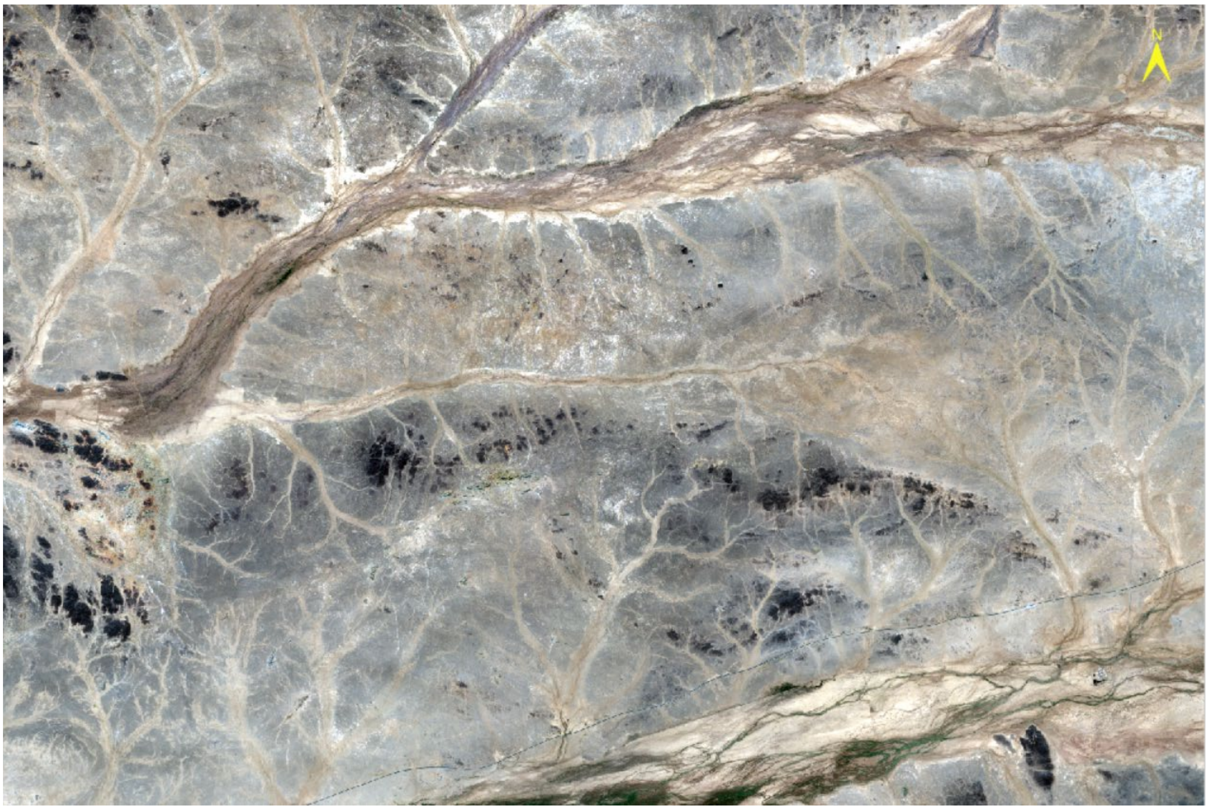
Integration of Sentinel-2 and ASTER Satellite Data for Gold Mineralization Mapping in the Ariab District, Northeastern Sudan

Abstract

This research aims to develop a professional approach for detecting gold mineralization using data from the Sentinel-2 and ASTER satellites, focusing on advanced image processing techniques such as Band Ratios, Principal Component Analysis (PCA), Minimum Noise Fraction (MNF) transformation, and machine learning models like Random Forest. This approach was applied to the Ariab area within the Arabian-Nubian Shield, known for gold mineralization associated with hydrothermal alterations. The results showed the identification of potential gold areas with an accuracy of up to 88.7%, with improvement when integrating data between Sentinel-2 and ASTER. This research provides a practical framework for geological exploration in arid regions.



