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# Hyperspectral remote sensing applied to uranium exploration: A case study at the Mary Kathleen metamorphic-hydrothermal U-REE deposit, NW, Queensland, Australia

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# ABSTRACT

The HyMap airborne hyperspectral scanner provides 128 spectral bands between Visible-Near Infrared (VNIR) and Short Wave Infrared (SWIR) wavelengths (0.45–2.5 µm). It transcends any currently operational orbital multispectral sensor (ASTER, WV3, Landsat-8) for mineral mapping in exposed areas. Here we employ HyMap data to study the type and spatial distribution of mineral assemblages in the world-class Mary Kathleen metamorphichydrothermal Uranium (U) - Rare Earth Elements (REE) deposit, situated in the Mount Isa Province, Australia. The focus is on Ca-bearing silicates and Fe-rich minerals. Two spectral libraries were built for the task based on publicly available data. The VNIR library comprises goethite and andradite. The SWIR library includes hornblende, epidote, calcite, kaolinite and montmorillonite. Scapolite SWIR spectra were yielded autonomously. These mineral spectra were used as endmembers for HyMap data classification and production of mineral abundance maps. Spectral Angle Mapper (SAM) and Mixture Tuned Matched Filtering (MTMF) were the methods employed for image classification. Results were combined in RGB color composites and enhanced to provide high quality maps of Ca-bearing silicates and other minerals associated with the Ca-skarn hosted U-REE mineralization. The spatial correlation of mineral abundance maps produced here and known exposed surfaces of equivalent minerals in the open pit mine proved plausible. Wallrock alteration halos show characteristic zonal arrangements. Andradite occurs in the outer alteration halo. Selectively pervasive alteration is characterized by calcite, scapolite, epidote and hornblende. These specific mineral types and their distribution in the Mary Kathleen deposit indicate multiple stages of metasomatic processes, resulting in high-temperature and retrograde Ca-bearing silicates associations. In addition, kaolinite, montmorillonite and goethite are the surface footprint of the skarn-hosted U-REE mineralization. HyMap proved to be a solid tool to characterize exposed hydrothermal mineral systems associated to skarns enriched in U and REE, providing the framework for advanced geologic interpretation and conception of a regional exploration model. The occurrence of goethite, kaolinite and montmorillonite and their zonal relationship with the U-REE mineralization, as also mapped here with HyMap, may be also an additional guide for U exploration in the Mount Isa Province, especially if combined with other exploration methods. © 2016 Elsevier B.V. All rights reserved.

## 1. Introduction

Remote sensing of reflected electromagnetic energy across the visible and near infrared (VNIR,  $0.45-1.35 \mu m$ ) and shortwave infrared (SWIR2,  $1.95-2.48 \mu m$ ) wavelength regions enables the measurement

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http://dx.doi.org/10.1016/j.gexplo.2016.07.002 0375-6742/© 2016 Elsevier B.V. All rights reserved. and mapping of specific minerals indicative of different geological processes. Over the last 30 years, data from a variety of government-funded sensors like ASTER (Abrams, 2000; Ducart et al., 2007; Zhang et al., 2007; Abrams et al., 2015), Hyperion (Cudahy et al., 2001; Farooq and Govil, 2014) and AVIRIS (Rowan et al., 2000), as well as commercial sensors, such as the airborne HyMap (Cudahy et al., 1999, 2000, 2001, 2005a, 2005b, 2006, 2008; Bierwirth et al., 2002; Ellis and Scott, 2004; Bedini et al., 2009; Bedini, 2011; Kokaly et al., 2013) have been used to remotely access exposed geology across the Earth's land surface, including superimposed metamorphic and metasomatic alteration and weathering effects. These studies span different styles of hydrothermal

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Au, Cu, Pb, Zn and Ag systems, though there has been little work on their role for mapping skarn-hosted uranium (U) and rare earth element (REE) mineralization.

The skarn-hosted Mary Kathleen U-REE deposit is located in northwestern Queensland, between Mount Isa and Cloncurry mining districts (Fig. 1) (Derrick et al., 1971, 1977). The deposit developed during regional metamorphism when metasomatic hydrothermal fluids interacted with preexisting Ca-rich skarns (Oliver et al., 1999). Discovered in 1954, Mary Kathleen pre-mining ore grades comprised, on average, 0.116% U<sub>3</sub>O<sub>8</sub> and 7.6% REE for 9.2 million tons of ore, which was mined in 1956–1963 and then in 1976–1982. Total production of U totalized 7532 t (8882 t of U<sub>3</sub>O<sub>8</sub>) (Matheson and Searl, 1956; Oliver et al., 1999; Mckay and Miezitis, 2001). Key alteration minerals associated with this deposit include andradite-grossular  $\pm$  epidote  $\pm$  hornblende  $\pm$  calcite  $\pm$  scapolite  $\pm$  hematite, as well as sulfides such as pyrite  $\pm$  galena  $\pm$  chalcopyrite.

# 2. Geological setting

The Mary Kathleen deposit is located in the Mount Isa Metamorphic Province, which hosts a number of world-class Proterozoic hydrothermal polymetallic mineral systems, including Mount Isa Cu, Century Zn, Merlin Mo-Re, and Starra Au deposits. The Mount Isa Block (Fig. 1A) comprises three north-south trending tectonic-metamorphic domains including from west to east: the Western Fold Belt (WFB); the Kalkadoon-Ewen Province (KEP); and the Eastern Fold Belt (EFB). Each of these Proterozoic terrains reflects complex periods of sedimentation, magmatism, tectonism, metamorphism, regional metasomatism, fluid flow and mineralization (Betts et al., 2006; Sayab, 2006, 2008; Blenkinsop et al., 2008; Ford and Blenkinsop, 2008). The main tectono-stratigraphic elements of these domains include a basal sequence of mafic and felsic volcanic rocks associated with granites dated at ca. 1780 Ma, restricted to the KEP. These rocks are overlain by carbonates, evaporites and mafic volcanic rocks (1800-1740 Ma) in the WFB. The latter are capped by carbonates and subordinate volcanic rocks typically found in an intracontinental rift system that characterizes the EFB (Jackson et al., 2000; Foster and Austin, 2008).

