



CORESCAN

Hyperspectral Core Imaging Applications in Skarn Deposits

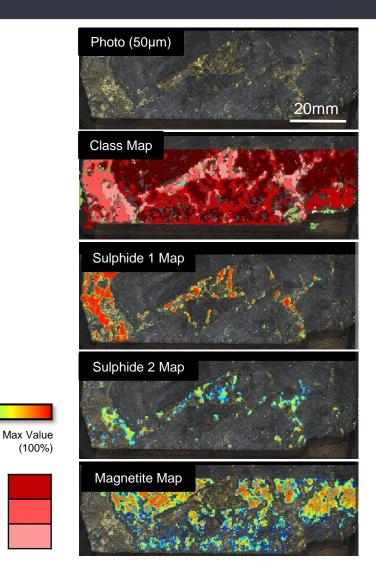
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Introduction to Skarn Deposits

- Skarns deposits are highly variable class of mineral deposits and economically important sources of Fe, W, Au, Cu, Zn, Mo and Sn.
- Deposits form during regional or contact metamorphism and can occur in a range of different geological settings.
- A common characteristic of all deposits is the occurrence of calc-silicate mineral assemblages, particularly garnet and pyroxene.
- Mineralogical zonation patterns are well established for a range of skarn types and can be an important tool for exploration at the deposit- or district-scale.
- Key mineralogical characteristics can be identified and mapped using VNIR-SWIR hyperspectral core imaging technology. This includes calc-silicate phases (pyroxene, garnet) as well as hydrous (retrograde) mineralogy such as epidote, chlorite, vesuvianite, etc.





Min Threshold

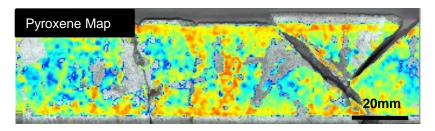
Magnetite

Sulphide 1 Sulphide 2

Skarn Terminology

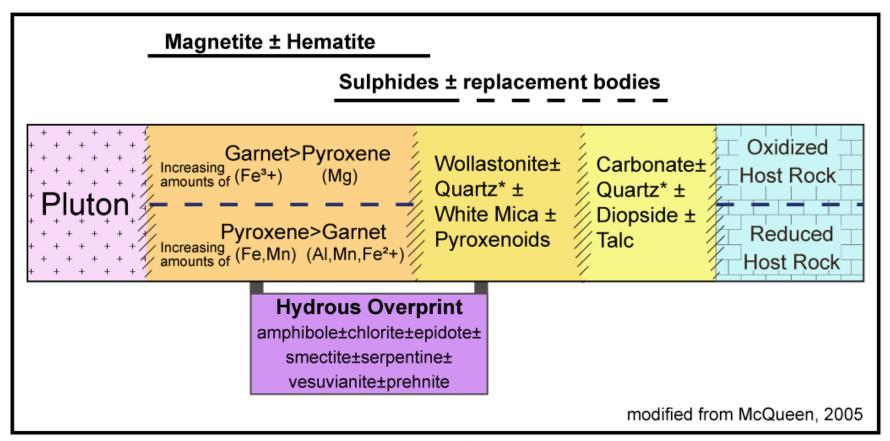


- Classification Schemes
 - Endoskarn the skarn protolith is of igneous origin
 - Exoskarn the skarn protolith is of sedimentary origin
 - Dolomitic protolith = magnesian skarn
 - Limestone protolith = calcic skarn
 - Skarnoid the intermediate stage of a finegrained hornfels and a coarse-grained skarn
 - From a mineral system point of view skarns are classified in terms of their metal association: Fe, Au, W, Cu, Pb-Zn, Mo, and Sn.



- Skarn Paragenesis it's complicated!
 - Distinctive mineral zoning related to thermal and chemical gradient from intrusion to reactive country rock.
 - Ore element patterns also related to prograde vs retrograde events.
- Prograde
 - Distinctive calc-silicate assemblages:
 - Garnets (grossular, almandine, spessartine, and andradite)
 - Pyroxenes (diopside & hedenbergite)
 - Wollastonite
 - and others!
- Retrograde
 - Sulphides
 - Hydrous mineral phases (epidote, chlorite, amphibole, talc, smectites...)



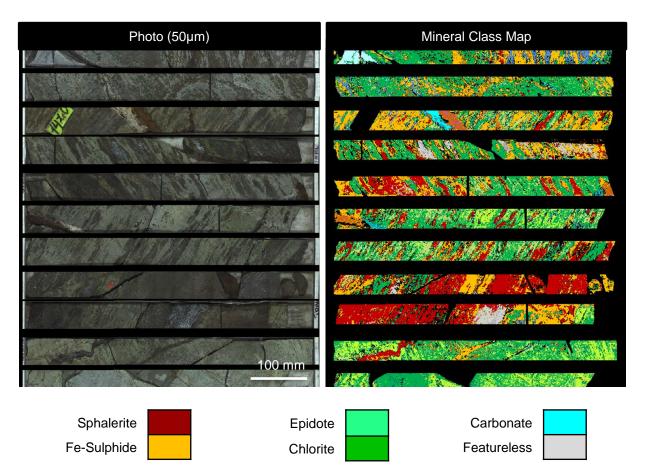


*Quartz is not strictly active in the VNIR-SWIR, however, if it contains water inclusions it can be mapped using a combination of a negative slope and the 1900nm feature. It is also mapped as a combined "Featureless Slope" group that also includes anhydrous feldspars.

Skarn Deposits with Hyperspectral Imaging



- Detection and mapping
 - Both host rock and skarn minerals
 - Including solid solution series
 - Sulphides
- Assemblage identification
 - Including Pro- and Retrograde
- Minerals as vectors narrow geochemical T and pH ranges can help locate zones of metal deposition
 - Fundamentally constrains geochemical environment of formation
- Deposit reconstruction including spatial form and extent
 - Can indicate relative size of resource and suggests source of heat and mineralising fluid
- Geometallurgical consideration
 - Clay occurrence & distribution
 - Deleterious mineral identification & mapping



