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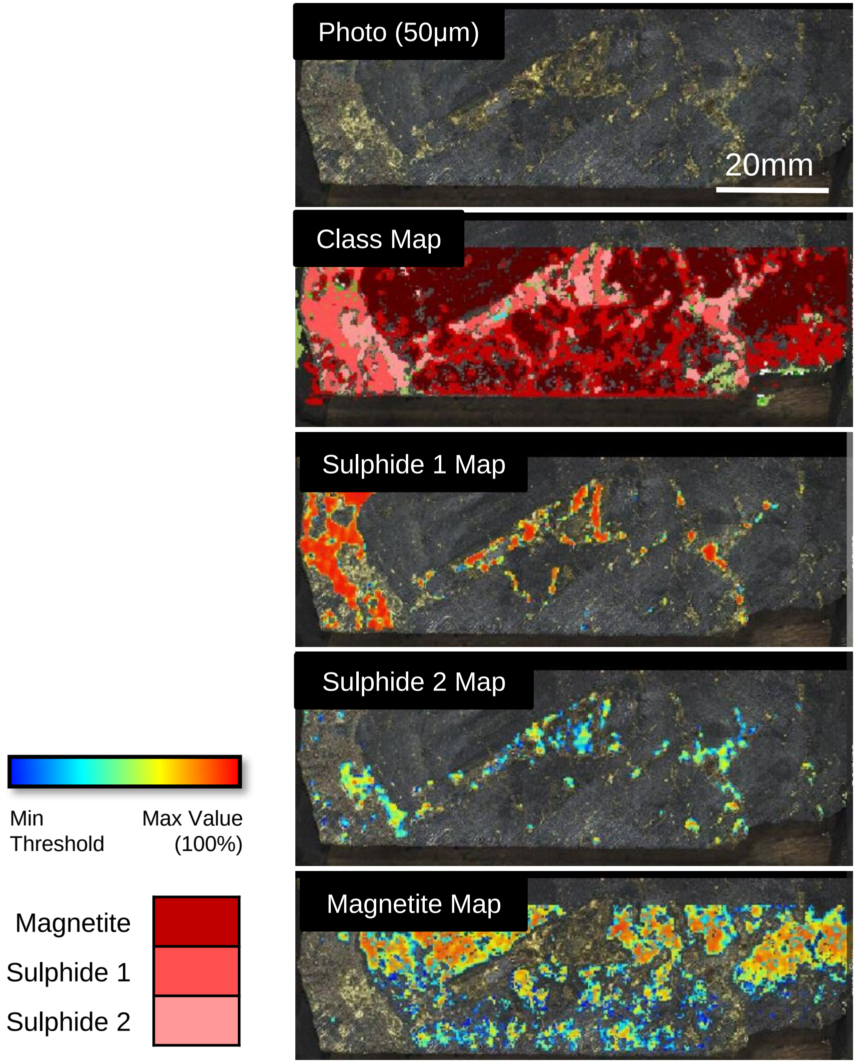
Hyperspectral Core Imaging Applications in Skarn Deposits

Presented by: Sam Scher, M.Sc. Cristal Palafox, M.Sc.
info@corescan.com.au

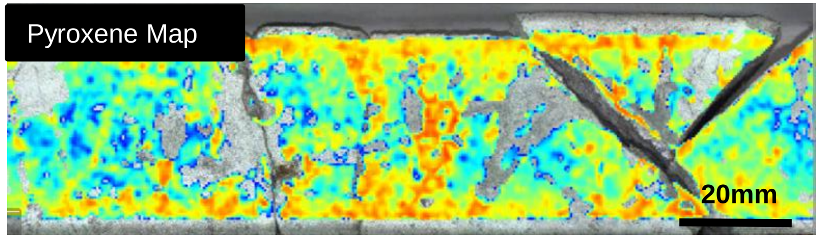
Introduction to Skarn Deposits

- 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.



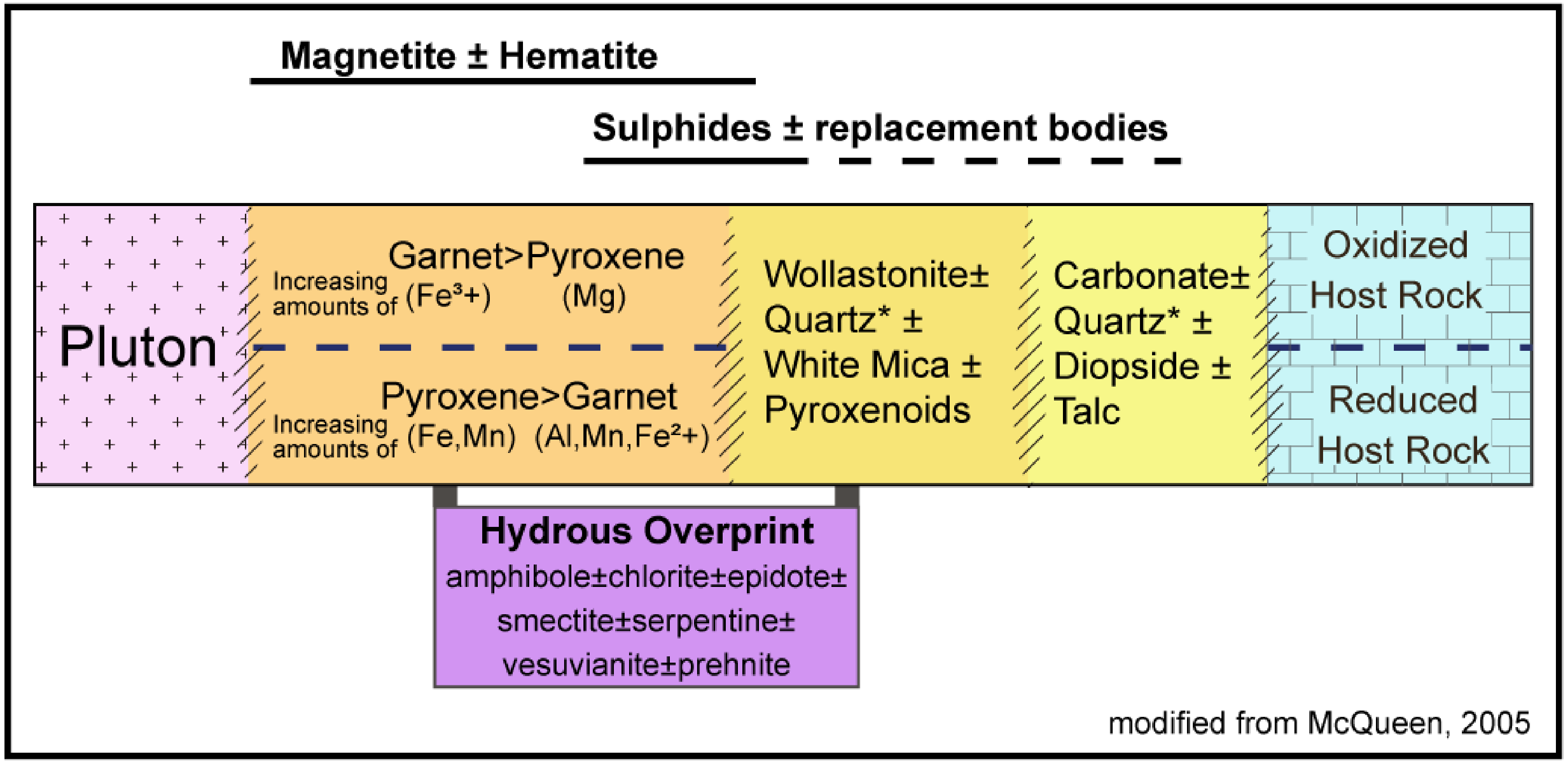
Skarn Terminology

- **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 fine-grained 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…)

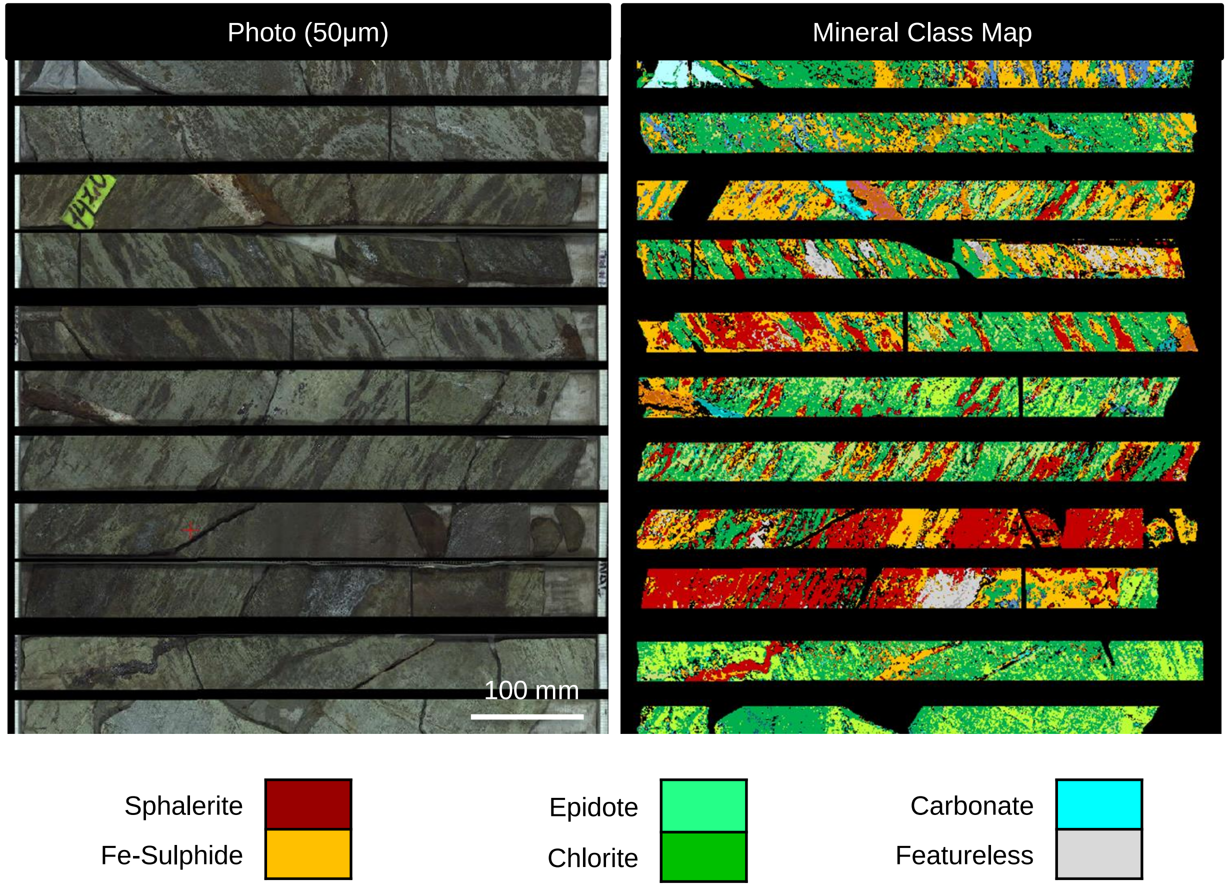
VNIR-SWIR Active Skarn Mineralogy



*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



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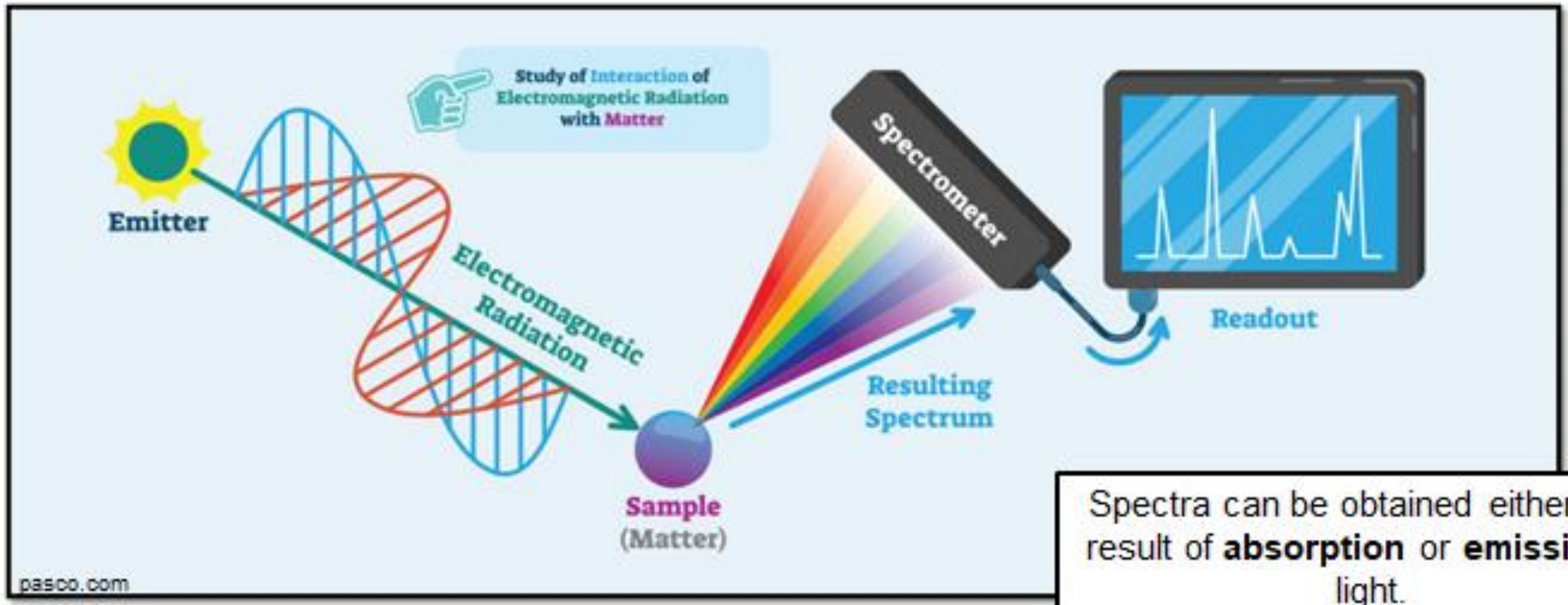
Introduction to Hyperspectral Imaging

Spectroscopy & Spectral Geology

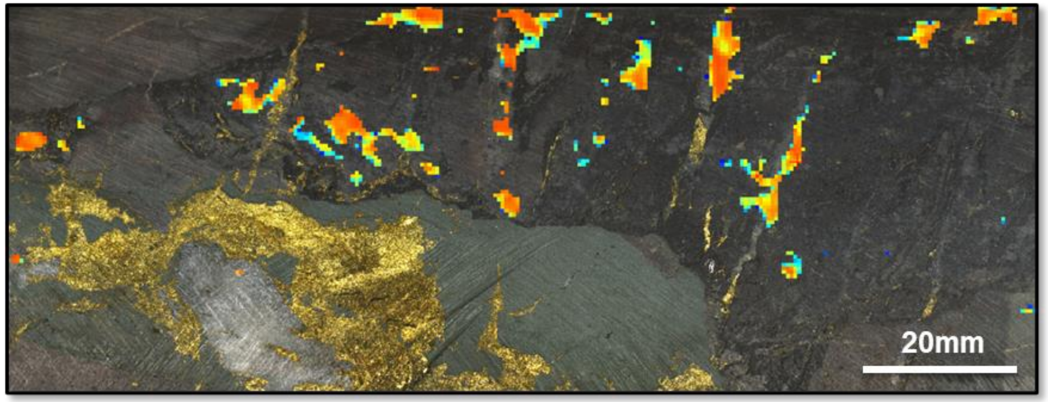
- Spectral geology is a form of mineralogical analysis.
- It is the measurement and analysis of certain portions of the electromagnetic spectrum to identify the mineralogy (and mineral geochemistry) of geological materials.
- Spectral data is measured using spectral sensors, which record energy <u>reflected</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.

