Hyperspectral logging for mineral deposits and its applications to mining

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Abstract. Automated hyperspectral drill core logging is capable of collecting detailed mineralogical information at close spatial resolution, complementing conventional (visual) logging with objective, data-rich information. An example of this technology is HyLogger-3™, a reflectance spectroscopic instrument equipped with VNIR[1], SWIR and TIR detectors. The deployment of HyLogger-3™ in major South American mineral deposits, such as the Chilean porphyry copper systems, has been in development through the Centre of Excellence for Mining and Mineral Processing at the AMTC since 2014. This document presents various examples of hyperspectral studies, and describe two case studies in detail that use this technology to solve mining-metallurgical and geological problems, in order to illustrate the potential of this analytic instrument. These cases are not directly related to the copper industry, but represent the way in which exploration and geometallurgical knowledge might be enhanced in porphyry systems via routinely acquired spectroscopic data.

Keywords. Spectral logging, HyLogger-3™, VNIR, SWIR & TIR spectra, reflectance spectroscopy, porphyry copper system, geometallurgy.

1. Introduction

The HyLogger-3™ instrument, which employs reflectance spectroscopy, was developed by CSIRO to improve the efficiency, productivity and objectivity of drill core, pulps and chips logging. Reflectance spectroscopy is used to determine diagnostic spectral features caused by molecular vibrations indicative of the chemical bonds in crystalline minerals and electronic transitions. Depending on the wavelength region used, it is possible to identify different minerals common to many hydrothermal alteration assemblages. The HyLogger-3™ is equipped with instruments to measure VNIR, SWIR and TIR wavelengths, detecting for example argillic, advanced argillic, sericitic and propyllitic alteration, but also quartz and carbonate veining. This data is analyzed using The Spectral Geologist software (TSG) developed by CSIRO to complement HyLogging. Quantitative models can also be built using TSG by calibrating the spectral data against standard laboratory techniques (typically XRD or QEMSCAN) and this information, combined with geological knowledge, allows development of 3D models of ore systems constituting a helpful tool for mine planning and mineral processing (Mason & Huntington, 2012).

The Centre of Excellence for Mining and Mineral Processing, a collaborative project between CSIRO and AMTC, has focused upon developing CSIRO's HyLogger-3™ for Andean copper systems. After installation in January 2014, the team has been working on local proof-of-concept studies and in reference libraries for local mineral identification, including those clays traditionally identified in SWIR wavelengths, plus the capability of the HyLogger-3™ to identify quartz, feldspars, garnets and other silicates with TIR wavelengths. In addition, clays such as kaolinite, smectite, pyrophyllite, chlorite and some sulphates are often hard to recognize visually, whereas the HyLogging system do this objectively on a routine basis.

1.1 Ore System Studies

Many studies using spectral data have been carried out in various parts of the world and in different types of mineral systems. SWIR hyperspectral data have been already applied to exploration for porphyry copper systems. For example, at Candelabro porphyry Cu and Mo prospect in Chile, Chang & Wilson (2012) identified elevated illite crystallinity in proximity to the mineralization by characterizing the SWIR spectral signatures of samples. Other example is the study of Cudahy et al. (2003), in which the authors used TIR spectral measurements of field samples to map the chemistry and spatial patterns of garnet, feldspar and carbonate associated with the Candelaria IOCG system in Chile. Epithermal systems (e.g. Witt et al., 2013) and skarn systems (e.g. Laukamp et al., 2014) have also been studied using spectral data. The capability of HyLogger-3™ to detect VNIR, SWIR and TIR wavelengths in the same analysis, gives many possibilities to start comprehensive hydrothermal systems studies, and advanced resource characterization in Chile.

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[1] VNIR-Visible and Near Infrared, SWIR-Shortwave Infrared, TIR-Thermal Infrared.

1.2 Geometallurgical Studies

The behavior of mineral species in processing is the key link between ore geology and metallurgical performance: whilst metal recovery is the objective, mineral grains and particles control the mining-metallurgical processes. Many mechanical causes of processing behavior are relatively well established through diagnostic process mineralogy studies. For example, high clay content is likely to influence rheological behavior of slurries, while fine grained Cu bearing sulfides usually implies poorly recovery in flotation circuits. The challenge for modern geometallurgical modelling is the quantification of this knowledge, which becomes problematic when required on a sampling scale providing statistically relevant data volumes.

