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Full Length Research

The analysis of Landsat 8 OLI image for delineation of hydrothermal alteration zones in the Artoli Area, Berber Province, Northern Sudan

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ABSTRACT: Based on the selection and development of exploration areas and the detection and mapping of mining areas, remote sensing has been used more frequently to acquire information about a geographic area of interest. Remote sensing-based applications reduce the need for field work and ultimately save costs. This effort explores the potential of remotely sensed digital data in highlighting mineralized zones through hydrothermal alteration studies. Landsat 8 OLI data covering the investigated area was used to detect and map locations of hydrothermal alterations. Image processing methods used were spectral enhancement, false colour composites, band rationing and Principal Component Analysis. Results of false colour composites (FCC) of band ratio highlighted generally locations of hydrothermal alterations. The band ratios image of Sabin's (6/7, 4/2, 4/6, and 4/6 in red–green–blue) revealed the presence of ferric, clay-rich, and ferrous iron minerals, respectively. The principal Components (PCs) of two sets of images (4, 5, 6, 7 H-image and 2, 3, 4, 5 F-image) were generated depicting iron-oxide and hydroxyl mineral deposits as bright pixels. The colour composite of H, F and H+F images enhanced the location of the mineral deposits by showing areas of mineralization in dark blue (clay-rich), bright yellow (Fe-rich), and white (alteration zones in bright reddish to orange) pixels. Fieldwork, previous remote sensing studies, and laboratory analysis were used to verify the image processing results. The remote sensing applications with field geochemical data results show that the spectral and spatial analysis of optical multispectral data in mineral exploration investigations is strengthened. This study recommends the use of remote sensing and geospatial technology in mineral studies through hydrothermal alteration within the basement complex rocks of the Arabian Nubian Shield.

Keywords: Band ratio, false colour composite, principal component analysis, Landsat-8 OLI.

INTRODUCTION

Remote sensing has been used in the past few decades in environmental geology and mineral and hydrocarbon exploration. In the initial stages of remote-sensing technology development in the 1970s, geological mapping and mineral exploration were the commonest applications (Rowan et al., 1974; Goetz *et al*., 1983). Multispectral and hyperspectral remote sensors were used in geological applications, ranging from a few spectral bands to more than 100 contiguous bands covering the visible to the shortwave infrared regions of the electromagnetic spectrum (Pour *et al*., 2013a; Pour *et al*., 2013b; Elsheikh *et al.,* 2014b). Geologic remote sensing has been widely applied in Sudan since the last century. It has been used for geological mapping, mineral exploration, geotechnical and hydrogeological investigations (Elsheikh *et al*., 2014a). The exploitation of remote sensing in mineral exploration is well understood by geological mapping and delineation of the regional and local structural features such as fractures, faults, and folds. Ore deposits were identified by detecting hydrothermally altered rocks by their spectral signatures (Gupta, 2003; Sabins, 1999a). Landsat-8 data have been widely used and are highly recommended for extracting areas of iron oxides and hydroxyl minerals that might be related to hydrothermal alteration zones of ore deposits (Kankara and Ohinowi, 2020).

The study area contains several exploration activities, and artisanal mining is widespread. It is located at the southern end of the Keraf Suture Zone (KSZ); it is sandwiched between the reworked older crust of Saharan Metacraton and the Neoproterozoic juvenile accreted arc terrine of the Arabian-Nubian Shield (Yang *et al*., 2024).

The area represents a basement complex terrain dominated by low-grade ophiolitic-decorated metavolcanosedimentary sequences, intruded by orogenic granitoid and anorogenic granites, and overlain by recent alluvial and aeolian sediments.

Few studies have been conducted in the Artoli area, and these studies have focused on geology and geochemistry (Lissan and Bakheit, 2010), this study utilizes remote sensing for the first time in the study area and produced good results for demarcating the alteration zones related to hydrothermal mineralization.

The objective of the present study is to map the alteration zones accurately and efficiently using an alteration extraction approach. This approach involved selecting the optimal band combination based on the Landsat-8 OLI satellite data of the Artoli area, Berber Province, Sudan.

STUDY AREA

Location and geomorphological setting

The study area is located in the northern part of the River Nile State of northern Sudan between Latitudes 17º 50` and 18º 30' N and longitudes 33º 40' and 34º 20' E. (Figure 1). The Artoli area is characterized by a typical desert terrain with an extensive peneplanation resulting in vast flat land. Remnants of isolated small hills and low ridges are scattered. The climate of the area is desert type with very few sporadic rains (less than 100 mm a year), that occur primarily between July and August. The temperature is above 40°C in summer and 15 to 20°C in winter. The area is very poor in vegetation due to the lack of rainwater; the vegetation is scarce where bushes of thorn trees rainwater; the vegetation is scarce where bushes of thorn trees rainwater; the vegetation is scarce where bushes of thorn trees, mainly acacia, are confined to khors and wadies.

Geomorphologically, the area characterized by occasional outcrops of the basement rocks are occasional outcrops of Basement rocks are exposed with 0.5 to 2 meters cover of alluvium and windblown sands. Several poorly defined drainage courses (wadies) flow westerly to the Nil River. The drainage in the study area is well developed, represented by many intermittent streams and khors. The drainage pattern is structurally controlled, where most wadies and khors follow fault plains and major joints.

