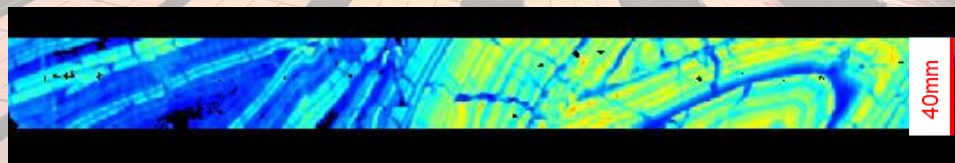


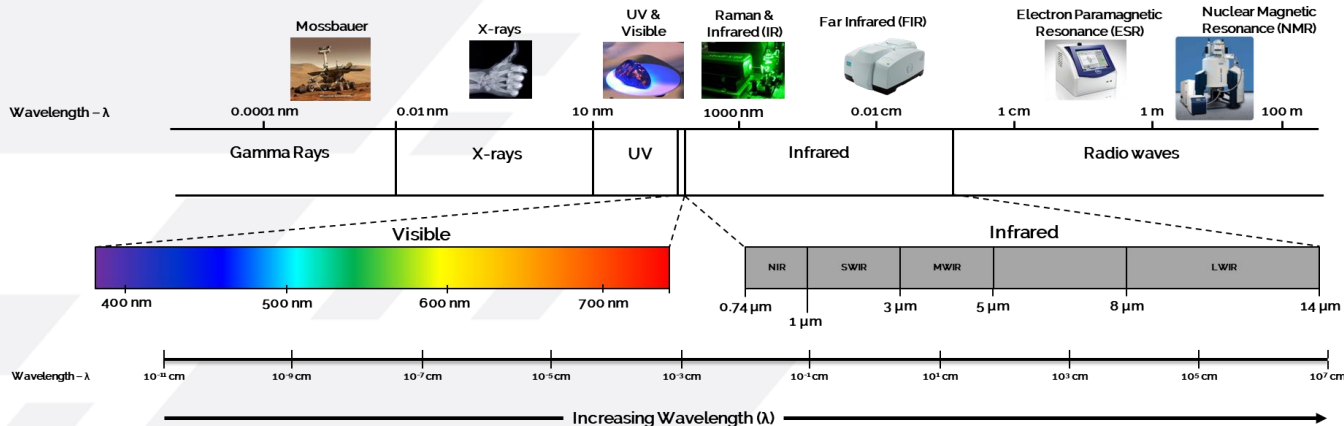
Application of Hyperspectral Core Imaging to Mineral Exploration (Iron Ore)

Lionel Fonteneau, Corescan, Ouro Preto (MG), Monday 20th May 2024



Infrared Spectroscopy

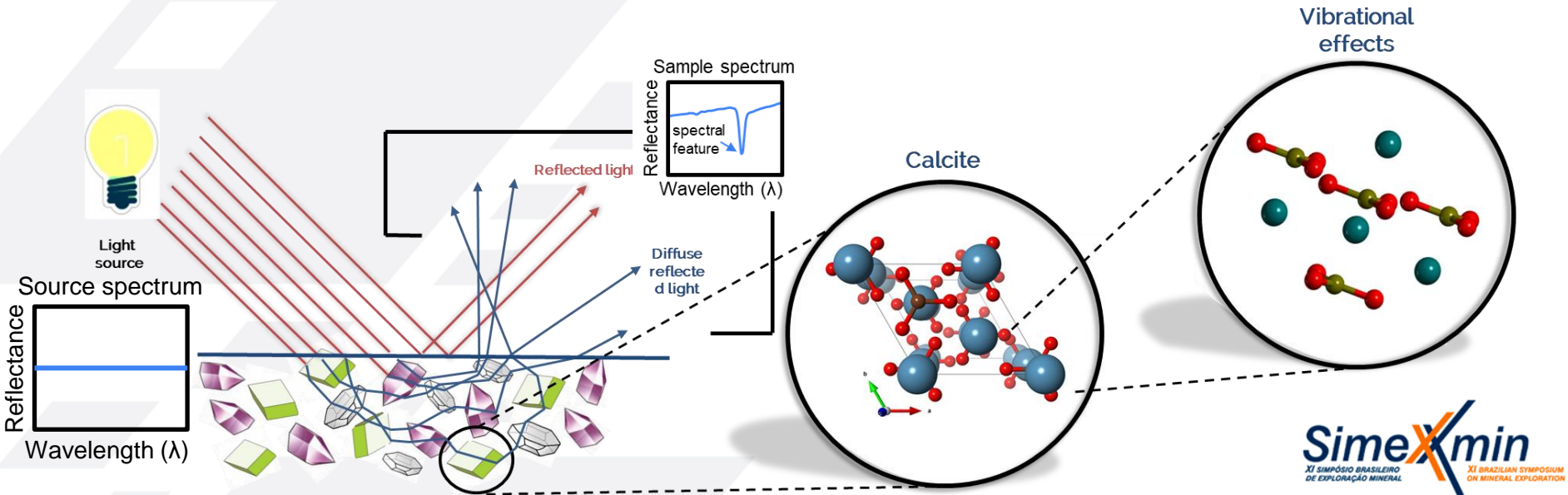
- Spectroscopy is the study of the absorption and emission of electromagnetic radiation (e.g., light) by matter, measured as a function of wavelength (or frequency).
- Used as a tool for characterizing the structures of atoms and molecules.
- Several types of EM radiation are used for the analysis of geological materials.
- Reflectance spectroscopy is one method used for mineral identification and geochemical analysis using energy in the Visible to Near Infra-red (VNIR) and Infrared (IR) range.



Reflectance Spectroscopy for Mineral Analysis

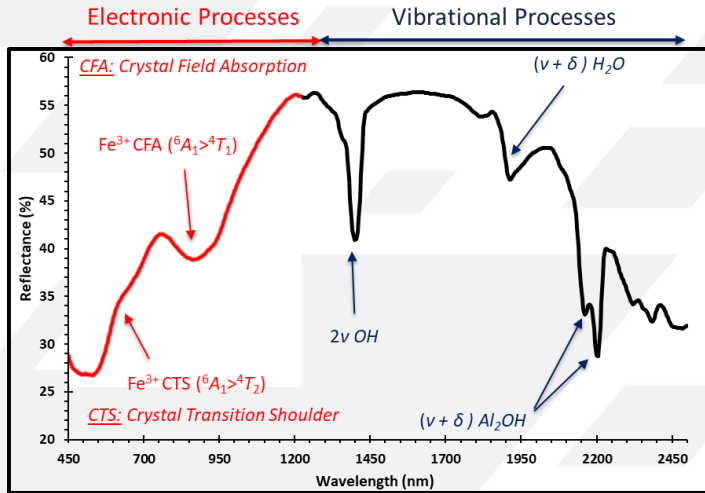
What happens if light directed on to a mineral surface?

- Some light is reflected directly back to the detector.
- Absorbed light (energy) interacts with the molecules in the sample material.
- This interaction causes changes to the energy of molecular bonds, either by causing changes in the electronic energy, and/or vibrational energy of the molecule*.



*and also rotational energy, in much higher wavelength ranges

Reflectance Spectroscopy: output



Example of hematitic shale reflectance spectrum

Reflectance spectroscopy directly records information about mineralogy.

