Multi-Scale integrated application of Spectral Geology and Remote Sensing for Mineral Exploration


1. Spectral geology and remote sensing consultant, Toronto, Canada
2. Inversiones Barrick Conosur Ltda., Santiago, Chile
3. Barrick Gold Corporation, Montreal, Canada
4. Minera Barrick Misquichilca, S.A., Lima, Peru
5. Center for Exploration Targeting, UWA, Perth, Australia

ABSTRACT

Corescan mobile lab based high resolution hyperspectral core imaging system, Worldview-3 and Pleiades space borne high resolution imaging systems represent some of the most significant advances with successful commercial implementation in the past decade in the field of visible-near infrared-infrared spectroscopy and remote sensing technology. Such advances have empowered field geologists with new insights for targeting through improved multi-scale alteration and structural characterization of ore systems.

Corescan high resolution hyperspectral mineralogical and textural data allows objective, fast, semi-quantitative and cost effective analysis of alteration minerals and mineral sub-species, style, intensity, spatial zonation, as well as alteration assemblages and their timing relation to mineralization of ore systems, and can assist the delineation of system footprint and the identification of vectors for targeting from drill hole to deposit, and on district and regional scales. Worldview-3 allows improved alteration mapping over Aster as a result of its higher spatial resolution and data quality. At sub-meter resolution, Worldview-3 and Pleiades satellite imageries prove to be cost effective for surface lineament analysis in rugged terrains from outcrop scale to deposit and district scales and can help define structural framework and, combined with surface alteration mapping, identify ore control structures for targeting. In addition, and not least important, progress has been made in improved field application of older technologies such as ASD field portable spectrometers, Probe-1 and Hymap airborne hyperspectral imaging systems. Understanding the fundamental capabilities and limitations of these technologies, continuously refining target alteration models and a field driven approach is critical for effective field application from data collection, data interpretation and synthesis analysis to data integration for targeting.

Field application examples for epithermal high sulfidation, porphyry and Carlin exploration are discussed in this paper to illustrate these advances, along with remaining limitations and new opportunities.

INTRODUCTION

Many important hydrothermal system indicator minerals are detectable by visible-near infrared-shortwave infrared (VNIR-SWIR) and/or thermal infrared (TIR) spectroscopy (Hunt and Salisbury 1970; Hunt, 1977; Clark et al, 1990; Salisbury et al, 1991; Cudahy et al, 2001, 2009; Kokaly et al, 2017) (Figure 1). The most widely adapted application for mineral exploration is the SWIR detection of phyllosilicates which are difficult to identify with the naked eye (Thompson et al, 1999). Mineral chemistry of white mica, alunite, chlorite and carbonate as well as mineral crystallinity of white mica and kaolinite can also be readily approximated through spectral indices (Scott et al., 1998; Thompson et al, 1999; Yang, et al, 2001; GMEX, 2012) (Figure 2). Such numerical parameters can be useful as an indicator of fluid pH and temperature gradience in hydrothermal systems (Dilles et al, 2012; Halley et al, 2015). However, the accuracy and detection limit of these indicator minerals and spectral indices depends on not only the instrument spectral band configuration, the spatial and spectral resolution and signal to noise ratio, but also the mineral’s reflective property vs interference from other co-existing minerals in a given field of view where the spectra is taken. In addition, because infrared spectroscopy does not penetrate rock surface beyond a few microns, surface weathering, and in the case of remote sensing data, vegetation, overburden, snow and clouds etc. are some of the additional constraints. The applicability and optimum use of such technologies therefore may vary depending on the system fundamentals of the spectral instrument, target types and indicator minerals of interest, host rocks, complexity of hydrothermal systems (e.g. multiple event overprints and modifications), weathering and, for airborne and space borne remote sensing applications, surface environment such as outcropping ratio, cloud cover, solar illumination level (latitude, sun angle, slope shadows, etc.), as well as the automated and semi-automated spectral data processing and pre-processing methodologies used. In porphyry systems for instance, as in epithermal high sulfidation and Carlin systems discussed in this paper, integrating geological (hand lens) observation with spectral analysis is critical for successful field applications (Harraden et al, 2013) and for synthesizing spatial alteration patterns (Dilles et al, 2012; Halley et al, 2015).
Figure 1: Common alteration gangue minerals in hydrothermal systems. Many indicator minerals have diagnostic spectral features in the VNIR-SWIR region, with the rest in TIR region. Modified from Corbett and Leach (1998) and Brommecker et al. (2011).

