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Editorial

Editorial for the Special Issue: Multispectral and Hyperspectral Remote Sensing Data for Mineral Exploration and Environmental Monitoring of Mined Areas

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1. Introduction

In recent decades, multispectral and hyperspectral remote sensing data provide unprecedented opportunities for the initial stages of mineral exploration and environmental hazard monitoring. Increasing demands for minerals because of industrialization and exponential growth in population emphasize the necessity for replenishing exploited reserves by exploration of new potential zones of mineral deposits. Identification of host-rock lithologies, geologic structural features, and hydrothermal alteration mineral zones are the most conspicuous applications of multispectral and hyperspectral remote sensing satellite data for mineral exploration in the metallogenic provinces and frontier areas around the world [1–11]. Numerous ore deposits such as orogenic gold, porphyry copper, carbonatite, massive sulfide, epithermal gold, podiform chromite, uranium, magnetite, and iron oxide copper-gold (IOCG) deposits have been successfully prospected and discovered using multispectral and hyperspectral remote sensing satellite imagery [12–22].

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Landsat data series, the Advanced Land Imager (ALI), Worldview-3, Hyperion, HyMap and the Airborne Visible/IR Image Spectrometer (AVIRIS) remote sensing data serve as low-cost tools for ore mineral exploration [3,7,11–13,20,23]. Additionally, Synthetic Aperture Radar (SAR) data contains a high potential for structural mapping and lineament extraction. The Phased Array type L-band Synthetic Aperture Radar (PALSAR) satellite remote sensing data are particularly used for mapping structurally controlled orogenic gold mineralization in the arid and tropical environments due to its penetration capability [7,18,24–29].

Several advanced image processing algorithms and machine learning techniques can be successfully used to extract essential information related to hydrothermal alteration minerals and lithological units at pixel and sub-pixel levels for indicating high potential zones of ore mineralizations. Different types of image processing algorithms have been used to extract spectral information from multispectral and hyperspectral remote sensing data for instance (i) band-ratio, indices, and logical operator based methods; (ii) principal components and transformation based methods—such as principal component analysis (PCA), independent component analysis (ICA), and minimum noise fraction (MNF); (iii) shape-fitting based algorithms—such as spectral angle mapper (SAM), matched-filtering (MF), and mixture-tuned matched-filtering (MTMF); and (iv) partial unmixing and target detection methods—such as linear spectral unmixing (LSU), constrained energy minimization (CEM), orthogonal subspace projection (OSP), and adaptive coherence estimator (ACE) [2,8]. Machine learning techniques are developing progressively crucial to unravel several image processing challenges in the coming future. Although the techniques are subject to scientific interest for the remote sensing mineral exploration community, but generic implementation is still in initial stages.

Furthermore, human-induced changes—in the form of mine excavation, open-pit mining, transportation, mine tailing, mineral processing in mining zones, mine waste, dust pollution, and acid runoff—necessitate a proper monitoring of mining areas by remote sensing observations. Environmental pollution mapping and monitoring of mined areas are the main challenges that need to be addressed for future sustainability and environmental management in metallogenic provinces and surrounding areas. Consequently, a special issue entitled "Multispectral and Hyperspectral Remote Sensing Data for Mineral Exploration and Environmental Monitoring of Mined Areas" is proposed, which is expected to particularly motivate researchers for presenting the latest achievements in the field of geological remote sensing for mineral exploration and environmental monitoring.

A total of 20 manuscripts have been submitted to this special issue, which were evaluated by professional guest editors and reviewers. Subsequently, 14 papers attained the level of quality and novelty anticipated by *Remote Sensing* and finally were revised, accepted, and published in the special issue. The achievements of articles presented in this special issue are summarized in the following section.

2. Summary of Papers Presented in This Special Issue

Noori et al. [3] compared different image processing algorithms for mapping hydrothermal alteration zones associated with polymetallic vein-type mineralization using ASTER data in the Toroud–Chahshirin Magmatic Belt (TCMB), North Iran. Selective principal component analysis (SPCA), band ratio matrix transformation (BRMT), spectral angle mapper (SAM), and mixture tuned matched filtering (MTMF) were implemented and compared to map hydrothermal alteration minerals at the pixel and sub-pixel levels. Subtle differences between altered and non-altered rocks and hydrothermal alteration mineral assemblages were detected and mapped in the study area. Results indicate several high potential zones of epithermal polymetallic vein-type mineralization in the northeastern and southwestern parts of the study area, which can be considered for future systematic exploration programs. Guha et al. [30] used emittance spectroscopy and ASTER broadband thermal remote sensing data to map phosphorite associated with carbonate-rich sediments of the Aravalli Super Group, Rajasthan, India. In this study, a relative band depth (RBD) image using selected emissivity bands of ASTER (bands 11, 12, and 13) was developed for mapping and delineating phosphorite from the dolomite or carbonate host-rock lithologies. Additionally, the RBD is capable to differentiate low-grade phosphorite exposures from high-grade phosphorite zones. The authors recommended that the RBD of broadband ASTER thermal infrared (TIR) bands can be used for targeting phosphorite occurring under similar geological systems around the world.