- Each mineral is composed of molecular bonds that absorb energy at specific wavelengths.
- The particular combination of molecules in any given mineral (e.g., mineral composition and structure) results in a diagnostic spectrum.

VNIR (450–1350 nm):

- Iron Oxides
- REEs
- Pyroxenes
- Olivines
- Garnets
- ...

SWIR (1350-2500 nm)

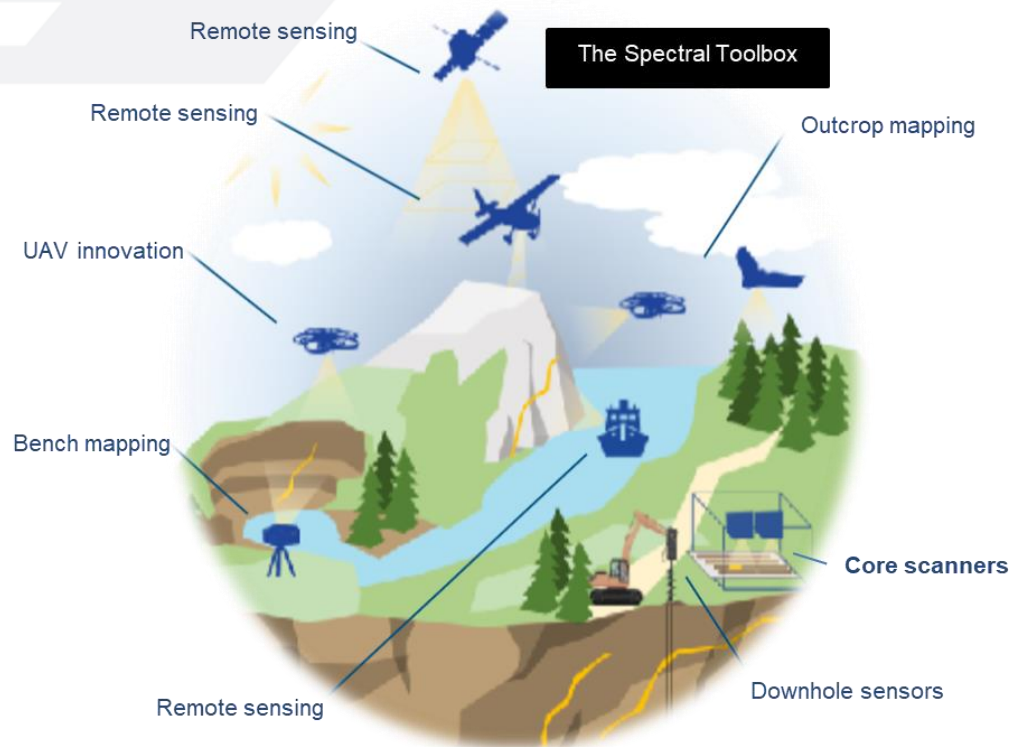
- OH-bearing minerals
- Silicates
- Carbonates
- Phosphates
- Sulphates
- ...

Some elemental substitutions within minerals can also be detected by variations in spectral features.

Reflectance Spectroscopy: Uses

Why use reflectance spectroscopy in mineral exploration?

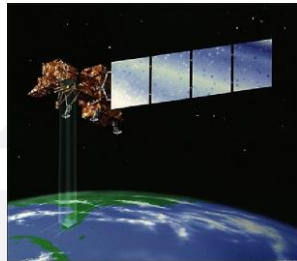
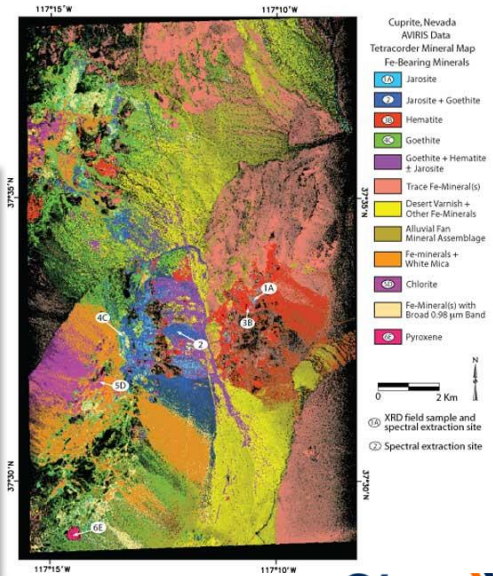
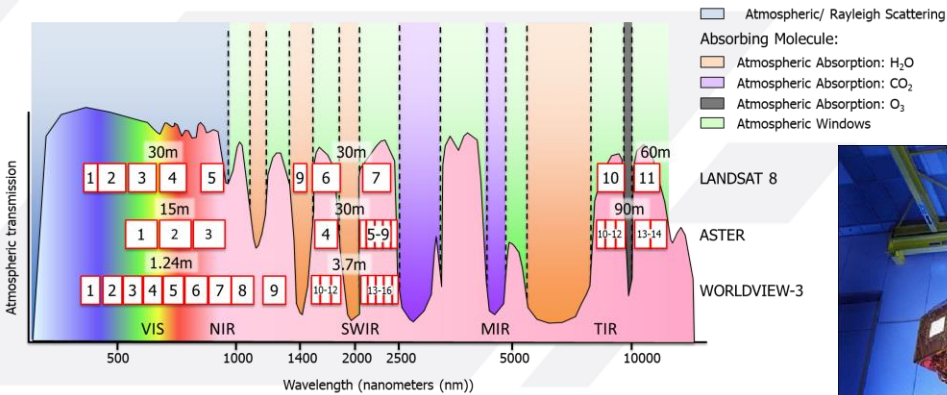
- Typically, fast and easy to acquire, and is non-destructive.
- One of the few techniques that identifies minerals (not elements).
- The method is sensitive to the chemical variations in functional groups (e.g., geochemical substitutions).
- Reflectance spectroscopy can be used to analyze a range of material types.
- For geological applications, this means it can be used to analyze different types of geological materials from outcrop to drill core to chips to powders to soils to dried slimes, etc.
- Instrumentation can be scaled from ~kilometers (e.g., airborne/satellite surveys) to micron scale (laboratory instruments, core-scanners).
- Spectral data can be used to deliver mineralogical knowledge, not only at the exploration stage but also across the entire mining cycle.



(after Jackisch et al., 2018)

First uses in mineral exploration – From distal source

- Imaging spectroscopy has been applied to mineral exploration for ~50 years.
- First data was generated using remote instruments (e.g. multispectral satellites).
- **Early instruments:**
 - **Landsat-1** 1972 (ERTS) with **4 spectral bands** in the VNIR
 - **Landsat-4** 1982 (Thematic Mapper) = first instrument to include **Band 7** or the “**Clay**” band



<https://directory.eoportal.org/web/eoportal/satellite-missions/l/landsat-7>



To proximal source

Corescan® HCI-4
(2005-present)



Laboratory



Spectrophotometers
(1950's-1960's)



The PIMA (early 1990's)

Hyperspectral profiling
Scanner



Hy-Logger™-3
(2000-2011)

Hyperspectral imaging
Scanner



Specim SisuRock
(2005-present)



Terraspec® (1990's – Present)

Field Spectrometers



PFRS
(1970s)

