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Spectral data applications in economic geology

Fundamentals of Economic Geology
CODES
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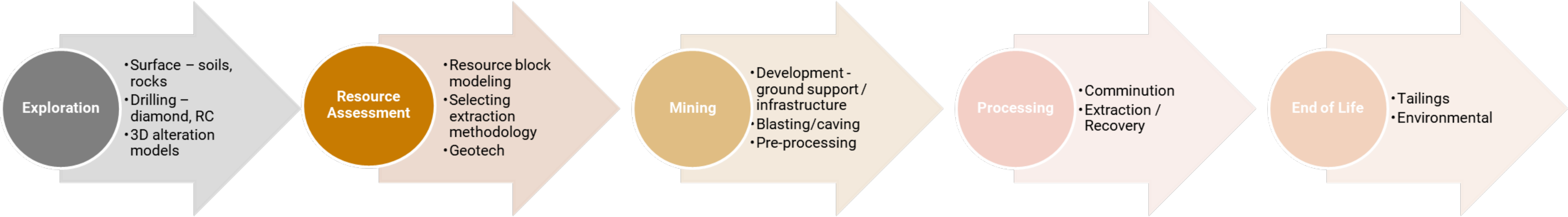
Why hyperspectral

- If a project has consistent and reliable mineralogy from the beginning of the project, then all future applications from exploration through to end of mine life will be easier to anticipate.



Exploration
- Surface – soils, rocks
- Drilling – diamond, RC
- 3D alteration models

Resource Assessment
- Resource block modeling
- Selecting extraction methodology
- Geotech

Mining
- Development - ground support / infrastructure
- Blasting/caving
- Pre-processing

Processing
- Comminution
- Extraction / Recovery

End of Life
- Tailings
- Environmental

The fundamentals of running a spectral program

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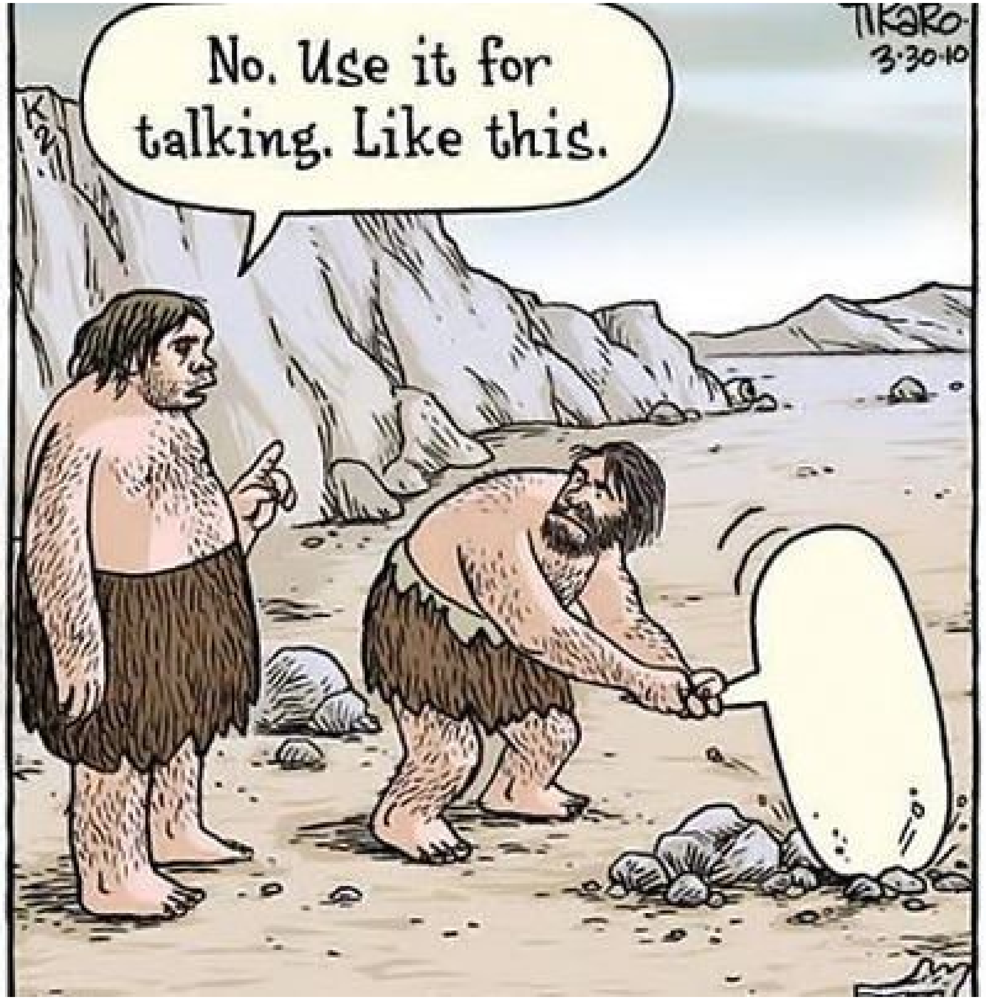
- What is your question?
- What are the parameters of your program?
  - What scale are you working at?
  - What type of ore body do you have?
- Is spectral right for your program?
- Establishing check points with providers.



Understanding spectral terminology

Optical spectrometers

- Optical spectrometers measure the properties of light, usually near the optical region of the EM spectrum, i.e., UV, visible and IR light.
- The change in the absorption and emission of the light intensity with wavelength allows for the identification of materials.
- The process simplified:
    - Photons reach the detector (at specific wavelength) and are converted to electrons via the photoelectric effect.
    - These electrons at-detector are converted to a voltage
    - The voltage is digitized (turned into a number) by an Analog to Digital Converter (Digital Number – DN).
    - Each DN value is tallied and summed into a final spectral signature.
    - Radiance is derived by applying gain and offset values (inherent to sensor) to the DN values, resulting in a radiance signature.

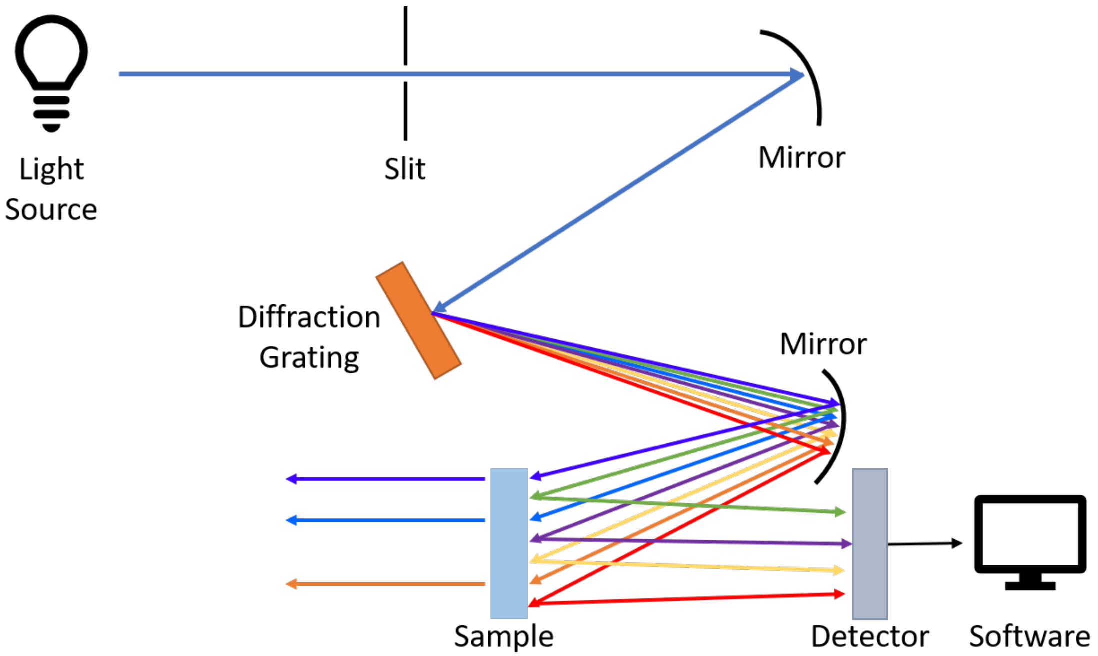
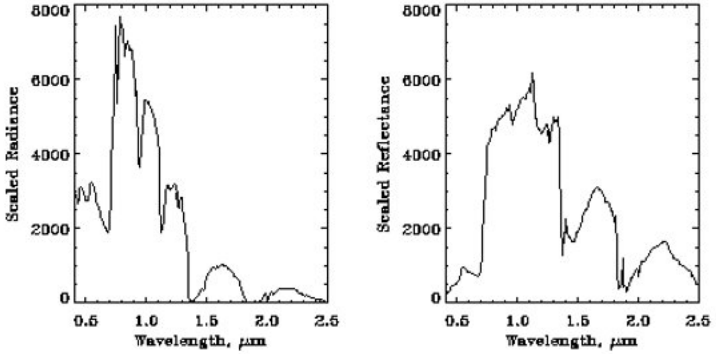


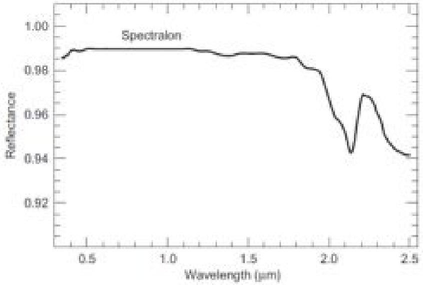
Image Credit: Wavelength Opto-Electronic

Converting spectral data from radiance to reflectance

- Spectrometers collect raw data in radiance.
- Reflectance is derived to both minimize the effects of variable irradiance values at-sensor, as well as to allow for the **direct comparison** of varied earth materials across different environments, atmospheric conditions, using different sensors, and at different times. It is a **normalization**.
- Reflectance is reported in either percent or as a value from 0.0 to 1.0. It is derived by comparison to a **standardized, NIST-certified** reflectance material (**Spectralon**) at the time of measurement.
- It is essential to keep the Spectralon **clean** (avoid wrong measurements) and to **calibrate often** (prevent shifts in absorption features)!



Radiance → **Reflectance**

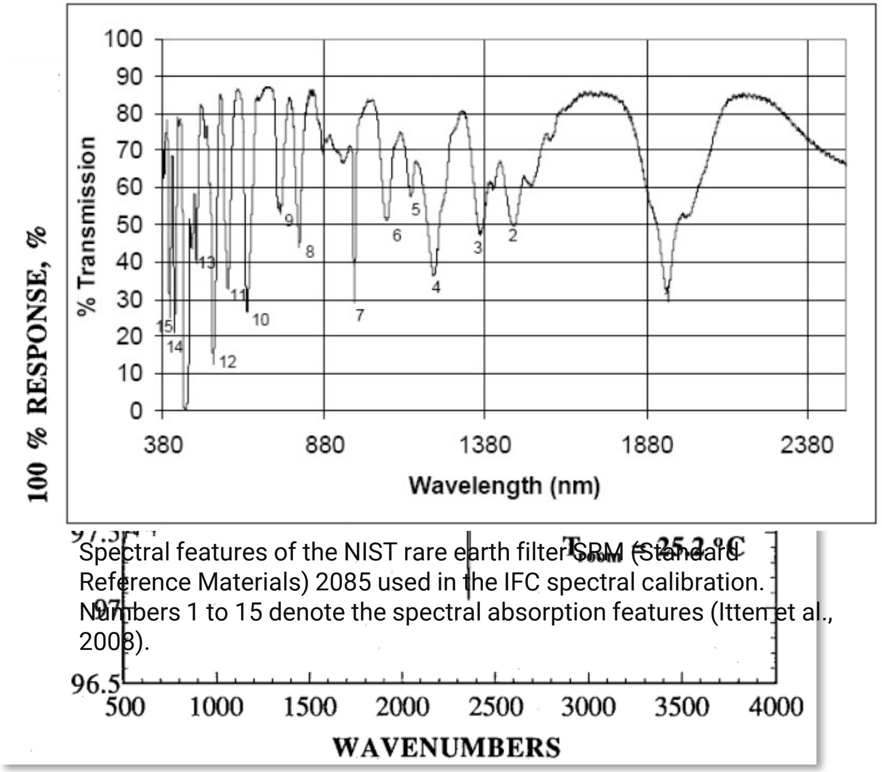


Instrument drift

- Instrument calibration is standard practice for most analytical techniques.
- Calibration aims to minimize systematic (instrumental) sources of error by:
  - Confirming the accuracy of the instrument.
  - Monitoring the repeatability of the measurements.
- Spectrometers are generally prone to “drift”
  - The performance of electronic, mechanical and optical components may vary with changes in temperature causing changes in SNR and shifts in wavelength positions.
  - Regular calibration is important to monitor these changes and deliver high quality, repeatable results.

Checking for instrument drift:

- Ensuring that the spectral bands are in the same location is important, i.e. there is no instrument drift.
- If drift is not regularly checked, this may preclude the usage of compositional features.
- An example of a standard is a REE-doped NIST standard (see right).



Spectral features of the NIST rare earth filter SRM (Standard Reference Materials) 2085 used in the IFC spectral calibration. Numbers 1 to 15 denote the spectral absorption features (Itten et al., 2008).

(FTIR spectrometer, MacBride, 1997)

Data collection & QA/QC

- It is essential to understand how your hyperspectral data is being collected:
    - Is it under a controlled environment that the spectrometer will be within specifications?
    - How is the calibration being performed?
    - Are there standards implemented in the data collection program?
    - Can your vendor confidently answer these questions?

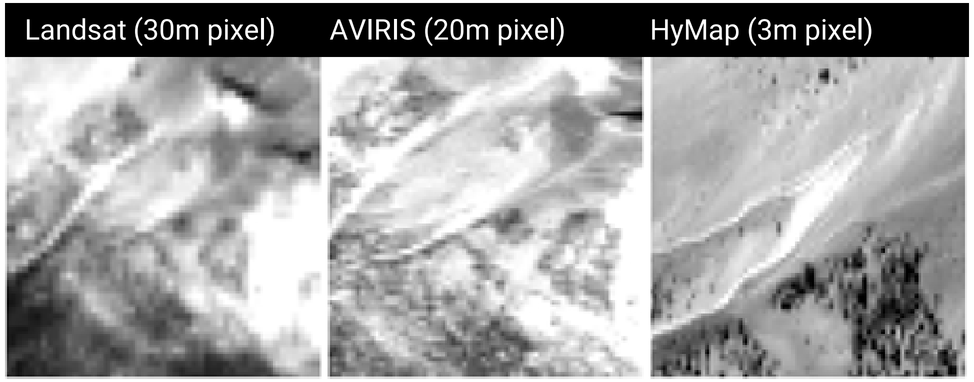
An example of a field duplicate that can be implemented in any program to provide confidence in the repeatability of measurements.

The system’s specifications

- Spatial resolution
- Spectral resolution
- Number of bands
- Band configuration
- Signal to Noise Ratio (SNR)
- Field of view (FOV) & swath width
- Type of sensor
- QA/QC: calibration and standards

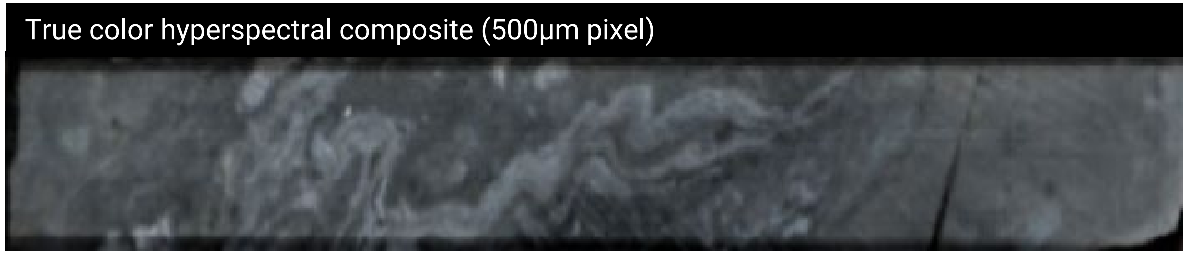
Spatial resolution

- Spatial resolution is generally reported as the dimension of the pixel or sample area that is measured by the spectrometer: the 'pixel size' or 'spot size'.
- Defined as the smallest object clearly imaged with distinct boundaries.
- Images with large pixel sizes are considered to be of coarse scale or low resolution (low spatial resolution).
- Fine scale or high-resolution images have small pixel sizes (high spatial resolution).



Landsat (30m pixel) AVIRIS (20m pixel) HyMap (3m pixel)

Image credit: Martini et al., 2001.

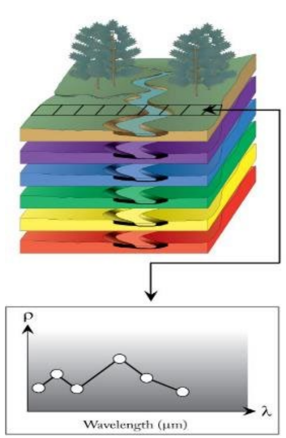


True color hyperspectral composite (500µm pixel)

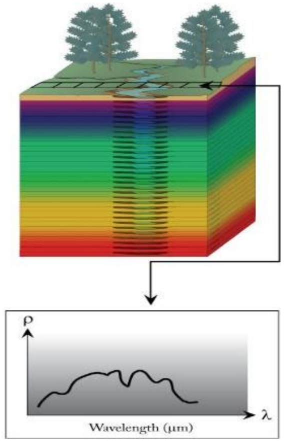
Hyperspectral core imaging data at 500µm. Image credit: Minnesota Department of Natural Resources.

Spectral resolution

- Spectral resolution describes the wavelength intervals over which each spectral band's measurement is made, and which determines the ability to discriminate fine spectral features.
- It typically refers to how "wide" each band is, or the range of wavelengths covered by a single measurement band.
- Important to consider for determining if you can identify the minerals / mineral groups of interest.



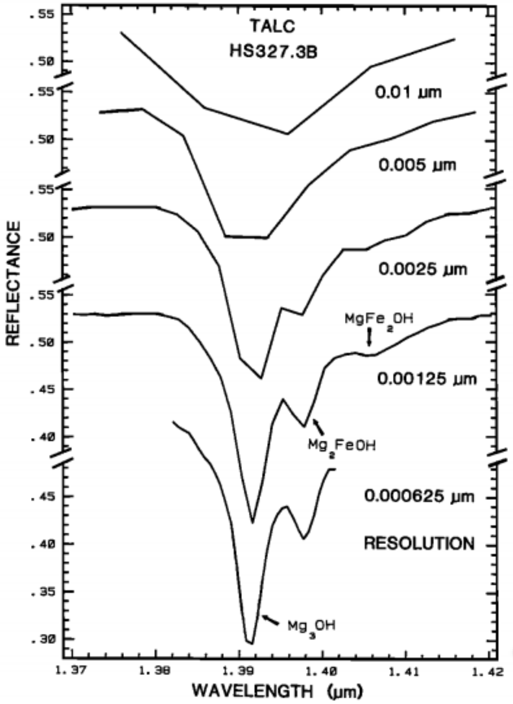
Example multi-band: 0.5µm or 500nm



Example hyperspectral: 0.004µm or 4nm

Higher spectral resolution = increased ability to resolve subtle differences in spectral signatures!