Geology and tectonic setting

The greater part of the Artoli area is underlain by crystalline basement rocks, exposed in most parts except the westernmost. The basement rocks comprise a series of spatially overlapping metamorphosed complexes of schist and gneisses of volcanic and sedimentary origin cut by various generations of syn to late-orogenic intrusive granitoid and post-orogenic minor intrusions, all covered locally by Nubian sands and Recent superficial deposits. The geological setting of the Artoli area, which is characterized by predominantly low-grade metavolcanic rocks and minor high-grade metasediments, is different from that of the adjacent Bayuda terrane to the west (Saharan Metacraton) (Figure 2). The Keraf petrotectonic assemblage to the north (Suture zone), as the former is the heterogeneous continental crust of high-grade gneisses, migmatites, and supracrustal rocks of sialic geochemical affinities and the latter is dominated by siliciclastic and carbonate-rich low-grade metasediments, ophiolitic nappes, and molasses type sediments (Lissan and Bakheit, 2010).

METHODOLOGY

In this study, digital image processing is used to demarcate the alteration zones related to hydrothermal mineralization by their spectral signatures of the related iron oxides/ hydroxides and clay minerals.

A spectral ratio colour composite image was generated utilizing the Feature-Oriented Principal Component Selection (FPCS) technique to highlight the spectral signatures of these alteration zones. The principle component analysis (PCA) was used for selecting the optimized band combinations of mineralized alterations. The proposed PCA was employed to map iron oxides and hydroxyl minerals using the most commonly adopted multispectral data, Landsat-8 OLI data in the study. Several fifteen-chip samples were collected during the fieldwork for geochemical analysis from the delineated alteration zones.

A laboratory–office digital image processing and GIS investigation were utilized as the main approach for this study, with a little fieldwork to check the obtained exploration results. Various digital image processing techniques were applied to produce enhanced delineation of the spectral signatures of alteration halos related to hydrothermal mineralization.

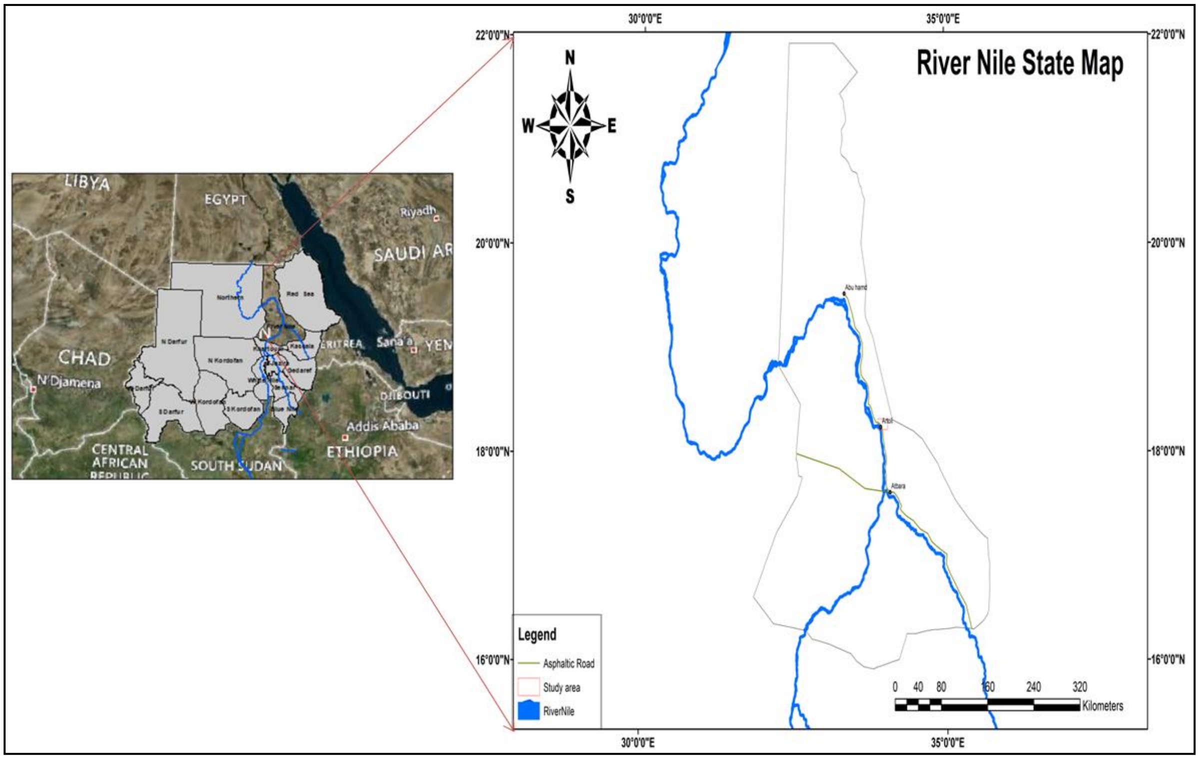

Figure 1. Location map of the study area.

