

# Rapid mineralogic analysis of copper ores

Dan Shiley, Brian Curtiss and Alexander F.H. Goetz

*ASD, Inc., Boulder, Colorado, 80301, USA, Corresponding author.*

*E-mail: dan.shiley@asdi.com*

## Introduction

Near Infrared (NIR) reflectance spectroscopy has been used to improve the efficiency and quality of products in many industries. Mining and ore processing industries could also benefit from the application of NIR. This technique is now being increasingly used as a rapid quantitative technique for analysis of mineral ores, to aid in decision making for metallurgical processing. While NIR is most commonly applied to analysis of organic materials, many inorganic minerals have significant NIR features that result from changes in their composition, thus providing the opportunity to create predictive models for these minerals.

## Background

It has been known for decades that certain minerals produce unique spectra. Remote sensing of the Earth for geologic and environmental mapping relies on spectral measurements of reflected sunlight.<sup>1</sup> NIR spectroscopy has been successfully applied to a wide range of geological problems including: mineral exploration;<sup>2</sup> airborne and spaceborne mapping of hydrothermal alteration;<sup>3</sup> mineralogical analysis of drill cores;<sup>4</sup> field mapping of expansive soils;<sup>5</sup> and field mapping of mineral assemblages for gold deposit exploration.<sup>6</sup> The use of chemometrics to relate measured NIR spectra to properties of interest quantitatively has expanded the use of NIR spectroscopy to a wider range of applications, for example field determination of soil swelling potential<sup>7</sup> and gangue mineral measurement over a conveyor.<sup>8</sup>

The shape of the spectra and the positions of absorption features are determined by electronic and vibrational processes in mineral lattices and are also a function of particle size;<sup>9</sup> NIR spectroscopic evaluation of minerals reveals that there are several kinds of electronic processes that result in the NIR spectrum produced by a specific mineral. Crystal field effects, charge transfer, colour centres and conduction band transitions all contribute to the mineral spectrum.

## Materials and methods

Spectra were collected on 100 copper ore samples that had been processed to pass through an 850-micron sieve. The mineralogy reference analyses were performed using a scanning electron

microscope (SEM), coupled with energy dispersive x-ray analysis to identify and quantify minerals of interest.

ASD's Indico Pro software was used to collect spectra on a LabSpec 5000, ASD, Inc. This spectrometer has a wavelength range of 350–2500 nm with a 1 nm wavelength interval. Samples were placed into a sample cup and diffuse reflectance spectra collected using ASD's muglight sample accessory. The samples were divided into separate calibration and test sets. Assignment of these samples was random, following a ranking from low to high by constituent, to assure representation of all mineral ranges in the test set. To assure representivity of the spectra three portions of each sample were scanned with each portion, using a sample count of 100 scans. The resulting averaged spectra were imported into GRAMS AI v8.0 and PLSPlus/IQ for model development as absorbance spectra. Savitzky-Golay first derivative with 3<sup>rd</sup> order polynomial was used for all of the mineral models that were created.

## Results and Discussion

### Kaolinite

Sample spectra shown in Figure 1 have been offset for clarity, and are from samples that contain Kaolinite,  $\text{Al}_2(\text{Si}_2\text{O}_5)(\text{OH})_4$ . Kaolinite can be readily identified, based on a pair of prominent doublets at 1400 nm, 1410 nm and at 2160 nm, 2200 nm caused by slightly different sites where the OH groups are located. The PLS (partial least squares), kaolinite model that was developed with this data set required only two factors to produce a calibration with an *RSQ* (squared Pearson product moment correlation coefficient) of 0.85 and the standard error of cross-validation (*SECV*) was 1.82. The independent test had an *RSQ* of 0.84 and standard error of prediction (*SEP*) of 1.6,