Reflectance spectra of talc ~1400nm

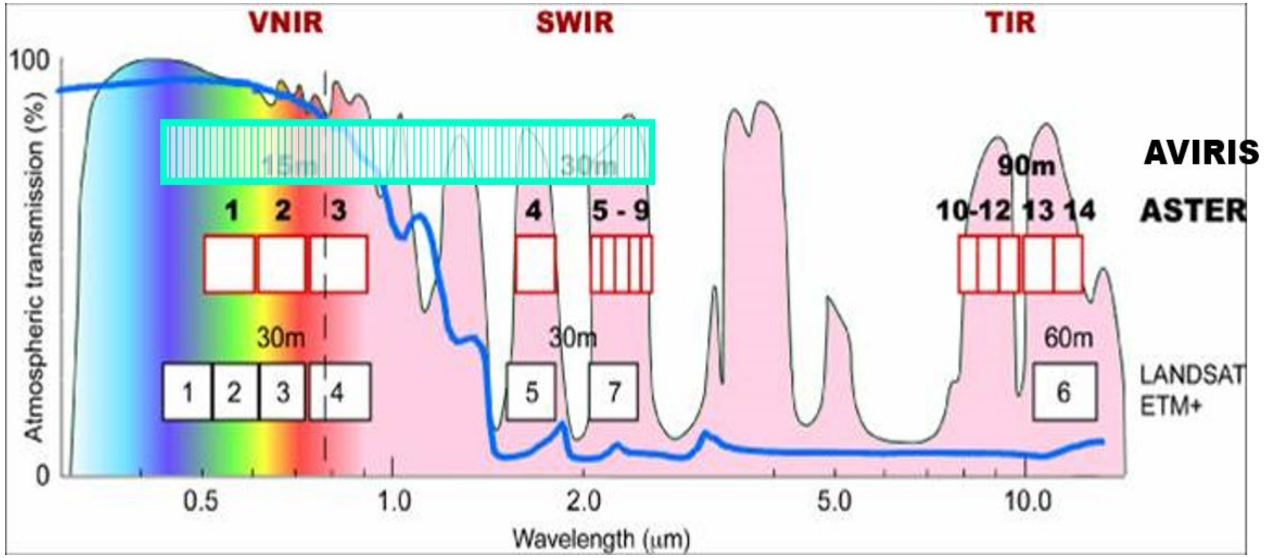


Increasing spectral resolution = more detailed spectral features

(from Clark et al.,1990)

Spectral range, number of bands & band distribution

- The spectral range refers to the specific wavelengths measured by a sensor.
- The number of bands (and whether they are contiguous) classifies hyperspectral from multi-spectral, i.e., absolute mineral identifications versus broad mineral classifications.



Examples drawn from remote sensing satellite data. Each shows the spectral range of the instrument, as well as how many bands of information are available for interpretation.

Signal to Noise Ratio (SNR)

- The Signal to Noise Ratio (SNR) is the measure of how much ‘signal’ (or energy) is measured versus the amount of background or instrument ‘noise’.
- Instrument noise can be due to several factors including poor sensor calibration, poor detector or optical quality, low source illumination or sample movement during measurement.
- Higher SNR improves the ability to interpret mineralogical information from the measured spectra (more defined spectral features).
- Note that in an imaging system the type of sensor that your vendor is using (e.g., frame, pushbroom, whiskbroom) is an important component to improving SNR, as is the field of view and swath width.

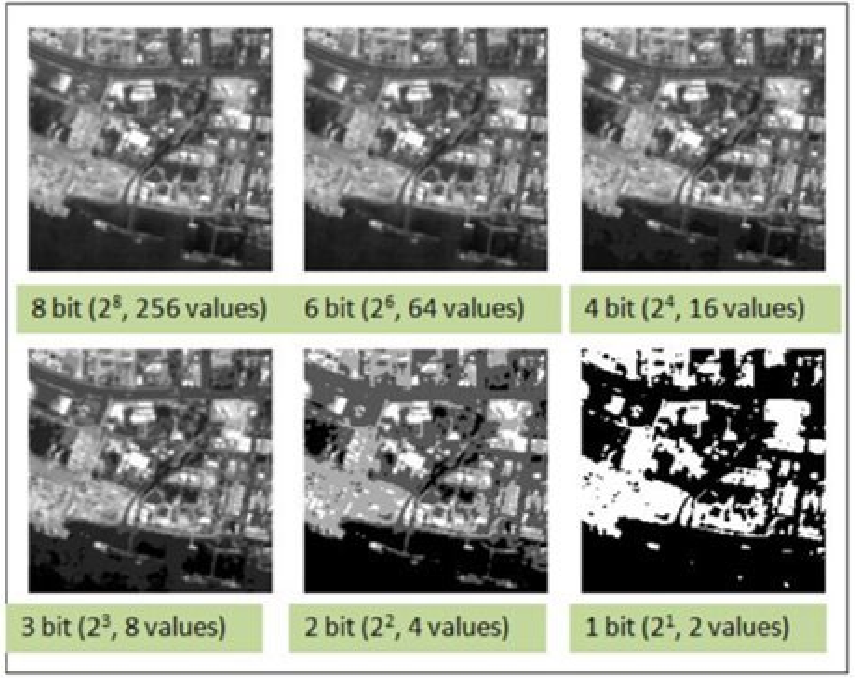


Image credit: Descartes Labs

Field of view (FOV) & swath width

- The Field of View (FOV) and Instantaneous Field of View (IFOV) is determined by the spectrometer's optical design.
- Altitude (A) refers to the distance between the detector and the surface and velocity (V) is the speed of the detector along the measurement path.
- These parameters directly relate to the spatial ground resolution and ground swath width (L).
- An important consideration in remote sensing: Wide FOV sensors cover more ground but sacrifice the spatial ground resolution provided by smaller FOV sensors.

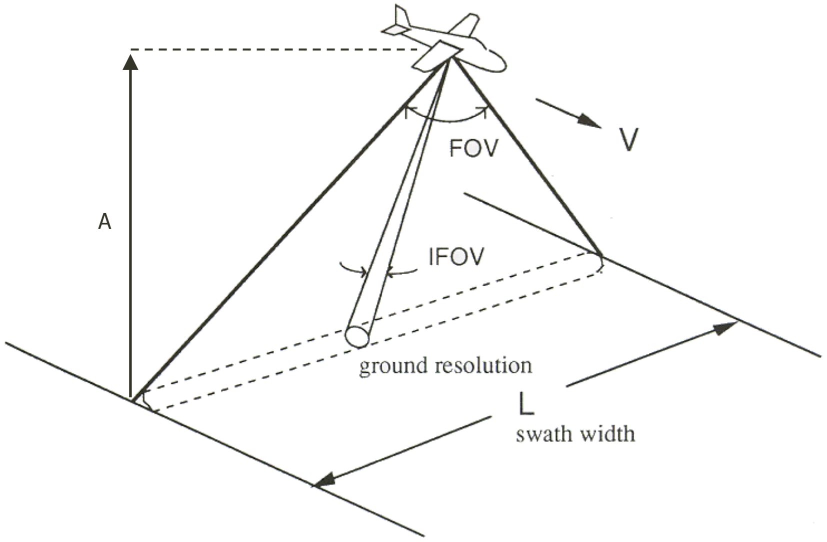
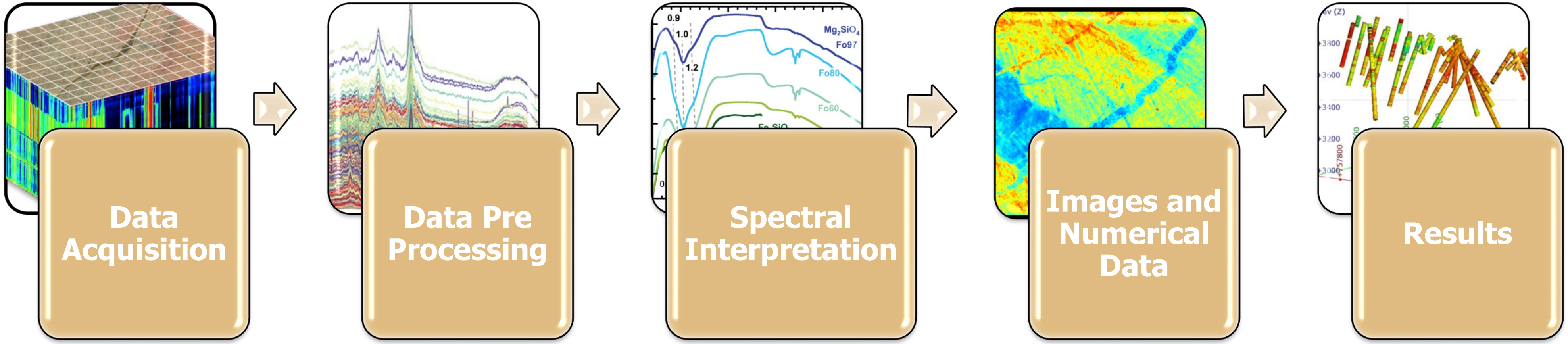


Image credit: Mukherjee University

$$L = \tan\left(\frac{FOV}{2}\right) \times altitude \times 2$$

Hyperspectral data analysis

- Hyperspectral data analysis is the process of transforming raw spectral response data into mineralogical or geological information including both images and numerical data.
- This is a highly specialized skillset that requires the right combination of mineral / geologic knowledge, appropriate software and the requisite amount of computing capacity.



Data Acquisition

Data Pre Processing

Spectral Interpretation

Images and Numerical Data

Results

Data processing

ML-based

- Supervised and unsupervised classification methods can be used on all or part of the spectrum.
- Current published techniques include RF, SOM, PCA, K-means clustering.
- Note: statistical clustering techniques require interpretation of groups that can represent one or more minerals.
- **It is important to understand the data inputs and assumptions used to derive results.**

Mineral mapping

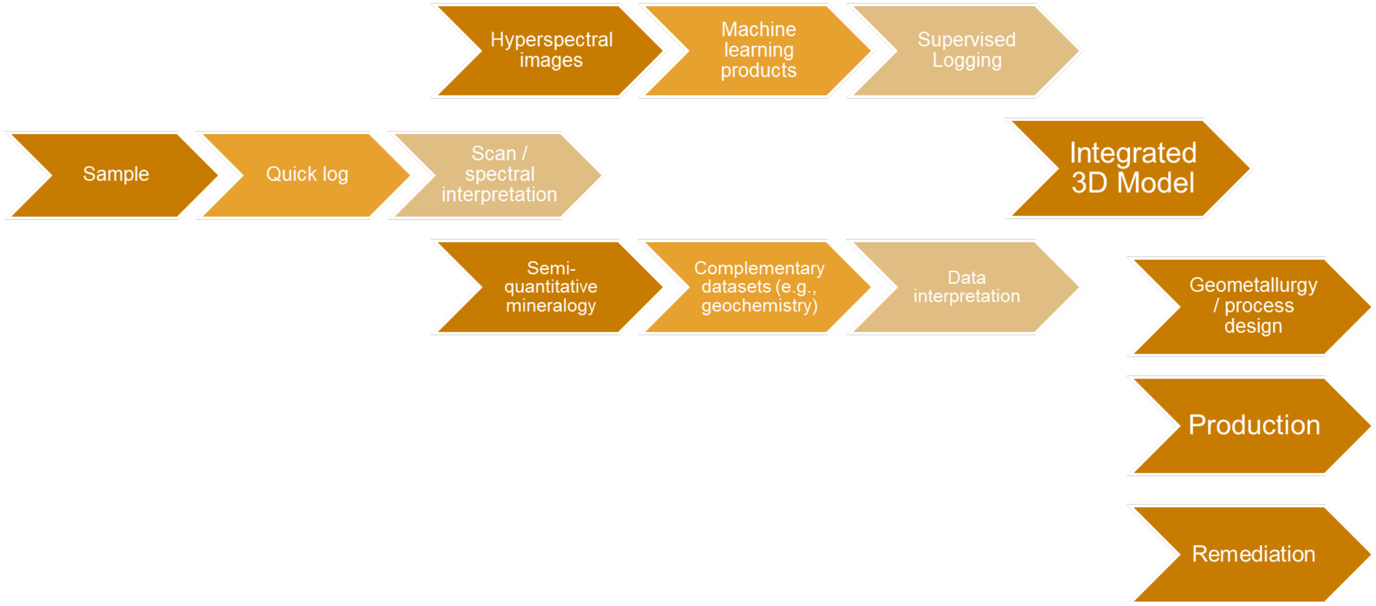
- Goal is to characterize individual mineral components of a spectrum and to map the distribution of individual mineral/mineral species.
- Basic methodology involves matching an unknown spectrum to a known reference (library) spectrum).
- For high-density datasets, automation can include algorithms such as SAM, SFF, SCM, etc.

What system do you require?

What is the goal of your study?

- Are trace mineral phases important?
- Is texture important?
- Are you looking to vector to ore using mineral chemistry?
- Are your minerals active in the IR? If so, what part?
- Who’s interpreting the data?
- What are your outputs?
    - Mineralogy
    - Combination: lithology + alteration
    - Clusters

Example Workflow



Hyperspectral images

Machine learning products

Supervised Logging

Sample

Quick log

Scan / spectral interpretation

Integrated 3D Model

Semi-quantitative mineralogy

Complementary datasets (e.g., geochemistry)

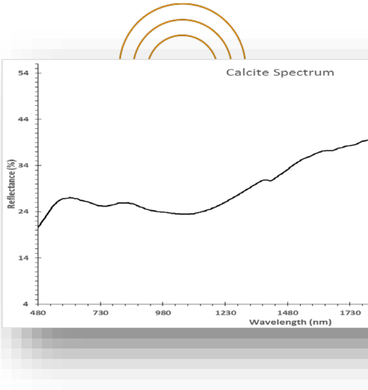
Data interpretation

Geometallurgy / process design

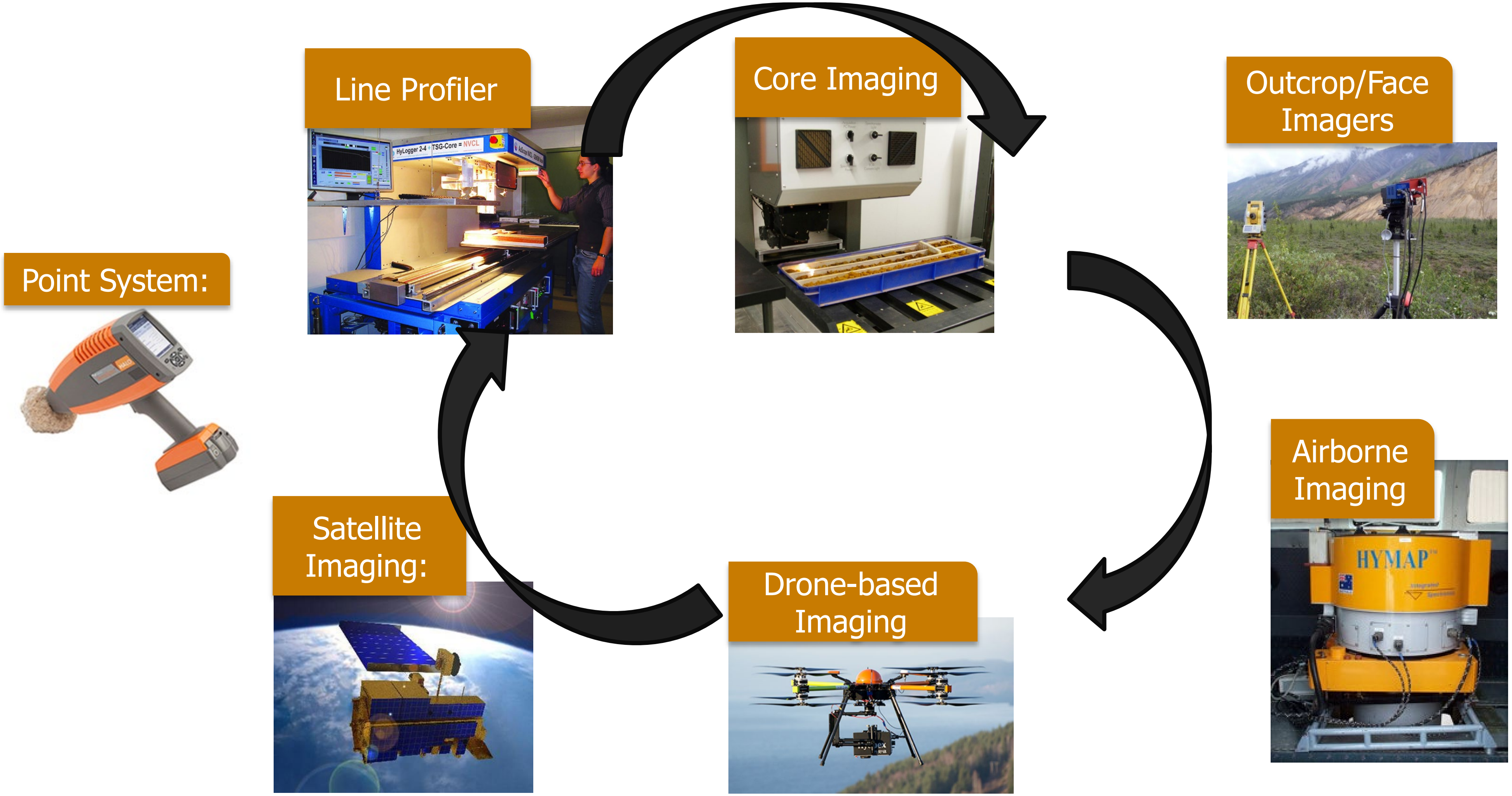
Production

Remediation

The spectral ecosystem



- ecosystem: a complex network or interconnected system



Point System:

Line Profiler

Core Imaging

Outcrop/Face Imagers

Airborne Imaging

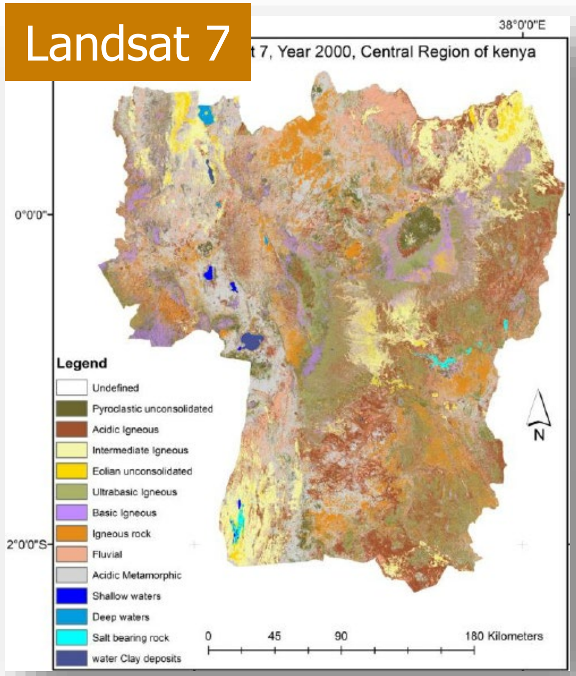
Drone-based Imaging

Satellite Imaging:

