



Editorial Editorial for the Special Issue: "Multispectral Remote Sensing Satellite Data for Mineral and Hydrocarbon Exploration: Big Data Processing and Deep Fusion Learning Techniques"

Amin Beiranvand Pour ^{1,*}, Omeid Rahmani ², and Mohammad Parsa ³

- ¹ Institute of Oceanography and Environment (INOS), Universiti Malaysia Terengganu (UMT), Kuala Nerus 21030, Terengganu, Malaysia
- ² Department of Natural Resources Engineering and Management, School of Science and Engineering, University of Kurdistan Hewlêr (UKH), Erbil 44001, Kurdistan Region, Iraq
- ³ Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada
- * Correspondence: beiranvand.pour@umt.edu.my; Tel.: +60-9-6683824; Fax: +60-9-6692166

Using multispectral remote sensing data in cooperation with big data processing and deep fusion learning techniques provides a new approach for mineral and hydrocarbon exploration. Regional-scale mineral exploration in metallogenic provinces and hydrocarbon exploration in inaccessible and harsh areas are challenging due to the difficultly of processing remote sensing big data and the variety of remote sensing datasets needed for different applications [1–5]. Nowadays, spaceborne remote sensing big data sources are available, appropriate and range from free to low-cost for mineral and hydrocarbon exploration projects. Landsat data series, Satellite Pour l'Observation de la Terre (SPOT) data series, Worldview-3 data series, Advanced Land Imager (ALI) data, Phased Array type L-band Synthetic Aperture Radar (PALSAR) data and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data have been successfully and continuously used for regional-scale mineralogical-lithological-structural mapping in metallogenic provinces and hydrocarbon exploration [6–8].

Numerous image processing algorithms and Geographic Information System (GIS) modeling can be used for extracting spectral information related to alteration minerals, ore-related lithological units and microseepage-related geochemical alterations. The fusion of extracted information using deep fusion learning techniques has been developing progressively and is crucial for unraveling several image processing challenges [9–11]. Although the techniques are specific to scientific interest in remote sensing in the mineral and hydrocarbon exploration community, a generic implementation is in the initial stages. This Special Issue focused on the recent developments in the applications of multispectral remote sensing satellite data for mineral exploration in metallogenic provinces, onshore oil slick detection, offshore oil spill monitoring and hydrocarbon exploration. We were interested in innovative solutions for deep fusion learning techniques for remote sensing data processing and difficulties. The submission of manuscripts was encouraged for a broad range of related mineral and hydrocarbon exploration themes. Researchers were encouraged to submit novel research or case studies, including: (i) innovative methods for fusing multispectral remote sensing satellite data for prospectivity mapping in vast metallogenic provinces; (ii) multispectral remote sensing satellite data for both macroseepage direct detection and microseepage indirect detection; (iii) mapping ophiolite complexes to understand mineral carbonation and CO_2 sequestration using novel remote sensing approaches and modeling; and (iv) Geographic Information System (GIS) modeling for integrating different remote sensing datasets and geophysical and geochemical techniques for mineral exploration.



Citation: Pour, A.B.; Rahmani, O.; Parsa, M. Editorial for the Special Issue: "Multispectral Remote Sensing Satellite Data for Mineral and Hydrocarbon Exploration: Big Data Processing and Deep Fusion Learning Techniques". *Minerals* 2023, 13, 193. https://doi.org/10.3390/ min13020193

Received: 24 January 2023 Accepted: 27 January 2023 Published: 28 January 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). A total of 19 manuscripts were submitted to this Special Issue, which were evaluated by professional Guest Editors and reviewers. Subsequently, 12 papers attained the level of quality and novelty expected by *Minerals*, and consequently, were revised, accepted and published. The accomplishments of the articles in this Special Issue are summarized in the following paragraphs.

