Mapping of Potential Alteration Zones for Mineralization Prospects Using Remotely Sensed Data: Case of Mankayan Mineral District, Benguet in Cordillera Administrative Region (CAR), Philippines

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Abstract

Mineral exploration through remote sensing has become integral, employing satellite or airborne imagery, to assess and characterize surface features indicative of concealed mineral deposits. Multispectral imagery is used to detect surface features including mineral alteration zones, vegetation stress, and soil geochemical anomalies, which are often associated with subsurface mineralization. This study focuses on the Mankayan Quadrangle, with emphasis on the Far Southeast (FSE) Project in northeastern Luzon, Philippines. The FSE is a copper-gold porphyry deposit. The mineral district serves as a calibration site for geological mapping, lineament delineation, and alteration zone identification. However, challenges arise due to the tropical climate and dense vegetation. This study evaluates the suitability of remote sensing for updating geological maps and generating potential mineralization maps. Data include Sentinel-2 L2A imagery and existing geological maps. Preprocessing involves spatial subsetting and resampling, while processing techniques involve contrast enhancement, color composites, spectral ratioing, and principal component analysis. The results reveal that Sentinel-2 L2A imagery effectively identifies intrusive complexes, metasedimentary rocks, pyroclastic and volcaniclastic rocks, and recent deposits. Lineament analysis reveals NE- and NW-trending splays of Ambuklao Fault. High band ratio values, >1.0 for 4/3 (ferric iron), >1.0 for 11/8 (ferric oxide), and >2.2 for 11/12 (hydroxyl and clay minerals), indicate hydrothermal alteration. Areas within approximately 2 km of fault splay intersections and hosted by pyroclastic or volcaniclastic rocks are classified as having inferred mineral resource potential. These areas include Cadad-anan, Mabaay, Lenga, Sadsadan, Dacudac, northern Monamon Sur, and the northeastern flank of Mount Data.

1. Introduction

1.1. Background of the Study

Remote sensing provides an effective and scientifically grounded approach to mineral explorations, facilitating the identification and evaluation of surface mineral composition and geological structures through the measurement of reflected and/or emitted electromagnetic radiation (Gupta, 2018). Modern remote sensing approaches that employ sensors mounted on satellites, aircraft, and surface instruments collect radiance information over an extensive range of spectral bands (Samadzadegan et al., 2024). These technologies penetrate a few micrometres in the visible to near-infrared (VNIR) range, a few centimetres in the thermal infrared (TIR) (Abdulraheem et al., 2023), and, in hyper-arid regions, potentially several meters in the microwave domain (Mansour et al., 2024). A key advantage of remote sensing is its ability to record diagnostic spectral signatures of surface materials for geological mapping (Mohamed et al., 2021), alteration zones (Olomo et al., 2025), lithologies (Chen et al., 2023), structural features (Zouggarh et al., 2024), lineaments (Olomo et al., 2025), oxidation zones (Yang et al., 2015), drainage patterns (Koganti et al., 2021), and landforms (Ye et al., 2019). Mineral groups such as clays, sulfates, and iron oxides exhibit unique spectral reflectance properties that make these mineral groups identifiable through remote sensing analysis (Sabins, 1999). This spectral information aids geologists by reducing costs and improving overall efficiency in all stages of an exploration program, though it is most useful in the prospecting stage (Gupta, 2018).

Numerous studies have showcased the effectiveness of alteration mapping using multispectral remote sensing data (Zouggarh et al., 2024, Olomo et al., 2025). The ease of detecting these minerals is largely attributed to the type of image processing algorithms used, such as band ratios (Habashi et al., 2024), false color composite (FCC) (Nafigin et al., 2022), principal component analysis (PCA) (Chen et al., 2025), minimum noise fraction (MNF) (Nafigin et al., 2022), and spectral angle mapping (SAM) (Chen et al., 2025). These methods enhance subtle spectral variations, enabling effective discrimination of alteration zones related to mineralized systems, such as argillic, phyllic, and propylitic assemblages. For example, combinations of ASTER SWIR band ratios and PCA have been effectively applied in various geologic settings to delineate zones of hydrothermal alteration associated with porphyry and epithermal mineralization (Habashi et al., 2024).

However, applying these techniques in densely vegetated tropical regions, such as the Philippines, introduces significant challenges. Thick forest canopies and persistent cloud cover obstruct the visibility of surface mineralogy, making it difficult to extract accurate spectral information (Gupta, 2018). The spectral dominance of vegetation masks the absorption features of alteration minerals, particularly in the VNIR and SWIR regions (Hede et al., 2017). Furthermore, high humidity and atmospheric scattering often degrade image quality, reducing the effectiveness of standard algorithms (Adams et al., 2021). Overcoming these limitations typically requires advanced preprocessing steps such as vegetation masking, cloud filtering, and the use of auxiliary datasets (Ghoneim et al., 2024). Integration with other multispectral (Pan et al, 2023), hyperspectral (Pour et al, 2013), LiDAR, or radar data, along with field validation, is often necessary to improve the reliability of alteration mineral detection in tropical environments (Shen et al., 2024).

