Spectral region	Spatial resolution (m)	Sensor
1	0.43–0.45	Coastal aerosol	30	OLI
2	0.45–0.51	Blue	30	OLI
3	0.53–0.59	Green	30	OLI
4	0.64–0.67	Red	30	OLI
5	0.85–0.88	Near infrared (NIR)	30	OLI
6	1.57–1.65	SWIR-1	30	OLI
7	2.11–2.29	SWIR-2	30	OLI
8	0.50–0.68	Panchromatic	15	OLI
9	1.36–1.38	Cirrus	30	OLI
10	10.60–11.19	Thermal infrared (TIRS-1)	100	TIRS
11	11.50–12.51	Thermal infrared (TIRS-2)	100	TIRS

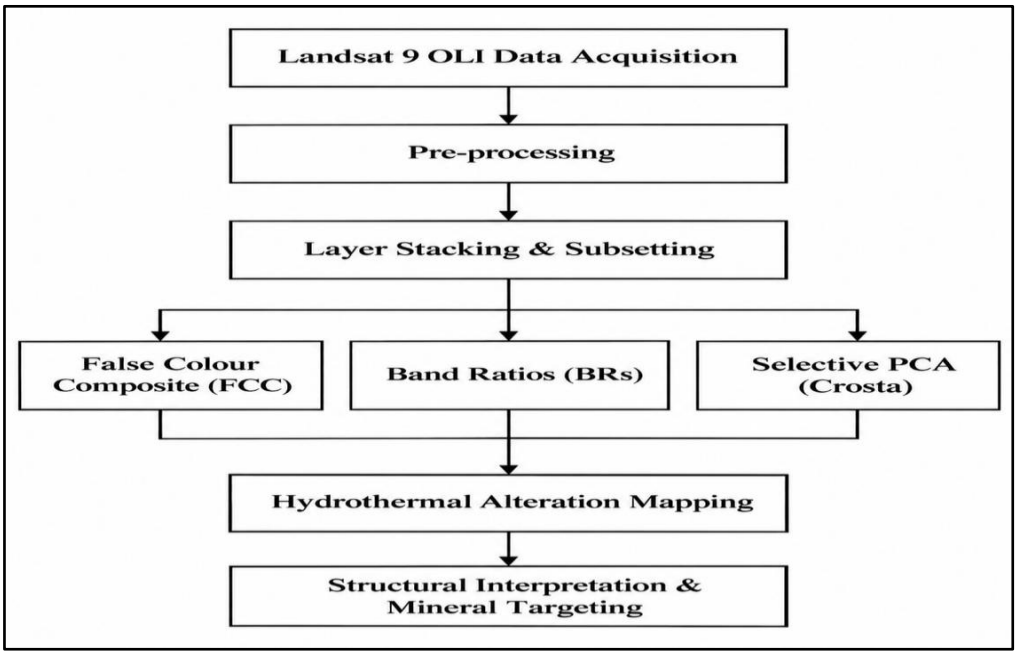


Figure 3. Workflow for processing and interpretation of Landsat 9 OLI data.

Presentation of Results and Discussion

Landsat 9 OLI imagery successfully delineated the major lithological units and their spectral contrasts within the Donko area. The 7-4-3 false-colour composite distinguished schist, gneiss, quartzite and water bodies based on their contrasting spectral responses (Figure 4). Band-ratio analysis further enhanced alteration-related mineral signatures, with the 4/2 ratio

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highlighting iron-oxide/hydroxide, 6/5 enhancing ferrous/silicate minerals, and 6/7 delineating hydroxyl/clay-carbonate responses, particularly around the gold-mineralized area (Figure 5). These results demonstrate the effectiveness of Landsat 9 OLI spectral combinations for reconnaissance-scale lithological and alteration mapping.

