HYPERSPECTRAL:

IMPROVING ORE BODY KNOWLEDGE

How to construct meaningful hyperspectral studies and implement programs with actionable deliverables.

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1. The scientific process

- Why are you doing this study?
- What are the questions that you need answered?
- Is hyperspectral appropriate for your program?
  - What part of the IR do you require?
- Creating a gated plan
- Selection of your champion

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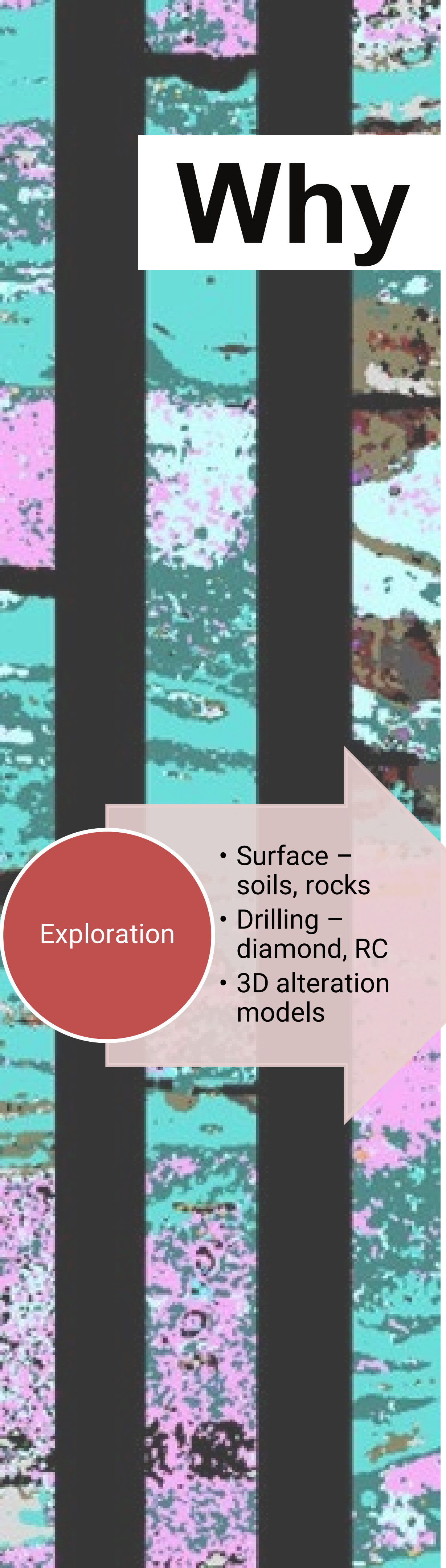

Why hyperspectral?

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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

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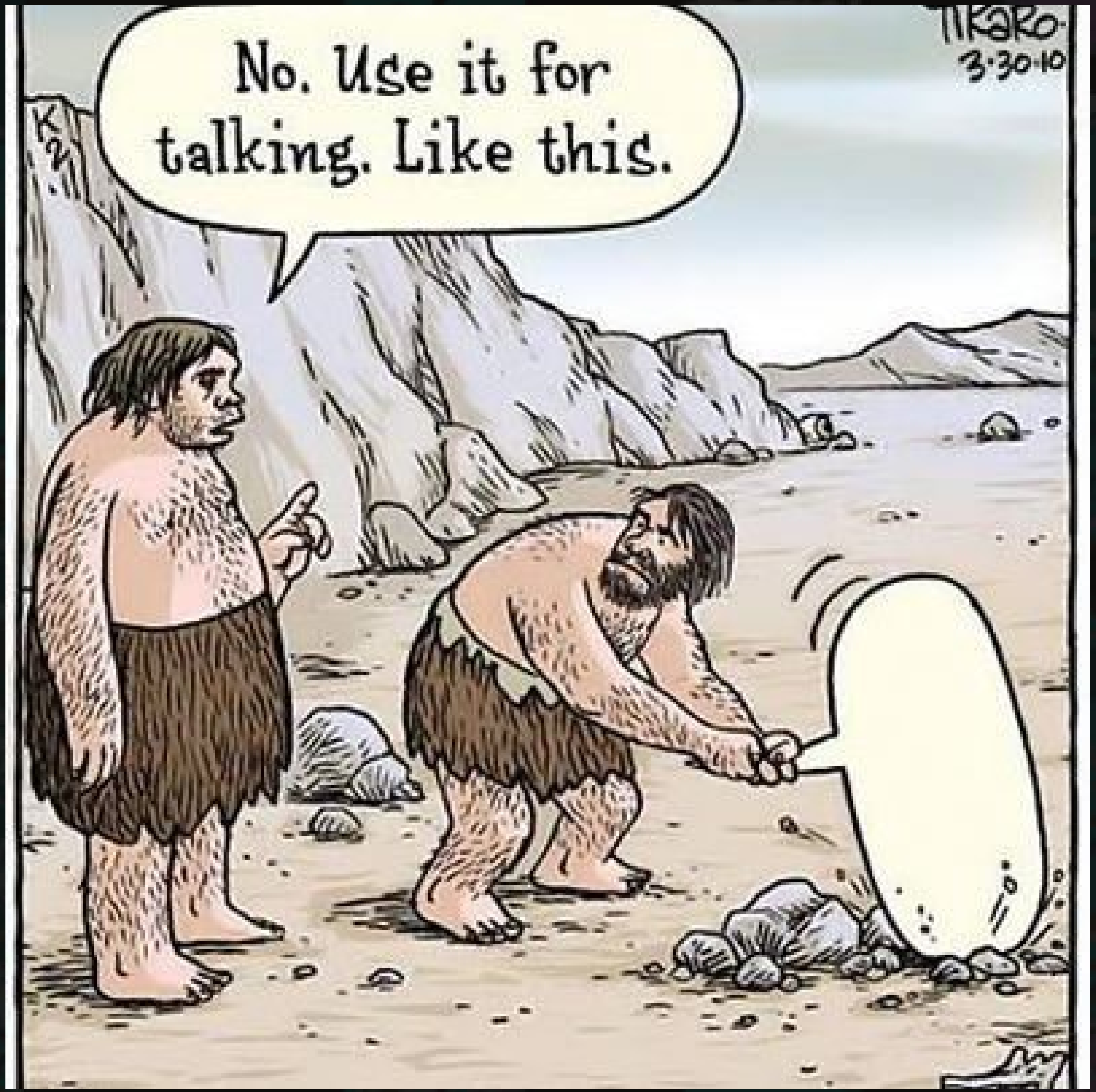
2. Understanding the terminology



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The system’s specifications

1. Spatial resolution
2. Spectral resolution
3. Number of bands & band configuration
4. Signal to Noise Ratio (SNR)
5. Field of view (FOV) & swath width
6. Type of sensor
7. 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.

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Spectral resolution

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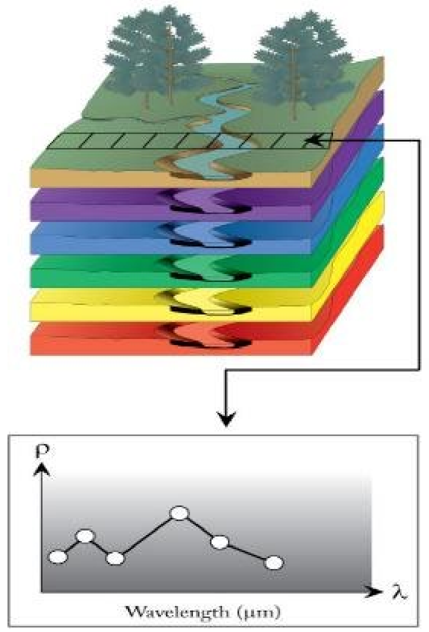
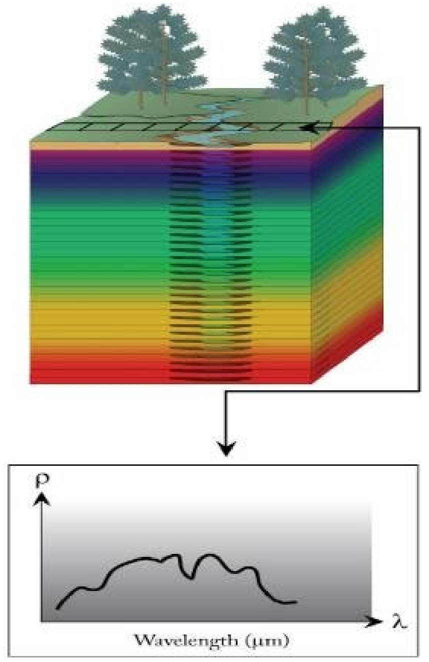
Spectral resolution describes the wavelength intervals over which each spectral band's measurement is made, and which determines the ability to discriminate fine spectral features.

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.