1.2. Study Area

This study is situated within the Philippine Island arc system, a tectonically active region shaped by complex geodynamic processes, including ophiolite accretion, arc magmatism, ocean basin closure, and crustal deformation (Queaño et al., 2007, Queaño et al., 2020). The island arc setting, characterized by long, curved chains of volcanic islands formed through subduction-related processes, provides an ideal framework for understanding regional mineralization (Yumul Jr et al., 2008). Specifically, the study focuses on the Far Southeast (FSE) Project in Mankayan, Benguet Province, a region renowned for its copper-gold porphyry systems (Mines and Geosciences Bureau, 2005, Sillitoe, 2010). The FSE deposit, concealed beneath the surface, is associated with a Pleistocene diorite-dacite intrusion emplaced into older Eocene basaltic country rocks, highlighting the potential for alteration zones and mineralized extensions beyond the currently defined deposit boundaries (Gaibor et al., 2013). The study area lies within the Mankayan quadrangle on Luzon Island, encompassing parts of four provinces and covering multiple municipalities in the Cordillera Administrative Region and Ilocos Region. The quadrangle hosts several key deposits within the Mankayan Mineral District, including the Victoria/Teresa, Lepanto Enargite, and Far Southeast deposits. These deposits are one of the largest undeveloped copper-gold-porphyry deposits globally (Claveria et al., 1999) (Fig. 1).

Remote sensing is widely used in mineral exploration worldwide, especially in sparsely vegetated areas, but remains underutilized in tropical regions like the Philippines. Despite being one of the most well-studied mining districts in the country, the Mankayan Mineral District lacks a comprehensive remote sensing–based study, primarily due to persistent cloud cover, dense vegetation, and intense tropical weathering. Cloud cover limits the availability of cloud-free imagery, fragmenting spatial analyses, while dense vegetation (comprising fruit-bearing and pine trees) obscures bedrock exposures and hinders direct detection of mineralogical signatures, necessitating reliance on indirect indicators such as geomorphological features and subtle spectral anomalies. Additionally, extensive surface weathering in tropical climates can mask primary lithologic and alteration signatures, increasing the risk of misinterpretation if not corroborated with existing geological data. These gaps underscore the need to evaluate and adapt remote sensing methodologies for tropical conditions, where conventional techniques may require significant modification. By applying remote sensing to the Mankayan area, this study aims to bridge the gap between proven geospatial exploration tools and the practical limitations of tropical terrains. The goal is to expand the applicability of remote sensing in Philippine mineral exploration and contribute to broader regional mapping and targeting efforts.

This study addresses several critical challenges. First, it evaluates the applicability of remote sensing techniques for mineral exploration under the tropical climate conditions of the Philippines, where dense vegetation and frequent cloud cover often hinder surface observations. Second, it examines the limitations posed by the lack of an up to date 1:50,000-scale geological map for the quadrangle, which affects geological interpretation and regional synthesis. Third, it investigates the potential extension of mineralized zones beyond known deposits, emphasizing the need for efficient and accurate remote sensing methodologies capable of identifying alteration signatures and lithologic contacts. These issues are particularly significant considering the Philippine government's increasing emphasis on critical minerals. These are deemed vital to national economic and security interests, given their limited global availability and rising demand.

In response, this study aims to: (1) determine the capability of remote-sensing data and analytical methods to aid mineral prospecting in tropical environments; (2) update the geologic map of the Mankayan quadrangle to improve understanding of local and regional geology; and (3) produce a mineral prospectivity map delineating inferred lithologies and potential alteration zones. These objectives will be pursued through the analysis of atmospherically corrected surface reflectance (SR) images acquired from Sentinel-2 L2A, utilizing image processing techniques tailored to extract spectral features associated with hydrothermal alteration. The expected outcomes of this study will support more effective exploration strategies and contribute to ongoing national efforts to assess and develop critical mineral resources in the Philippines.

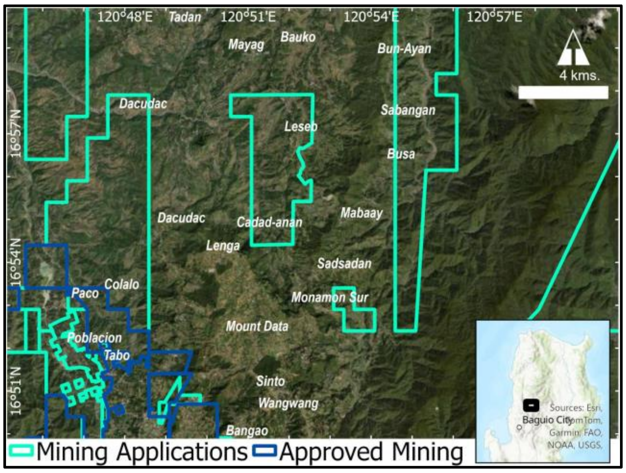


Figure 1. Mankayan Quadrangle in Luzon Island, Philippines.