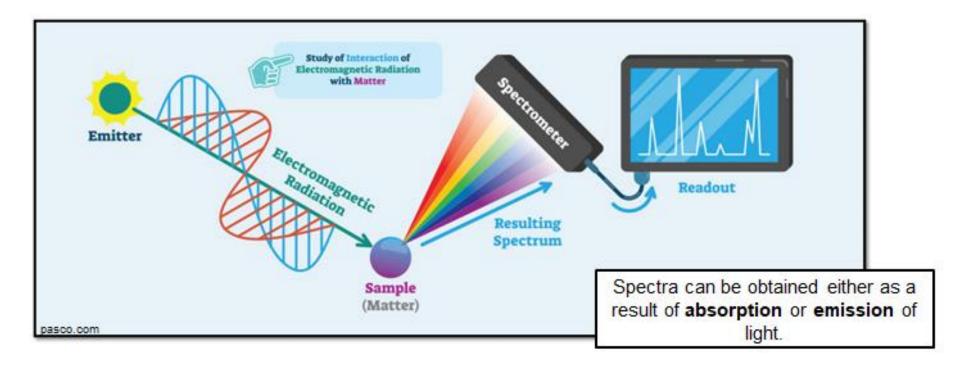


Corescan Introduction to Hyperspectral Imaging

Spectroscopy & Spectral Geology



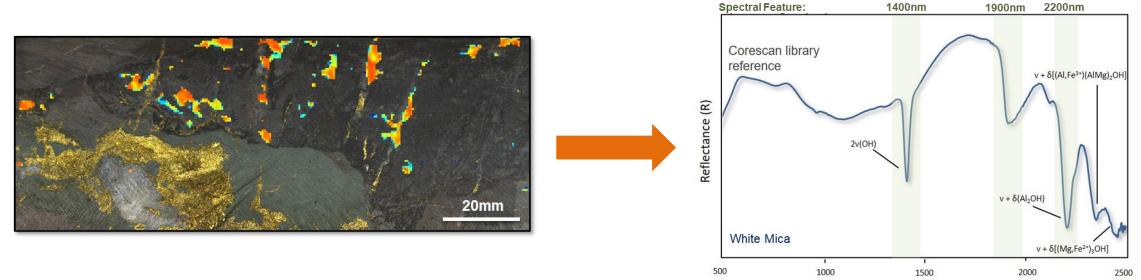
- Spectral geology is a form of mineralogical analysis.
- It is the measurement and analysis of certain portions of the electromagnetic spectrum to identify the mineralogy (and mineral geochemistry) of geological materials.
- Spectral data is measured using spectral sensors, which record energy <u>reflected</u> from the surface of materials. Because many materials <u>absorb</u> radiation at specific wavelengths it is possible to identify them by their characteristic absorption features.



The Physics of Spectroscopy

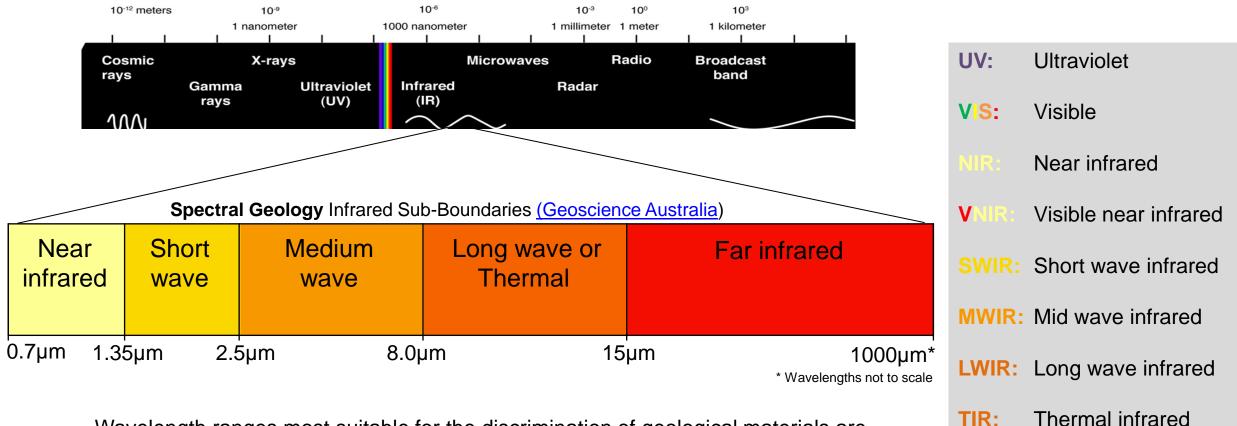


- In order to understand spectral mineral analysis, it is important to first understand the basic physics of the interaction of electromagnetic (EM) energy with their targets (i.e., rocks).
- Namely:
 - What is light ?
 - How does it travel from point A to point B?
 - What does light do once it gets to point B (i.e., the basic interaction of light with other matter) ?



Electromagnetic Energy: Terminology



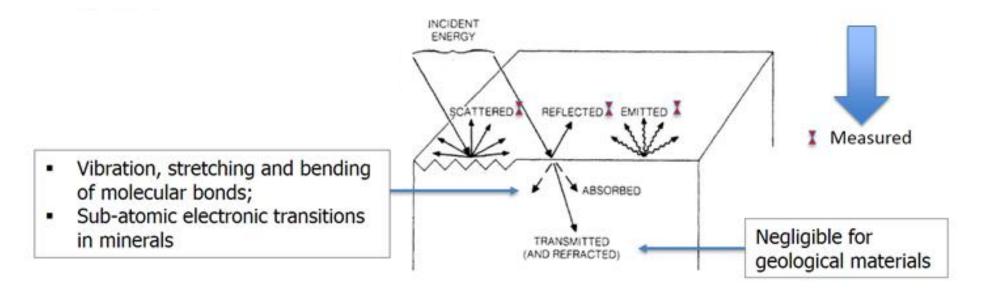


Wavelength ranges most suitable for the discrimination of geological materials are the visible and near infrared (VNIR), shortwave infrared (SWIR), the mid-wave infrared (MIR), and the long wave or thermal infrared (TIR).

Reflectance Spectroscopy for Geology



- Infrared reflectance-emission spectroscopy
 - Interaction of photons with material surface (e.g., rock)
 - Light / energy source
 - Generally, no penetration beyond 3-6µm

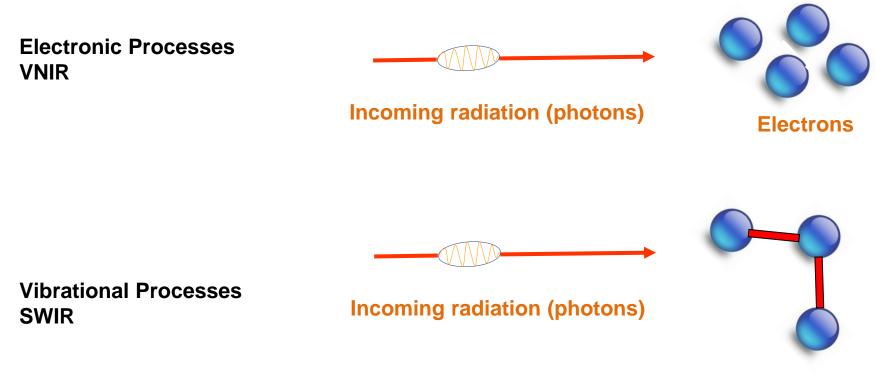


Zhou, 2021

IR Spectroscopy: Absorption



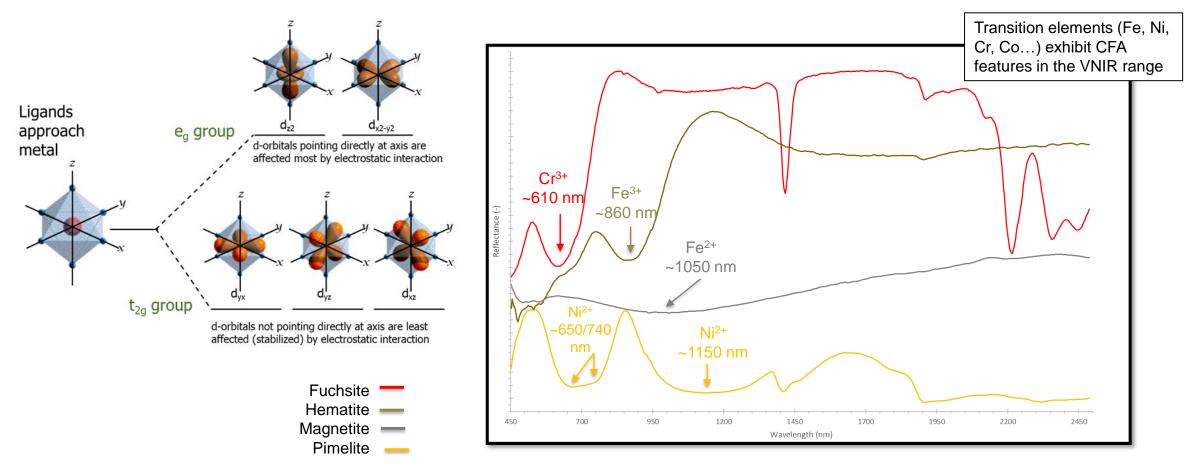
• Characteristic spectral features are produced when energy from the electromagnetic spectrum is absorbed (rather than reflected).