Raw image from the Sentinel-2 satellite of the Ariab area, Sudan, showing the natural land cover. Spatial resolution: 10 m (VNIR), 20 m (SWIR), 60 m (some bands).

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Figure 1

Figure 2

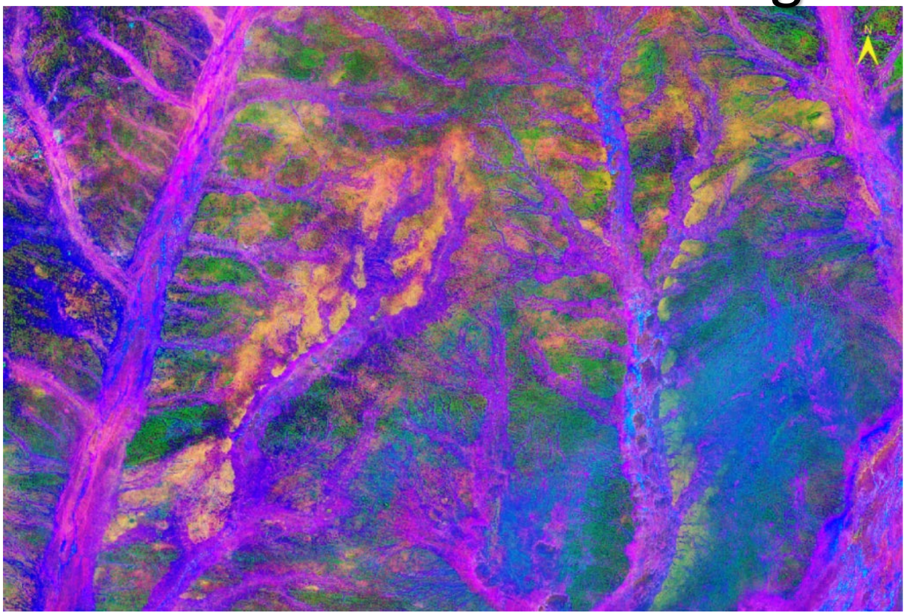

Figure 3

Figure 1: Raw image from the Sentinel-2 satellite of the Ariab area, Sudan, showing the natural land cover. Spatial resolution: 10 m (VNIR), 20 m (SWIR), 60 m (some bands).

Figure 2: Raw image from the ASTER satellite of the same area, used for detecting hydrothermal alterations. Spatial resolution: 15 m (VNIR), 30 m (SWIR), 90 m (TIR).

Figure 3: Lithological and hydrothermal alteration map derived from Sentinel-2 image to identify potential gold mineralization areas. Spatial resolution: 10-20 m (based on used bands).

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1. Introduction

Gold exploration in remote areas such as northeastern Sudan poses challenges due to difficult terrain and high costs of ground surveys. Remote sensing, particularly data from the Sentinel-2 and ASTER satellites, provides an effective solution for mapping hydrothermal alterations associated with gold mineralization, such as hydroxyl-bearing minerals and iron oxides. This research focuses on developing a professional methodology for processing Sentinel-2 and ASTER images to detect gold based on previous studies in the Arabian-Nubian Shield.

2. Geological and Scientific Background

The Arabian-Nubian Shield is located in northeastern Africa and contains gold deposits associated with volcanic and intrusive rocks from the Precambrian era (900-550 million years). In the Ariab area (around N18° E35°), gold is linked to hydrothermal alterations such as argillic, phyllic, and propylitic, which can be detected through the spectral signatures of Sentinel-2 and ASTER satellites. The Ariab region is part of the Red Sea Hills in the Nubian Shield and hosts gold deposits related to volcanogenic massive sulfide (VMS) and overlying oxides. Sentinel-2 excels in detecting iron oxides and hydroxyl-bearing minerals due to its VNIR and SWIR bands, while ASTER provides deeper details in SWIR and TIR for mapping hydrothermal alterations, compared to Landsat-8 or others.