Selection of the Mankayan quadrangle as the study area provides both applied value and research significance. Its extensively studied mining history, complex geology, and existing gaps in geospatial data make it a suitable location for testing and refining remote sensing methodologies. The updated regional geologic and mineral prospectivity maps produced through this study aim to support local exploration efforts and provide a framework for similar studies in other mineralized tropical regions in the Philippines and Southeast Asia.

2. Data and Methodology

The primary remote sensing datasets used include the Copernicus Sentinel-2 L2A imagery and the Interferometric Synthetic Aperture Radar Digital Elevation Model (InSAR-DEM). Additional data incorporated into the study include the regional geological map, mining tenement shapefiles and active faults obtained from the national government agencies of the Philippines, particularly the Department of Environment and Natural Resources-Mines and Geosciences Bureau (DENR-

MGB) and Department of Science and Technology-Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS). Mineral alteration maps were sourced from various published studies (Hedenquist et al., 2017, Claveria et al., 2019) (Fig.2).

Preprocessing and processing of the remote sensing images were done using the Sentinel Application Platform (SNAP) Desktop version 9.0.0. Data integration and map production were carried out using ArcMap Desktop 10.8.2. The Sentinel-2 L2A image used in this study was acquired on Nov. 18, 2020 with a cloud coverage of approximately 4%. A total of ten 3′ × 3′ InSAR-DEM tiles cover the entire study area.

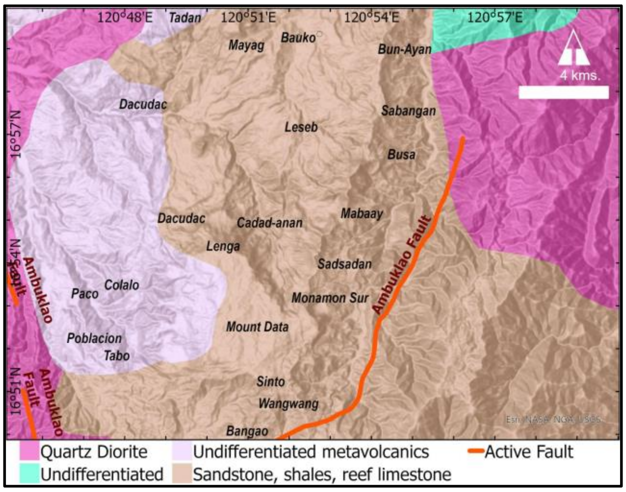


Figure 2. Geologic map of the Mankayan Quadrangle (MGB, 2010). Active fault traces are from DOST-PHIVOLCS (2012).

This study addressed remote sensing challenges in tropical regions like the Philippines through strategic dataset selection, targeted preprocessing, and integrated analysis. Sentinel-2 L2A imagery was chosen for its high revisit rate, improving chances of cloud-free acquisition. The workflow was specifically tailored to overcome persistent vegetation cover, frequent cloud interference, and subdued lithologic contrasts that typically hinder mineral mapping in tropical environments. Spatial subsetting ensured analysis was confined to the exact study extent, while resampling all selected bands to 10 m resolution maintained pixel alignment for accurate spectral analysis. To counter low-contrast imagery caused by canopy cover and atmospheric scattering, contrast enhancement was applied after key processing steps to improve the visibility of lithologic and alteration features without distorting spectral values. FCC shifted emphasis into NIR and SWIR ranges, where vegetation effects are reduced and mineralogical variations are more discernible. Spectral ratios targeting ferric and ferrous iron, clay minerals, and hydroxyl-bearing minerals enhanced subtle absorption features. PCA was used to minimize spectral redundancy and isolate alteration-related variance, adapting proven band combinations from Landsat studies to Sentinel-2 equivalents for tropical settings. For structural analysis, SWIR composites combined with high-pass filtering, edge enhancement, and negative gray-level transformation improved the detection of lineaments such as the Ambuklao Fault, overcoming visual obstructions from vegetation and low-relief terrain. Figure 3 illustrates the general flow diagram of the procedure executed in this study.

Spatial subsetting was performed on the raw digital images to resize the image to specific coordinates: longitude = 120°45’E - 121°00’E and latitude = 16°50’N - 17°00’N. Subsequently, The selected images corresponding to bands 5, 6, 7, 8A, 11, and 12 were then converted to a 10-m spatial resolution using the nearest-neighbor resampling procedure.