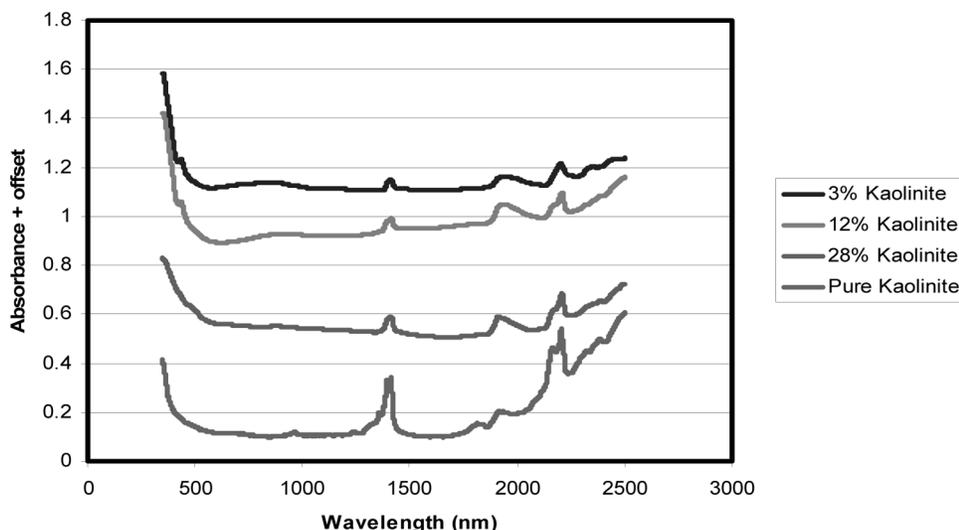


Figure 1. Comparison of low, medium, high and pure kaolinite samples.

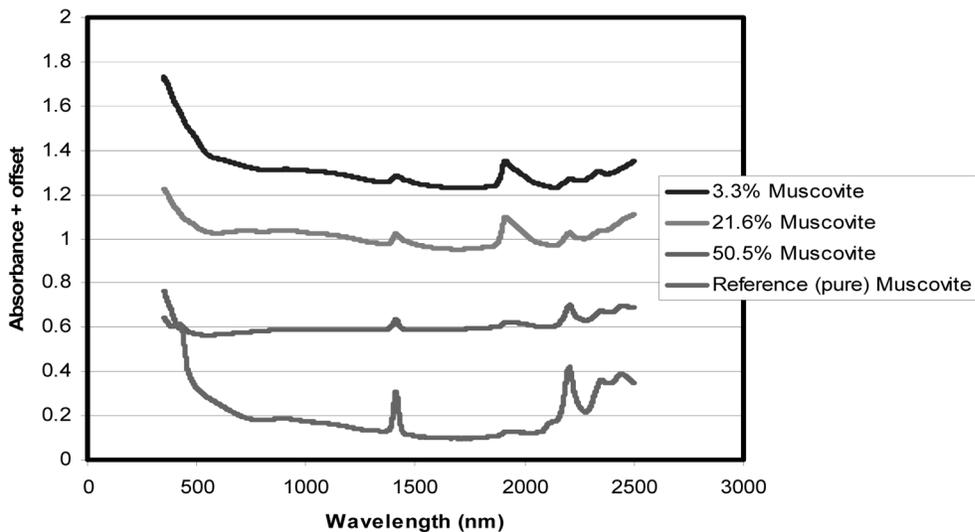


Figure 2. Absorbance spectra of samples with high, medium, low and pure muscovite.

which confirmed the validity of the calibration indicating that additional samples of a similar type would be expected to have similar performance characteristics.

## Muscovite

Spectra for samples containing muscovite,  $\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH},\text{F})_2$  in Figure 2 have been offset for clarity.

Muscovite has absorbance bands at 1400 nm, 2200 nm, 2350 nm and 2440 nm, which are primarily the result of Al-OH vibrations. Spectral features similar to pure muscovite can be observed, but because minerals are complex blends rather than pure components we also see other features related to the other minerals that make up the remainder of the sample weight. Due to these complex interactions it is not possible to simply ratio a peak height to muscovite concentration; instead we need to model using a multivariate chemometric approach.

The PLS1 model developed for muscovite required 6 factors to produce an *RSQ* of 0.90 with 77 of 81 calibration samples. The 19 sample independent test set confirmed this result with an *RSQ* of 0.91 and *SEP* of 4.7. Unlike the Kaolinite set, the muscovite samples were more uniformly distributed, which likely contributed to the success of this model.

## Chlorite

Chlorite,  $(\text{Mg},\text{Fe}^{2+})_5\text{Al}[(\text{OH})_8\text{AlSi}_3\text{O}_{10}]$ , spectra shown in Figure 3 have the unique 2250 and 2350 nm absorptions and the broad  $\text{Fe}^{2+}$  electronic transition around 1000 nm. Spectra also have many other features found in the other minerals present in the samples.