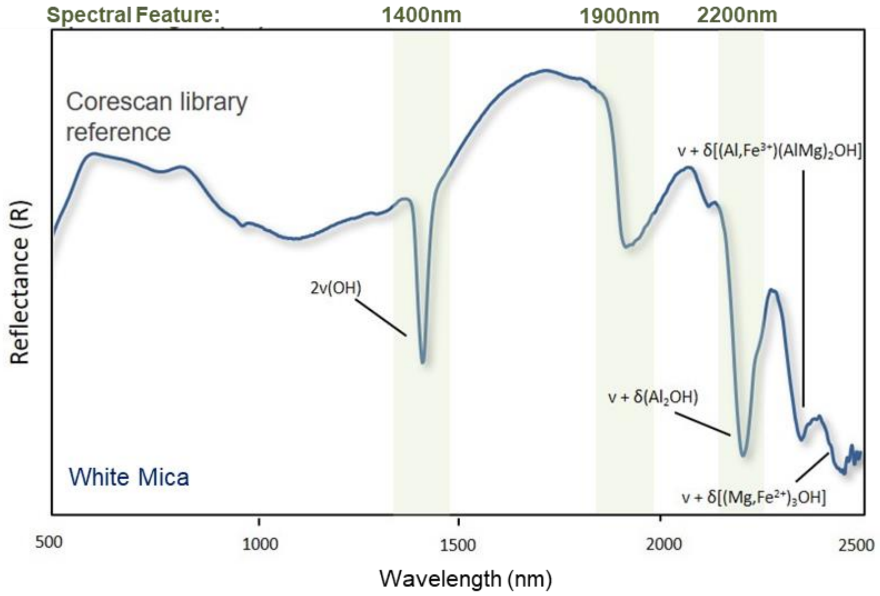


Spectra can be obtained either as a result of **absorption** or **emission** of light.

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

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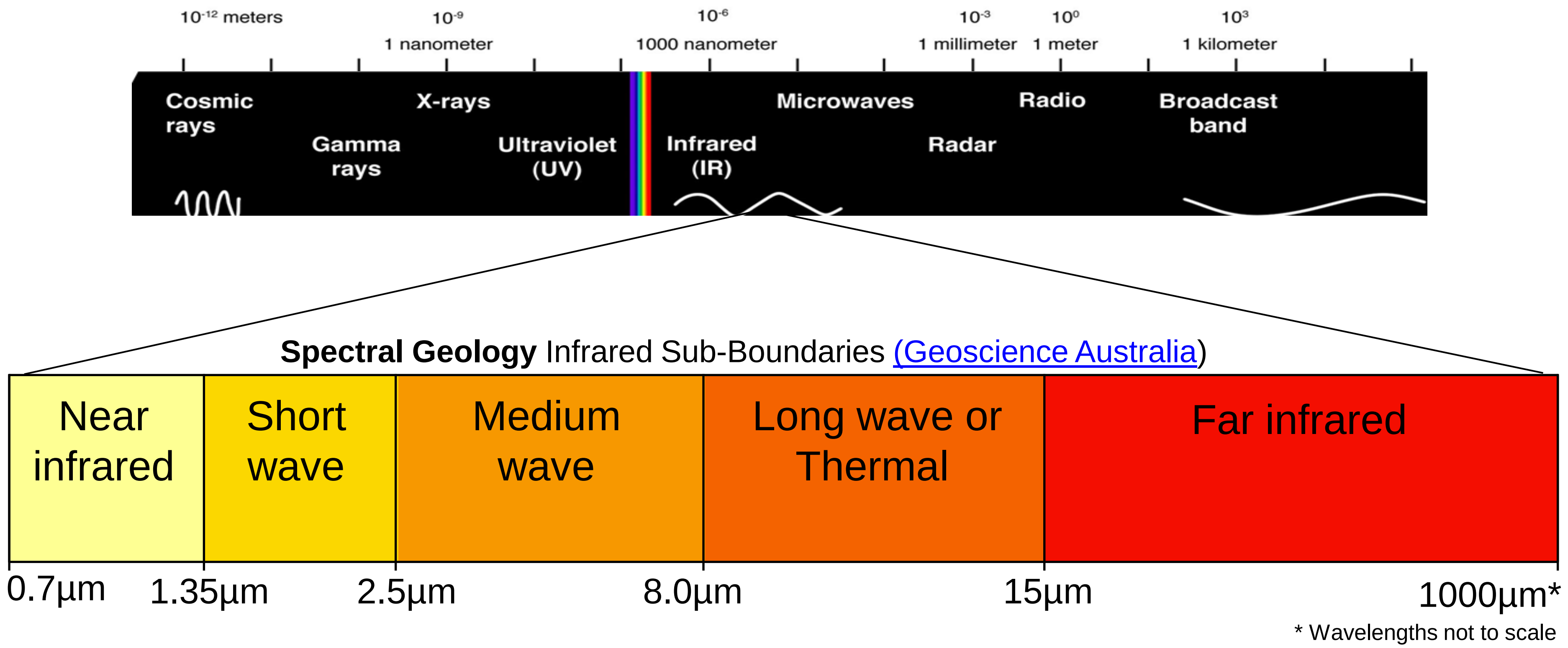

UV: Ultraviolet

VIS: Visible

NIR: Near infrared

VNIR: Visible near infrared

SWIR: Short wave infrared

MWIR: Mid wave infrared

LWIR: Long wave infrared

TIR: Thermal infrared

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

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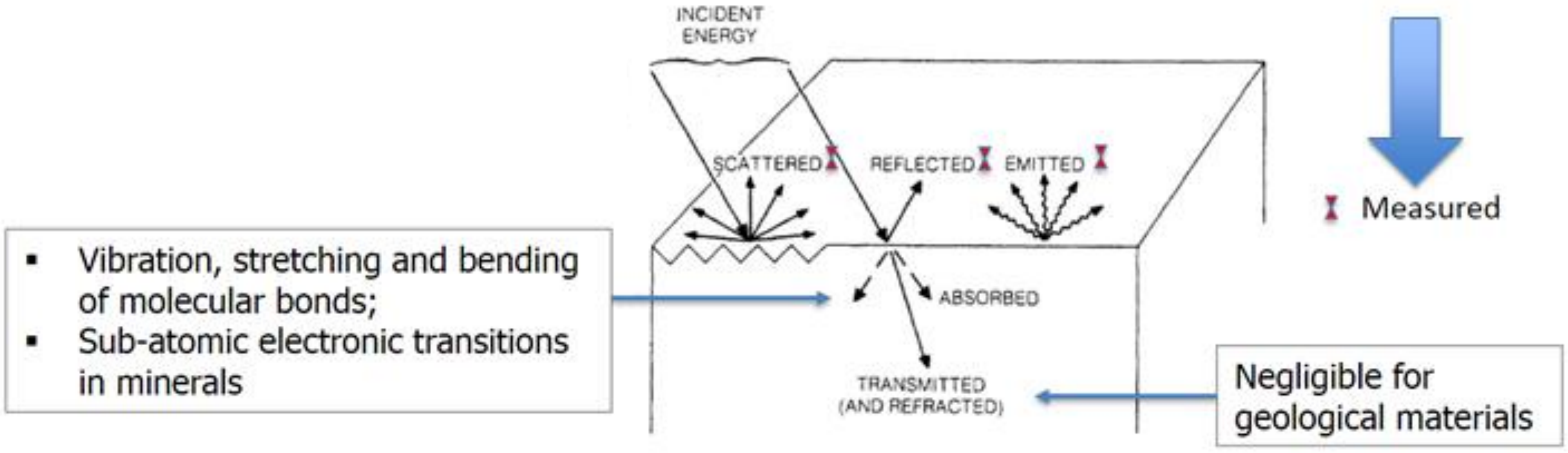
- Infrared reflectance-emission spectroscopy
  - Interaction of photons with material surface (e.g., rock)
  - Light / energy source
  - Generally, no penetration beyond 3-6μm



Zhou, 2021

IR Spectroscopy: Absorption

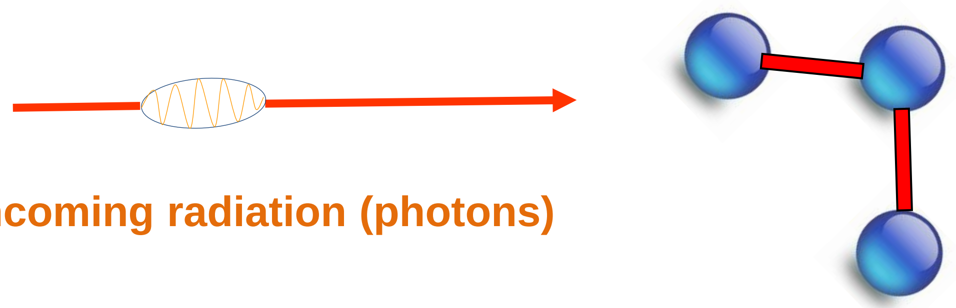
- Characteristic spectral features are produced when energy from the electromagnetic spectrum is absorbed (rather than reflected).

Electronic Processes
VNIR

Incoming radiation (photons)

Electrons

Vibrational Processes
SWIR



Incoming radiation (photons)

Molecules

IR Spectroscopy: Absorption – Electronic Energy

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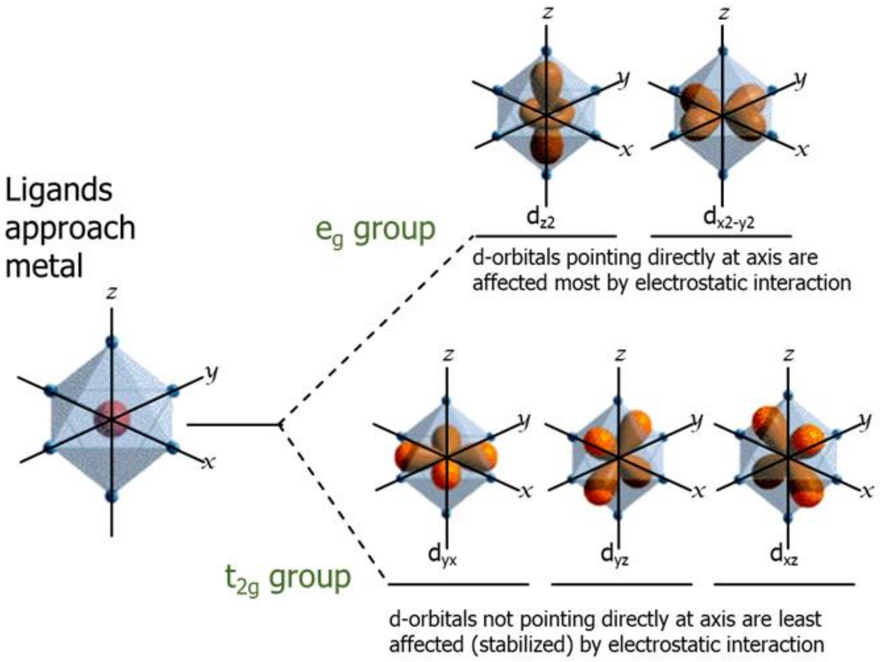
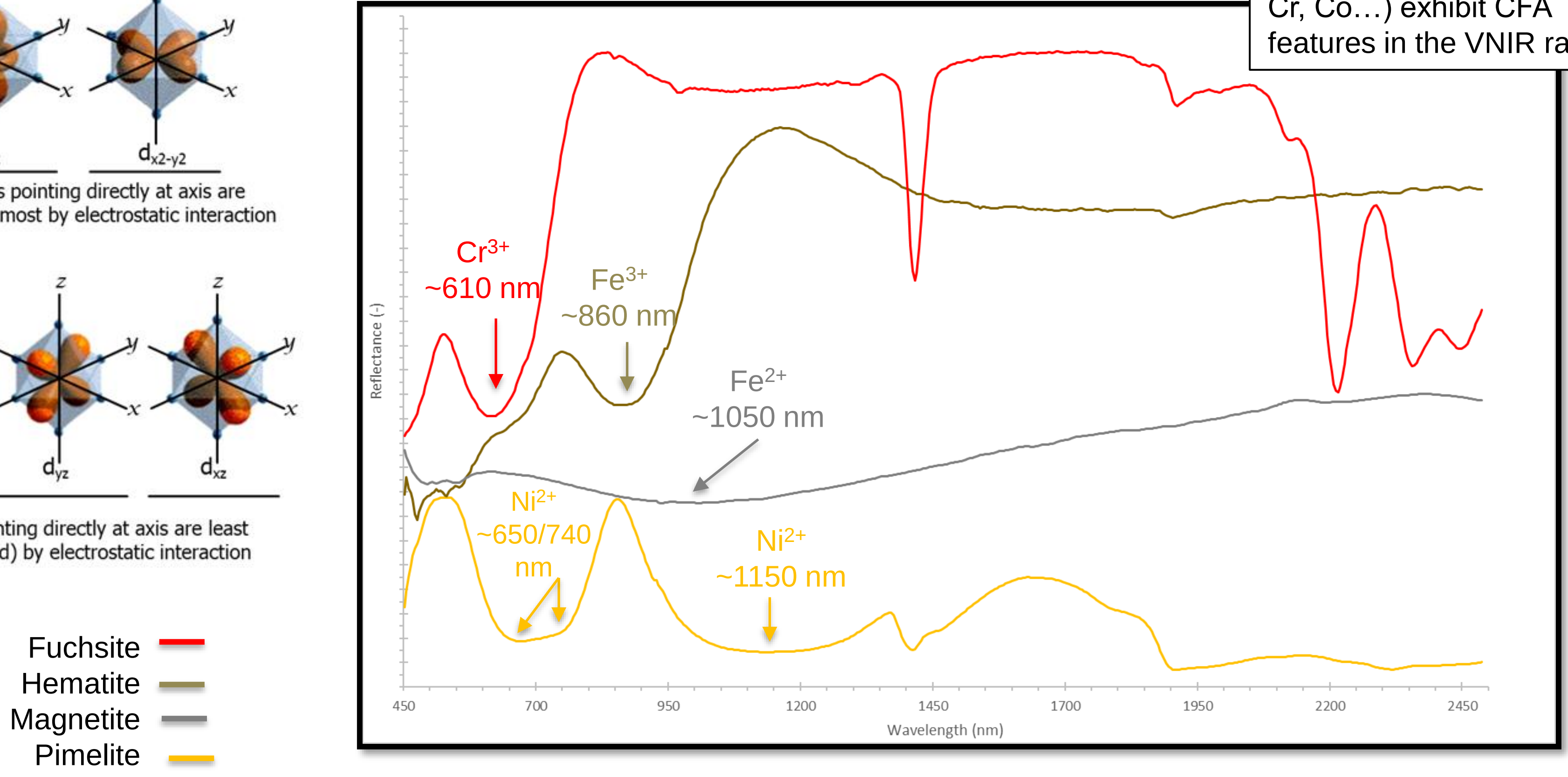
- We see mainly crystal field absorptions features in the VNIR that are the result of the splitting of energy in the d-orbitals of positively charged metal cations. The splitting of the energy levels is due to the interaction between a positively charged metal cation (say Fe^{2+}) and the negative charge of non-bonding electrons of ligands (say O^{2-}).