Hyperspectral Core Imager 4 or HCI-4

Specifications	HCI-3.2	HCI-4.1	HCI-4.2
RGB photography - spatial resolution	50 µm	25 µm	25 µm
Surface profiling - spatial resolution	500 µm	50 µm	50 µm
Spectrometer type	Imaging	Imaging	Imaging
Imaging spectrometer - spatial resolution	500 µm	500 µm	Up to 250 µm
Spectra per meter (1000mm x 60mm)	240,000	240,000	960,000
Spectral range – VNIR (nm)	450 – 1,000	450 – 1,000	450 – 1,000
Spectral range – SWIR (nm)	1,000 – 2,500	1,000 – 2,500	1,000 – 2,560
Spectral resolution (nm)	4nm	4nm	2nm
Core tray length (maximum)	1,550mm	1,550mm	1,550mm
Core tray width (maximum)	600mm	600mm	700mm
Supports material weighing	-	-	Yes
Supports pass-through workflow	-	-	Yes
Scanning speed	~10mm per second	~25mm per second	~Up to 30mm per second



Hyperpsectral core imaging: game changer



Sampling
(soils, core)

Quick
Log

Corescan
Spectral
Interpretation

Hyperspectral
Images

Supervised
Core Logging



Machine Learning
Prediction

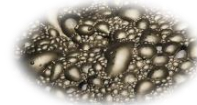
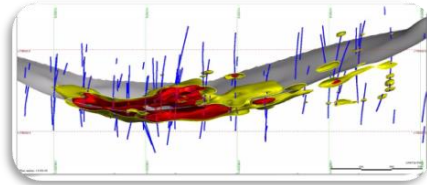
Resource
Modeling

Quantitative
Mineralogy

Complimentary
datasets
(geochemistry,
geophysics....)

Geometallurgy

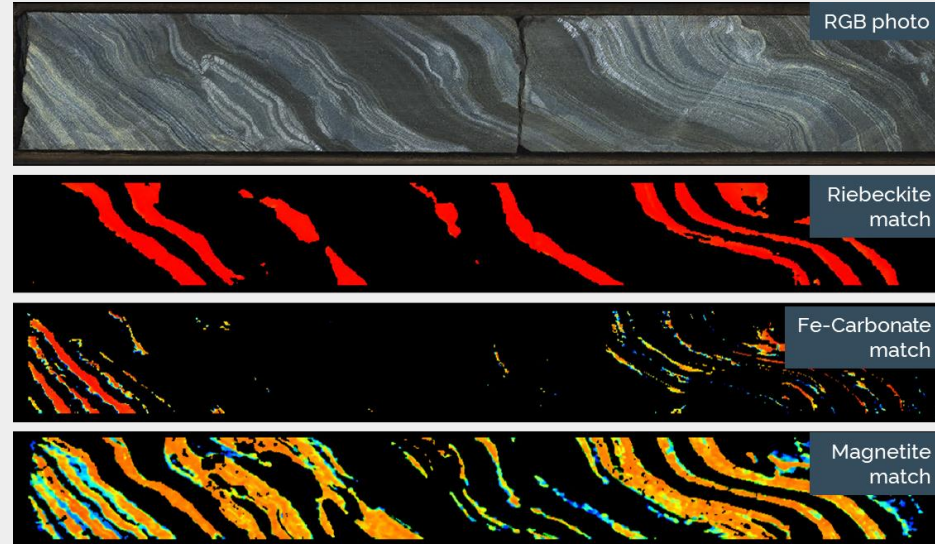
Process Design



Deposit types

- Historically:
 - Porphyries
 - Low/High sulphidation epithermal
 - Orogenic Gold
- But thanks to spatial/spectral resolution and advances sensors/algorithms:
 - Sediment-hosted Cu
 - Oil & Gas
 - Iron Ore
 - Nickel Laterites
 - Nickel Sulphides
 - Kimberlites
 - VMS
 - Skarn
 - IOCG
 - Carlin-type
 - ...

Application to sedimentary iron ore



Location

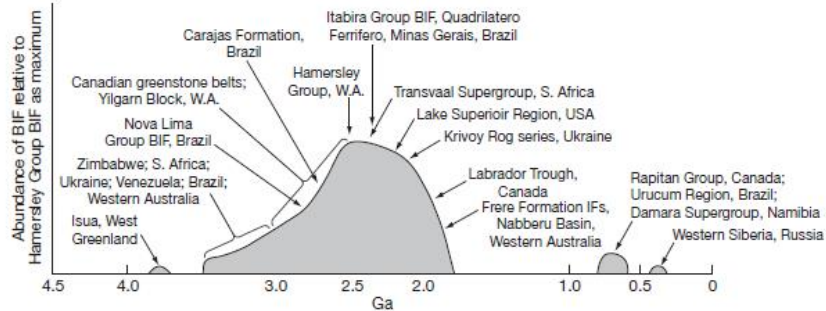


Figure 2 Relative abundance of Precambrian and Neoproterozoic BIF including the main BIF areas. Modified from Klein C (2005) Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origins. *American Mineralogist* 90: 1473–1499.

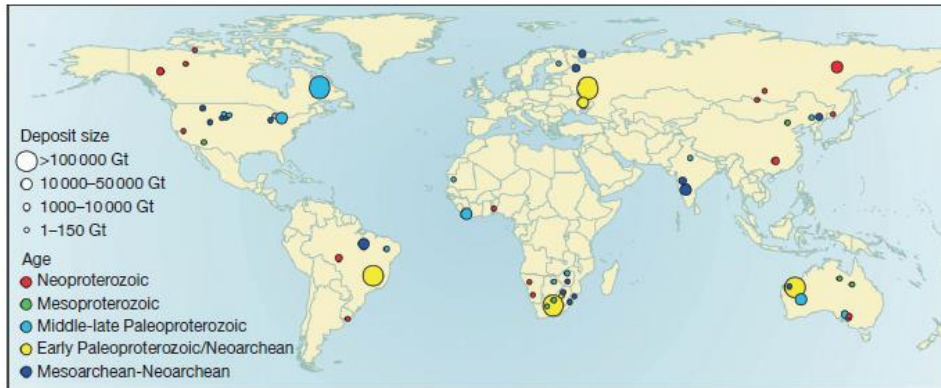


Figure 3 Occurrences of Precambrian iron-formations. Modified from Bekker A, Slack JF, Planavsky N, et al. (2010) Iron formation: The sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric processes. *Economic Geology* 105: 467–508. With permission from the Society of Economic Geologists.