Contrast enhancement was applied after various image processing to improve the final image, rather than being used as an independent enhancement step. A true-color composite (TCC) combines the visible red, green, and blue bands mapped to their respective color channels, producing an image that closely resembles natural human vision (ITC, 2009). In contrast, a false-color composite (FCC) uses band combinations beyond the visible spectrum to reveal features not discernible in TCC imagery (ITC, 2009). Spectral ratioing, a technique in which the digital number (DN) values of one spectral band are divided by those of another, enhances specific spectral features by reducing the influence of illumination and topographic effects (Lillesand et al., 2015). Van der Meer et al., (2014) outlined effective FCC configurations and spectral ratios for geological interpretation. Following their guidance, this study used TCC 4-3-2 and FCC 12-4-2 for lithologic mapping, and FCC 11-12-4 for structural mapping. The same reference informed the selection of spectral ratios (4/3, 12/8 + 3/4, 12/11, 11/8, 12/8, and 11/12) which were applied to enhance the detection of ferric iron, ferrous iron, ferrous silicates, ferric oxides, clay minerals, and hydroxyl-bearing alteration minerals within the study area.

Additionally, PCA is commonly used for data enhancement in geological applications such as lithological classification (Chen et al., 2023) and mineral prospecting (Mohamed et al., 2021). For example, Parcutela et al., (2022) utilized Landsat 8-OLI bands 2, 4, 5, and 6 to identify FeO alteration and bands 2, 5, 6, and 7 to detect clay alteration. These Landsat 8-OLI bands correspond to Sentinel-2 L2A bands 2, 4, 8, and 11 and 2, 8, 11, and 12, respectively.

Lineament detection was performed using the color combination 11-12-4 and a combination of image enhancement processes in band 11. A high-pass filter accentuates fine, high-frequency features within the visual data and diminishes broader, low-frequency content (Lillesand et al., 2015). However, edge-enhanced images attempt to preserve both local contrast and low-frequency brightness information by “adding back” all or a portion of the gray values in an original image to a high-frequency component image of the same scene (Lillesand et al., 2015). To accentuate the linear features in the image, a negative gray-level transformation was applied.

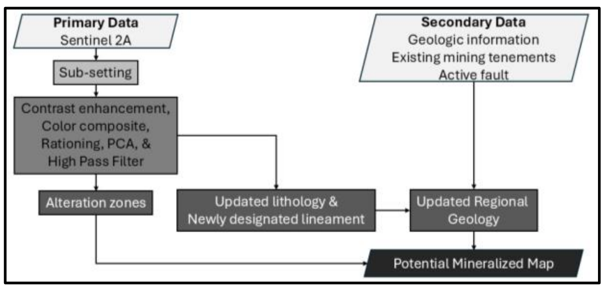


Figure 3. General workflow used in this study.

3. Results and Discussion

3.1 Lithology and Lineament

The simplicity of the spectral band rationing technique is widely used in the identification of geological materials, as it requires no additional input data for implementation (Mohamed et al., 2021). This technique is valid for all incidence angles and is capable of enhancing features on multispectral images (Lillesand et al., 2015).

The regional mapping identifies various lithologic assemblages within the area, with diorite, undifferentiated metavolcanic units, and alternating beds of sandstone, shale, and limestone forming the principal rock types (Mines and Geosciences Bureau, 2010) (Fig. 2). Detailed geological mapping by Manalo et al., (2020) in the Mankayan Mineral District identified rock unit such as the Bato Dacite Porphyry, Bato Dacite Pyroclastic, Bagon Intrusive Complex and Lepanto Metavolcanic, among others.

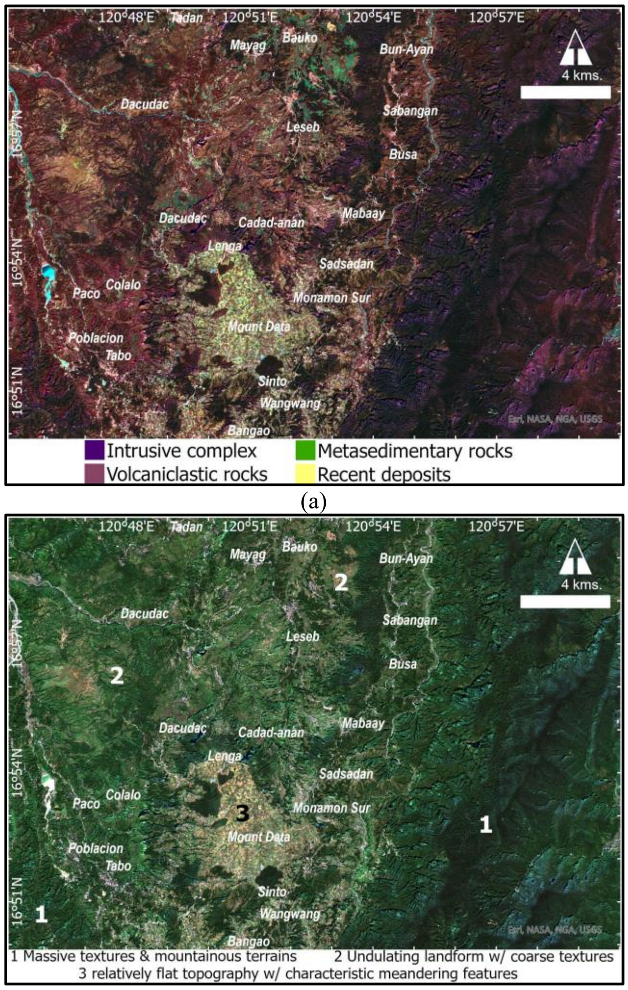
FCC 12-4-2 display shows the intrusive complex appears in magenta, metasedimentary rocks in green, pyroclastic and volcaniclastic rocks in pinkish-brown, and recent deposits in yellowish (Fig. 4a). TCC terrain analysis provides additional information about the lithology. Intrusive complexes with massive textures and mountainous terrain occur in the west and southeast. Undulating, coarse-textured areas in the center and northwest indicate mixed pyroclastic and metavolcanic rocks. Recent deposits show flat topography with meandering features. (Fig. 4b).