Credit: Brigette Martini

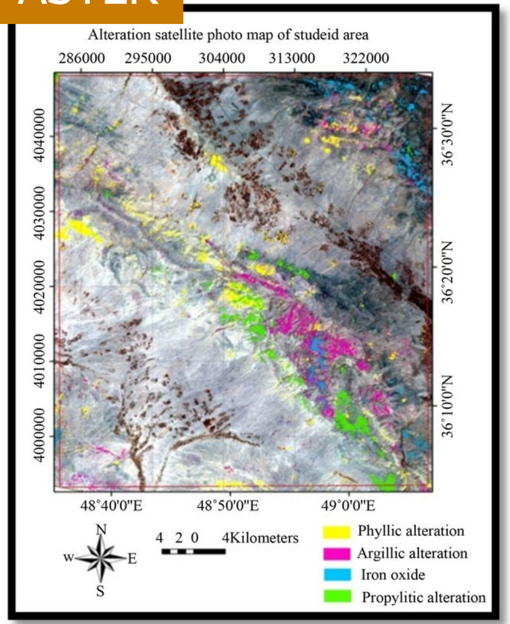
Scale: Satellite & Airborne

Landsat 7



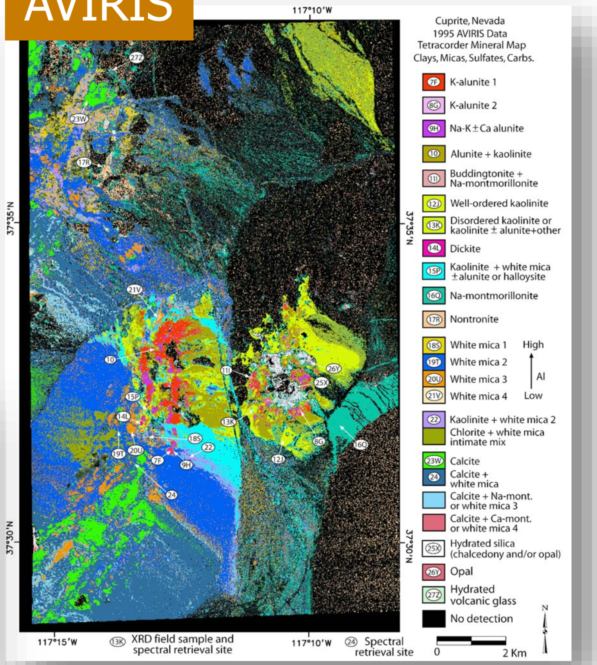
Mwanitki et al., 2015

ASTER



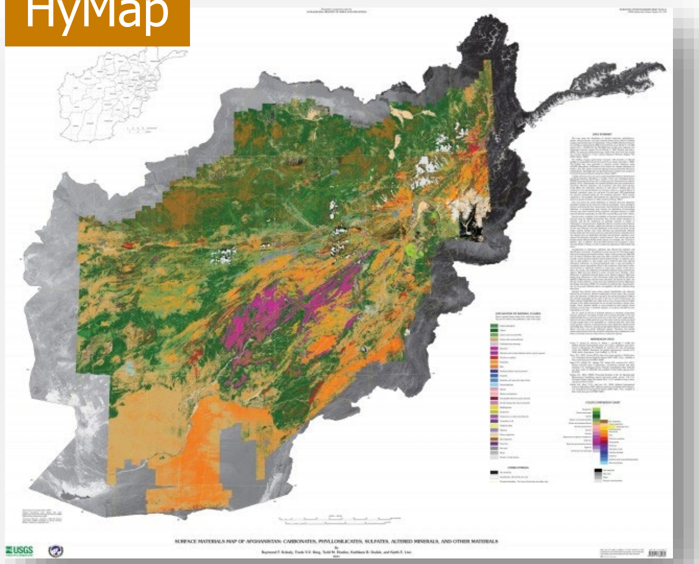
Feizi and Mansuri, 2013

AVIRIS



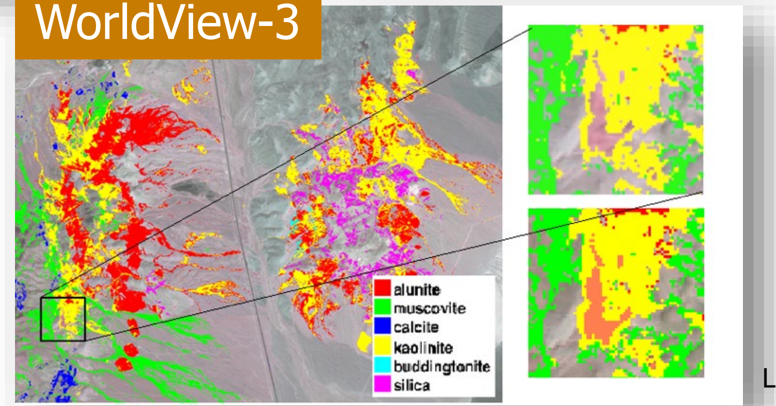
Swayze et al., 2014

HyMap



Kokaly et al., 2015

WorldView-3

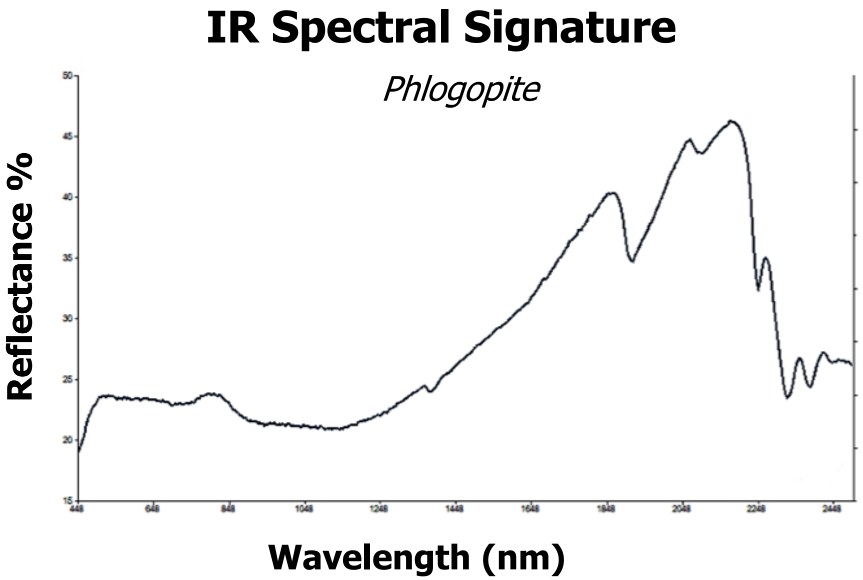


Lasica, 2015

Credit: Corescan

Point data

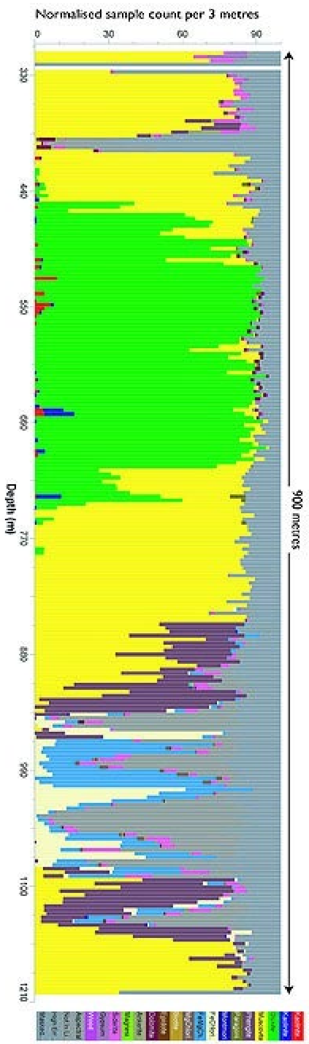
- Advantages
    - Low operating and purchase cost
    - Easy to use
- Challenges
    - Limited spatial / spectral resolution
    - Irregular sampling
    - Low sampling rates



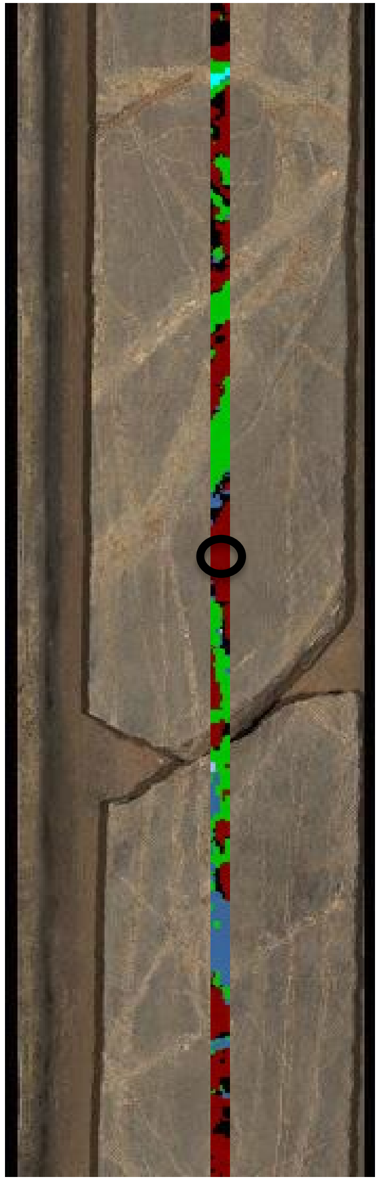
Credit: Corescan

Line scan systems

- Advantages
    - Relatively low operating cost
    - Regular sampling
    - Low amount of data (GB)
- Challenges
    - Limited spatial resolution
    - Cannot see texture



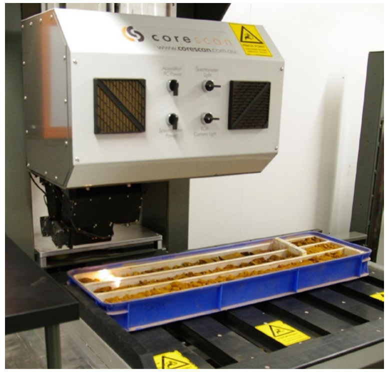
Mineral	% (Line)
Calcite	0.006
Chlorite	31.9
Kaolinite	0
Montmorillonite	0
Phlogopite	48.6
Tourmaline	0
White Mica	0.083



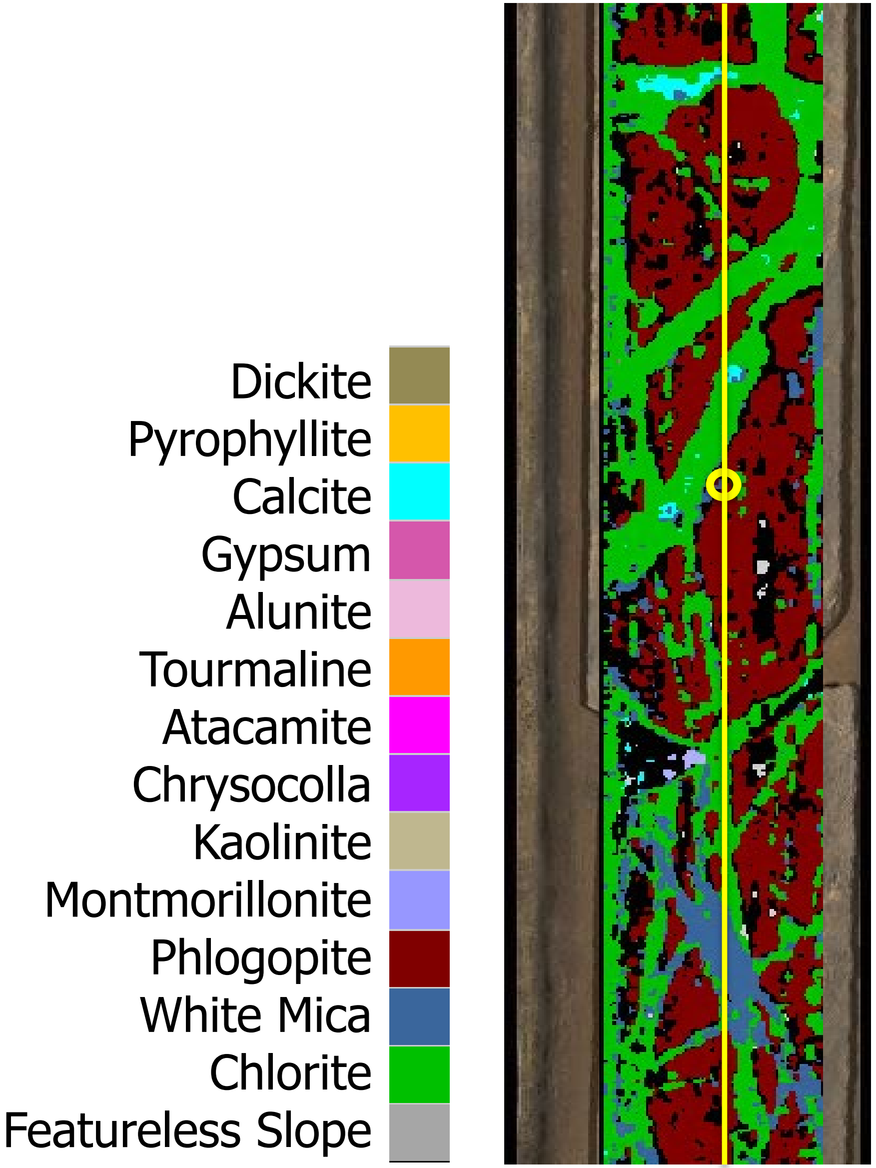
Credit: Corescan

Imaging systems

- Advantages
    - High resolution
    - Regular sampling
    - High sampling rates
- Challenges
    - Higher data volume
    - Logistics considerations

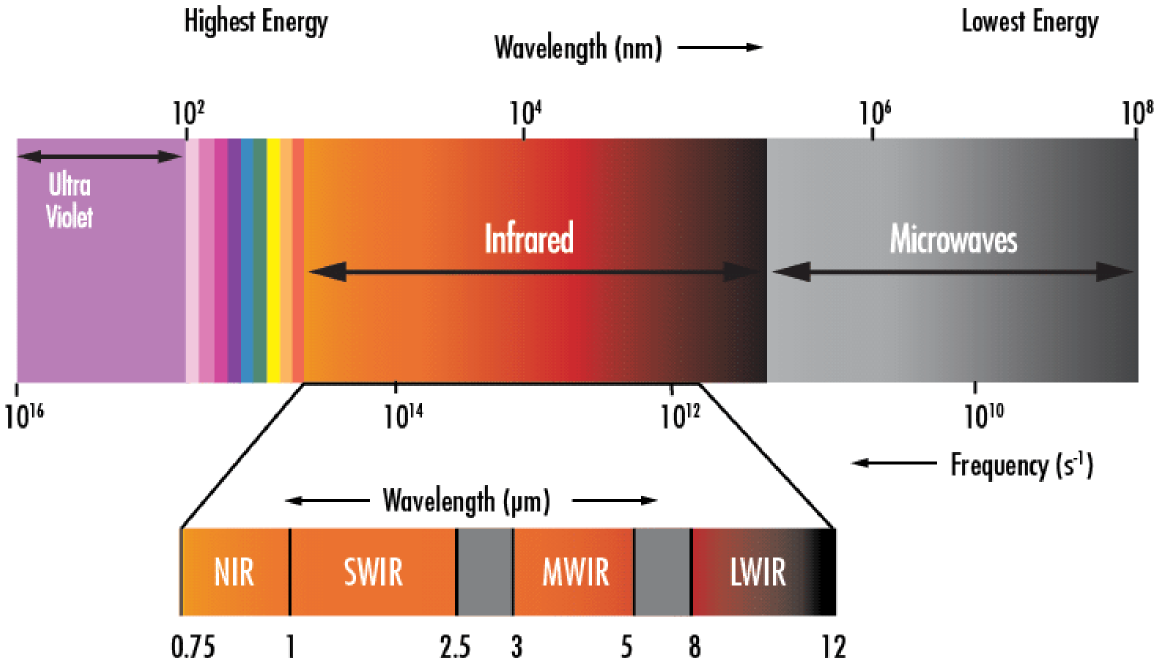


Mineral	% (Line)	% (Image)
Calcite	0.006	0.005
Chlorite	31.9	27.6
Kaolinite	0	0.002
Montmorillonite	0	0.03
Phlogopite	48.6	37.6
Tourmaline	0	0.01
White Mica	0.083	26.9



Credit: Corescan

Spectral range: the electromagnetic spectrum is relevant

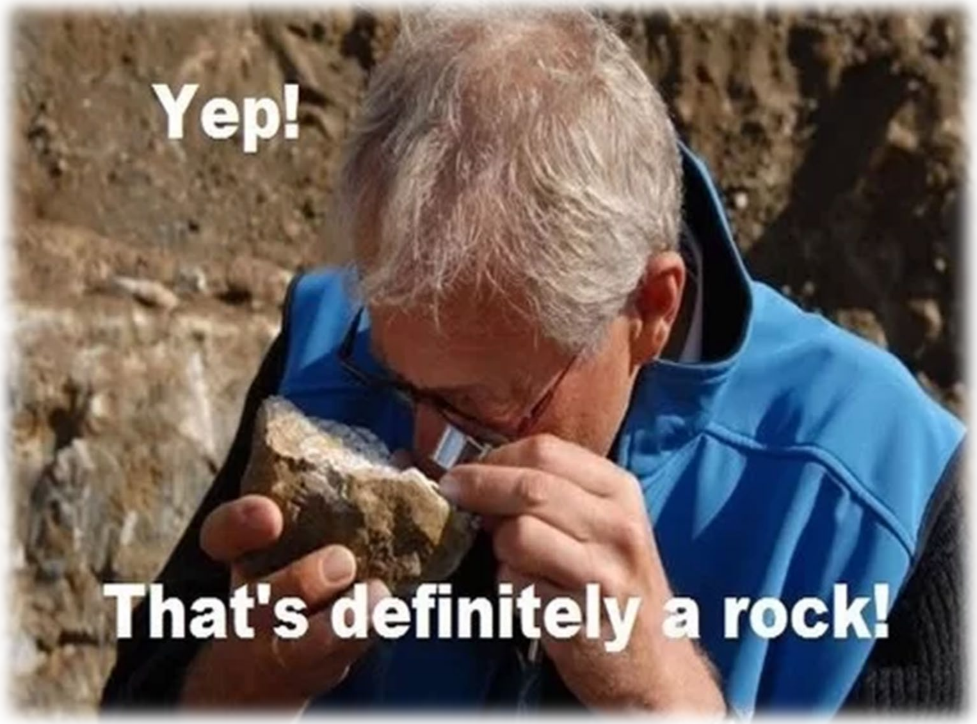


Mouahid, 2018

Garnet – VNIR / LWIR

Pyrophyllite - SWIR

Hematite - VNIR



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Exploration Applications

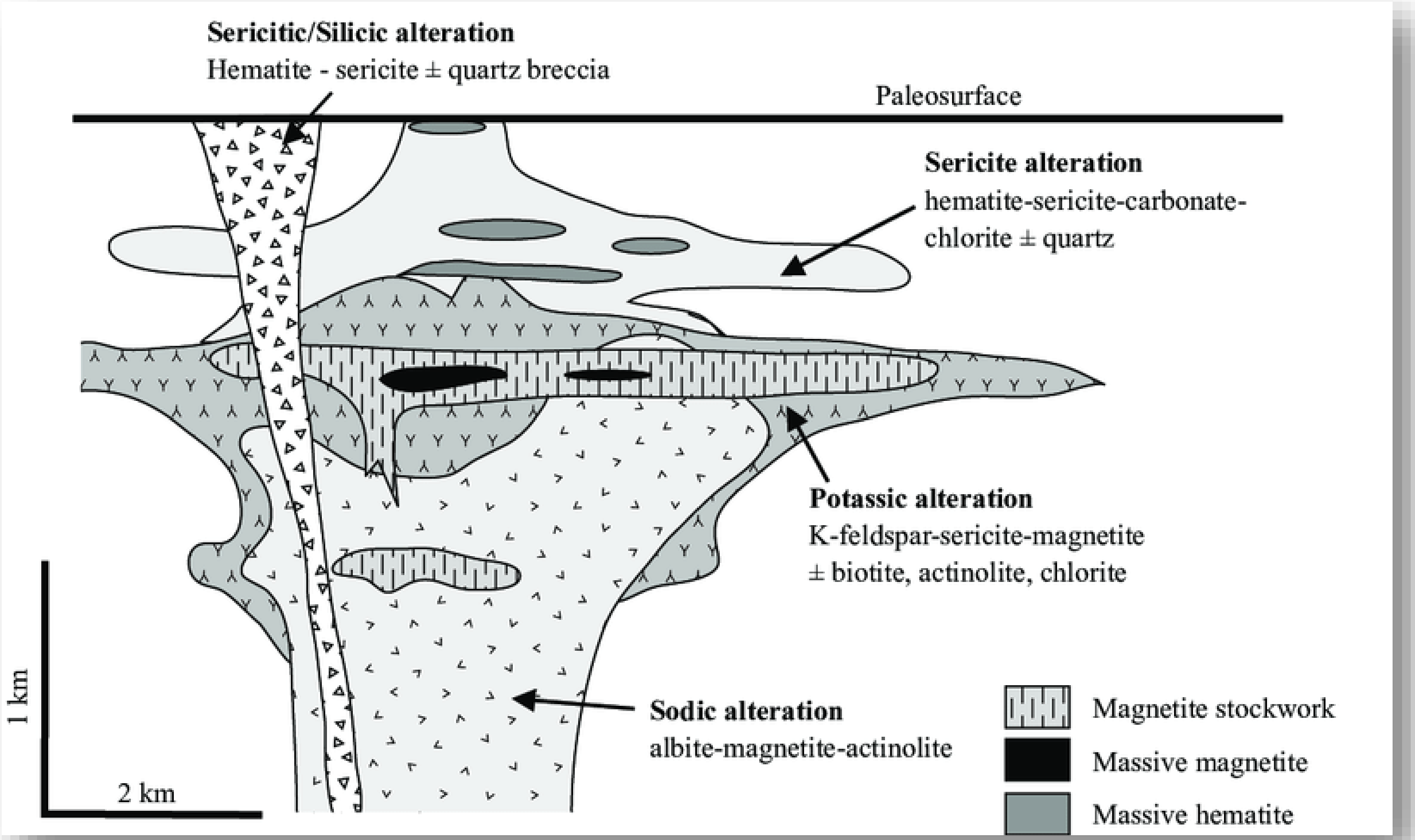
Case study credit

- **The following case studies are courtesy of Lionel Fonteneau and Corescan.**

- Note that since starting with hyperspectral technologies, I have seen success in:
    - Porphyry
    - LS and HS epithermal
    - VMS
    - IRGS
    - **IOCG**
    - U
    - Li and Li-B
    - REE
    - Greenstone Au
    - **Fe ore**
    - Skarn
    - Sedimentary Cu
    - Polymetallic
    - **Ni laterite / Ni sulfide**
    - Diamond (kimberlites)
    - Oil & gas
    - PGE / magmatic sulfide