## 2.1. Geology of the Mary Kathleen U-REE deposit

The Mary Kathleen Group that hosts the U-REE mineralization comprises mainly calcareous rocks of the Corella Formation (1780–1760 Ma), including impure carbonates, quartzites and shales (Derrick, 1977; Maas et al., 1987; Oliver et al., 1999). The Mary Kathleen deposit is located along the Mary Kathleen Shear (MKS) zone, which truncates the western limb of the Mary Kathleen Syncline some 2 km to the west of its axial trace (Fig. 1C). The eastern limb of the Mary Kathleen Syncline is cut 3 km to the east by the Burstall granite and to the west by the Wonga granite (Fig. 1C). The emplacement of these granites and associated felsic dyke swarms resulted in contact metamorphism, metasomatism and calcic skarns (Table 1), which partially replace the calcareous rocks of the Corella Formation (Oliver, 1995; Oliver et al., 1999; Hammerli et al., 2014). These were followed by other granite intrusions (e.g. Williams and Naruka Batholiths) and regional metamorphism (Table 1).

Hydrothermal U-REE mineralization developed during the peak to the waning stages of regional metamorphism and felsic intrusions. Fluid-flow (metamorphic, magmatic and/or meteoric) focused along the MKS zone (Oliver, 1995; Oliver et al., 1999). Within the most intense zone of alteration associated with the cooling of the system (Table 1), high-grade U mineralization resulted in disseminated uraninite. This alteration zone comprises allanite + diopside + stillwellite + andradite  $\pm$  grossular + pyrite  $\pm$  galena  $\pm$  scapolite  $\pm$  epidote  $\pm$ hornblende  $\pm$  hematite  $\pm$  pyrrhotite  $\pm$  chalcopyrite (Matheson and Searl, 1956; Oliver et al., 1985, 1999). This diversity of minerals indicates that the mineralizing fluids were rich not just in U and REE but also Si, Fe, Na, Al, Cu and B, which is evidence for multiple fluid sources. It remains unclear what were the key physicochemical drivers (e.g. pH, REDOX, pressure and temperature) that firstly mobilized U and REE into transporting solutions and later induced their precipitation into specific traps, though REDOX is often considered important (Skirrow et al., 2009). The remote detection of changes in REDOX could be important for exploration purposes, such as change in the proportion of ferric (Fe<sup>3+</sup>) versus ferrous (Fe<sup>2+</sup>) bearing minerals.

# 3. Description of skarns

According to Einaudi and Burt (1982) and Meinert (1993), skarn deposits occur in several geological settings formed between the Paleoproterozoic and the lower Paleogene, as well as adjacent to plutons and along faults and regional shear zones. The metasomatic process of skarn development is more efficient at relatively deeper crustal levels. However, alteration is more intense at relatively shallow depths due to the interaction with meteoric waters. The conventional classification of skarns is usually based on the type of metasomatized rock or mineralization. Terms such as endoskarn (igneous) and exoskarn (sedimentary) are commonly used to indicate the protolith and to indicate if mineral paragenesis is internal or external to the intrusion (Einaudi and Burt, 1982; Meinert, 1993; Robb, 2004). Several commodities are associated with skarns, including Fe, W, Cu, Zn and Au (Meinert, 1993; Meinert et al., 2005). However, only few skarns are enriched in U-REE (Lentz, 1996; Ray and Dawson, 1998; Lentz and Suzuki, 2000; Laznicka, 2006). Mary Kathleen represents also an unusual mineral deposit because skarn formation was followed by regional metamorphism and a complex history of focused and structurally controlled fluid flow.

## 4. Hyperspectral Mapper data

The airborne Hyperspectral Mapper (HyMap) was designed and manufactured by Integrated Spectronics Pty Ltd. (ISPL). Commercial HyMap surveys are available through HyVista Corporation. HyMap is a whisk-broom scanning system with 126 spectral bands spanning the visible-near infrared (VNIR – 64 bands) and shortwave infrared (SWIR – 62 bands) wavelengths (Cocks et al., 1998). Calibration includes onboard lamp and dark current measurements for each scan augmented by regular (each flight campaign) ground-based calibration methods, all of which helps in ensuring the captured data are accurately reduced to radiance at sensor ( $\mu$ W/cm<sup>-2</sup>/nm<sup>-1</sup>/sr<sup>-1</sup>).

The Mary Kathleen 4.5 m pixel-resolution HyMap L1B radiance-atsensor data were processed to apparent reflectance by the HyVista Corporation Pty Ltd. using CSIRO's HyCorr software package. HyCorr is an IDL-based front-end widget to ATREM3, which is based on the 6S model (Gao et al., 1993). No attempt was made to remove systematic, high-frequency, residual atmospheric absorption-line features because this typically involves the use of scene-dependent statistics (Cudahy et al., 2008).

The efficacy of the calibration and reduction to apparent reflectance of the HyMap data is demonstrated in Fig. 2. Here, a USGS laboratory spectrum (Clark et al., 1993) of pure kaolinite (sample CM9) is compared to a kaolinite HyMap pixel-spectrum positioned near the Mary Kathleen mine. Both the laboratory and airborne spectra clearly show the diagnostic kaolinite absorption doublet at 2.16 and 2.21 µm and an intrinsic, subtle feature at 2.31 µm.

## 5. Image processing methods

All hyperspectral data analysis was carried out using the Environment for Visualizing Images software (ENVI). The spectra of Ca-bearing silicates were extracted from the USGS spectral library (Clark et al., 1993). The mineral abundance maps were plotted in ArcGIS.

The mineral spectra classification was divided in two phases. The processes performed with the aid of the USGS spectral library were



Fig. 1. Regional geology of the Mary Kathleen project. The black polygon in the center of the map marks the location of the area that is covered by the HyMap survey. (A) Regional tectonic map. (B) Morphotectonic compartmentalization of the Mount Isa Province: I – Western Fold Belt, II – Kalkadoon-Ewen Province, III – Eastern Fold Belt, Cameron fault and Mary Kathleen Shear zone (MKS) are inferred.

Table 1

Skarn mineral assemblages associated with Mary Kathleen U-REE mineralization.