Molecules

IR Spectroscopy: Absorption – Electronic Energy

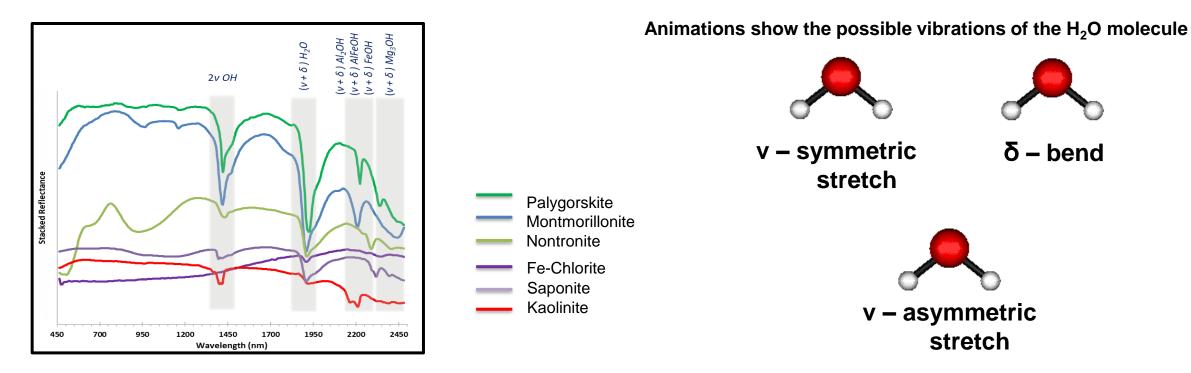
 We see mainly crystal field absorptions features in the VNIR that are the result of the splitting of energy in the dorbitals of positively charged metal cations. The splitting of the energy levels is due to the interaction between a positively charged metal cation (say Fe²⁺) and the negative charge of non-bonding electrons of ligands (say O²⁻).



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IR Spectroscopy: Absorption – Vibrational Energy

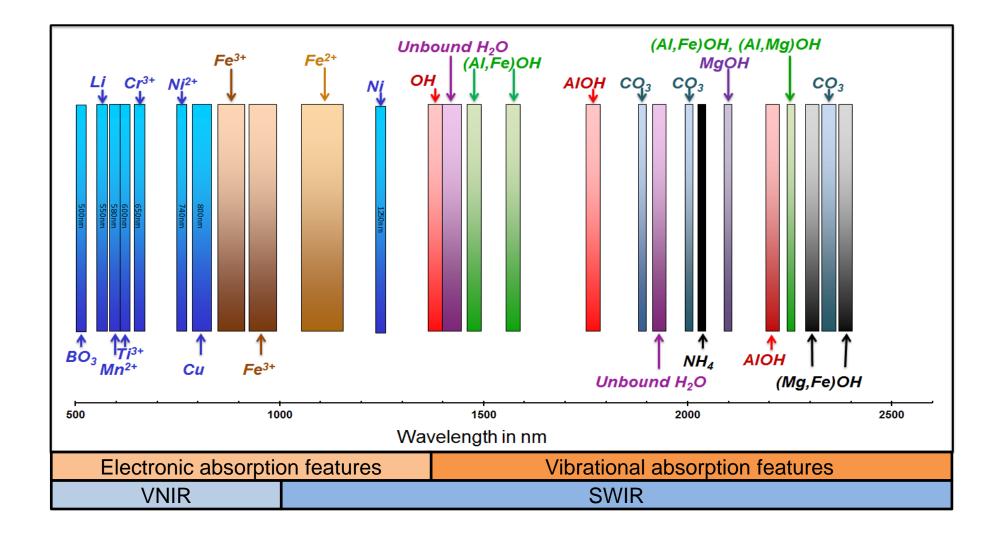
- Incoming radiation can also cause molecules to 'vibrate' the bonds between atoms bend and stretch in predictable geometries.
- The energy associated with these motions or "fundamental vibrational modes" are located in the MIR and FIR range of the electromagnetic spectrum.
- In the SWIR, only overtones and combination of bending (δ) and stretching (v) modes are observed.



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VNIR-SWIR: Molecular Bonds and Elements