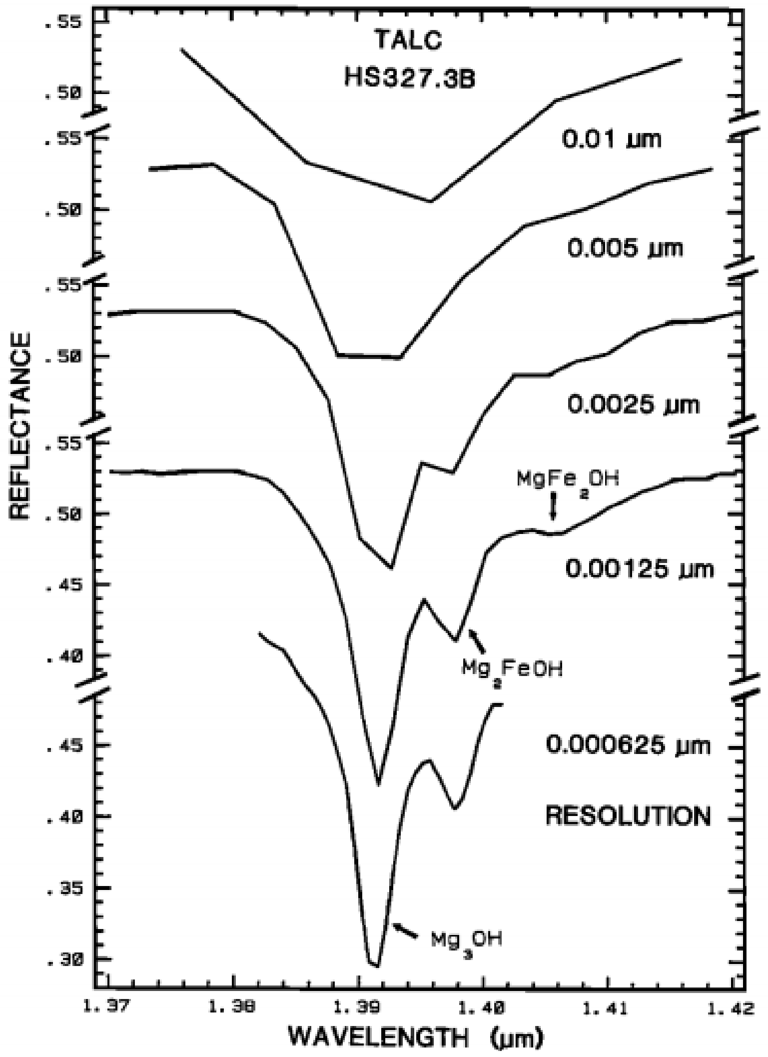


Example multi-band: 0.5μm or 500nm



Example hyperspectral: 0.004μm or 4nm

Reflectance spectra of talc ~1400nm



Increasing spectral resolution = more detailed spectral features

(from Clark et al.,1990)

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

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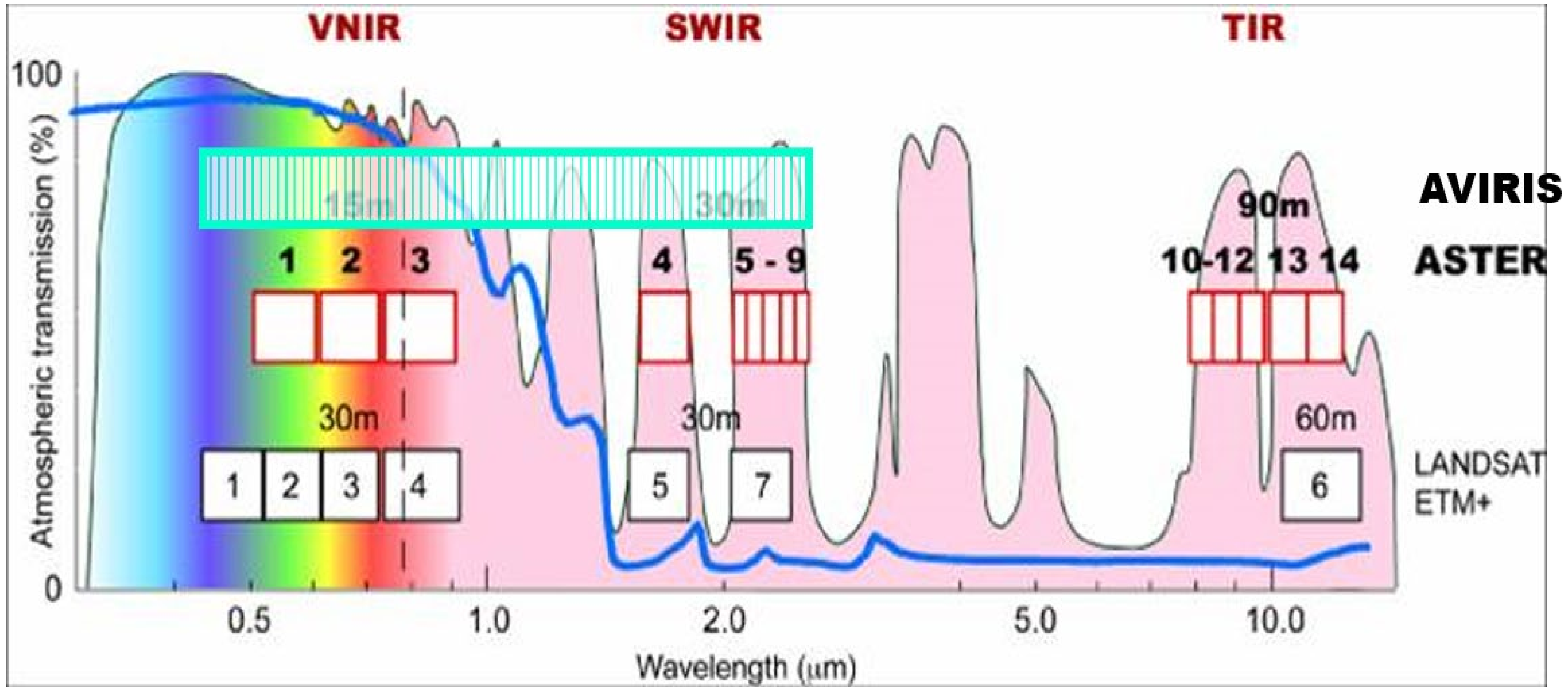
Spectral range, number of bands & band distribution

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.

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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 (frame, pushbroom, whiskbroom) is an important component to improving SNR, as is the field of view and swath width.

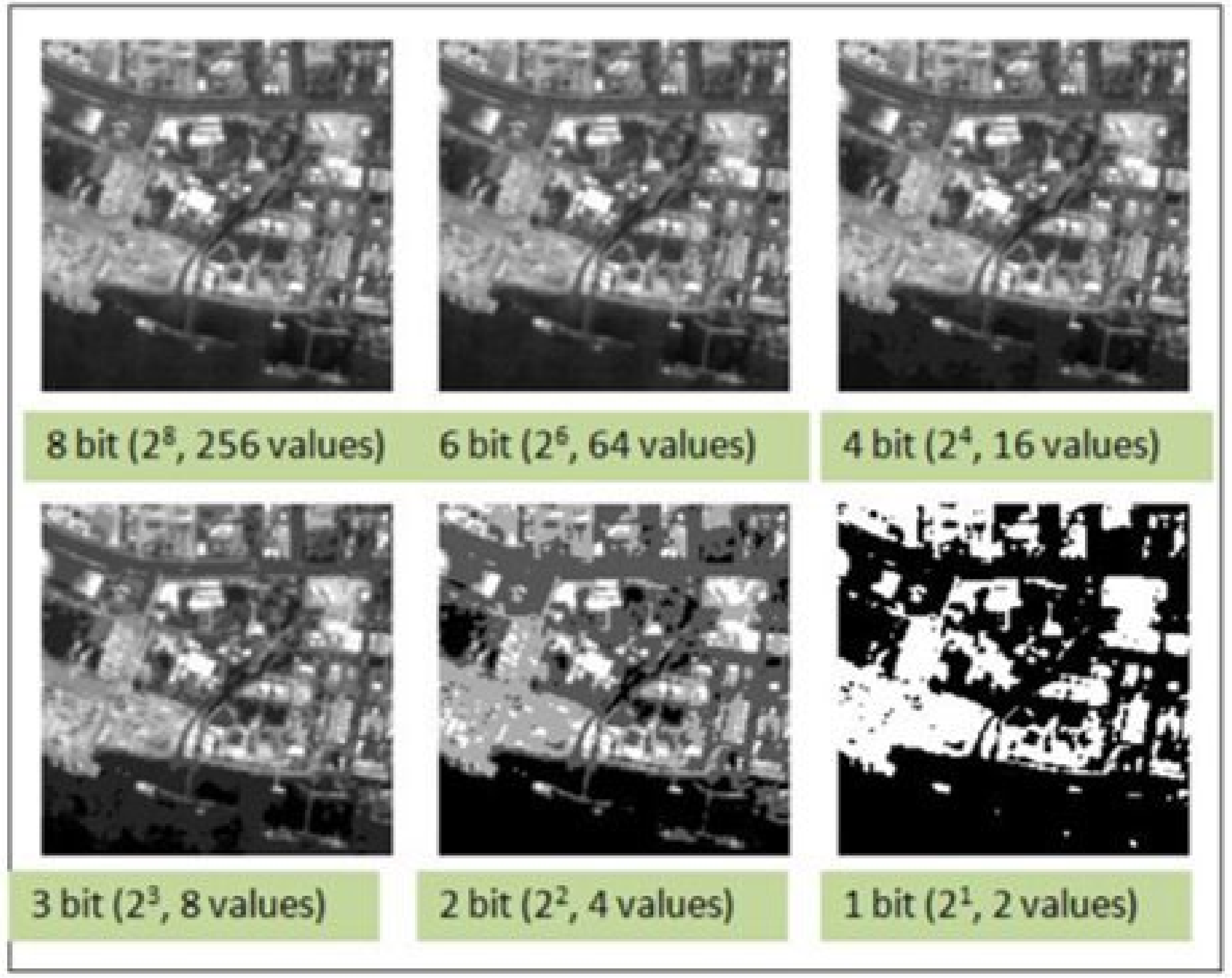

Image credit: Descartes Labs

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.