Abd El-Wahed et al. [12] used Landsat-8, ASTER and PALSAR satellite remote sensing datasets to map geological contacts, lithologies and structural elements controlling goldbearing quartz veins in the Wadi Hodein Shear Belt, South Eastern Desert of Egypt. Several image processing techniques such as band combinations, band math, Principal Component Analysis (PCA), decorrelation stretch and mineralogical indices were executed and integrated with fieldwork data. The data layers were exported to the GIS environment and, subsequently, fused to produce a potentiality map for shear-related gold mineralization in the study area. The results demonstrated that the gold mineralization was typically restrained to steeply dipping strike-slip shear zones in the marginal parts of the shear belt. Gold-mineralized zones cut heterogeneously deformed ophiolites and metavolcaniclastic rocks and attenuate inside and around granodioritic intrusions. The gold mineralization event was evidently epigenetic in the metamorphic rocks and was likely attributed to rejuvenated tectonism and the circulation of hot fluids during transpressional deformation. Accordingly, it was recommended that the concurrence of shear zones, hydrothermal alteration and crosscutting dikes creates high potential zones for new gold targets in the study area.

Bruno et al. [13] utilized a spatial component analysis to improve mineral estimation using the ferrous iron oxide (4/11) band ratio of Sentinel-2 in a Greek bauxite residue. This study proposed a model to map the iron concentration as the strategic metal within a bauxite residue in Greece. Due to the probability of substituting in a co-kriging system, the whole band ratio information with only the correlated components was analyzed. The approach represented three estimation alternatives: ordinary kriging, co-kriging and component co-kriging. Firstly, only direct samples from the site were used (ordinary kriging—OK estimation). Then, the band ratio (4/11) known for iron detection was used as additional information to map the iron variability within the bauxite residues (cokriging—CK estimation). For map accuracies, a new method (component co-kriging—CCK estimation) was described to reconstruct the coregionalization model between the sample data and the band ratio information by exploiting the possibility of extracting a specific component from the Sentinel-2 data and using it in the coregionalization models. Lastly, all three models and their products were compared to check the enhancement given by the proposed model for iron estimation maps. Results indicated how utilizing the most correlated component reduces the estimation variance and improves the estimation results. Generally, when a good correlation with ground samples exists, co-kriging of the Sentinel-2 (4/11) band ratio component improves the reconstruction of the mineral-grade distribution, and consequently, affects the selectivity.

Mehdikhani and Imamalipour [14] evaluated mapping chromite-bearing mineralized zones within the Khoy ophiolite complex in NW Iran by analyzing spectral bands (VNIR+SWIR) of the ASTER satellite sensor. The optimum index factor (OIF), band ratio (BR), spectral angle mapper (SAM) and PCA analysis were used for lithological mapping. A specialized OIF, the RGB (8, 6, 3) color composite, was generated for discriminating lithological units in the study area. The RGB color composition of (4 + 2)/3, (7 + 5)/6 and (7 + 9)/8 band ratios showed good performance for identifying ophiolite complex lithology units. The SAM and PCA analysis were able to map harzburgite and dunite as the host units of the chromite lens. The results showed that the integration of information extracted from ASTER data is very useful for chromite prospecting and lithological mapping in ophiolitic zones located in mountainous and remote regions around the world. Yousefi et al. [15] applied Dirichlet Process (DP) and Support Vector Machine (SVM) techniques for mapping alteration zones associated with the Zefreh porphyry copper deposit in the Urumieh-Dokhtar Magmatic Arc (UDMA) of central Iran using ASTER remote data. The DP process was utilized to specify the training data, where alteration zones were detected by using spectral mapping methods such as Relative Band Depth (RBD), Linear Spectral Unmixing (LSU), Spectral Feature Fitting (SFF) and Orthogonal Subspace Projection (OSP). Executing the SVM and SAM methods on the ASTER data helped with identifying phyllic, argillic, propylitic and iron oxide alterations at a regional scale. This study demonstrated the use of the SVM algorithm for mapping hydrothermal alteration zones associated with porphyry copper deposits in metallogenic provinces worldwide.