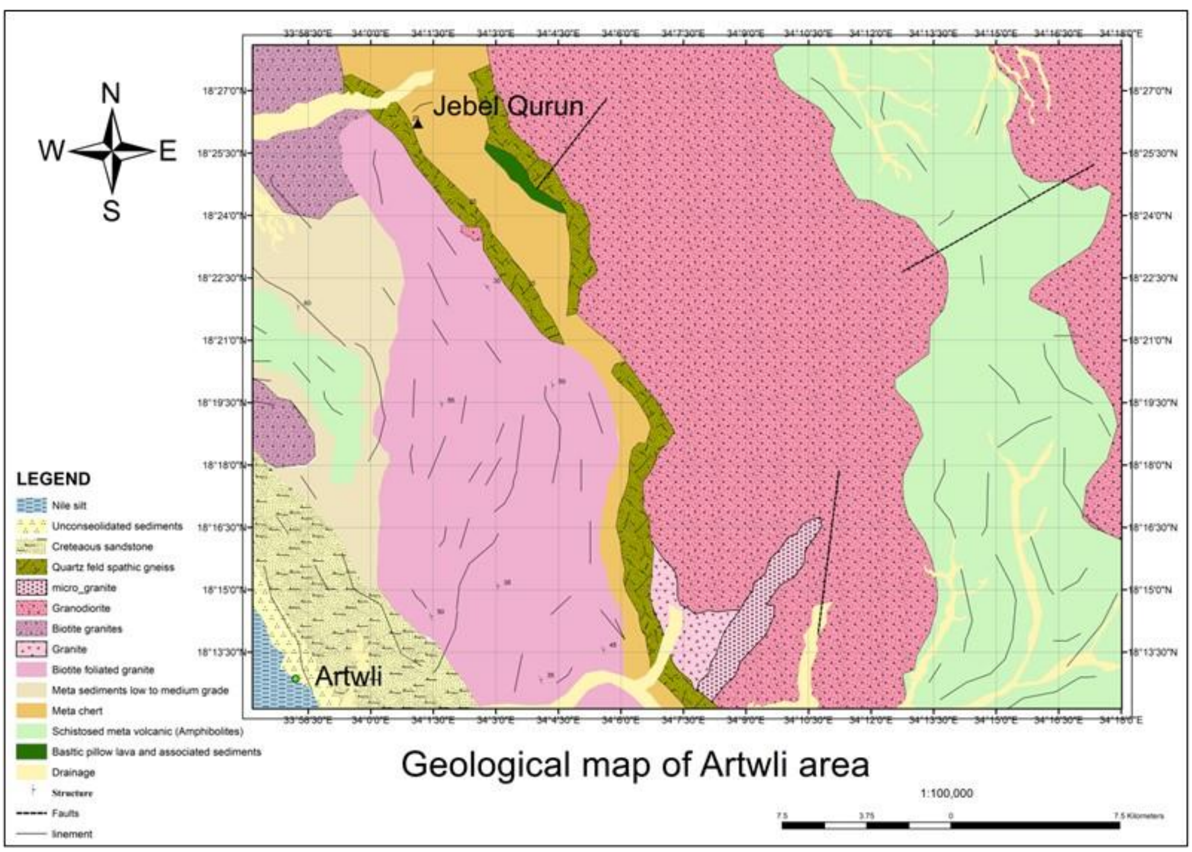

Figure 2. Geological map of the study area (after Lissan and Bakheit, 2010).