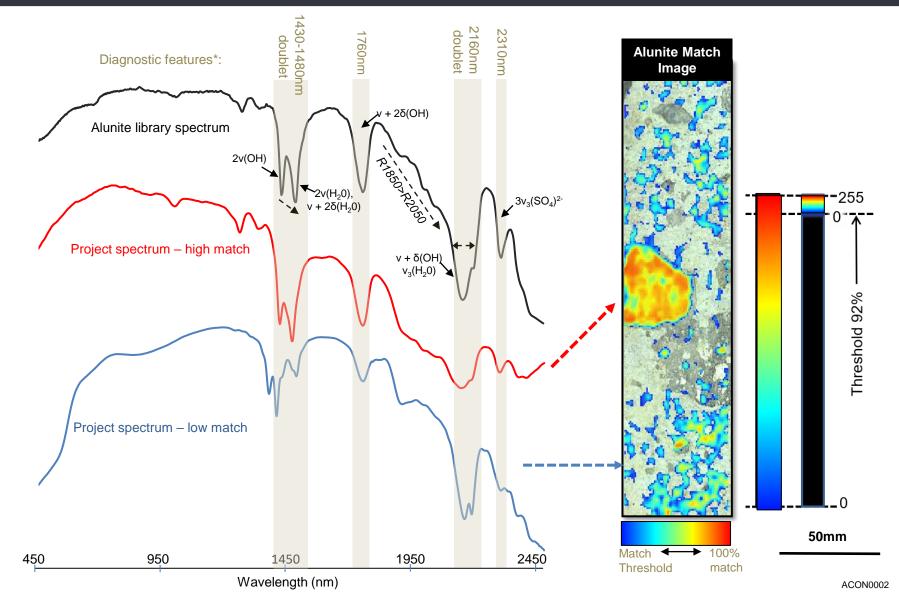




Mineral Identification and Mapping

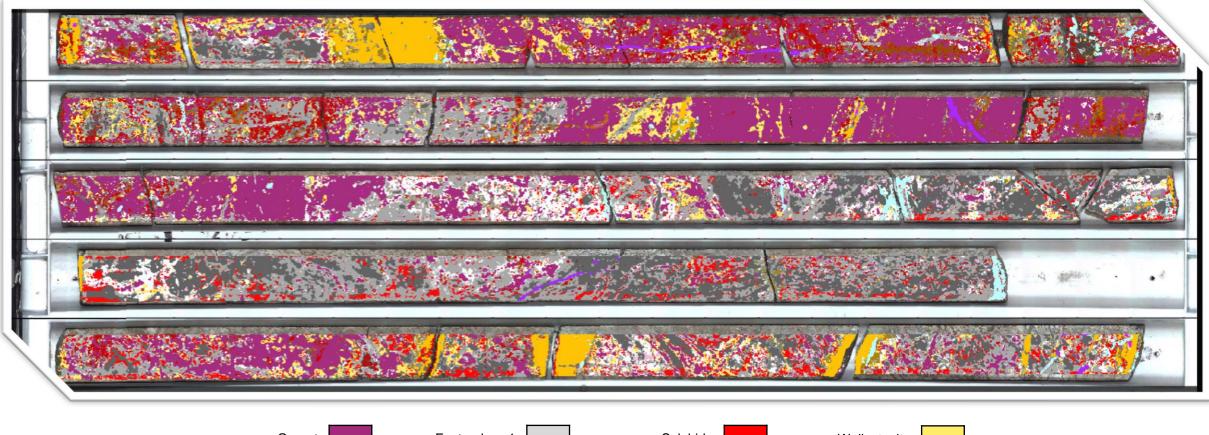


- A match value for each mineral is calculated across all hyperspectral pixels
- Cut-off thresholds are determined by quantitative comparison to known spectral behaviour as well as qualitative identification processes
- Project-specific spectralmineral libraries are developed



"Prograde" Skarn Assemblage Images

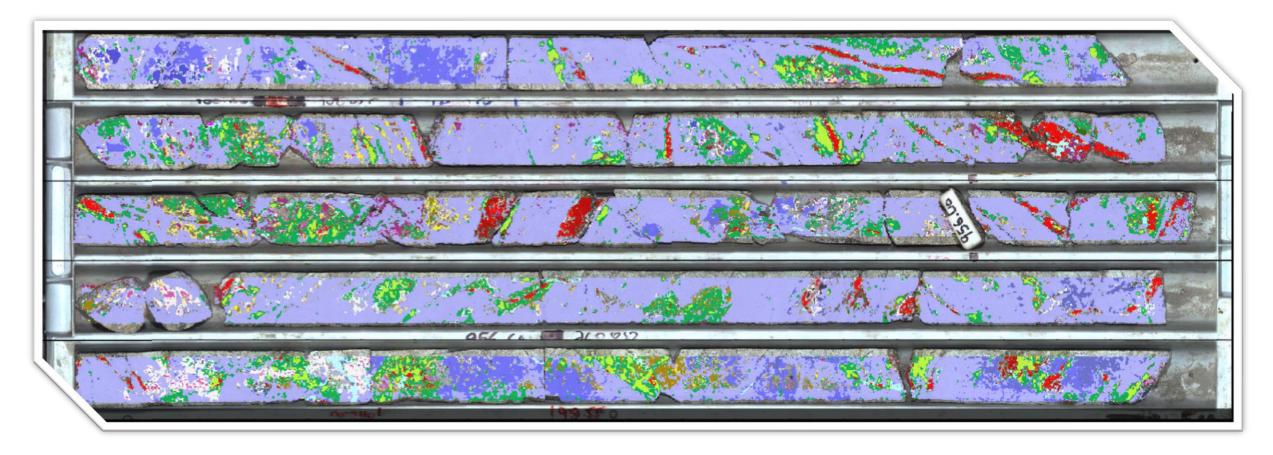






"Retrograde" Skarn Assemblage Images





Garnet	Epidote	Sulphide	Wollastonite	
Beidellite	Chlorite	Montmorillonite	Quartz	

Corescan Mineral Logs



• Mineralogical data for each depth interval is exported as standard '.csv' files. These interval-based logs include abundances of major mineral groups (such as white micas and chlorite) as well as the relative proportions of mineral sub-species (such as paragonite, muscovite, phengite) derived from specialized spectral parameters.

LOG CATEGORY	VALUE	DESCRIPTION
White mica abundance	11.39 pxa	Normalized abundance of white mica pixels, per interval (includes illite + muscovite)
Montmorillonite abundance	34.51 pxa	Normalized abundance of montmorillonite pixels, per interval
ISM	0.68	Average 2200D/1900D, per interval, for combined white mica + montmorillonite
ISM_Montmorillonite_pct	63.68	Number of pixels with $ISM < 0.75$, relative to total white mica + montmorillonite pixels
ISM_IIIite-Montmorillonite_pct	21.47%	Number of pixels with $ISM = 0.75 - 0.99$, relative to total white mica + montmorillonite pixels
ISM_IIIite_pct	5.03%	Number of pixels with $ISM = 0.99 - 1.25$, relative to total white mica + montmorillonite pixels
ISM_Muscovite-Ilite_pct	<mark>9.52%</mark>	Number of pixels with ISM = 1.25 - 2, relative to total white mica + montmorillonite pixels
ISM_Muscovite_pct	0.30%	Number of pixels with $ISM > 2$, relative to total white mica + montmorillonite pixels

Example of Corescan log outputs reporting mineral abundances and Illite Spectral Maturity (ISM) categories

🕨 Sum= 100%

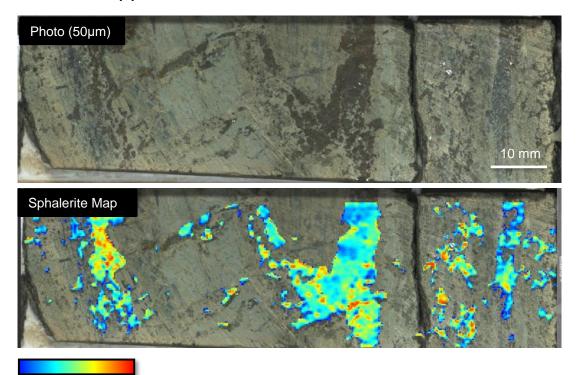


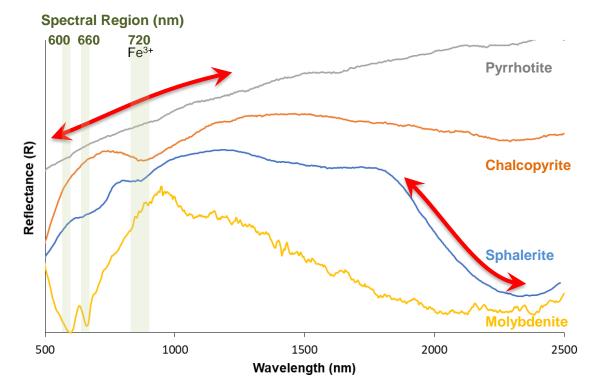
Corescan Skarn Mineralogy

Sulphide Mapping in Skarns



- Iron sulphides and sphalerite are commonly found in many types of skarns.
- Whereas most sulphides do not have identifiable absorption features in the VNIR-SWIR, both sphalerite and molybdenite have identifiable spectral features; sphalerite has a unique spectral profile in the SWIR and molybenite has mappable Mo features in the VNIR.