According to Lillesand et al., (2015), lineaments can be mapped using simple data products and image processing or enhancement techniques. The Ambuklao Fault was mapped by DOST-PHIVOLCS in 2012. This fault, along its segments, is also mapped in this study, and the results align with the work conducted by DOST-PHIVOLCS. Other lineament elements were manually extracted from the FCC 11-12-4 and the image enhancement of band 11 (Figures 5a and 5b). The data reveal two primary fault trends, being northeast and northwest directions, similar to those observed for the Ambuklao Fault segments. The NE-trending faults are intersected by the NW-trending fault. As such, the former is relatively younger than the latter. (Fig. 5c).

The integration of lithologic and lineament maps contributes to a more in-depth understanding of the studied area. Recent deposits have been identified in agricultural areas and in river channels. The major rivers are structurally controlled by lineaments, trending northwest and northeast directions. Lineament movement, in general, indicates first-order sinistral and second-order dextral faulting. It is noteworthy that lineaments are also observed in massive intrusive complexes and pyroclastic or volcaniclastics rocks (Fig. 6).

3.2 Alteration, Mineral Prospecting, and Mineralization Zones

Band ratios are known for enhancing spectral contrast among the bands identified during ratioing and have been successfully employed in mapping alteration zones (Mohamed et al., 2021, Parcutela et al., 2022). In this study, these band ratios (4/3, 12/8 + 3/4, 12/11, 11/8, 12/8, and 11/12) were utilized for mapping the alteration zones. The 4/3 and 11/8 ratios yielded values ranging from >1 to 33 and >1 to 41, respectively, corresponding to ferric iron (Fe^{3+}) and ferric oxide alteration minerals (e.g., hematite, geothite) (Figs. 7a and 7b). The 11/12 ratio emphasized clay minerals (e.g., kaolinite, montmorillonite) and hydroxyl-bearing alteration minerals, with values from >2.2 to 6.2 (Fig. 7c), consistent with their narrow absorption features in band 12. Meanwhile, the 12/11 ratio was effective in distinguishing ferrous silicate minerals (e.g., biotite, chloride).



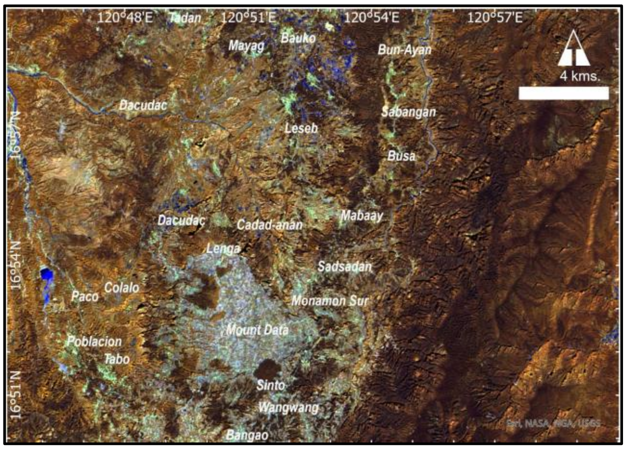
(b)

Figure 4. (a) FCC 12-4-2 image illustrating distinct lithologic units and (b) TCC 4-3-2 image highlighting major geomorphological features.

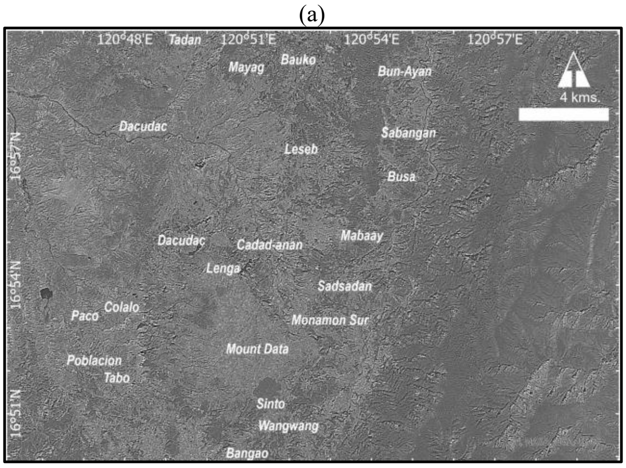
The selected PCA bands for each combination highlight iron oxides and clay minerals (Figs. 8a and 8b). In these PCA images, values around 0.01 indicate minimal presence of iron oxides or clay minerals, whereas values of 1.16 and 0.83 represent strong occurrences of iron oxides and clay minerals, respectively.