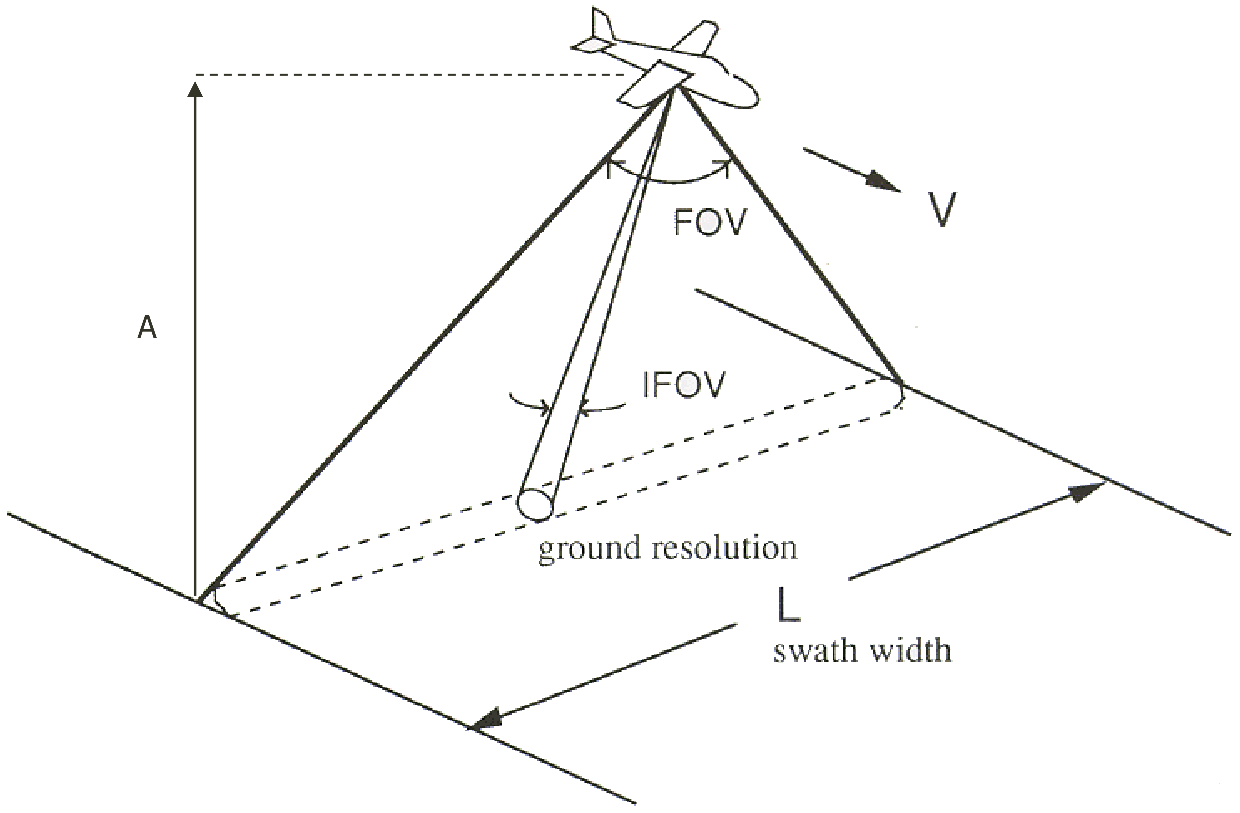

Image credit: Mukherjee University

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

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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?

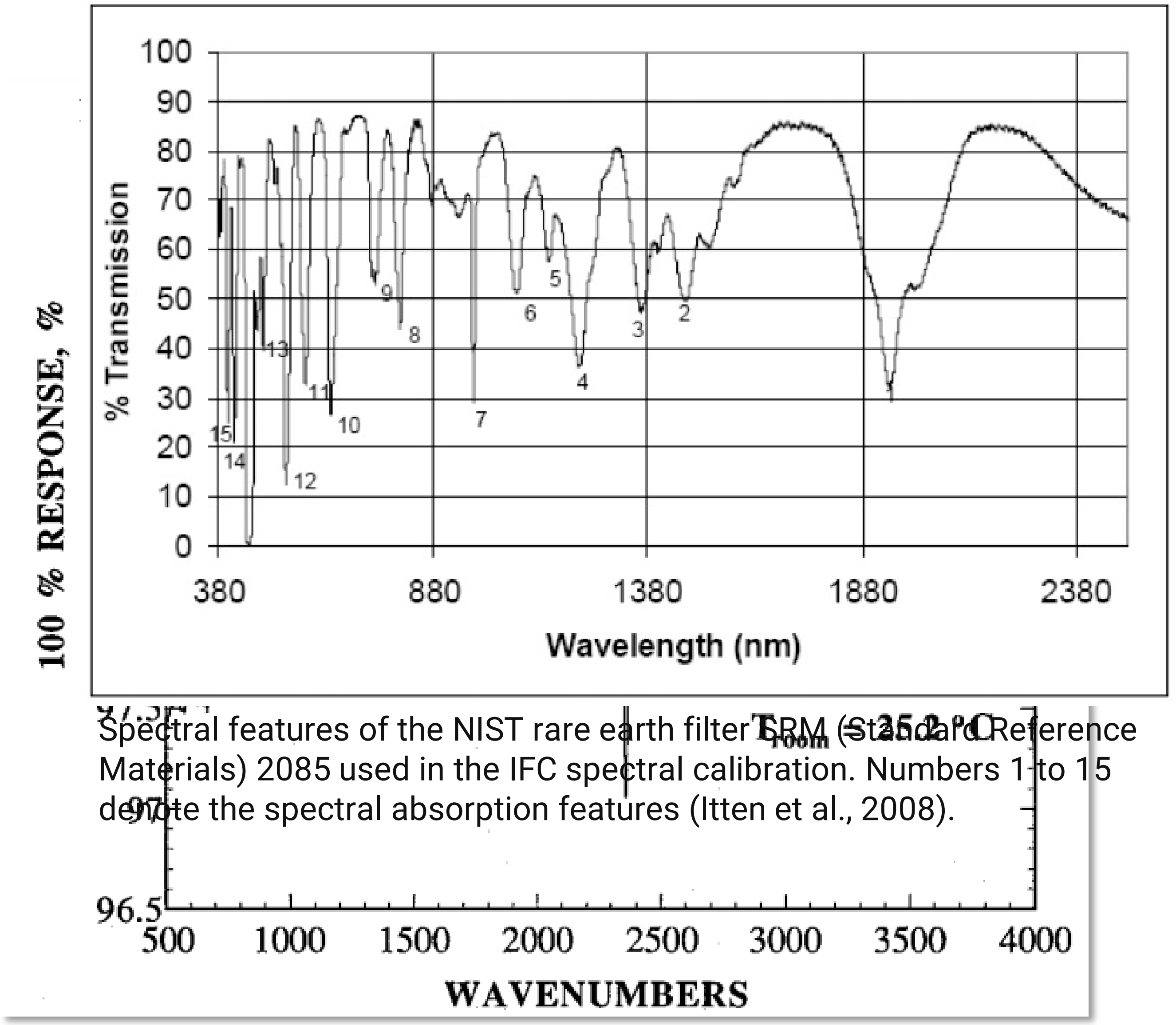
An example of a field duplicate that can be implemented in any program to provide confidence in the repeatability of measurements.