Case Study 1: VNIR-SWIR Applications in IOCG

General alteration for IOCG systems



Hitzman et al., 1992

Typical mineralogy mapped in the VNIR-SWIR:

- Magnetite
- Hematite
- Scapolite
- Carbonates
- Epidote
- Amphibole
- Zeolites
- White mica
- Clays
- Biotite
- Chlorite
- Prehnite
- Gypsum
- Hydrated silica
- Garnet
- Pyroxenes

Rover-1 IOCG Prospect, NT, Australia

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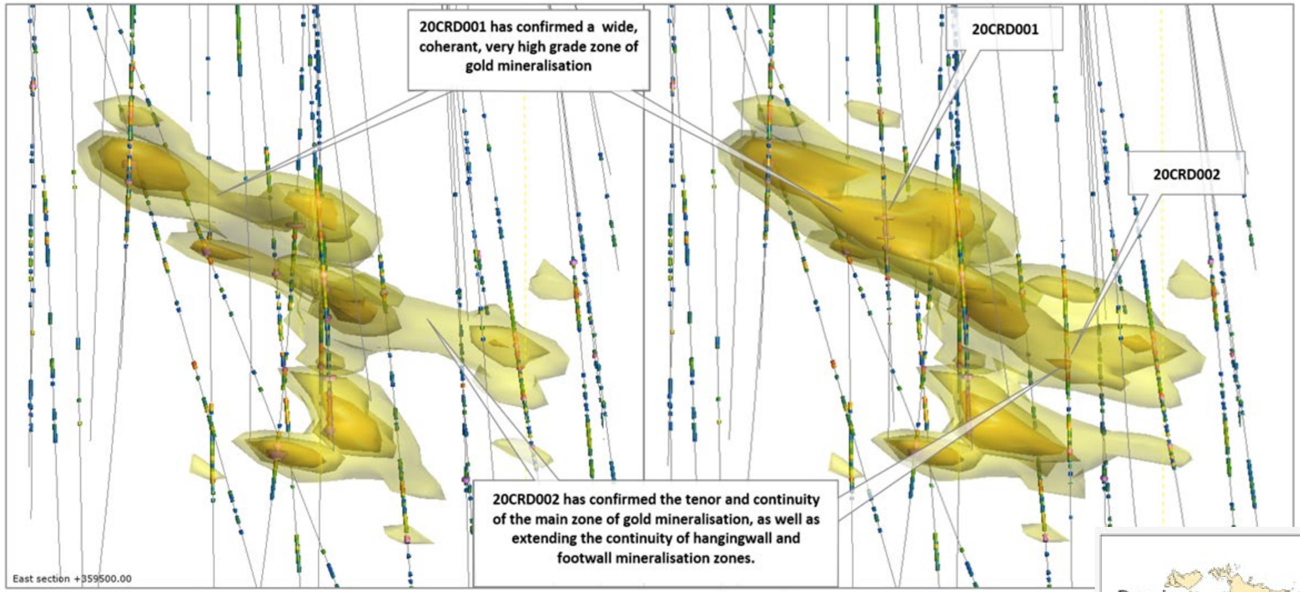

20CRD001 has confirmed a wide, coherant, very high grade zone of gold mineralisation

20CRD002 has confirmed the tenor and continuity of the main zone of gold mineralisation, as well as extending the continuity of hangingwall and footwall mineralisation zones.

Jupiter Gold Zones prior to 2020
Leapfrog 1g/t, 2.5g/t and 5g/t iso shells

Gold Zones after 20CRD001 and 20CRD002 results
Leapfrog 1g/t, 2.5g/t and 5g/t iso shells

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- Located 70km southwest of Tennant Creek, NT.
- Under 60-200m of Wiso Basin cover.
- Geophysics is the primary method of target identification.
- Drilling supports a high grade Au-Cu deposit.

Mineral mapping with VNIR-SWIR: Fe-oxides

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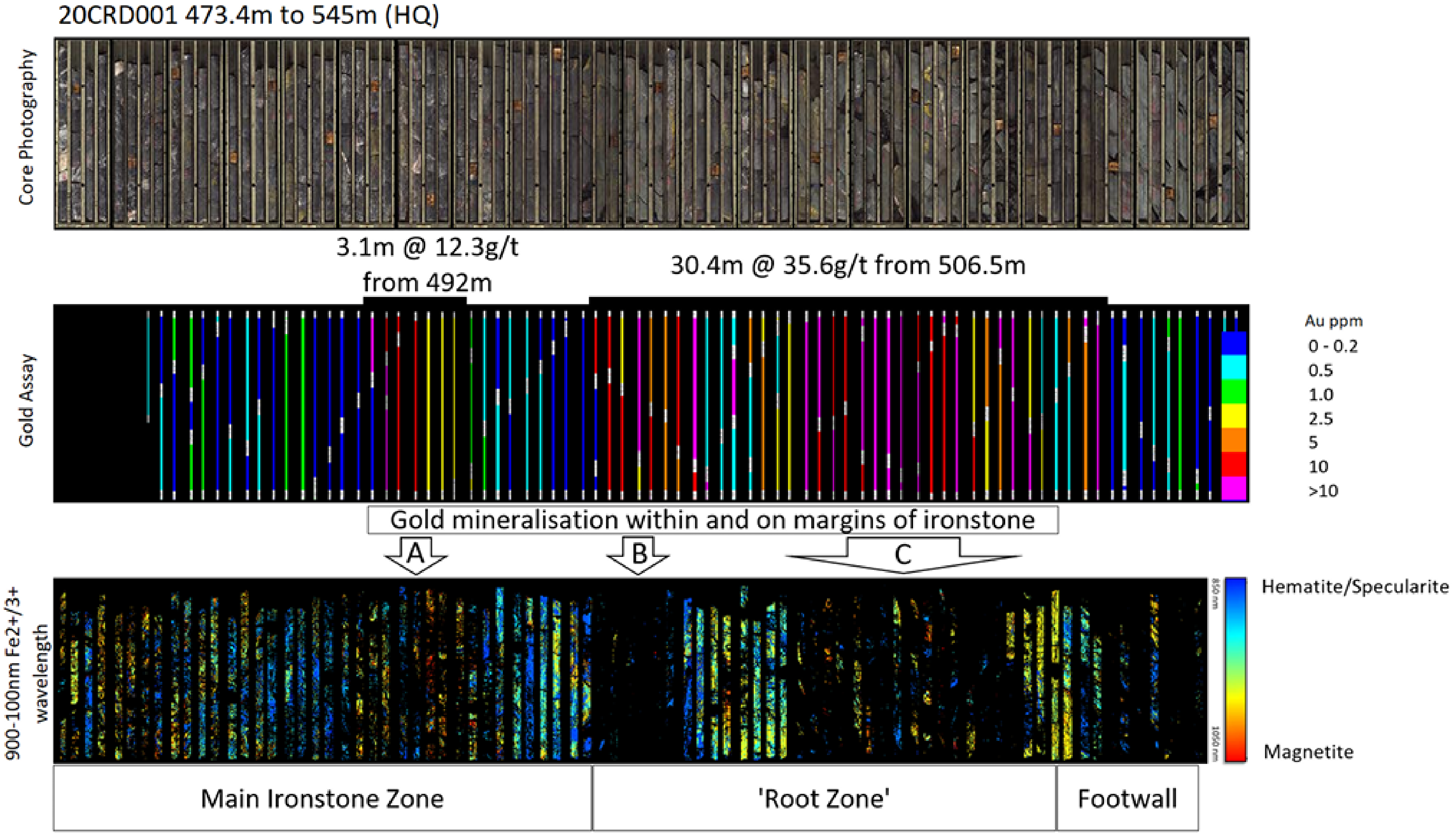

- VNIR-SWIR able to differentiate magnetite from specularite.
- Au mineralization is association with brecciation within ironstone (A) and the transitional ‘root zone’ (B,C).

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Fe-oxide textures

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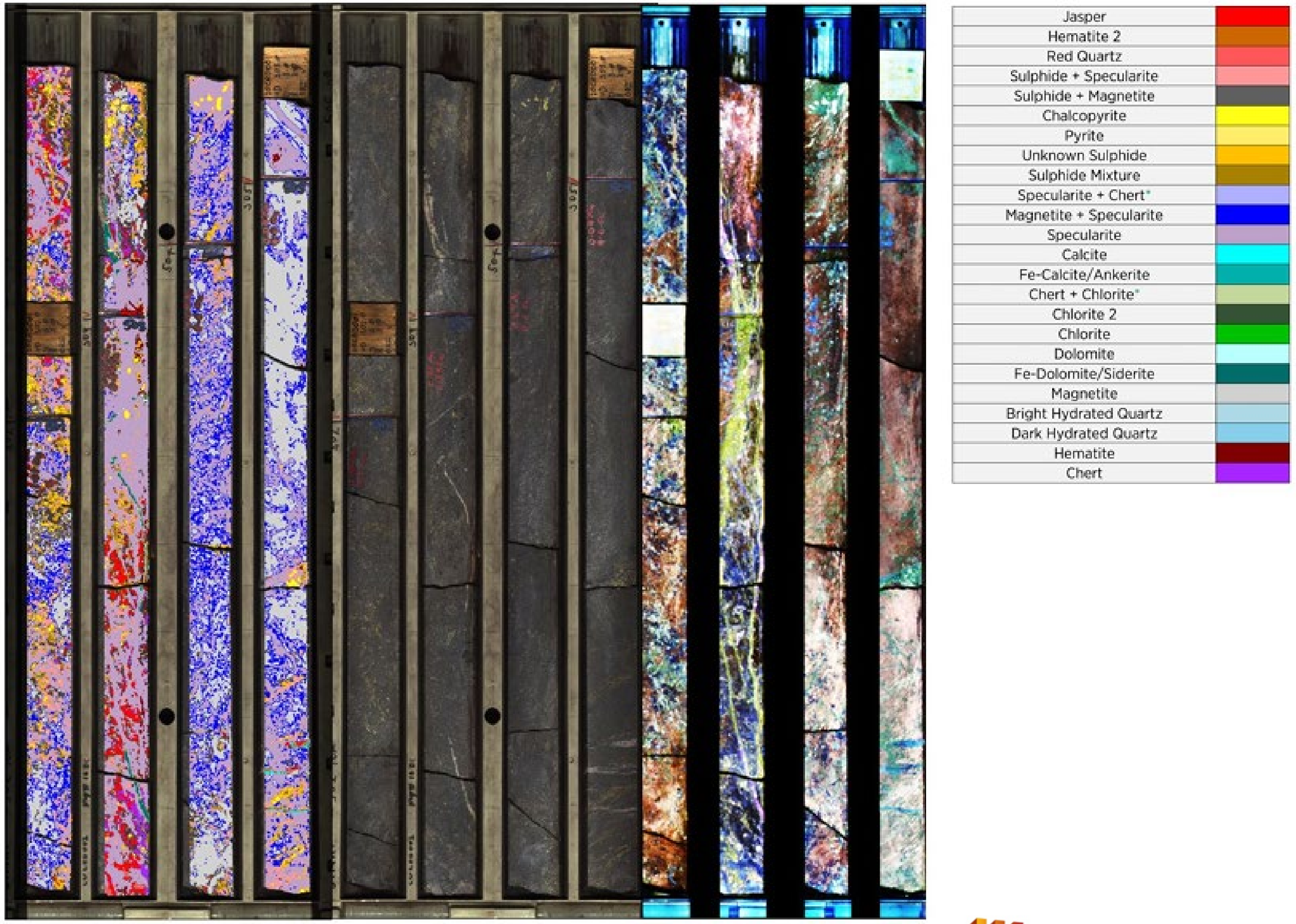

A. Mineral Classification Map

B. Core Photography

C. False Colour Spectral Image

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- Mineral classification map highlights microbrecciation textures in massive magnetite ironstone.
- False color spectral imagery provides important relative timing evidence of multiple alteration events with similar mineral assemblages.

Chlorite

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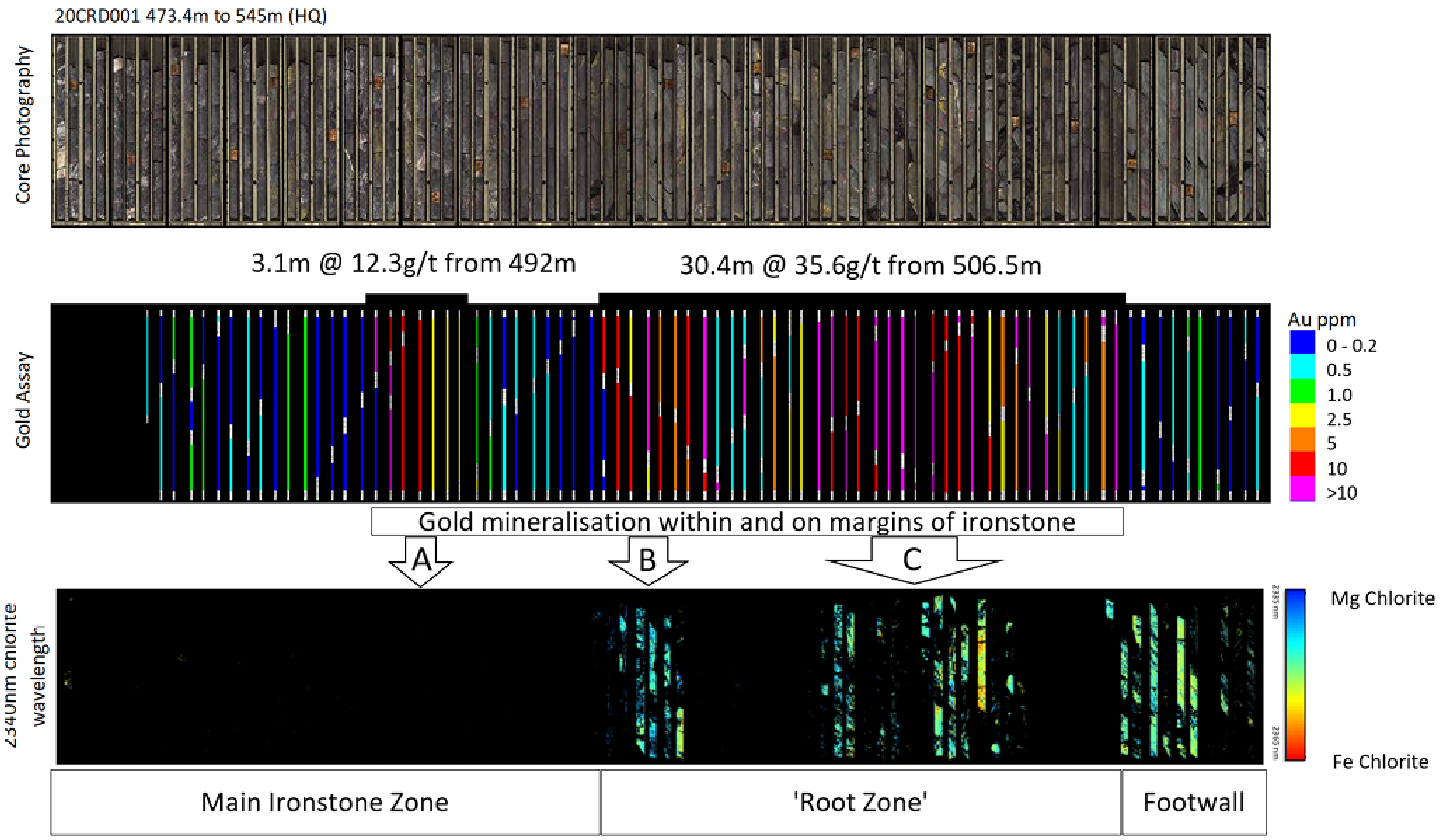

- High tenor Au mineralization has a moderate association with Fe-chlorite alteration in the ‘root zone.’
- Fe-chlorite has a strong relationship with Cu mineralization.