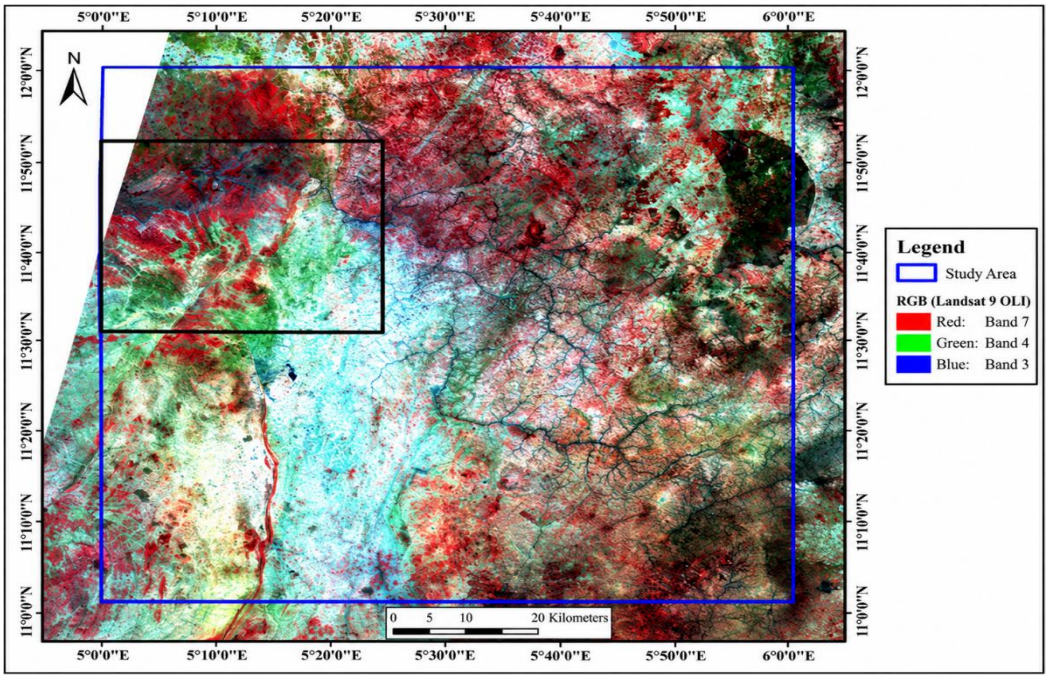


Figure 4. False colour combination image of Landsat 9 OLI (743) discriminating several rock units in Donko area.