The use of hyperspectral data as input to mine modelling has been impeded by the limited mineralogical range of SWIR measurements, and by the limited data analysis capability for linking spectroscopic data to metallurgical parameters. The first of these impediments is no longer the case using HyLogger-3™, because measurement of the TIR region means that 90-95wt% of typical ore mineral assemblages will be detected. The second impediment is somewhat subtler. Calibration of spectroscopic signatures using Partial Least Squares (PLS) modelling has been used extensively in soil science and in other disciplines (e.g. Soriano-Disla et al., 2014). However, human expertise is required to establish good models, controlling the invested time in this exercise. A pragmatic approach would limit PLS modelling to cases where mineralogical understanding would suggest a high probability of success, thus, a rheological PLS model would be favored over a metal recovery model since the clays are both spectroscopically active and rheologically influential. Sulfide grain size on the other hand, is not immediately associated with spectroscopically identifiable species. As the ability to manage and analyze data increases, these obstacles may be overcome. In the Table 1 (at the end of this document) geometallurgical applications of hyperspectral data can be seen to comprise both qualitative (e.g. 'ore-type') and quantitative (e.g. mineral abundance, 'reactive silica') use-cases. Comparison with the examples from the soil sciences, hints that the application of spectroscopic data in mining may have reached only a fraction of its potential, even if a number of metallurgical parameters inevitably remain refractory to useful spectrally-based PLS modeling.

2. Case Studies

To illustrate how spectral data has been used to provide deposit scale mineralogical models, two published examples are described below. In each case analogy can be made to Chilean ore systems for the purpose of geometallurgical mine planning (section 2.1) or geological exploration (section 2.2).

2.1 Yeelirrie Uranium Deposit

Yeelirrie is one of Australia's largest undeveloped uranium deposits, located in the northern Goldfields region of Western Australia. It is a near surface deposit amenable to open-pit mining techniques, emplaced in the Yeelirrie paleochannel along the drainage convergence within an incised and laterised peneplain. Alluvial sediments have infilled the paleochannel, resulting in an interbedded sequence of clay and quartz-rich horizons. The ore here comprises calcrete hosted uranium mineralization, within interbedded clays and sands (Cameron, 1990). The presence of clay minerals in this deposit could be deleterious to the efficiency of the uranium recovery process, because clay minerals in mining-metallurgical processes can cause increased slurry viscosity, poor agitation in stirred tanks, poor solid liquid separation, loss of metals to tailings and slower production rates. The key factors determining the extent to which clays can deleteriously affect ore processing are the grade and type of clay mineral within the slurry, so if mine planners know the nature of these factors beforehand, they can be substantially reduced or eliminated by selective mining or blending, and special design of the processing plants in order to manage these unwanted effects.

The HyLogging system was implemented as a primary method of clay mineral analysis for Yeelirrie. The spatial data set obtained, allowed the interpretation and geo-statistical analysis of geo-metallurgical domains across the deposit. Clay block models were generated (figure 1) and used in geometallurgical resource calculations. Trough XRD data, quantitative models where generated with PLS modeling and results were reported in this case to a mineral group level (%wt), acceptable for current investigation because the minerals within each group detected display the same or very similar metallurgical properties. Mineral groups used for block models were: kaolin, smectite, carbonates (calcite and dolomite) and gypsum. This study and a comparison between data acquired using XRD and HyLogger-3™ in Yeelirrie, can be found in Lower et al. (2011).

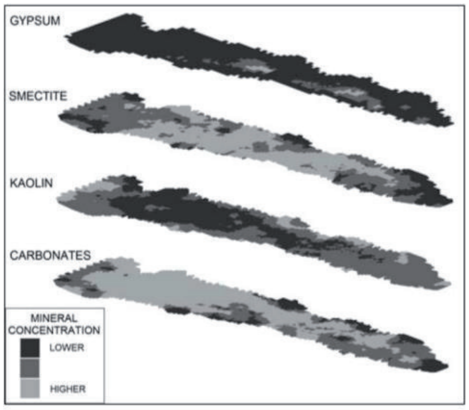

Figure 1. Clay block models developed using HyLogging data for Yeelirrie uranium deposit. Figure from Lower et al. (2011).

2.2 Henty Gold Mine

Henty is an underground gold mine, located in the West coast of Tasmania. It is comprised of a series of gold bearing sulphide rich lodes. Rocks that hosts gold lodes appear to be the result of deposition of magmatic gold-sulphide bearing exhalatives, and felsic ashfalls on a shallow sea floor. S, C, O and Pb isotopes provide evidence that Henty was formed from a seawater dominated hydrothermal system at around 200°C. Zones of quartz, pyrophyllite and topaz alteration found in Henty are however typically associated with porphyry copper mineralization, suggesting that the hydrothermal system here must have had a magmatic component to account for this acidic footwall alteration (Callaghan, 2001).