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Chlorite textures

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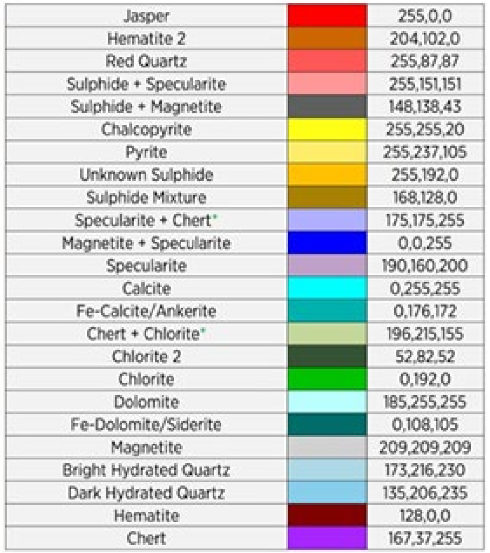
A. Mineral Classification Map B. Core Photography C. False Colour Spectral Image



Jasper	🟥	255,0,0
Hematite 2	🟧	204,102,0
Red Quartz	🟥	255,87,87
Sulphide + Specularite	🟥	255,151,151
Sulphide + Magnetite	⬛	148,138,43
Chalcopyrite	🟨	255,255,20
Pyrite	🟨	255,237,105
Unknown Sulphide	🟨	255,192,0
Sulphide Mixture	🟫	168,128,0
Specularite + Chert*	🟪	175,175,255
Magnetite + Specularite	🟦	0,0,255
Specularite	🟪	190,160,200
Calcite	🟦	0,255,255
Fe-Calcite/Ankerite	🟦	0,176,172
Chert + Chlorite*	🟩	196,215,155
Chlorite 2	🟩	52,82,52
Chlorite	🟩	0,192,0
Dolomite	🟦	185,255,255
Fe-Dolomite/Siderite	🟦	0,108,105
Magnetite	⬜	209,209,209
Bright Hydrated Quartz	🟦	173,216,230
Dark Hydrated Quartz	🟦	135,206,235
Hematite	🟥	128,0,0
Chert	🟪	167,37,255

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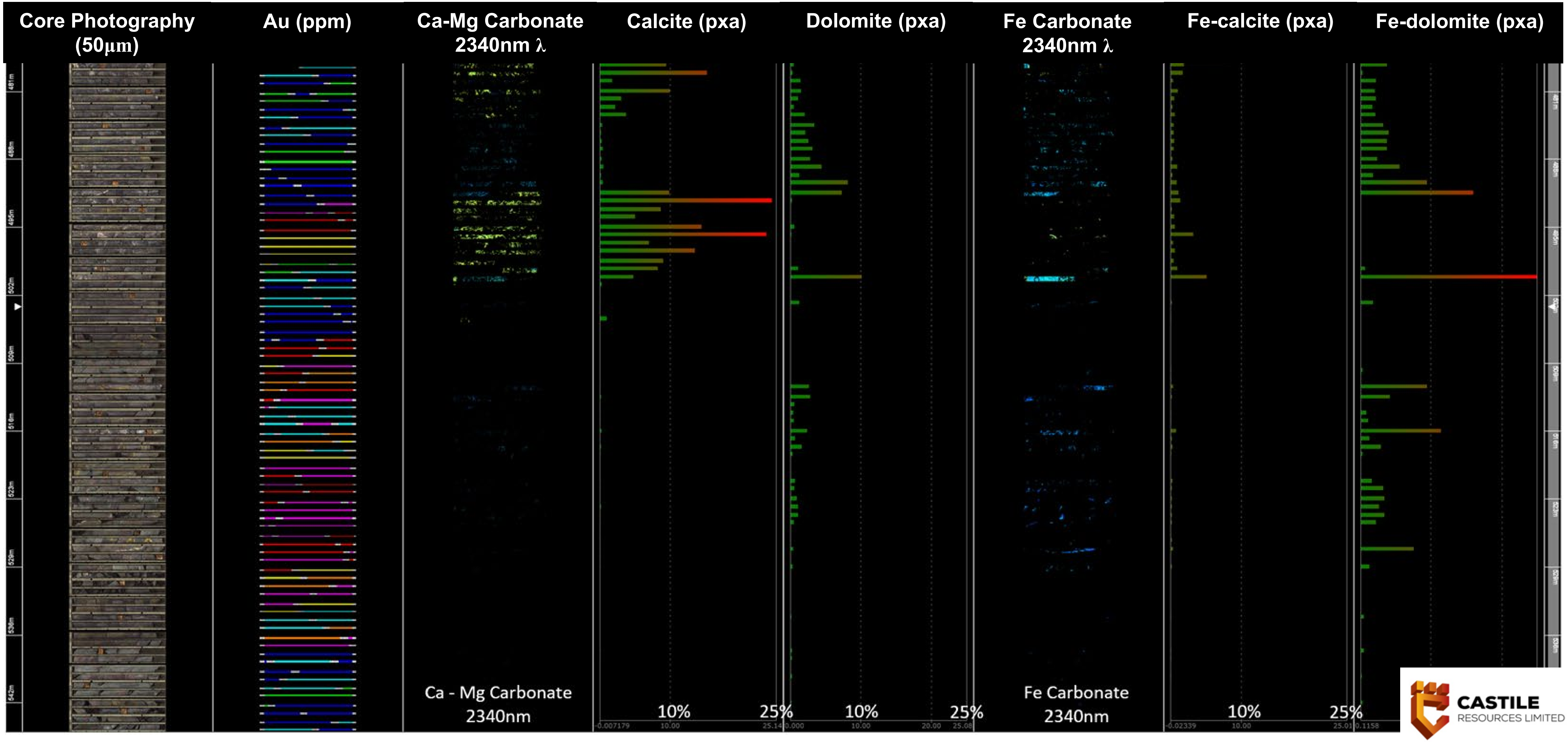
- Mineral classification map highlights brecciation and mineral replacement in the 'root zone.'
- False color spectral imagery provides important relative timing evidence of multiple mineralization and alteration events with similar mineral assemblages.

Carbonates



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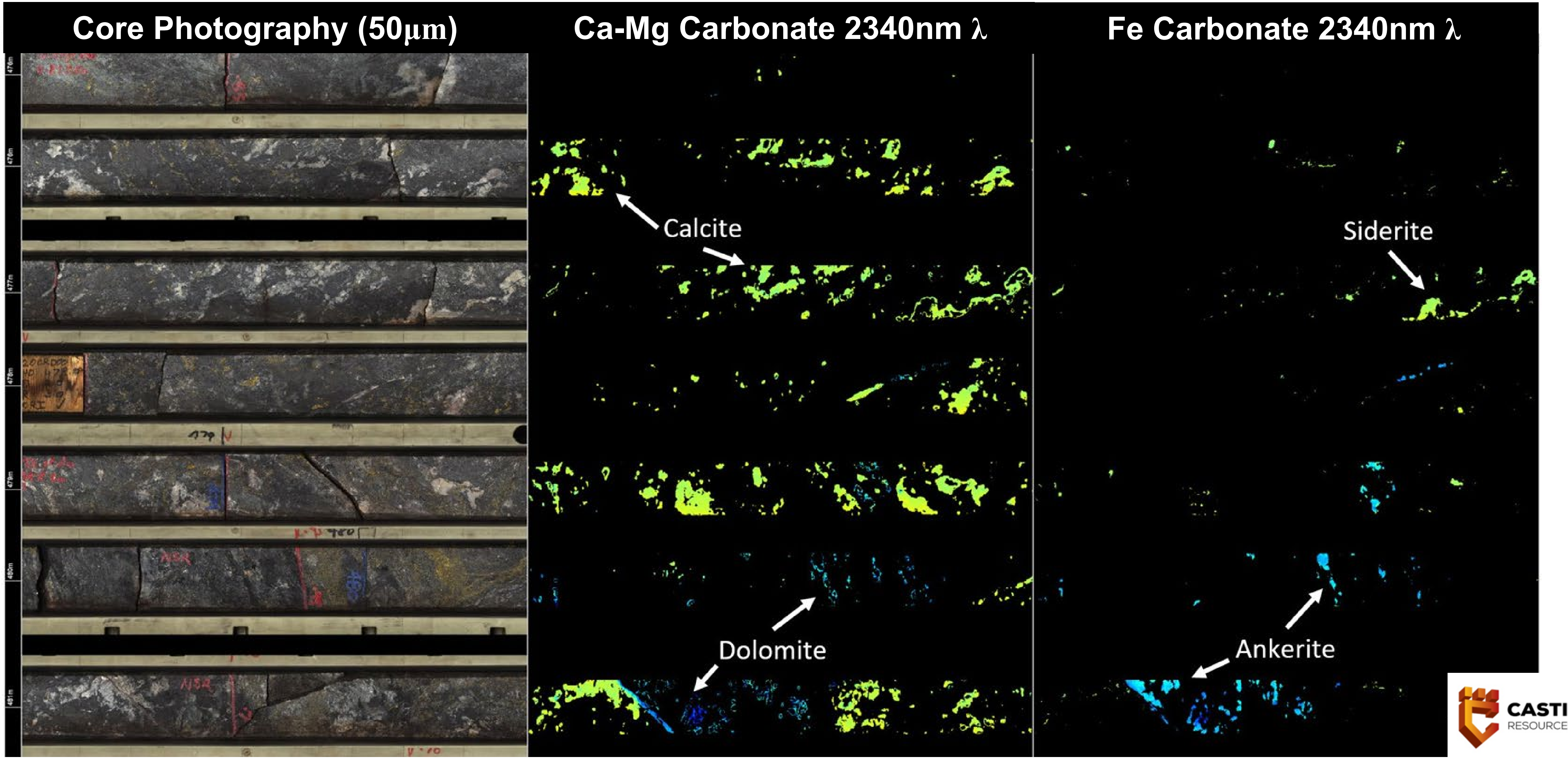
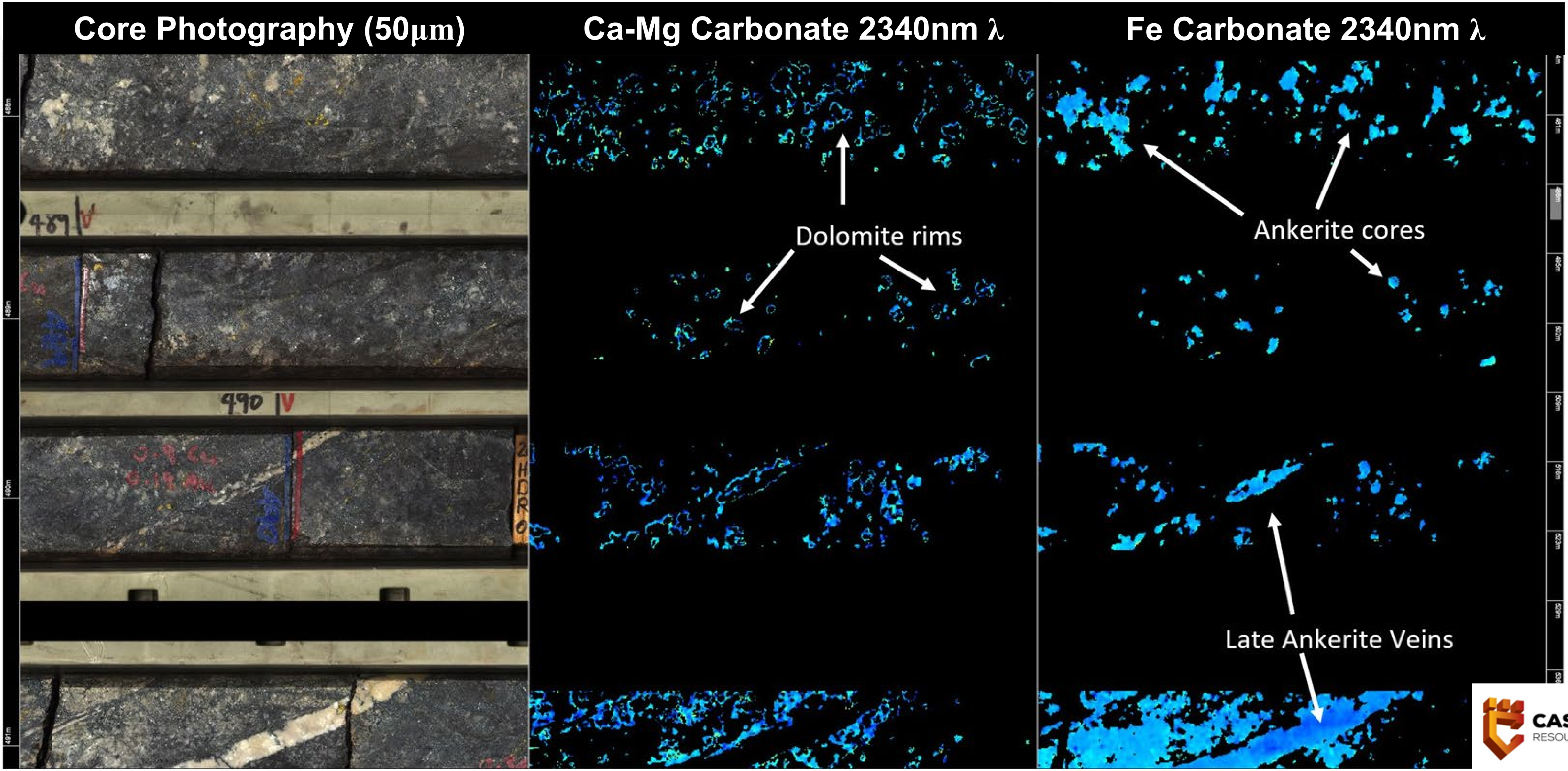
Carbonate texture



Carbonate chemistry

LKI Consulting



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Mineralization

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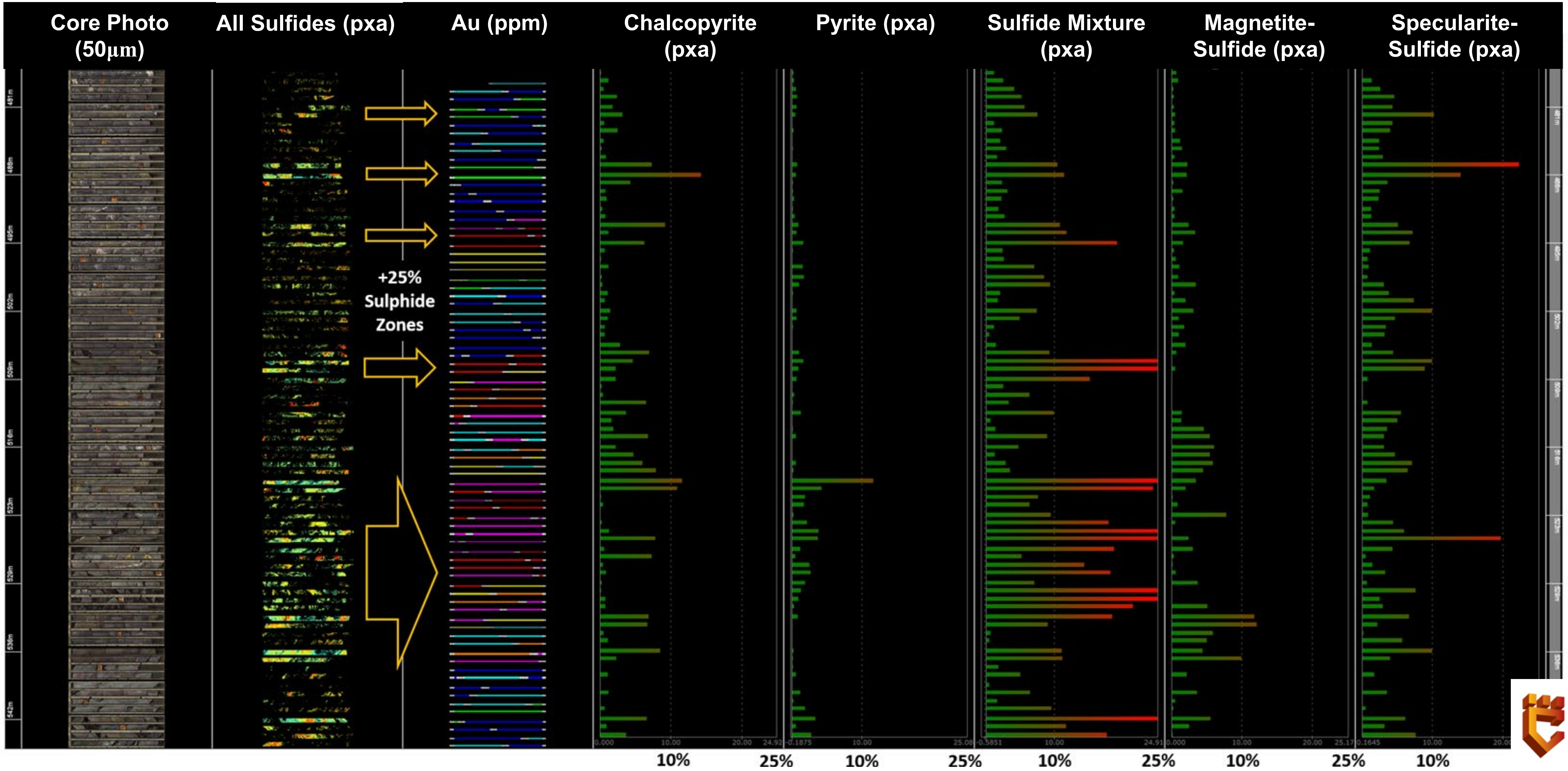