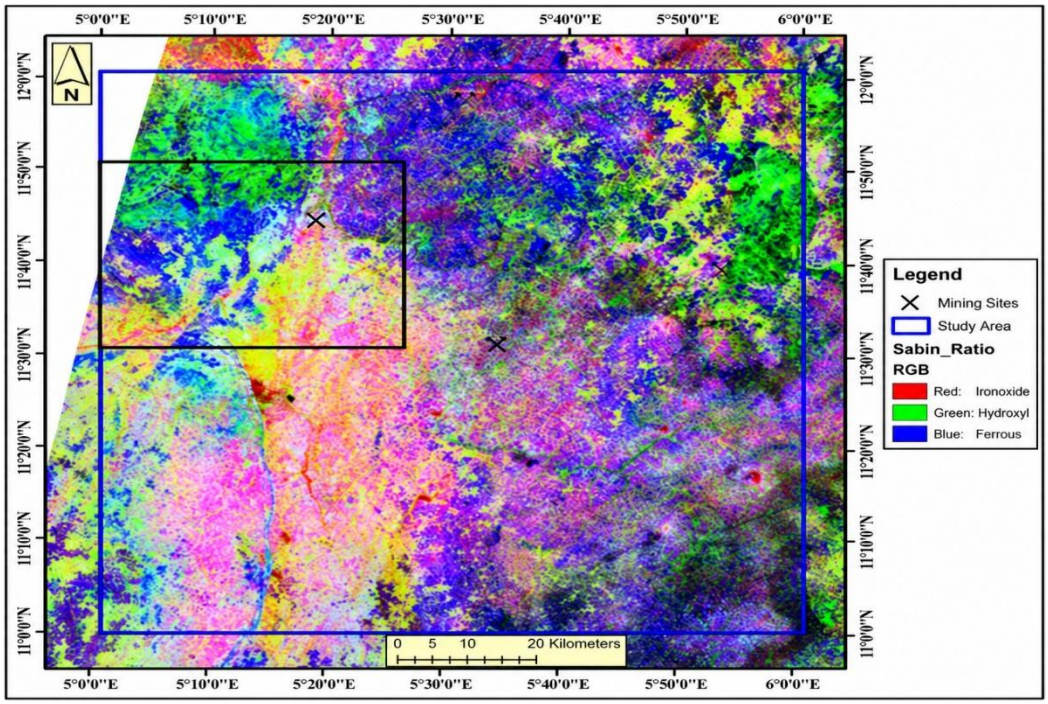


Fig. 5 Sabin ratio (4/2, 6/7, 6/5 in RGB) highlighting various rock units

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Selective Crosta-PCA provided additional enhancement of the alteration signatures using bands 2, 4, 5 and 6 for iron oxides and bands 2, 5, 6 and 7 for hydroxyl/carbonate minerals. The eigenvector loadings in Tables 2 and 3 identified the principal components associated with the respective mineral responses, with PC1 explaining 99.69% and 99.50% of the variance in the iron-oxide and hydroxyl/carbonate analyses, respectively. The Crosta composite integrates iron-oxide, hydroxyl/carbonate and ferrous-mineral responses, with distinctive colour patterns indicating areas of enhanced alteration (Figure 6). The spatial distribution of these alteration signatures provides evidence of hydrothermal activity and highlights areas potentially favourable for mineralization.

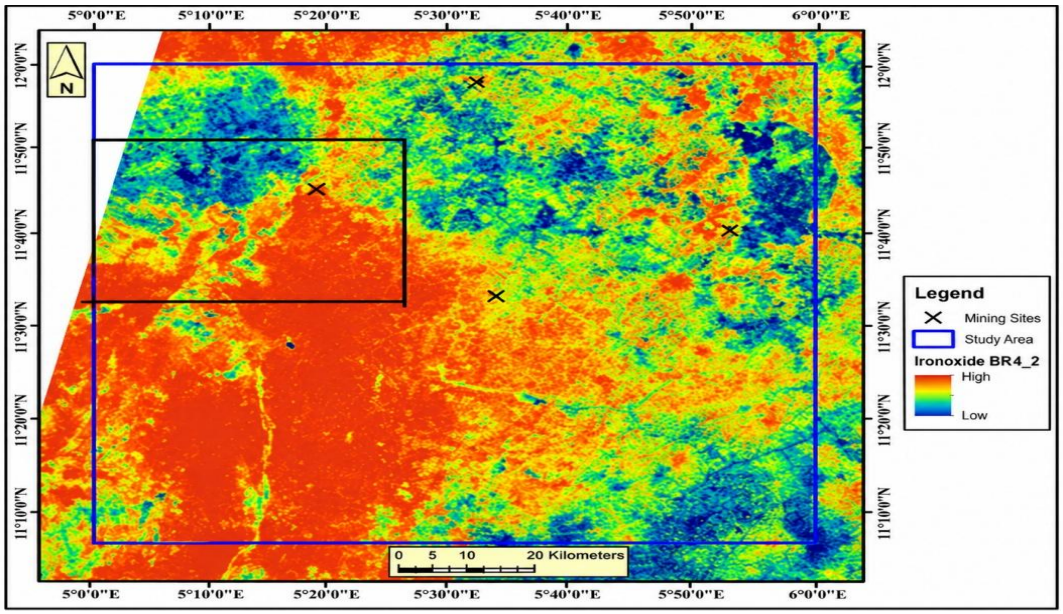
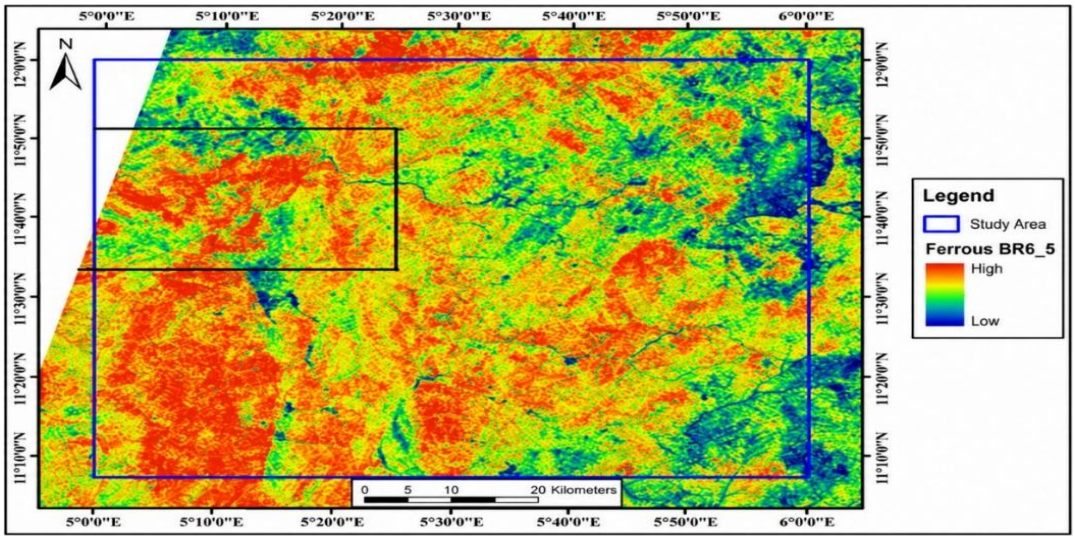


