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Mini Review

# Hyperspectral Mineralogical Characterization for Geometallurgy

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## Abstract

The integration of hyperspectral characterization into the mining industry represents a transformative shift in how mineralogical and geometallurgical data are utilized for exploration, processing, and operational optimization. This review highlights the advancements in hyperspectral imaging technologies and their applications, including mineral identification, core logging, ore sorting, and geometallurgical modeling. Technologies such as HyLogger, Corescan, and SisuRock have proven instrumental in capturing spectral data across VNIR, SWIR, and TIR ranges, enabling detailed mineralogical mapping and enhanced process control. Case studies demonstrate the effectiveness of hyperspectral techniques in predicting key variables such as grinding media consumption, tailings rheology, and ore classification, with notable contributions from advanced spectral databases like TSG and HIDSaG. Despite challenges, including data variability and integration into workflows, the combination of hyperspectral imaging with machine learning offers significant opportunities to improve decision-making and sustainability in mining operations. This review underscores the importance of hyperspectral characterization as a critical tool in addressing the complex demands of modern mining.

## Introduction

Infrared spectroscopy has long been employed in the mining and minerals industries for a variety of applications, including field surveys, laboratory analyses, and face mapping. Hyperspectral imagery, commonly acquired from airborne platforms [1], has significantly advanced the ability to rapidly identify alteration mineral assemblages and key parameters, such as mineral variations. This capability has heightened interest in hyperspectral technologies within the mining industry. Over the past 15 years, automated systems for core logging, such as HyLogger [2-4], have been developed, leading to their widespread application in exploration and mineral characterization. The development of automated hyperspectral data acquisition methods for core logging represents a critical response to an emerging challenge in the mining industry: how to transform abundant spectral data into actionable information that enhances sustainable business operations. Addressing this challenge involves three stages.

First, spectral data interpretation remains complex due to overlaps and subtle differences among mineral signatures. However, extensive research and resources now support this process, enabling more accurate data interpretation. Second, inferring geological and metallurgical significance from spectral and mineralogical data requires specialized expertise and multidisciplinary collaboration. This step is crucial for translating spectral data into meaningful insights to guide mining decisions. Lastly, the third stage involves the development of computational methods that can manage abundant and diverse datasets. These methods aim to apply insights flexibly, enhancing mine models and improving business outcomes.

Hyperspectral characterization has emerged as a sophisticated analytical tool for capturing detailed spectral data across a wide range of wavelengths. This technique enables the identification of mineralogical and textural properties in geological materials by leveraging the unique spectral signatures of minerals. These signatures, captured as reflectance or absorbance values, span the visible (VNIR), Near-Infrared (NIR), Shortwave-Infrared (SWIR), and, for some technologies, Thermal-Infrared (TIR) ranges. Such spectral data offer critical insights into the composition, distribution, and chemical properties of analyzed mining samples.

The application of hyperspectral techniques in mineral characterization is based on the principle that each mineral interacts with light in a unique manner, dictated by its molecular structure. This interaction produces distinct spectral fingerprints that advanced imaging systems can capture. Technologies such as HyLogger, TerraSpec, and Corescan have proven instrumental in integrating hyperspectral imaging into mining and geometallurgical workflows. These tools provide non-destructive, rapid, and high-resolution analyses of mineralogical variations, delivering essential information for exploration, resource estimation, and process optimization.

Recent advancements have underscored the value of hyperspectral data in developing robust mineralogical models, improving ore sorting efficiency, and predicting key geometallurgical variables, such as grinding media consumption and rheological properties. For instance, in addition to TSG (The Spectral Geologist), the HIDSaG database consolidates hyperspectral and geometallurgical data to facilitate machine learning applications for mineral classification and process optimization. Furthermore, integrating hyperspectral data with complementary analytical techniques, such as X-Ray Diffraction (XRD) for crystallographic structures, X-Ray Fluorescence (XRF), Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN), Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), allows quantitative results, enhances the accuracy of mineralogical assessments, providing more precise and actionable insights for decision-making in mining operations.

## Geological Sample Collection and Management

Diamond drilling is the primary method for mineral exploration, representing a significant portion of exploration budgets due to its high costs. Geological cores obtained through diamond drilling are typically logged visually by a geologist, who determines sampling intervals and assays. However, the adoption of advanced core analysis techniques can extract significantly more information from these valuable cores, including detailed mineralogical and geometallurgical data. Quantifying these parameters can contribute to achieving several critical goals: enhancing geological knowledge to refine exploration efforts, improving the objectivity, consistency, and efficiency of geological core logging, and better understanding the relationships between mineralogy, geotechnical, and geometallurgical properties. These advancements ultimately lead to more effective exploration, mining, and processing strategies.