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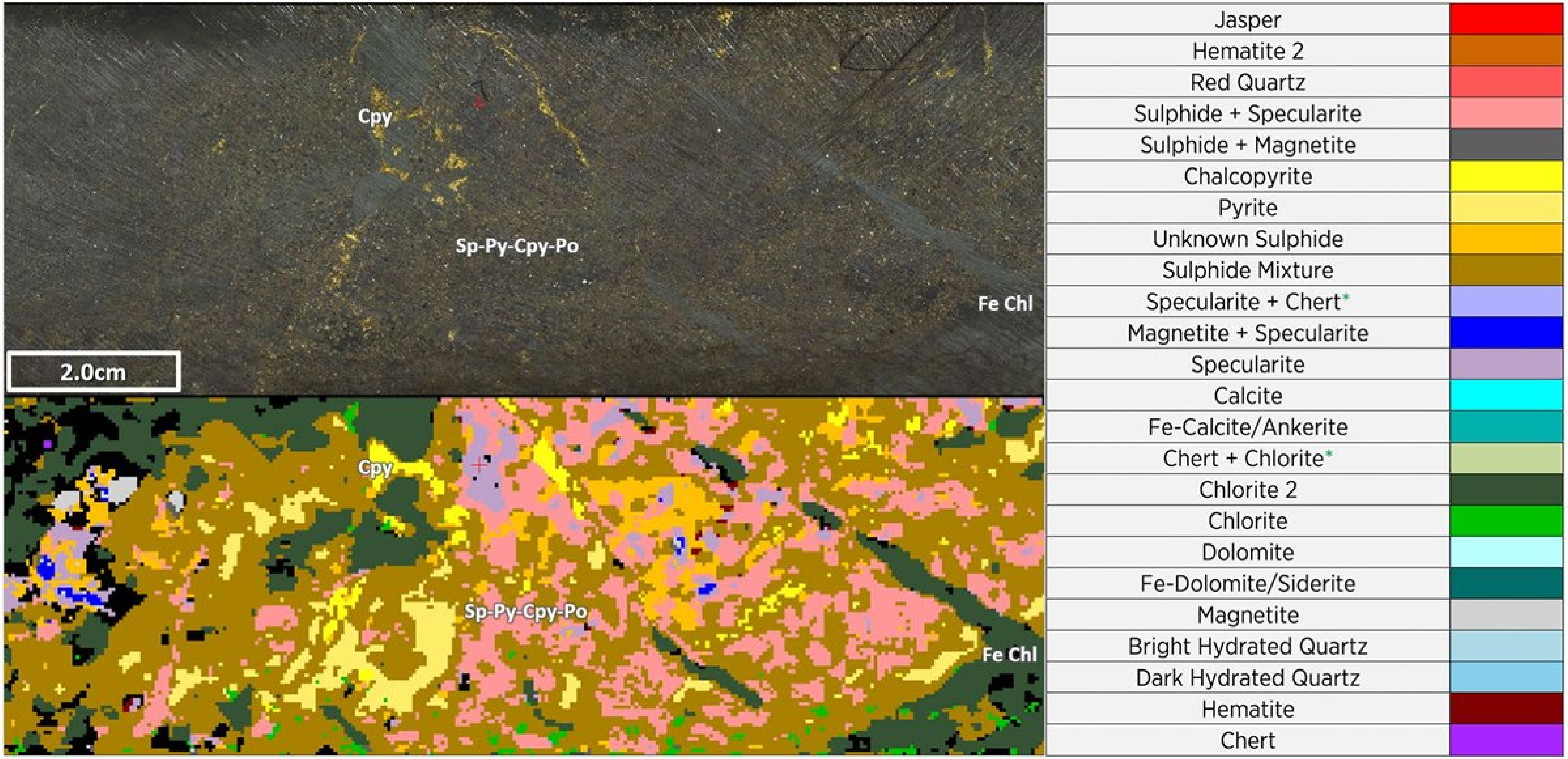
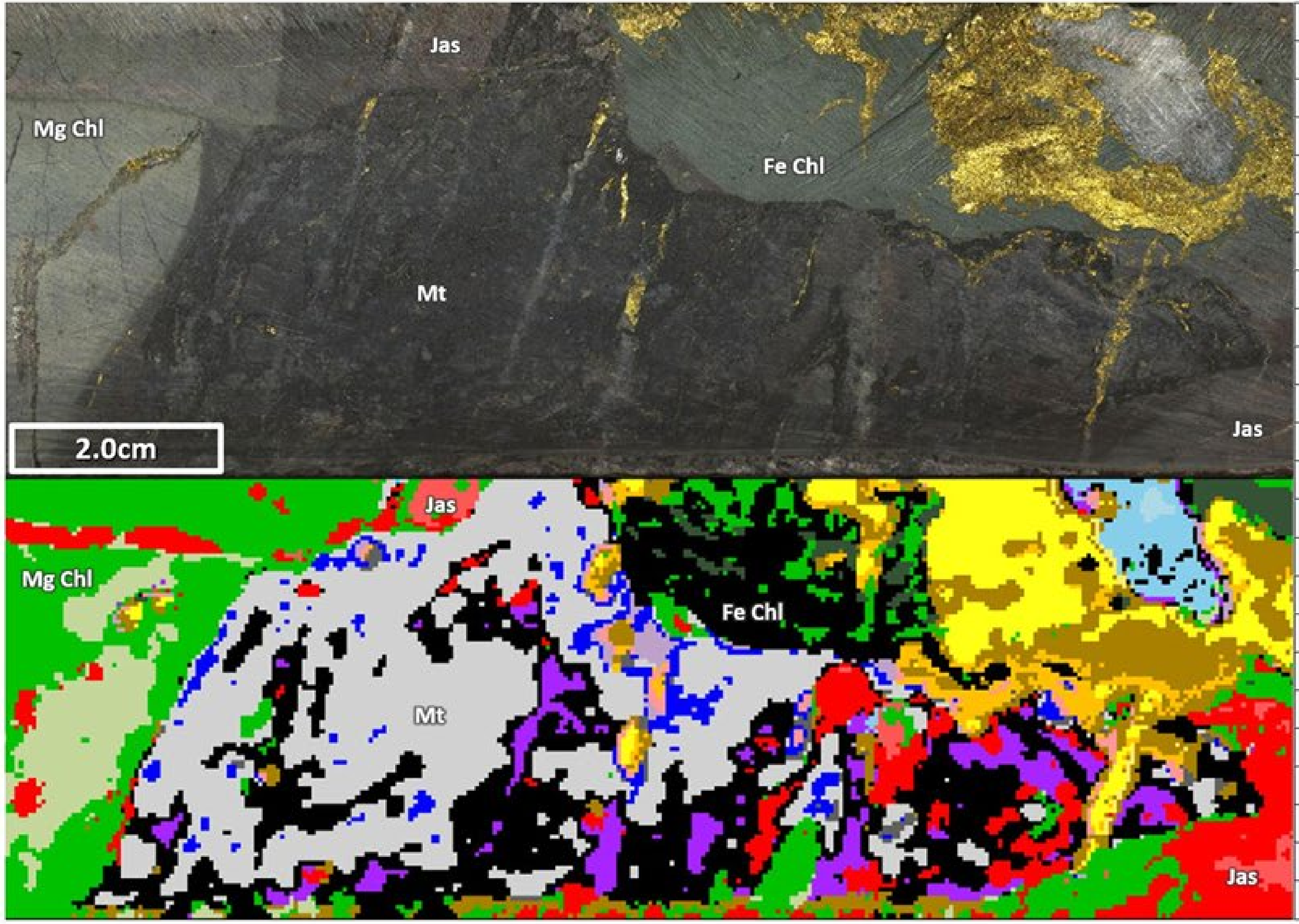
Mineralization textures



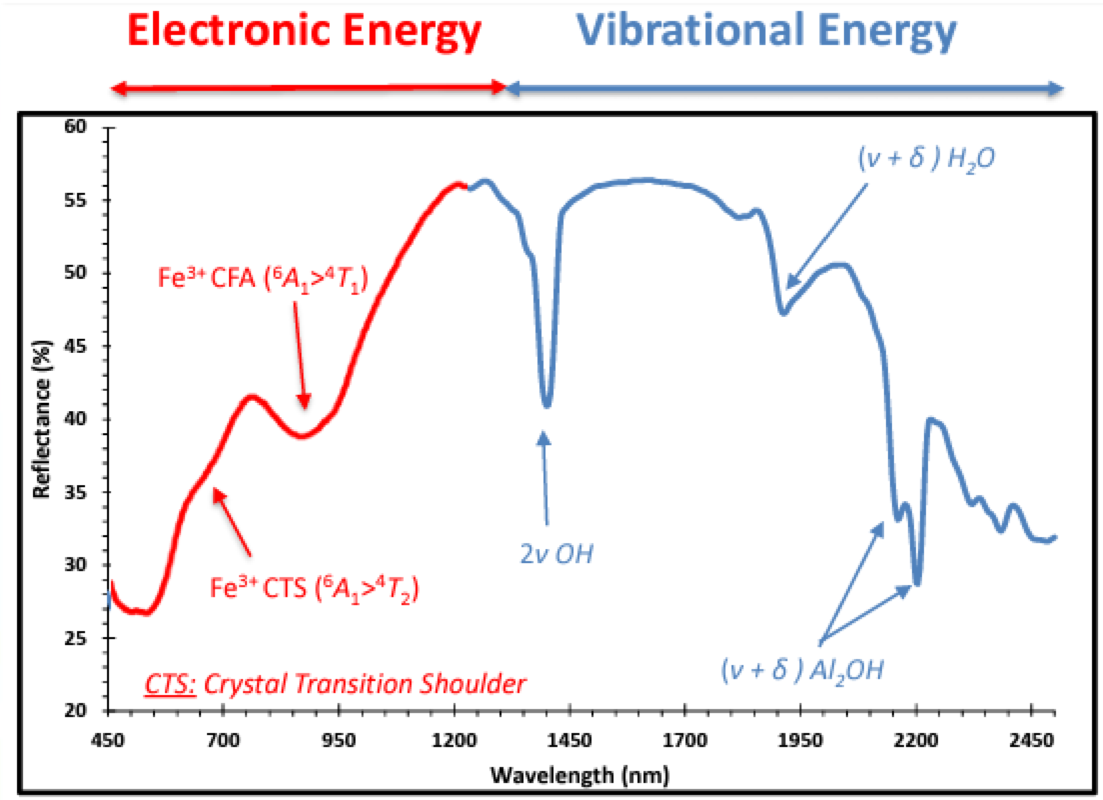
Mineralization textures



Jasper	🟥
Hematite 2	🟧
Red Quartz	🟥
Sulphide + Specularite	🟥
Sulphide + Magnetite	⬛
Chalcopyrite	🟨
Pyrite	🟨
Unknown Sulphide	🟧
Sulphide Mixture	🟫
Specularite + Chert*	🟪
Magnetite + Specularite	🟦
Specularite	🟪
Calcite	🟦
Fe-Calcite/Ankerite	🟦
Chert + Chlorite*	🟩
Chlorite 2	🟩
Chlorite	🟩
Dolomite	🟦
Fe-Dolomite/Siderite	🟦
Magnetite	⬜
Bright Hydrated Quartz	🟦
Dark Hydrated Quartz	🟦
Hematite	🟫
Chert	🟪

Case Study 2: VNIR-SWIR applications in Fe-ore

Requirements of the EM in iron ore



This spectrum is a mixture of hematite and kaolinite.

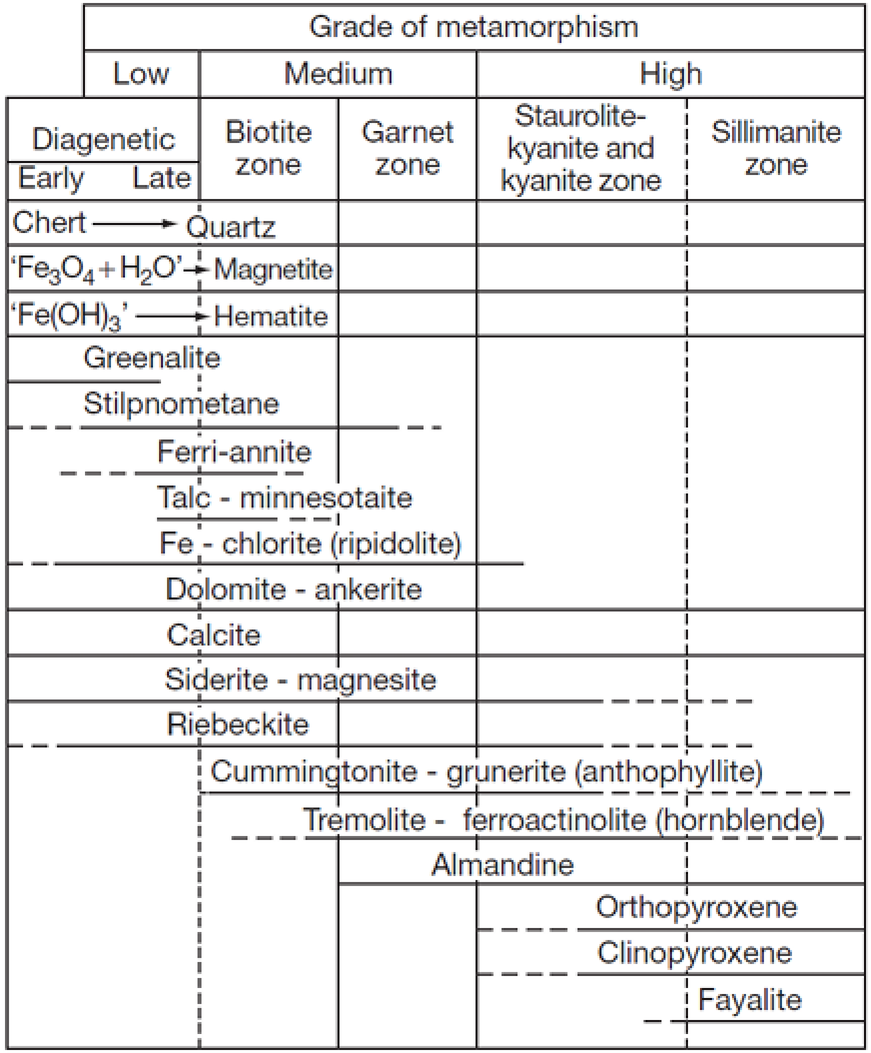
- Absorbing energy initiates a reaction whereby the **excited electrons** jump to higher **energy levels.**
- This leaves a fingerprint in the **VNIR** range recorded as crystal field absorptions (i.e., CFA).

- This absorbing radiation can also cause molecules to **vibrate** which is recorded in the **SWIR**, as **overtones** and **combinations** of **bending (δ) and stretching (ν)** fundamental modes.

How can hyperspectral assist in sedimentary Fe-ore?

- Why is the characterization of gangue mineralogy so important for downstream processing?
  - Si increases the slag content.
  - Al increases the viscosity of the melt.
  - P is costly to remove and increases brittleness.
  - S increases emissions of sulfur oxides by the plant.
  - Mg decreases the strength of both the pellets and sinters.

- Overall, how can hyperspectral imaging be a reliable assistant to characterize both the ore and gangue mineralogy, as well as their associated **textures?**



Source: Modified from Klein (2005)

Biwabik Iron Fm (Mesabi Range, MN)

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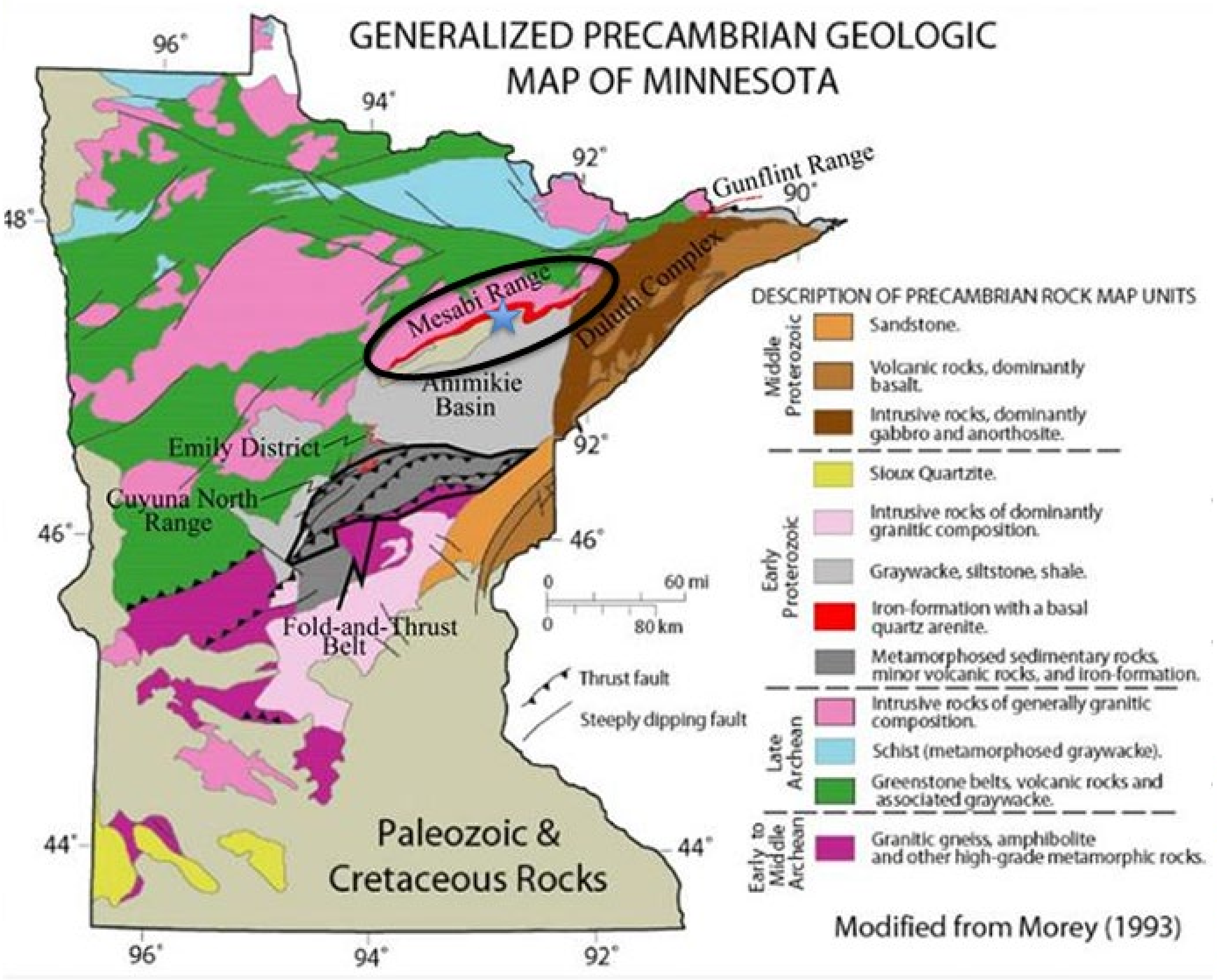

Modified from Morey (1993)

- The Biwabik Iron Formation, Mesabi Range, MN (USA).
- These are sedimentary, granular iron formations (GIF).
- The Mesabi Range produces 90% of all US Fe.
- When first mining, production comprised of high-grade “natural” hematite ores.
- Today, low-grade magnetite ores are enriched and taconite pellets are produced.