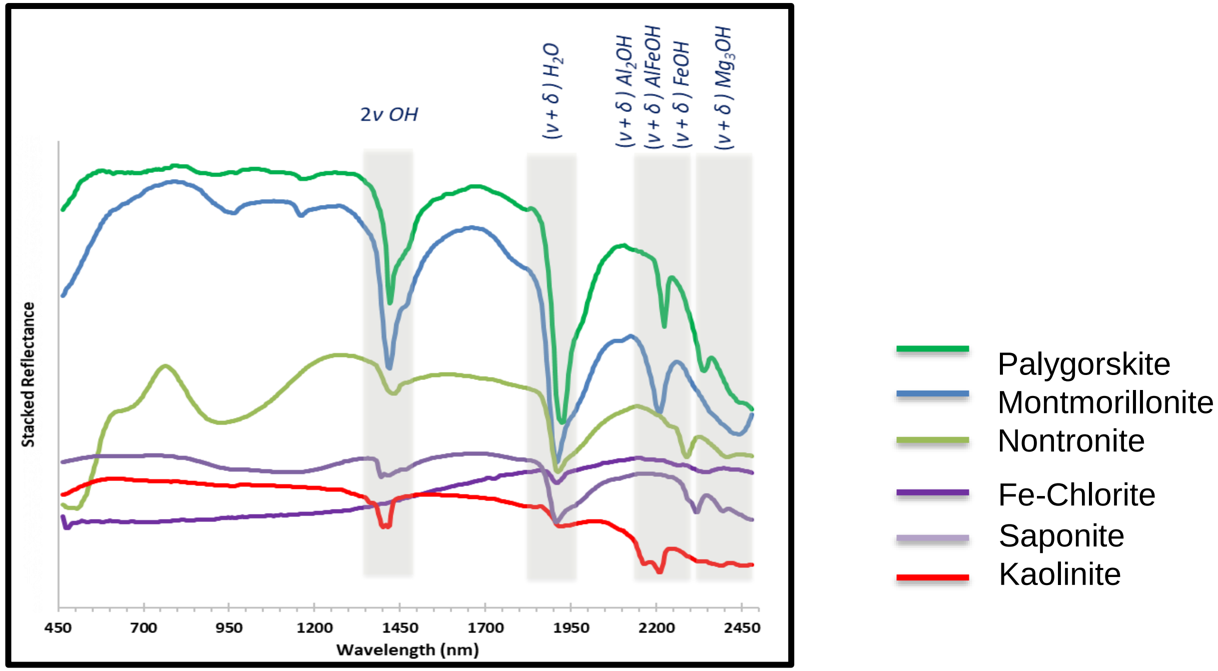


Transition elements (Fe, Ni, Cr, Co…) exhibit CFA features in the VNIR range

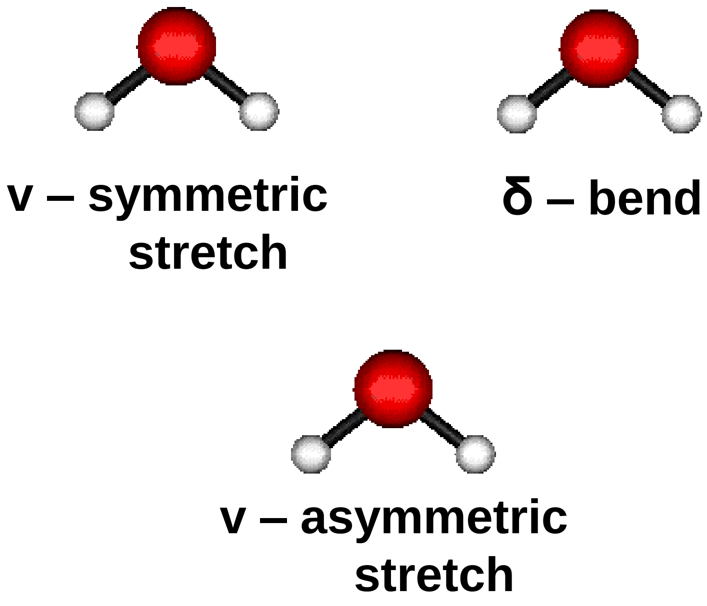


IR Spectroscopy: Absorption – Vibrational Energy

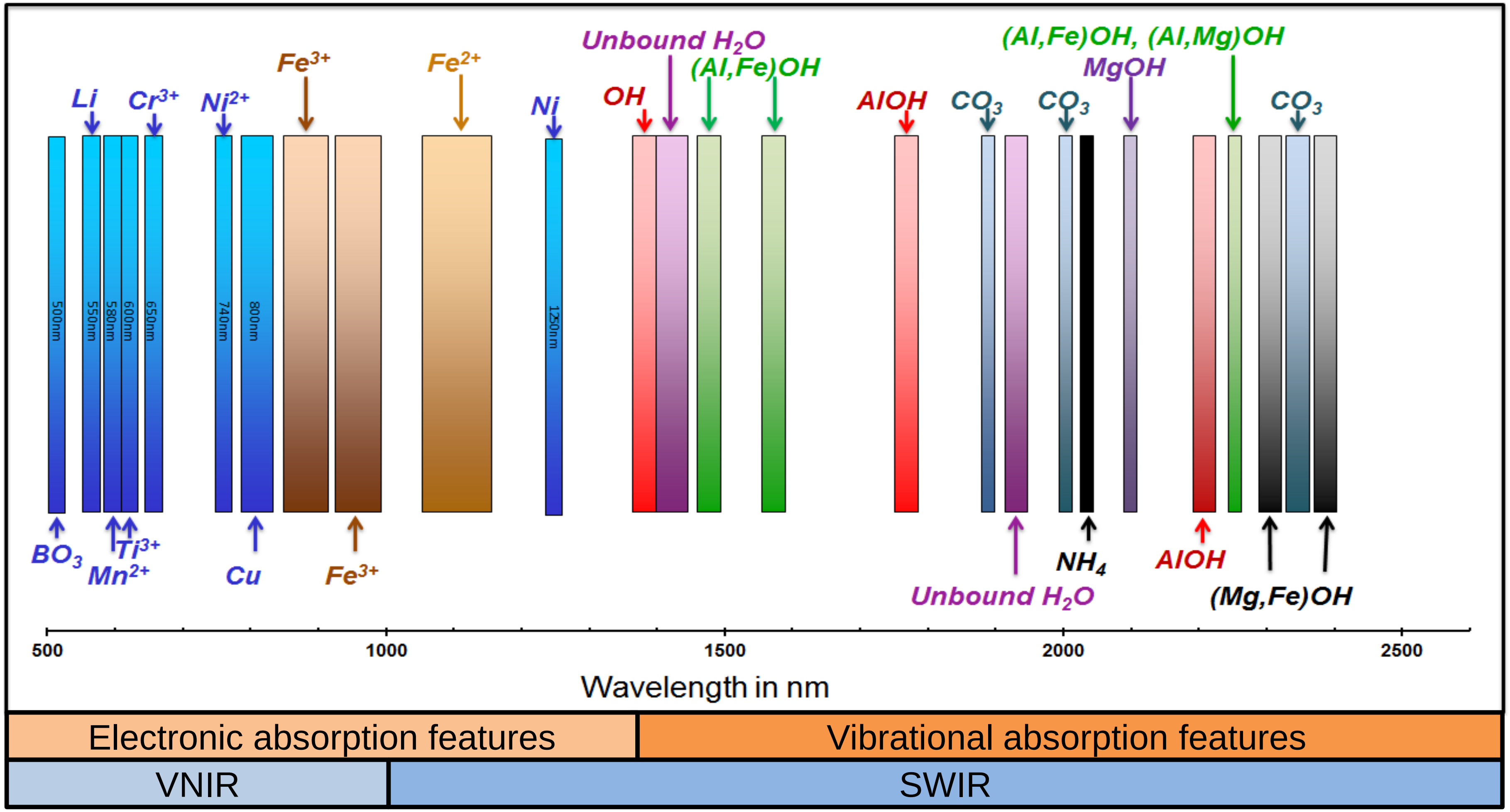
- Incoming radiation can also cause molecules to 'vibrate' - the bonds between atoms bend and stretch in predictable geometries.
- The energy associated with these motions or "fundamental vibrational modes" are located in the MIR and FIR range of the electromagnetic spectrum.
- In the **SWIR**, only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



Animations show the possible vibrations of the H_2O molecule



VNIR-SWIR: Molecular Bonds and Elements



Mineral Identification and Mapping

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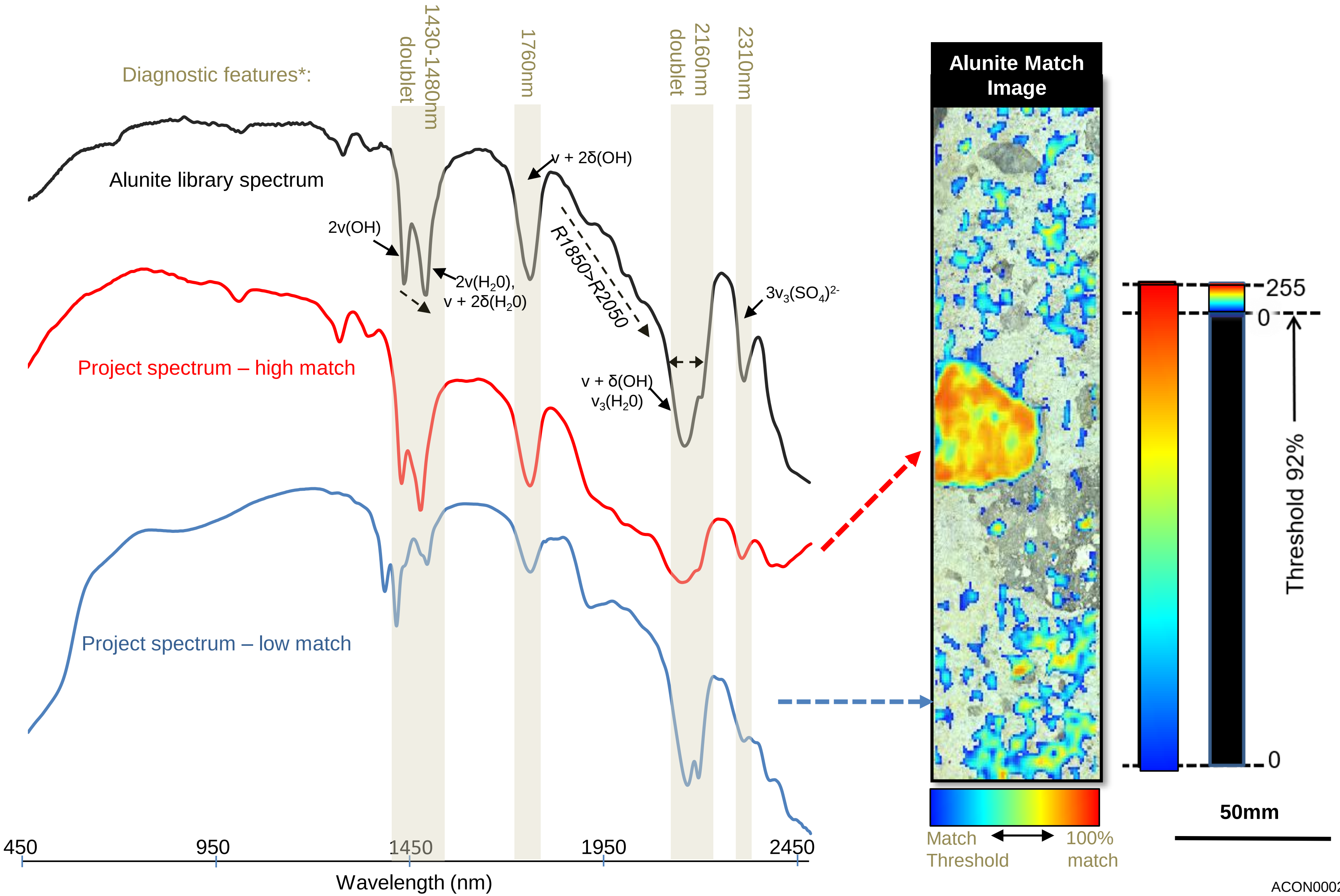
- A match value for each mineral is calculated across all hyperspectral pixels
- Cut-off thresholds are determined by quantitative comparison to known spectral behaviour as well as qualitative identification processes
- Project-specific spectral-mineral libraries are developed



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“Prograde” Skarn Assemblage Images

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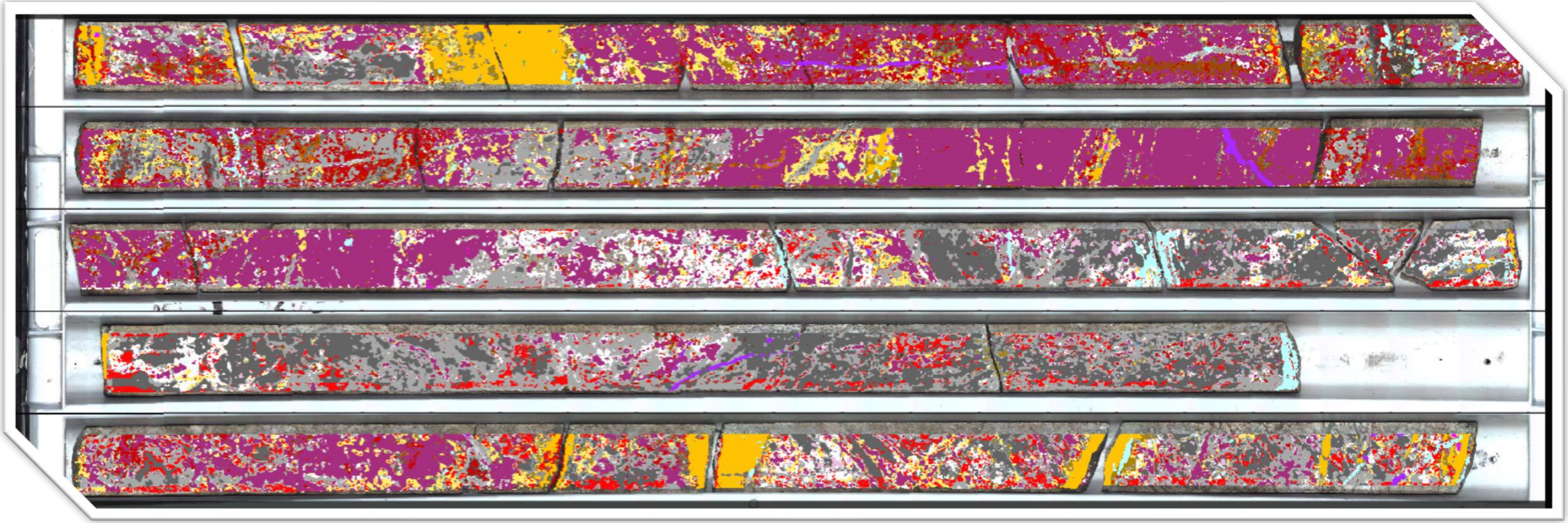

Garnet		Featureless 1		Sulphide		Wollastonite	
Datolite		Featureless 2		Pyroxene		Quartz	

“Retrograde” Skarn Assemblage Images

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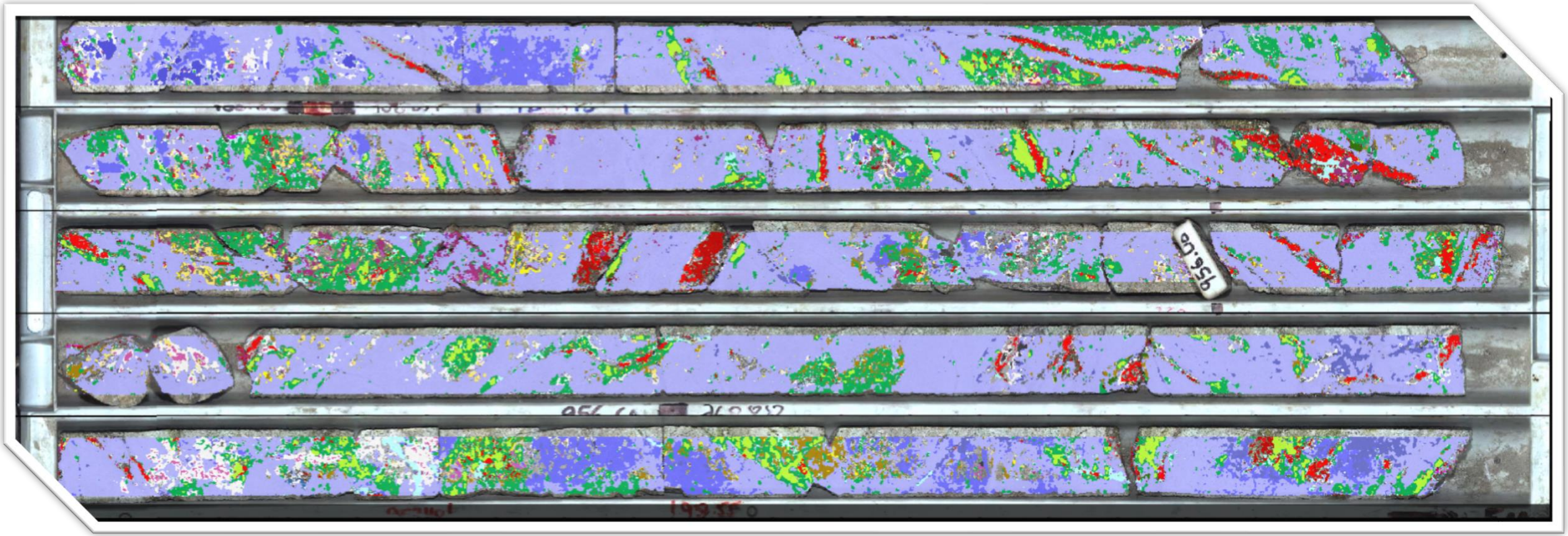

Garnet	Epidote	Sulphide	Wollastonite
Beidellite	Chlorite	Montmorillonite	Quartz

Corescan Mineral Logs

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- 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.