Mineral identification is a cornerstone of mineral processing, as the mineralogical characteristics of ore determine the appropriate processing and extraction methods. Thus, non-destructive, rapid, and effective identification techniques are essential. Traditional methods such as XRD, QEMSCAN, SEM-EDS and ICP-MS are widely employed, they come with notable limitations. Although X-Ray Fluorescence (XRF) provides rapid elemental analysis, it is often hindered by low precision. These techniques generally require extensive sample preparation, specialized equipment, and prolonged processing times, which increases costs and reduces efficiency (Geoscience Australia), [5,6]. Furthermore, the subjective variability in core descriptions and interpretations among geologists introduces an additional layer of inconsistency to the process.

Infrared spectroscopy offers a powerful alternative for mineral identification, leveraging the diagnostic spectral features in the infrared region of the electromagnetic spectrum. Minerals exhibit unique absorption and reflectance patterns at specific wavelengths due to electronic and vibrational processes within their molecular lattice. These processes, resulting from the bending and stretching of molecular bonds, produce spectral responses characteristic of the mineral's chemical composition and crystal structure.

Hyperspectral imaging, a refined application of reflectance spectroscopy, enables the creation of precise surface mineralogy maps, including mineral boundaries, relative abundances, and assemblages. This technology provides geologists with a rapid and reliable tool for identifying mineral species and understanding mineralogical variability. Hyperspectral mapping techniques can distinguish individual species of iron and clay minerals, delivering critical insights into hydrothermal mineralization and alteration zones [7,8]. Such capabilities make hyperspectral imaging an indispensable tool for advancing exploration and optimizing mineral processing workflows.

## Comparison among the Technologies

The application of infrared spectroscopy presents significant opportunities for the mining industry, providing innovative pathways to enhance both sustainability and productivity. Comprehensive knowledge of ore mineralogy contributes to multiple facets of mining operations, including grade estimation, mine stability assessment, metallurgical property analysis, and the optimization of ore processing. Furthermore, it deepens the understanding of ore-forming processes, facilitating more efficient exploration and extraction strategies. The data gathered from the literature highlights variability in the characteristics of available technologies, encompassing both laboratory-based and portable devices. Table 1 summarizes the specifications of laboratory equipment commonly used for core logging, while Table 2 provides a comparison of portable infrared spectroscopy devices.

**Table 1:** Features of available laboratory technologies to scan drilling. * Estimated value.

| Developer | | CSIRO | | CoreScan | GEOTEK | SisuROCK |
|---|---|---|---|---|---|---|
| Model | | HyLogger 1 | HyLogger 3 | HCI - 3 | MSCL - S | SisuROCK |
| Spectral Range | VNIR, nm | 400-2500 | 400-2500 | 450-2500 | Depend on the different sensors and configuration | 400-2500 |
| | SWIR, nm | | | | | |
| | TIR, nm | N.A. | 6000 14500 | N/A | | 8000 12000 |
| Spectral Resolution (min,max), nm | | 10 in steps | 4-10 (VNIR , SWIR); 35 (TIR) | 4 | | 2,8 (VNIR); 10 (SWIR); 100 (TIR) |
| Pixel Size on Target (mm) | | 8 | 8 | 0.5-5 | N.I. | 0,2-2 mm (SWIR) 0,09 - 0,64 mm (VNIR) 1,7 mm (TIR) |
| Image Resolution | | 0,2 mm | 0,2 mm | 60 µm | 25 µm | 0,016 - 0,16 mm |
| Max Core Scan Rates (m/d) | | 200-300 | 700 | 1000 | 20 m/h (resolution 50 µm) | 1200* |
| Chip Looging rates (m/d) | | 3000 | 3000 | N.I. | N.I. | N.I. |
| Sample Preparation | | Minimal sample preparation , samples must be free of dust | | | | |
| Operation Conditions | | Laboratory type environment. Small amount of dust accepted. Air conditioned room recommended | | | | |
| Processing and Data Interpretation | | The Spectral Geologist software (TSG) | The Spectral Geologist software (TSG) | Coreshed | N.I. | BIL file format (ENVI/Evince compatible) |
| Other Characteristics | | Analysis of Drill core, chips and fine materials. Core tray up to 2m** | | Drill core, Trays box from 0,6 m to 1,5 m | Drill core, Trays box up to 1,5 m length and diameters from 50 to 150 mm | Drill core or single core up to 1,5 m length , 0.63 m width and 0.3 m height |
| General | | The HyLogger is a tool developed by CSIRO to improve the efficiency, productivity and objectivity of drill core | | Corescan is able to capture a large number of pixels within the image providing a comprehensive and easily | Equipment with multiple configurations and sensors | Sisu Rock is a fast scan and not external cooling required |

