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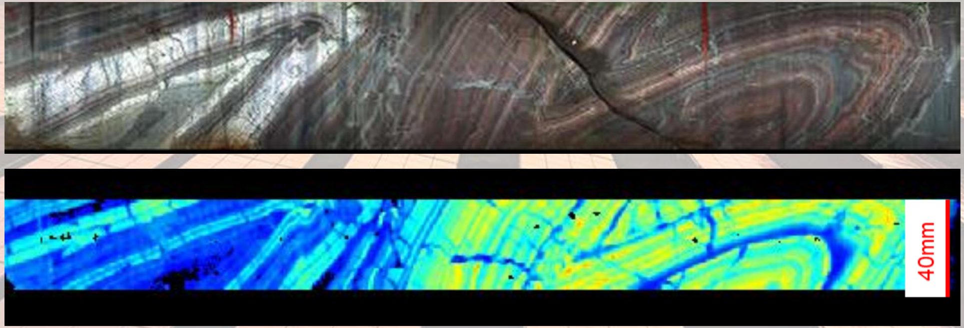
XI SIMPÓSIO BRASILEIRO DE EXPLORAÇÃO MINERAL

XI BRAZILIAN SYMPOSIUM ON MINERAL EXPLORATION

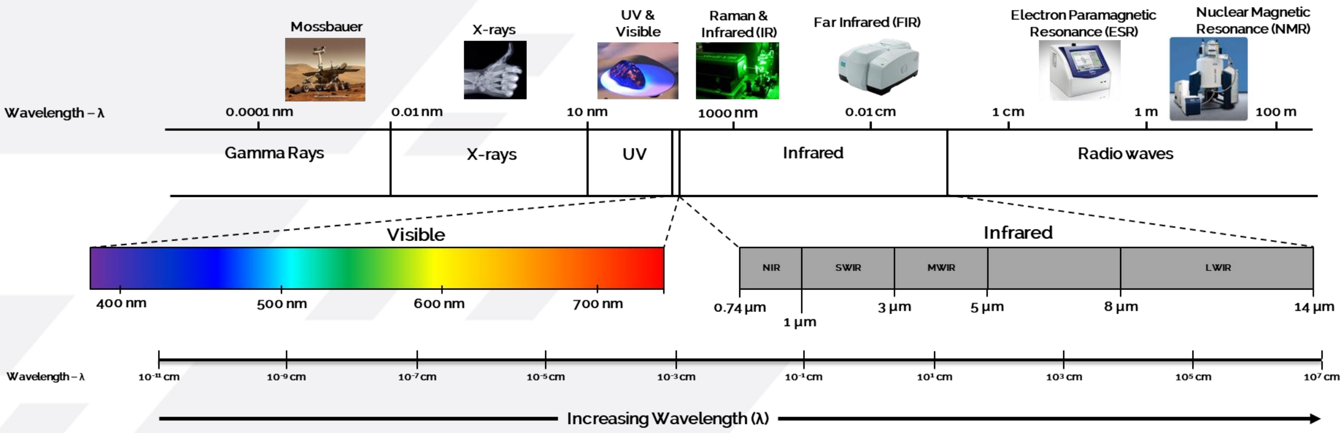
Application of Hyperspectral Core Imaging to Mineral Exploration (Iron Ore)

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



Infrared Spectroscopy

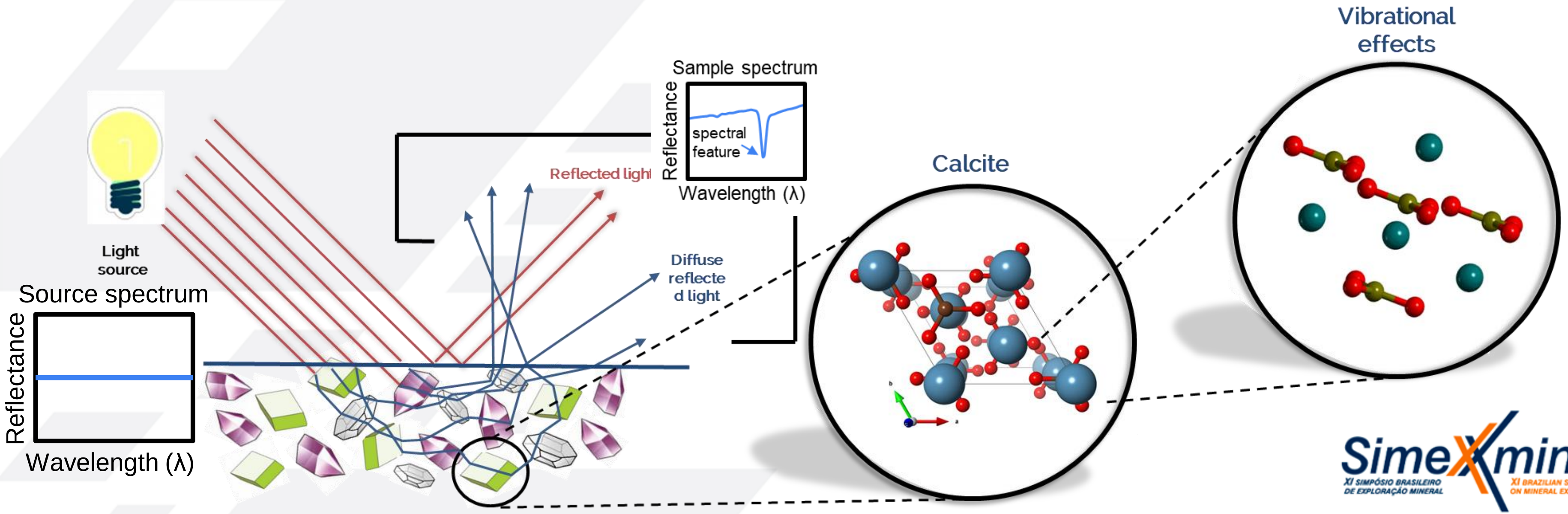
- Spectroscopy is the study of the absorption and emission of electromagnetic radiation (e.g., light) by matter, measured as a function of wavelength (or frequency).
- Used as a tool for characterizing the structures of atoms and molecules.
- Several types of EM radiation are used for the analysis of 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*.



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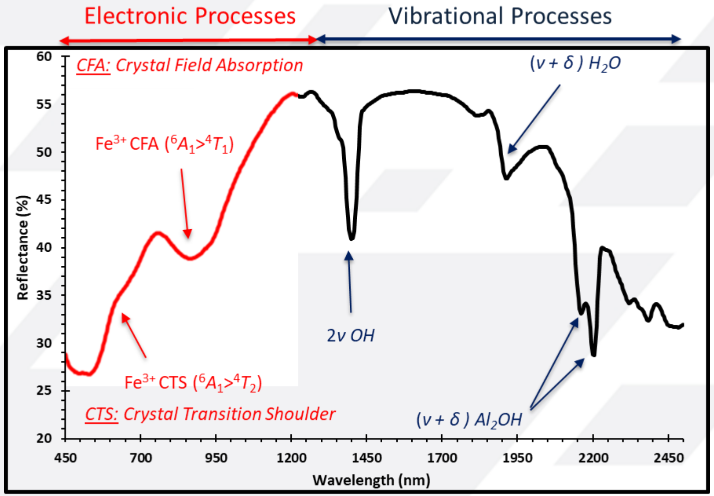
*and also rotational energy, in much higher wavelength ranges