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

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_Illite-Montmorillonite_pct	**21.47%**	Number of pixels with ISM = 0.75 – 0.99, relative to total white mica + montmorillonite pixels
ISM_Illite_pct	**5.03%**	Number of pixels with ISM = 0.99 – 1.25, relative to total white mica + montmorillonite pixels
ISM_Muscovite-Ilite_pct	**9.52%**	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

Sum= 100%

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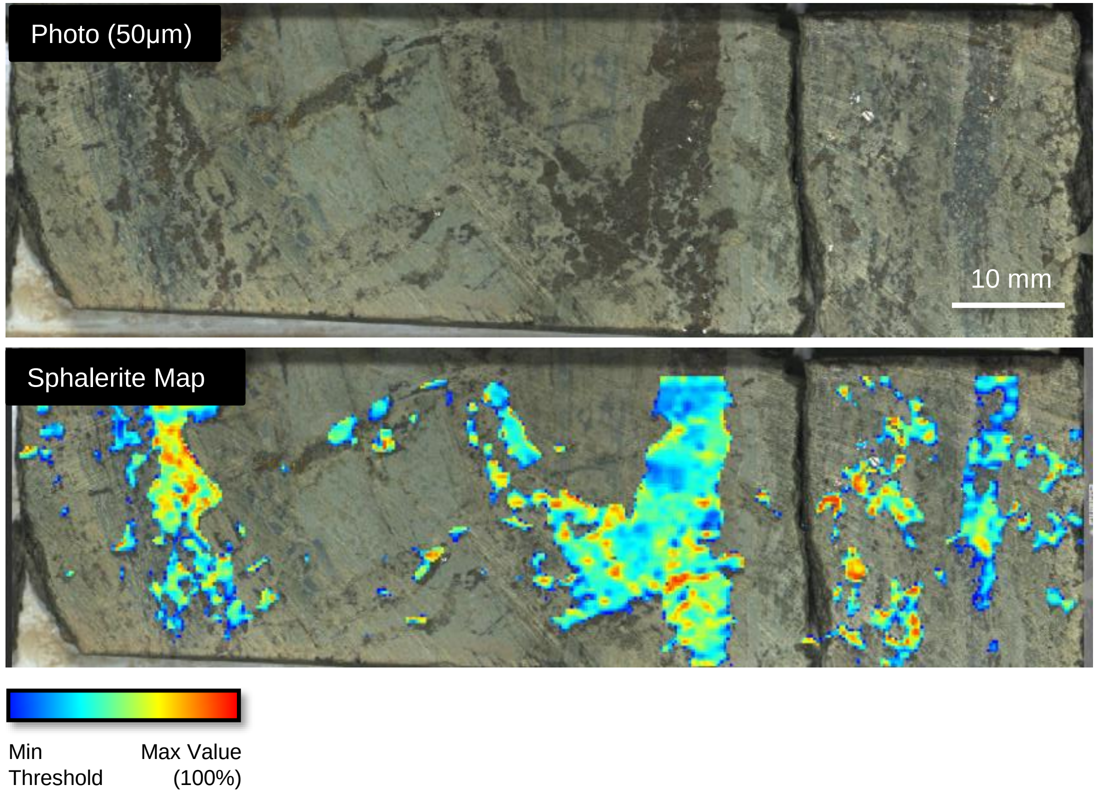
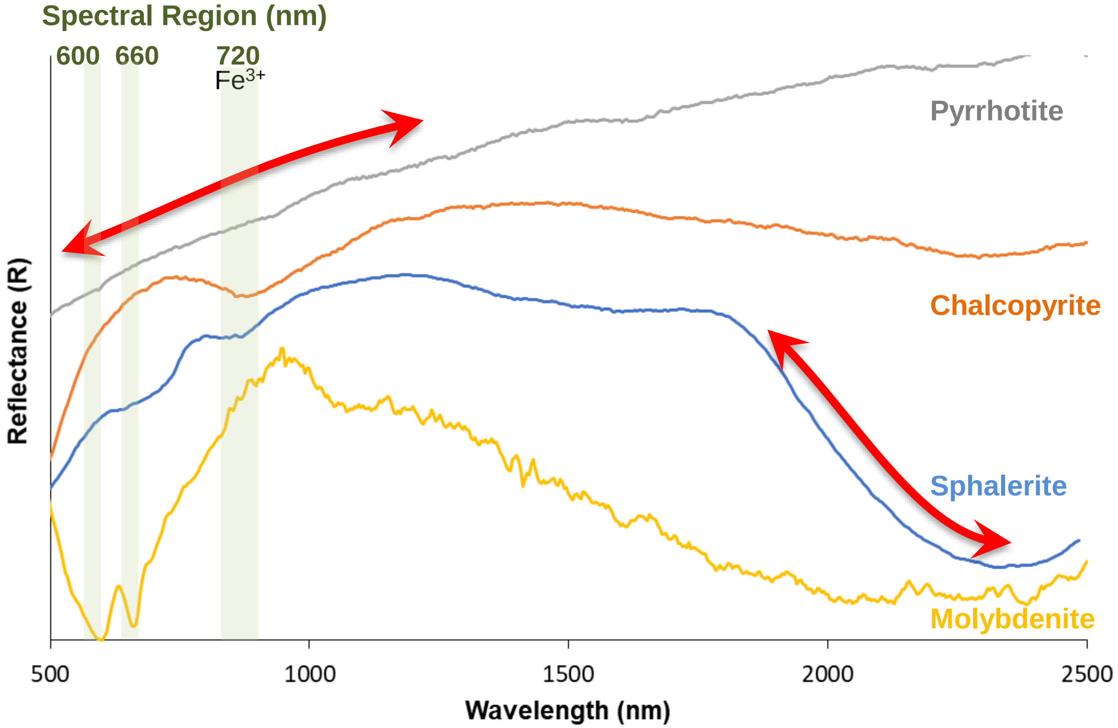
Skarn Mineralogy

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.





Ore Mineralogy in Skarns

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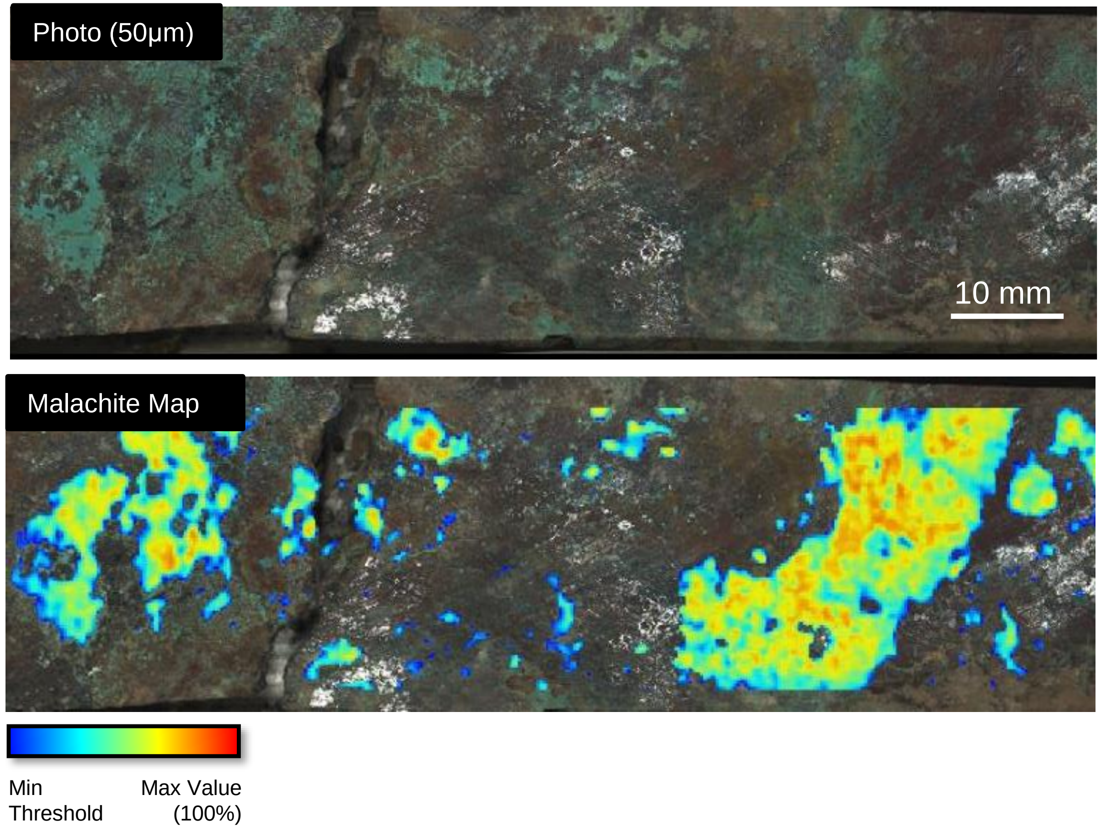
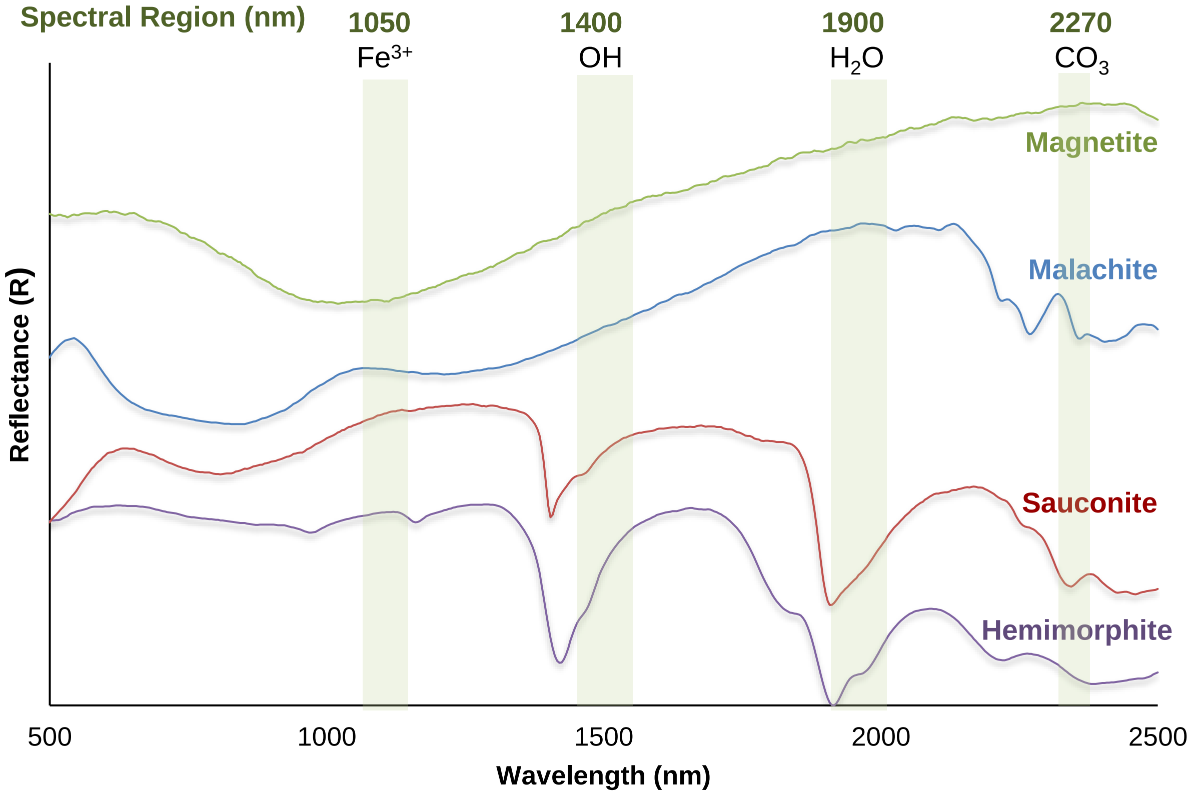
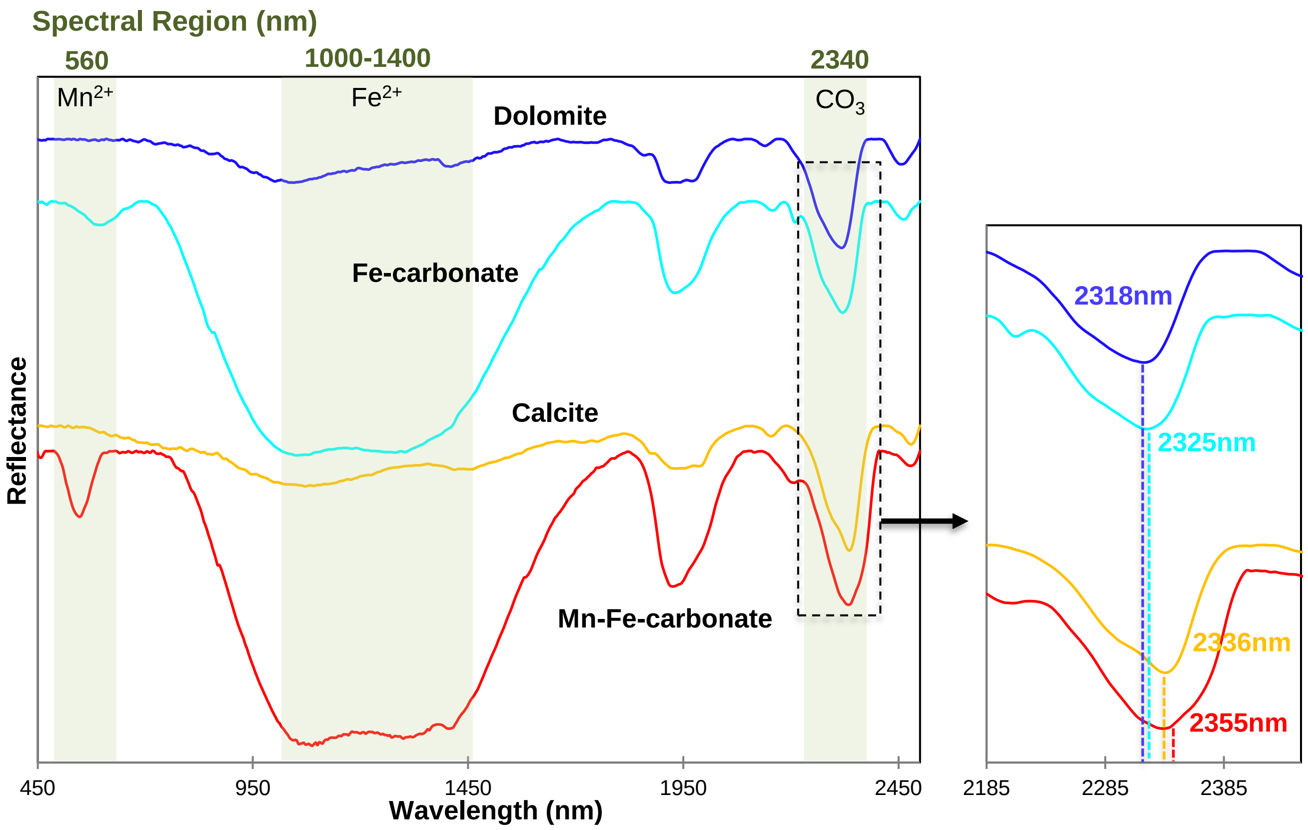
- In addition to sulphides, skarn ore minerals can include oxides (e.g., magnetite), carbonates (e.g., malachite) and a wide range of silicates (e.g., sauconite and hemimorphite).