Grade of metamorphism				
Low		Medium		High
Diagenetic	Biotite zone	Garnet zone	Staurolite-kyanite and kyanite zone	Sillimanite zone
Early	Late			
Chert	→ Quartz			
'Fe ₃ O ₄ + H ₂ O'	→ Magnetite			
'Fe(OH) ₃ '	→ Hematite			
Greenalite				
Stilpnometane				
Feri-annite				
Talc - minnesotaite				
Fe - chlorite (ripidolite)				
Dolomite - ankerite				
Calcite				
Siderite - magnesite				
Riebeckite				
Cummingtonite - grunerite (anthophyllite)				
Tremolite - ferroactinolite (hornblende)				
Almandine				
Orthopyroxene				
Clinopyroxene				
Fayalite				

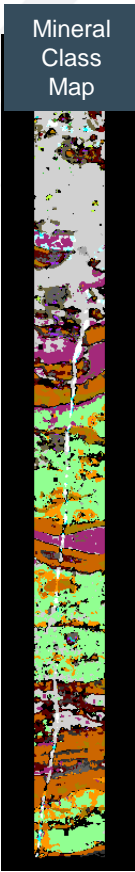
Key Outputs: Mineral Class Map

Mineral Name	RGB Code	Colour
Hematite + Quartz	255,200,200	
Goethite	255,153,0	
Montmorillonite	175,175,255	
Chert + Illite/White Mica	31,76,131	
NH4-Illite/White Mica	141,180,226	
Illite/White Mica	58,102,156	
Carbonate (Fe-rich)	0,108,105	
Quartz	0,176,240	
Jasper + Carbonate (Fe-rich)	0,219,214	
Jasper	255,0,0	
Chert + Carbonate (Fe-rich)	112,104,64	
Microplaty Hematite	168,128,0	
Martite	204,102,0	
Fe-Oxide Mixture	255,192,0	
Talc (Fe-rich)	145,255,145	
Talc	255,255,20	
Minnesotaitite	255,153,255	
Stilpnomelane	163,41,122	
Chlorite (Fe-rich)	0,255,0	
Chlorite	0,192,0	
Carbonate + Silicate	188,255,255	
Chert + Carbonate	255,255,255	
Carbonate	0,255,255	
Magnetite Mixture	167,37,255	
Magnetite	95,95,95	
Chert Mixture	166,166,166	
Chert	209,209,209	
Chert + Slate	128,0,0	
Slate Mixture	88,0,0	
Slate	50,50,80	

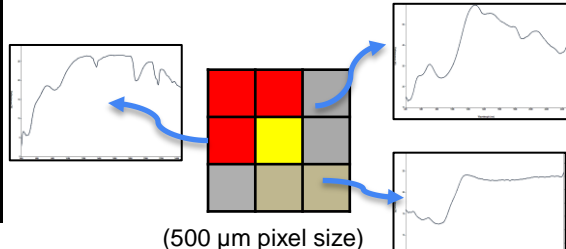
First

Display Priority

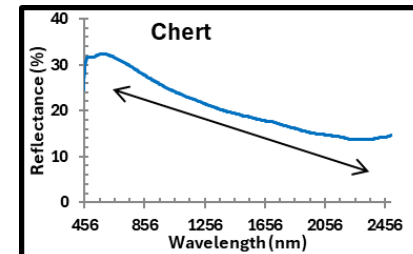
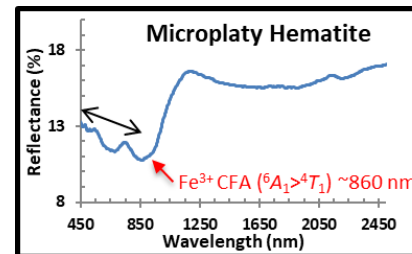
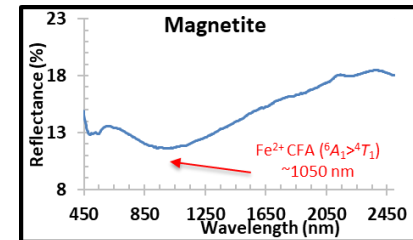
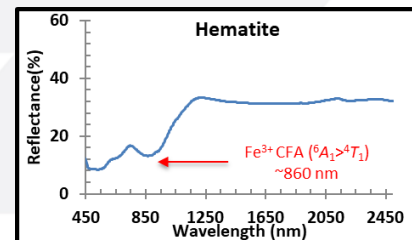
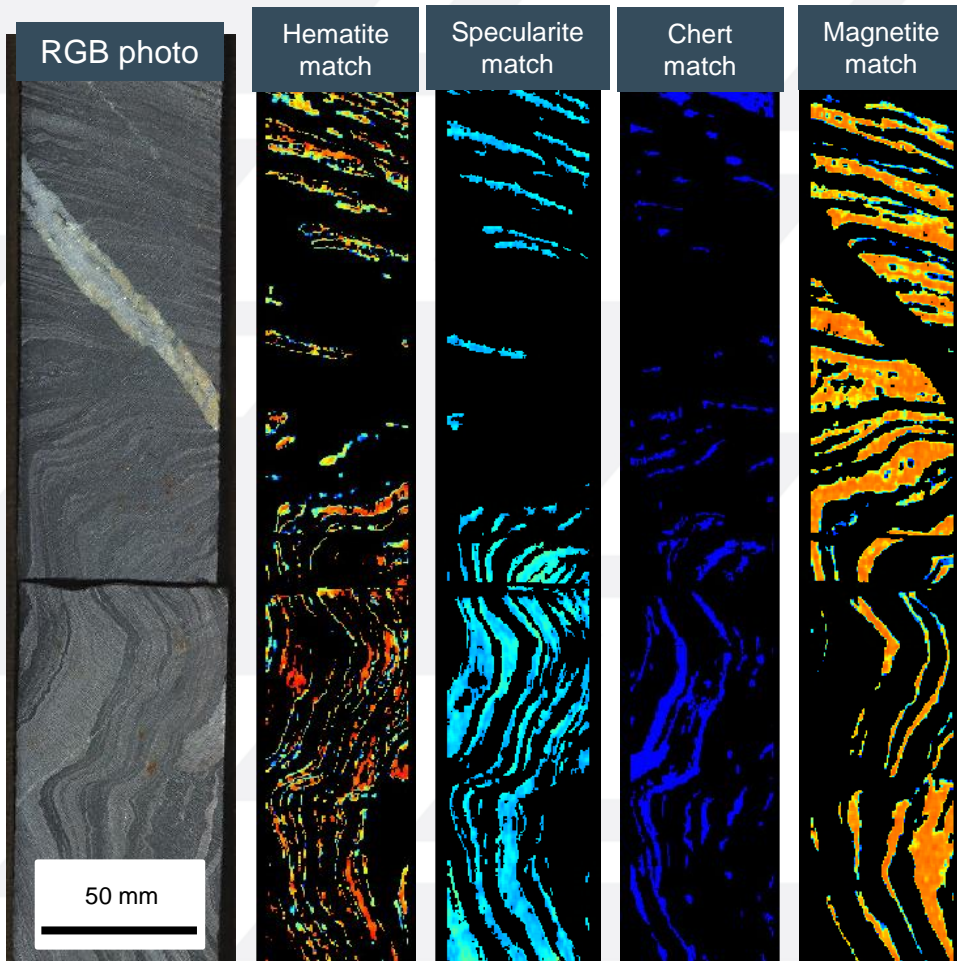
Last



- A **MINERAL CLASS MAP** compiles the multi-dimensional hyperspectral images into a single product for a **quick visual overview** of trends in the data
- Each **pixel** is assigned a **mineral colour** based on the associated spectrum and the associated minerals can be ranked by priority
- In this example of the American GIF core, the granular character of the banding textures are well captured by the hyperspectral imaging system.