Figure 5 (a) BR 4/2 mapping iron-oxide.



Eigenvector	Band2	Band4	Band5	Band6	Eigenvalues	Variance (%)	Cumulative %

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PC1	-0.324229	-0.436638	-0.544333	-0.638690	223002721.555932	99.69	99.69
PC2	-0.373087	0.009050	-0.607634	0.701074	426458.955456	0.19	99.88
PC3	-0.751230	-0.308158	0.574660	0.102268	220482.179785	0.10	99.98
PC4	-0.751230	-0.845165	0.065184	0.300186	220482.179785	0.02	100.00

Figure 5 (b) BR 6/5 targeting unaltered rocks and silicate or ferrous minerals

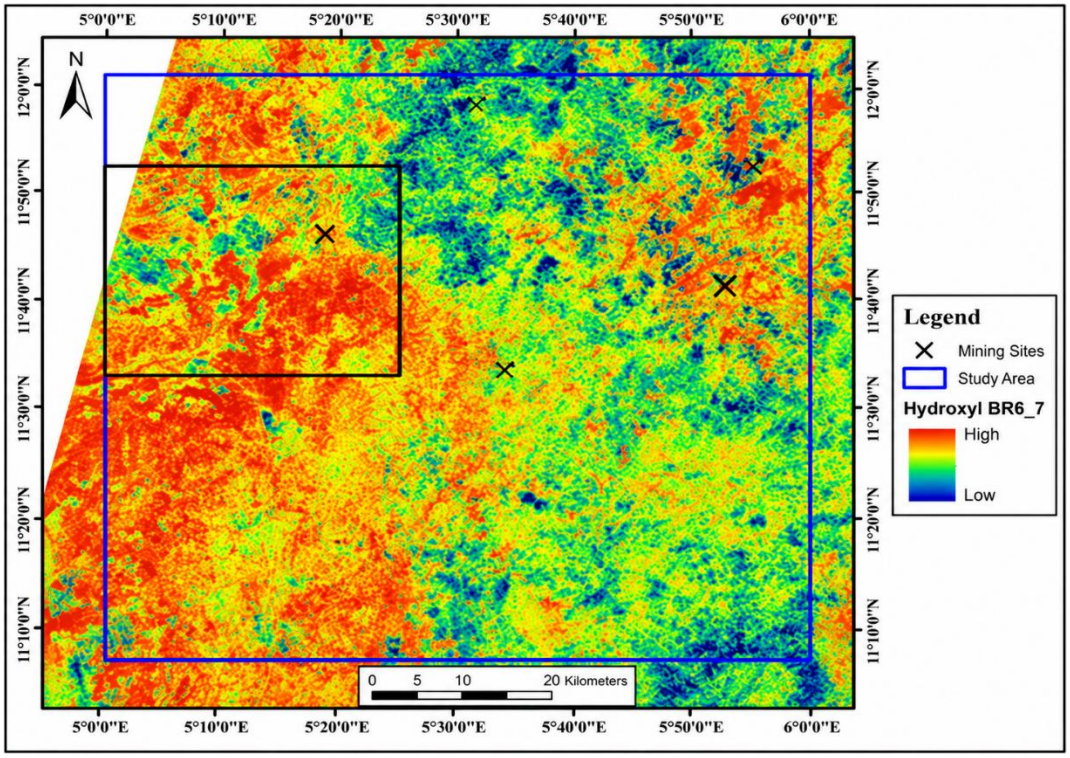


Figure 5 (c) BR 6/7 illustrating OH-bearing and carbonate minerals

Table 2. Landsat 9 OLI PCs data loadings of band 2, 4, 5 and 6 for iron oxide mineral