The ratioing, FCC, and PCA output images depict the spatial distribution of alteration minerals on the updated regional geologic map (Fig. 9).Within the massive intrusive complexes, clay minerals exhibit values greater than 2.3, while pyroclastic/volcaniclastic and metasedimentary rocks display values ranging from greater than 2.2 to 2.3. Ferric iron and ferric oxide minerals are observed in recent deposits, in pyroclastics/volcaniclastics, and in metasedimentary rocks.

These results provide insights into the geological, structural, and alternation conditions in areas with applied and approved mining tenements. As a note, areas with mining activities, termed mineralized zones in this study, have the following features: (1) they occur within approximately 2 km of lineaments, (2) they are hosted by pyroclastics or volcaniclastic rocks, and (3) they have high values in the corresponding band ratios (>1.0 in 4/3 or 11/8 for ferric iron and ferric oxides, and >2.2 in 11/12 for clay and hydroxyl-bearing minerals) indicating the presence of alteration mineral assemblages.



(a)



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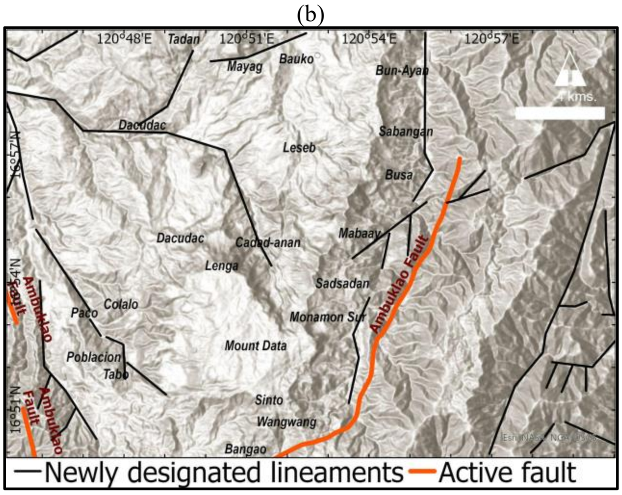

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Figure 5. Images utilized for geologic structural interpretation. (a) Sentinel-2 L2A FCC 11-12-4 analysis image. (b) Band 11 high-pass 3x3 filter with edge enhancement analysis and negative transformation. (c) Newly designated lineaments of the Mankayan Quadrangle derived from the images.

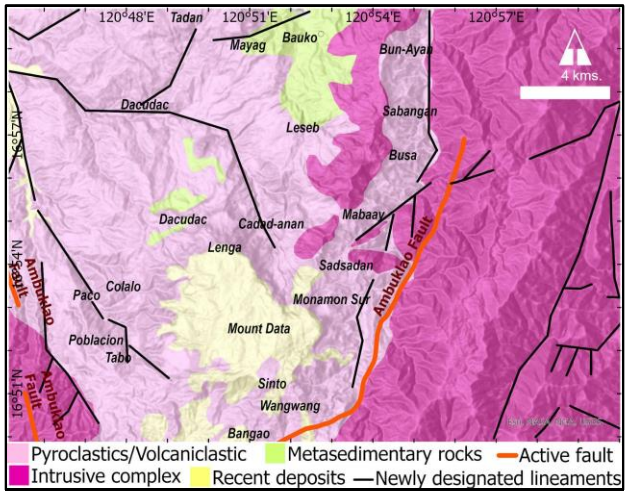
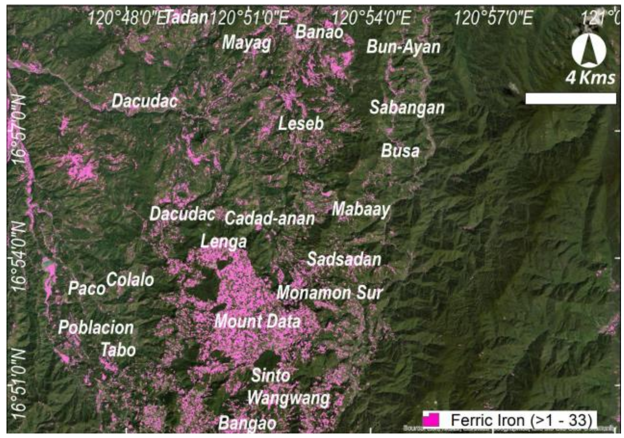
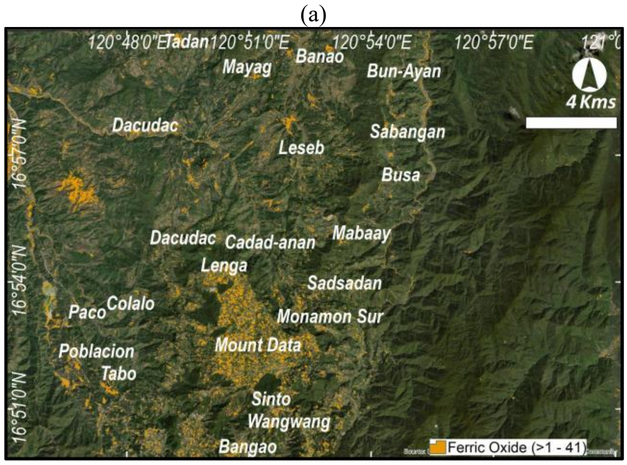


Figure 6. Updated regional geologic map of the study area.