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)

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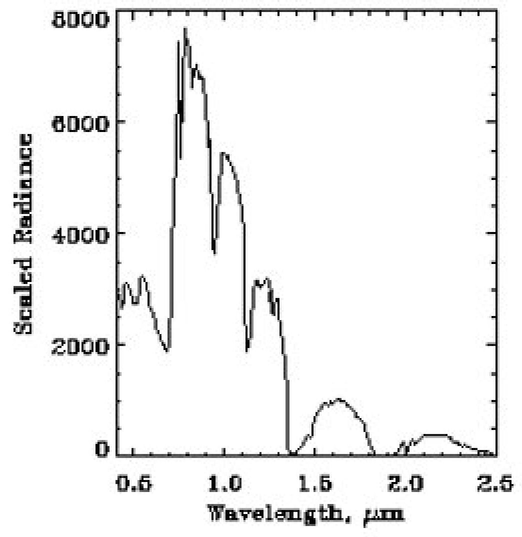
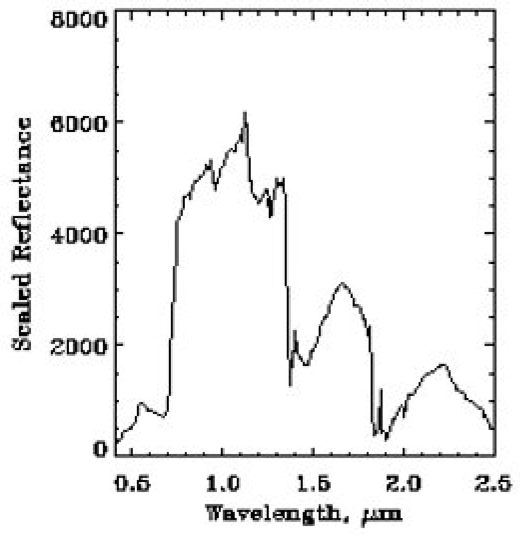
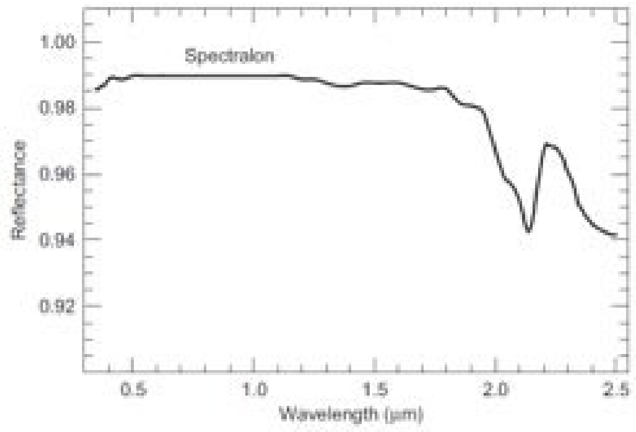
Converting spectral data from radiance to reflectance

- 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**



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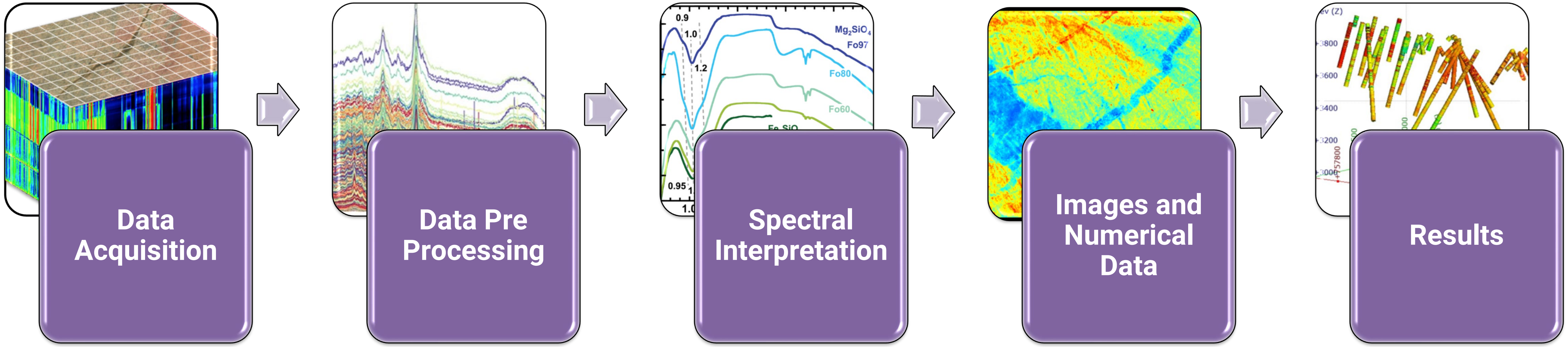
Hyperspectral data analysis

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 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.

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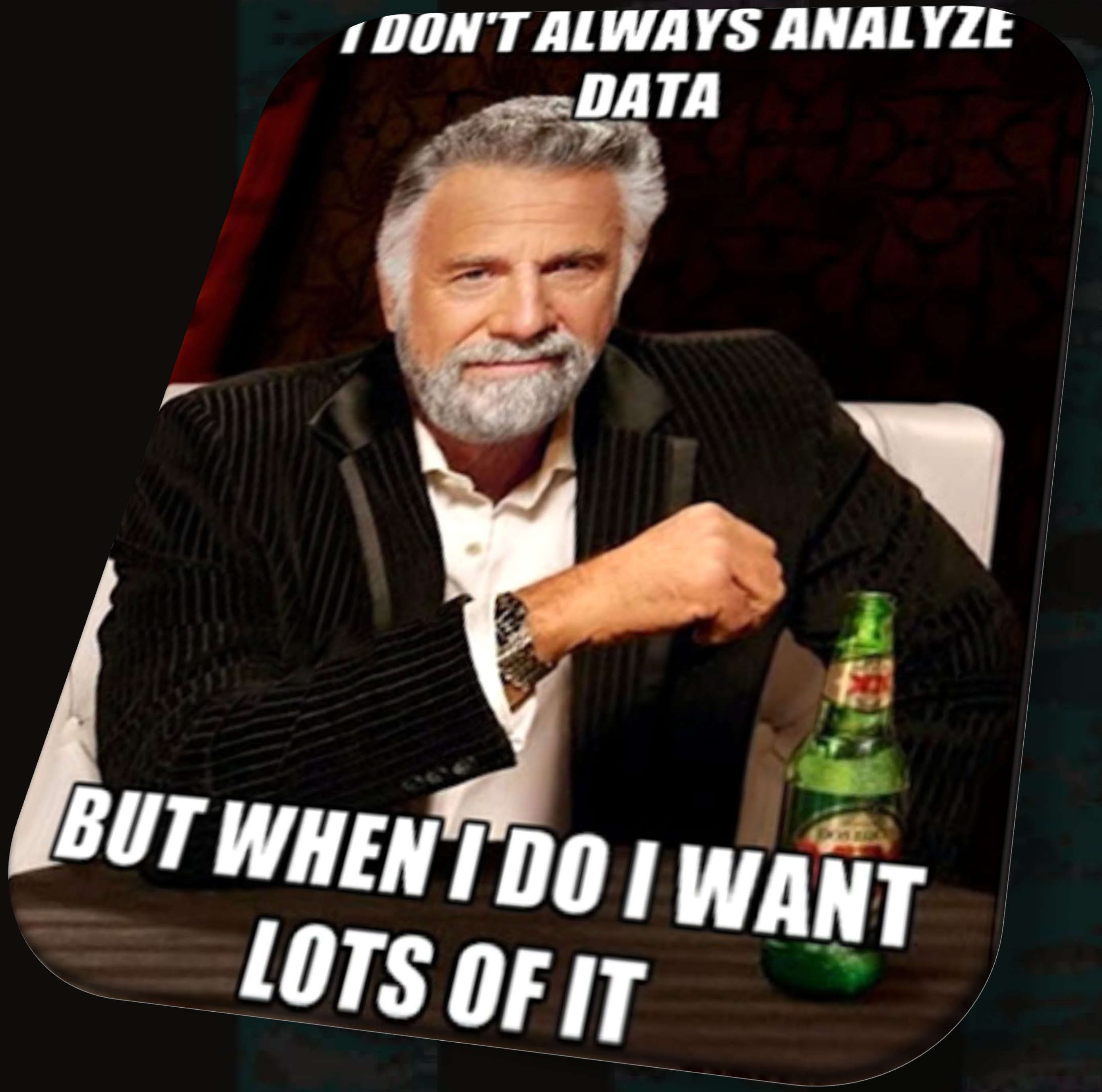
3. Data outputs