Eigenvector	Band2	Band5	Band6	Band7	Eigenvalues	Variance (%)	Cumulative %
PC1	0.499782	0.499852	0.500503	0.499863	3.980141	99.50	99.50
PC2	0.442326	0.531655	-0.332032	-0.641440	0.011616	0.29	99.79
PC3	0.698836	-0.539207	-0.402184	0.243171	0.007137	0.18	99.97
PC4	-0.257282	0.420413	-0.691013	0.528734-	0.001105	0.03	100.00

Table 3. Landsat 9 OLI PCs data loadings of band 2, 5, 6 and 7 for Hydroxyl minerals

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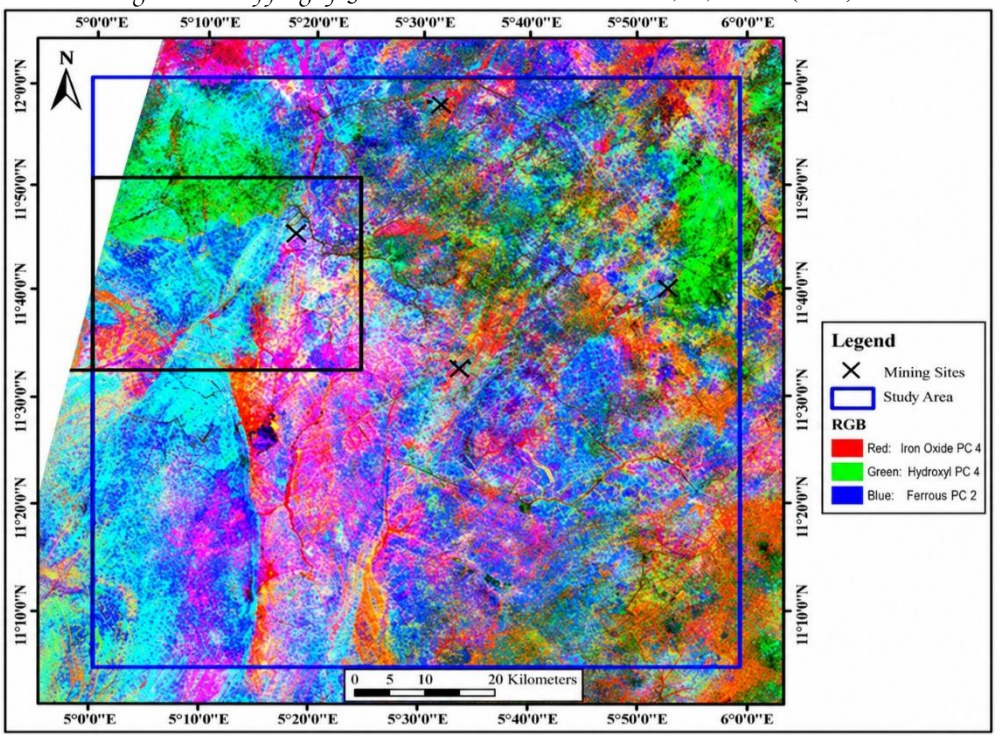


Figure 6. PCA (Crosta method) RGB combinations of iron-oxides, hydroxyl/carbonate and ferrous minerals in Donko area.

Lineament analysis revealed relatively high structural densities in the northeastern and central parts of the study area and lower densities toward the south (Figure 7a), with dominant NE–SW and NW–SE orientations and subordinate N–S trends (Figure 7b). Superimposition of Landsat-derived and aeromagnetic lineaments on the geological map showed higher structural concentrations over granite gneiss, undifferentiated schist and slate–phyllite, with moderate concentrations over graphite and migmatite and lower concentrations over quartzite and quartz–mica schist (Figure 8). The coincidence of alteration signatures with concentrated and intersecting lineaments identifies structurally favourable zones that may have facilitated hydrothermal fluid migration. Collectively, the results from Figures 4–8 and Tables 2–3 indicate that areas showing coincident lithological, alteration and structural signatures represent the most prospective remote-sensing targets for subsequent geological and geochemical validation.