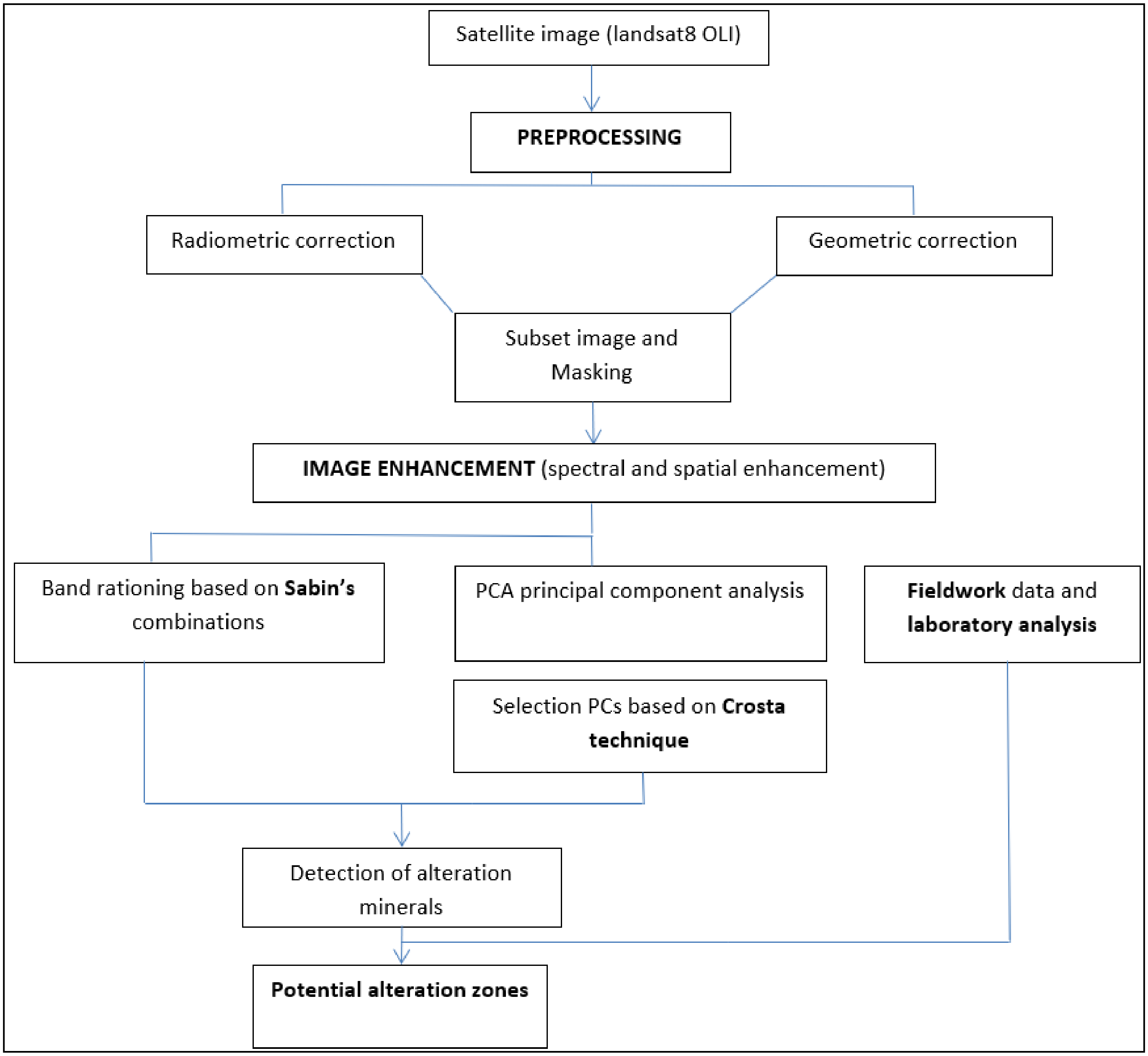

Figure 3. Flow chart showing the methodology of this study.

Fieldwork was performed to collect rock samples, and geochemical laboratory analyses were performed on the collected samples to confirm the potentialities of the alteration zones identified through the remote sensing and GIS techniques (Figure 3).

Data and material

Fifteen chip samples were collected during the fieldwork for geochemical analysis, and the data presented in Tables 1 and 2, as reference data in Table 3, were used during this study:

Data collection and analysis

Preprocessing of Landsat- 8 OLI data

The Landsat-8 image of the target site was processed with ENVI (Environment for Visualizing Images) version 5.3 software package. The Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) algorithm was applied for atmospheric correction for the Landsat 8 OLI data as the main preprocessing operation. Landsat-8 data were converted to surface reflectance by the internal average relative reflection method (IARR), which is recommended for calibration in mineralogical mapping, The IARR

Table 1. Remote sensing images for the study.

Area of interest image (AOI)	Data	Date of acquisition	Resoluti on	Path and rows
LC08_L1TP_173047_20240305_20240315_02_T1 (Artoli area)	Landsat8 OLI	March 5th, 2024	30	WRS173, WRS 047

Table 2. The software used for the study.

Software	Classification
Envi5.3	image analysis software
ArcGIS Desktop10.8	Geographic information systems
Microsoft Office	Data organization, analysis, and visualization

Table 3. The reference data used for the study.

Reference data	Acquisition date	Sources
Previous georeferenced digital map of Robertson Research Map, Berber Sheet	1988	Robertson Research Map GRAS

reflectance technique is recommended for mineralogical mapping as a preferred calibration technique. During the atmospheric correction, raw radiance data from the imaging spectrometer is re-scaled to reflectance data. This study did not use cirrus cloud (band 9) and TIR bands. Before doing image processing, the rich wadies were excluded by creating a mask using ENVI tools; wadies were excluded by creating a mask using ENVI tools to exclude the water and wide wadies pixels.

Image processing methods

The preparation and enhancement of the image were done by contrast stretching method. This image processing method is designed to transform multispectral image data format into an image display that increases the contrast between interesting targets and the background. False colour composite, band rationing, and principal component analysis (Crosta technique) were used in this study.

Band rationing method

Band rationing for hydrothermal alteration mapping was carried out using ENVI 5.3 software. Band ratio composites were formed: Sabin's ratio (6/7, 4/2, and 4/6 in RGB), which was used to map hydrothermal alteration and in the mapping of the sequence of the lithological features as colour composite (FCC) image using Sabins (1999a).

Principal component analysis (PCA)

This study applied selective principal component analysis (Crosta Technique) to Landsat 8 OLI imagery to map for argillites and iron stain areas (Crosta, 1989). Using this technique, an image displaying iron oxide alteration as light tone (F- Image) was produced by applying principal component analysis to bands 2, 3, 4, and 5 and negating the resulting principal component image. Also, an image displaying variation in clay (H- Image) was produced by applying principal component analysis on bands 4, 5, 6, and 7 and negating the resultant principal component image. The production of F and H image was followed by a combination of the F and H to generate an image displaying iron oxide and clay as a light tone (F+H) image. The F, F+H, and H images were assigned to the red, green, and blue channels. This image is expected to display iron stain and argillite-rich areas as white pixels, more argillite than iron stain areas as bright reddish to orange pixels, and more argillite than iron stain areas as bright cyan to bluish pixels. Band rationing and PCA techniques have been proven powerful in detecting hydrothermal alteration of clay minerals and iron oxides from the rest of the country rocks. Geochemical analysis was conducted for samples collected during the fieldwork.

RESULTS AND DISCUSSION

Mineralization in the study area

The study's results highlight the effectiveness of remote sensing techniques in detecting and mapping hydrothermal alterations linked to mineralized zones. Through various image processing methods such as false colour composites (FCC), band ratios, and Principal Component Analysis (PCA), the study identified key areas of hydrothermal alteration, including ferric, ferrous iron, and clay-rich minerals. The study identified key areas of hydrothermal alteration, including ferric, ferrous iron, and clay-rich minerals. For example, the use of Sabin's band ratios (6/7, 4/2, and 4/6) in red-green-blue (RGB) composites helped distinguish different mineral assemblages. The PCA results were especially valuable, revealing iron-oxide and hydroxyl minerals as bright pixels in the image, suggesting the presence of significant mineral deposits.