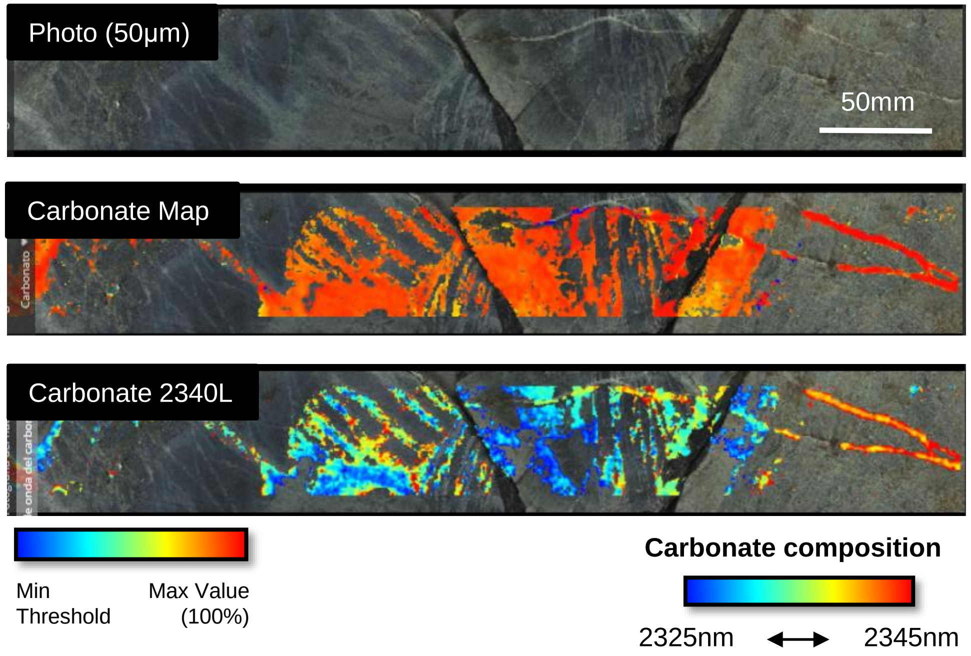




Protolith Skarn Mineralogy: Carbonates

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

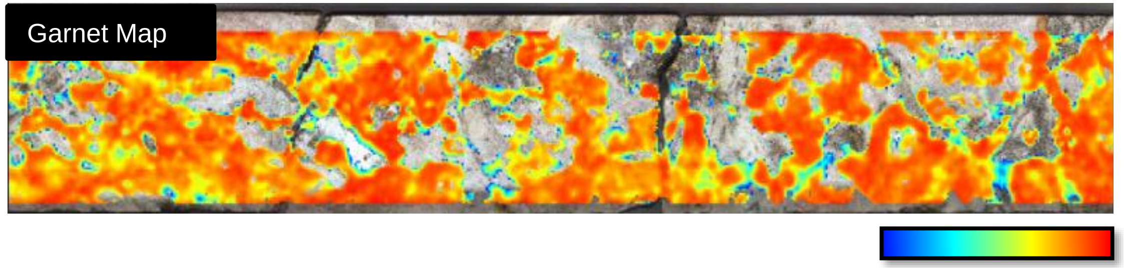


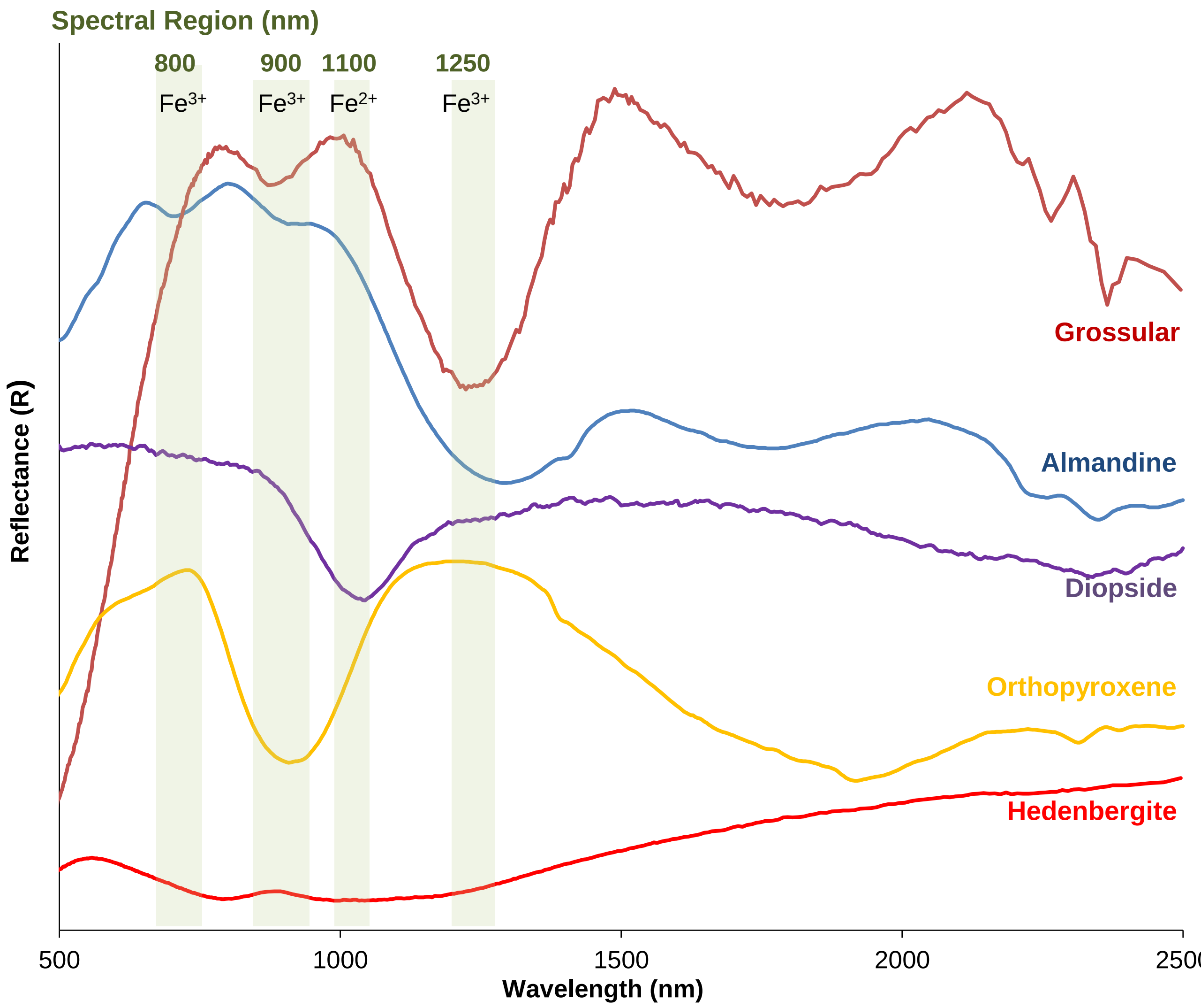


- Mg-metasomatism (calcite to dolomite) is easily traced in Ca-Mg carbonate varieties using variations in the ~2340nm absorption feature.
- Fe substitution in carbonate also results in a very distinctive spectral feature in the VNIR that is easily mapped using the Corescan HCI system.

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

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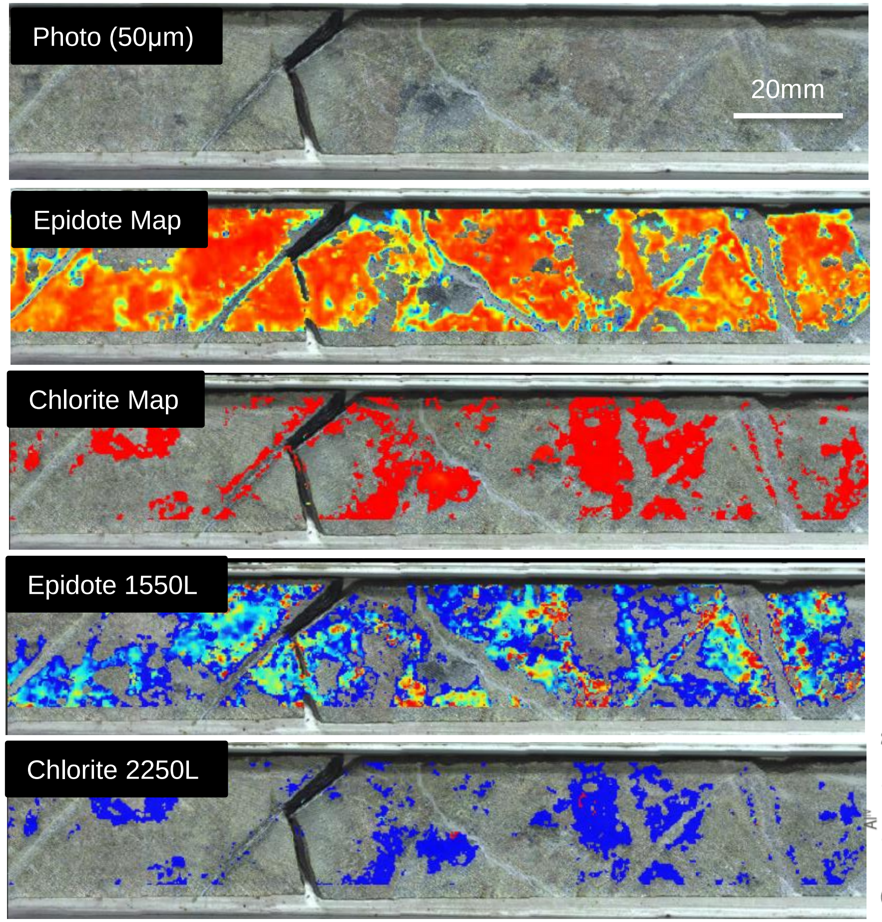
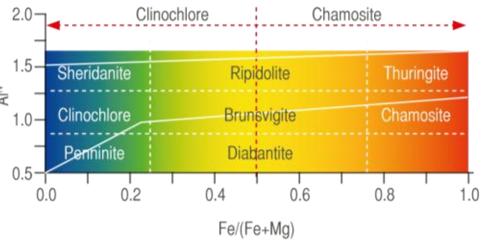
- Fe- and Mg-bearing clays, micas and silicates are common in skarn deposits. They can occur as overprinting (retrograde) assemblages, distal to core of the skarn system, and / or along fluid conduits.

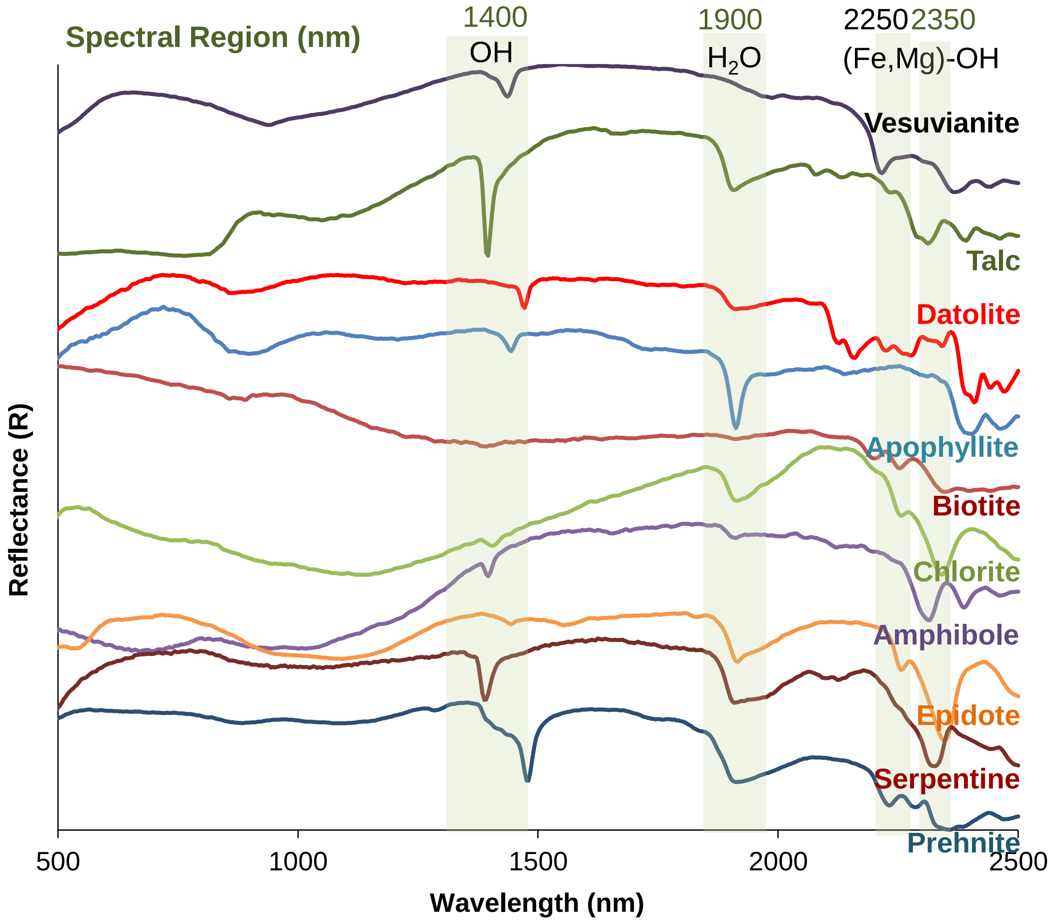


Min Threshold — Max Value (100%)

