MAPPING MINERAL FOOTPRINTS THROUGH COVER USING SURFACE AND SUBSURFACE MINERALOGY AND GEOCHEMISTRY

Carsten Laukamp[1], Alistair White[1], Andrew Rodger[1], Justin Gum[2], Vasek Metelka[1], Ian C Lau[1], Georgina Gordon[3], Lionel C Fonteneau[4]

[1] CSIRO Mineral Resources, Australia
[2] Southern Gold Ltd, Adelaide, Australia
[3] Geological Survey of South Australia, Adelaide, Australia
[4] Corescan Pty Ltd, Perth, Australia

ABSTRACT

Mapping footprints of mineral deposits is often hindered by substantial weathering profiles developed atop buried mineralization. Understanding the mineralogical and geochemical trends in the weathering profile can be crucial for enabling successful exploration, especially when using remote sensing data.

Drill core hyperspectral and geochemical data were analyzed in detail to develop a 3D mineralogical/geochemical model that allowed an evaluation of which footprints, associated with gold mineralization in the Bulong area of the Eastern Goldfields (Western Australia), could be discovered at the surface. The combined analysis of hyperspectral and geochemical drill core data also helped to map out clusters of mineral assemblages that are 1) associated with gold, 2) are inversely correlated with gold and/or 3) form a halo in proximity to gold mineralization. White mica was found to be of phengitic composition proximal to gold mineralization, whereas talc-carbonate alteration forms a shell around the mineralized intervals. Phengitic white micas were successfully traced at the surface, indicating potentially new prospective areas. However, due to issues with vegetation and related overlapping absorptions with talc and carbonate, talc-carbonate alteration could not be found in the airborne hyperspectral data.

The Bulong case study highlights the need for advancing vegetation un-mixing of remotely sensed hyper- and multispectral imagery. Recent efforts of un-mixing green and dry vegetation on a per pixel basis considerably improved the mapping of single mineralogical components of alteration and background mineral assemblages.

Index Terms— Mineral Footprints, Bulong Area, Gold exploration, Exploration through cover, Remote Sensing, HyLogger3, HCI3, pXRF, hyperspectral, multispectral, vegetation un-mixing

1. INTRODUCTION

Hyperspectral surface (remote sensing and field spectrometer data) and subsurface data (e.g. hyperspectral drill core and chip data) have been used extensively in the Eastern Goldfields of Australia for 1) regolith characterization and identifying previously undescribed outcrops/subcrops of lithologies potentially hosting Au and/or Ni mineralization [1], and 2) mapping alteration mineral footprints spatially and/or genetically associated with Au mineralization ([2]; [3]; [4]). In particular, the relative abundance of white mica has been used to map out the extents of potassic alteration, whereas compositional variations of white mica between proximal to distal alteration footprints have been observed at numerous orogenic gold deposits (e.g. St Ives: [5]; Kanowna Belle & Sunrise Dam: [4]). Opposite trends of the white mica compositional changes were interpreted as differences in ore forming fluids at the respective deposits, with oxidized, alkaline, and silica-rich ore fluids playing a major role in the formation of gold mineralization at Kanowna Belle, whereas reduced, acid, Fe-rich and silica-poor fluids were prominent at Sunrise Dam ([4]). [6] discussed the potential for mapping serpentinized and carbonatized ultramafic rocks in the St Ives area by using a combination of airborne hyperspectral, magnetic and radiometric data.

The Bulong area is located about 30 km East of Kalgoorlie and features both, smectite clay hosted Ni-Co mineralization as well as mesothermal (300–400 °C) gold-pyrite lodes with proximal sericite-ankerite or biotite-dolomite alteration. The aim of this project was to evaluate whether mineral footprints associated with gold mineralization found in drill hole data from bedrock and regolith material could be detected at the surface. This could help to extend known mineralization at the Cannon deposit located in the western half of Southern Gold's Bulong Gold Project tenements, and to evaluate the resource potential in the region and in the immediate vicinity of the Cannon deposit. The here tested approach included the integration of hyperspectral surface and hyperspectral and geochemical subsurface data to design a more efficient exploration strategy.