The findings reinforce the value of remote sensing for mineral exploration, particularly for reducing fieldwork and associated costs. This is consistent with other studies that have found remote sensing to be highly effective in highlighting mineralized zones, especially in areas like the Arabian Nubian Shield, where access can be challenging. The study's results match those of similar research that has employed band ratio techniques to detect hydrothermal alteration minerals. Integration of PCA with Fieldwork: The PCA results revealed mineralized areas in distinct colours, which were later verified through fieldwork. This underscores the importance of integrating remote sensing results with ground truthing and laboratory analysis. Previous studies have also recommended this approach to increase the accuracy of remote sensing predictions. However, this study goes a step further by not only confirming the presence of minerals but also mapping the extent of alteration zones, enhancing mineral exploration efforts. Comparison with Previous Studies: The findings align with earlier research on the Arabian Nubian Shield, where remote sensing techniques have successfully mapped mineralization zones. However, this study contributes additional insights by refining the spectral signatures associated with hydrothermal alteration, using a combination of H and F image sets to depict areas rich in clay and Fe minerals. Earlier studies might have focused on broader geological mapping, but this research narrows in on mineral alteration processes, making it more targeted for economic geology.

Band ratio

The band ratio results in this study were particularly effective in identifying hydrothermal alteration zones and different mineral assemblages. Band ratio techniques involve dividing the reflectance values of different bands, which enhances the spectral contrast between various surface materials, allowing specific minerals to be detected more easily.

Key band ratio results

Sabin's Band Ratios (6/7, 4/2, and 4/6 in RGB): 6/7 (Red): This ratio helped highlight ferric iron minerals, which are often indicative of oxidized zones in hydrothermal alteration. These minerals are associated with iron oxides such as hematite, which are common in mineralized zones. 4/2 (Green): This ratio is useful for identifying clay-rich minerals. Clay minerals are often formed in alteration zones as a result of hydrothermal activity, indicating areas where fluid-rock interaction has occurred. 4/6 (Blue): This ratio revealed the presence of ferrous iron minerals, which are common in reduced environments and are associated with deeper alteration zones or zones where oxygen is less available.

The combination of these ratios in a red-green-blue (RGB) composite allowed for a clearer differentiation of mineral types across the study area. Specifically: Red areas represented zones rich in ferric iron. Green areas were associated with clay minerals, which are common in hydrothermal alteration. Blue areas indicated the presence of ferrous iron minerals, pointing to potential mineralized zones. Mohammed and El Khidir (2023) employed the same band ratio image to identify alteration zones. This comparison allows us to assess the reliability of our method and demonstrates the applicability of these band ratios in similar geological settings.

Significance of band ratio results

These band ratios provided a detailed view of the mineralogical composition of the area, allowing researchers to identify potential sites for further exploration. The ability to distinguish between different iron oxides (ferric vs. ferrous) and clay minerals is crucial in mineral exploration, as these are often markers for hydrothermal systems associated with valuable ore deposits. The use of band ratios not only enhanced the visual representation of the alteration zones but also provided a more targeted approach for field verification, reducing the need for extensive ground surveys. Overall, the band ratio results were essential in highlighting the mineralogical variability in the study area, confirming the presence of hydrothermal alteration zones, and guiding subsequent exploration efforts. Most granitoid areas appear in green and navy-blue hues, while the metavolcanosedimentary sequences display greenish hues according to their composition. The wadies alluvial deposits display cyanic hues (Figure 4).

Principal component analysis (Crosta Technique)

Crosta's technique is used to map alteration zones. The OLI bands 2, 3, 4 and 5 are transformed to obtain the PCs defining iron oxides richer zones. The obtained PC image is called the F-image, while the OLI bands 4, 5, 6, and 7 are transformed to depict zones richer in hydroxyl-bearing minerals, the H-image. These images are produced after examining the eigenvector loading for both sets (Tables 4 and 5), which are PC2 in image the F-image, and PC4 in the H-image, and contain bigger arithmetic differences.

A low-pass filter is applied to remove small noises. The FPCS image defines alteration zones usually in terms of their iron oxides and clay minerals richer zones by the mathematically added image: F-image, (F-image+ H-image), and H-image in the R, G, and B colour gun,