Reflectance Spectroscopy: output



Example of hematitic shale reflectance spectrum

VNIR (450–1350 nm):
- Iron Oxides
- REEs
- Pyroxenes
- Olivines
- Garnets
- …

SWIR (1350-2500 nm)
- OH-bearing minerals
- Silicates
- Carbonates
- Phosphates
- Sulphates
- …

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

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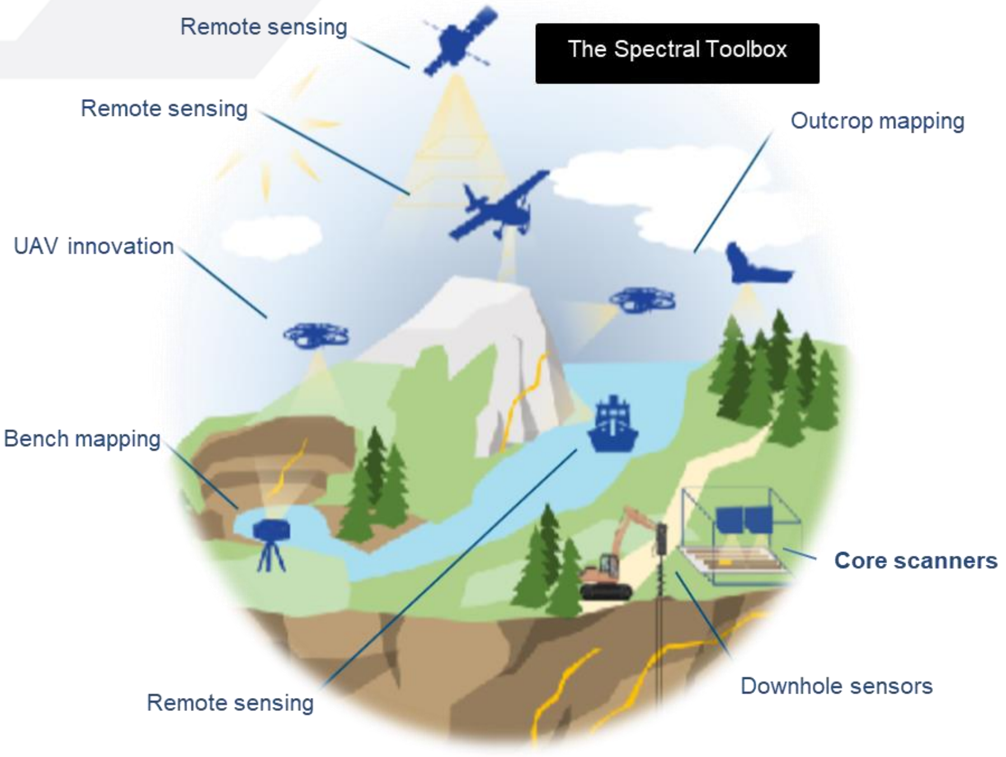
Reflectance Spectroscopy: Uses

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)

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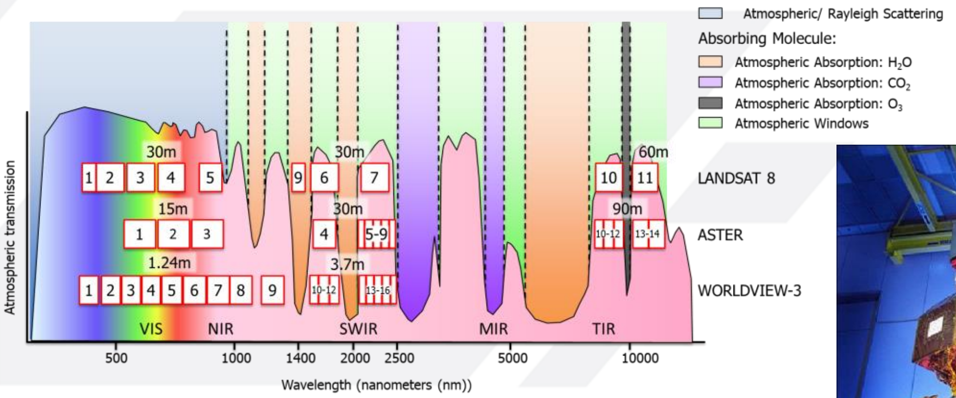
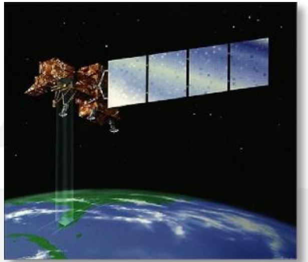
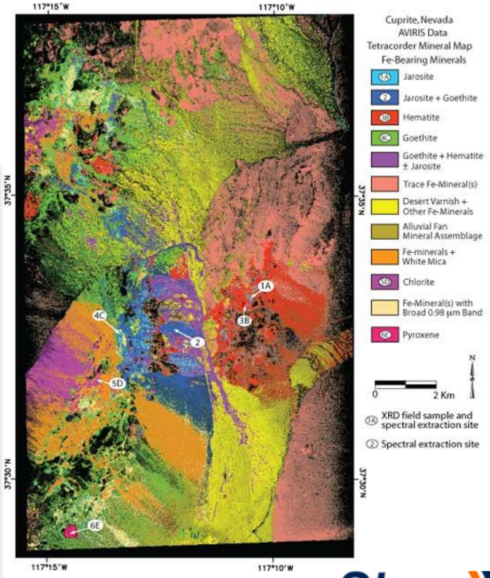
First uses in mineral exploration – From distal source

- 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

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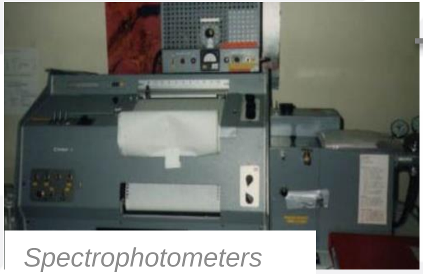
To proximal source

Laboratory



Spectrophotometers (1950's-1960's)

The PIMA (early 1990's)

PFRS (1970s)

Terraspec® (1990's – Present)

Field Spectrometers

Hyperspectral profiling Scanner

Hy-Logger™-3 (2000-2011)

Corescan® HCI-4 (2005-present)

Hyperspectral imaging Scanner

Specim SisuRock (2005-present)