Rocks	Mineral parageneses	T (°C)	Deformation and metamorphism phases
Dikes and veins, alteration of pre-existent skarns	$\begin{array}{l} Scp \pm Ab \pm Ep \pm Spn;\\ Ep \pm Ab \pm Prh \pm\\ Hem \pm Grs;\\ Cal \pm Chl \pm Tr/Act \pm Ep \pm\\ (Ap \pm Hem \pm Prh) \end{array}$	300–350	(₹ 2nd Phase metamorphic- hydrothermal, e- emplacement of the Williams and Naraku
Skarns mineralized in U-REE	$\begin{array}{l} Aln \pm Adr \pm Urn \\ Scp \pm Ap \pm Qz \pm \\ (Amp \pm Cal \pm Ep) \\ \pm Ccp \pm Hem \end{array}$	400–550	ca. 1550–1500 Ma; secondary Ca- bearing silicates and retrograde phases
Skarns enriched in garnet	Grt ± Scp ± Di/Fs ± Cal ± Qz	500-650	<ul> <li>Ist phase magmatic- hydrothermal ca. 1750–1730</li> <li>Ma; emplacement of the Burstall granite (ca. 1740 Ma).</li> <li>Primary Ca-bearing silicates</li> </ul>

Scp = scapolite, Ab = albite, Ep = epidote, Spn = (sphene) titanite, Prh = prehnite, Hem = hematite, Grs = grossular, Cal = calcite, Chl = chlorite, Tr = tremolite, Act = actinolite, Ap = apatite, Aln = allanite, Adr = andradite, Urn = uraninite, Qz = quartz, Ccp = chalcopyrite, Grt = garnet, Di = diopside; Fs = ferrosilite. Abbreviations for the mineral names are based on Whitney and Evans (2010).

the following: (i) pixel-spectra target generation with the RX anomaly detection (RXD) algorithm, (ii) extraction and resampling of the USGS library end-members for the HyMap spectral resolution, (iii) Minimum Noise Fraction Transform (MNF) to reduce noise and dimensionality of the data, (iv) EFFORT polishing to remove spectral residual errors and enhance the spectral features, and (v) hyperspectral classification with Spectral Angle Mapper (SAM) and Mixture Tuned Matched Filtering (MTMF) (Fig. 3 – Phase A). Subsequently, we performed rigorous spectral analysis in areas with high mineral abundances to extract the HyMap pixel-spectral signatures. We then repeated the same process described in Phase-A with the HyMap spectral library and regions of interested (Fig. 3 – Phase B).

The classification flowchart shows the processes used to compile the Ca-bearing silicate abundance maps for the VNIR and SWIR spectral range (Fig. 3). The approach is discussed below.

## 5.1. Hyperspectral remote sensing

The spectra and absorption features of the main Ca-bearing silicates associated with skarns are shown in Table 2 (Meinert, 1992, 1993; Clark et al., 1993). The diagnostic wavelengths occur between 0.45 and 1.35 µm (VNIR) and 2.00–2.48 µm (SWIR). The VNIR spectral range



**Fig. 2.** Detail of kaolinite absorption features. (Y) kaolinite (CM9) from the USGS spectral library resampled to HyMap spectral resolution and (X) kaolinite spectrum extracted from a HyMap pixel. The pixel reference is 397,424 E, 7,704,877 N.

enables distinguishing Ca-bearing silicates containing ferrous (Fe<sup>2+</sup>) and ferric (Fe<sup>3+</sup>) ions. Normally, the Fe—O charge transfer (e.g.,  $Fe^{+2} \rightarrow Fe^{+3} + e^{-}$ ) mechanism in the blue region of the spectrum produces important diagnostic signatures of goethite and andradite. Absorption features depicted within 0.66–0.90 µm and 0.90–1.10 µm ranges enable distinguishing surfaces enriched in hematite (Fe<sup>2+</sup><sub>2</sub>+O<sub>3</sub>) and goethite (Fe<sup>3+</sup>OOH) (Hunt and Ashley, 1979; Souza Filho and Drury, 1998; Wenk and Bulakh, 2008).

Hydroxyl-bearing species, such as Al–OH (2.22  $\mu$ m), Fe–OH (2.25  $\mu$ m), Mg–OH (2.33  $\mu$ m) and X–CO<sub>3</sub> (2.33–2.35  $\mu$ m), produce simple and multiple absorption features in the SWIR range. The skarn assemblages show absorption features that are attributed to the presence of (Mg, Fe)–OH and (Fe, Al)–OH (Hunt and Ashley, 1979; Pontual et al., 1997). These minerals are commonly associated with hydrothermal alteration and are the surface footprint of skarn-hosted U-REE mineralization (Wilde et al., 2004; Hewson et al., 2005; Vaughan et al., 2005; Ducart et al., 2007; Harraden et al., 2013).

# 5.2. Empirical flat field optimal reflectance transformation

After the conversion to apparent reflectance, the hyperspectral images still contain residual noise, which inhibit the analytical comparison between pixel-spectra features against mineral-spectra features. The Empirical Flat Field Optimal Reflectance Transformation (EFFORT polishing) applies a low-intensity linear transformation to all the bands to attenuate residues known as 'sawtooth' within spectra (Boardman, 1997, 1998; Kruse et al., 2008). Hence, the absorption features are intensified. In our study, EFFORT polishing was applied for each Ca-bearing silicate spectra separately aiming to improve the quality of the pixel spectra.

## 5.3. RXD target detection

The first step in our study was to apply the Reed-Xiaoli Anomaly Detection algorithm (Chang and Chiang, 2002) to the HyMap dataset. The Reed-Xiaoli Detector (RXD) algorithm is based on the following formulae (Eq. (1)).

$$\delta_{RXD}(r) = (r - \mu)^T K_{LXL}^{-1}(r - \mu) \tag{1}$$

where *r* is the sample vector in feature space,  $\mu$  is the sample mean, and  $K_{LxL}$  represents the sample covariance matrix.

RX anomaly detection performs a statistical comparison based on pixel color or spectral differences between the neighboring pixels for all datasets. The abrupt differences are highlighted by bright pixels this indicates pixels with low probability of occurrence (Chang, 1998; Chang et al., 2000; Chang and Chiang, 2002). The RX anomaly detection provided a fast guide for spectral analysis in the open pit and near mines of the Mary Kathleen deposit.

# 5.4. Spectral libraries and spectroscopy

Spectral libraries in our study were divided in VNIR-USGS and SWIR-USGS (Table 3). The reference spectra of Ca-bearing silicates were extracted from the USGS digital spectral library (Clark et al., 1993, 2007; Clark, 1999). The majority of spectral signatures of Ca-bearing silicates used here were identified in the SWIR spectral range. To detect the "fingerprint" of these silicates, preliminary comparisons between pixel-spectra against mineral-spectra features (Clark et al., 1993) were based on wavelength positions of the main absorption bands (Table 3). In addition, we consider the shape and the depth of features for each mineral spectrum. The absorption features for each end-member were adjusted by the continual removal mathematical function (Clark and Roush, 1984).