The Bulong Mafic-Ultramafic sequence of the study area extends over about 20 km in a north-south direction and is part of the Kurnalpi Subprovince, which is part of the Eastern Goldfields Superterrane. The Bulong Mafic-Ultramafic sequence comprises of komatiitic rocks of mesocumulate and orthocumulate character, as well as dunites within a sequence of high Mg-basalts ([7]). The peridotitic, layered sills are represented by thick sections of serpentinized olivine-rich cumulates that are capped by thin altered pyroxenites and norites ([8]). The ultramafic rocks are completely serpentinized and affected by local talc-carbonate alteration in association with transverse shears and lithologic contacts ([7]).

The weathering profile atop ultramafic rocks is highly variable in terms of its thickness as well as its mineralogical and geochemical composition ([8]). Oxidation of primary minerals can occur down to 100 m depth in joints and fractures. The grey-green saprolite zone (10 to 50m thickness) comprises of altered primary minerals and aragonite, nontronite, chlorite, talc ± spinels (chromite or magnetite). The Mg# (Mg/(Mg+Fe)) decreases towards the top of the saprolite zone, whereas SiO_2, Ni and Mn increase.

Lithologies in the study area have undergone several phases of alteration, including 1) alteration pre-dating gold deposition (e.g. serpentinization), 2) alteration coeval with gold deposition (e.g. potassic alteration), and 3) weathering. Primary mineral assemblages have been largely obliterated and subsequent metamorphism and hydrothermal alteration has led to mineral assemblages dominated by hydroxylated silicates (e.g. amphiboles, chlorites, dark micas, serpentine, talc, white micas), carbonates, feldspars (e.g. albite, anorthite), quartz and iron oxides, as well as sulfides and spinel phases (e.g. chromite, magnetite). Intensive weathering had a substantial impact on the mineral assemblages. Depending on the original composition of the bedrock and the intensity/type of hydrothermal alteration, feldspars, amphiboles, dark micas and chlorites have been replaced by an assemblage of kaolin group minerals (including Fe-rich kaolinites) and Fe-Mg sheet silicates (e.g. chlorite and serpentine to vermiculite). White micas and talc are more stable and may be present at detectable quantities at the surface. The respective minerals can be detected by means of hyperspectral technologies in the visible-near infrared (VNIR: 350 to 1000 nm), shortwave infrared (SWIR: 1000 to 2500 nm) and/or thermal infrared (TIR: 6000 to 14500 nm) wavelength ranges, respectively.

2. METHODS

The analytical technologies combined for this project comprised of:

1. airborne hyperspectral ("HyMap") data collected by HyVista Corporation (184km^2 @ 3m spatial resolution);
2. hyperspectral drill hole ("HyLogger3"; [9]) data acquired by the Geological Survey of South Australia and the CSIRO, in Adelaide (2500 chip samples from 22 drill holes);
3. portable X-ray fluorescence ("pXRF"; Olympus Innov-X 50 kV Delta) data collected by the CSIRO, in Adelaide (674 chip samples from 7 drill holes); and
4. hyperspectral drill core imaging ("HCI3") data acquired by Corescan Pty Ltd, Perth (22 drill cores; 1850 m).

A suite of mineral mapping products for characterization of regolith and outcropping/covered prospective lithologies, as well as identification of mineral footprints associated with known and potential gold mineralization were generated from the collected airborne and drill core hyperspectral data. The geochemical data obtained with pXRF were compared with the HyLogger3 data. Selected mineral mapping products (e.g. white mica composition) produced from the HyLogger3 and HCI3-derived subsurface data were combined to create 3D mineral surfaces in 3D modelling software package Leapfrog^{TM} (http://www.leapfrog3d.com). The observed patterns of mineral assemblages were extrapolated beyond the mine site scale using the airborne hyperspectral data. All hyperspectral data collected for this project encompass the VNIR and SWIR wavelength ranges. In addition, the HyLogger3 data collected from measurement of drill chips feature data from the TIR wavelength range.