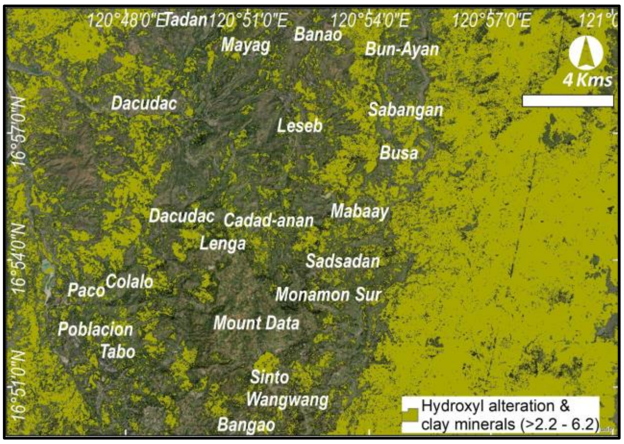


(a)

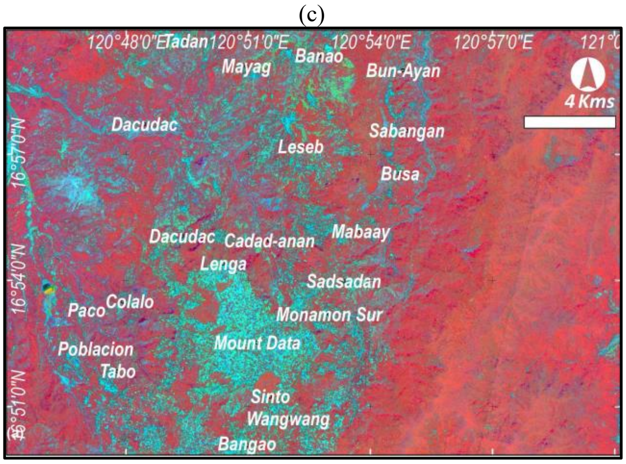


(b)

These associations suggest that other occurrences could serve as markers for potential mineralization zones. Seven (7) communities (locally termed "barangays") in the central part of the quadrangle are identified as having potential for mineralization zones. These are barangays Cadad-anan, Mabaay, Lenga, Sadsadan, Dacudac, north side of Monaman Sur, and northeast of Mount Data (Fig. 10).

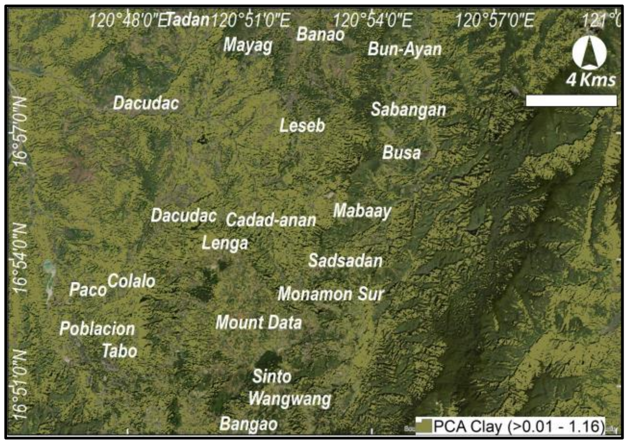


(c)



(d)

Figure 7. Ratio images are presented as follows: (a) ferric iron 4/3, (b) ferric oxide 11/8, (c) hydroxyl alteration zones and clay minerals 11/12. Arrows indicate high reflectance value. (d) FCC of these (11/12, 4/3, 11/8) ratio image reveals hydroxyl-bearing.



(b)

Figure 8. PCA component 1 highlighting (a) iron oxide and (b) clay minerals.

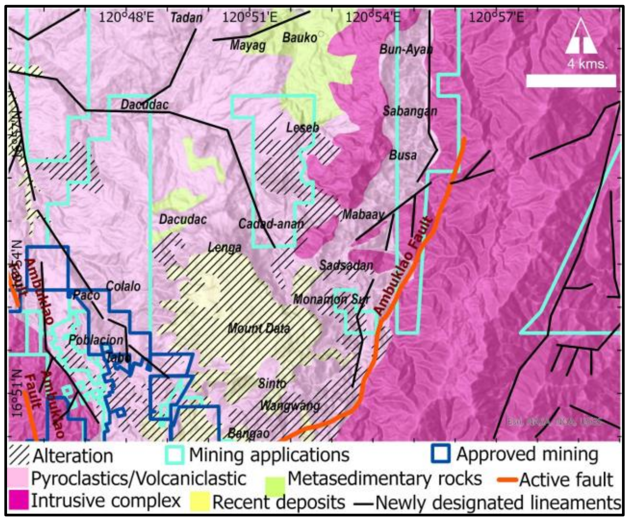


Figure 9. Mineral prospecting map.