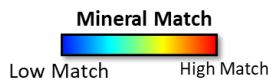


Fresh BIF/Itabirites



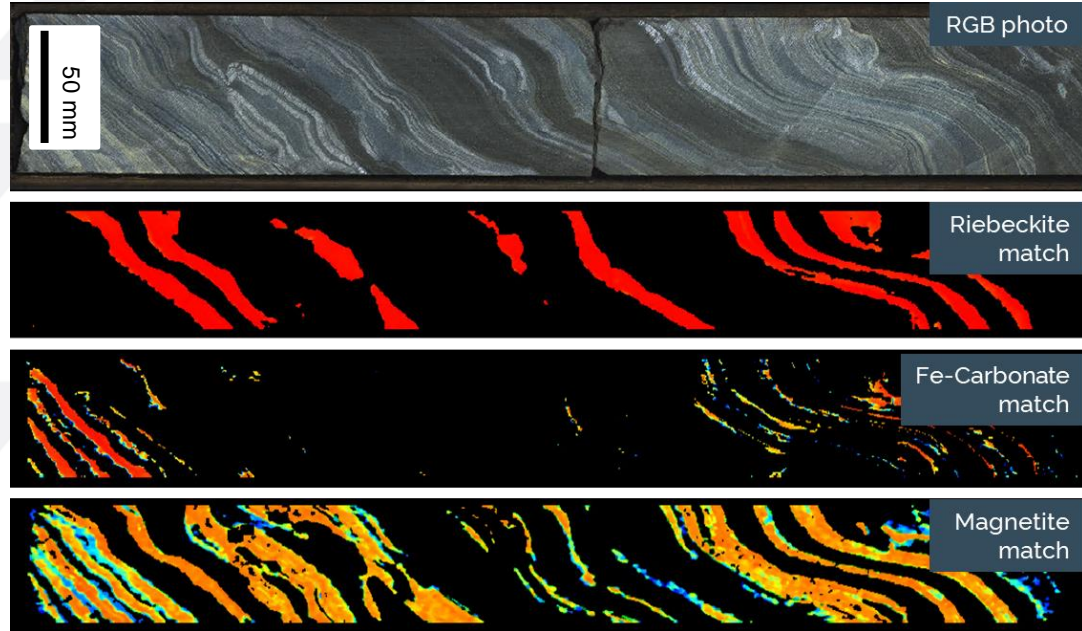
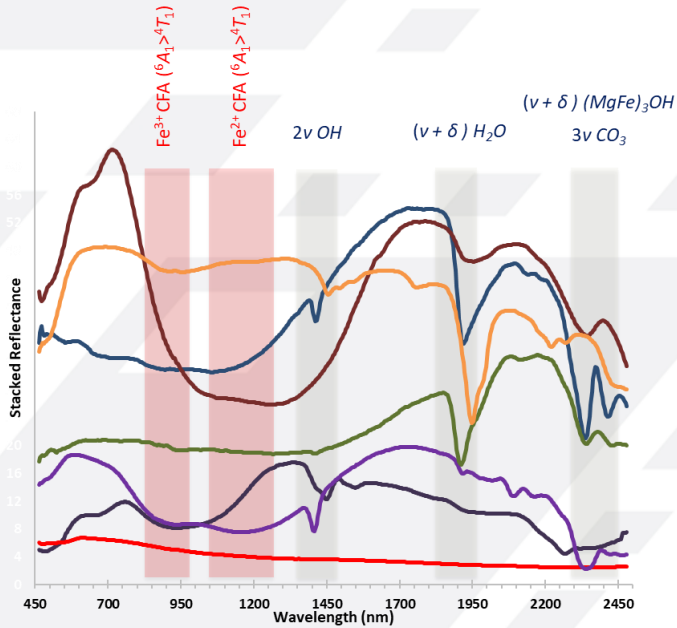
Benefits of Hyperspectral imaging:

- Iron Ore Texture
- Magnetite/Hematite abundance, important for magnetic separation
- Bedded vs veined textural relationship
- Identification of specularite, related to hypogene alteration



Metamorphosed Jaspilite

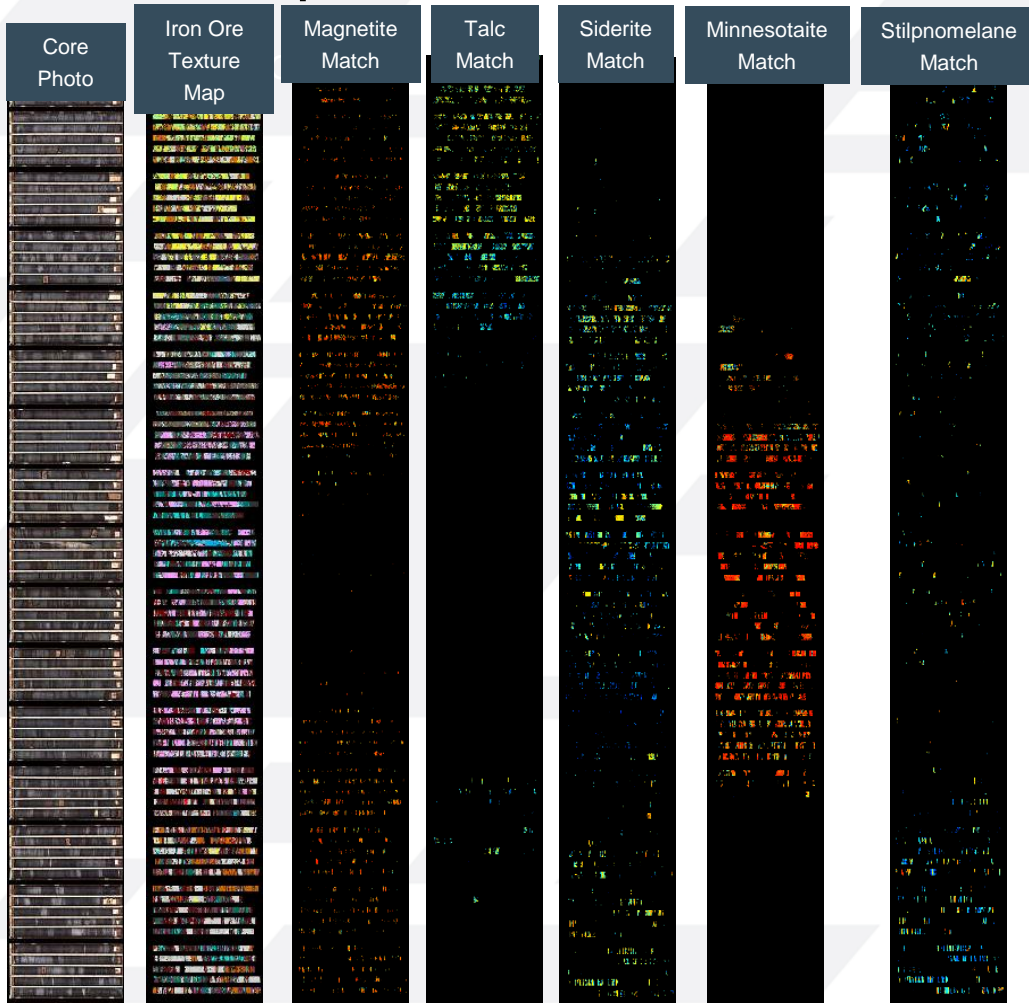
Mineral Match
 Low Match High Match



- Siderite
- Gypsum
- Riebeckite
- Stilpnomelane
- Minnesotaite
- Gibbsite
- Chert