3. RESULTS

3.1. Hyperspectral Drill Core Data

Based on hyperspectral drill core data the ultramafic and mafic rocks show a large mineralogical variability. Two major populations of the ultramafic rocks are characterized by high talc contents and high biotite-chlorite contents, respectively. In contrast, mafic rocks are almost void of talc, but contain more amphiboles. Chlorite-white mica assemblages are restricted to mafic rocks and felsic extrusives. Regolith atop mafic and ultramafic rocks can contain kaolinite with or without iron, with Fe-rich kaolinite indicated by a small absorption feature located at around 2240 nm in combination with the major kaolinite-related features at 2160 and 2200 nm [10]. Amphiboles present in ultramafic rocks are dominantly tremolites, whereas mafic rocks are dominated by actinolites, indicated by a wavelength shift of the absorption at 2380 nm [11]. Fe-Mg smectites are identified on the base of their absorptions at around 2290 nm and occur predominantly in ultramafic rocks. A large population of ultramafic rocks is affected by talc-carbonate alteration, which is evident from TIR spectral signatures. The quartz content is increased in weathered mafic and ultramafic rocks. Au values are higher in mafic when compared to ultramafic rocks. A cluster of gold-bearing samples is associated with Fe-rich kaolinite in saprolitic mafic rocks. Weathered ultramafic rocks do not contain elevated amounts of gold. Amphiboles are inversely correlated with gold in both mafic and ultramafic rocks.

3.2. pXRF

All collected pXRF data cover a continuous spread from ultramafic through to intermediate igneous compositions (34 – 65 wt. % SiO_2), with the majority being ultramafic – mafic (35 – 50 wt. % SiO_2). When plotted against K_2O contents, a significant proportion of samples display a distinct K-enrichment (K_2O > 1 – 2 wt. %). It is not clear whether this K-enrichment is related to hydrothermal alteration or primary igneous fractionation processes. There is a slight general trend towards higher SiO_2 contents nearer the surface, consistent with residual quartz enrichment during weathering.

3.3. Hyperspectral and pXRF

To fully explore and integrate the geochemical and hyperspectral data, principle component analysis (PCA) was performed on the compiled data sets. PCA serves to identify the vectors of greatest variation through multi-dimensional clouds of data, where principle component 1 (PC1) represents the largest axis of variation through the data set. In the case study data set, PC1 distinguishes between more ultramafic compositions towards positive values, and relatively more evolved mafic compositions towards negative values. In contrast, PC2 primarily accounts for 'fresh' material towards positive values, and weathered regolith samples towards negative values. When plotting PC1 against PC2, three broad groups can be distinguished: 1) Group 1: Positive PC1, negative PC2 – near surface samples representing regolith material (high in Si, Al-clays, ferric oxides, kaolinite and low in Ca, Mn; 2) Group 2: Very negative PC1, neutral PC2 – fractionated rocks (very high in Sr and Ba, as well as K, Rb, Y, Zr, and other HFSE and low in Fe, Ni; and 3) Group 3: PC1 > -1.5, positive PC2 – represents the majority of the remaining samples (high Mn).

The distribution of Au in PC1-PC2 space highlights two major clusters of Au-rich samples. One cluster is relatively tightly defined within Group 1, and another cluster more dispersed on the boundary between groups 2 and 3. A comparison of PCs versus sample depth indicates the Group 1 cluster corresponds to Au within the regolith, while the other cluster is Au in fresh rock.