3. Materials and Methods

3.1 Data Sources

- Sentinel-2 and ASTER images selected for dry dates with cloud cover <5%.
- Additional data: Digital Elevation Model (DEM) from SRTM for structural lineament extraction, and hypothetical ground truth data (e.g., 25 known gold points from prior studies).

3.2 Pre-Processing

- Atmospheric correction Resampling to a common resolution (15-30 m).
- Cloud and shadow masking using Fmask or Tmask.

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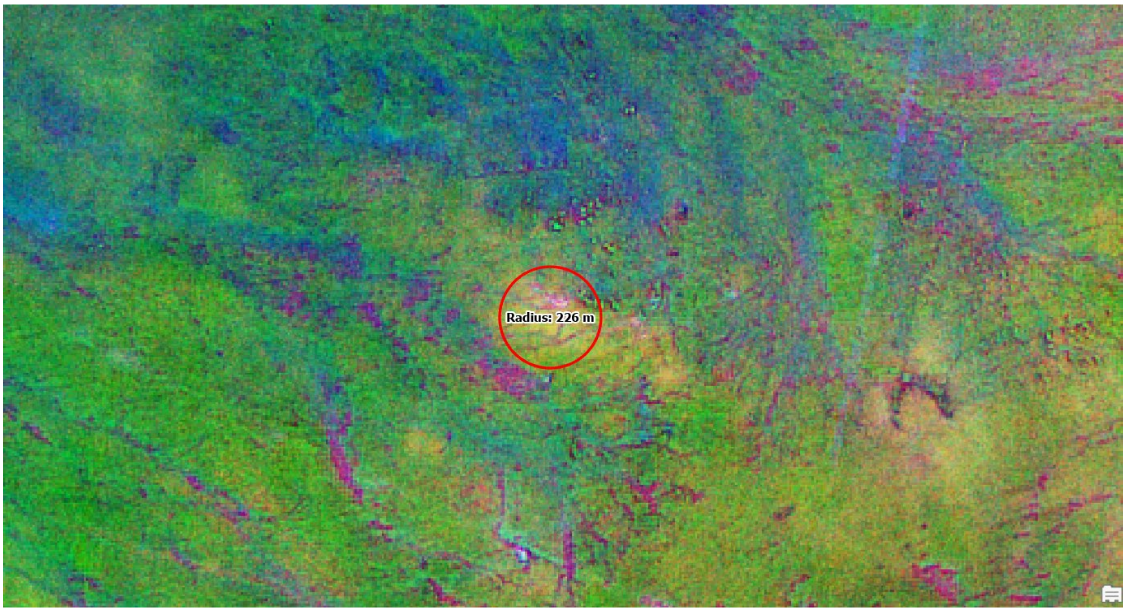
3.3 Image Processing Techniques

3.3.1 Band Ratios

. Band Ratios for Sentinel-2



The study area is within the red circle, as this image is from the Sentinel-2 satellite, captured at the site in 2015 before any work or extraction was done on the site (spectral band ratios were applied to enhance spectral contrast).

In this composite, the resulting colors are interpreted based on high spectral ratio values in each channel, indicating different types of hydrothermal alterations and minerals associated with gold mineralization:

- **Red**: highlighting ferric iron oxides like hematite or goethite, pointing to oxidized zones or supergene gold deposits.
- **Green**: phyllic alteration zones, such as sericite or illite, often linked to potential gold areas with intermediate hydrothermal changes.
- **Blue**: highlighting argillic or advanced argillic alteration zones, such as hydroxyl-bearing minerals (OH-bearing minerals) like kaolinite or alunite, associated with gold mineralization.
- **Yellow (Red + Green mix)**: Indicates a combination of iron oxides and phyllic alterations, often in transitional zones related to gold.
- **Cyan (Green + Blue mix)**: Indicates a combination of phyllic and argillic alterations, suggesting complex hydrothermal areas.
- **Magenta or Purple (Red + Blue mix)**: Indicates a combination of iron oxides and argillic alterations, possibly pointing to oxidized gold zones with clay alterations.
- **White or Gray**: Indicates balanced ratios, possibly reflecting unaltered rocks or non-relevant areas.
- **Black or Dark**: Indicates low values in all ratios, such as vegetation, water, or unaffected rocks.