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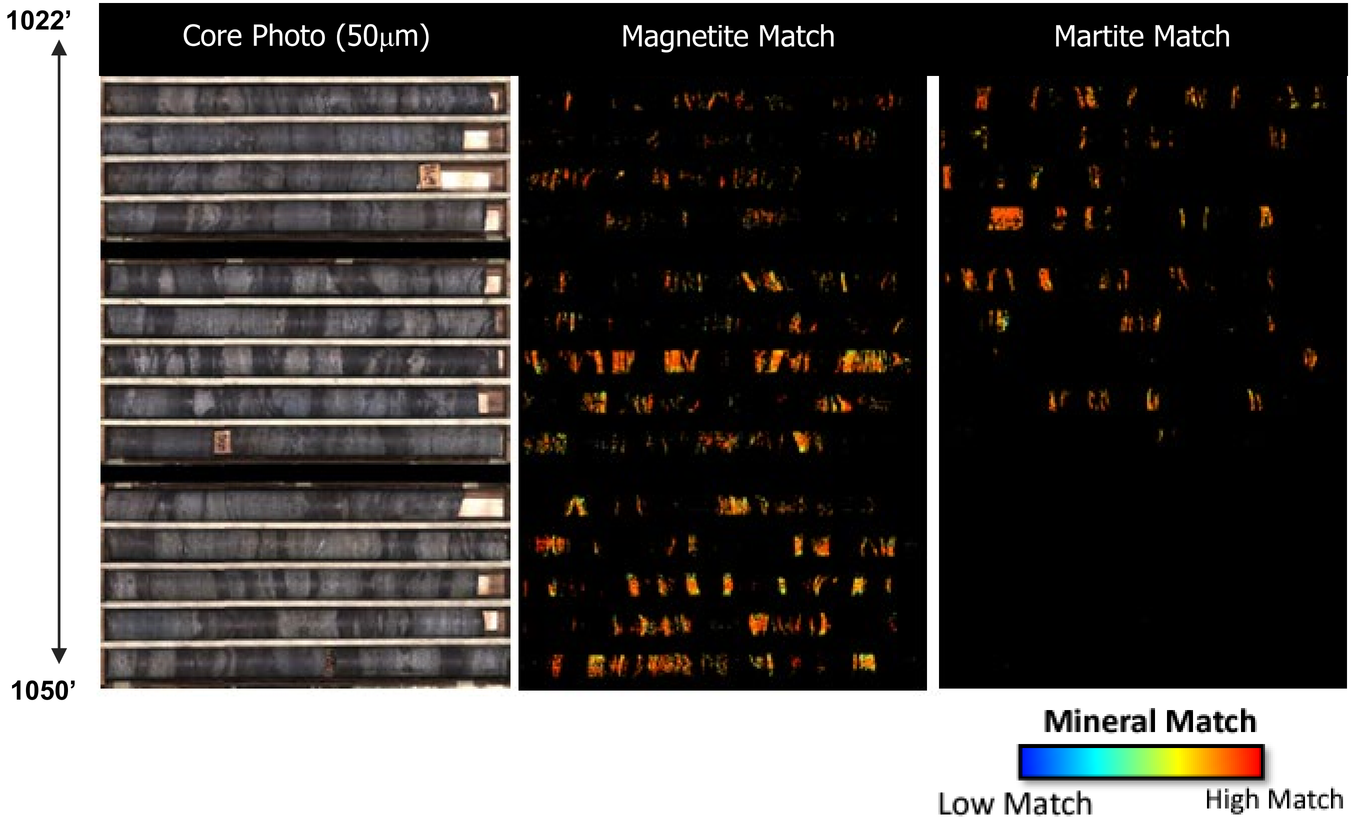
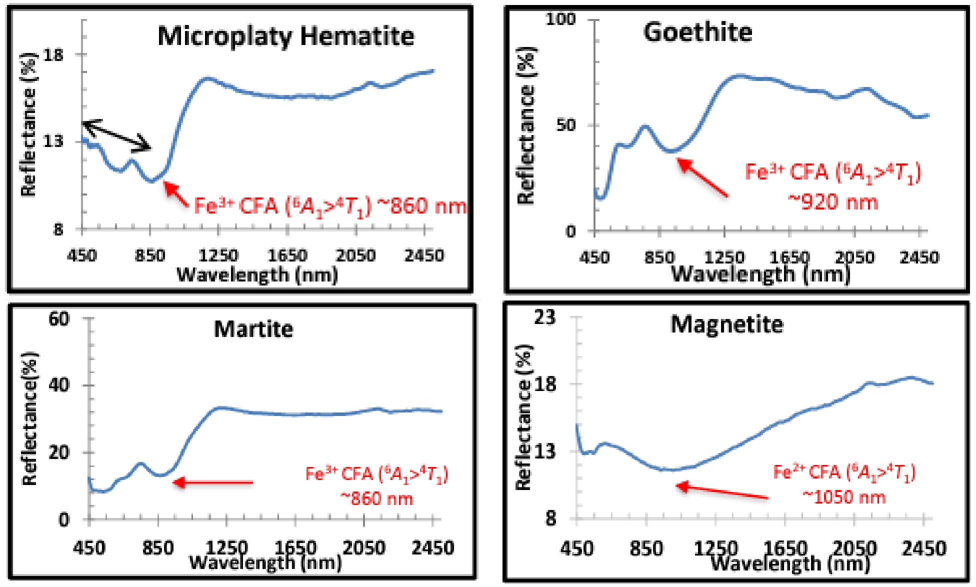
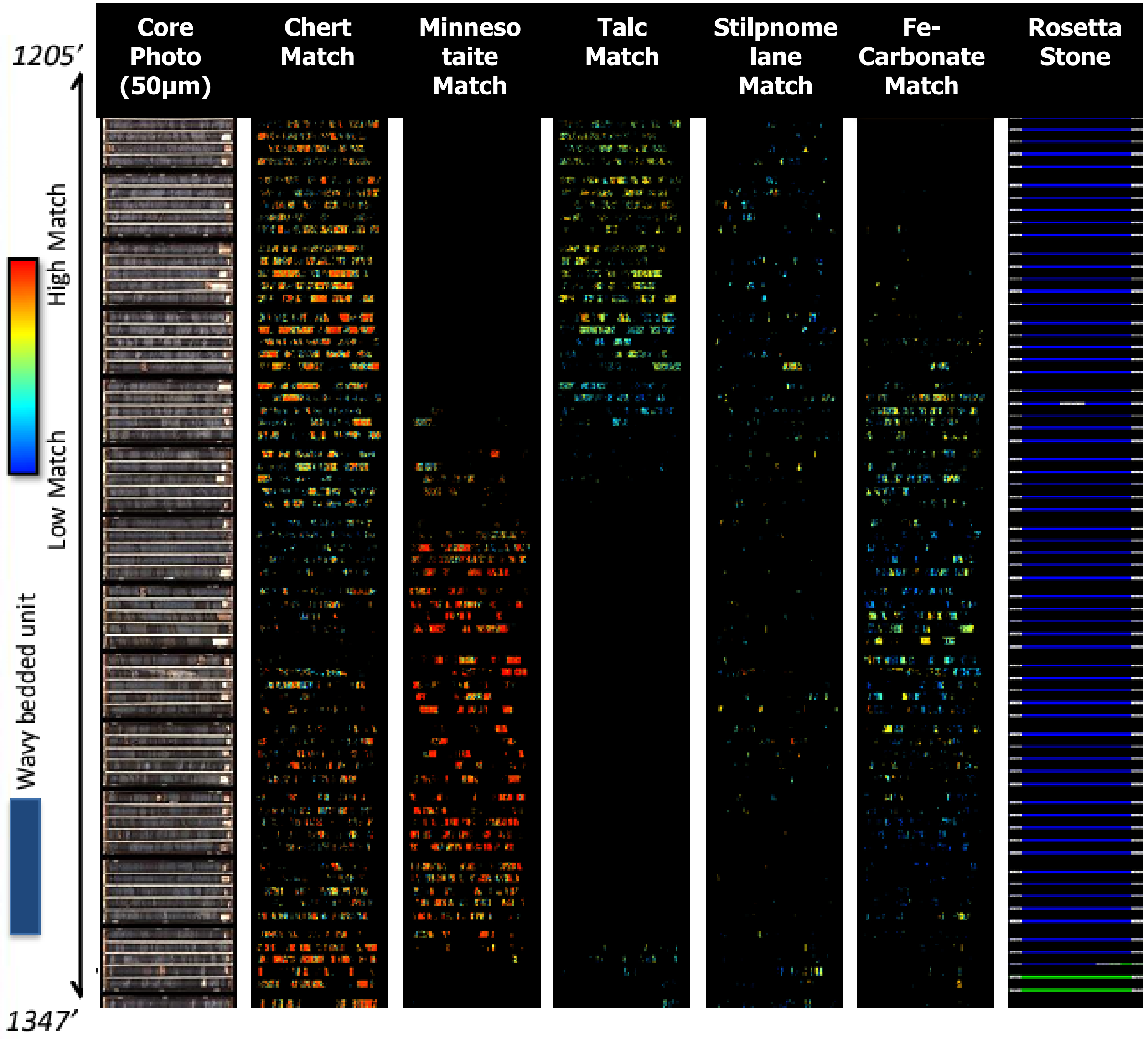
Fe-oxide species in GIFs

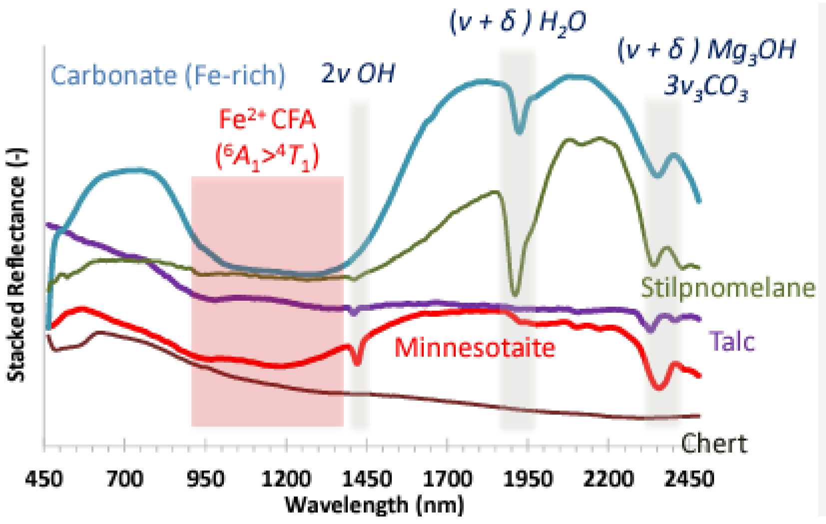




- VNIR: capability to consistently separate magnetite from hematite.
  - The magnetite / martite ratio is critical for pellet production.
- Other mapped species in this project: goethite and microplaty hematite.

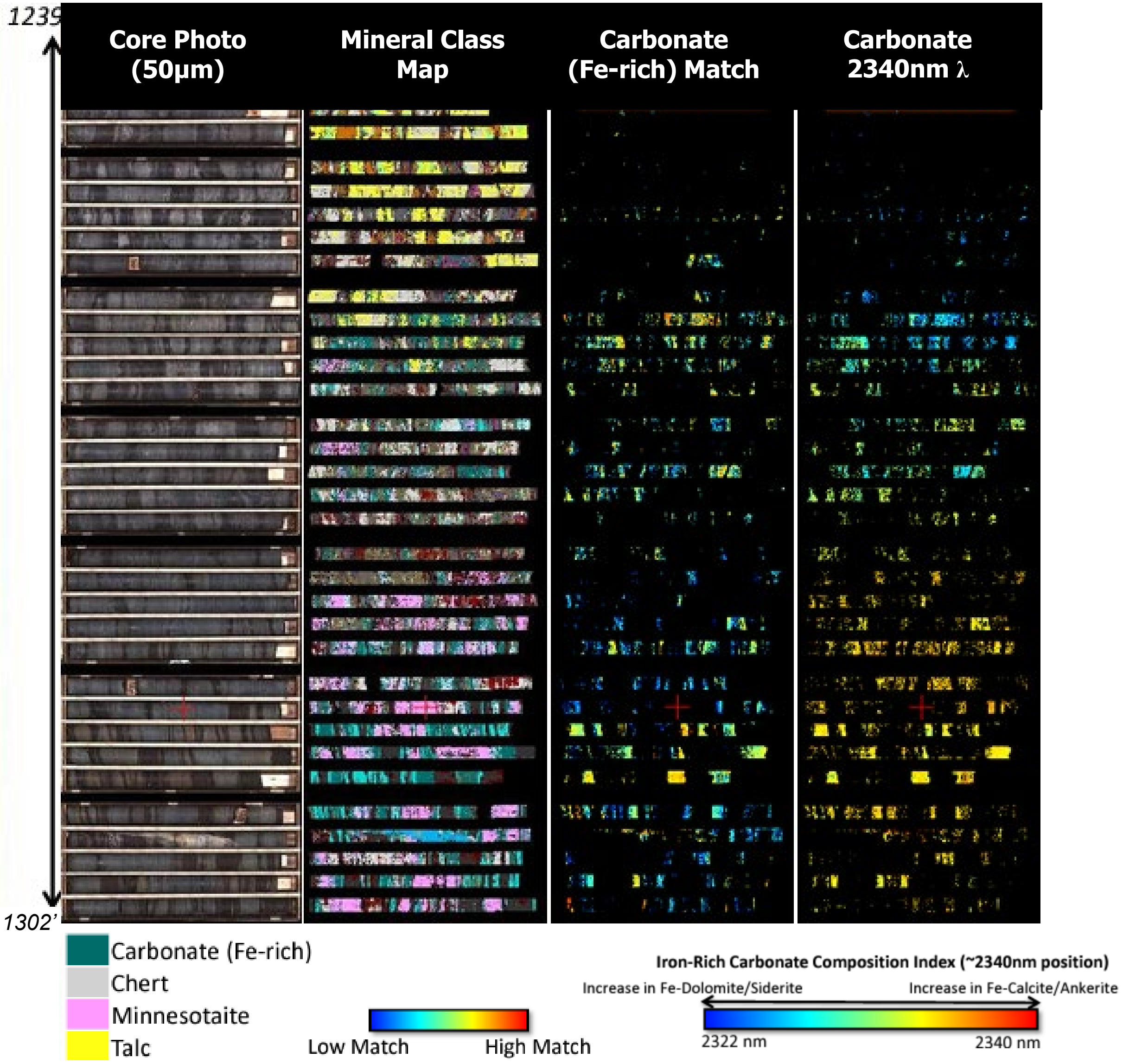
GIF gangue mineralogy

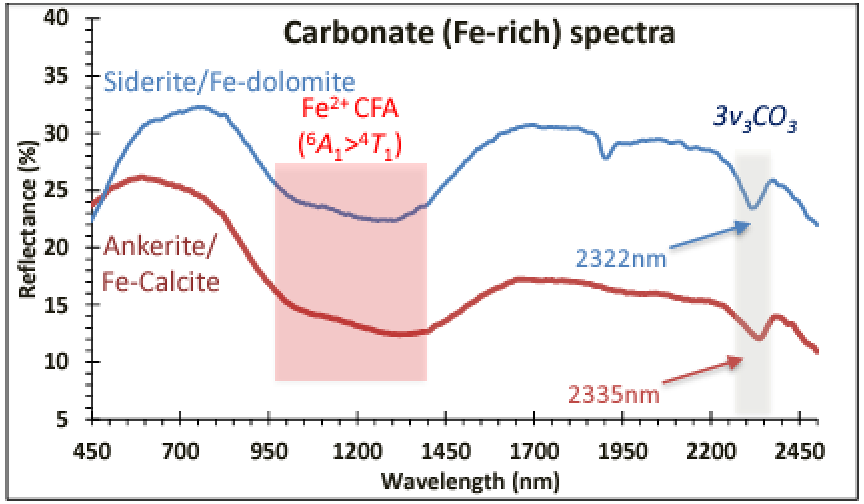




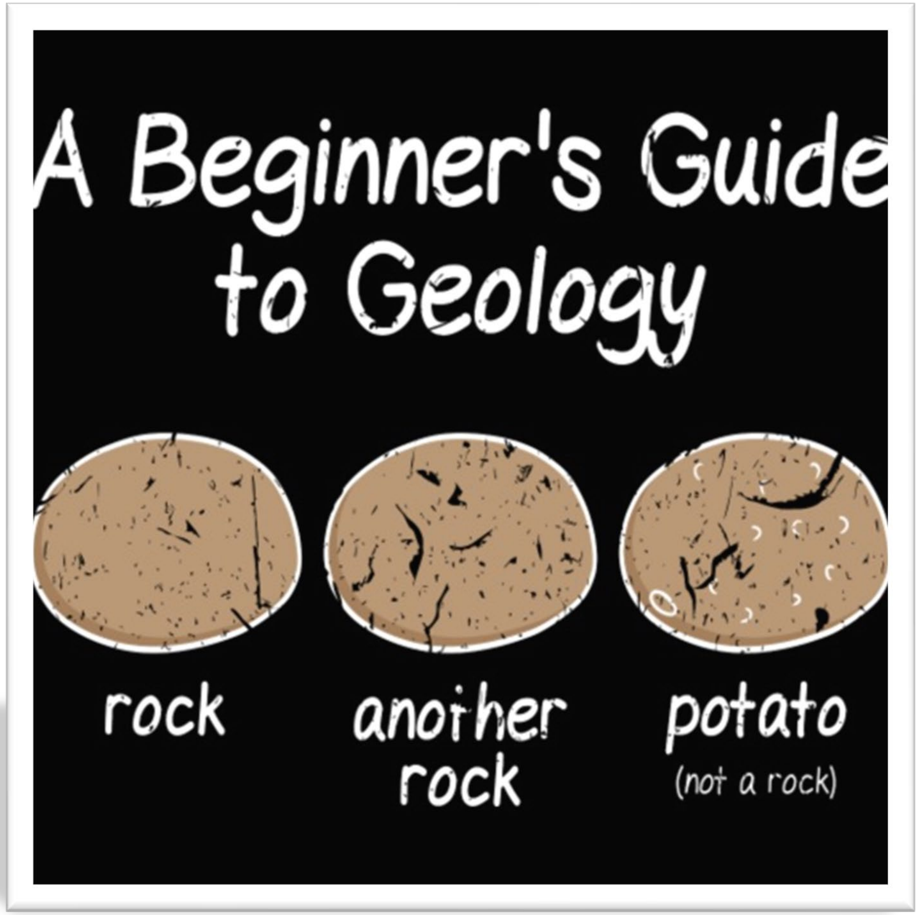
- Successfully mapped the well-known BIF metamorphic mineralogy (e.g., Klein, 2005 and McSwiggen, 2008).
- Advantages of consistent and continuous mineralogy from HIS:
    - Identification and mapping of deleterious minerals.
    - Aid in establishing mineral paragenesis.
    - Help to refine the existing stratigraphic "Rosetta Stone" (Severson, 2009).

Fe-carbonate mineral composition





- Fe-carbonate is the main carbonate species.
- The 2340nm feature shifts from 2322nm to 2335nm, i.e., from sideritic (or Fe-dolomitic) to ankeritic (or Fe-calcitic) composition.
- The short wavelength Fe-carbonates occur at the transition between the talc and minnesotaite-rich units.



Geometallurgy Applications

Hyperspectral & geometallurgy

- Phyllosilicate “clay” minerals commonly occur as gangue minerals in porphyry deposits
- These minerals can have a significant impact on all aspects of mineral processing
  - Development: ground support and infrastructure
  - Mining: blasting and caving behavior
  - Comminution: crushing and grinding (energy consumption), liberation, throughput
  - Recovery: flotation, gravity and magnetic separation, leaching
  - Waste & Tailings: dewatering, acid neutralization, reclamation
- But we’re not going to talk about clays today…

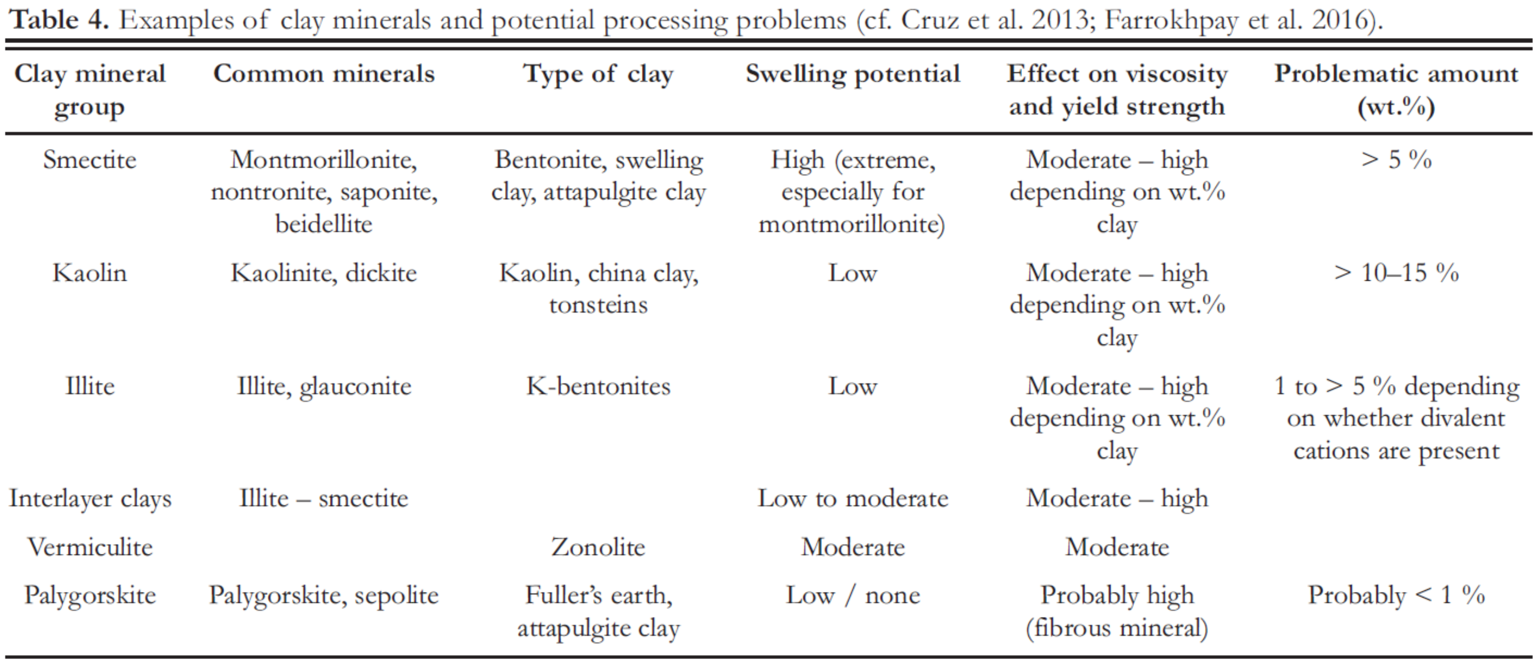
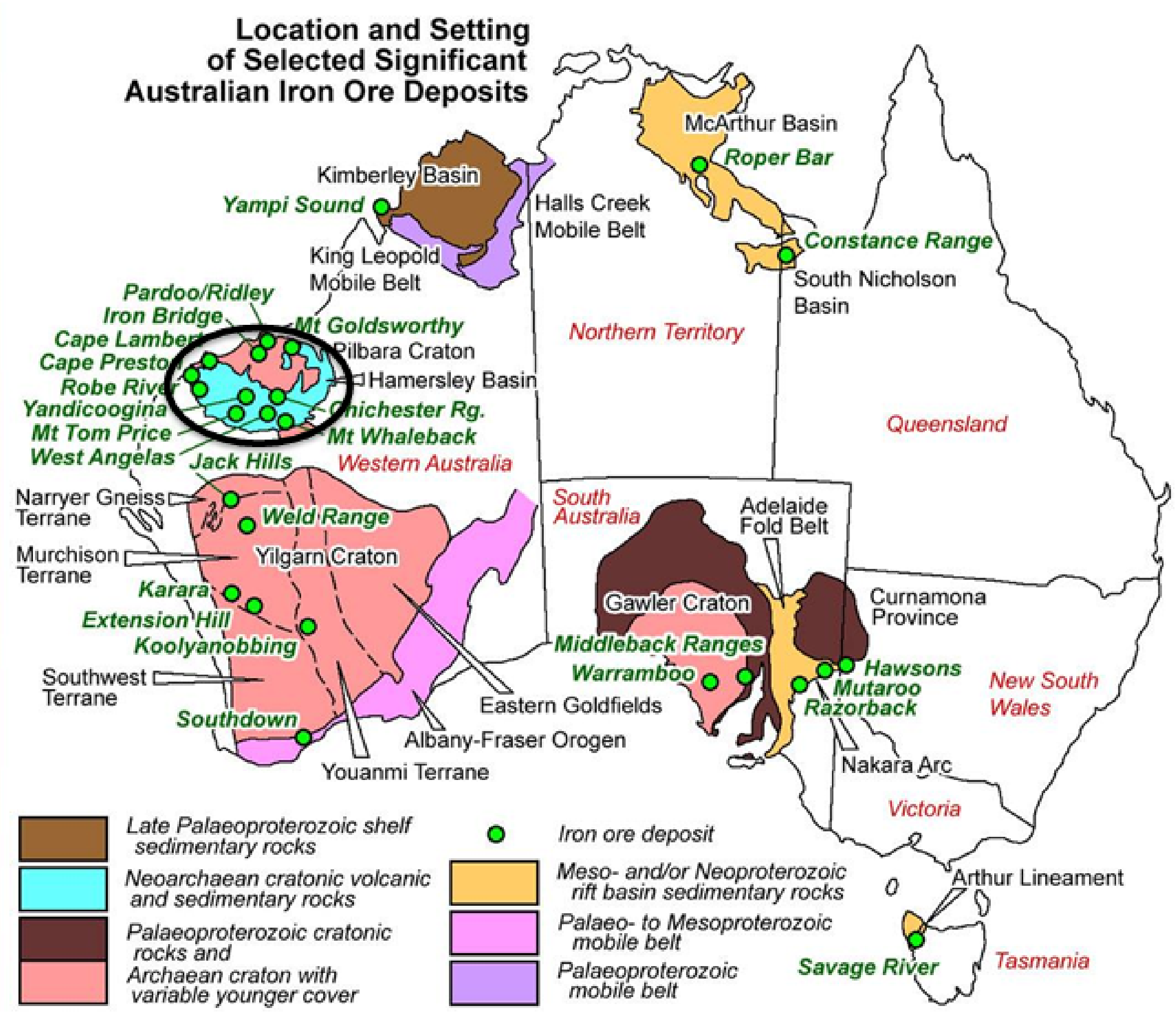