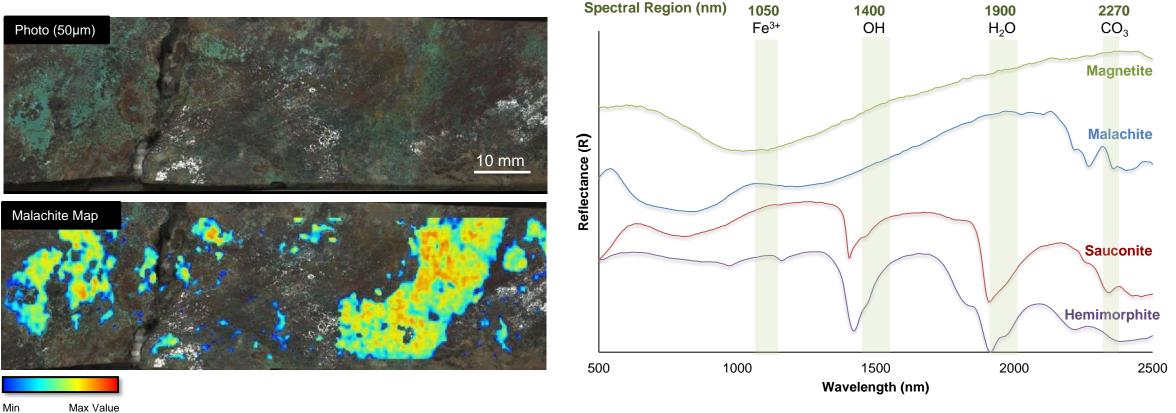


Min Max Value Threshold (100%)

Ore Mineralogy in Skarns



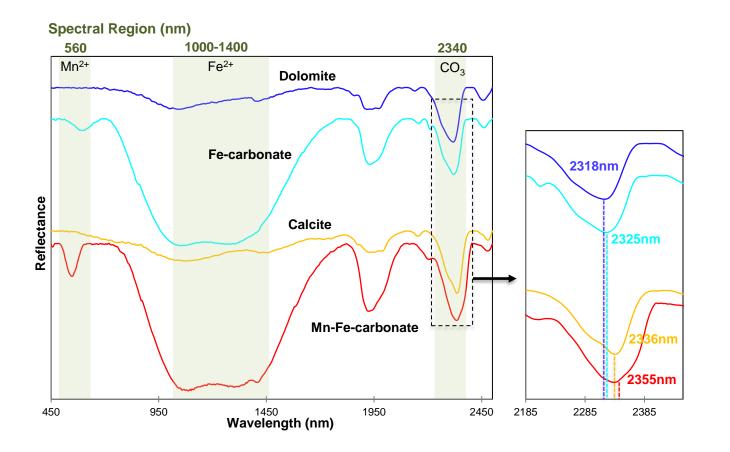
• In addition to sulphides, skarn ore minerals can include oxides (e.g., magnetite), carbonates (e.g., malachite) and a wide range of silicates (e.g., sauconite and hemimorphite).

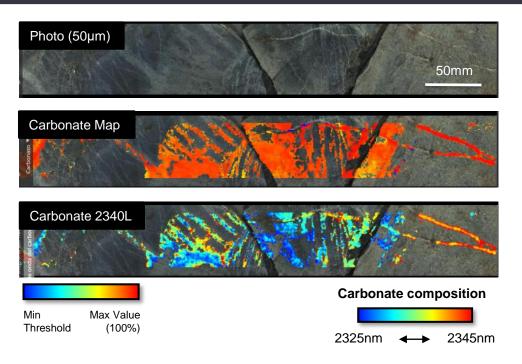


Protolith Skarn Mineralogy: Carbonates



• Many different species of carbonates, particularly dolomite, calcite and Fe-rich varieties, are common in skarn systems.



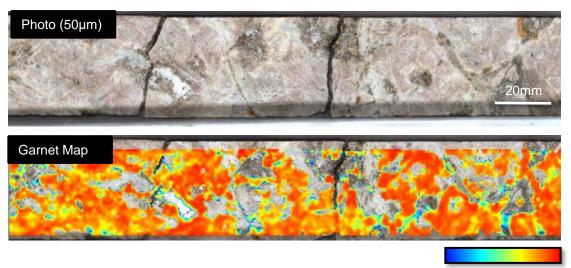


- Mg-metasomatism (calcite to dolomite) is easily traced in Ca-Mg carbonate varieties using variations in the ~2340nm absorption feature.
- Fe substitution in carbonate also results in a very distinctive spectral feature in the VNIR that is easily mapped using the Corescan HCI system.

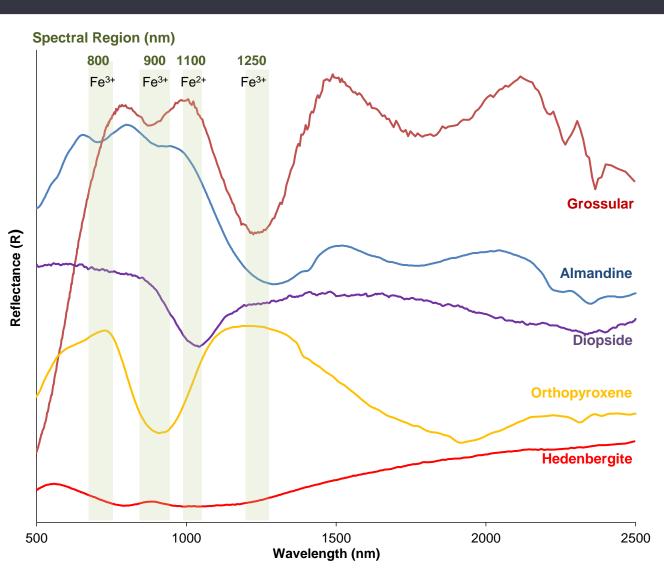
Calc-Silicate Mineralogy: Garnet & Pyroxene



- Garnets and pyroxenes are characteristic components of nearly all skarn deposits.
- They have distinct, but variable, VNIR features due to Fe and transition metals incorporated in the mineral structures.
- Garnets and pyroxenes are often featureless across the SWIR region unless mixed with other minerals as a result of overprinting or alteration.



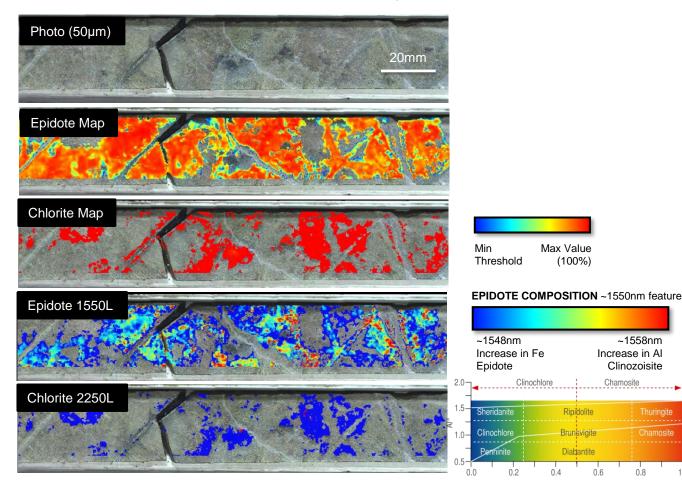


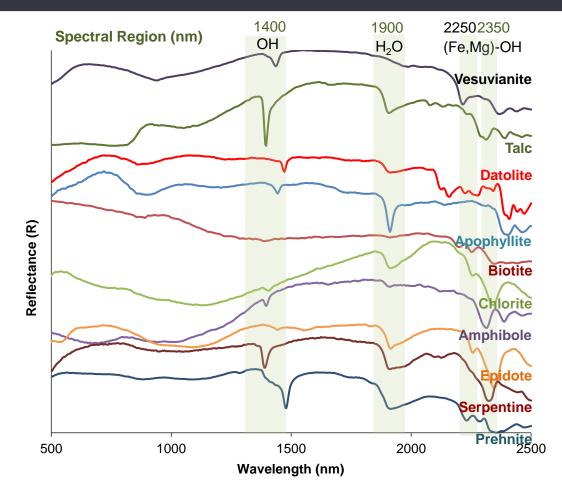


Hydrous Minerals Commonly Found in Skarns



Fe- and Mg-bearing clays, micas and silicates are common in skarn deposits. They can occur as overprinting (retrograde) assemblages, distal to core of the skarn system, and / or along fluid conduits.