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

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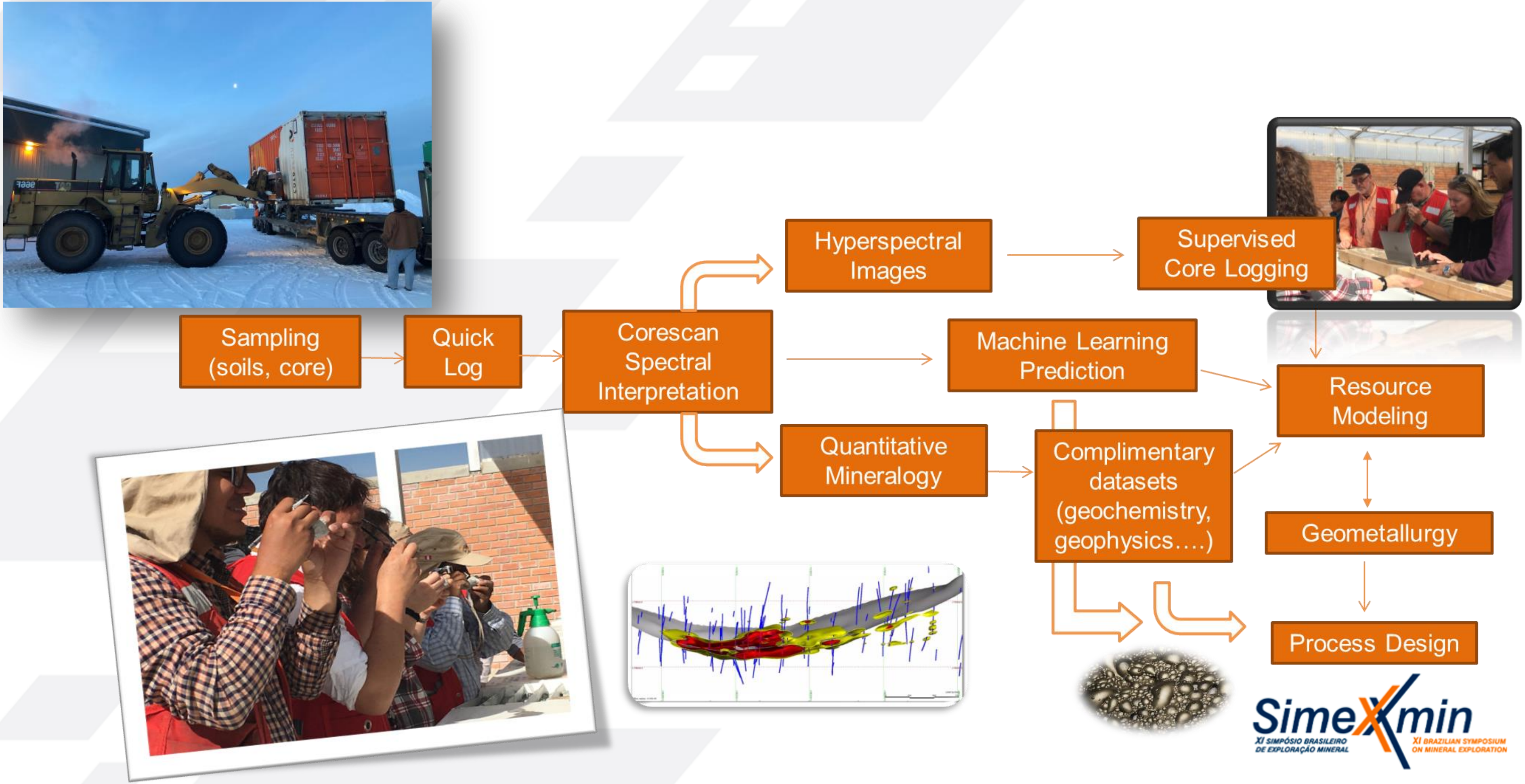
Hyperpsectral core imaging: game changer

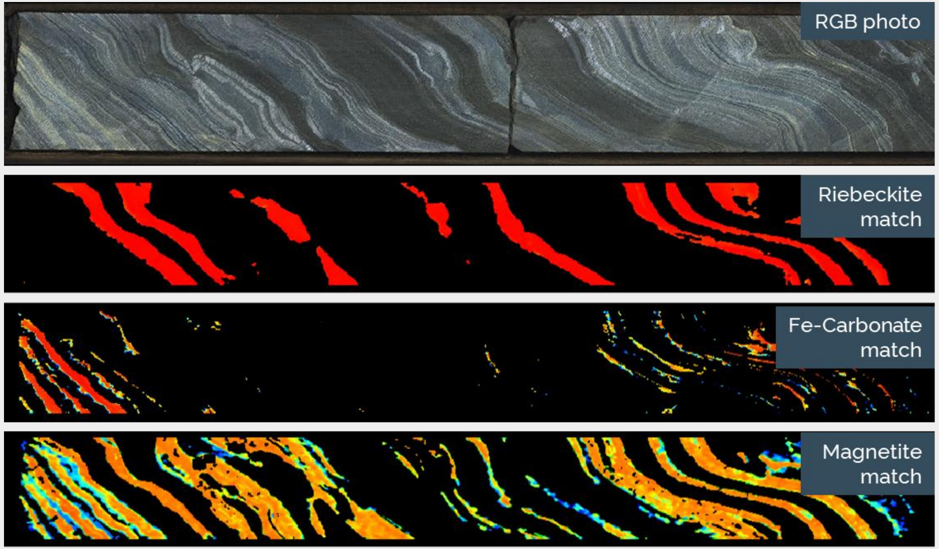


Deposit types

- 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

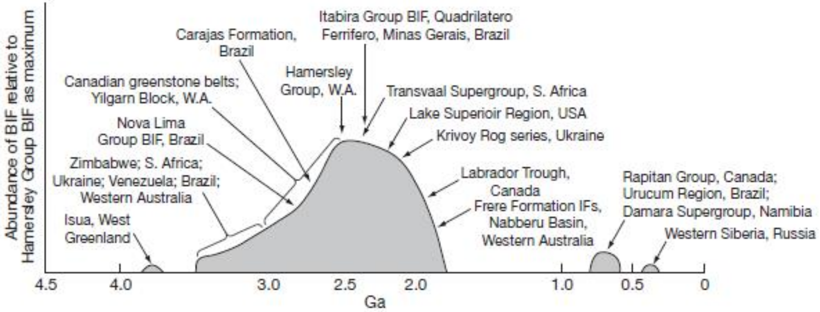


Figure 2 Relative abundance of Precambrian and Neoproterozoic BIF including the main BIF areas. Modified from Klein C (2005) Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origins. *American Mineralogist*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

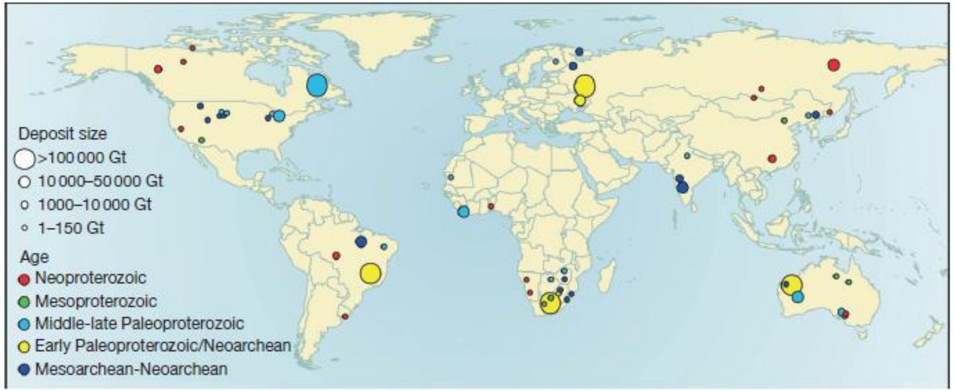
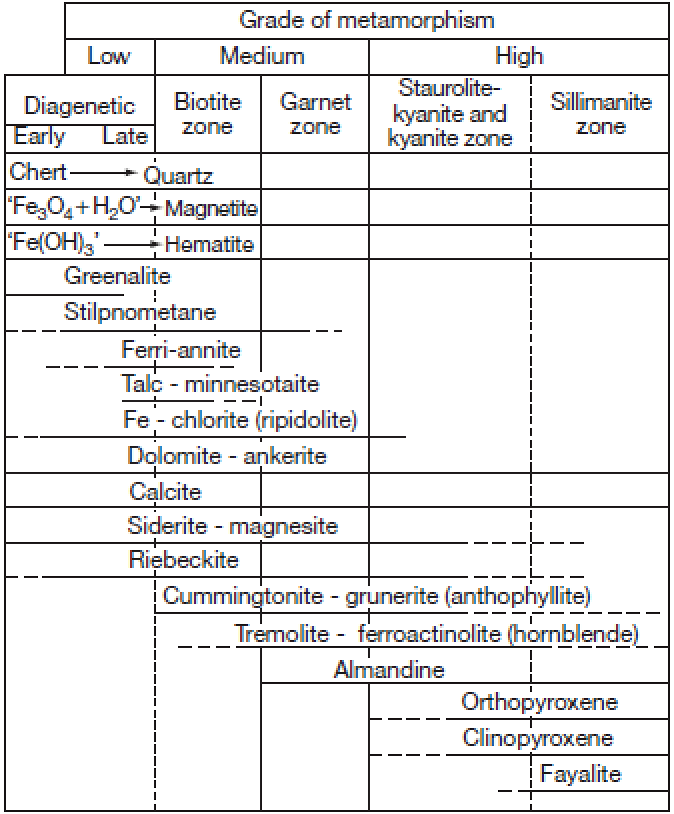


