Doctoral Dissertation
Doctoral Program in Civil and Environmental Engineering (38^{th}cycle)

Multi-scale Hyperspectral Characterisation of Mineral Systems Relevant to CRMs

Integration of Satellite Observations and Laboratory Analysis

By

Giorgia Carano

******

Supervisor(s):
Prof. Blengini Giovanni Andrea, Supervisor
Prof. Boccardo Piero, Co-Supervisor
Dott.ssa Claudia Baranzelli, Co-Supervisor

Doctoral Examination Committee:
Prof. van der Meijde Mark, Referee, University of Twente
Prof. Perotti Luigi, Referee, University of Turin

Politecnico di Torino
2026

Abstract

The accelerating transition towards low-carbon energy systems and digital technologies is driving an unprecedented increase in demand for Critical Raw Materials (CRMs), intensifying pressure on global mineral supply chains and amplifying concerns related to supply security, geopolitical dependence, and environmental sustainability. In response, the European Union has placed CRMs at the core of its industrial and strategic agenda, emphasising the need for diversified sourcing, improved geological knowledge, and innovative exploration approaches capable of supporting early-stage decision-making while minimising environmental impact.

Within this framework, this thesis investigates the potential of satellite-based hyperspectral remote sensing to contribute to CRMs exploration, with a particular focus on the Earth Surface Mineral Dust Source Investigation (EMIT) mission. EMIT provides contiguous hyperspectral coverage across the visible to short-wave infrared (VNIR–SWIR) range at 60 m spatial resolution, enabling the detection of subtle mineralogical variations that are difficult to resolve using conventional multispectral data.

The research adopts a multi-scale and multi-method approach integrating satellite hyperspectral observations, laboratory hyperspectral imaging, point-based reflectance spectroscopy, X-ray diffraction, and geochemical screening by portable X-ray fluorescence. Two complementary case studies located in southern Namibia are used to assess the applicability of hyperspectral techniques across spatial scales and geological settings. The first case study focuses on the Haib porphyry copper system, where EMIT data are employed to investigate hydrothermal alteration patterns through the analysis of spectral shifts in the Al–OH absorption feature of white micas at around 2200 nm. Variations in the wavelength position of this feature provide insights into compositional changes in muscovite related to alteration intensity and fluid evolution, allowing mineralogical zonation associated with porphyry-style mineralisation to be

assessed using transparent and unsupervised approaches such as wavelength mapping and band ratios.

The second case study targets carbonatite-hosted mineralisation along the Kudu Lineament. EMIT observations are complemented by detailed laboratory-scale analyses conducted on twenty carbonatite hand specimens from the Dicker Willem complex. These analyses include SWIR-based carbonate mineral classification using wavelength mapping and decision tree approaches, as well as VNIR investigations aimed at identifying neodymium-related absorption features. Laboratory hyperspectral imaging, point spectroscopy using a Halo spectrometer, and mineralogical and geochemical characterisation provide essential validation for the interpretation of spectral signatures observed.

Results demonstrate that EMIT hyperspectral imagery is effective in mapping mineralogical variability and alteration assemblages at regional scale in arid and semi-arid environments. In the carbonatite case study, however, neodymium-related spectral features are not directly detectable in EMIT data, likely due to the combined effects of spatial resolution, spectral mixing, and the dominance of other mineral phases at the pixel scale. At laboratory scale, neodymium can exhibit diagnostically useful VNIR absorption features under favourable conditions; nevertheless, high elemental concentrations measured by geochemical screening do not necessarily translate into clear spectroscopic signatures. Grain size, mineralogical context, phase mixing, and signal-to-noise limitations have a strong control on the detectability of rare earth element features in hyperspectral data.

Overall, this work highlights both the opportunities and current limitations of spaceborne hyperspectral remote sensing for CRMs exploration. By systematically integrating satellite-scale observations with laboratory-based validation, the thesis provides a robust framework for linking European raw materials policy objectives with practical, scalable, and environmentally responsible exploration methodologies.