Chemical variations in many mineral groups can be tracked using the wavelength of spectral absorption features (e.g., chlorite at ~2250nm, epidote at ~1550nm).

0.4

0.6

Ripidolite

Max Value

Clinochlore

(100%)

~1558nm

0.8

1.0

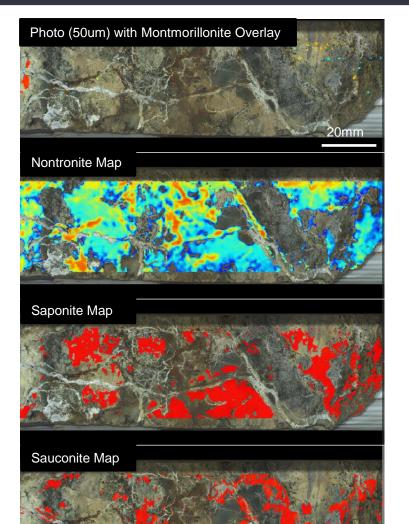
Increase in Al

Chamosite

Clinozoisite

Variability in Chemistry: Smectites

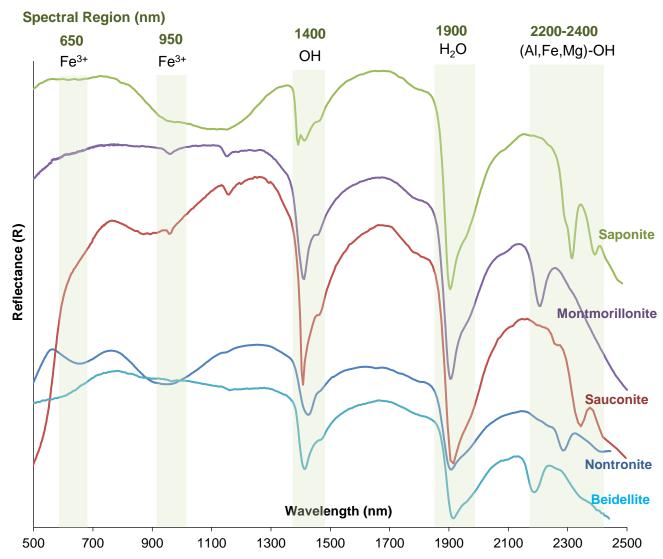




- A large variety of smectite-group minerals can occur in skarn systems from Ca±Nabearing montmorillonite, to Fe-rich nontronite, to Mg-rich saponite and to Zn-rich sauconite.
- These smectite species have distinct SWIR absorption features that enable accurate mineral identification and mapping.



Min Max Value Threshold (100%)



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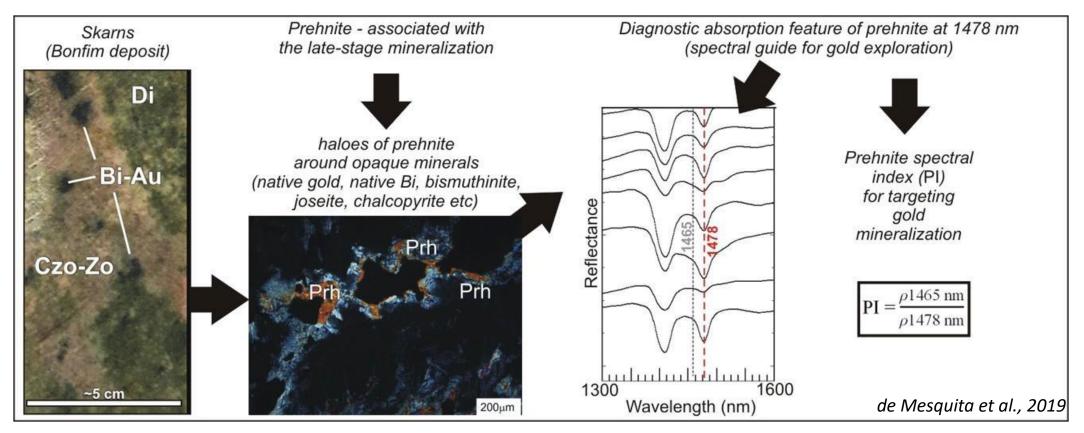


Corescan Applying Hyperspectral Core Imaging Data

Prehnite: A Potential Vector in Au Skarn



- Prehnite {Ca₂Al(AlSi₃O₁₀)(OH)₂} is a relatively common component of many Au skarns. It can be difficult to identify visually but has a very distinct SWIR signature and easily be mapped using hyperspectral imaging.
- The intensity of prehnite alteration (based on spectral absorption features) may be used as a vector to Au mineralization.
- See a recent example from the Bonfim W-Mo-Au-Bi-Te skarn, Brazil (de Mesquita et al., 2019).



Metallurgical Considerations: Skarn Ore



- Skarns are typically host to a wide variety of anhydrous and hydrous minerals that require careful characterization with regards to blasting, mining, comminution and processing behavior.
- Hyperspectral imaging provides consistent and accurate mineralogical identification as well as critical data on mineral distribution, assemblages and

texture.

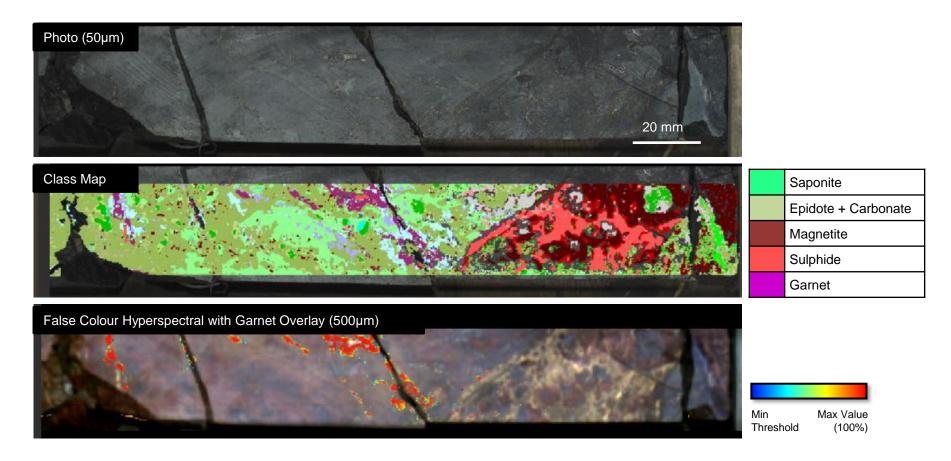
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Copper Skarn, Peru

Metallurgical Considerations: Calc-Silicates



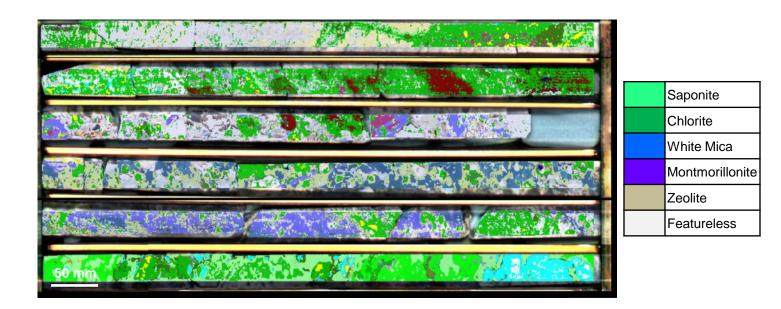
- Geometallurgical characterization of skarn deposits can be challenging due to mineralogical complexities.
- The relative abundance and distribution of calc-silicates versus clays is one significant factor that can affect comminution and mineral processing behavior.