Different types of white mica where detected by the reflectance spectroscopy in this mineral deposit as shown in the study of Halley (2010). As the example in figure 2 (corresponding to drill core MJ 021 from same study), the HyLogging data shows variations in the wavelength of white mica absorption feature (from 2194 to 2218 nm) proving progressive substitution of Fe^{2+} and Mg (phengite) for Al in octahedral sites of muscovite. According to Halley (2010), this muscovite to phengite reaction could be controlled by pH, in a way that muscovite would mean presence of acid fluids, and phengite presence of more alkaline fluids, so the shift in white mica wavelength could be used as a hydrothermal pH indicator. In this deposit albite zones were found to be associated to longer white mica wavelengths (high pH), topaz zones associated to shorter white mica wavelengths (low pH), and a strong sericite zone in the area approaching to the Henty Fault (with intermediate mica wavelengths). In general, gold zones in the mineralized area tend to correlate with the latter, which is more alkaline in the hangingwall, but more acidic in the footwall (also shown in figure 2).

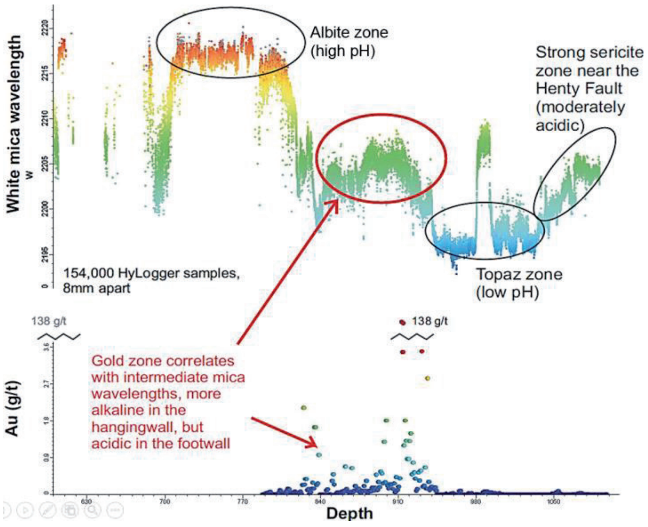

Figure 2. Wavelength of 2200 nm absorption feature in white mica, plotted against depth down hole and gold content (MJ 021) in a drill core from Henty mine. Figure from Halley (2010).

The interpretation regarding muscovite-phengite reaction presented in this work is one of a few possibilities. Numerous reasons for the zoning of white mica composition in different hydrothermal systems are discussed in literature, such as pH and concentration of ferrous iron and potassium in the hydrothermal fluids (Halley et al., 2015), and others.

3. Current and future research

Examples from logging and data analysis presented in this work demonstrate the potential power of the HyLogging method for detailed-scale mineralogical characterization and increase objectivity in this kind of research. HyLogger-3™ is currently operating on six in Geological surveys around Australia and the system has been successfully tested at different mining operations. This technology do not replace a trained geologist, it gives new opportunities and information, because the major benefit of the HyLogging system is the identification of parameters unable to be resolved by eye, such as intensity and chemistry variations, or clay identification. In the CSIRO-AMTC project, the use of HyLogger-3™ goes along with the Chilean copper industry, and the local team has developed expertise analyzing thousands of meters from different mining companies, focusing on the mineral identification of clays (kaolinite, smectites, pyrophyllite, chlorite, talc, etc.) and various sulphates and silicates. This information can be used to determine different minerals associations, changes in compositions against depth, and so on. The generated information is hoped to be exported for further analysis of 3D modeling in the future.

The possibility of develop geometallurgical models with the application of HyLogging technology to porphyry copper systems integrating geology, mining and metallurgic data, can lead to greater efficiencies in mine planning and processing. The main benefits of advanced ore characterization are identifying and quantifying the impacts of ore properties on the efficiency of unit processes, and this is expected to be demonstrated in the future with the engagement of the Chilean industry with this project. Other possible information that could be considered to join and complement the HyLogging spectral data eventually are rgb images, structural information, geochemistry and geotechnical data that might be combined into advanced analytic packages.

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Table 1: Examples of geometallurgical studies using spectral data. Qualitative and quantitative use-cases.

Ore description	Mineral identification	Associated Metallurgy	References
Iron Ore	Hematite, goethite, gibbsite, silica, kaolinite, smectite.	Textural types affecting sintering, and ore quality.	Magalhaes et al. (2007)
Bauxite	Gibbsite, kaolinite, goethite.	Direct PLS modeling of caustic digest results for 'available alumina' and 'reactive silica'.	Carioca et al. (2011)
Nickel laterite	Serpentine, goethite, smectite.	Mineral quantification for blend control.	Basile et al. (2010)
Gold	Mica, chlorite, carbonates.	Alteration associated with Au mineralization.	Mauger et al. (2007)
Porphyry Copper	Sericite, pyrophyllite, chlorite.	Mineral quantification for heap permeability and agglomeration, crush strength and sampling domains.	Quigley &Yıldırım (2015) Allen et al. (2007)