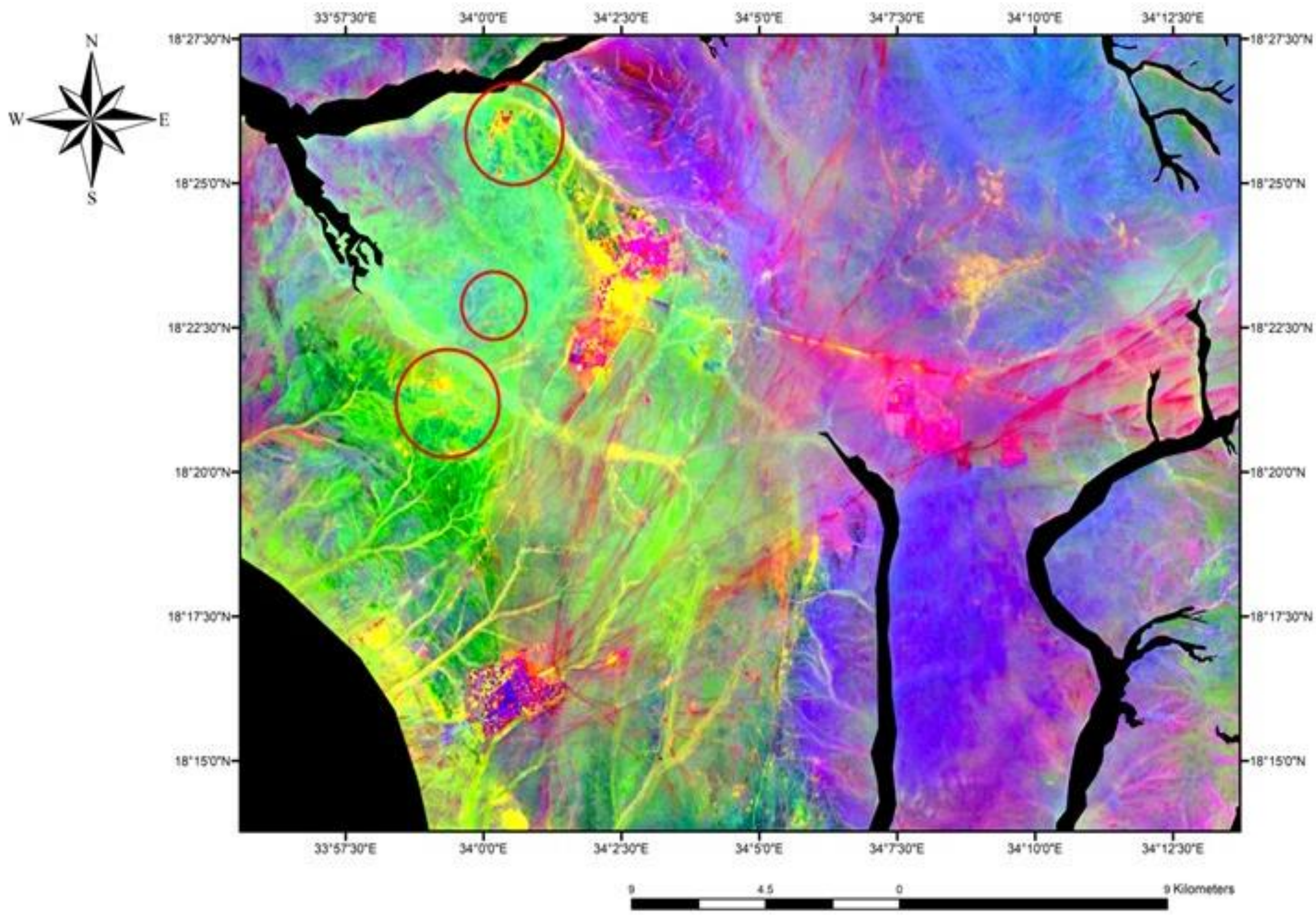

Figure 4. FCC Sabins' band ratio image of Landsat 8 OLI data of band ratio (6/7), (4/2), and (4/6) in the R, G & B, respectively. The image depicts alteration zones in crimson-reddish hues (after Sabin's 199b) Red circles highlight alteration zones.

Table 4. Eigenvectors of covariance matrix used to select F- image.

Eigenvectors	Band 2	Band 3	Band 4	Band 5
PC1	5.11	5.03	5.00	4.87
PC2	7.49	1.07	3.11	5.76
PC3	3.05	3.49	5.98	6.54
PC4	2.93	7.84	5.45	5.75

Table 5. Eigenvectors of covariance matrix used to select H- image.

Eigenvectors	Band 4	Band 5	Band 6	Band 7
PC1	5.05	4.94	4.98	5.02
PC2	5.92	3.95	4.4	5.47
PC3	5.13	5.82	4.19	4.72
PC4	3.62	5.11	6.18	4.75

depicting the potential alteration zones in bright reddish to orange (Figure 5). The results obtained in this study was compared with those from previous studies. For instance, Mohammed and El Khidir (2023) used Principal Component Analysis (PCA) to identify hydrothermal environments, and both studies produced consistent and