Mineralogy: identification, scale & sampling

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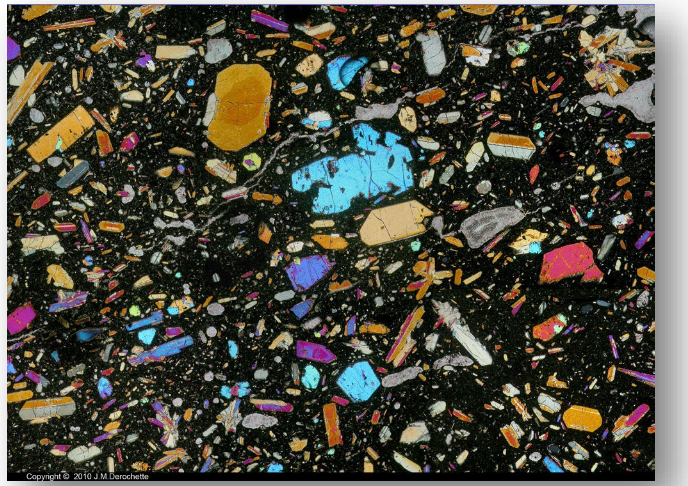
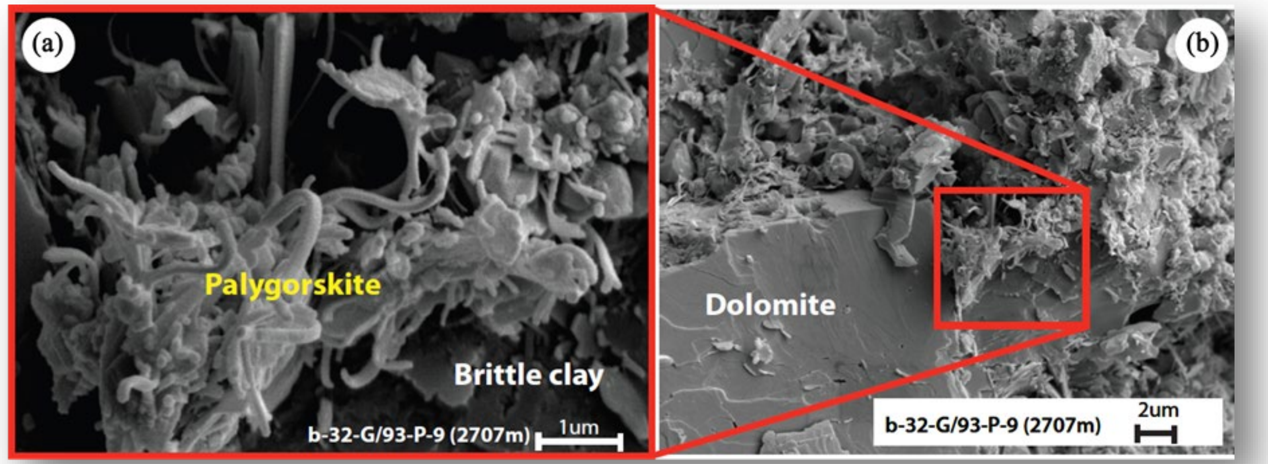
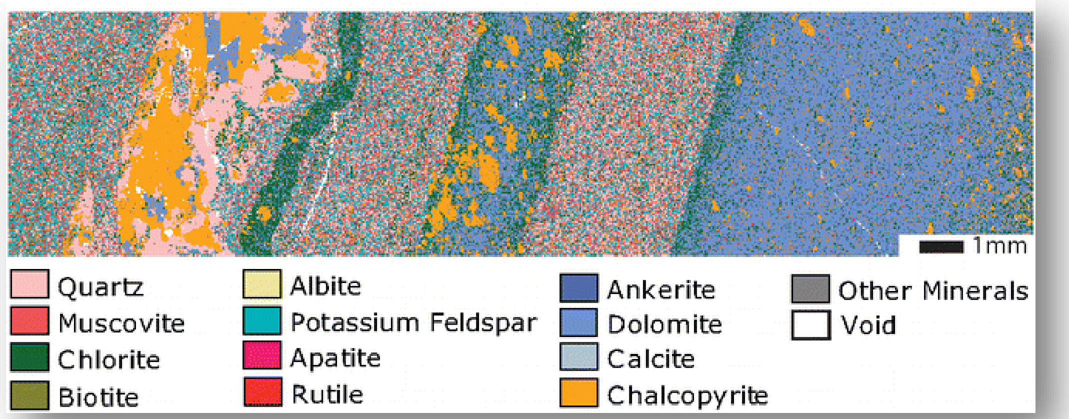
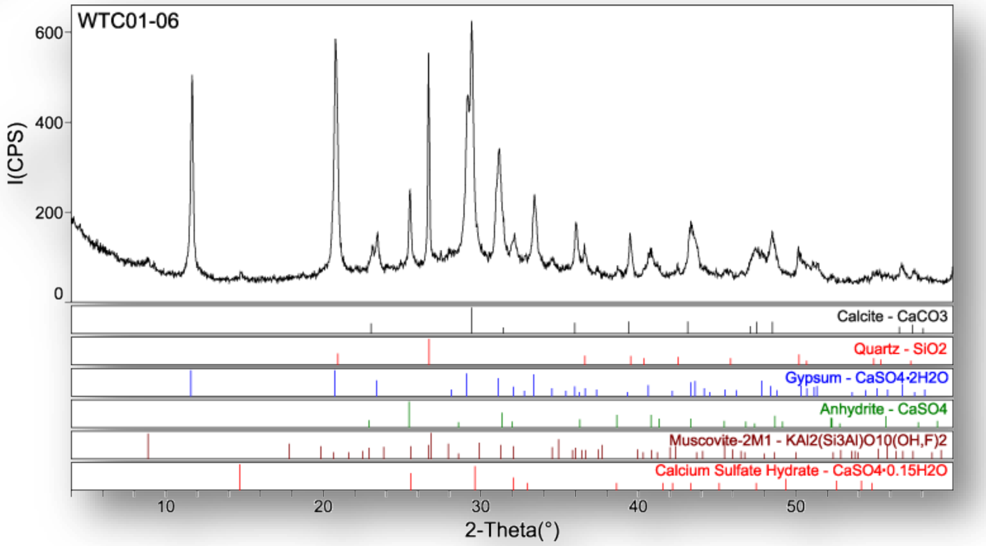
For many years in the mining industry we have assumed that a few hundred point measurements, whether from XRD, QEMSCAN, other point data, or some combination of these, properly characterize the mineralogy of an entire deposit.

Is it time to more seriously question this?









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What is a surface technique? And why is this important?

Surface analysis is where only the surface material is analyzed to a predetermined depth.

- Hyperspectral
- LIBS
- pXRF
- Core logging

Composite analysis is where an interval of rock material is crushed to a fine fraction and a small aliquot of material is analyzed. This composite is a representation of the whole rock.

- XRD
- Lithogeochemistry/assay

Nuances of surface techniques

Sample type scanned/logged

- Whole core
- Diamond cut core
- Split core
  - Preferentially breaks along planes of weakness, may cause overestimation of soft minerals and minerals in veins/fractures
- Coarse rejects
- Pulps

Mineral stability

- Not all minerals are stable at surface conditions (historic core)
  - Secondary sulfate replacement
  - Sulfide weathering (Fe-oxide overestimation)
  - Hydration (anhydrite to gypsum)
  - Coarse rejects in particular may become coated; washing and sieving has large effect

Pixel counting and spectral contribution

- Even if a mineral comprises <1% of a pixel spatially (e.g., at 500um), it can be counted as upwards of 100% in that pixel.
- Is this 'overestimation' meaningful at the drillhole scale?

What's in your hyperspectral output?

"Global spectral parameters"

- Absorption feature wavelength and depth values that are reported for all pixels with no mineral species filtering, e.g., 2200D and 2200L will contain all mineral information not just limited to white micas.

Mineralogy

Mineral composition

- Chemical changes indicated through changes in the wavelength of certain absorption features (e.g., white micas, chlorites, amphiboles…)
- Mineral structure information, such as crystallinity, derived from the shape of certain absorption features (e.g., illite v. muscovite).

Spectral Parameter	Application
Alunite 1480nm wavelength	K:Na substitution (alunite-natroalunite)
Amphibole 2380nm wavelength	Fe:Mg substitution
Biotite 2350nm wavelength	Fe:Mg substitution
Carbonate 2340nm wavelength	Ca:Mg substitution (calcite-dolomite-magnesite)
Chlorite 2250nm wavelength	Fe:Mg substitution (chamosite-clinochlore)
Epidote 1550nm wavelength	Fe:Al substitution (epidote-clinozoisite)
Iron oxide 900nm wavelength	Hematite to goethite variation
Jarosite 1460nm wavelength	K:Na substitution
Kaolinite 2165 crystallinity	Proxy for degree of ordering in crystal structure
White mica 2200nm wavelength	Na:Al:Fe substitution (paragonite-muscovite-phengite)
White mica 2200nm crystallinity	Proxy for degree of ordering in crystal structure
Olivine 1000nm wavelength	Mg-Fe substitution (forsterite-fayalite)