Figure 3 Occurrences of Precambrian iron-formations. Modified from Bekker A, Slack JF, Planavsky N, et al. (2010) Iron formation: The sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric processes. *Economic Geology* 105: 467–508. With permission from the Society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



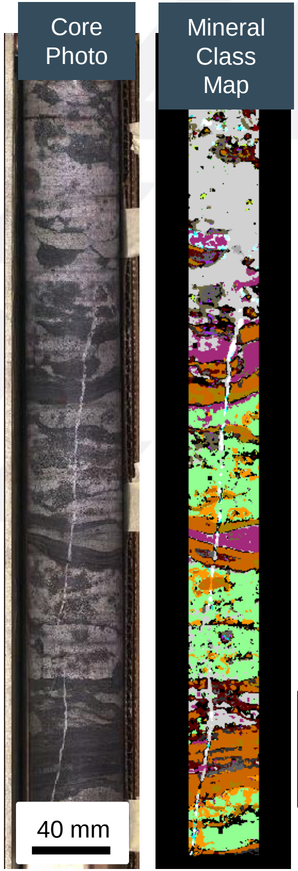
Key Outputs: Mineral Class Map

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	
Minnesotaite	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	

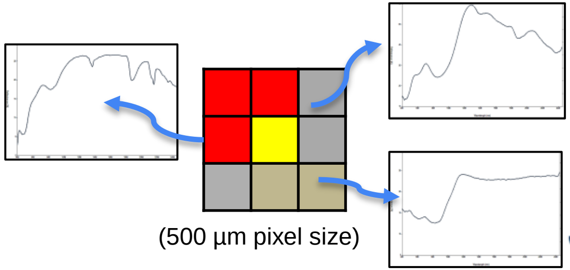
First

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.



(500 µm pixel size)

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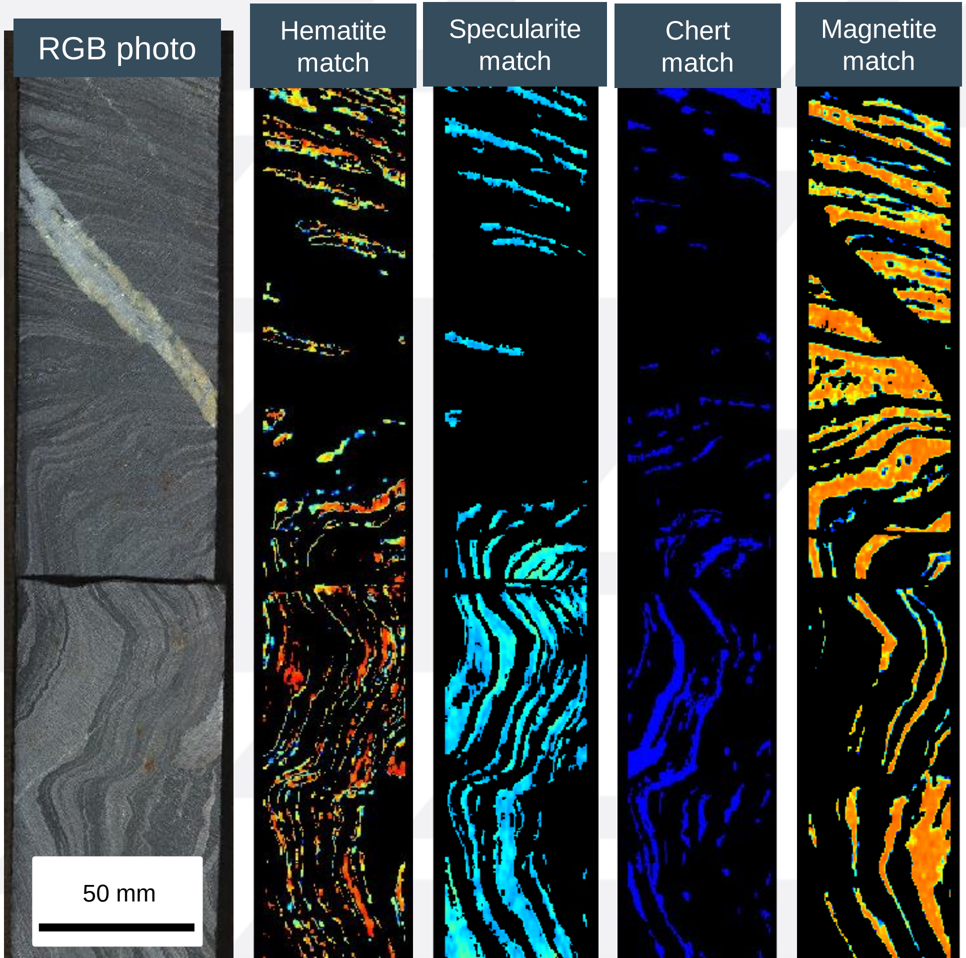
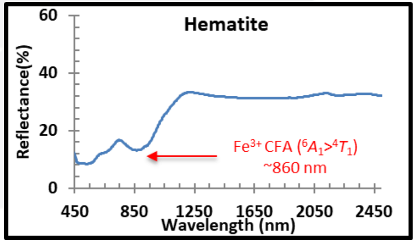
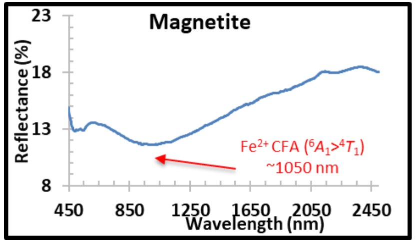
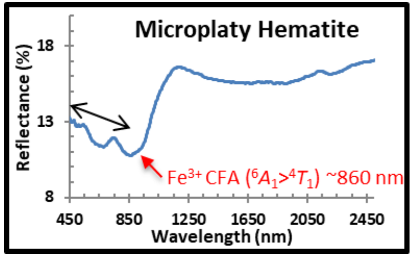
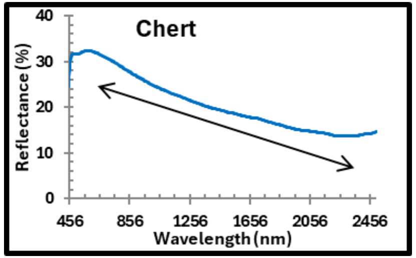
Fresh BIF/Itabirites