Figure 2: Spectral profiles of white mica and alunite, showing spectral index classification for white mica and alunite chemistry and white mica crystallinity. Insets on the right show correlation between white mica and alunite absorption wavelength indices and composition.
Spectral instruments in the exploration tool box range from point measurement, profiler and imaging systems of different spectral and spatial resolutions, operated from different platforms including hand held, field portable, lab based, airborne and space borne systems. Figure 3 shows some of the spectral tools discussed in this paper.

**Figure 3:** Platform, spectral range, spectral and spatial resolution of different spectral tools discussed in this paper. Illite and alunite spectral profiles illustrate mineral identification capabilities with respect to spectral band configuration and spectral resolution. See details on system specifications in Martini et al., (2017) for Corescan, ASD Inc. for ASD Terraspec 4 and Fieldspec, Cocks et al., (1998) for Hymap, Digital Globe for Worldview-3, and Rowan et al., (2003) for Aster.

One of the most significant technical advances in the last decade is Corescan high resolution hyperspectral core imaging system. Corescan combines rapid, automated, high resolution hyperspectral core imaging data collection with real time data processing and user friendly data visualization and integration capacities (Martini et al., 2017). Continuous, semi-quantitative abundance of alteration minerals detectable in the VNIR-SWIR spectral region coupled with textural characteristics in drill core and RC chips can be mapped at deposit scale at 4 nanometer spectral resolution and 500 micron spatial resolution.

The Worldview-3 satellite has improved alteration mapping capabilities compared to Aster at district-deposit scales due to its higher spatial resolution, high signal to noise ratio, pixel based atmospheric correction and an on-going vigorous vicarious radiometric calibration program. In addition, sub meter resolution satellite panchromatic images from Worldview-3 (0.31 m), Worldview-2 (0.46 m) and Pleiades (0.5 m) provides outcrop details for lineament analysis and structural interpretations at district-deposit scales. High resolution satellite stereo images for 3D terrain model and 3D visualization are available at additional cost.

Several field examples are discussed in this paper to illustrate multi-scale, integrated application of a wide variety of spectral tools for porphyry, epithermal high sulfidation and Carlin exploration, as well as limitations, challenges and emerging opportunities.

**REGIONAL EXPLORATION, EL INDIO BELT, CHILE**

The highly endowed north-south trending El Indio Belt (EIB) is located along the border between Chile and Argentina, over a flat subduction zone in the high Andes, about 500 km north of Santiago. EIB contains several world class epithermal high sulfidation deposits including El Indio-Tambo, Pascua Lama, Veladero and the recent discovery of Alturas (see Astorga et al., 2017 for details on production, reserves and resources). At regional to camp scale, gold mineralization is localized at the intersection of north-south to north-northeast structures and northwest structures (Figure 4).

**Figure 4:** Regional geology of EIB, Chile. Epithermal gold mineralization is localized at the intersections of north to north-northeast and northwest structures. Modified from Charchafli et al., (2007) and Astorga et al., (2017).