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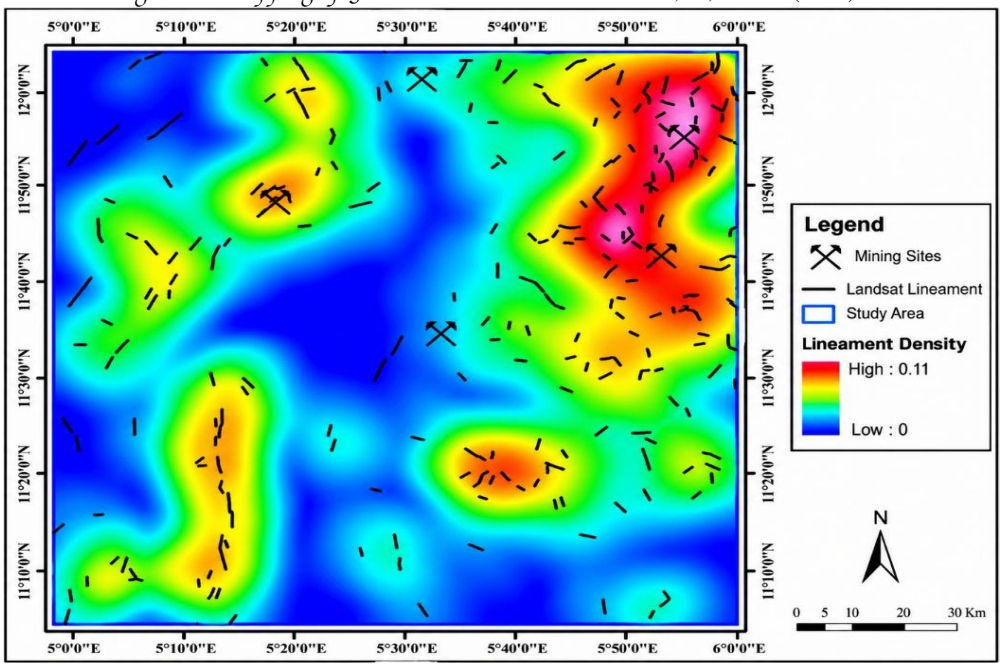


Figure 7a: Lineaments density map of Landsat 9 OLI Imagery of the Donko area.

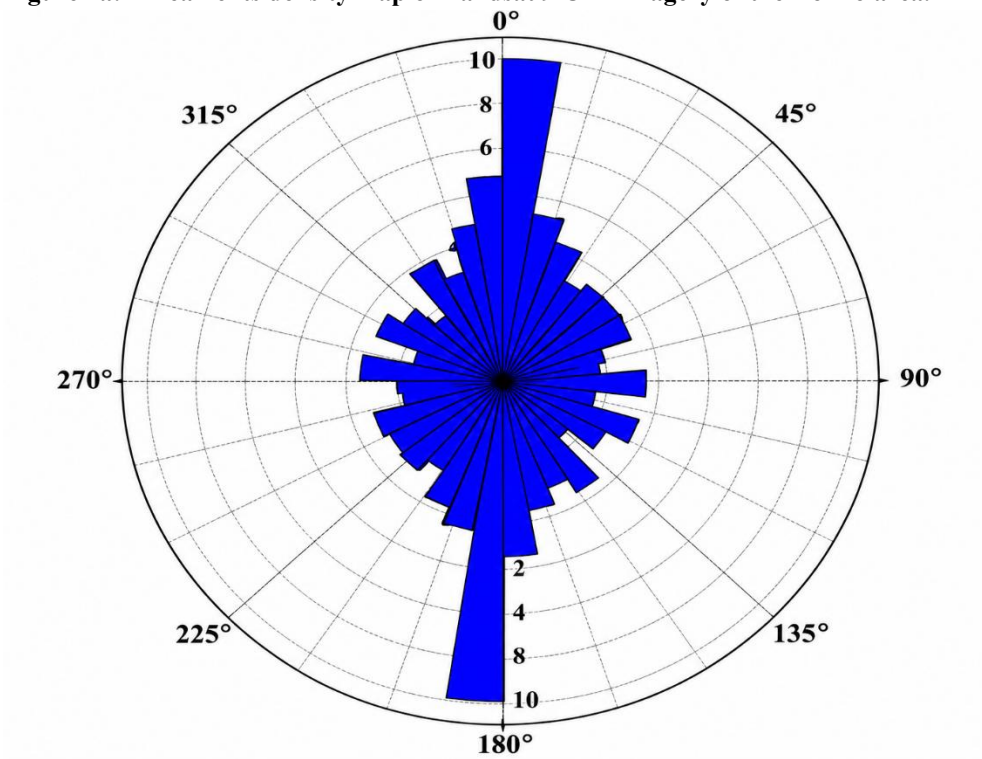


Figure 7b: Rose diagram of lineaments extracted from the Landsat 9 OLI Imagery of the Donko area.