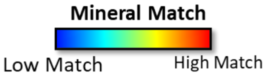






<u>Benefits of Hyperspectral imaging:</u>

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



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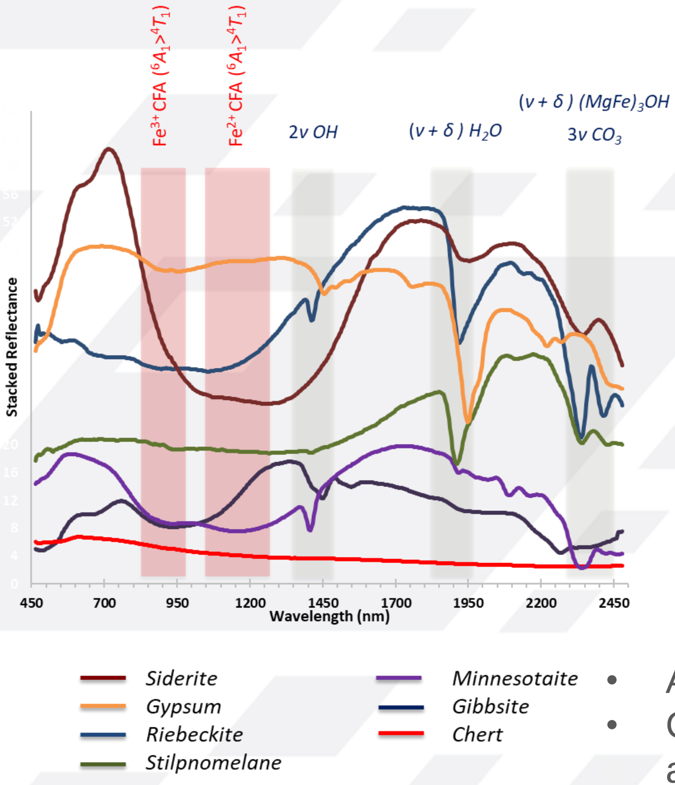
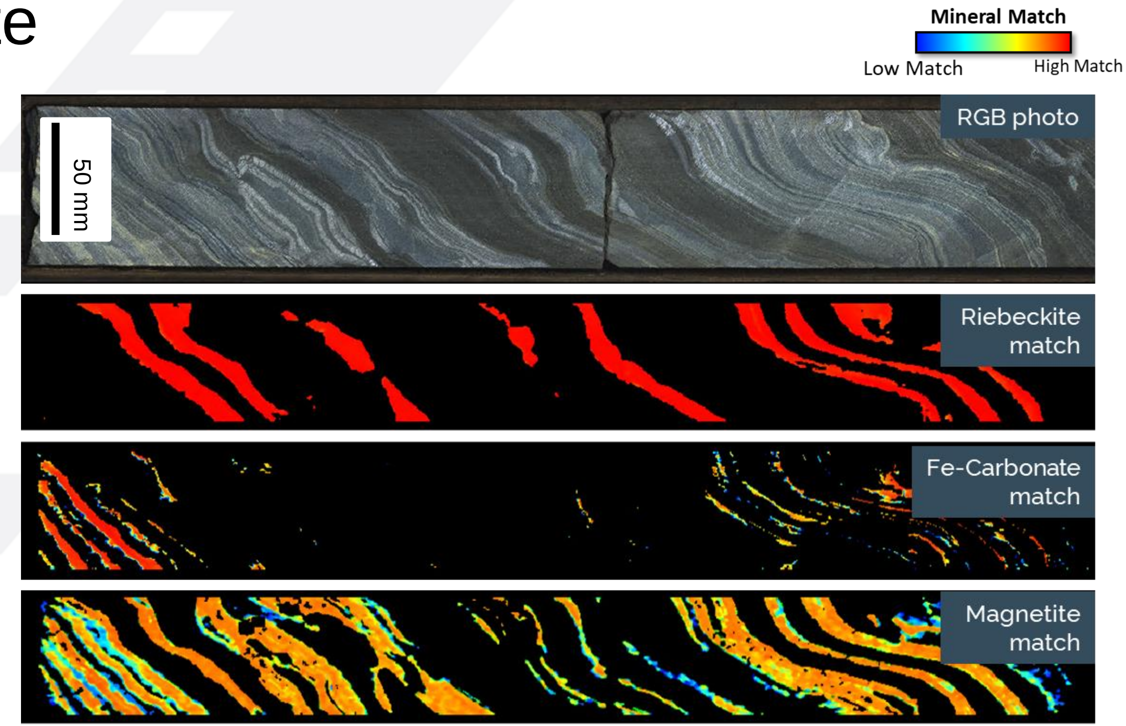
Metamorphosed Jaspilite