Probe-1 is a Hymap prototype airborne hyperspectral sensor (Figure 3) prior to commercialization. Probe-1 airborne hyperspectral surveys were flown in 1999–2000 at 8 m resolution over approximately 170km x 22 km, aimed to assist high sulfidation exploration on EIB. During 2010–2011, the historical Probe-1 data was reprocessed for porphyry generative programs in light of the up to date porphyry alteration model (Sillitoe, 2010), research findings (AMIRA, 2013), in-house knowledge and critical field input. Close collaboration with the
project team resulted in the incorporation of target model in the context of Probe’s poor detection capability for potassic alteration, and identified sericite and high crystallinity illite of phyllic alteration as an important proxy to porphyry centers. The resulting Probe-1 sericite map distinguishes discrete sericite and high crystallinity illite from very wide spread low crystallinity illite alteration in the region, validated by a successful blind test with very good spatial correlation with known porphyry occurrences in the belt (Figure 5). Following field and desktop validation, Probe-1 mineral and mineral composition maps of sericite, pyrophyllite, alunite, illite, chlorite, gypsum, jarosite and topaz were visualized in 3D Google Earth Pro to create thematic and synthesis maps (Figure 6). Transported anomalies in the alluvial and colluvial cover were visually identified and eliminated. Vertical and lateral zonation of alteration assemblages from phyllic, transitional, and advanced argillic to intermediate argillic alteration were synthesized to highlight higher temperature, near neutral pH zones proximal to hydrothermal centers. A 1:25,000 sericite map was created with anomalies ranked based on alteration zoning patterns in relation to geology, aeromagnetics, rock chip geochemistry and geochronology data. Data integration was key in generating new target areas for field follow up.

Probe-1 sericite anomaly map provided a quick overview of the prospective areas at favorable erosion levels along EIB, in addition to and as a cross reference for the structural block interpretation (Astorga et al, 2017). However, none of the optical sensors including Probe-1 can penetrate surface. Phyllic zones with post mineral covers are not detectable. While sericite is found intact in the phyllic zones around several porphyry occurrences along the belt, field evidence suggests that it may breakdown in advanced weathering process where abundant pyrite occurs. In addition, incomplete elimination of transported anomalies in colluvium and alluvium cover may also result in pseudo zoning pattern in relation to their prospective elevation levels and systems of multiple event overprinting vs telescoping cannot be consistently discriminated through Probe-1 alteration distribution patterns. These limitations are commonly encountered with optical remote sensing tools and should be kept in mind in data integration and field follow ups.

ALTERATION AND STRUCTURAL CHARACTERIZATION FOR TARGETING, ALTURAS HIGH SULFIDATION DEPOSIT, EIB, CHILE

Alturas is a semi-concealed, diatreme complex related high sulfidation gold deposit in EIB with an inferred resource of 211 Mt at 1.0 g/t gold (Astorga et al, 2017). Mineralization is associated with multiple stages of pyritic microcrystalline silicification and a late stage jarosite alteration, overprinting early advanced argillic alteration of alunite+/−dickite and vuggy silica outboard upwards and laterally zoned to kaolinite+/−dickite and illite alteration. Steam heated alunite alteration occurs at the most shallow level of the system.

Figure 5: Porphyry alteration model and El Indio Probe-1 airborne hyperspectral mineral mapping results: illite-sericite map (upper right) vs sericite map (lower right), showing a “blind test” of Probe-1 sericite mapping successfully identified phyllic alteration proximal to porphyry occurrences (marked with x).
Figure 6: Google Earth 3D visualization and synthesis interpretation of Probe-1 mineral maps. From Zhou and Jara (2011).

Figure 7: Alturas Corescan assemblage classification, showing corresponding alteration assemblages in hand samples and zonation on section.

**Alteration**

As with other high sulfidation systems, gold mineralization at Alturas shows strong spatial association with advanced argillic alteration, and hyperspectral logging and mapping is critical to discriminate clay alteration zoning beyond the naked eyes.

Following the initial ASD Terraspec spectral logging and a Corescan high resolution hyperspectral core imaging orientation study, on-site Corescan hyperspectral imaging of 15,403 m of...
core from 41 diamond drill holes was carried out successfully during the 2014–2015 drilling campaign. Through close collaboration between Barrick and Corescan, a real time on-site workflow was implemented from drilling to hyperspectral core scanning, on-site processing, on-site hyperspectral “Coreshed” data access and visualization and daily acquire database updates. Real time data visualization to assist logging was enhanced by a customized alteration assemblage classification scheme incorporating field input on alteration model and findings from ASD Terraspec spectral logging at Alturas (Figure 7).