In the skarn alteration of Mary Kathleen, uraninite  $(UO_2)$  replaces andradite  $(Ca_3Fe_2(SiO_4)_3)$  in the proximal mineralized zones



Fig. 3. Flowchart of steps used for the hyperspectral classification.

#### Table 2

Skarn assemblages and spectra of some Ca-bearing silicates (modified from: Meinert (1992, 1993); Clark et al. (1993)).

	Groups	Minerals	Compositions	Pure minerals - USGS Spectral Library
Nesosilicates	Garnet (Grt)	Almandine (Alm) Andradite (Adr) <sup>a</sup> Pyrope (Prp) Grossular (Grs) <sup>a</sup> Spessartine (Sps)	$\begin{array}{l} Fe_{3}Al_{2}(SiO_{4})_{3}\\ Ca_{3}(Fe,Ti)_{2}(SiO_{4})_{3}\\ Mg_{3}Al_{2}(SiO_{4})_{3}\\ Ca_{3}Al_{2}(SiO_{4})_{3}\\ Mn_{2}Al_{2}(SiO_{4})_{3}\\ Mn_{2}Al_{2}(SiO_{4})_{3}\\ \end{array}$	Fe Fe Fe Adr WS488
	Olivine (Ol)	Tephroite (Tep) Diopside (Di) <sup>a</sup>	Mn <sub>2</sub> SiO <sub>4</sub> CaMgSi <sub>2</sub> O <sub>6</sub>	Grs HS113.3B-HCL
	Clinopyroxenes (Cpx)	Fassaite (Fas) <sup>b</sup> Hedenbergite (Hd)	Ca(Mg,Fe,Al)(Si, Al) <sub>2</sub> O <sub>6</sub> CaFeSi <sub>2</sub> O <sub>6</sub> Ca(Mp,Fe)Si <sub>2</sub> O <sub>2</sub>	Prp WS474
Inosilicate	Orthopyroxene Rhodonite	Ferrosilite (Fs) Rhodonite (Rdn)	FeSiO <sub>3</sub> (Mn,Ca,Fe)SiO <sub>3</sub>	5ps NMNH14143 Tep HS419.3B
	Clinoamphiboles (Cam)	Mn-actinolite (Mn-Act) Tremolite (Tr)	$C_{42}Fe_5S_{18}O_{22}(OH)_2$ $C_{a_2}Mn_5Si_8O_{22}(OH)_2$ $C_{a_2}Mg_5Si_8O_{22}(OH)_2$ $C_{a_2}Mg_5Si_8O_{22}(OH)_2$	In         Fe         Fas HS118.3B         In           In         Hd HS10.3B         Hd HS10.3B         Hd HS10.3B         Hd HS10.3B
Sorosilicates	Epidote	Hornblende (Hbl) <sup>a</sup> Allanite (Aln) <sup>a</sup> Clinozoisite (Czo) Epidote (Ep) <sup>a</sup> Piemontite (Pmt)	$\begin{array}{l} Ca_{2}(Mg,Fe)_{4}Al_{2}Sh_{7}O_{22}(OH)_{2}\\ (Ca,REE)_{2}(Fe,Al)_{3}(SiO_{4})_{3}(OH)\\ Ca_{2}Al_{3}(SiO_{4})_{3}OH\\ Ca_{2}(Fe,Al)_{3}(SiO_{4})_{3}(OH)\\ Ca_{2}(Fe,Al)_{3}(SiO_{4})_{3}(OH)\\ Ca_{2}(Mn,Fe,Al)_{4}(SiO_{4})_{3}(OH) \end{array}$	Rdn HS325.3B Act HS315.4B
	Axinite Vesuvianitte Plagioclase (Pl)	Axinite (Ax) Vesuvianite (Ves) Anorthite (An)	$\begin{array}{l} (Ca,Mg,Mn,Fe)_{3}Al_{2}BSi_{4}O_{15}(OH)\\ Ca_{10}(Mg,Fe,Mn)_{2}Al_{4}Si_{9}O_{34}(OH,Cl,F)_{4}\\ CaAl_{2}Si_{2}O_{8} \end{array}$	> , Tr HS18.3 5 Fe Fe Ep GD526.a 5
Tectosilicate	Scapolite (Scp) <sup>a</sup> Scapolite (Scp) <sup>a</sup>	Marialite (Mar) Meionite (Mei)	Na <sub>4</sub> Al <sub>3</sub> Si <sub>9</sub> O <sub>24</sub> (Cl,CO <sub>3</sub> ,OH,SO <sub>4</sub> ) Ca <sub>4</sub> Al <sub>3</sub> Si <sub>6</sub> O <sub>24</sub> (CO <sub>3</sub> ,Cl,OH,SO <sub>4</sub> )	Fe Ves HS446.3B
Phyllosilicates		Prehnite (Prh)	$Ca_2Al_2Si_3O_{10}(OH)_2$	An HS349.3B Mar NMNH126018-2 + + Fe Fe Mei WS700.HL sép + +
				0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5
Phyllosilicates		Prehnite (Prh)	Ca <sub>2</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>	An HS349.3B Mar NMNH126018-2 i t Fe Fe Mei WS700.HLsep A x HS34.3B 0.5 06 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 VIS NIR SWIRT SWIRT SWIRT

Wavelength

<sup>a</sup>Minerals and group of minerals that occur at Mary Kathleen. <sup>b</sup>Fassaite = Variety of augite with very low iron content.

Table 3

End-members used as input to perform the hyperspectral classifications.

Ca-bearing silicates	Spectral range	Chemical bonds	Absorption features (µm)
Gth (WS222)	VNIR	$Fe^{3+}$ $Fe^{2+} \rightarrow Fe^{3+} + e^{-}$	0.65, 0.92 0.61 <b>→</b> <0.49
Hem	VNIR	Fe <sub>2</sub> <sup>3+</sup>	0.85
(2% + 98%QtzGS 76)		$Fe^{2+} \rightarrow Fe^{3+} + e^{-}$	0.74 → <0.54
Adr (GDS12)	VNIR	$Fe^{2+} \rightarrow Fe^{3+} + e^{-}$	0.78 → <0.45
Hbl (Mg_NMNH117329)	SWIR	(Al,Mg)-OH	2.31, 2.38
Ep (GDS26.a)	SWIR	(Al,Mg,Fe)-OH	2.24-2.26, 2.33
Scp <sup>a</sup>	SWIR	OH, HCO₃	2,19-2.21, 2.33-2.36
Cal (WS272)	SWIR	Ca-CO <sub>3</sub>	2.15, 2.33
Kln (CM9)	SWIR	Al-OH	2.15-2.19, 2.21
Mnt (SWy-1)	SWIR	Al-OH	2.08, 2.19-2.21, 2.38

<sup>a</sup> The scapolite spectrum was yielded from a mineral sample collected in the Carajás IOCG (Iron oxide copper gold) deposits (Brazil) and measured by the author with a FieldSpec-3 Hi Res spectrometer.