- 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

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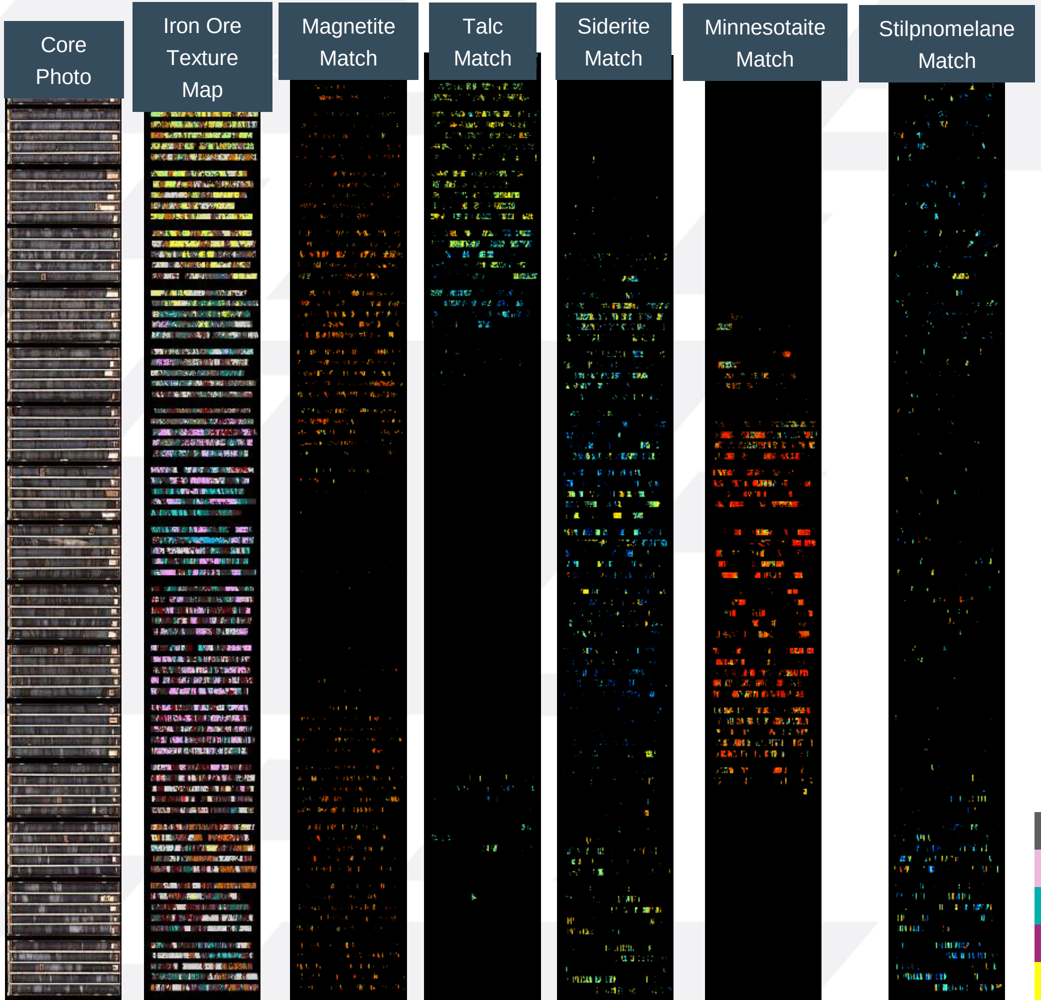
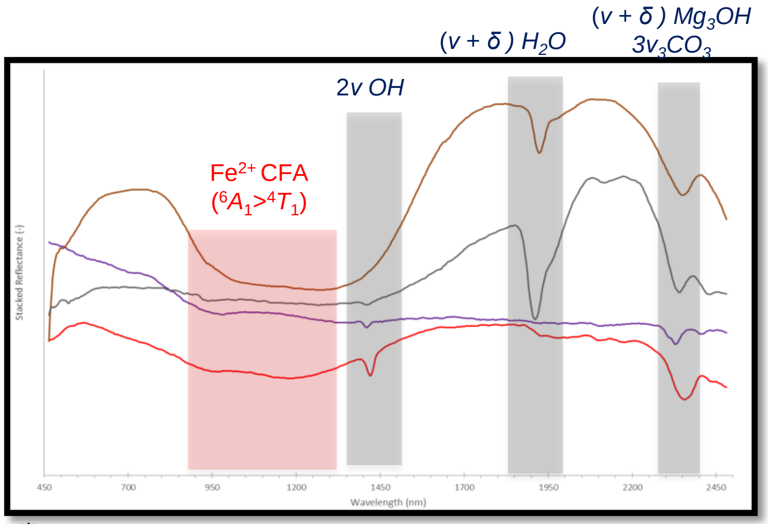
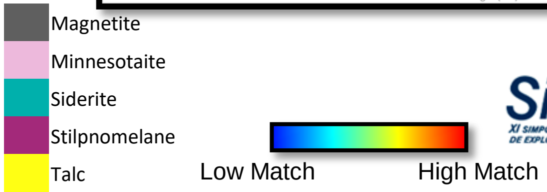
Metamorphosed BIF



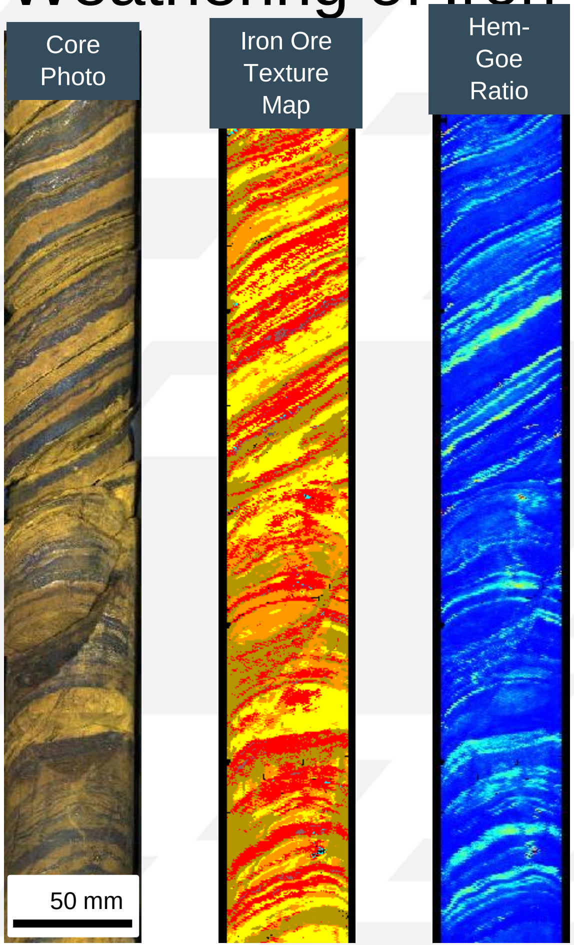
Benefits of Hyperspectral imaging:

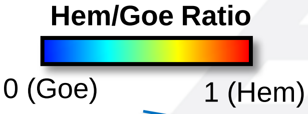
- **Gangue** abundance and type, important for ore processing and ore recovery model
- **Paragenesis** (metamorphism (P,T conditions), multi magnetite generations, late carbonates…), important for geological models



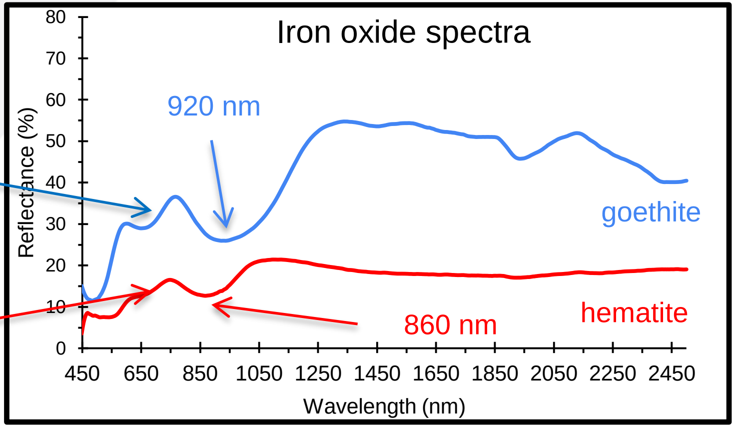


Weathering of Iron Ore





- 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)

$$y = 1.5727x10^{-4}\, x^2 - 0.2936x + 139.54$$

(where x = 900L)