Calibrations had *RSQ* values that are sufficiently high to be useful for mine sample analysis. The high throughput and rapid analysis time could contribute to an improved mine plan and more efficient resource allocation.

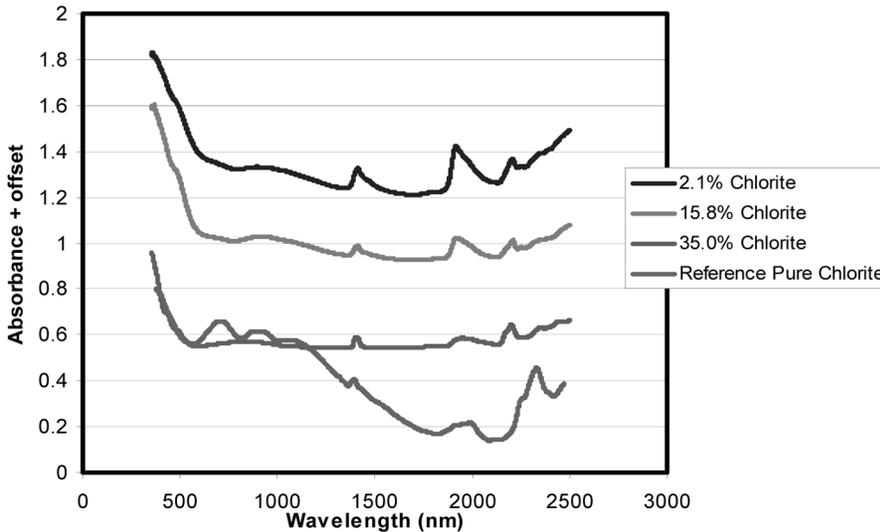


Figure 3. Spectra of low, medium, high and reference chlorite.

## Conclusion

NIR has been used qualitatively for decades to identify minerals based on their reflectance and absorbance spectra, that result from electronic transitions primarily in the 400–1000 nm region, and vibrational overtones and combination bands beyond 1000 nm. We have demonstrated quantitative models to predict concentration of mineral species within ore samples. NIR models were successfully developed for kaolinite, muscovite and chlorite using crushed ore samples. The speed, low cost and limited sample processing required all make NIR analysis ideal for mining applications.

## References

1. A.F.H. Goetz and L.C. Rowan, "Geological remote sensing", *Science* **211**, 781 (1981).
2. A.F.H. Goetz, B.N. Rock and L.C. Rowan, "Remote sensing for exploration: An overview", *Econ. Geol.* **78**, 573 (1983).
3. F.A. Kruse, J.W. Boardman and J.F. Huntington, "Comparison of airborne hyperspectral data and EO-1 Hyperion for mineral mapping", *IEEE Trans. on Geosci. Remote* **41**, 1388 (2003).
4. F.A. Kruse, "Identification of mapping of minerals in drill core using hyperspectral image analysis of infrared reflectance spectra", *Int. J. Remote Sens.* **17**, 1623 (1996).
5. S. Chabrilat, A.F.H. Goetz, H.W. Olsen and L. Krosley, "Field and imaging spectrometry for identification and mapping of expansive soil", in *Imaging Spectrometry: Basic Principles and Prospective Applications*, Ed by F. van der Meer and S.M. de Jong. Springer, Dordrecht, The Netherlands, pp. 87 (2002).
6. P. Bierwirth, D. Huston, R. Blewett, "Hyperspectral mapping of mineral assemblages associated with gold mineralisation in the Central Pilbara, Western Australia", *Econ. Geol.* **97**, 819 (2002).
7. A.F.H. Goetz, S. Chabrilat and Z. Lu, "Field reflectance spectrometry for detection of swelling clays at construction sites", *Field Anal. Chem. Technol.* **5**, 143 (2001).
8. A.F.H. Goetz, B. Curtiss and D.A. Shiley, "Rapid gangue mineral concentration measurement over conveyors by NIR reflectance spectroscopy", *Miner. Eng.* **22**, 490 (2009).
9. G.R. Hunt, "Spectral signatures of particulate minerals in the visible and near infrared", *Geophysics* **42**(3), 501(1977).