(Matheson and Searl, 1956; Oliver et al., 1999). Sulfides, such as chalcopyrite (CuFeS<sub>2</sub>) and subordinate amounts of pyrrhotite ( $Fe^{2+}S$ ), pyrite ( $Fe^{2+}S_2$ ) and galena (PbS), are accessory minerals and are concentrated in the mineralized zones. Nevertheless, they cannot be mapped using remote sensors as they lack prominent spectral signatures. With the exception of galena, alteration products of these sulfides and Ca-bearing silicates that contain Fe in their structure are altered to Fe-bearing oxy-hydroxides minerals. These may be detected in the VNIR spectral region. Hence, the VNIR-USGS spectral library was built with andradite (GDS12), goethite (WS222) and hematite (2% + 98% QtzGS 76).

The reference minerals of the SWIR-USGS spectral library were composed of epidote (GDS26.a), hornblende (Mg\_NMNH117329), calcite (WS272), kaolinite (CM9), montmorillonite (SWy-1) and scapolite (this work).

Scapolites available in the USGS spectral library have end-member sodium chlorine-bearing marialite (NMNH126018-2) and calcium carbonate-bearing meionite (WS70.HLsep and WS701). However, the absorption diagnostic features are indistinguishable, probably because some scapolites are chemically depleted in OH and CO<sub>3</sub> anions. These unusual scapolites have high complexity and/or cannot be mapped with hyperspectral sensors using the VNIR-SWIR range. Therefore, we used a large sample (40 cm in length) of scapolite collected in the IOCG deposits of the Carajás Polymetallic Province (Brazil) and derived its spectral signature using a FieldSpec-3 High Resolution spectrometer (PANalytical, www.panalytical.com), which detects electromagnetic radiation in the 0.350–2.50 µm range with 2151 spectral channels.

Calcite is a common mineral found in limestone of Corella Formation. At Mary Kathleen, calcite is associated with host rocks, mineralization zones and veins which also contain accessory minerals such as clinopyroxene, garnet and chalcopyrite (Oliver et al., 1999).

Clay minerals such as kaolinite  $(Al_2Si_2O_5(OH)_4)$  and montmorillonite  $((Na,Ca)Al_2Si_4O_{10}(OH)_2(H_2O)_{10})$  are generally common in weathering profiles of granite rocks, due to alteration of K-feldspars. Normally, the association between goethite  $\pm$  kaolinite  $\pm$  montmorillonite with strong weathering and extensive formation of regolith masks the surface geochemical expression of the deposit. However, replacement of skarn assemblages by retrograde alteration results in the deposition of clay minerals (Pirajno, 2009), which are relevant to this study.

# 5.5. Hyperspectral classifiers

Comparison of mineral abundance output values via classifiers is beyond the scope of this study. Nevertheless, SAM was used to classify goethite and montmorillonite. SAM is a robust classifier to map mineral mixtures at the pixel level (Kruse et al., 1993; Rashmi et al., 2014). Such spectral characteristics are particularly unique in areas affected by regolith processes where Fe oxyhydroxides and clay secondary minerals are common. The MTMF technique allows unmixing of pixel-spectra features at the sub-pixel level. It assumes that the target material is rare (Boardman and Kruse, 1994, 2011). We found that MTMF is an ideal algorithm to map Ca-bearing silicates such as garnet, hornblende, among other minerals that are geologically restricted to the Ca-rich skarn.

Before building the HyMap spectral libraries and performing mineral abundance mapping, the image was georeferenced and spatially subset to limit this application around the open pit of the Mary Kathleen deposit. A Normalized Difference Vegetation Index (NDVI) (Tucker, 1979) was calculated using the formula given below (Eq. (2)) and then used to mask the vegetation in the image subset:

$$float \frac{(b1-b2)}{(b1+b2)} \tag{2}$$

where b1 and b2 are bands with 0.8455 µm and 0.6593 µm. The Interactive Data Language (IDL) function "float" is used to output results in single-precision floating-point values and prevent arithmetic overflow errors during calculation (ENVI, 2015).

After hyperspectral classifications with VNIR-USGS and SWIR-USGS spectral libraries, the output of gray scale images with an abundance of Ca-bearing silicates were combined in the red, green and blue (RGB) color composites. Interactive processes such as image contrast stretching and analysis of scattergrams were performed to reduce false positive pixels. Pixels with higher abundance were selected as regions of interest (ROIs) to provide an average of the pixel-spectra (ENVI, 2015; Ellis and Scott, 2004).

## 5.5.1. Minimum Noise Fraction transform

The Minimum Noise Fraction (MNF) linear transformation attempts to maximize the signal-to-noise (Green et al., 1988). The noise level in hyperspectral data is not continuous. Thus, the MNF function orders the relationship between information content and signal-to-noise ratio. The advantage of this process is to reduce the requirements of the computing hardware and software for SAM and MTMF classifiers (Boardman and Kruse, 1994). MNF is performed in two steps: (i) firstly, a transformation reduces noise autocorrelation within the signal that is based on noise covariance matrix, and (ii) secondly, principal component analysis (PCA) is applied for noise whitening suppression. All bands of the dataset (input) are employed. The output data comprise MNFn bands (eigen images) that are displayed as gray scale images ordered in terms of decreasing quality of signal. The MNF bands with an abundance of bright pixels are associated with large eigenvalues and contain relevant spectral information. The MNF bands with low eigenvalues (normally below 1) contain noise, and the bright pixels are strongly disorganized. The cutoff eigen image can be determined by the plot of eigenvalues versus eigenimages. The MNF eigenimages are used as input for SAM and MTMF classifiers.

## 5.5.2. Spectral Angle Mapper

The Spectral Angle Mapper (SAM) is an algorithm for pixel level classification based on the angular distance between pixel-spectra of unknown composition and reference mineral-spectra (Kruse et al., 1993). SAM is calculated by applying the following equation:

$$\alpha = \cos^{-1} \left( \frac{\sum_{i=1}^{n} x_{i} r_{i}}{\sqrt{\sum_{i=1}^{n} x_{i}^{2} \sqrt{\sum_{i=1}^{n} r^{2}}} \right)$$
(3)

where  $x_i$  = pixel-spectra features,  $r_i$  = mineral-spectra feature and n = number of spectral bands.