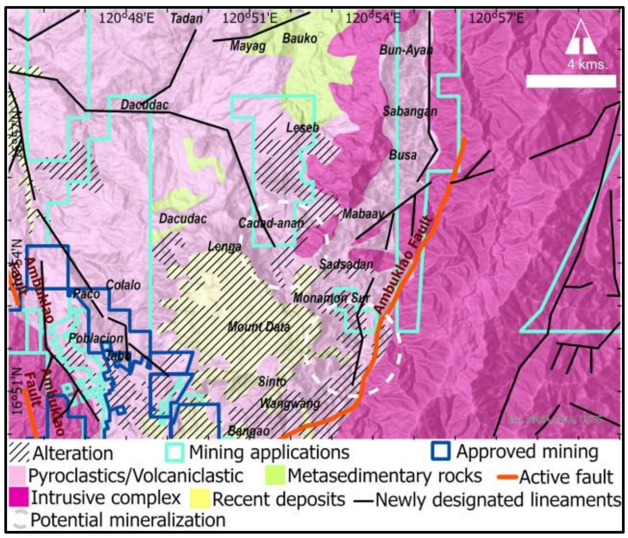
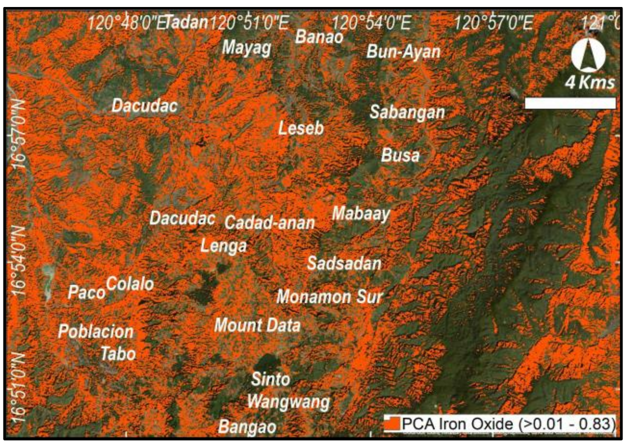


Figure 10. Potential mineralized map.

4. Conclusions and Recommendations

The combination of satellite images and remote sensing techniques has proven to be a powerful tool for geological and mineral prospecting mapping. This study demonstrates the application of Sentinel-2 L2A imagery and image enhancement techniques in updating geological maps, lineament delineation, and identification of alteration zones and prospective mineralization zones in the Mankayan Mineral District and its surrounding areas in the Central Cordillera Region.



(a)

This study yields three main conclusions:

a. Sentinel-2 L2A data analysis, using color composites 4-3-2, 12-4-2, and 11-12-4, proves effective in identifying Ambuklao Fault splays and the major lithological units in the area, namely massive intrusive complexes, metasedimentary rocks, pyroclastic and volcaniclastic rocks, and recent deposits. Spectral ratioing and/or PCA approaches in bands 2-8, 11, and 12 are useful in mapping hydroxyl, clay, ferric iron, and oxide alteration zones.

b. Areas with inferred mineral resource potential occur approximately 2 km from the intersections of Ambuklao fault splays and are hosted by pyroclastic or volcaniclastic rocks. High values in key spectral band ratios, specifically 4/3 for ferric iron, 11/8 for ferric oxide, and 11/12 for hydroxyl alteration zones and clay minerals, indicate hydrothermal alteration.
c. From the data processing and analysis, several areas were identified as having potential for mineralization. These areas, located in the central part of the mapped quadrangle, are Cadad-anan, Mabaay, Lenga, Sadsadan, Dacudac, northern side of Monamon Sur and northeast of Mount Data.

To enhance confidence in the interpretations, the delineated alteration areas and potential mineralized zones will be verified through field-based validation techniques. These include detailed geological mapping, petrographic and geochemical investigations, and when supported by initial findings, exploratory drilling. The study will be conducted in one of the mineral districts of the Bicol region in the Philippines, an area characterized by significant mineralization and artisanal mining activities. A comprehensive validation, scheduled for implementation within the current year, will involve direct field observations, systematic sampling, and spatial data verification to evaluate the spatial and thematic accuracy of the generated maps. This validation is essential to confirm the presence, type, and extent of mineralization, thereby enhancing the credibility of remote-sensing approaches for mineral exploration. Furthermore, the results are consistent with the known presence of mining permit applications in the area, supporting the reliability and potential wider use of the proposed methodology.

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