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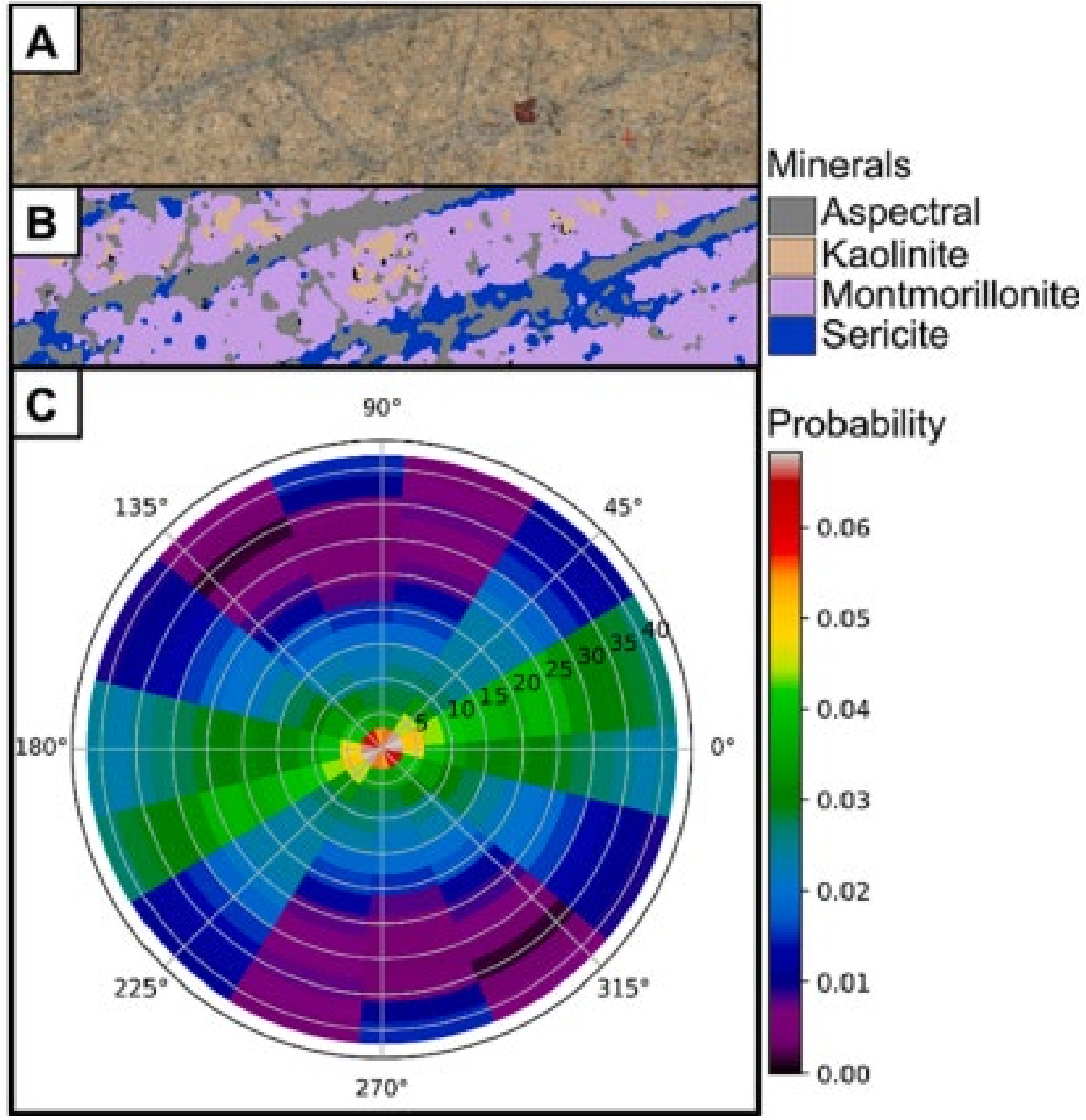
My outputs are percentages…

1. Spectral contribution:
    1. An algorithm is applied to the raw spectral data and the ‘contribution’ of end member spectra is determined.
    2. Depending on the algorithm this is typically due to the intensity of the absorption features.
    3. This does not imply the actual percentage of a mineral in a pixel.
    4. This number will then be averaged over an interval to calculate the ‘percentage’ of a mineral in that interval.
2. Pixel counting
    1. A mineral is either present or absent in a pixel – 0 or 100%
    2. This number will then be averaged over an interval to calculate the ‘percentage’ of a mineral in that interval.

Images are data

- Most machine learning workflows require large amount of high resolution and **consistent data**
- Hyperspectral imaging datasets collect hundreds of thousands of pixels of data per meter
- Significantly, these datasets provides spatial relationships between the pixels in the form of an image; therefore we know which minerals exist as a given and the position of every other mineral

Images are data



(A) RGB image of drillcore, (B) the corresponding mineral classification map to the RGB image, (C) minerals co-occurrence probability fields extraction (MCOPF) polar representation for the sericite-sericite pair (Merill et al., 2023).

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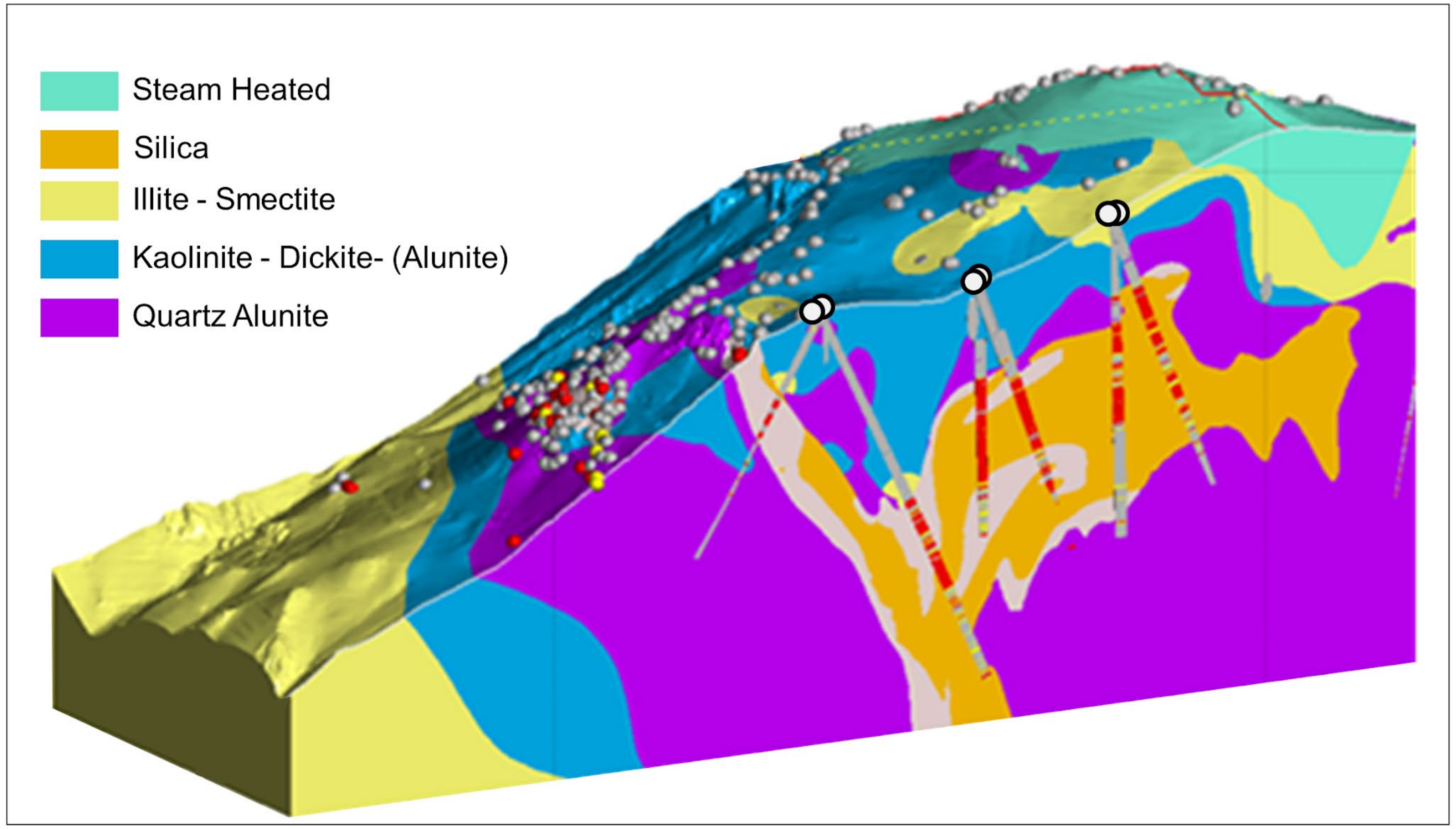
4. Understanding your opportunities

Integration with other datasets

The integration of continuous hyperspectral data and hyperspectral image data lends greater dimension to core logging programs, helping core loggers to identify mineralogy that is difficult to discern visually.