Table 4. Examples of clay minerals and potential processing problems (cf. Cruz et al. 2013; Farrokhpay et al. 2016).

Clay mineral group	Common minerals	Type of clay	Swelling potential	Effect on viscosity and yield strength	Problematic amount (wt.%)
Smectite	Montmorillonite, nontronite, saponite, beidellite	Bentonite, swelling clay, attapulgite clay	High (extreme, especially for montmorillonite)	Moderate – high depending on wt.% clay	> 5 %
Kaolin	Kaolinite, dickite	Kaolin, china clay, tonsteins	Low	Moderate – high depending on wt.% clay	> 10–15 %
Illite	Illite, glauconite	K-bentonites	Low	Moderate – high depending on wt.% clay	1 to > 5 % depending on whether divalent cations are present
Interlayer clays	Illite – smectite		Low to moderate	Moderate – high	
Vermiculite		Zonolite	Moderate	Moderate	
Palygorskite	Palygorskite, sepolite	Fuller’s earth, attapulgite clay	Low / none	Probably high (fibrous mineral)	Probably < 1 %

Berry and Hunt, 2017

Case study 5: BIFs and BIDs in Australia



www.portergeo.com.au

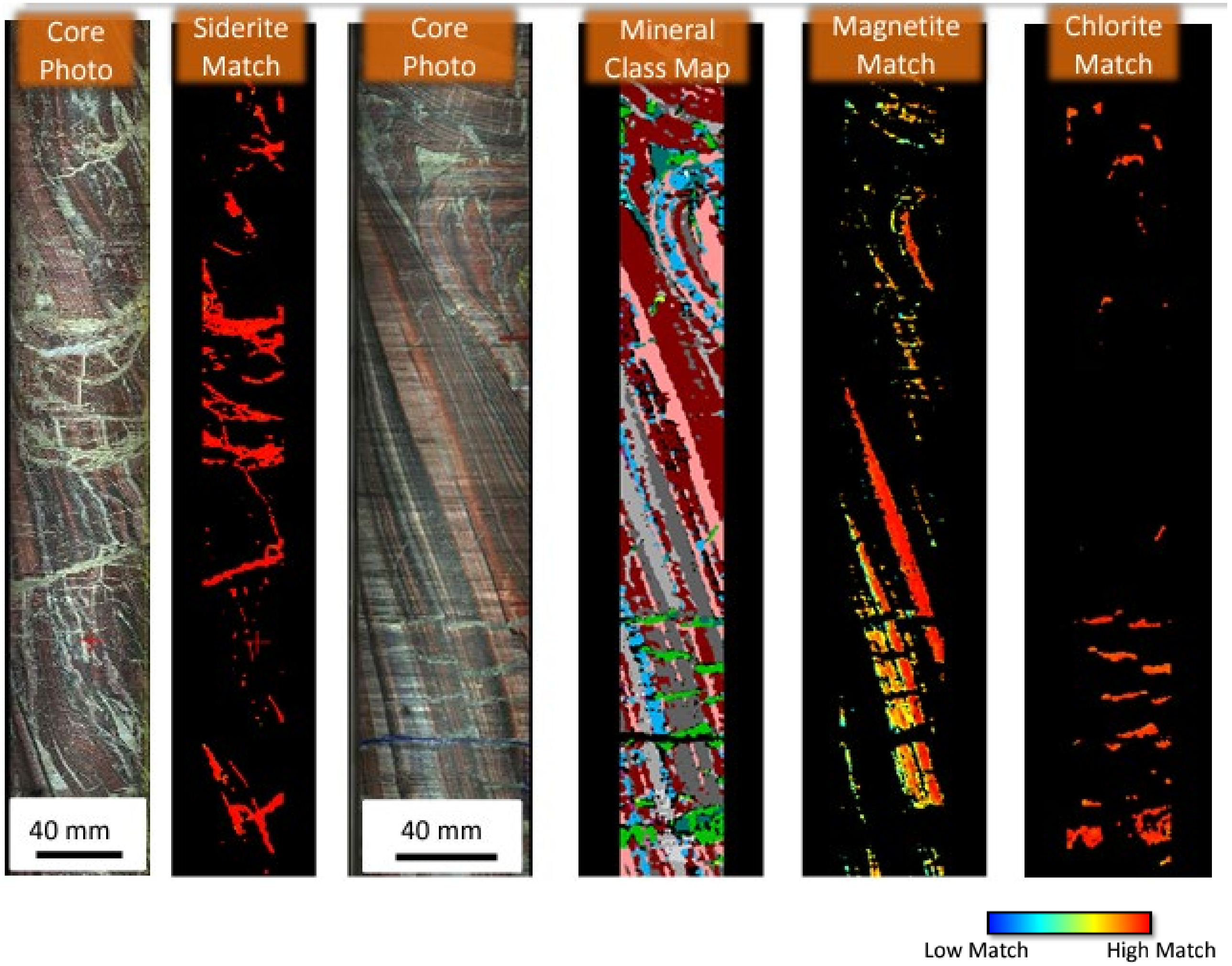
- BIF drill cores from the Pilbara Craton, WA
- Enriched BIR cores (or BID) from the Hamersley Basin, WA

- BID: bedded iron deposits
  - Originally BIF that are enriched by superimposed hypogene and supergene processes.
  - These are high grade iron ores.

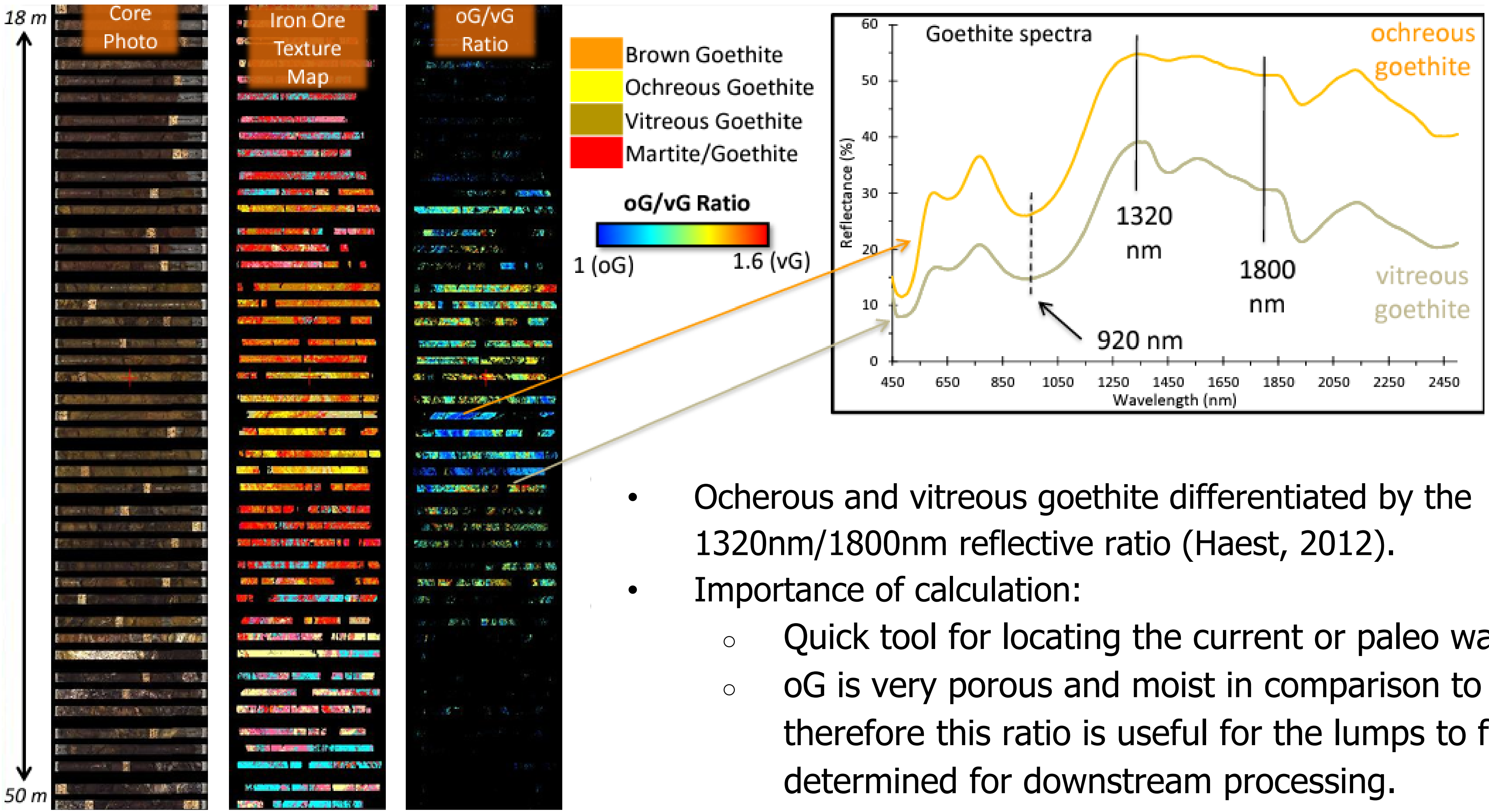
BIF mineralogy and texture

- Low grade metamorphic mineralogy similar to Biwabik Iron Formation.
- Meso- to micro-scale banding of BIFs can be mapped with the 500um pixel size.
- Textural relationships: bedded vs veined textures.
- Quick understanding of the paragenesis; important for geological models.

Mineral Name	RGB Code	Colour
Jasper + Fe-Carbonate	255,151,151	🟥
Chert	209,209,209	⬜
Chert-Carbonate	0,176,240	🟦
Chert-Magnetite	166,166,166	⬜
Chert-Silicate	163,41,122	🟪
Goethite	255,255,20	🟨
Jasper	255,0,0	🟥
Maghemite	204,102,0	🟫
Magnetite	95,95,95	⬛
Magnetite + Jasper	168, 0, 0	🟥
Magnetite-Silicate	52,82,52	🟩
Martite	167,37,255	🟪
Martite-Goethite	255,154,0	🟧
Carbonate	0,108,105	🟦
Carbonate-Quartz	188,255,255	🟦
Carbonate-Stilpnomelane	0,176,172	🟦
Chamosite	188,255,55	🟩
Chlorite	0,192,0	🟩
Kaolinite	148,138,84	⬛
Montmorillonite	175,175,255	🟪
Nontronite	105,105,255	🟦
Silica/Quartz	0,255,255	🟦

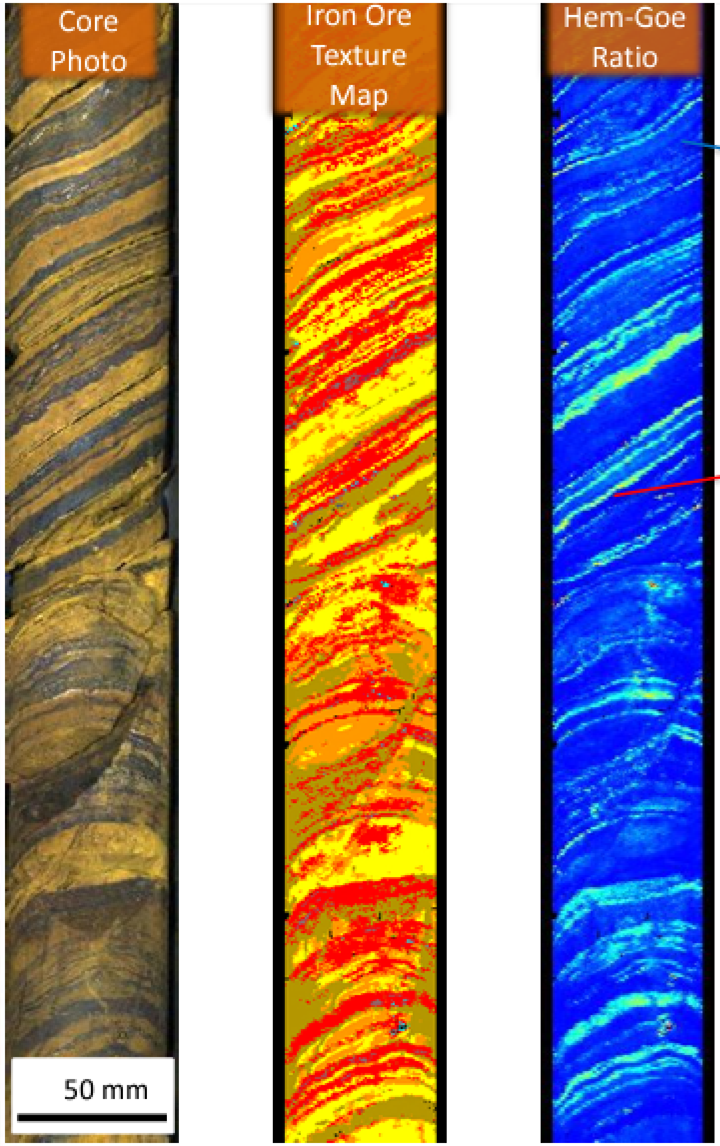


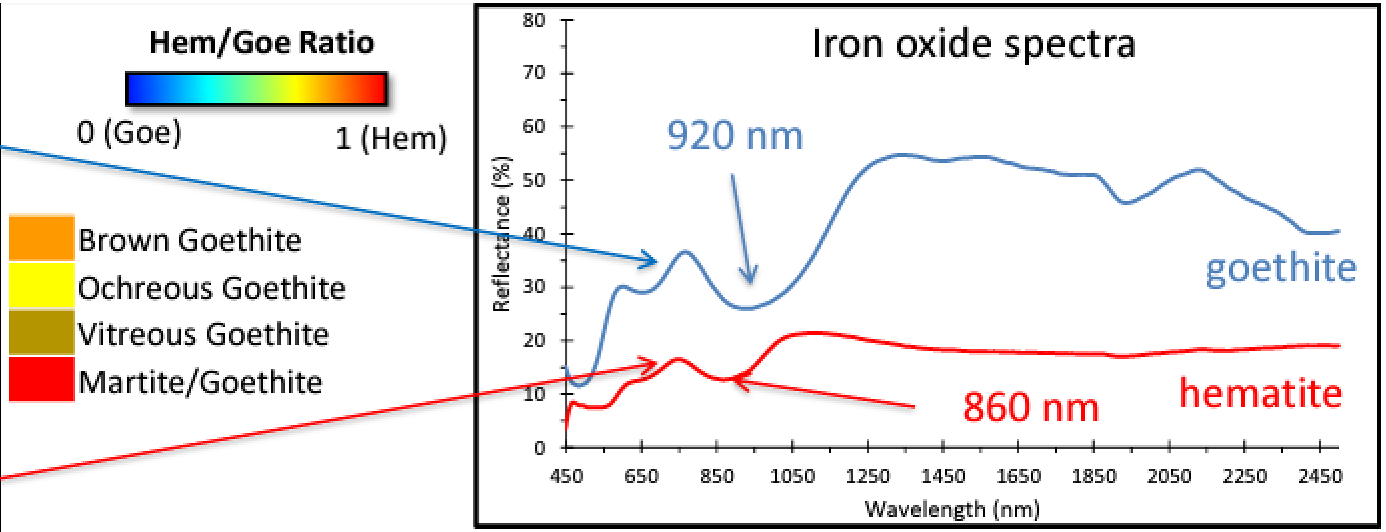
BID Fe-oxide mineral composition



- Ocherous and vitreous goethite differentiated by the 1320nm/1800nm reflective ratio (Haest, 2012).
- Importance of calculation:
  - Quick tool for locating the current or paleo water table.
  - oG is very porous and moist in comparison to vG, therefore this ratio is useful for the lumps to fine ratio determined for downstream processing.

BIFs / BIDs geometallurgy and grade control





- In the VNIR, the Fe-oxide feature shifts according to the relative abundance of hematite (~860nm) and goethite (~940nm).
- The hematite to goethite ratio varies from 0 (pure goethite) to 1 (pure hematite; Ramanaidou et al., 2008):

$$y = 1.5727\times10^{-4}\, x^2 - 0.2936x + 139.54$$
$$\text{(where } x = 900L\text{)}$$

- This provides vital information on grade control and geometallurgical properties.

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Spectral data applications in economic geology

Fundamentals of Economic Geology
CODES
April 11, 2024
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