Corescan data provided objective, semi-quantitative alteration mineralogy at deposit scale, coupled with textural information at microscopic resolution. Continuous core imaging at 500 micron resolution enables consistent, systematic alteration characterization of all styles and intensities such as pervasive replacement vs patchy or partial replacement, breccia clasts vs breccia cements, vein or fracture coating and vug fill. This resulted in improved logging consistency, accuracy and efficiency and increased confidence in the delineation of alteration zonation (Figure 8). Combined with sound geological knowledge, Corescan data aided section interpretation, ore body definition, 3D modelling and resource estimation (Astorga et al., 2017).

It also reveals the hydrothermal alteration assemblages and their timing relations in the diatreme complex. Pyrophyllite, sodic alunite, illite, tourmaline, and gypsum alteration are found in breccia clasts and rock flour matrix at shallow levels that appear to be pre-mineral and were either missed or mischaracterized by previous ASD Terraspec systematic spot sampling with an approximately 1–2 cm field of view (Figure 9).

Figure 8: Corescan alteration zonation in relation to mineralization with inset (lower left) showing late stage ore bearing jarosite in fractures.

Figure 9: Corescan images of illite alteration in breccia clasts and fine fragments of rock flour matrix, which is difficult to resolve with ASD Terraspec 1–2 cm field of view. See Figure 7 for “Alturas Detail” class map legend.
Earlier studies on alunite modes of occurrence and composition in EIB suggest that potassic alunite dominates the advanced argillic alteration in high sulfidation systems at Pascua Lama and El Indio whereas sodic alunite occurs at depth in higher temperature with the exception of Tambo where mafic host rocks prevail (Deyell and Dipple, 2005). In the Far South East porphyry district, Philippines, sodic alunite is also found forming at higher temperature proximal to intrusions (Chang et al., 2011). Much more complicated alunite composition paragenesis is found at Caprite, Nevada, suggesting multiple intertwined cycles of potassic and sodic alunite alteration (Swayze, 2014).

At Alturas, ASD Terraspec systematic logging, conducted prior to Corescan implementation, identified sodic alunite in the breccia at shallow levels, overlapping with potassic alunite alteration above the mineralization (Figure 10). This vertical distribution pattern was first interpreted as a compositional gradient which can be used as a vector towards mineralization. However, evidence from Corescan data demonstrates that sodic alunite occurs in some of the breccia clasts and fine fragments in the rock flour matrix which was difficult to resolve by ASD Terraspec's 1–2cm spatial resolution or spot sample field of view, even when sampling systematically at one meter interval. Similarly, Corescan data revealed the occurrence of altered clasts of illite, as well as tourmaline and pyrophyllite above the advanced argillic alteration, all of which was missed by previous ASD analysis.

These findings led to a new hypothesis that sodic alunite, illite, tourmaline and pyrophyllite might have been brought to shallow levels from depth through phreatomagmatic brecciation, prior to syn-mineral potassic alunite alteration and pyritic silicification. In other words, the vertical compositional variation involves a transported component and the zoning is not produced in response to a depth control.

This hypothesis sheds new light on the significance of alteration pattern at deposit scale and its implication for targeting at district and regional scales. In particular, it cautions against the use of the apparent vertical zoning of alunite composition as a vector for targeting elsewhere. It also suggests that the surface expression of Alturas hydrothermal system is complicated by pre-, syn- and post- mineral volcanism, multiple brecciation and hydrothermal events. At the surface, the mechanically redistributed illite is found at the center of the deposit surrounded by advanced argillic alteration, mappable by ASD.

**Figure 10:** Alturas preliminary section (as of June 2013), showing geology, alteration and Terraspec alunite composition zoning in relation to mineralization. Lower right: A - 2014 Corescan image of Na-alunite clasts (red) with potassic alunite replacing matrix at shallow levels, and B - Na-alunite matrix, with high crystalline K-alunite clasts at depth.
Terraspec, Probe-1 as well as Worldview-3 (Figure 11). As shown in Figure 11, illite alteration at Alturas is not mappable by the 30 m resolution Aster data. This is partly due to the common co-occurrence of illite with alunite and/or kaolinite at 30 m resolution, but not at the 7.5 m resolution. The "a-typical" alteration pattern detectable by Worldview-3 7.5 m resolution satellite imageries and airborne hyperspectral surveys may be used to screen similar breccia systems elsewhere, with field follow ups guided by the understanding of alteration assemblages and timing relation derived from Corescan data. This approach of integrating alteration characteristics at all scales results in a more predictable exploration model for targeting beyond empirical patterns.