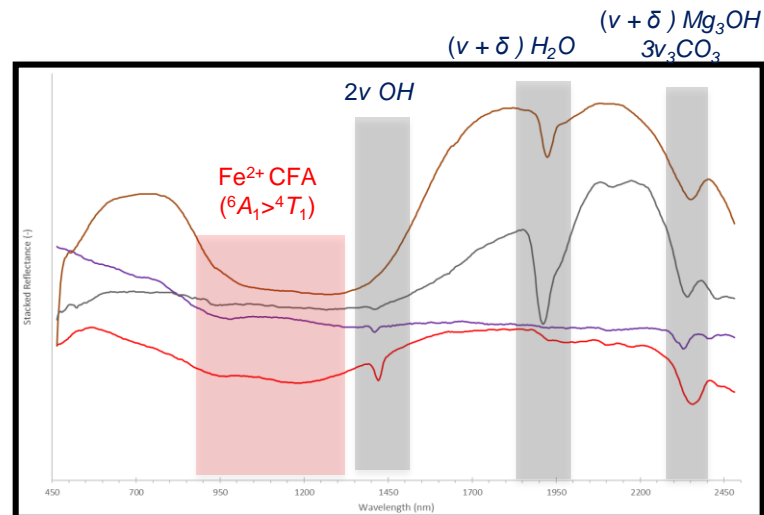
- Able to separate the different type of jaspilite
- Compared to a point system, less mixture, so easier to separate as you are dealing with mm bedding
- Critical information ahead of downstream processing

Metamorphosed BIF



Benefits of Hyperspectral imaging:

- **Gangue** abundance and type, important for ore processing and ore recovery model
- **Paragenesis** (metamorphism (P,T conditions), multi magnetite generations, late carbonates...), important for geological models

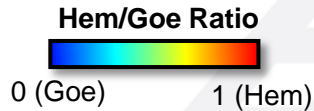
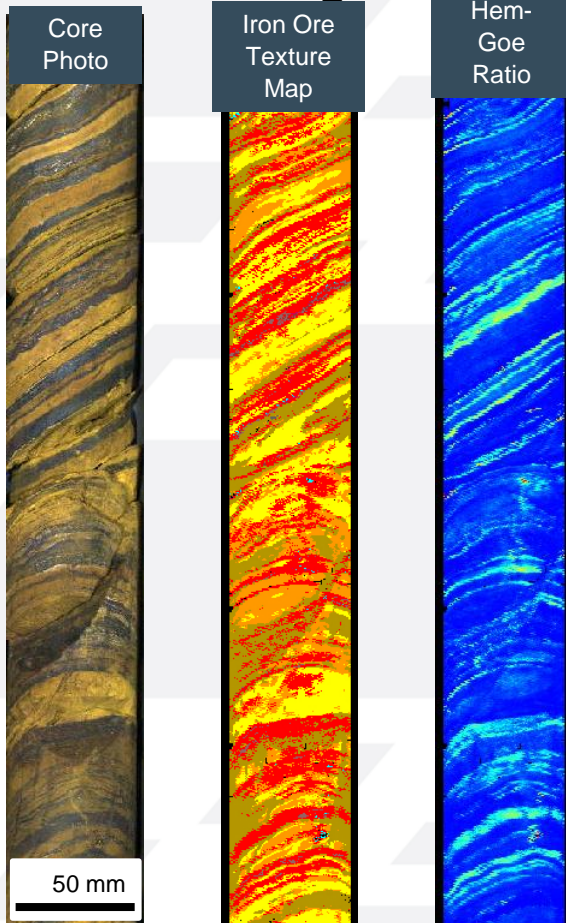


Low Match

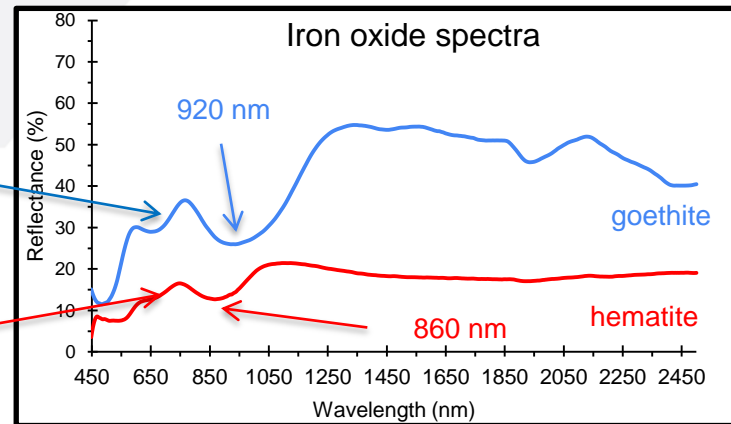


High Match

Weathering of Iron Ore



- Brown Goethite
- Ochreous Goethite
- Vitreous Goethite
- Martite/Goethite



- In the VNIR, hematite ~ 860 nm and goethite ~ 940 nm; this feature shifts according to the relative abundance of goethite and hematite
- hematite/goethite ratio varying from 0 (pure goethite) to 1 (pure hematite) (Ramanaidou et al., 2008)
- Vital information on grade control and geometallurgical properties

$$y = 1.5727 \times 10^{-4} x^2 - 0.2936x + 139.54$$

(where x = 900L)

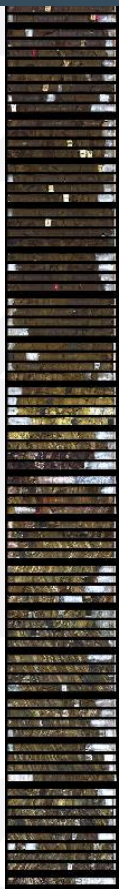
Weathering of Iron Ore

0 m

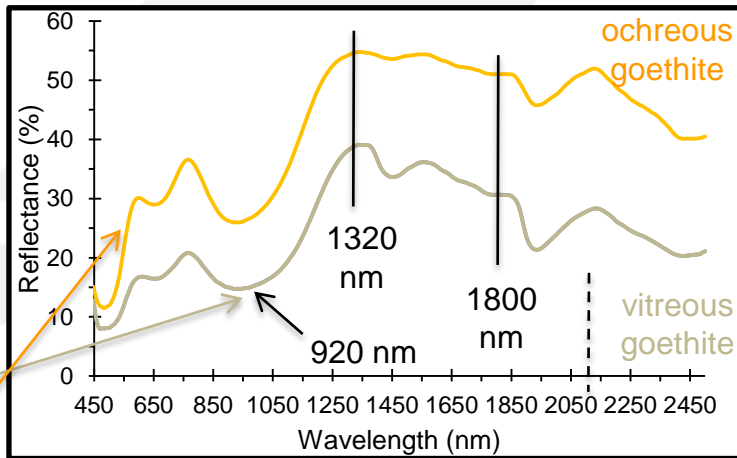
Core Photo

Iron Ore
Texture Map

oG/vG
Ratio



50 m



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

oG/vG Ratio



1 (oG) 1.6 (vG)