- Vital information on grade control and geometallurgical properties

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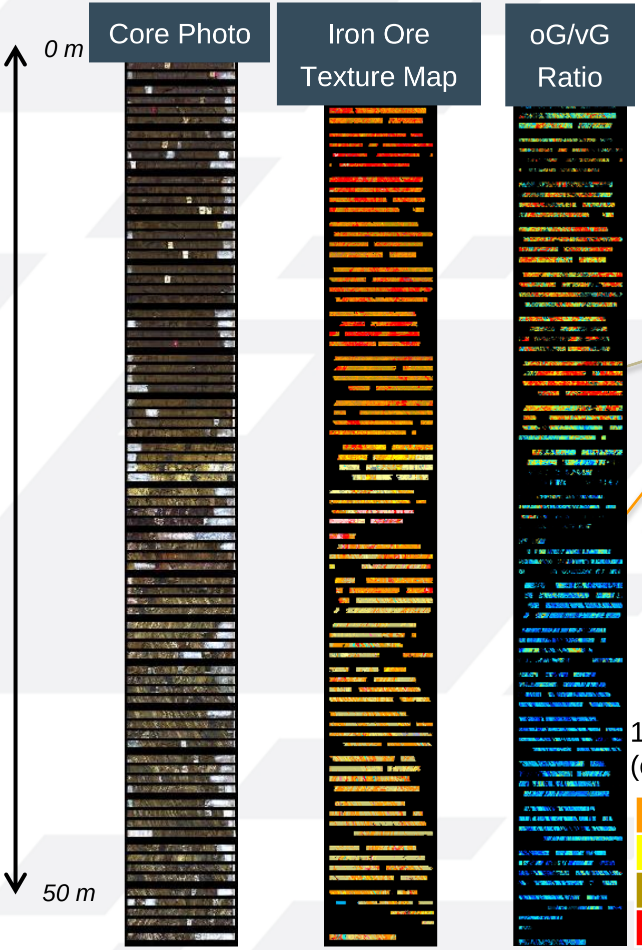

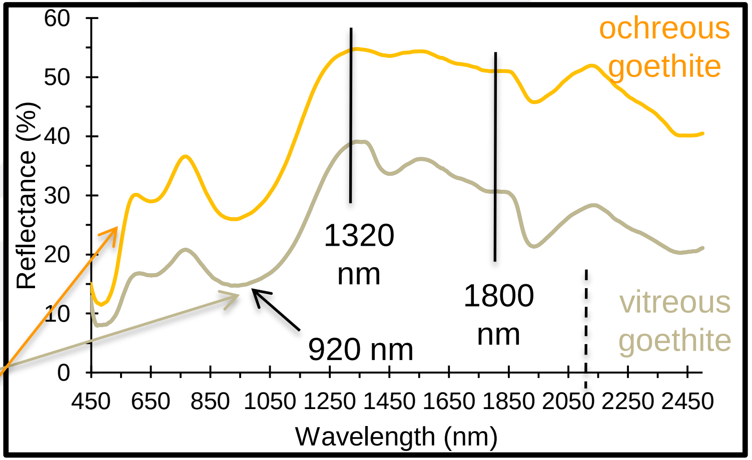

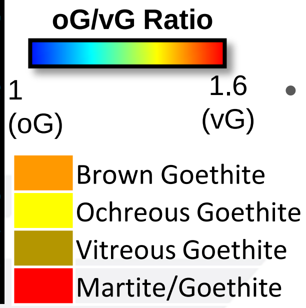

- Ochreous and vitreous goethite differentiated by the 1320/1800nm reflective ratio (Haest, 2012).
- Importance of calculation:
  - Quick tool for locating the current or past water table and the hard cap
  - As oG is very porous and moist compared to vG, this ratio is useful for the lumps:fine ratio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

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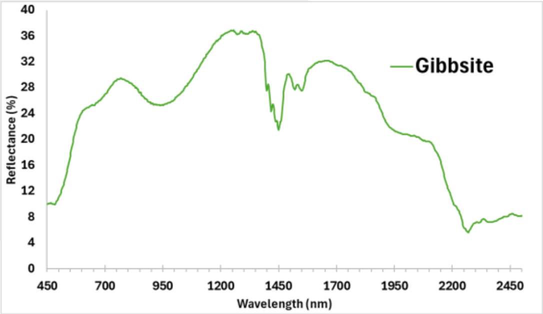
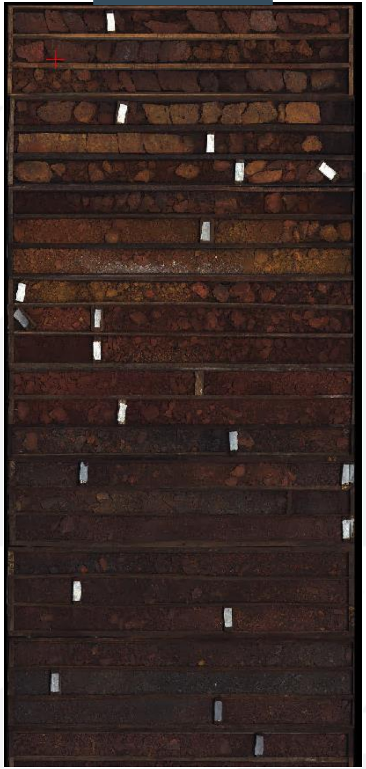
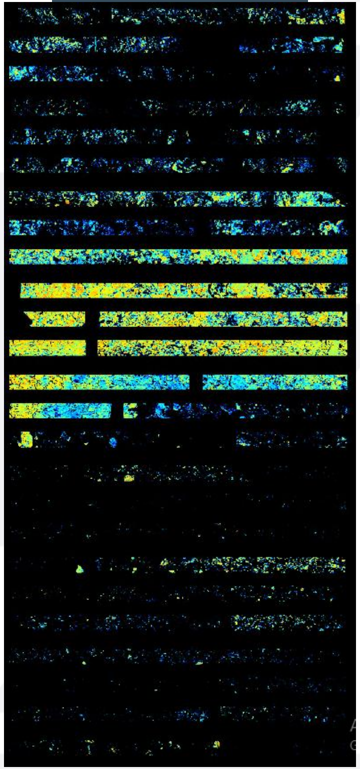
Hard cap/Canga