The algorithm produces two output images labeled Rules and Classification. The dark pixels in the Rule image hosts angular information. The darker pixels represent lower angles between reference mineral-



Fig. 4. The SAM classifier principle. S1 and S2 represent the pixel-spectra and mineral-spectra, respectively. (A) Classification with more false positives shows extensive areas with bright pixels. (B) Classification excludes the pixel outliers (gray scale) and the smallest angular distance represents a classification with fewer false positives.

spectra and unknown pixel-spectra and comprise the targets of interest. To enhance these pixels, they are commonly converted to bright pixels via histogram inversion, using the following formula in ENVI (Eq. (4).):

input spectra employed here were goethite (WS222) and montmorillonite (SWy-1).

$$float(b1)*(-1)$$
 (4)

where b1 is the Rule image.

Fig. 4 shows a graphic explanation of how SAM works using reference mineral-spectra against pixel-spectra features. The reference

5.5.3. Mixture Tuned Matched Filtering The Mixture Tuned Matched Filtering

The Mixture Tuned Matched Filtering (MTMF) is an expert approach to detect material abundance much smaller than the pixel level. The MTMF combines Matched Filtering (MF) and Mixture Tuned (MT) algorithms sequentially and the results are displayed as sets of two gray-scale images (Chen and Reed, 1987; Boardman, 1998). MF



Fig. 5. Image derived from the RXD detection. Some of the brightest pixels, delimited by white polygons, correspond to potential targets for spectral analysis. At the southern part of the open pit, many pixels were highlighted. Areas 'A' and 'B' were selected for pixel-spectra analysis. (A) Spectra with features indicating minerals containing ferric iron. (B) Spectra typical of kaolinite. The pixel reference is at coordinates 397,427 E, 7,704,877 N.

estimates the abundance of known endmembers at the sub-pixel level and suppresses the response of other components at the pixel level or background. MT is an algorithm used to reduce the number of false positives found in the MF processing. The output comprises two images labeled MF score and infeasibility. The classification yielded based on each endmember is usually plotted on a 2D scatter plot where the MF score is set against infeasibility values, so that thresholds can be established interactively by the user. Properly mapped pixels have a MF score exceeding the background distribution around zero and a low infeasibility value. The input mineral spectra used in MTMF for the Mary Kathleen deposit were andradite (GDS12), epidote (GDS26.a), hornblende (Mg\_NMNH117329), calcite (WS272), kaolinite (CM9) and scapolite (measured with FieldSpec).

# 6. Results and discussions

## 6.1. Hyperspectral targets

The RXD algorithm was applied to find areas of contrasting exposed minerals against pervasive background composed of green and dry vegetation. The RXD algorithm enhanced areas with distinct spectral characteristics and the majority of the Ca-bearing silicate signatures were found by analyzing the brightest pixels (Fig. 5). The first spectrum collected from bright pixels was andradite, which occurs in the open pit of the Mary Kathleen deposit (Fig. 5-A). The rich detail in these signatures distinguishes them from goethite and hematite. Their absorption is strongly attenuated between 0.65 and 0.90 µm. Another noteworthy



Fig. 6. MNF components plotted with eigenvalues versus the MNF bands. The cutoff image was MNF14, which marks the limit between MNFs withy stronger signal and noisier components. The dashed line in the MNF1 image indicates the contact of the Wonga Granite with the Corella Formation. Major structures such as the Cameron Fault and the Mary Kathleen Shear (MKS) zone were inferred.

characteristic is the accentuated gradient of the spectrum towards the ultraviolet - a feature derived from the Fe charge transfer.

The spectra shown on Fig. 5-B indicate absorption features centered at 2.21  $\mu$ m in the form of a subtle doublet. These features are characteristic of the presence of Al–OH covalent bond within the crystalline structure of kaolinite. The geometry and the depth of these signatures, and the doublet feature at 2.21  $\mu$ m, indicate low-crystallinity kaolinite. Abundant areas of kaolinite were observed approximately 600 m to the south of the open pit near the Mary Kathleen Shear (Fig. 5-B).

# 6.2. Minimum Noise Fraction transformation

The Minimum Noise Fraction (MNF) transform was applied to 64 VNIR bands ( $0.45-1.39 \mu m$ ) and to 29 SWIR2 bands ( $2.00-2.49 \mu m$ ). Fig. 6 shows the output eigenimages (MNF1–MNF29) obtained for the SWIR2 bands.

MNF1 hosts most of the data variance and comprises higher eigenvalues. This information is translated by areas with several bright pixels, which are correlated to outcrops, waste piles and the open pit of the Mary Kathleen mine. Note in Fig. 6 that the noise features (smallest eigenvalues represented by the flat line) are observed more systemically from the MNF14 image onwards, which is marked by a break in the slope of the eigenvalues.

MNF14 to MNF29 were eliminated from further analysis as they host too much noise and may jeopardize the reliable hyperspectral classification of Ca-bearing silicates.

# 6.3. Spectral libraries

Iron is a common element in the crystalline structure of goethite (WS222), hematite (2% + 98%QZ GS 76) and andradite (GDS12) (Fig. 7). These minerals extracted from the VNIR-USGS library were used to enhance areas with iron abundance in the HyMap data. Andradite and hematite are associated with skarn systems and are also common in the Mary Kathleen mine. The 0.45–1.39  $\mu$ m spectral range was used here to identify iron absorption features. Main features occur at 0.65  $\mu$ m and between 0.85 and 0.90  $\mu$ m. The electronic charge transfer (0.74  $\rightarrow$  0.40  $\mu$ m) produces a strong spectral absorption towards the 0.40  $\mu$ m (ultraviolet). The hematite and goethite abundance maps are closely identical. So, they were used as a common map in the classification procedures.

The SWIR-USGS spectral library comprises minerals with absorption features in the HyMap SWIR2 ( $1.95-2.48 \mu m$ ) (Fig. 8-A). These minerals are closely associated with the mineralized zone observed in the Mary Kathleen mine. Details of the absorption features remain evident after spectral resampling for the HyMap resolution (Fig. 8-B). The scapolite spectrum shows subtle absorption features centered at 2.21  $\mu m$  (Al–OH) and 2.33–234  $\mu m$  (X–CO<sub>3</sub>) (Fig. 8-C).