EPIDOTE COMPOSITION ~1550nm feature

~1548nm Increase in Fe Epidote — ~1558nm Increase in Al Clinozoisite





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

Variability in Chemistry: Smectites

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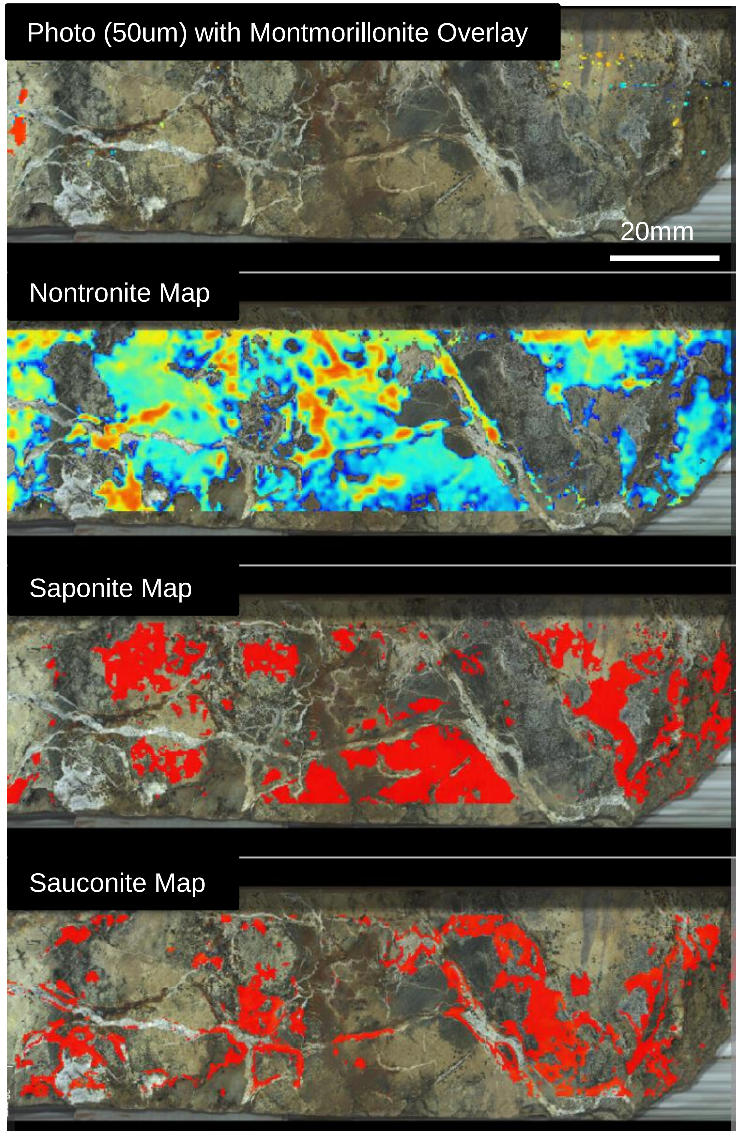
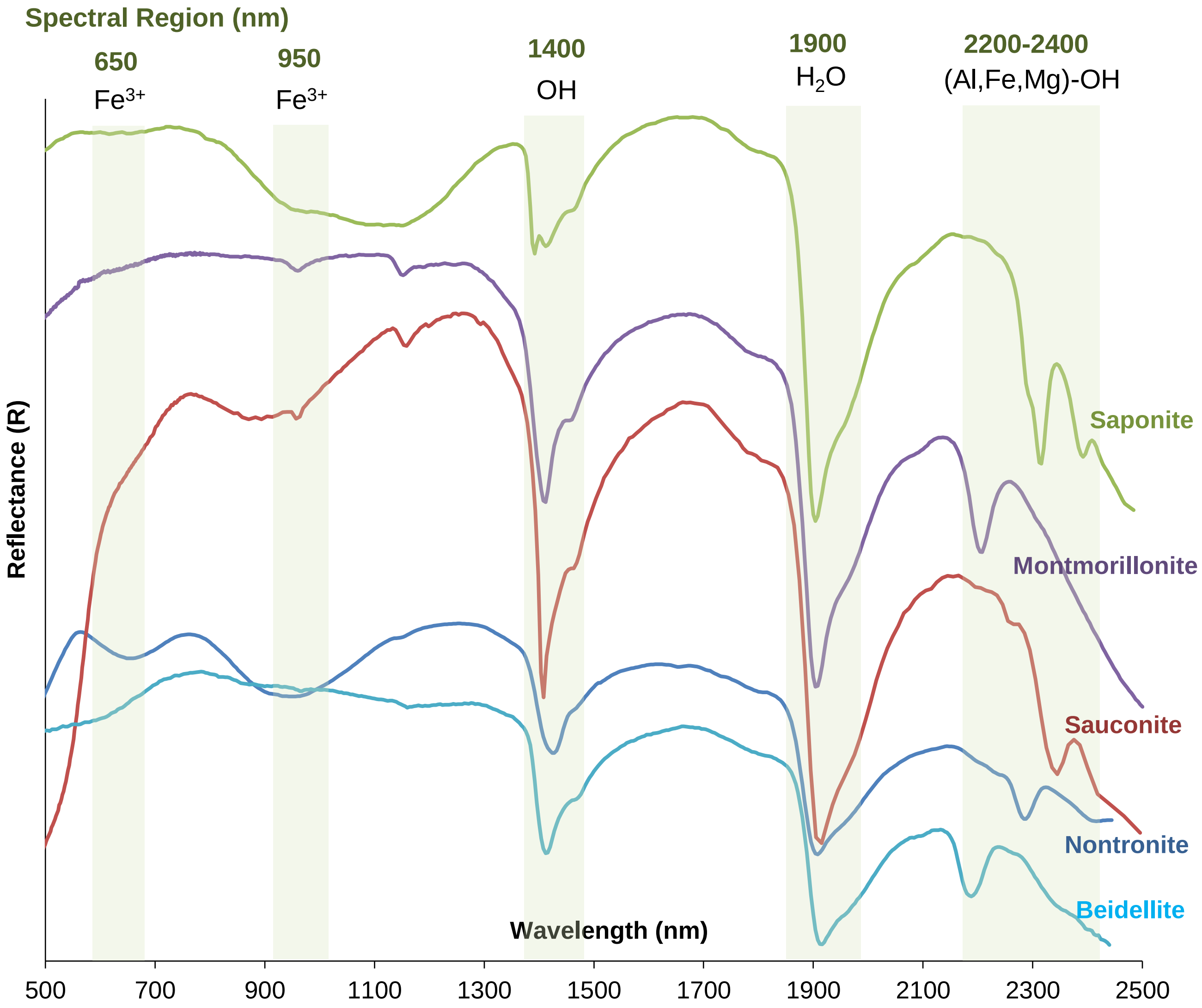


- A large variety of smectite-group minerals can occur in skarn systems from Ca±Na-bearing montmorillonite, to Fe-rich nontronite, to Mg-rich saponite and to Zn-rich sauconite.
- These smectite species have distinct SWIR absorption features that enable accurate mineral identification and mapping.



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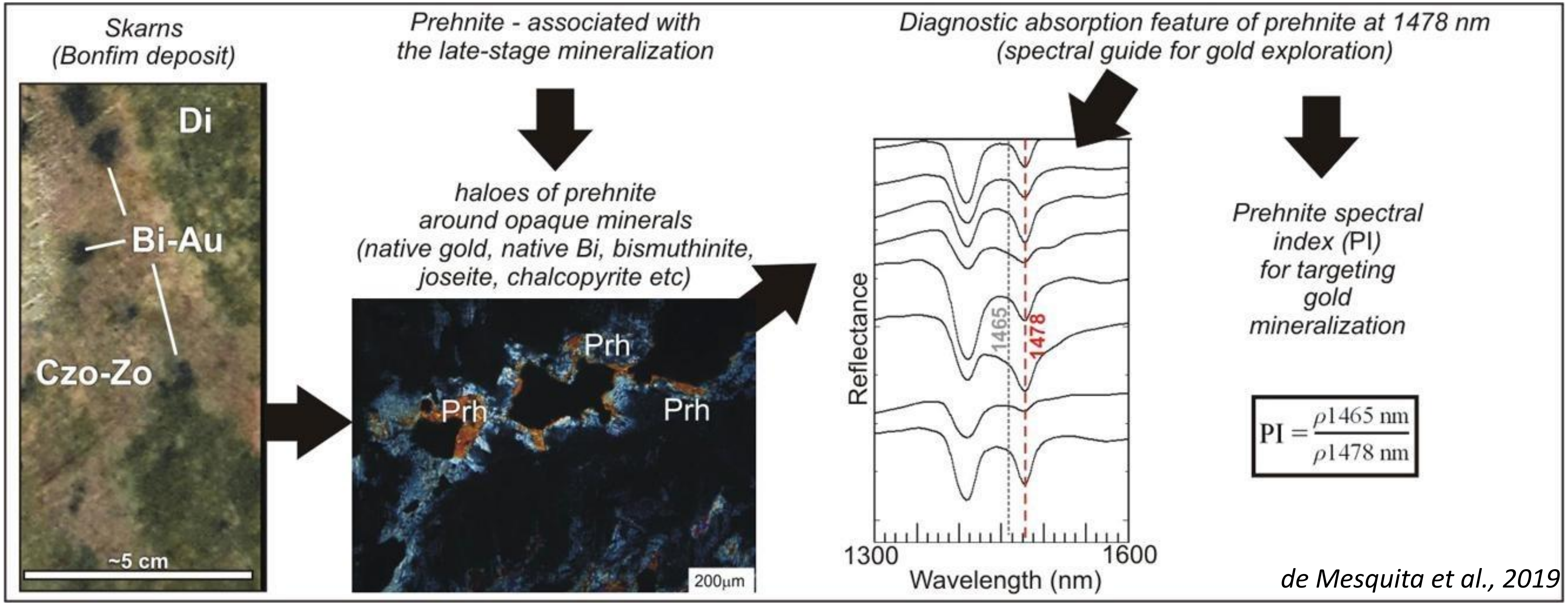
Applying Hyperspectral Core Imaging Data

Prehnite: A Potential Vector in Au Skarn

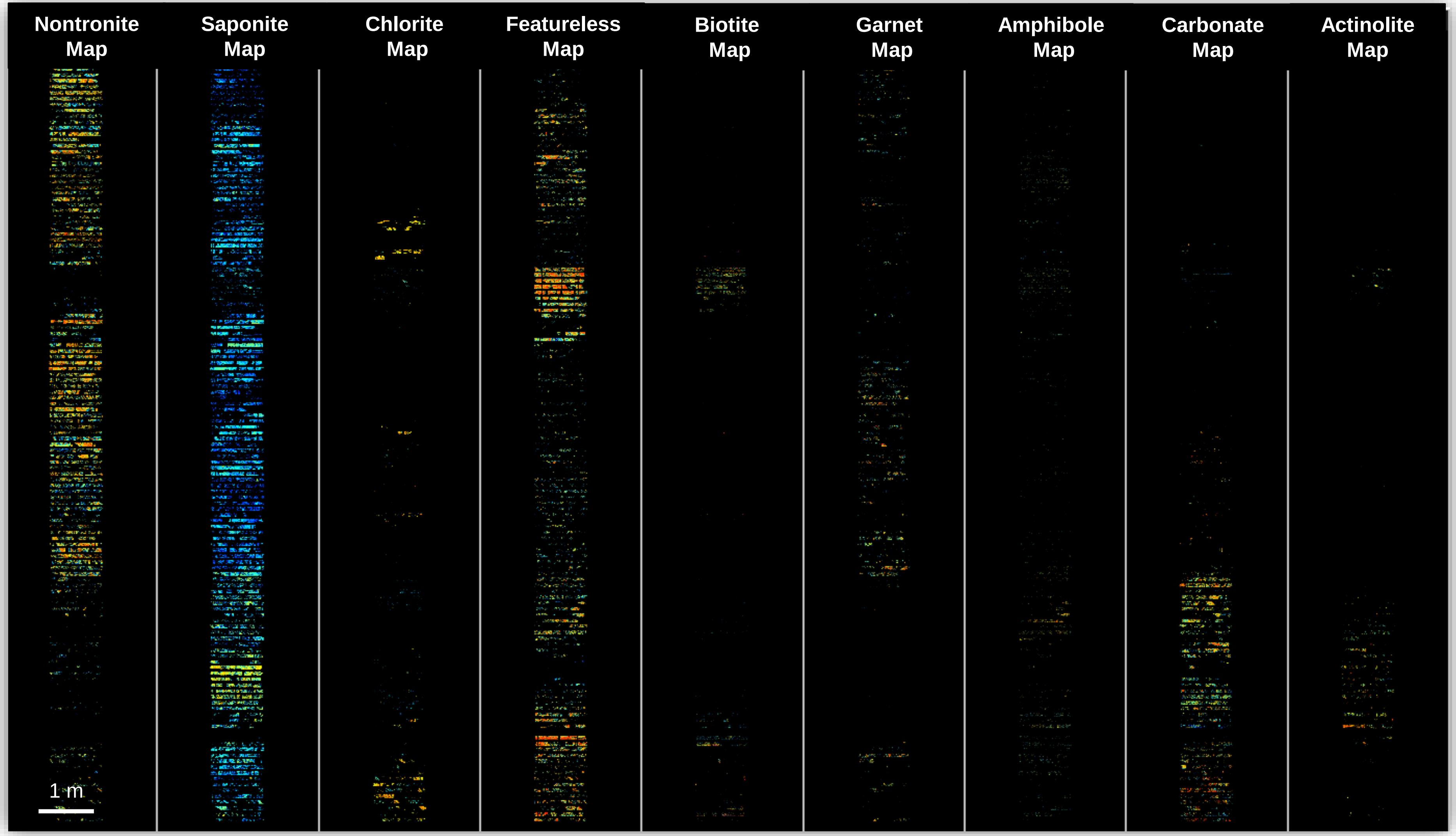
- Prehnite {$Ca_2Al(AlSi_3O_{10})(OH)_2$} is a relatively common component of many Au skarns. It can be difficult to identify visually but has a very distinct SWIR signature and easily be mapped using hyperspectral imaging.
- The intensity of prehnite alteration (based on spectral absorption features) 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).



de Mesquita et al., 2019

Metallurgical Considerations: Skarn Ore

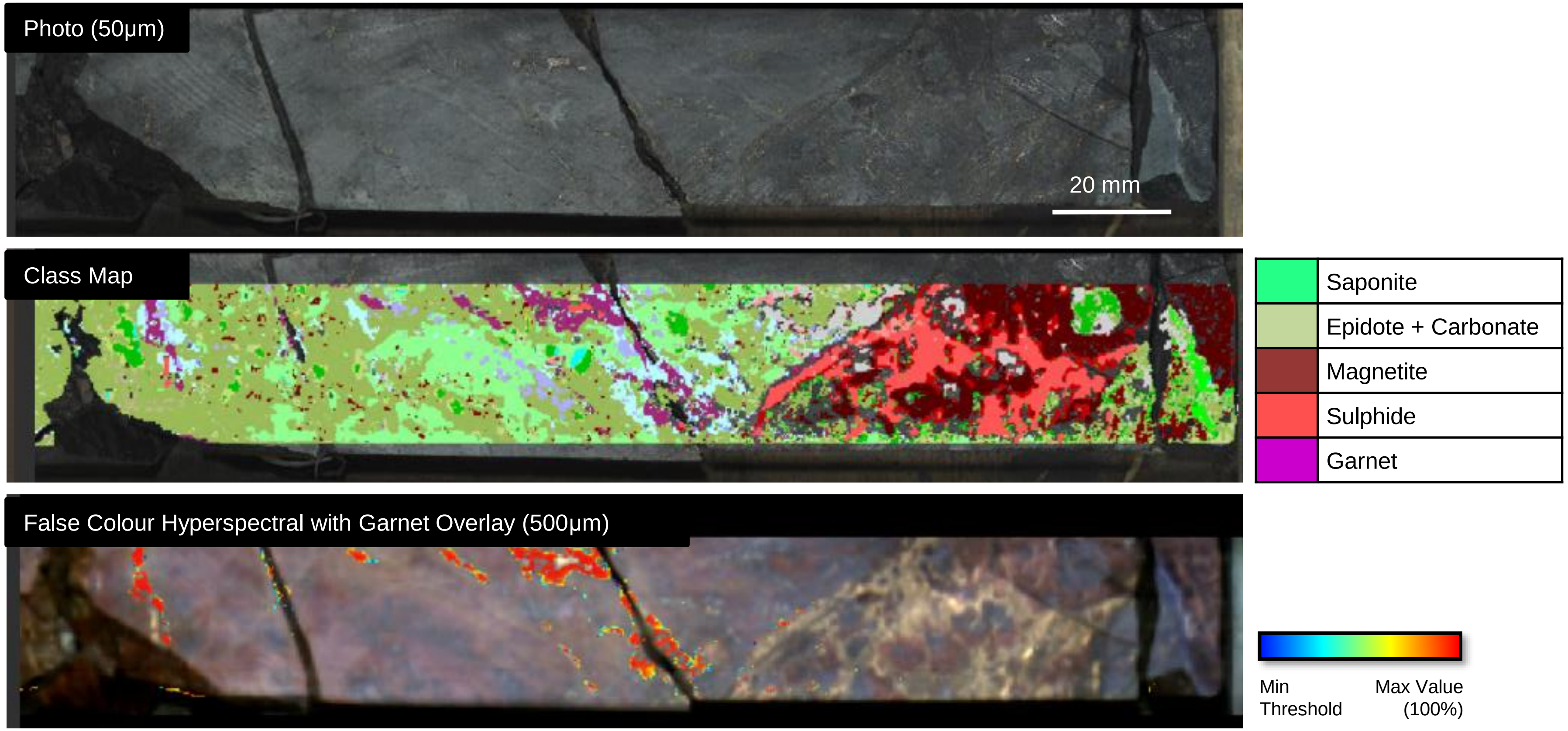
- Skarns are typically host to a wide variety of anhydrous and hydrous minerals that require careful characterization with regards to blasting, mining, comminution and processing behavior.
- Hyperspectral imaging provides consistent and accurate mineralogical identification as well as critical data on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



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

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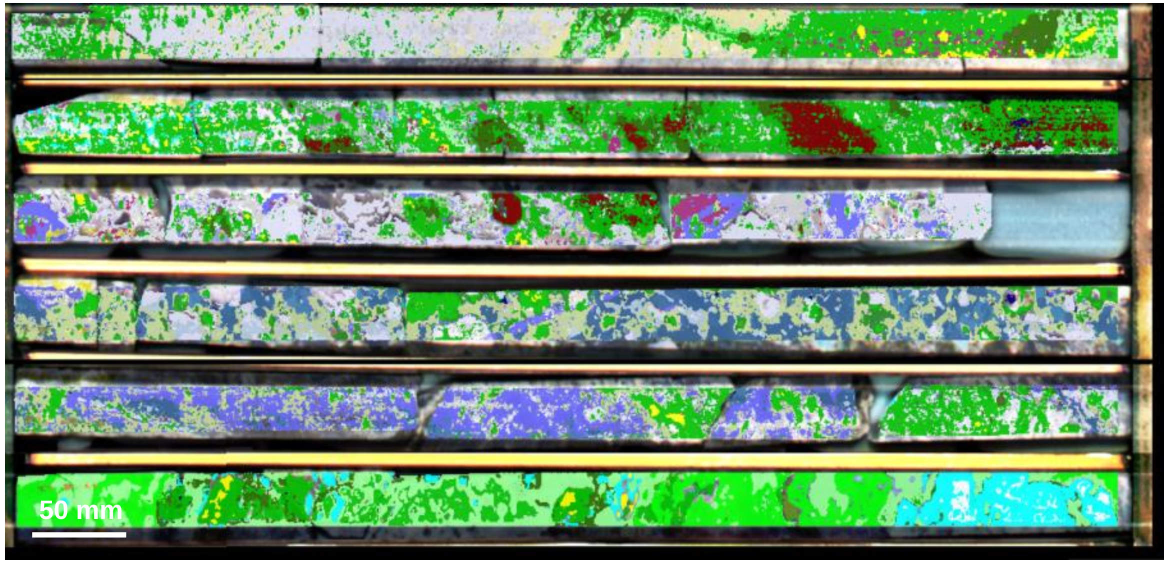
- Phyllosilicate “clay” minerals display variable compositions, structures and charge properties.
- These minerals can have a significant impact on all aspects of mineral processing:
  - swelling minerals increase in volume in wet circuit, examples: montmorillonite, nontronite, saponite, sepiolite
  - 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.