Structures and lineaments

Regional structural trends in EIB are manifested at local scales at Alturas. Detailed field mapping in the region delineated NW, NE and NS principal trends of joints and faults, which are also recognizable from downhole Televiewer data (Figure 12). These three trends are all consistent with the lineaments observed in Pleiades 0.5 m resolution panchromatic images. Outcrop scale details such as subvertical fracturing and bedding are also recognizable from Pleiades image, allowing structural interpretation based on strata bedding orientation. Most lineaments are interpreted as faults as they appear to offset strata of variable ages that are often differentially tilted. In the middle of the Alturas deposit, all three structural trends are relatively difficult to define due to strong argillic alteration causing poor outcrop quality and whitening of the image. However, in the immediate vicinity of Del Carmen to the east of Alturas, there is very clear evidence of three principal trends of joints/faults (Figure 12, shown in red lines in the inset image) that have been recognized in the field to be associated with hydrothermal alteration and mineralization. In addition, the alteration distribution pattern mapped by Probe-1 revealed additional lineaments over areas where field observations are obscured by strong argillic alteration.
Field mapping is very challenging in areas such as Alturas in the high Andes. The terrain is not only remote and rugged, but also at elevations typically above 4000 m where one can only walk very slowly due to the thin air. As a result, it takes much longer to map from one outcrop to another and it is difficult to keep track of the structural features in the field. In such environment, lineament analysis using high resolution satellite images, combined with alteration mapping, if available, can be a very cost effective tool to serve as a reference for more effective field mapping and assist the interpretation of the structural framework and ore control structures.

**“CARLIN” ALTERATION CHARACTERIZATION, CORTEZ DISTRICT, NEVADA**

Cortez district is located on the Battle Mountain-Eureka trend in the Great Basin province of the western U.S. Three giant Carlin-type deposits of Eocene age in the district display varied styles and geometry, with stratabound oxidized replacement mineralization at Pipeline, oxidized breccia pipe style and stratabound refractory replacement style mineralization at Cortez Hills, and stratabound refractory breccia at Goldrush. Mineralization is localized at the axial crests of a series of east verging asymmetrical anticlines propagated by the Roberts Mountain thrusts, hosted in the Lower Plate continental margin slope facies of silty carbonates, debris flow, turbidites of the Devonian Wenban Formation, Silurian Roberts Mountain Formation and to less extent, calcareous mudstones and siltstones of Devonian Horse Canyon Formation (Leonardson, 2015; Bradley and Eck, 2015). Like other Carlin type systems, alteration associated with Carlin mineralization in the district includes decalcification, carbon remobilization, argilization of illite, kaolinite and dickite, disseminated arsenopyrite and silicification. At both outcrop and hand lens scales, clay alteration is observed as replacement along bedding plane and low angle thrust planes, in breccia clasts and cements, and intensifies in fold hinges and high angle “bounding” structures (Figure 13).

![Figure 13](image)

**Figure 13:** Typical styles of clay alteration observed in Pipeline deposit, Cortez district, Nevada.

Illite-kaolinite-dickite has long been recognized as the clay alteration assemblage associated with Carlin mineralization (Kuehn and Rose, 1992, Drews-Armitage et al, 1996), which can be readily detected through field portable spectrometers (Hauff, 1997). In addition, very extensive illite composition zonation in Carlin systems on the North Carlin Trend was mapped by 10 m resolution Hymap airborne hyperspectral survey with high aluminum illite spatially associated with mineralization, validated by Pima field portable spectrometer (Zhou, 1999, 2000). ASD spectral analysis also identified illite composition variations at Getchell deposit (Cail and Cline, 2001), and ammonia illite in mineralized structures in Jerrit Canyon district and at Goldstrike (Mateer, 2010).