As described above, Group 1 is well characterized by high ferric oxide abundance, while the mafic end of the Group 1 array (low PC1 values) are low in Ni and contain moderate Zr contents. Using these three parameters together is useful for defining the set of samples that are most likely to contain Au within the regolith.

In contrast, identifying Au in fresh rock effectively is much more difficult than in the regolith as high-Au samples are more lithologically and chemically varied. However, a number of broad, useful trends are still evident. One of the most effective parameters is in fact the complete absence of samples showing an absorption at 2290 nm, which is related to Fe-rich smectites.

Based on the hyperspectral drill chips/core data and the combined investigation of geochemical and hyperspectral parameters by means of PCA analysis, clusters of mineral assemblages were identified that are associated with gold, are inversely correlated with gold and/or form a halo in proximity to gold mineralization. The respective six classes of mineral assemblages are: 1) Fe-kaolin, iron oxide-quartz (regolith only; can host low amounts of gold, weathering product); 2) white mica-chlorite-feldspar-quartz (bedrock & regolith; white mica composition changes with proximity to gold from Al-rich proximal to Al-poor distal); 3) biotite, carbonate ± amphibole, quartz & chlorite-amphibole ± quartz (bedrock only; associated with majority of gold in bedrock); 4) biotite ± quartz (bedrock & regolith; can be associated with Au); 5) talc-carbonate alteration (bedrock only; Halo, Pre- or syn-Au) ± Fe-kaolinite (regolith only); and 6) Fe/Mg smectites (regolith only; only in samples where Au is absent).

3.4. Airborne Hyperspectral

The integrated analysis of drill core hyperspectral and geochemical data and the visualization of mineral assemblage classes in 3D suggested that some of the mineral footprints related to gold mineralization may be able to be mapped using airborne hyperspectral data. Specifically, white mica alteration and talc-carbonate alteration are persisting through the *in-situ* regolith to the surface and can therefore potentially be mapped using remote sensing data.

Using the airborne hyperspectral data, white mica footprints were detected to the west of the Cannon deposit, but could not be followed to the north or south of the open pit. To the north, extensive paleochannels are recognizable in the Al-clay index map. To the south, the Fe/Mg-smectite geoscience product as well as the MgOH-based mineral maps identify a large area of mafic/ultramafic rocks corresponding to the Cannon deposit, however, with distinctly lower (or absent) white mica (potassic) alteration. The remote mapping of talc-carbonate alteration was limited by a considerable presence of vegetation and overlap of the talc-related absorption band at 2080 nm with absorptions due to cellulose.

Furthermore, hyperspectral drill core data showed that, in the study area, carbonates can't be successfully mapped using the SWIR wavelength range and, therefore, not by means of airborne hyperspectral data. A TIR-based remote sensing system could be considered to map the strong absorption bands of talc and carbonate in this wavelength range. Alternatively, green and dry vegetation un-mixing could improve the mapping of single mineralogical components of alteration and background mineral assemblages. Un-mixing vegetation from hyperspectral data can be achieved by estimating the green and dry vegetation as well as the mineral components using continuum-removed depths of diagnostic absorptions on a per pixel basis ([12], [13]). Similar methods can be applied to multispectral imagery as shown by the recent vegetation un-mixed ASTER-derived mineral maps generated for Queensland, Australia ([14]).

4. CONCLUSION

The combined analysis of pXRF and hyperspectral data from drill samples provided important information about if and which mineral footprints associated with gold mineralization in the Bulong area of the Eastern Goldfields in Western Australia could potentially be mapped using airborne hyperspectral data. Though, only white mica alteration of limited extent was successfully mapped to the west of the Canon deposit. Remote mapping of talc-carbonate alteration was limited mainly due to issues with vegetation. However, the airborne hyperspectral data in this case study proved also useful for mapping out transported versus *in-situ* regolith, and identifying the source regions of channel material, and distinguishing subcrops of different rock types that are difficult to discern using true colour imagery or during fieldwork.

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