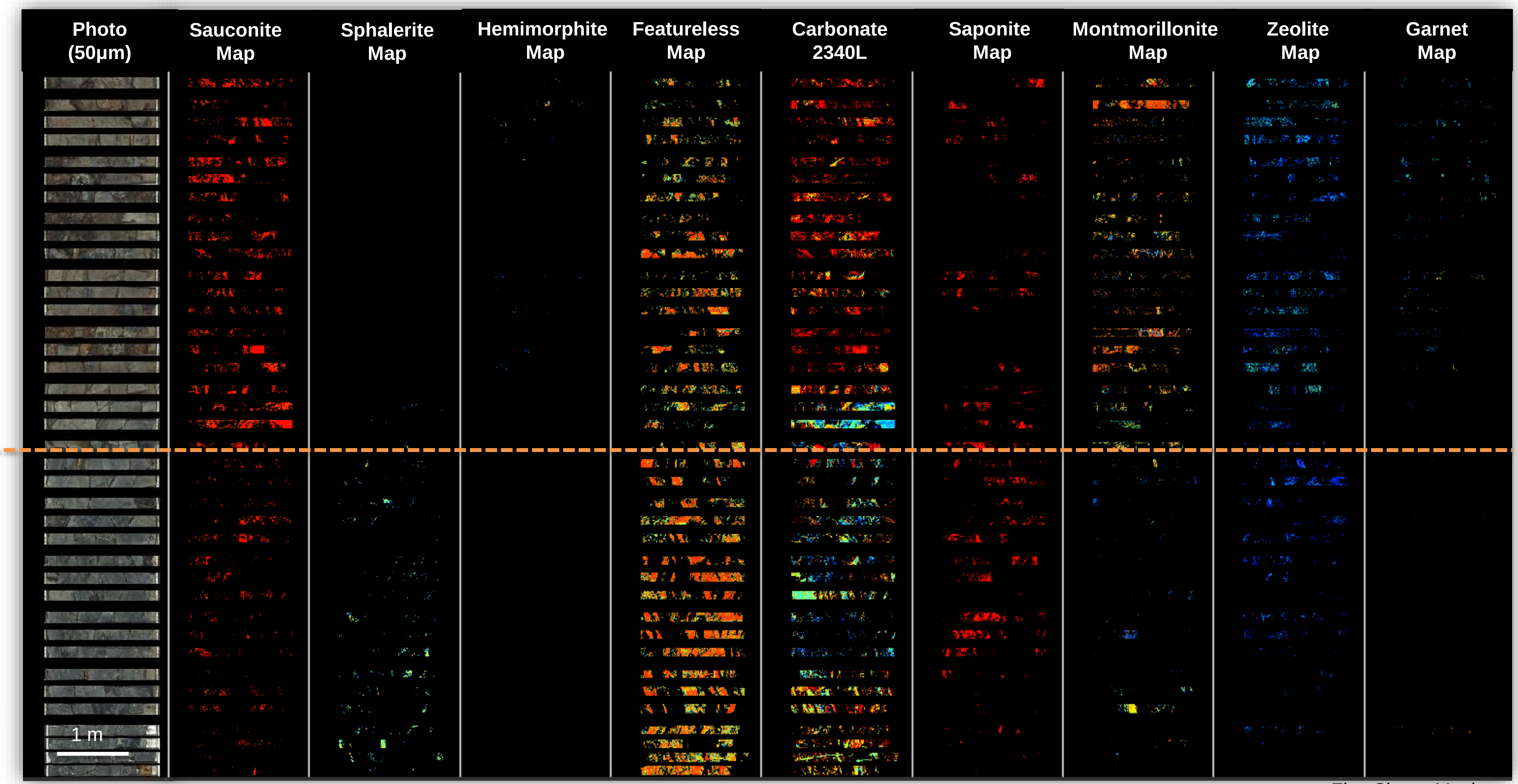


	Saponite
	Chlorite
	White Mica
	Montmorillonite
	Zeolite
	Featureless

Example: Zinc Skarn Mineralogy

Zn hosted largely in sauconite, a Zn-smectite

Mixed Zn-ore (+sphalerite)



Zinc Skarn, Mexico

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Mineralogical Diversity in Blast Hole Data

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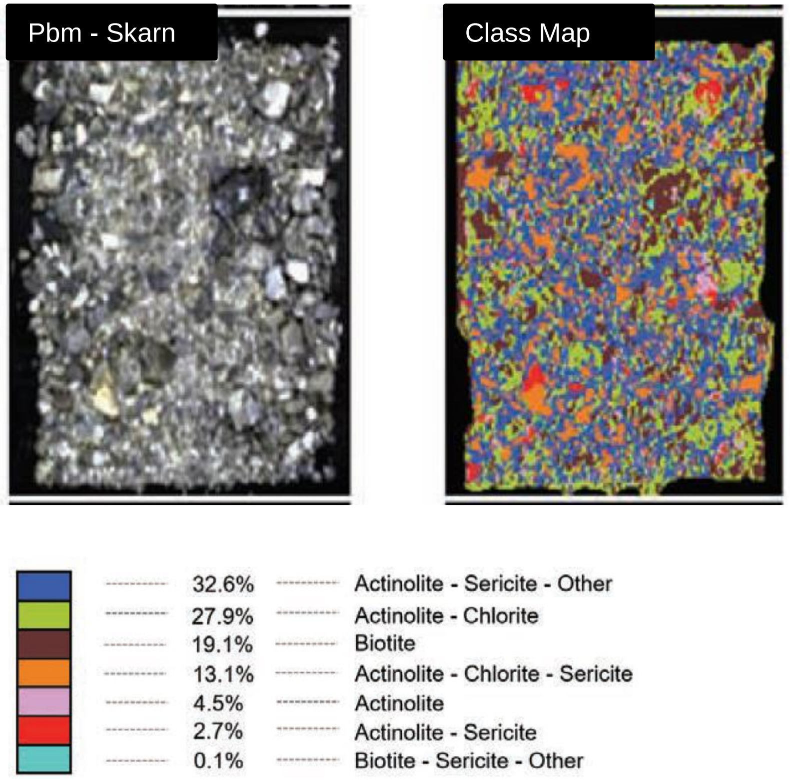
- Ultimately what is being mined, processed and milled are minerals
- Significant value can be added with an improved understanding of the nature of the material being mined
- Hyperspectral imaging provides opportunities for mapping mineralogy at a fine scale, such as seen in Johnson et al., 2019.



Johnson et al., 2019

Mineralogical Diversity in Blast Hole Data

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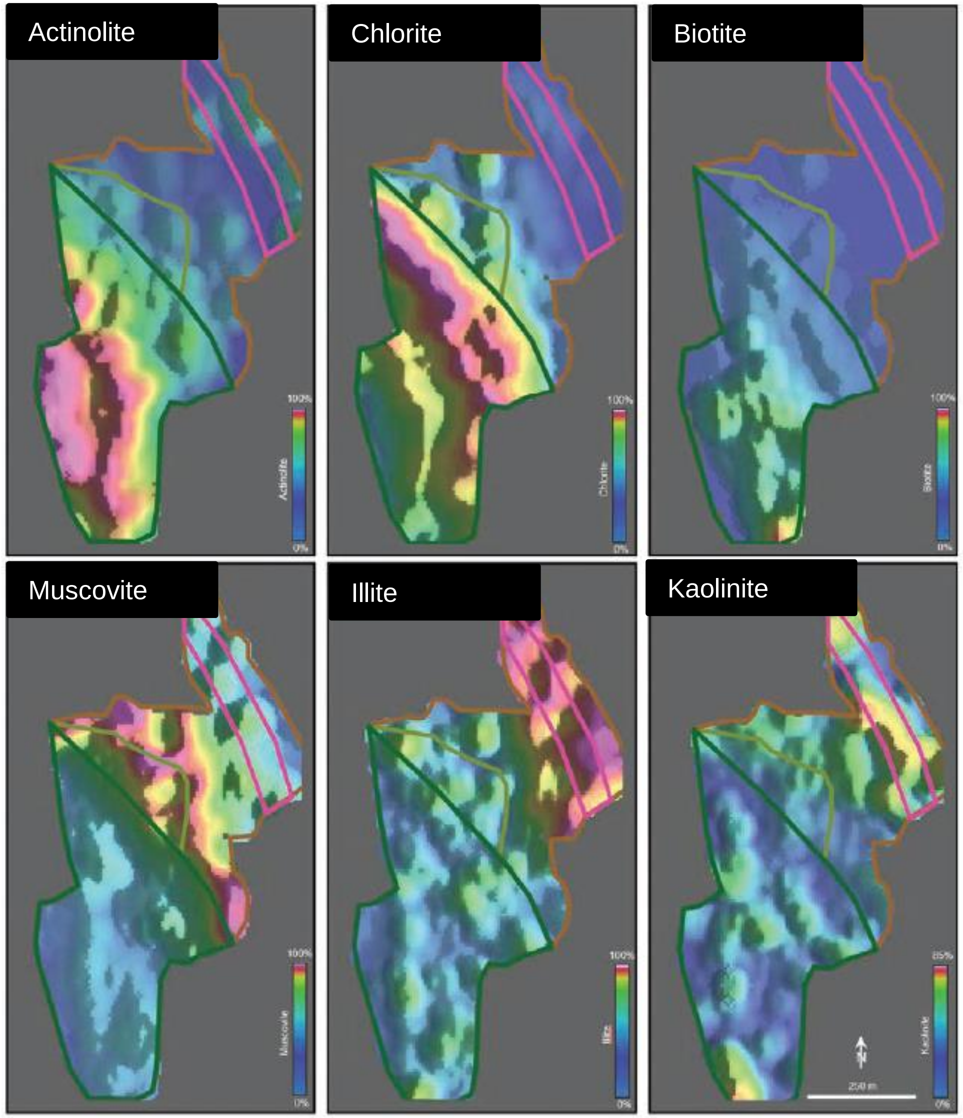
- Johnson et al. (2019) when hyperspectral mineralogy from blast hole cuttings is gridded, important mineral assemblages and spatial relationships can be mapped.
- The polygons overlaying the mineral images (outlined in dark green, light green, brown and pink) represent the alteration as originally mapped 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.

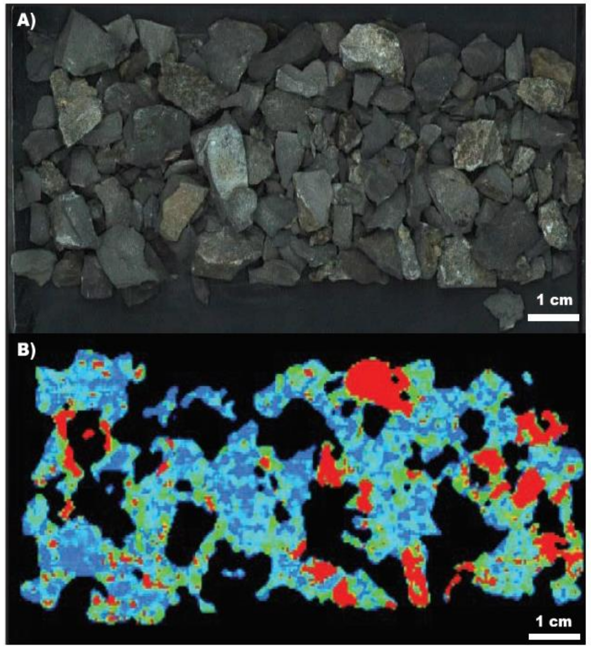


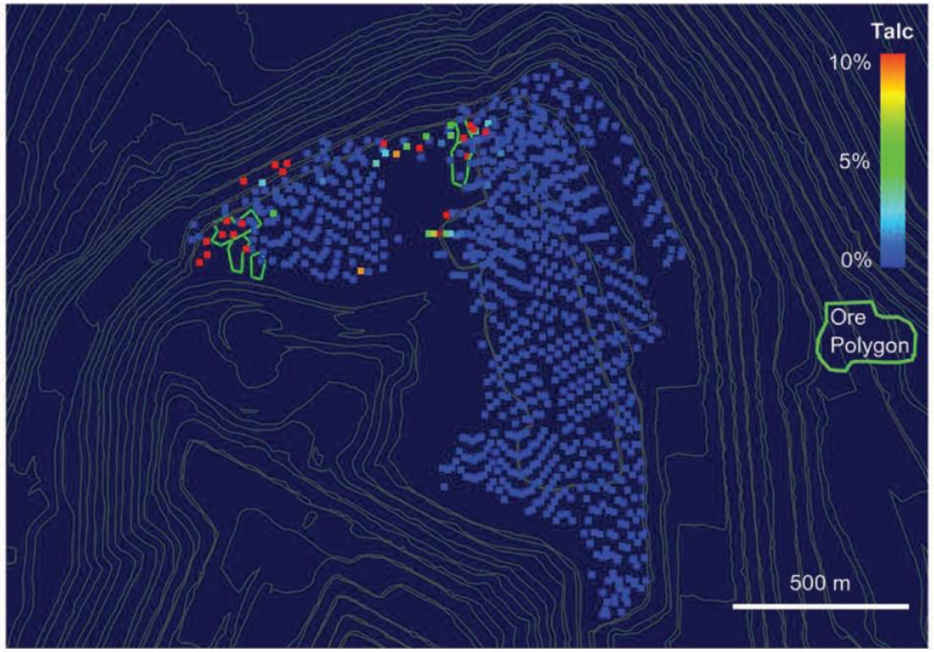
Johnson et al., 2019

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.

A) Photograph of blast hole cuttings; and
B) Hyperspectral talc index heat map.





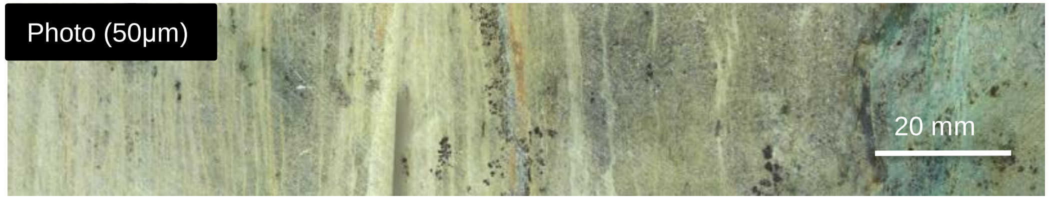
Map of talc percentages determined via hyperspectral imaging overlaid on mill polygons that resulted in significant upset in flotation conditions due to talc entrainment.