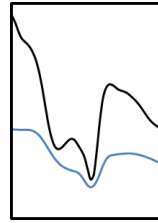
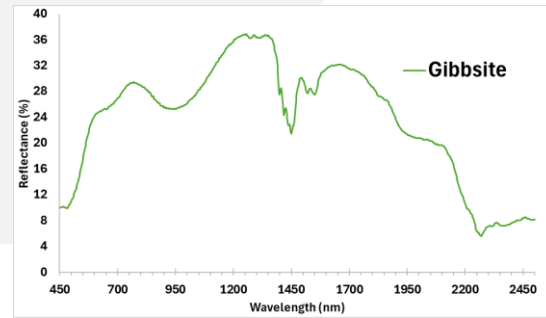
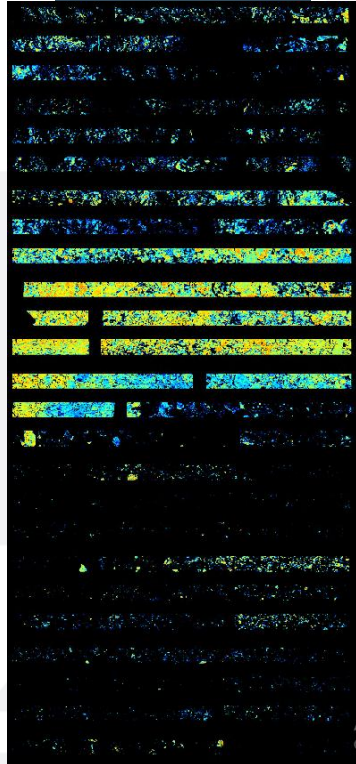
- Brown Goethite
- Ochreous Goethite
- Vitreous Goethite
- Martite/Goethite

Hard cap/Canga

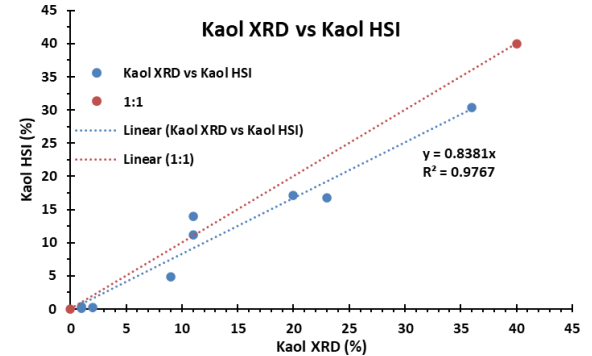
Core photo



Gibbsite match



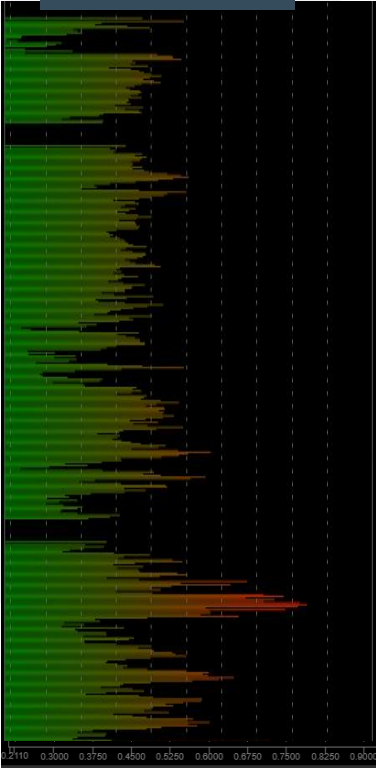
2200nm depth in kaolinite



- Another Al-rich mineral can be found in hard caps and canga, gibbsite
- In some cases, the Al content can be estimated from the depth of 2200nm feature from kaolinite (Wells et al. ,2013)
- This value will be underestimated if gibbsite is present
- Can the depth of the 1460nm feature in gibbsite also estimate the Al content?

Hardness proxy

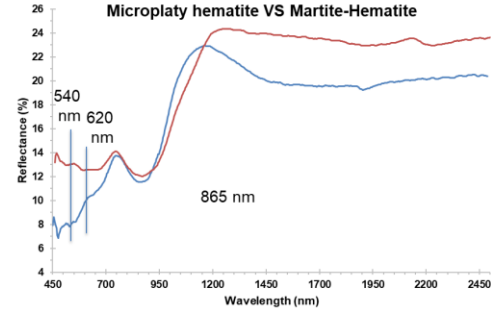
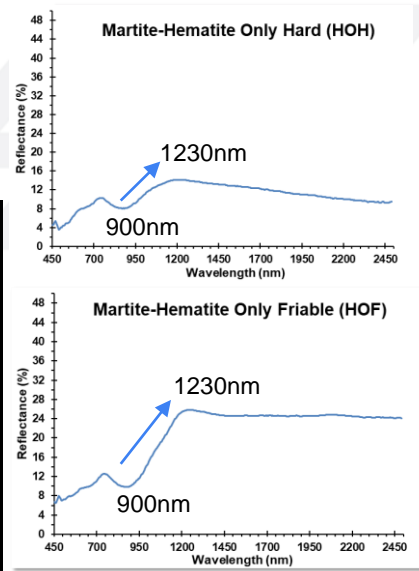
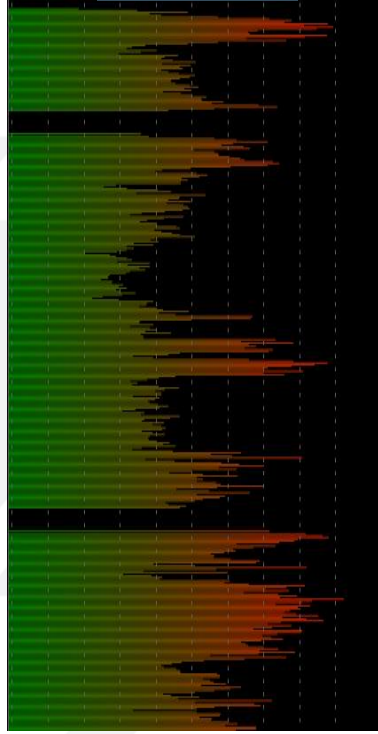
Hematite
Hardness Proxy



Lithology



Specularite
Ratio



- The specularite ratio is able to differentiate the more specularite-rich from the more hematite-rich ore
- Ratio 900/1230nm: can be used as a proxy for hematite hardness
- Hard hematite will display high values and friable hematite lower ones
- Similar for specularite

From Pretty Images to Semi-Quantitative Logs to Data Integration

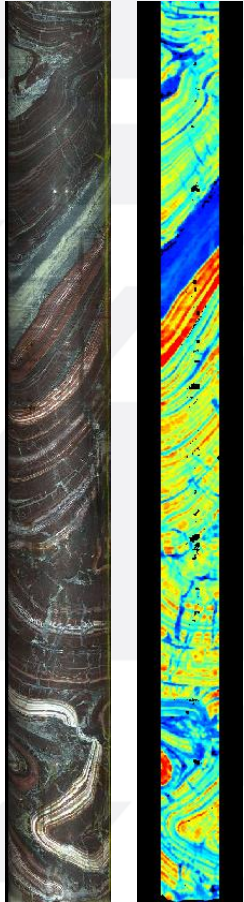
- Hyperspectral images are not just pretty picture – they are data
- ~240,000 mineralogical data points per meter of core are calculated and exported into .csv files at desired intervals (m, cm, mm)