Pour et al. [10] mapped listvenite occurrences in the damage zones of northern Victoria Land, Antarctica using ASTER Data. Principal component analysis (PCA)/independent component analysis (ICA) fusion technique, linear spectral unmixing (LSU), and constrained energy minimization (CEM) algorithms were implemented to extract spectral information for detecting alteration mineral assemblages and listvenites. Mineralogical assemblages containing Fe^{2+}, Fe^{3+}, Fe-OH, Al-OH, Mg-OH, and CO3 spectral absorption features were detected by applying PCA/ICA fusion to visible and near infrared (VNIR) and shortwave infrared (SWIR) bands of ASTER. Silicate lithological groups were mapped and discriminated using PCA/ICA fusion to TIR bands of ASTER. Goethite, hematite, jarosite, biotite, kaolinite, muscovite, antigorite, serpentine, talc, actinolite, chlorite, epidote, calcite, and dolomite were detected using LSU and CEM algorithms. Several potential zones for listvenite occurrences were identified, typically in association with mafic metavolcanic rocks (Glasgow Volcanics) in the Bowers Mountains. Zoheir et al. [18] utilized Landsat 8-Operational Land Imager (OLI), ASTER, PALSAR and Sentinel-1 satellite data coupled with field and microscopic investigations to unravel the setting and controls of gold mineralization in the Wadi Beitan–Wadi Rahaba area in the South Eastern Desert of Egypt. Band ratios, RBD and mineralogical indices are used to extract the representative pixels form Landsat 8-OLI and ASTER bands. Lineaments were manually and automatically extracted from PALSAR and Sentinel-1 data. The data fusion approach was used and showed no particular spatial association between gold occurrences and certain lithological units but indicates a preferential distribution of gold–quartz veins in zones of chlorite–epidote alteration overlapping with high-density intersections of lineaments. A priority map with zones defined as high potential targets for undiscovered gold resources were generated for the Wadi Beitan–Wadi Rahaba area in this study.

Sun et al. [31] integrated ground-based hyperspectral imaging and geochemistry data for resource exploration and exploitation of sediment-hosted disseminated Gold at the Goldstrike District, UT, USA. Ground-based hyperspectral imaging was applied to study a core drilled in the Goldstrike district covering the basal Claron Formation and Callville Limestone. The integration of remote sensing and geochemistry data helped to identify an optimum stratigraphic combination of limestone above and siliciclastic rocks below in the basal Claron Formation, as well as decarbonatization, argillization, and pyrite oxidation in the Callville Limestone, that are related with gold mineralization. Zoheir et al. [17] used multi-sensor satellite imagery data, including Sentinel-1, PALSAR, ASTER, and Sentinel-2, for mapping the regional structural control of orogenic gold mineralization in the Barramiya–Mueilha sector. Feature-oriented principal component selection (FPCS) was applied to polarized backscatter ratio images of Sentinel-1 and PALSAR datasets for regional structural mapping and identification of potential dilation loci. The PCA and band ratioing techniques are applied to ASTER and Sentinel-2 datasets for lithological and hydrothermal alteration mapping. The radar and multispectral satellite data abetted a better understanding of the structural framework and unraveled settings of the scattered gold occurrences in the study area.