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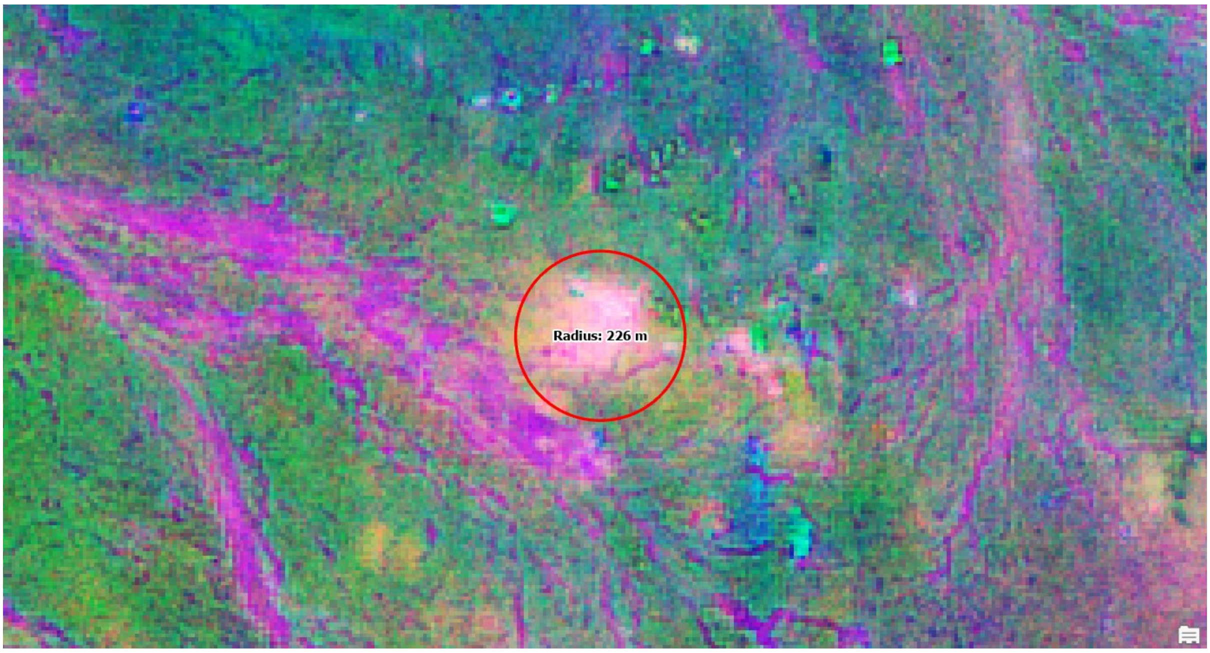
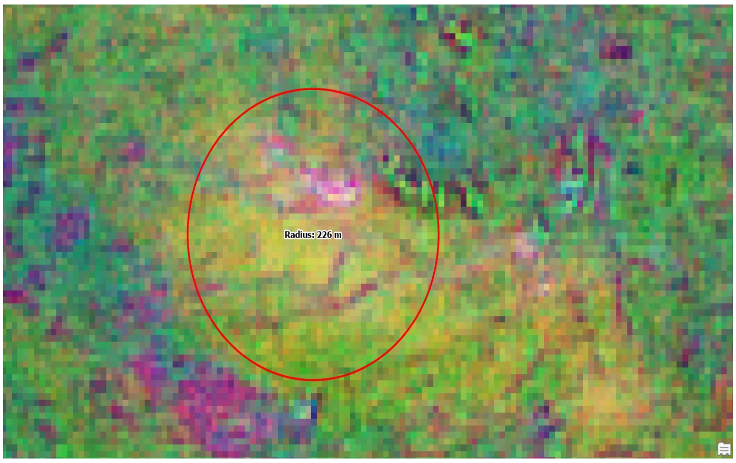
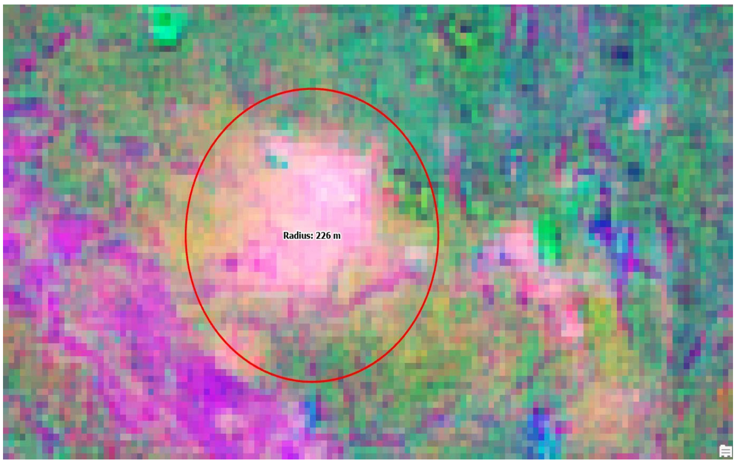