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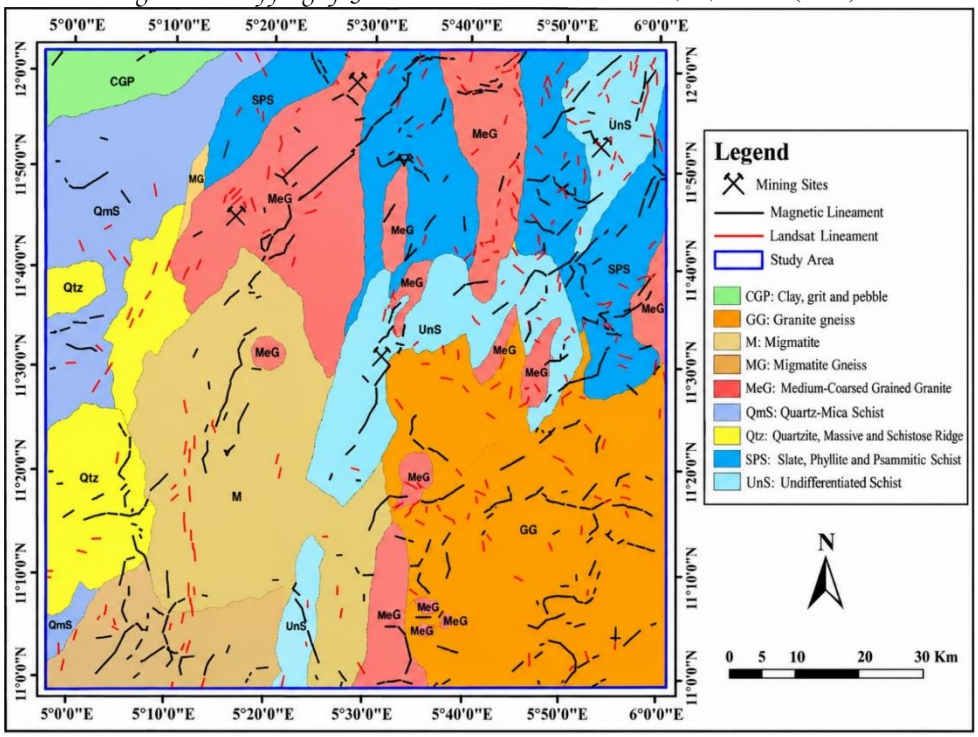


Figure 8: Superimposed Lineaments on the Geological Map of the Study Area

Conclusion

The Landsat 9 OLI-based investigation successfully demonstrated the capability of multispectral remote sensing to delineate lithological variations, hydrothermal alteration signatures and surface structural features associated with gold-mineralization potential in the Donko area of the Zuru Schist Belt. The 7-4-3 false-colour composite effectively discriminated the principal lithological units and their contacts, with distinct spectral responses observed for schist, gneiss and quartzite. Band-ratio analysis further enhanced the spatial distribution of iron-oxide/hydroxide, ferrous/silicate and hydroxyl/carbonate mineral responses, with the hydroxyl/carbonate signatures particularly occurring around the known gold-mineralized area. The selective Crosta-PCA analysis provided additional enhancement of these alteration assemblages and demonstrated strong spectral separation of iron-oxide, hydroxyl/carbonate and ferrous-mineral responses. Landsat-derived lineament analysis revealed relatively high lineament densities in the northeastern and central portions of the study area, with dominant NE–SW and NW–SE orientations and subordinate N–S trends, identifying structurally complex areas that may have provided pathways for hydrothermal fluids. The integration of lithological, alteration and structural information indicates that areas where iron-oxide, hydroxyl/carbonate and ferrous-mineral signatures coincide with concentrated lineaments constitute the most favourable remote-sensing targets for gold mineralization. Importantly, these results represent prospective alteration and structural signatures rather than direct confirmation of gold mineralization, and the delineated targets should therefore be subjected to detailed geological mapping and geochemical investigation for validation.

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