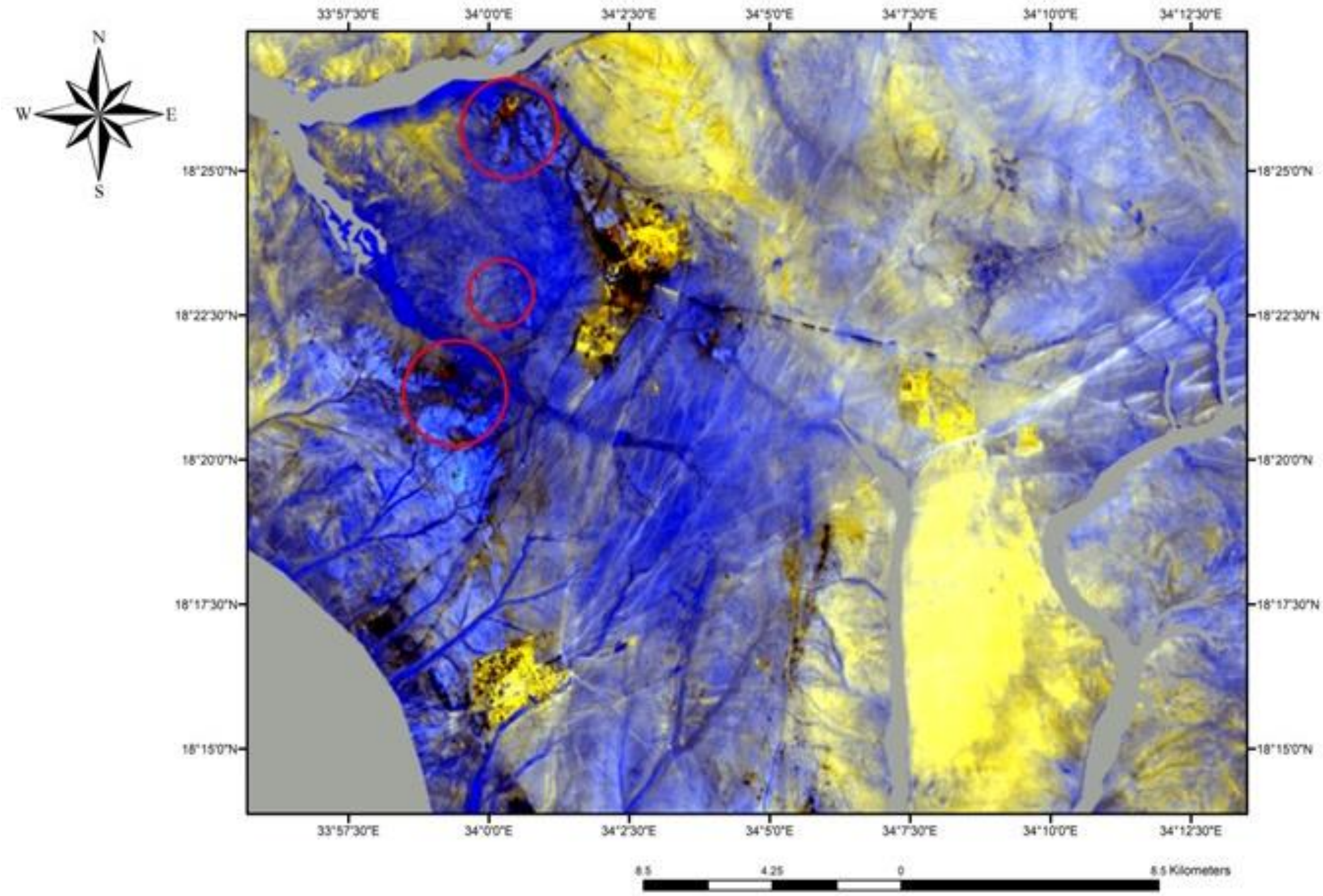

Figure 5. Crosta's alteration image (F—image, F—image + H—mage, H—image in the R, G, B, respectively) depicts alteration zones in bright reddish to orange. Red circles highlight the alteration zones.

valuable results. While this study confirms the effectiveness of PCA demonstrated in earlier research, some variations were observed. For example, Loughlin (1991) applied PCA to Landsat TM images for alteration mapping, but in this study, the alteration zones are more distinctly visible. This clarity is likely due to the specific satellite data that was used, enhancing the method's value for our analysis.

Geochemical evaluation

The outcome of the remote sensing and GIS investigations have been validated by ground thrusting for assessing the delineated alteration zones. 15 alteration zone samples were used to delineate hydrothermally altered rocks located by the global position system (GPS). Alterations and Quartz vein samples were selected for Atomic Absorption Spectrometry (AAS) from the delineated hydrothermal veins. The obtained results are displayed in Table 6. These samples were taken from different areas of the Artoli area (Figure 6).

The results from the gold-bearing quartz veins and alteration zones show a clear variation in gold distribution. Gold concentrations range between 0.001 and 0.25 parts per million (ppm), with an average concentration between 0.02 and 0.03 ppm. These values are considered low from an economic perspective, as the minimum profitable threshold for gold extraction is typically between 0.5 and 1.0 ppm. The higher value found (0.25 ppm) is still below the economic threshold, but it indicates the potential presence of better mineralization in the area, warranting further exploration.

The variation in gold distribution suggests that gold may be concentrated in local structural formations or specific areas within quartz veins and alteration zones. Remote sensing can guide fieldwork efforts towards potential zones but chemical analysis remains crucial for evaluating the mineral potential. Further analysis at different depths to determine if higher gold concentrations exist.

The outcome of the present study proved the effectiveness of using remote sensing methods in mineral