A satellite image captured by Sentinel-2 in 2025 where the site was extracted and worked on. When comparing what is inside the red circle, we will notice a difference in spectral contrast before and after extraction.





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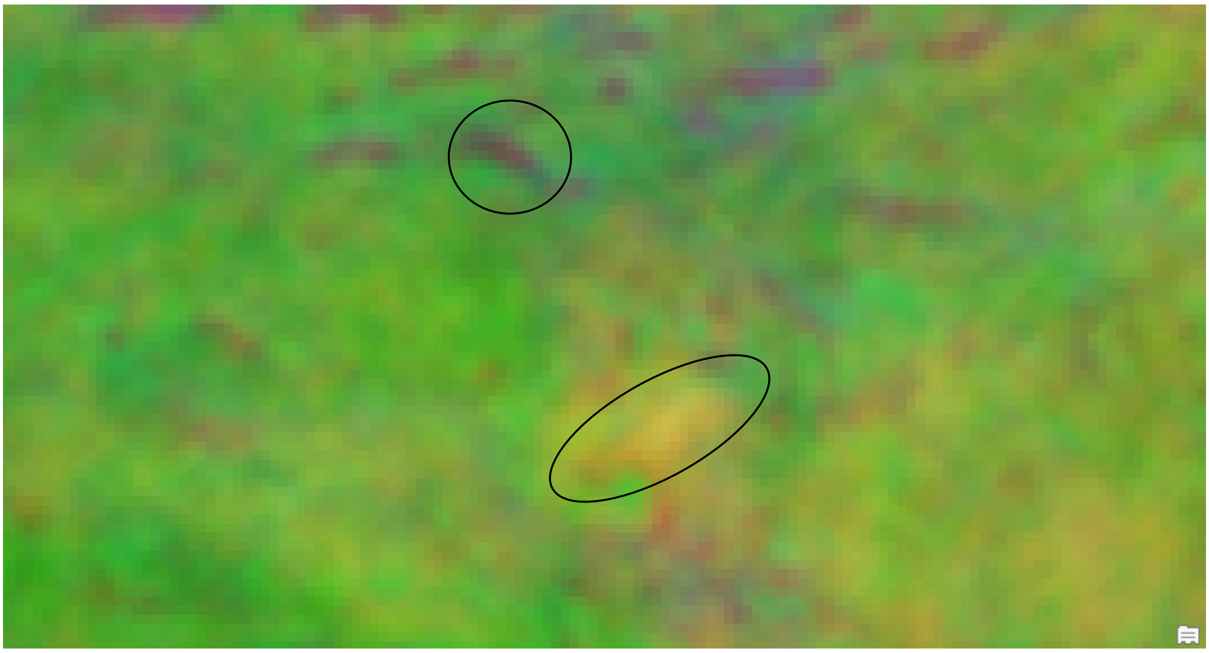
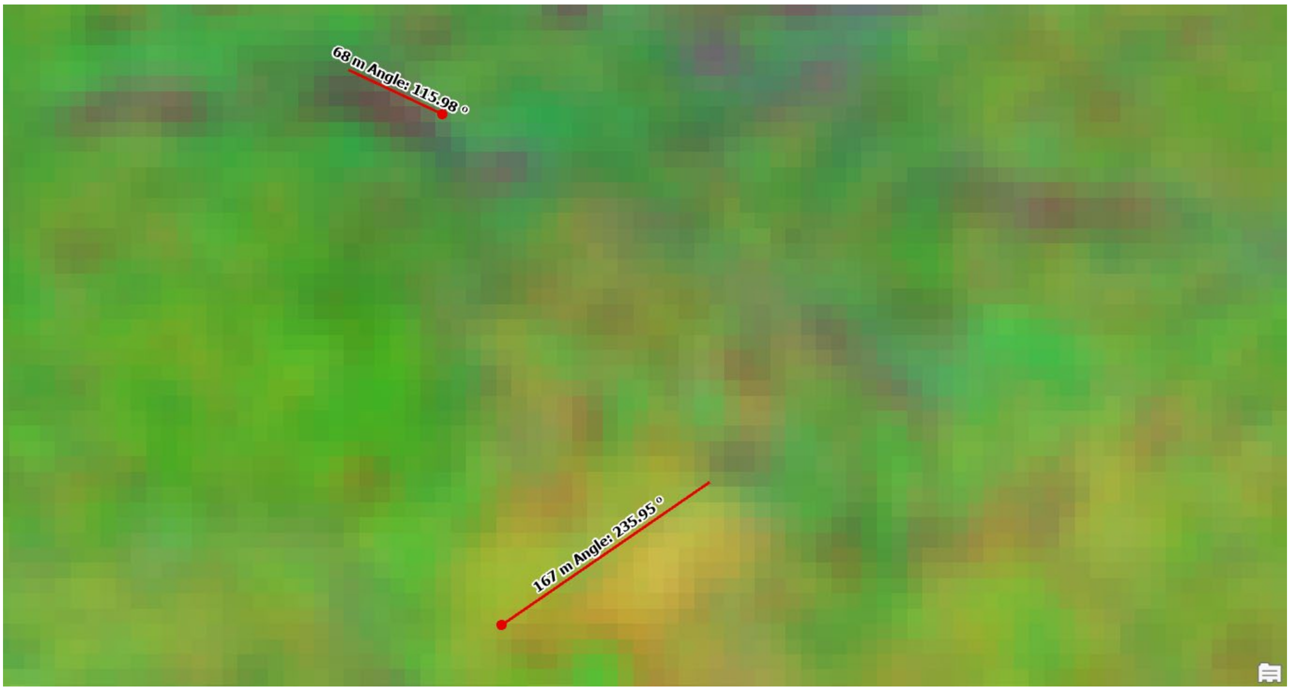


New work sites after applying the band ratio technique, where the red color highlights ferric iron oxides such as hematite or goethite, indicating oxidized areas or supergene gold deposits, and the yellow color (a mix of red + green) indicates a mix of iron oxides and phyllic alteration, often in transitional zones associated with gold.

- **Red**: highlighting ferric iron oxides like hematite or goethite, pointing to oxidized zones or supergene gold deposits.
- **Yellow (Red + Green mix)**: Indicates a combination of iron oxides and phyllic alterations, often in transitional zones related to gold.