Astorga et al., 2017

Machine learning

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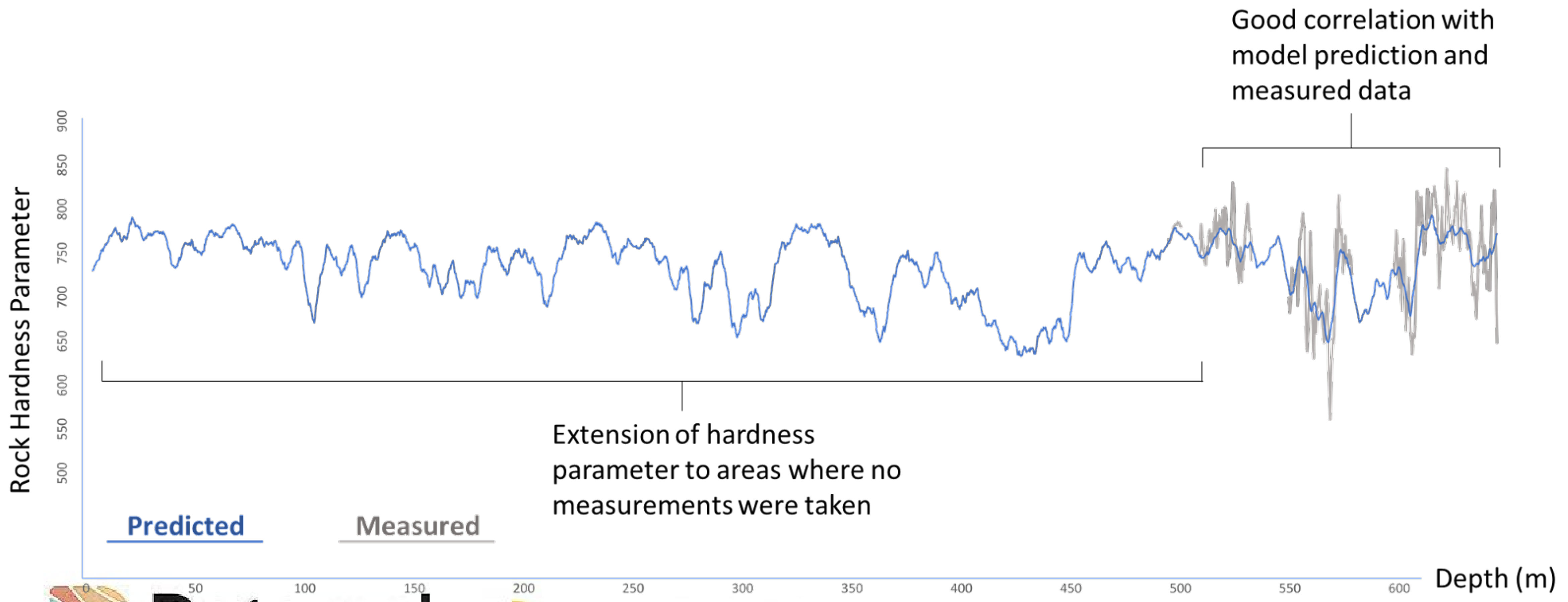
Predicting Rock Strength Parameters: Integrating Hyperspectral Imaging and Equotip data

If a robust relationship between HSI and other datasets can be identified, they can be predicted across areas where no measurements were taken.

Continuous hyperspectral data may be used to predict datasets that are more expensive or suffer from long lead times.



Carmichael et al., 2019

Datarock unearth possibility

corescan Powered by Epiroc

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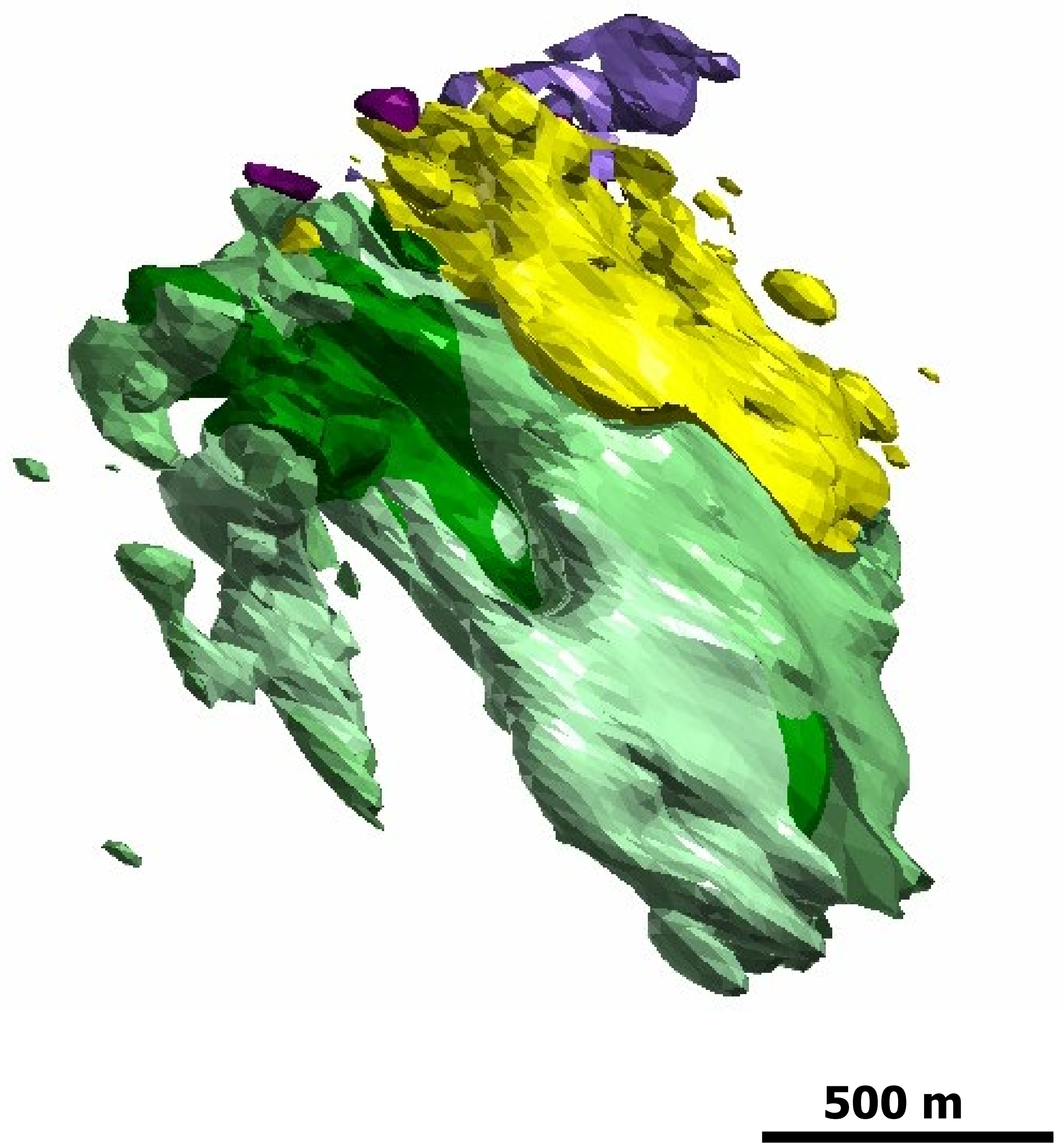
3D modeling

Using a UMAP dimensionality reduction and DBScan clustering, eight distinct alteration domains were identified from the hyperspectral imaging (HSI) mineralogical data at an Andean porphyry.

Using Leapfrog, these domains were modeled and integrated with the Cu and Au grade shells.

Understanding complex distribution of mineralogy with ore has metallurgical implications.



- Amphibole, Biotite, Chlorite, Epidote, Featureless Slope, Fe-Carbonate, Unclassified
- Amphibole, Biotite, Chlorite, Epidote, Featureless Slope, Unclassified
- Amphibole, Featureless Slope, Fe-Carbonate, Illite, Kaolinite
- Featureless Slope, Kaolinite, Muscovite, Pyrophyllite
- Fe-Oxide, Illite, Muscovite
- Fe-Oxide, Muscovite
- Fe-Oxide, Pyrophyllite
- Fe-Oxide, Pyrophyllite, Unclassified

All shells are 0.2% Cu and 0.5ppm Au.
From Scher, 2022.