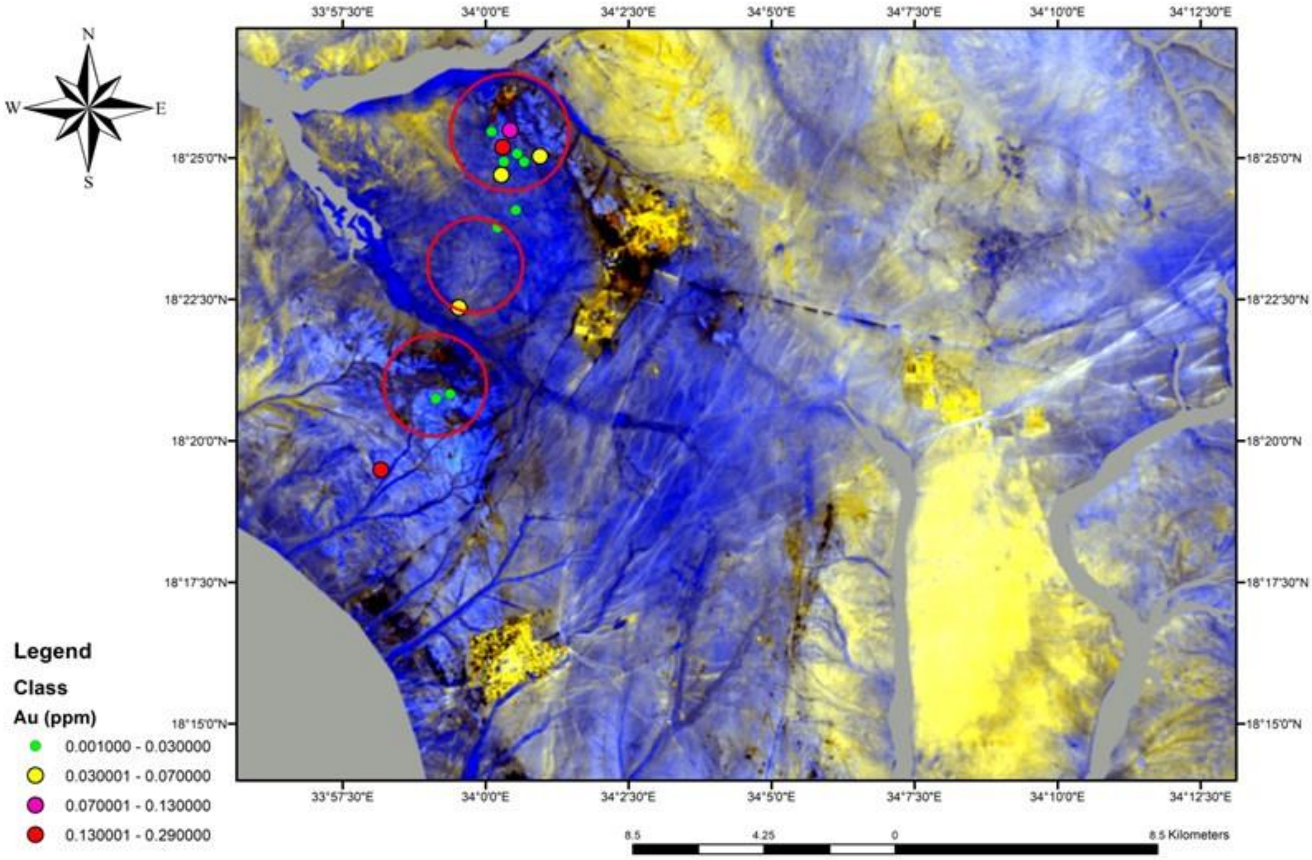

Figure 6. The potential alteration zones produced by intersection spatial analysis of the alteration zones produced from Crosta's, with geochemical analysis data for the collected chip samples.

Table 6. The geochemical analysis of the collected chip samples.

Sample	Easting	Northing	Au (ppm)	Lithology
240275	605784	2037433	0.02	ST-QTZ
130732	606135	2036930	0.25	QTZ
240279	605788	2037433	0.01	QTZ
131364	606356	2037483	0.13	Alteration
130683	606180	2036463	0.01	QTZ
239956	606099	2036025	0.04	QTZ
130679	606582	2036724	0.02	QTZ
20003	605992	2034307	0.03	Alteration
19698	606554	2034883	0.02	Alteration
219097	604127	2028724	0.01	Alteration
219091	604563	2028876	0.01	Alteration
3235	602442	2026393	0.29	QV
240232	604817	2031695	0.07	Alteration
19426	606799	2036452	0.001	Alteration
130674	607286	2036637	0.05	Alteration

exploration and delineation of hydrothermal alteration zones. Several studies have adopted these methods, Mohammed and El Khidir(202) studied "the use of Landsat 8 OLI image for the delineation hydrothermal alterations zones in the Haiya Area, Red Sea hills, NE Sudan, and El Khidir and Babikir (2013) studied the "Landsat ETM+7 digital image processing techniques for lithological and structural lineament enhancement: A case study around Abidiya area, Sudan. These methods have become more important in mineral exploration, and they reduce fieldwork time and cost.

Conclusion and Recommendations

The digital image processing revealed areas with favourable hydrothermal alteration signals that were later verified in the field. The Landsat 8 OLI data processing allowed us to map the potential targets of mineralization around the Artoli area. In addition, it showed traces of mining operations in the study area. Indeed, band rationing and principal component analysis techniques showed pertinent results in the discrimination of hydrothermally altered rocks. Thus, the occurrence of hydrothermal minerals (iron oxides, hydroxyl-bearing, and clays) has been noticed, Geochemical analysis of the atomic absorption spectrometry (AAS) revealed the presence of alterations in the area. These two methods were combined to identify and delineate alteration zones.

By identifying key alteration zones, the study's findings can guide future exploration and potentially lead to new mining projects. This has broader implications for the mining industry, particularly in countries like Sudan that are looking to expand their mineral resources. The use of remote sensing data could accelerate the process of discovery and evaluation of mineral deposits, reducing reliance on time-consuming and costly field surveys.

The study's results not only validate the use of remote sensing in detecting mineralized zones but also show that advanced image processing techniques can produce highly accurate and actionable information. When compared with previous studies, this research demonstrates a more precise application of spectral data in mineral exploration, making it a valuable contribution to the field.
Based on the results of the study, the following recommendations are made:

- Remote sensing techniques should be integrated with fieldwork and laboratory analysis to enhance the accuracy of mineral detection and confirm results with lower costs and higher reliability.
- Utilize additional exploration techniques such as Geophysical surveys (magnetic or electrical resistance methods) can be used to identify subsurface structures that might contain higher concentrations of gold.
- Use of multispectral and hyperspectral data is recommended to improve the accuracy of mineral identification and more precisely determine alteration types.
- It is recommended to conduct similar studies in other areas of the Arabian Nubian Shield to increase knowledge of the mineral resources and support future exploration activities.
- Remote sensing should be adopted as a primary tool in the early stages of exploration, especially in remote or hard-to-access areas, to reduce costs and prioritize areas for field studies.

CONFLICT OF INTEREST

The authors declare the they have no conflict of interest.

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