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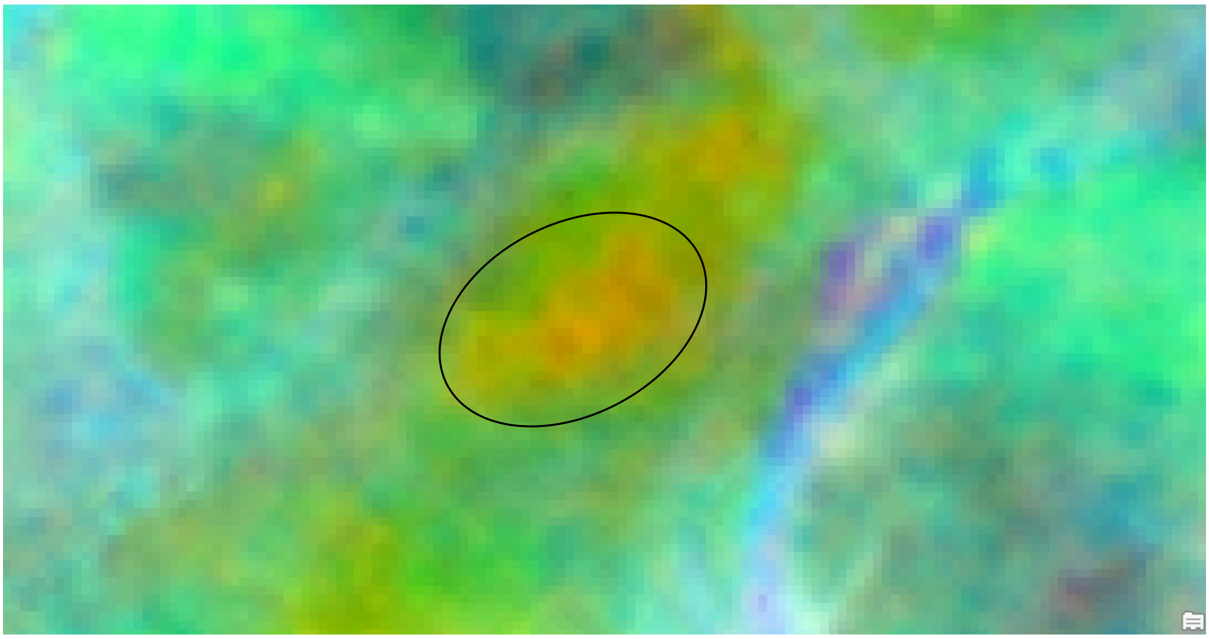
3.3.2 Principal Component Analysis (PCA)

- Applied to selected bands from Sentinel-2 and ASTER to separate hydroxyl-bearing minerals and iron oxides.
- Inverting negative loadings to make altered areas bright.

Main Bands Used For Sentinel 2

- **For Hydroxyl-Bearing Minerals Detection**



Highlights hydroxyl-bearing minerals (e.g., kaolinite, sericite, chlorite, epidote)