Core ID	Depth (m)	Depth (cm)	Depth (mm)	Total Pixel Counts	Amphibole	Pyroxene	Magnetite-Silicate	Chert-Magnetite	Monazite	Ilmenite	Carbonate-DF	Mantle	Microplata Hematite	Mantle/Carbonate	Quartzite	Chert
NS000030	67.25	67.25	67.25	57894	5.56	53.76	0.00	4.37	2.96	3.21	4.19	15.65	0.00	1.51	0.19	1.00
NS000030	67.75	67.75	67.75	38877	2.46	37.64	0.00	1.62	4.02	4.50	7.09	1.00	0.00	0.41	0.04	1.00
NS000030	68.25	68.25	68.25	36631	3.93	50.52	0.41	1.65	3.83	7.37	9.42	0.51	0.00	0.37	0.01	0.98
NS000030	68.75	68.75	68.75	37966	2.18	38.85	0.00	1.05	3.33	3.39	9.56	0.22	0.00	0.41	0.11	0.40
NS000030	69.5	68.75	30001	4.18	51.11	2.35	5.70	1.96	1.82	16.12	0.69	0.00	0.00	0.07	0.14	0.17
NS000030	69.75	69.5	38993	2.18	26.44	1.69	16.79	1.97	7.13	12.75	0.87	0.00	0.06	0.00	0.44	0.44
NS000030	69.25	68.25	48259	1.26	48.67	1.11	25.10	6.72	1.60	3.53	0.00	0.00	0.00	0.03	0.02	0.27
NS000030	69.25	69.5	39000	3.42	26.90	0.39	35.79	5.40	1.08	4.38	0.86	0.00	0.00	0.25	0.00	0.21
NS000030	69.5	69.75	38990	2.11	41.65	1.60	15.00	4.49	4.30	11.49	0.66	0.00	0.02	0.02	0.02	0.02
NS000030	69.75	70	38612	2.75	56.28	0.32	11.21	4.90	8.03	6.16	0.02	0.00	0.00	0.04	0.01	0.06
NS000030	70	70.25	38704	1.66	50.62	0.36	7.64	7.04	9.83	9.17	0.07	0.00	0.00	0.20	0.02	0.95
NS000030	70.25	70.5	38930	8.19	84.82	0.32	9.00	2.51	6.30	4.22	1.63	0.00	0.00	0.43	0.01	0.00
NS000030	70.5	70.25	48987	0.34	17.07	0.34	36.01	2.24	3.14	4.07	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	70.75	71	47723	0.42	21.78	5.43	25.77	6.53	9.35	5.82	0.98	0.00	0.00	0.00	0.00	0.00
NS000030	71	71.25	38997	0.08	31.05	1.09	15.97	3.62	9.56	7.62	1.86	0.00	0.00	0.00	0.00	0.00
NS000030	71.25	71.5	52681	1.98	31.06	1.00	12.85	8.53	9.98	5.90	3.27	0.00	0.00	0.00	0.00	0.00
NS000030	71.5	71.75	37690	0.79	39.53	1.09	32.61	13.93	0.89	1.10	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	71.75	72	38921	1.11	36.70	0.65	8.37	3.22	8.53	9.16	0.25	0.00	0.00	0.00	0.00	0.00
NS000030	72	72.25	29467	2.00	16.63	4.14	22.35	6.06	2.25	3.05	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	72.25	72.5	38814	2.22	28.45	3.37	22.04	11.51	3.45	1.16	0.39	0.00	0.00	0.00	0.00	0.00
NS000030	72.5	72.75	38939	1.32	15.60	0.00	33.14	4.37	2.83	1.90	0.45	0.00	0.00	0.00	0.00	0.00
NS000030	72.75	73	53777	5.51	42.97	0.00	22.00	6.42	4.70	2.76	0.38	0.00	0.00	0.00	0.00	0.00
NS000030	73	73.25	47346	1.81	51.09	1.19	25.23	1.82	3.11	5.25	0.45	0.00	0.00	0.00	0.00	0.00
NS000030	73.25	73.5	38765	4.58	30.72	2.01	18.09	1.23	9.18	7.72	0.84	0.00	0.00	0.00	0.00	0.00
NS000030	73.5	73.75	48294	3.78	28.36	4.02	29.79	1.50	6.05	6.25	0.02	0.00	0.00	0.00	0.00	0.00
NS000030	73.75	74	38843	1.11	27.02	1.00	52.38	1.23	0.02	3.58	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	74	74.25	38864	3.93	61.05	13.95	30.56	0.42	6.46	6.51	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	74.25	74.5	17959	1.01	20.58	0.35	23.45	0.70	0.30	0.75	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	74.5	74.75	38847	3.18	19.67	0.00	10.96	5.74	1.15	1.42	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	74.75	75	38957	2.10	6.25	19.80	38.37	1.68	6.24	0.58	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	75	75	42327	5.45	45.55	1.49	15.73	0.38	5.95	3.46	0.02	0.00	0.00	0.00	0.00	0.00
NS000030	75.25	75.5	38409	14.63	69.20	0.00	18.80	2.36	4.21	3.42	0.43	0.00	0.00	0.00	0.00	0.00
NS000030	75.75	76	38197	3.08	27.00	0.30	23.57	15.54	4.67	3.74	1.67	0.00	0.00	0.00	0.00	0.00
NS000030	76	76	48298	2.18	44.77	0.00	20.16	10.35	2.06	3.27	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	76.25	76.5	41002	2.43	41.16	1.93	16.47	8.09	1.96	1.27	0.03	0.00	0.00	0.00	0.00	0.00
NS000030	76.5	76.75	38177	3.35	39.51	1.01	13.79	13.99	9.26	1.10	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	76.75	77	38994	6.00	17.17	1.49	24.84	23.17	3.17	1.46	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	77	77.25	54221	4.78	29.21	0.44	7.40	22.42	16.77	3.72	1.56	0.00	0.00	0.00	0.00	0.00
NS000030	78.25	78.5	38634	4.40	33.43	4.14	4.74	4.44	6.00	30.69	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	78.75	78.75	38962	10.12	47.71	2.81	4.50	3.28	1.90	10.39	4.60	0.00	0.00	0.00	0.00	0.00
NS000030	79	79	42324	2.23	37.96	0.00	22.11	2.91	4.75	0.26	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	79	79.25	33514	13.48	35.96	1.96	33.13	2.36	0.28	3.04	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	79.25	79.5	38170	1.91	34.36	0.00	19.14	2.81	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	79.5	79.75	29364	2.09	60.32	0.83	2.84	3.89	2.54	6.60	6.51	0.00	0.00	0.00	0.00	0.00
NS000030	79.75	80	38115	3.91	30.25	1.59	1.59	1.68	4.34	6.00	0.00	0.00	0.00	0.00	0.00	0.00
NS000030	80	80.25	58993	1.34	38.35	2.22	16.49	0.11	2.73	1.51	1.75	0.00	0.00	0.00	0.00	0.00
NS000030	80.25	80.5	38629	8.02	67.44	0.71	8.11	0.96	8.43	7.65	5.10	0.00	0.00	0.00	0.00	0.00



- Easy import into third-party software for statistical and 3D analysis to build improved, more consistent geological models and optimise process and metallurgy

Summary



- Hyperspectral core imaging (HCI) is able to map key iron ore minerals and gangue mineralogy, including high-grade metamorphic mineralogy described in the literature (e.g. amphibolite facies)
- If implemented as the start in exploration campaign, cost effective as it already give information for the ore recovery and grade control such as:
- It allows for the quantification of clay, specularite, ochreous/vitreous goethite and hematite/goethite ratios, hardness proxy which are key products to determine the grade quality and the behaviour of the ore in the processing plant
- HCI provides textural visualisation/information which allows a better understanding of the paragenesis of the deposit
- High definition semi-quantitative mineralogical % logs (m, cm ,mm)
- Easy import and integration into 3rd party software which produces better 3D models and improves resource development including better planning and decision-making



Obrigado!