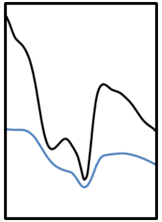


Core photo

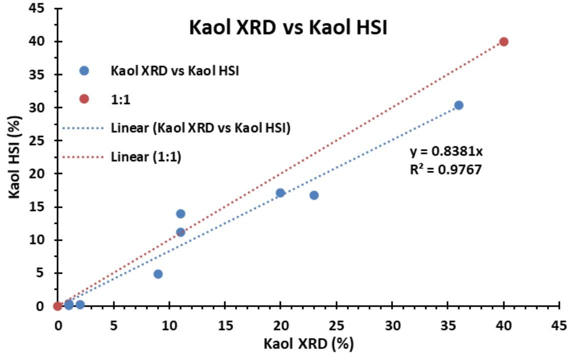


Gibbsite match





2200nm depth in kaolinite



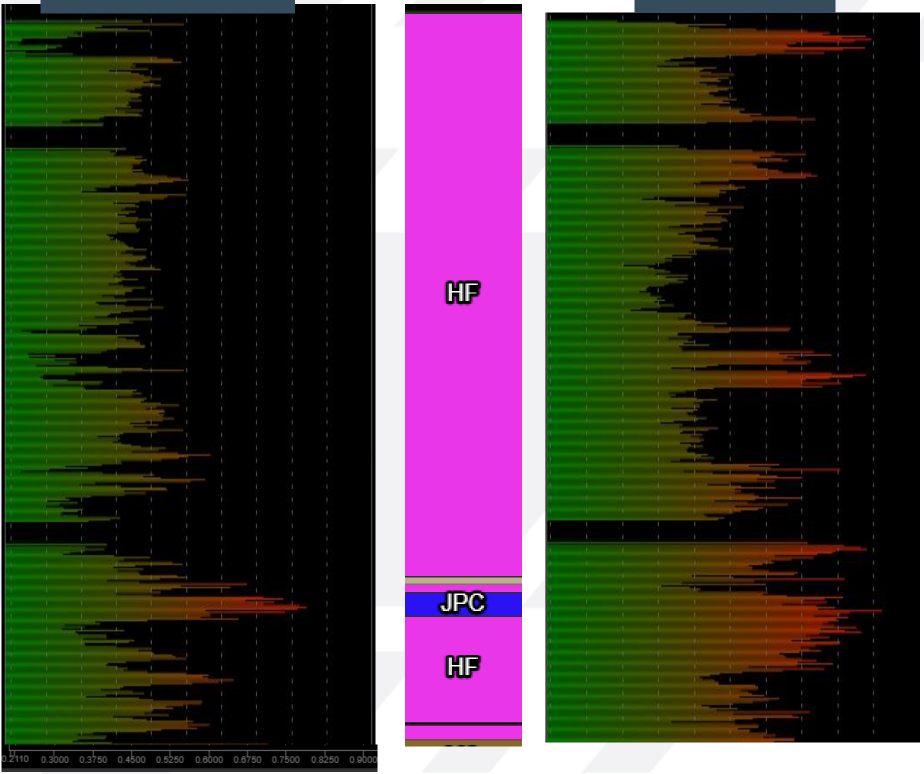
- Another Al-rich mineral can be found in hard caps and canga, gibbsite
- In some cases, the Al content can be estimated from the depth of 2200nm feature from kaolinite (Wells et al. ,2013)
- This value will be underestimated if gibbsite is present
- Can the depth of the 1460nm feature in gibbsite also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

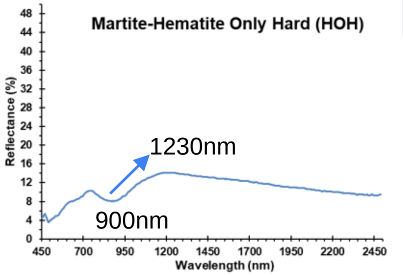
Hardness proxy

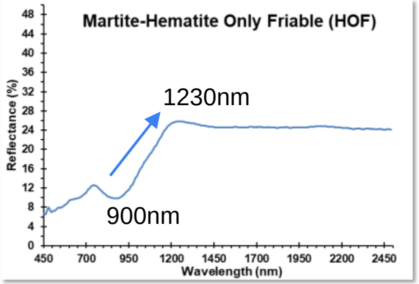
Hematite Hardness Proxy

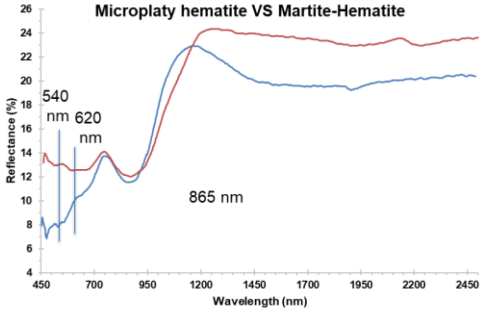
Lithology

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

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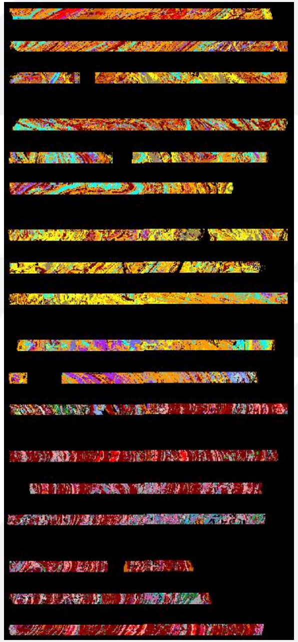
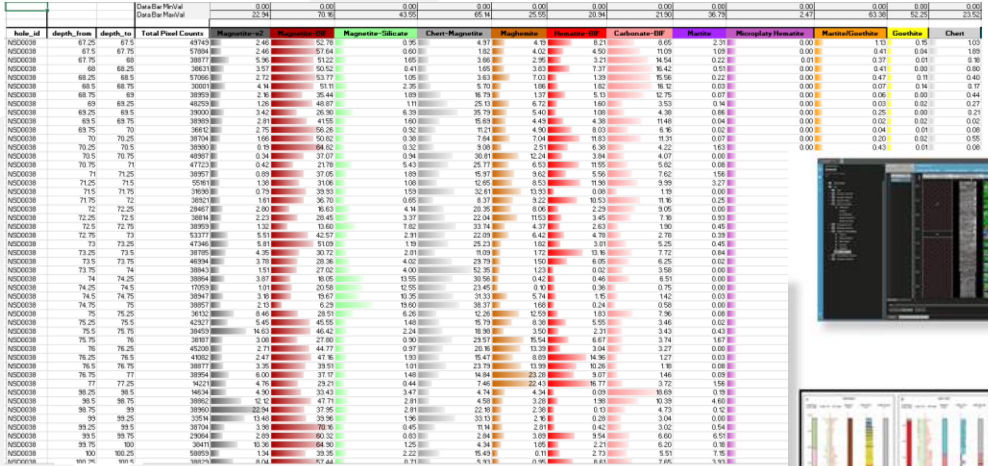
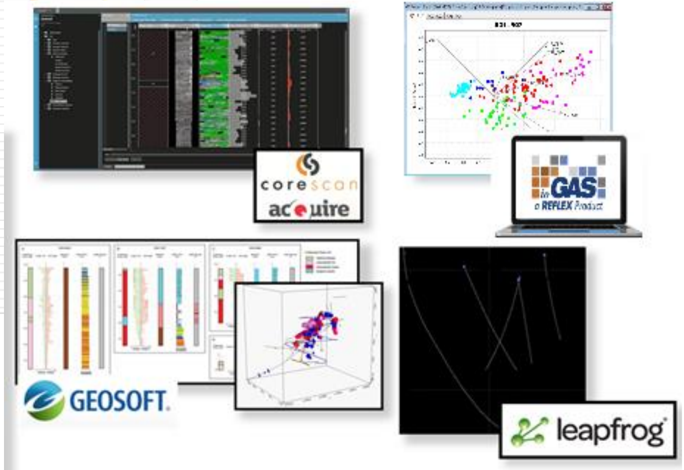
From Pretty Images to Semi-Quantitative Logs to Data Integration



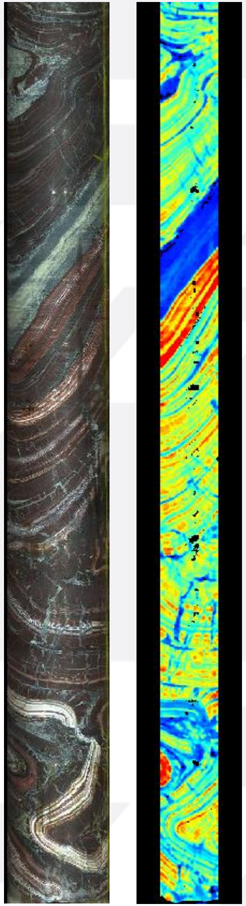
- **Hyperspectral images are not just pretty picture – they are data**
- ~240,000 mineralogical data points per meter of core are calculated and exported into .csv files at desired intervals (m, cm, mm)





- 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

SimeXmin

XI SIMPÓSIO BRASILEIRO DE EXPLORAÇÃO MINERAL

XI BRAZILIAN SYMPOSIUM ON MINERAL EXPLORATION

Obrigado!