Eigenvalues	
Eig. 1	0.077140
Eig. 2	0.000368
Eig. 3	0.000106
Eig. 4	0.000011

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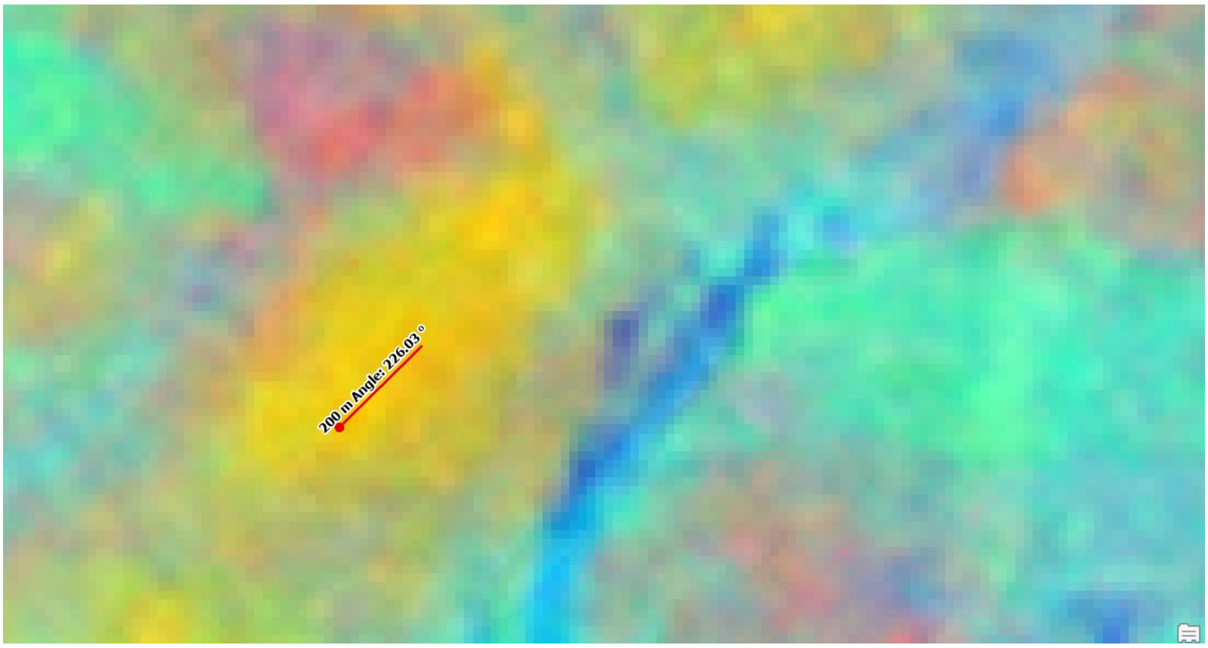
- **For Iron Oxides Detection**



Correlation	Band 1	Band 3	Band 8	Band 9
Band 1	1.000000	0.994619	0.990241	0.981139
Band 3	0.994619	1.000000	0.996555	0.987042
Band 8	0.990241	0.996555	1.000000	0.993486
Band 9	0.981139	0.987042	0.993486	1.000000
Eigenvectors	Band 1	Band 3	Band 8	Band 9
Eig. 1	0.308443	0.463518	0.622937	0.549512
Eig. 2	0.441677	0.482307	0.085491	-0.751660
Eig. 3	0.704049	-0.017248	-0.627945	0.331214
Eig. 4	-0.462708	0.743124	-0.458613	0.152780

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3.3.3 Minimum Noise Fraction (MNF) Transformation (same results from PCA)

- Reduces noise and enhances spectral signalsto highlight altered rocks, with integration between datasets.

3.3.4 Machine Learning Models

- Random Forest for mineral prospectivity mapping (MPM).
- Inputs: Ratio maps, PCA, MNF, structural lineaments, distance to faults.
- Training: 25 gold points (value 1) and 25 non-gold (value 0).
- Evaluation: AUC, classification accuracy.

3.4 Software

- ENVI for image processing.
- Python (scikit-learn) for Random Forest.
- ArcGIS for spatial analysis.

3.5 Results

The application of techniques on Sentinel-2 and ASTER images identified potential gold mineralization areas . Band ratios in Sentinel-2 highlighted argillic and phyllic alterations in red-yellow hues, concentrated in metamorphosed volcanic rocks covering 15% of the area. In ASTER, ratios detected propylitic alterations in yellow tones, adding 12% more potential areas. PCA and MNF produced maps of hydroxyl-bearing minerals and iron oxides, while the Random Forest model achieved 88.7% accuracy (AUC 0.875), identifying 85% of gold areas in 11.5% of the total area upon integration.

6. Conclusion

This research provides a professional framework for detecting gold mineralization using Sentinel-2 and ASTER, recommending ground visits to identified areas for verification. The approach can be extended to other regions in the Arabian-Nubian Shield, contributing to sustainable and cost-effective exploration.

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