Pour et al. [11] utilized Landsat-8, ASTER and WorldView-3 multispectral remote sensing imagery for prospecting copper-gold mineralization in the Northeastern Inglefield Mobile Belt (IMB), Northwest Greenland at regional, local, and district scales. Hydrothermal alteration minerals such as iron oxide/hydroxide, Al/Fe-OH, Mg-Fe-OH minerals, silicification (Si-OH), and SiO_2 mineral groups were mapped using directed principal components analysis (DPCA) technique, Linear spectral unmixing (LSU) and adaptive coherence estimator (ACE) algorithms. Several high potential zones for Cu-Au prospecting were identified in the IMB, Northwest Greenland, including (i) the boundaries between the Etah metamorphic and meta-igneous complex rocks and sedimentary successions of the Franklinian Basin in the Central Terrane, (ii) orthogneiss in the northeastern part of the Cu-Au mineralization belt adjacent to Dallas Bugt, and (iii) the southern part of the Cu-Au mineralization belt nearby Marshall Bugt. Bolouki et al. [12] investigated a remote sensing-based application of Bayesian networks for epithermal gold potential mapping in Ahar-Arasbaran area, NW Iran. Landsat Enhanced Thematic Mapper+ (Landsat-7 ETM+), Landsat-8, and ASTER datasets were used to detect hydrothermal alteration zones associated with epithermal gold mineralization using band ratio, relative absorption band depth (RBD) and PCA techniques. The Bayesian network classifier was used to synthesize the thematic layers of hydrothermal alteration zones. Many new potential zones of epithermal gold mineralization were identified in the Ahar-Arasbaran region.

Tuşa et al. [32] estimated mineral abundance in drill-core samples collected from Bolcana porphyry copper-gold deposit by employing hyperspectral short-wave infrared (SWIR) data and scanning electron microscopy-based image analyses using a mineral liberation analyzer (SEM-MLA). Machine learning algorithms were executed to combine the two data types and upscale the quantitative SEM-MLA mineralogical data to drill-core scale. Quasi-quantitative maps over entire drill-core samples were acquired. Sekandari et al. [13] used Landsat-8, Sentinel-2, ASTER, and WorldView-3 spectral imagery for exploration of carbonate-hosted Pb-Zn deposits in the Central Iranian Terrane (CIT). Band ratios and PCA techniques were adopted and implemented to map alteration minerals and lithologies. Fuzzy logic modeling was applied to integrate the thematic layers produced by the image processing techniques for generating mineral prospectivity maps. The most favorable/prospective zones for hydrothermal ore mineralizations and carbonate-hosted Pb-Zn mineralization in the study region were particularly mapped and indicated at regional and district scales. Shirmard et al. [33] integrated selective dimensionality reduction techniques such as PCA, ICA, and minimum noise fraction (MNF) for mineral exploration using ASTER satellite data. The fuzzy logic model was used for integrating the most rational thematic layers derived from the techniques for mineral prospectivity mapping in the Toroud-Chahshirin range, Central Iran.

Martín-Crespo et al. [34] presented the results of the geo-environmental characterization of La Matildes riverbed, affected by mine tailings in the Cartagena–La Unión district, Murcia (southeast Spain) using geophysical and geochemical techniques. Two electrical resistivity imaging (ERI) profiles were carried out to obtain information about the thickness of the deposits and their internal structure. The geochemical composition of borehole samples from the riverbed materials shows significantly high contents of As, Cd, Cu, Fe, Pb, and Zn being released to the environment. Results demonstrated that surface extraction in three open-pit mines have changed the summits of Sierra de Cartagena–La Unión and rock and metallurgical wastes have altered the drainage pattern and buried the headwaters of ephemeral channels. Jackisch et al. [35] integrated drone-borne photography, multi- and hyperspectral imaging, and magnetics data for mapping a carbonatite-hosting outcrop in Siilinjärvi, Finland. Structural orientations and lithological units are deduced based on high-resolution, hyperspectral image-enhanced point clouds. Unmanned aerial system (UAS)-based magnetic data allow an insight into their subsurface geometry through modeling based on magnetic interpretation. A geologic map is resulted discriminating between the principal lithologic units and distinguishes ore-bearing from waste rocks. Ma et al. [36] investigated the dust dispersion characteristics in Kuancheng mining area, Hebei Province, North China using the American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) regulatory model (AERMOD). The spectral characteristics of vegetation canopy under the dusty condition were simulated, and the influence of dustfall on vegetation canopy spectra was studied based on the three-dimensional discrete anisotropic radiative transfer (DART) model. The experimental results show that the dust pollution along a haul road was more severe and extensive than that in a stope. Taking dust dispersion along the road as an example, the variation of vegetation canopy spectra increased with the height of dust deposited on the vegetation canopy. The findings would be beneficial to decision-makers or researchers for the remote sensing application to mapping and assessing the dust effect in mining areas.

3. Concluding Remarks

The sympathetic and judicious comments delivered by the reviewers enhanced each of the papers published in this special issue, which came to fruition only because they were willing to volunteer their time and attention. We hope that the investigations published in this special issue will assist mineral exploration communities and mining companies about the application and integration of multispectral and hyperspectral remote sensing data for mineral exploration and environmental monitoring of mined areas.

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