Timkin et al. [16] used geochemical and remote sensing techniques to identify blind mineralization (BM) and zone-dispersed mineralization (ZDM) in the Abrisham-Rud porphyry copper deposit, Semnan province, Iran. Sentinel-2 and ASTER data were utilized for mapping lineaments and alteration zones in the study area using Automatic Line Extraction, Logical Operator and PCA algorithms. The zonality method was applied to separate geochemical anomalies and to calculate erosion levels. Using the zonality method, the geochemical maps of multiplicative haloes were produced. The K-nearest neighbor (KNN) algorithm was implemented to fuse rock units, faults and alterations as a geological layer. The results of both methods correspond to each other in the southern part of the study area, indicating a high potential zone. Ekwok et al. [17] used high-resolution airborne magnetic (HRAM) and gravity data to understand the genesis of brines in southeast Nigeria. The result of the analytic signal exposed the locations and spatial distribution of short- and long-wavelength geologic structures associated with igneous intrusions. Low-pass filtering, upward continuation and 2D modeling procedures indicated critical synclinal structures, which corresponded with the location of brine fields. The study discloses that igneous intrusions and associated hydrothermal fluids are responsible for brine generation. Ekwok et al. [18] used HRAM data to evaluate the thicknesses of sedimentary series in the Bornu Basin, northeast Nigeria, utilizing three depth approximation techniques including source parameter imaging, standard Euler deconvolution and 2D GM-SYS forward modeling methods. The maximum sediment thickness values from the various depth estimation methods used in this study correlate relatively well. Additionally, the anomalous depth zone exposed using the 2D forward model overlaps with the locality of the thick sedimentation revealed via the source parameter imaging and standard Euler deconvolution (St-ED) methods.

Shirazi et al. [19] fused a lineament factor (LF) map analysis and multifractal technique for massive sulfide copper exploration in the Sahlabad Area, Eastern Iran. The rose diagram analysis, Fry analysis, LF map analysis and multifractal technique were implemented using geological and geophysical data. Aeromagnetometric data were analyzed to determine the presence of intrusive and extrusive masses associated with structural systems. The results showed that the NW-SE fault systems control the host rock's lithology for copper mineralization. Therefore, the NW-SE fault systems are consistent with the main trend of lithological units related to massive sulfide copper mineralization in the area. He et al. [20] identified radioactive mineralized lithology and mineral prospectivity mapping techniques using Worldview-2 and Landsat-8 TIRS thermal infrared data in the Narsaq Region of Greenland. Employing a weight-of-evidence analysis technique that combines machinelearned lithological classification information with information on surface temperature thermal anomalies, the prediction of radioactive element-bearing deposits in the study area was performed. Sholeb et al. [21] evaluated the hydrocarbon functional groups, aromaticity degree, and depositional environment in the Silurian–Devonian Kroh black shales of western peninsular Malaysia using Fourier transform infrared spectroscopy (FTIR). The existence of humic acid and the enrichment of aromatic hydrocarbons in the Kroh shales confirmed that the organic matter in these shales contains plant-derived hydrophilic minerals with terrestrial origin. These discoveries may offer evidence on the depositional and thermal maturation of organic matter for the exploration efforts into the pre-Tertiary sedimentary successions of peninsular Malaysia. Alarifi et al. [22] used multiple criteria inferred from Landsat-8, Sentinel-2 and ASTER data using a GIS-based weighted overlay multicriteria decision analysis approach to construct a model for the delimiting of hydrothermal mineral deposits in the Khnaiguiyah district, Saudi Arabia. Mohamed Taha et al. [23] investigated the proficiencies of several multispectral remote

sensing data to map mineral prospectivity using the random forest predictive model for gold deposits in the Hamissana area, NE Sudan.

The comments provided by the reviewers helped improve each of the papers published in this Special Issue, which was possible only because they were willing to volunteer their time and attention. We hope that the investigations published in this Special Issue will assist the mineral exploration communities and mining and hydrocarbon exploration companies to apply and integrate multispectral remote sensing satellite data and big data processing and deep fusion learning techniques for mineral and hydrocarbon exploration.

Author Contributions: A.B.P. writing; O.R. and M.P. editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The Guest Editors would like to thank the authors who contributed to this Special Issue and the reviewers who helped to improve the quality of the Special Issue by providing constructive recommendations to the authors. We would like to express our appreciation to all authors and reviewers who contributed their time, research and special knowledge to this Special Issue. We extend our sincere gratitude to the MDPI Editorial Team for supporting the Guest Editors in efficiently processing each manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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