Johnson et al., 2019

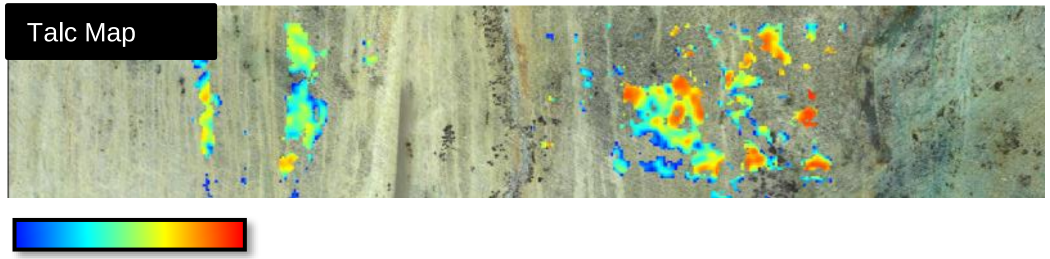
Talc Mapping Using Hyperspectral Imaging

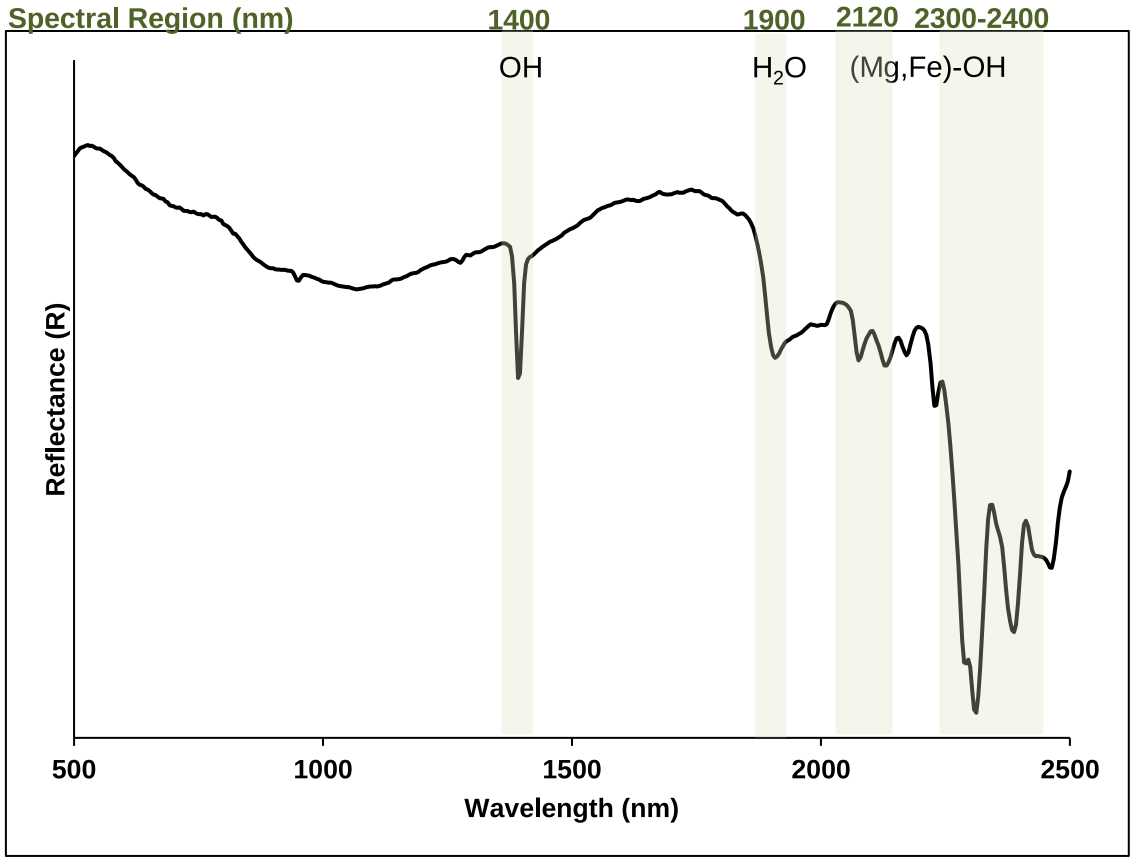
- Talc is dominantly formed during retrograde hydrothermal alteration in Mg-rich carbonate protoliths, although it can also be formed during the prograde stage via reaction between dolomite and silica.

Photo (50µm)



Talc Map

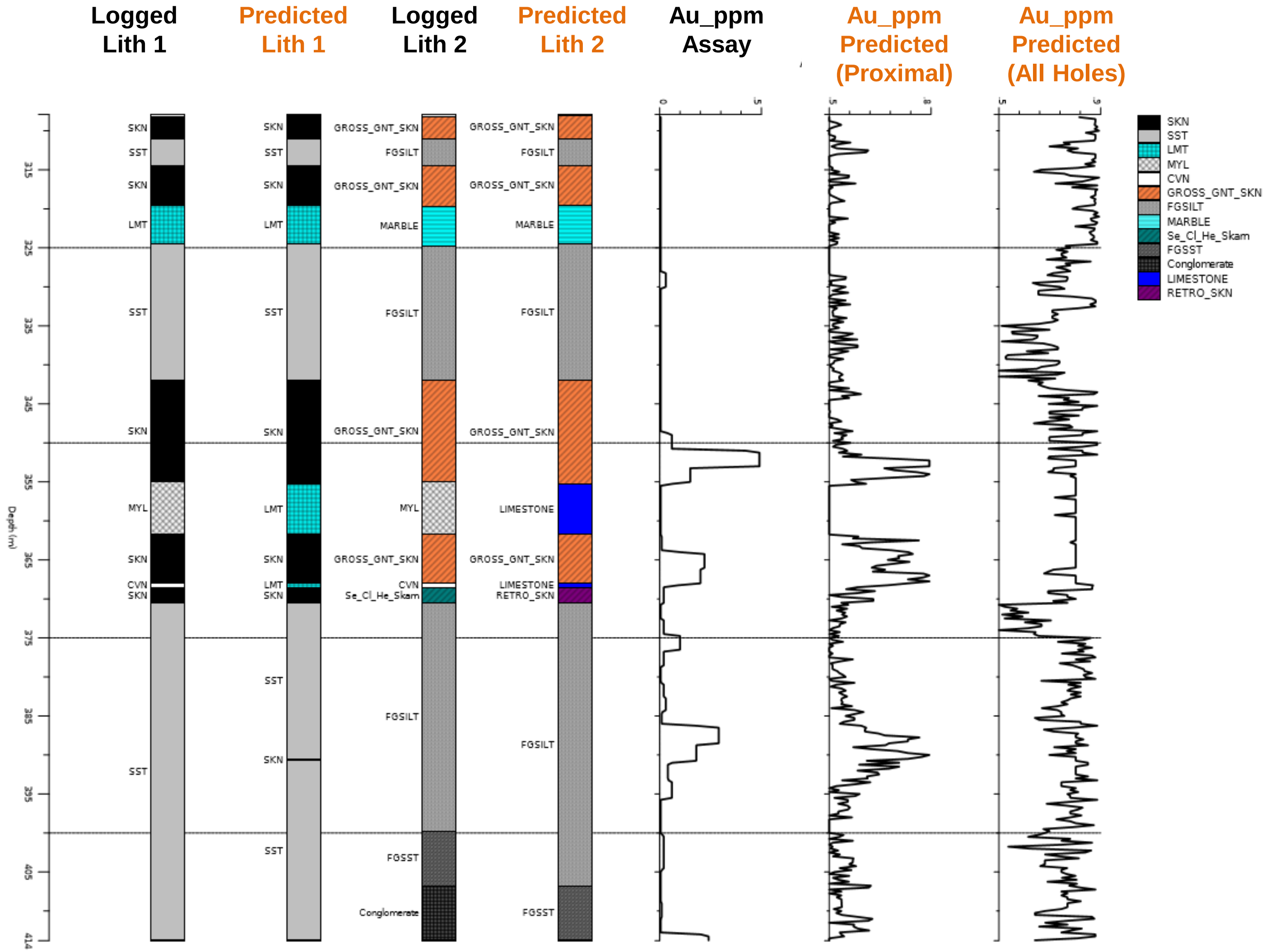




- The sharp triplets around 2120nm and doublets at 2310nm / 2385nm are diagnostic absorption features for talc and are identifiable in the mapped spectra.

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.



Martini et al., 2017

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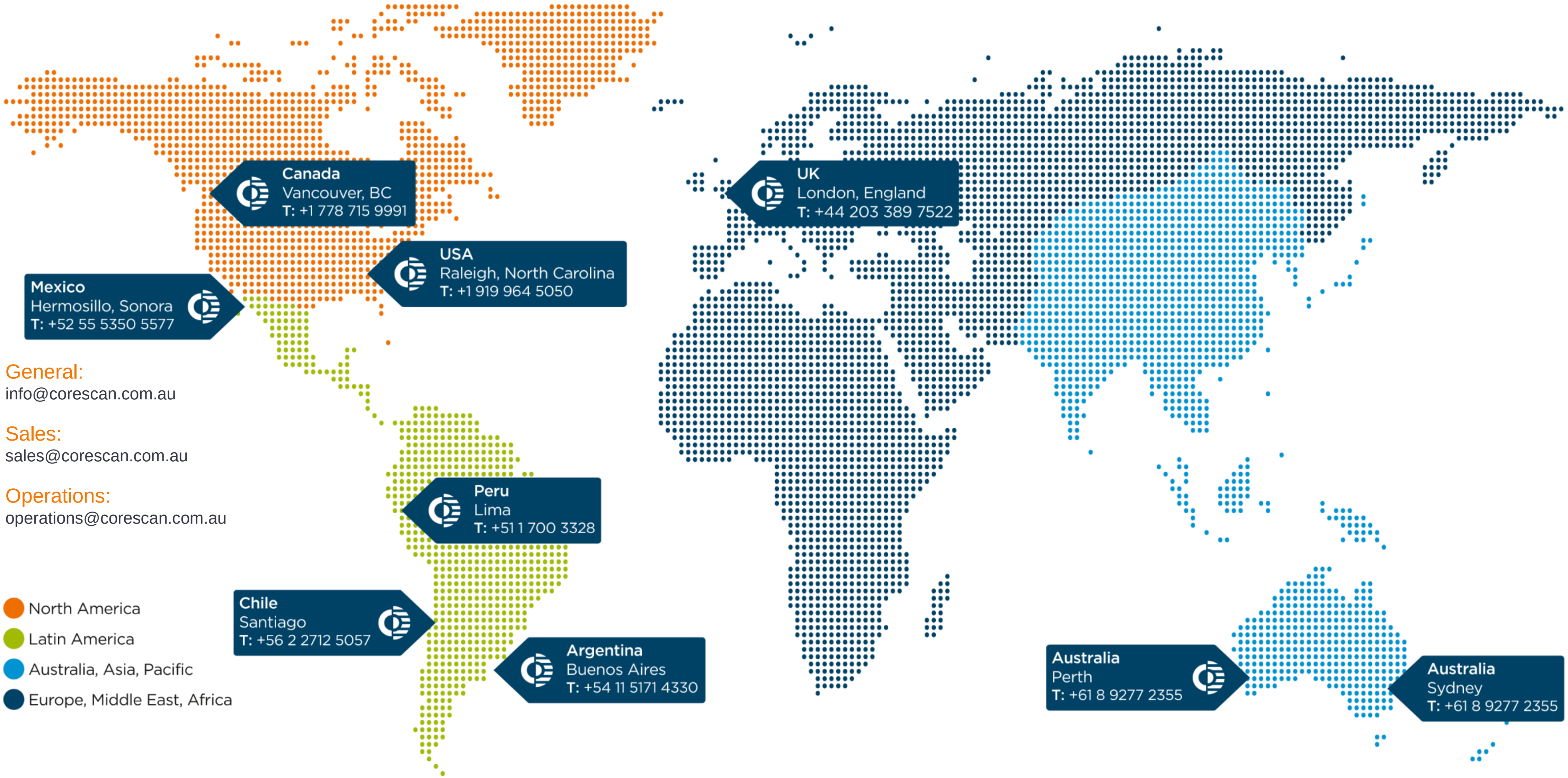

General:
info@corescan.com.au

Sales:
sales@corescan.com.au

Operations:
operations@corescan.com.au

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CORESCAN

Hyperspectral Core Imaging Applications in Skarn Deposits

Sam Scher, M.Sc.
Cristal Palafox, M.Sc.
info@corescan.com.au

Corescan

Appendix: Additional Information on the Corescan System

Hyperspectral Core Imaging Services

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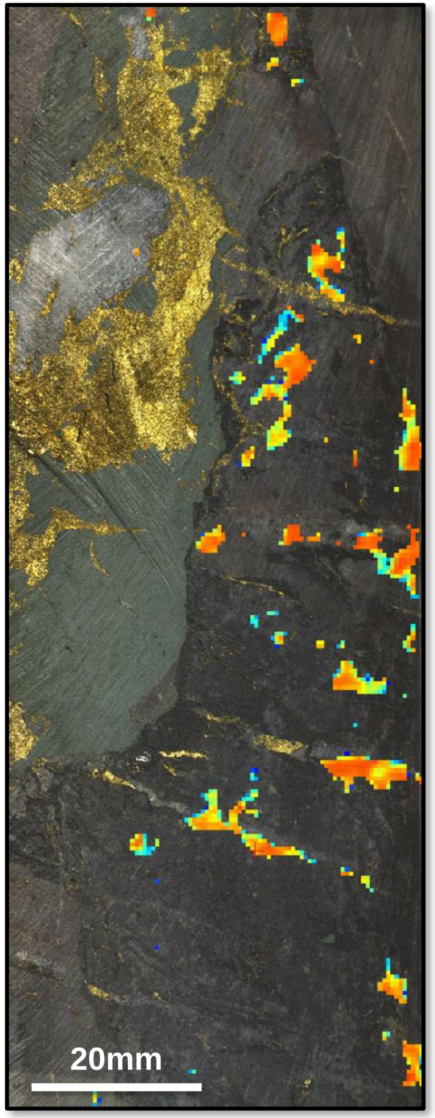
Mineral identification and mapping across the mining cycle:

- 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

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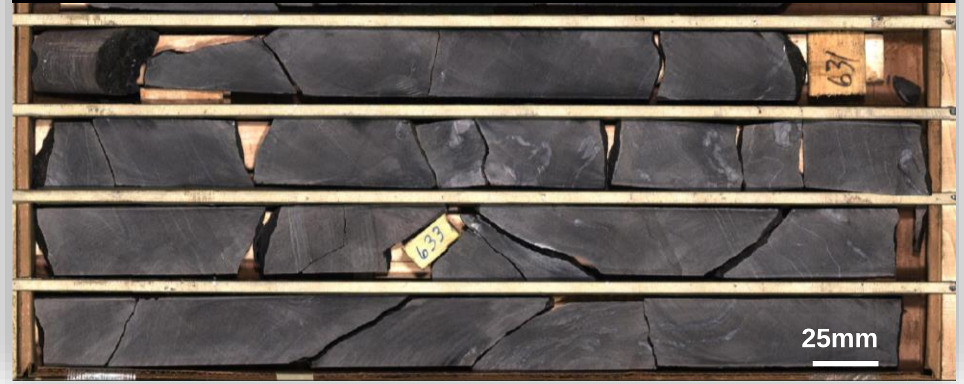
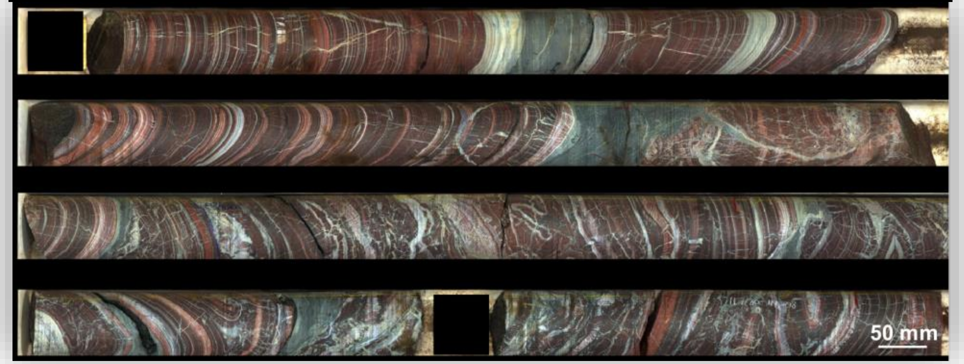
Cut / split core



Hand samples

Soils

Uncut / whole core



Chips, cuttings, blast holes

Hyperspectral Core Imaging Services

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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