**Table 2:** Other equipment developed for infrared spectroscopy analyses.

| Developer | | Integrated Spectronics Pty Ltd | ASD | SpecTIR | | |
|---|---|---|---|---|---|---|
| **Model** | | **PIMA II** | **TerraSpec 4 Hi - Res Mineral Spectrometer** | **AisaEAGLE** | **AisaHAWK** | **AisaOWL** |
| Spectral range, nm | VNIR | N/A | 350-2500 | 400-970 | N/A | N/A |
| | SWIR | 1300-2500 | | N/A | 970-2500 | N/A |
| | TIR | N/A | N/A | N/A | N/A | 7700-12000 |
| Spectral Resolution (min, max), nm | | 7 | 3-6 | 3.3 | 12 | 100 |
| Intervalo Muestreo Espectral | | 2 nm | | 1,15-9,2 nm | 6,3 nm | 48 nm |
| Scan rate | Min | 10 s/sample | 0,1 s/sample | N/A | N/A | N/A |
| | Max | 5 min | | N/A | N/A | N/A |
| Samples | | Drill core, chips, fine material, soil, etc. | Drill core, chips, fine material, soil, etc. | Air mapping | Air mapping | Air mapping |
| Sample preparation | | No Information | Samples must be free of dust and other impurities | N/A | N/A | N/A |
| Processing and Data Interpretation | | Pima View (old operative system), TSG recommended | RS3, compatible with TSG y SpecMin. Also is possible to use ENVI, ASD ViewSpec Pro, Indico Pro | RSCube | RSCube | RSCube |

As shown in Table 1, a variety of technologies for spectral analysis of drill cores are currently available on the market. Among them, only HyLogger 3 and SisuRock operate across the VNIR, SWIR, and TIR ranges, enabling the identification of a broader spectrum of minerals. In contrast, Corescan offers superior image resolution but is limited to the VNIR and SWIR ranges. Portable devices, as presented in Table 2, provide the flexibility to analyze samples on-site. However, most portable instruments operate predominantly in the SWIR range, offering reduced mineral identification capabilities compared to laboratory equipment.

## Summary of Case Studies in Geometallurgical Applications

Díaz et al. [9,10] highlighted the importance of hyperspectral and XRD data in understanding grinding media consumption and grinding performance. In 2018, they developed predictive models linking mineralogical properties, such as pulp pH and mineral hardness, to wear mechanisms in grinding processes. A year later, their focus shifted to the influence of geological textures at meso- and micro-scales, demonstrating that traditional indices like the Bond Work Index could not fully account for textural variations, which hyperspectral data could address to improve grinding behavior predictions Merrill et al. (2017) applied hyperspectral characterization to estimate rheological behavior in mineral suspensions. Their findings revealed the potential of hyperspectral models to predict slurry viscosity and yield stress based on mineral composition, particularly clay content, enabling improved process control in mineral processing plants.

In another significant contribution, Voisin et al. [11] investigated the use of hyperspectral techniques to characterize tailings and predict their rheological behavior. By integrating hyperspectral reflectance data with XRD and particle sizing analyses, the study highlighted the impact of phyllosilicates on viscosity and yield stress, providing actionable insights for tailings management and process optimization. Halim et al. (2021) compared HyLogger hyperspectral imaging with Itrax core scanning to enhance petrophysical characterization workflows. This multi-scale analysis improved the accuracy of mineralogical assessments, aiding in resource estimation and supporting more efficient mining operations.

The integration of hyperspectral imaging in geometallurgy is further exemplified in case studies such as “Efficient Hyperspectral Mineralogical Mapping Using Clustering-Matching and NMF” (2023), which demonstrated the efficiency of clustering-based spectral matching for ore sorting. This methodology reduced processing times while enhancing the accuracy of mineral classification. Studies on automated ore sorting using hyperspectral systems, like “Hyperspectral Imaging Systems Deployed for Mining Operations” (2021), highlight how this technology can improve energy efficiency and resource utilization in mining operations.

“Hyperspectral Imaging in Mining: Boosting Efficiency and Enhancing Sustainability” (2023) integrated hyperspectral cameras into mining workflows, demonstrating how this technology balances profitability with ecological stewardship. These systems provided enhanced mineral identification capabilities, streamlining the entire mining value chain. Finally, Ehrenfeld et al. [12] introduced the HIDSaG database, a comprehensive repository for supervised machine learning in geometallurgy. The integration of hyperspectral and geometallurgical data has enabled more precise mineral classification and operational decision-making, paving the way for advanced predictive models.

## Challenges and Opportunities

Despite its numerous benefits, hyperspectral characterization faces challenges, including variability in data acquisition conditions, high initial costs, and the need for advanced computational tools to process and interpret large datasets. Results emphasize how the adoption of robust spectral databases, such as TSG and HIDSaG, and advanced predictive models have improved mineralogical characterization. These tools enable mining operators to make more informed decisions, particularly in identifying geometallurgical units and their performance on mineral processing and extractive metallurgical operations. A primary challenge remains the variability in spectral data acquisition conditions. Factors such as illumination and equipment used affect data quality, complicating comparisons between different datasets. Moreover, integrating these technologies into industrial workflows requires specialized technical training. Opportunities should be explored to develop more generalizable models that can adapt to the variable operational conditions of the mining industry [13,14]. Additionally, combining hyperspectral techniques with machine learning promises to improve the prediction of key variables and reduce uncertainty in decision-making.

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