The HyMap spectra comprises numerous spectral features, which makes the analysis more difficult (Fig. 9-A). However, continuum removal was used to normalize the spectra and to allow comparison between mineral spectra features against pixel spectra features from a common baseline. HyMap processing with the EFFORT polishing algorithm helped to constrain the features of interest (Fig. 9-B).

# 6.4. Ca-skarn mineral abundance maps

Andradite is chiefly located in the open pit and waste rocks of the Mary Kathleen deposit and probably envelops the high-grade U-REE mineralization (Fig. 10). Ca-bearing silicates represented by andradite  $\pm$  epidote (shades of yellow-orange) and andradite  $\pm$  hornblende (magenta) are less abundant and occur proximal to the Mary Kathleen Shear zone and correlate with waste material (Fig. 10-A, B and D). The andradite  $\pm$  calcite abundance is very restricted (Fig. 10-B).

Epidote (Ep) was identified in several pixels. Main occurrences are restricted to the upper end of the open pit and waste piles near the mine (Fig. 10-A, B and D). Epidote, when associated with calcite, shows light-cyan tones. Equivalent abundances of andradite  $\pm$  epidote  $\pm$  calcite produce white pixels that are surrounded by calcite  $\pm$  epidote and calcite-only (Fig. 10-B).

The spatial distribution of hornblende partially correlates with calcite abundance, as Fig. 10-A and B suggests. This association was expected because the volume of Ca, Mg, Fe and Si in the skarn is relatively high. Furthermore, discrete pixels mapped with hornblende were marked in the Mary Kathleen Shear zone.

Calcite is a common mineral in the Corella Formation and its estimate abundance is displayed with a blue pattern (Fig. 10-B and C). The brightest blue areas correlate with calcite  $\pm$  epidote-rich outcrops and are associated with the Mary Kathleen open pit and Mary Kathleen Shear zone.

Scapolite is commonly found in the Mary Kathleen Shear zone in the southern portion of the open pit. This plays a significant role in the



Fig. 7. (A) Spectra of the minerals with Fe in their crystalline structure selected from the USGS spectral library. (B) The same minerals resampled to the HyMap VNIR 64 spectral bands. Note that the main charge-transfer and absorption features remain evident after resampling.



**Fig. 8.** (A) SWIR-USGS spectral library with montmorillonite (Swy-1 = Mnt), kaolinite (Cm9 = Kln), calcite (WS272 = Cal), epidote (GDS 26.a = Ep) and hornblende (NMH117329 = Hbl) spectra. (B) Minerals in 'A' were resampled to 29 HyMap spectral bands. (C) Spectral features of scapolite from Carajás, Brazil. The spectra S1, S2, S3 and S4 were measured at four different sides on the sample.

exploration of Ca-skarn hosted U-REE mineralization (Figs. 10-C and 11-A). Yellow tones indicates scapolite  $\pm$  and radite (Fig. 10-C) and scapolite  $\pm$  goethite (Fig. 11-A) assemblages.

Goethite is commonly found in Australian regolith and maybe formed in hydromorphic environments (Scott and Pain, 2009). Skarn systems are fertile in Fe-bearing minerals and supergene processes of ferromagnesian minerals usually yield goethite as a product (Robb, 2004). Matheson and Searl (1956) report occurrences of oxidized zones that probably result from hydrolytic decomposition of the sulfides mentioned above, as well as hematite and Ca-bearing silicates containing iron. Goethite was mapped in the HyMap imagery in association with andradite (magenta tones). It is abundant in the open pit and waste piles of the Mary Kathleen mine. Spatial association between goethite  $\pm$  kaolinite occurs in the waste rocks located approximately 560 m to the south of the open pit (Figs. 10-D and 11-A Kln2).

The kaolinite abundance map shows areas correlated with waste rocks and associated with goethite (magenta) and montmorillonite, which are highlighted in yellow (Fig. 11-A and B). Areas with dominance of kaolinite appear in orange tones at Fig. 11-B. In some cases, destruction of skarn assemblages by retrograde alteration results in the deposition of clay minerals (Pirajno, 2009). This high correlation of kaolinite with waste rocks of the Mary Kathleen deposit likely reveals the weathering process of feldspar minerals.

Montmorillonite is another clay mineral that usually accompanies kaolinite in the hydrothermal alteration as well as in the weathering environment. The Mary Kathleen Shear zone is marked by cyan tones indicating simultaneous presence of montmorillonite  $\pm$  scapolite.



Fig. 9. (A) Spectra without continuum removal. X = USGS spectrum of pure calcite (WS272). Y and Z = spectra extracted from HyMap pixels. Respectively, Y and Z represent the spectra after and before HyMap data processing with EFFORT. (B) After continuum removal, note that Y contains sharp features centered at 2.33 µm. The absorption features of calcite (WS272) are comparable to the HyMap pixel-spectral features. The reference pixel is at coordinates 397,410 E, 7,705,568 N.



**Fig. 10.** Ca-bearing silicate abundance maps. Abundances of Adr  $\pm$  Scp  $\pm$  Ep  $\pm$  Hbl  $\pm$  Cal (mapped by MTMF) show spatial correlation with the Mary Kathleen Shear (MKS) zone. The location of HyMap pixels from which spectral data were extracted are given by the arrows with abbreviated mineral names. Goethite abundance was yielded by SAM.

All abundance maps displayed the same areas with scapolite  $\pm$  and dradite  $\pm$  epidote  $\pm$  calcite  $\pm$  hornblende  $\pm$  goethite  $\pm$  montmorillonite. These were mapped and correlated with the Mary Kathleen Shear zone in the southern part of the open pit.

To verify the consistency of the mineral abundance maps, spectral features were extracted from the HyMap pixels located in areas with

the highest mineral abundance. Therefore, the spectra shown in Fig. 12 decrease the subjectivity of the methods used here to separate the correctly mapped pixels from those that are 'false positives'.

The HyMap spectra of andradite (Fig. 12 – Adr1 and Adr2) and goethite (Fig. 12 – Gth1 and Gth2) show subtle differences in shape. The pervasive andradite alteration was mapped by its intense band around



**Fig. 11.** Detail of the Mary Kathleen open pit. (A) Mineral abundance maps of Ca-bearing silicates and clay minerals. (B) White pixels show the co-occurrence of Kln  $\pm$  Mnt  $\pm$  Scp, which are spatially correlated to the Mary Kathleen Shear (MKS) zone. The location of HyMap pixels from which spectral data were extracted are given by the arrows with abbreviated mineral names. Goethite (A) and scapolite (B) were assigned to different RGB channels to highlight their spatial distribution distinctively in each product. Goethite and montmorillonite abundances were yielded by SAM. The other minerals by MTMF.