Metallurgical Considerations: Clay Mineralogy



- Phyllosilicate "clay" minerals display variable compositions, structures and charge properties.
- These minerals can have a significant impact on all aspects of mineral processing:
 - swelling minerals increase in volume in wet circuit, examples: montmorillonite, nontronite, saponite, sepiolite
 - phyllosilicates may impact fluid viscosity, examples: smectites, kaolinite, pyrophyllite, chlorite
 - certain phyllosilicates may consume reagents, examples: chlorite, kaolinite, illite, vermiculite
- Some phyllosilicates are difficult to distinguish visually and chemically, but hyperspectral imaging assists in distinguishing species and mapping their spatial distribution.



Example: Zinc Skarn Mineralogy



	Photo (50µm)	Sauconite Map	Sphalerite Map	Hemimorphite Map	Featureless Map	Carbonate 2340L	Saponite Map	Montmorillonite Map	Zeolite Map	Garnet Map
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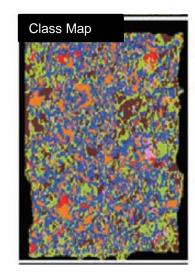
Zinc Skarn, Mexico

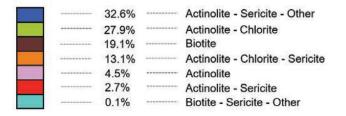
Mineralogical Diversity in Blast Hole Data



- Ultimately what is being mined, processed and milled are minerals
- Significant value can be added with an improved understanding of the nature of the material being mined
- Hyperspectral imaging provides opportunities for mapping mineralogy at a fine scale, such as seen in Johnson et al., 2019.





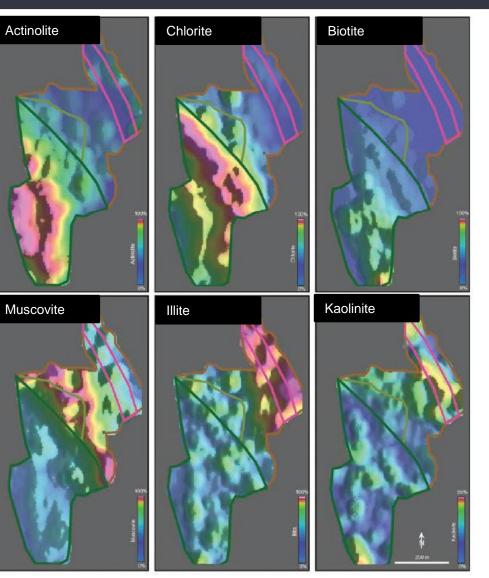


Johnson et al., 2019

Mineralogical Diversity in Blast Hole Data

Corescan

- Johnson et al. (2019) when hyperspectral mineralogy from blast hole cuttings is gridded, important mineral assemblages and spatial relationships can be mapped.
- The polygons overlaying the mineral images (outlined in dark green, light green, brown and pink) represent the alteration as originally mapped in the field.
- Four general groupings of skarn, calc-silicate hornfels, biotite hornfels, and supergene phyllosilicate are now defined minerals that metallurgists can use in their models.



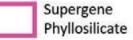
Field Mapped Alteration (Blast Hole Cuttings)







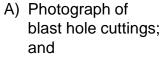




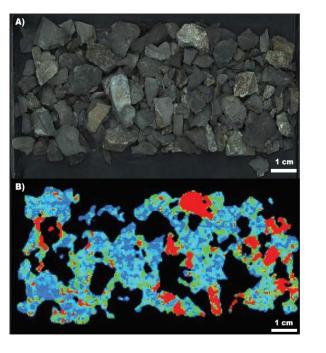
Blast Hole Cuttings for Geomet: Mapping Talc

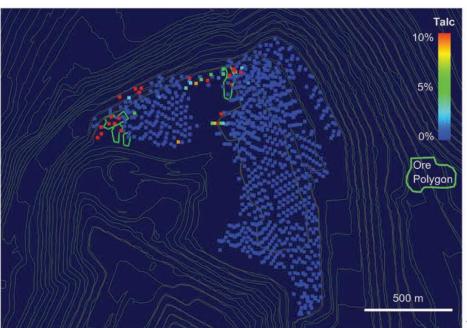


- At the Phoenix Mine (NV, USA), talc is the most problematic mineral to the process circuit. Even small concentrations (<1%) cause major over-frothing, requiring significant cleanup and cost, decreasing sulfide recovery, and increasing silicate entrainment in concentrate (Johnson et al., 2019).
- Accurately identifying fine-grained talc prior to feeding the mill is critical.
- Consistent identification of talc, however, is challenging from field observations alone; the addition of hyperspectral imaging of blast hole cuttings to identify and quantify the amount of talc present in mill ore has helped metallurgists create a threshold for acceptable volumes of talc allowed through the mill at any given time.



B) Hyperspectral talc index heat map.





Map of talc percentages determined via hyperspectral imaging overlaid on mill polygons that resulted in significant upset in flotation conditions due to talc entrainment.

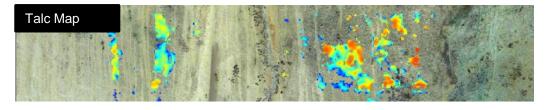
Johnson et al., 2019

Talc Mapping Using Hyperspectral Imaging

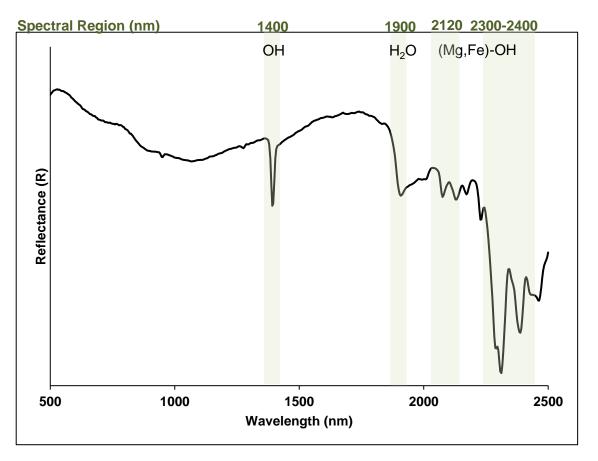


 Talc is dominantly formed during retrograde hydrothermal alteration in Mg-rich carbonate protoliths, although it can also be formed during the prograde stage via reaction between dolomite and silica.