These findings led to an extensive ASD Fieldspec spectral study in the Pipeline open pit in 2006, followed by systematic spectral logging of over a hundred core holes and RC holes to construct cross-sections and long sections over Pipeline-Gold Acres subdistrict, Cortez Hills, and Horse Canyon deposits in 2007–2008. An interactive, integrated approach was applied throughout the spectral mapping and logging program, combining stratigraphy, geochemistry and hand lens observations with real time spectral mineralogical and illite composition identification during spectral data collection and synthesis analysis, supported by close collaboration with the Cortez geological team. This resulted in the delineation of spectral alteration distribution on cross sections and long sections at the deposit scale and a refined empirical alteration model for Carlin-type deposits (Figures 14 and 15). Subtle but extensive lateral zonation from proximal potassic illite to distal phengitic illite and a prominent vertical zonation for illite dominated alteration at shallow levels to illite-kaolinite and illite-dickite alteration at depth, and late to post mineral ammonia illite overprinting at shallow levels and in structures. Pervasive kaolinite alteration is commonly found in pre- to syn-mineral dykes. The spatial zoning pattern of clay alteration approximates the pH and temperature gradient (Hemley and Meyer, 1967; Dilles et al, 2012; Halley et al, 2015) (Figure 1) as Carlin acid fluid becoming neutralized through movement within the calcareous host rocks along the fluid path and is spectrally detectable from hand sample, outcrop to deposit and district scales.

Reprocessing of historical 8 m resolution Hymap airborne hyperspectral survey data over the Cortez district was subsequently carried out, guided by the findings from the integrated spectral logging and pit mapping. Field follow ups in 2009 confirmed gold mineralization in rock chip samples from numerous prominent illite anomalies east of the Horse Canyon deposit. Some of these anomalies suggest mineralization at depth of about 270 m, on strike from the Red Hill prospect.

As clay alteration associated with Carlin mineralization tends to be extensive laterally along the low angle thrust planes and beddings planes, sound understanding of stratigraphy is critical in integrating surface alteration for targeting. Furthermore, the carbonaceous material in un-oxidized host rocks of Carlin systems is strongly light absorbent, and significantly reduces clay detectability in the VNIR-SWIR region. This hampers the VNIR-SWIR spectral application especially in deep drilling programs. More work is needed to assess TIR scanners such as that of TerraCore hyperspectral imaging system and Hylogger hyperspectral profiling system for their use and limitations for mineral mapping in carbonaceous rocks (Schodlok et al, 2016; Bedell et al, 2017; Coulter et al, 2017).
DISCUSSIONS AND CONCLUSIONS

Integrated use of spectral tools, combined with field geological observations, have been critical for mapping and logging extensive alteration footprint and subtle zonation beyond what is possible with the naked eyes in epithermal high sulfidation, porphyry and Carlin systems. The Corescan hyperspectral core imaging system enables more consistent and accurate logging and characterization of alteration assemblages, style and intensity, and allows rapid, integrated analysis of alteration assemblages and their timing relation to mineralization, controls of and vectors to mineralization. Worldview-3 satellite data provides more detailed alteration mapping capability compared to Aster and, with the increasing global archive coverage, sub-meter resolution Pleiades and Worldview-3 satellite data can be very cost effective for lineament analysis, especially in rugged terrains.

Figure 14: Geology cross section of Cortez Hills deposit, Nevada, looking north, showing correlation of ASD Fieldspec alteration mineralogy with gold mineralization and structures. Geology from Jackson et al. (2010).

The increasingly versatile array of spectral tools available to exploration allows more integrated, multi-scale approach for targeting. Geoscientists can not only use the spectral data to reveal spatial distribution patterns of indicator minerals for area selection at regional to prospect and deposit scales, but also rapidly characterize clay alteration at microscopic resolution to synthesize the significance of such patterns and define more predictable exploration models for targeting.

Figure 15: Generalized alteration model for Carlin type deposits. Modified from Robert et al. (2007) and Zhou, (2009).

Like any technology, none of these spectral tools is a “silver bullet”. Understanding the fundamental capabilities and limitations of these technologies, sustained close collaboration of multi-disciplinary team is essential to ensure a field driven, integrated approach is applied to the entire exploration process from data collection, data processing and synthesis analysis, to data integration and targeting.
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