0.4  $\mu m$  (attributed to spin-forbidden bands of octahedrally bonded Fe<sup>3+</sup>) and absorption features at 0.91 and 1.23  $\mu m$ . Goethite displays the characteristic charger transfer bands towards the ultraviolet and the diagnostic 0.66  $\mu m$  feature, which is absent in andradite spectra. It also exhibits the classic Fe<sup>3+</sup> crystal field absorption between 0.91 and 0.94  $\mu m$ .

Reflectance spectra of epidote, calcite and hornblende (Fig. 12) all show absorption features, respectively at 2.335–2.342  $\mu$ m (Fe–OH absorptions), 2.340–2.345  $\mu$ m (carbonate absorptions) and 2.320–2.330  $\mu$ m + 2.390–2.400  $\mu$ m (Mg–OH absorptions). Epidote also shows a 2.2  $\mu$ m feature that helps in separating it from calcite and hornblende.

The scapolite (Fig. 12 – Scp1 and Scp2) HyMap spectra show two absorption features centered at 2.21 and 2.36  $\mu$ m that are vibrations caused by OH and HCO<sub>3</sub><sup>-</sup> or HSO<sub>4</sub><sup>-</sup> in the anion sites of scapolite (Swayze and Clark, 1990). Kaolinite (Fig. 12 – Kln1 and Kln2) and montmorillonite (Fig. 12 – Mnt1 and Mnt2) show intense bands at 2.21  $\mu$ m due to OH bonds. Montmorillonite and kaolinite mapped in HyMap pixels also show subtle absorption features at 2.08  $\mu$ m and 2.16  $\mu$ m, respectively, which facilitate their discrimination.

# 7. Conclusions

The zoning pattern of Ca-bearing silicates in skarn ore-forming systems may be quite complex because of superimposed events of mineral deposition during prograde and retrograde alteration. HyMap data offer comprehensive mineralogical examination between skarn assemblages and uneconomic host rock. From these inputs, a series of studies can be oriented to increase the level of detail about mineralization, including geochemistry and petrography. These mapped minerals, especially Cabearing silicates, can be used as a potential guide to define new exploration targets near mines, brownfields and greenfields.

The Reed-Xiaoli Detector (RXD) algorithm provided a quick guide for preliminary spectral analysis of targets in the open pit of the Mary Kathleen mine. It is a powerful tool for areas where the geology is not well known. Pixels enhanced by this technique detected minerals composed of Fe, Fe–OH, Al–OH, Mg–OH and X–CO<sub>3</sub> chemical bonds. The Minimum Noise Fraction (MNF) function successfully segregated noise, reduced further computational requirements needed for mineral information extraction and yielded images, particularly the first MNF, that can be used to constrain fieldwork and spectral analysis.

The application of the MTMF classification method allowed us to produce abundance maps of Ca-bearing silicates associated with the skarn-hosted U-REE mineralization. Wallrock alteration halos related to the Mary Kathleen skarn do show characteristic zonal arrangements. The comparison between abundance maps showed that andradite dominates the overall geometry of the alteration halo with lesser amounts of 'selectively pervasive' alteration represented by goethite  $\pm$  calcite  $\pm$  scapolite + epidote  $\pm$  hornblende  $\pm$  montmorillonite, respectively. The association of andradite  $\pm$  goethite dominates toward the inner zones of the alteration.

Alteration zoning found specifically in the Mary Kathleen Shear zone is characterized by scapolite  $\pm$  andradite  $\pm$  hornblende  $\pm$  calcite  $\pm$  epidote and secondary goethite  $\pm$  montmorillonite. This assemblage allows inferences on the hydrothermal activity associated with the U-REE mineralization. The specific mineral types and distribution found in the Mary Kathleen deposit probably indicates that this area was strongly affected by multiple stages of metasomatic transfer resulting in widespread high-temperature and retrograde Ca-bearing silicates.

Evidence of goethite  $\pm$  kaolinite  $\pm$  montmorillonite association and their zonal relationships with skarn-hosted U-REE has been rarely



Fig. 12. Pixel-spectra features associated with skarn-hosted U-REE. These spectra were extracted from the pixels in areas of greatest mineral abundance. The vertical dotted lines indicate main absorption features. These are compared to the mineral-spectra andradite (GDS12), goethite (WS222), epidote (GDS26.a), hornblende (Mg NMNH117329), calcite (WS272), kaolinite (CM9), and montmorillonite (SWy-1) (USGS spectral library). Scapolite spectrum was measured with a FieldSpec-3 Hi Res spectrometer.

documented convincingly. However, where the regolith cover is partly eroded, soils potentially suggest the U footprint. Thus, a cautious use of maps showing goethite  $\pm$  kaolinite  $\pm$  montmorillonite associated with Ca-bearing silicate may suggest areas for U exploration in the Mount Isa Province.

A remarkable characteristic of spectra of andradite versus goethite is the straight line continuously decreasing from 0.80  $\mu$ m towards the ultraviolet region. In the same wavelength interval, the goethite spectrum shows a typical attenuated concavity at 0.60  $\mu$ m. Additional analysis between andradite, goethite and hematite spectra are required due to the similarity of their features.

Goethite may be derived from the weathering process of some Cabearing silicates that contain Fe their crystalline structure. An important aspect of the secondary Fe-hydroxides is their ability to absorb trace metals that can be used as a pathfinder element for U-REE mineralization. For example, in the Mary Kathleen deposit, trace metals such as  $Cu^{2+}$  and  $Pb^{2+}$  were yielded from decomposition of chalcopyrite and galena. This is revealed by geochemical exploration. Consequently, near the mine, reconnaissance of areas with goethite with trace metals can be used to set targets for exploration with auger drilling as well as rock and soil sampling.

The pixel-spectra analysis comparison between scapolite and montmorillonite requires further investigation. Areas spectrally classified with these mineral signatures were dissimilar, except in the Mary Kathleen Shear zone, where the association showed consistency.

The Mount Isa Province has areas where granitic rocks with acid and intermediate composition intrude limestones and/or dolomites. It is an excellent laboratory to apply hyperspectral analysis, as documented here. HyMap data allows a solid interpretation of hydrothermal mineral systems and this notion may be augmented when other exploration methods are combined, such as ground and airborne geophysics. Such data fusion provides a possible framework for robust geological interpretation and conception of a successful exploration model for skarnhosted U-REE mineralization.

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