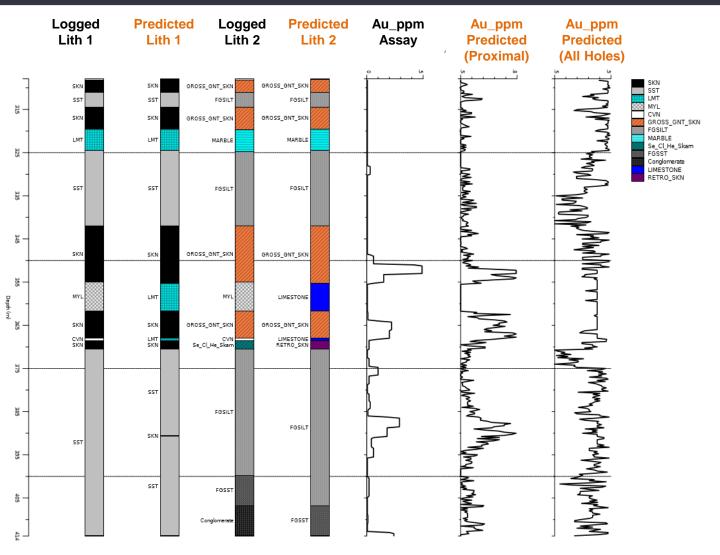


 The sharp triplets around 2120nm and doublets at 2310nm / 2385nm are diagnostic absorption features for talc and are identifiable in the mapped spectra.

Lithology and Gold Grade Predictions in Skarn

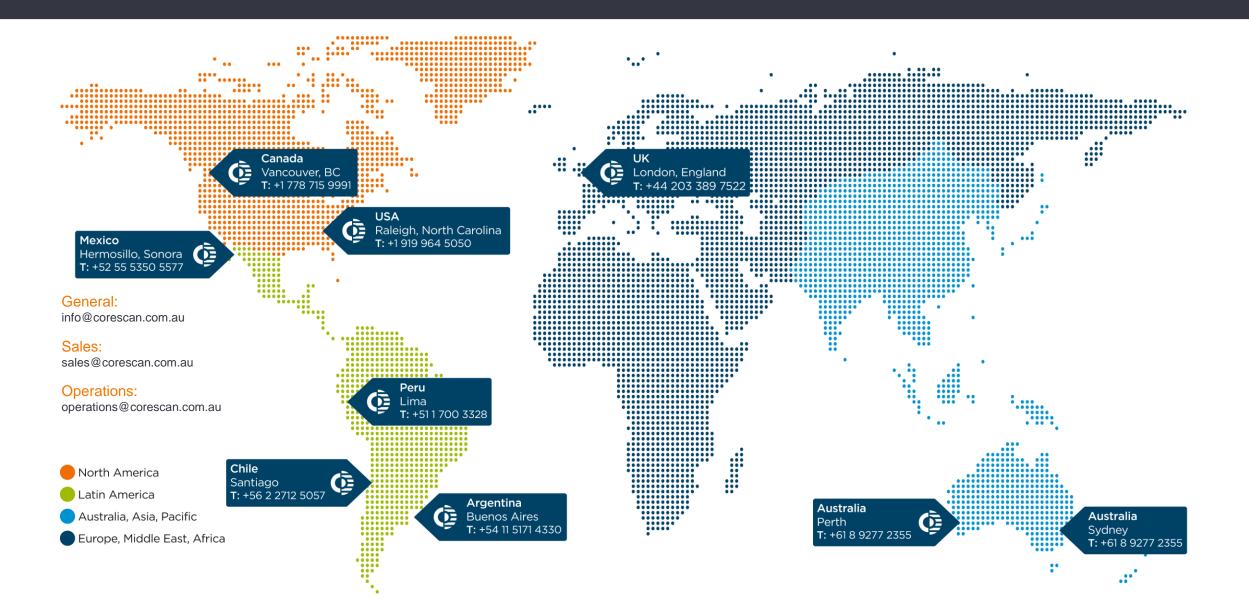


- Rich datasets generated by hyperspectral imaging can be used for enhanced data modelling, analysis, and deep learning algorithms.
- In particular, the integration of hyperspectral data (both mineral abundances and mineral images) with geochemical analyses allows for detailed rock characterization and classification.
- Example: Random Forest (RF) algorithms to predict lithology and the probability of having Au > 1ppm in an Australian skarn system.



Contact Us





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Hyperspectral Core Imaging Applications in Skarn Deposits

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Corescan Appendix: Additional Information on the Corescan System

Hyperspectral Core Imaging Services



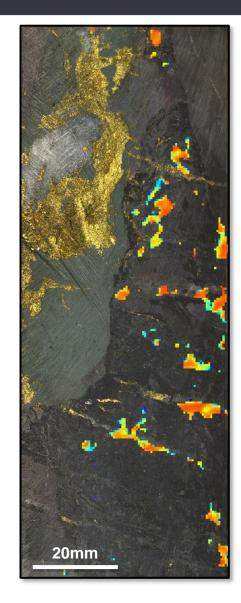
Mineral identification and mapping across the mining cycle:

- Improved alteration domains and mineral assemblages
- Metallurgical and geochemical sample selection and characterization
- Geotechnical measurements for mine design and engineering
- Identification of alteration vectors for exploration targeting
- Ore and gangue characterization for mineral processing and optimisation
- Ground truthing of airborne hyperspectral surveys

Corescan's Hyperspectral Core Imagers (HCI) integrate high resolution reflectance spectroscopy, visual imagery and 3D laser profiling to map mineralogy, mineral composition and core morphology, delivering enhanced geological knowledge.

Summary timeline:

- Sensor engineering commenced 2001
- Commercial operations commenced 2011
- 580+ projects / 1.2 million metres successfully scanned, processed and delivered...



Hyperspectral Core Imager: Model 4



Specifications	HCI-4.1	HCI-4.2
RGB Photography - Spatial resolution	25µm	25µm
3D Profiling - Spatial resolution	50µm	50µm
Sensor type	Imaging	Imaging
Imaging Spectrometer Module - Spatial resolution	500µm	250µm
Spectra per metre (1000mmx60mm)	240,000	960,000
Spectral Range – VNIR (nm)	450 – 1,000	450 – 1,000
Spectral Range – SWIR (nm)	1,000 – 2,500	1,000 – 2,500
Core tray length (Max)	1,550mm	1,550mm
Core tray width (Max)	600mm	700mm
Supports material weighing	-	Yes
Supports pass-through workflow		Yes
Scanning speed	~25mm per second	~25mm per second





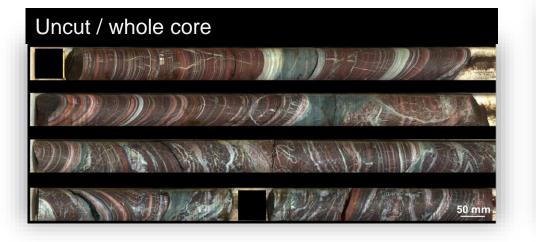
For further information please visit: https://corescan.com.au/products/hyimager/

Hyperspectral Core Imaging: Material Types









Chips, cuttings, blast holes





Hyperspectral Core Imaging Services



Onsite Scanning Services

- Mobile, self-contained laboratory
- 20' sea container for protection and ease of mobilization
- Ruggedized construction and environmentally controlled for optimal spectrometer operation
- Turnkey operation
- Rapid data outputs and products
- Integration to geological databases and core logging software
- Performance and operational reporting
- Supports 24 / 7 operations