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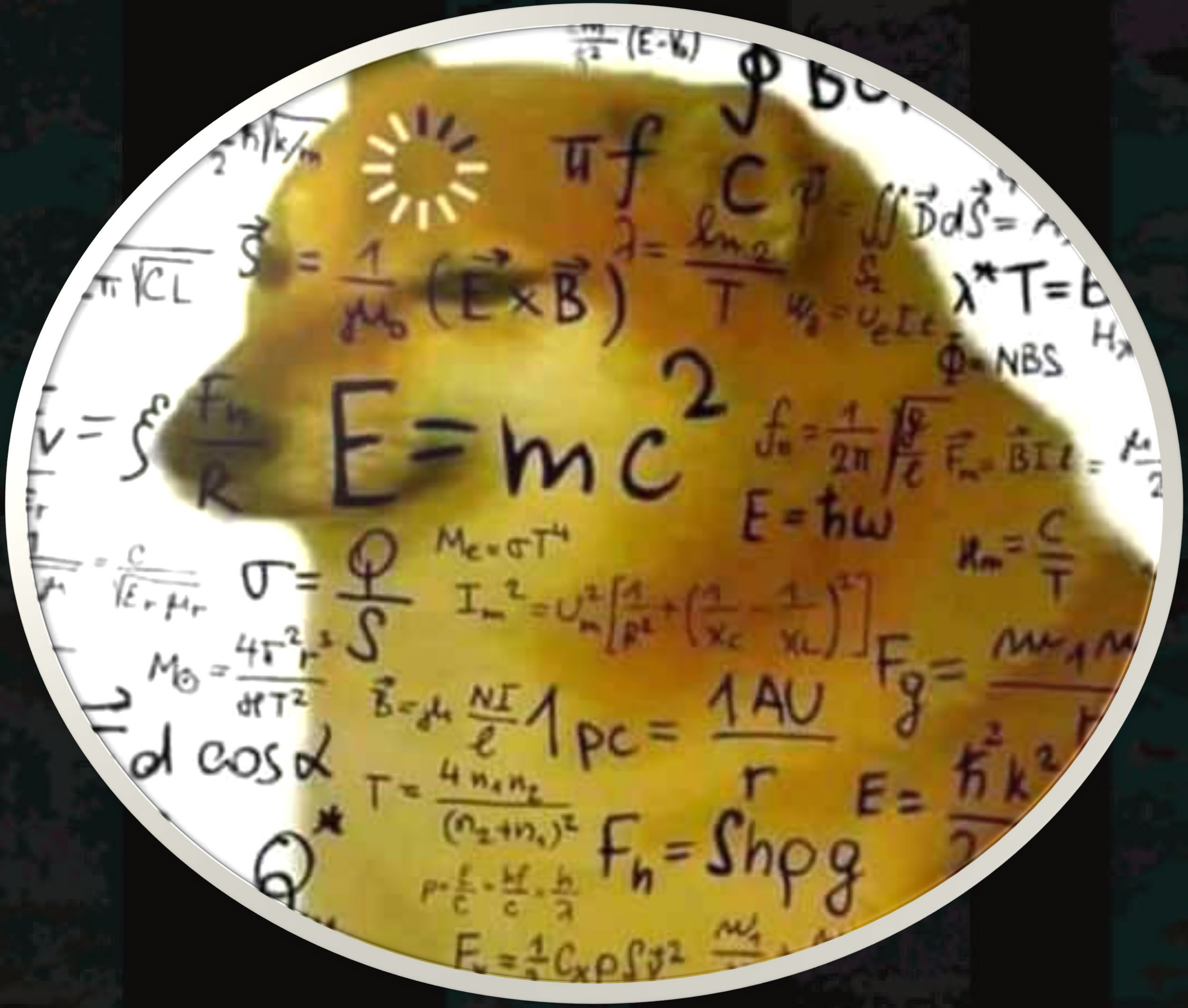
5. Selecting vendors



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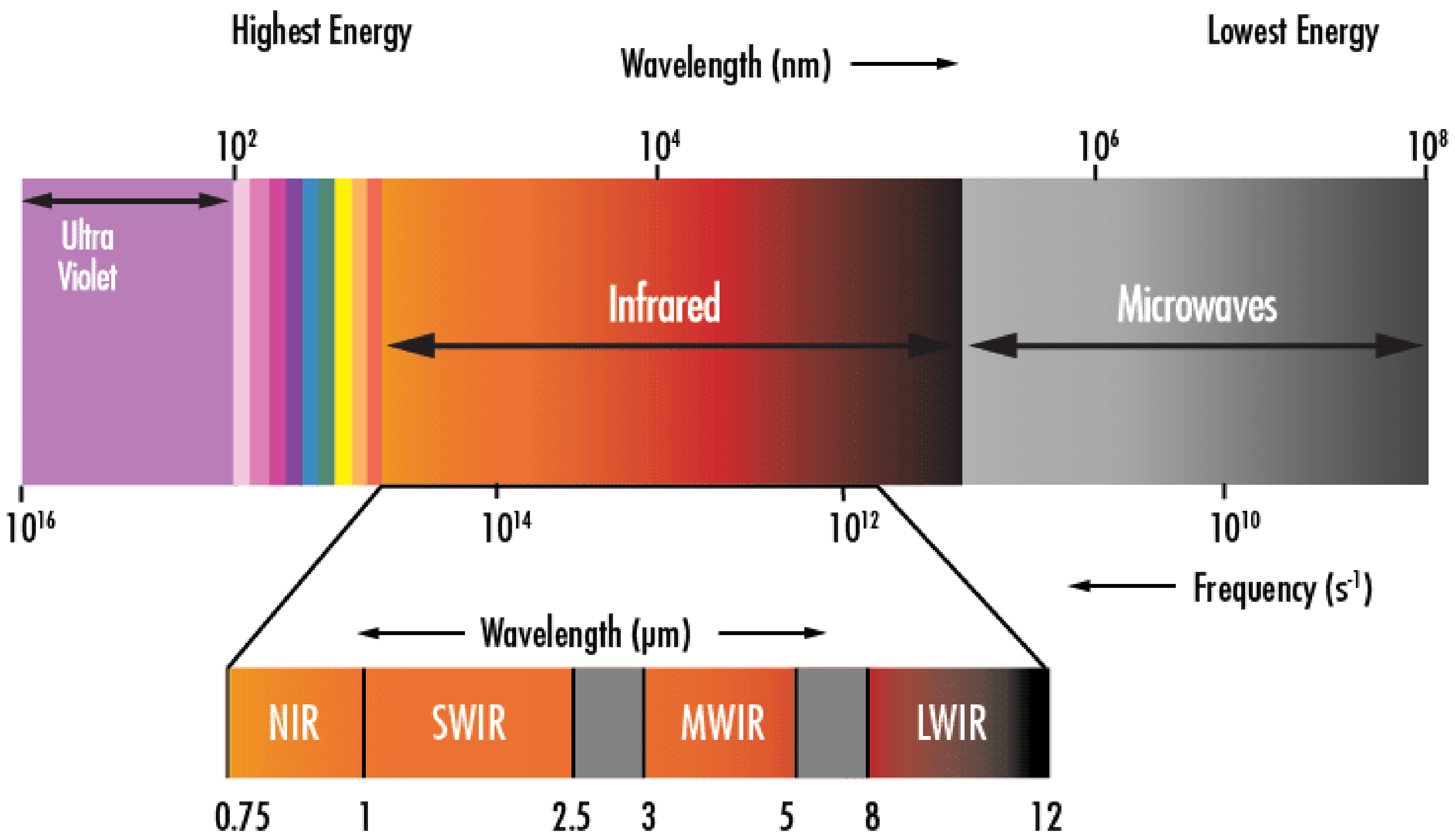
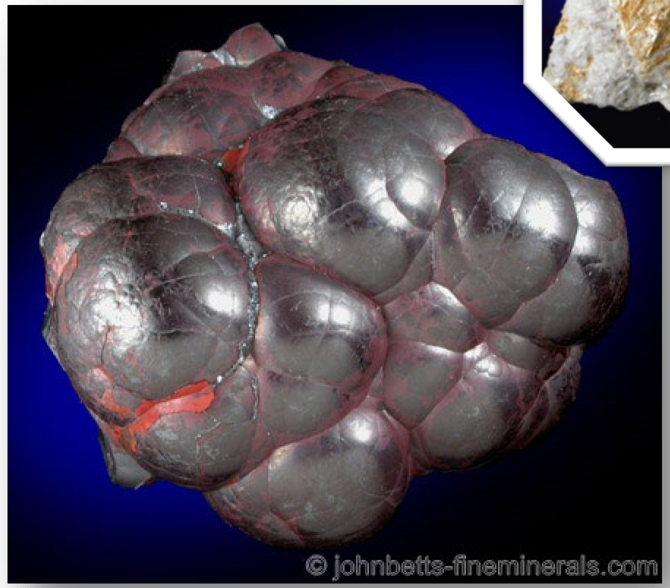
The electromagnetic spectrum is relevant…



Mouahid, 2018

Garnet - LWIR

Pyrophyllite - SWIR



Hematite - VNIR

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Can you answer your questions with your vendor?

…and can your vendor answer your questions?

Where's your champion? This is not a C-Suite decision.

6. Orientation studies

What is an orientation survey?

- An effective hyperspectral program requires a basic understanding of the geological and *hyperspectral* environment in which the program is being carried out.
- This is best achieved by careful review of available relevant information, communicating with one or multiple vendors, and through small trials; every geologic environment, ore body and project is different!
- Ultimately, the data acquired not only helps ensure development of a great hyperspectral mineral library, but also enables planning for large-scale implementation of the technology, possibly at various scales (point, line and imaging).
- It should be noted that the initiation of the design phase of any hyperspectral program requires a clear understanding of both the technical objectives and economic parameters.
- Upon completion of the orientation study, there should be sufficient information to enable informed decisions as to the optimum survey procedures under the prevailing conditions.
- Program planning, in which the practical details of survey procedures and the order in which they are to be applied, can then be initiated.
- The exact purpose of an orientation survey is dependent on the question that your team is trying to answer, but ultimately we are trying to identify the best means to prepare the media, and collect and interpret the data.

What does this look like for a hyperspectral program?

It is important to capture the variability of your deposit, as opposed to putting a hard limit of 2-3 drillholes or 3,000m, etc.

It is also important to consider the what the focus of the study is:

- Vectoring to mineralization in a PCD
- Understanding texture and mineral relationships for geometallurgy
- Understanding mineralogy for an environmental study
- Integration of consistent mineralogy in a 3D model

Finally, is the goal a large-scale implementation that requires near-real time data processing or will this only ever be a small scale program?

What does this look like for a hyperspectral program?

Important things to consider:

1. Make sure to capture the full range of mineral variability with the samples you have submitted.
2. When creating the mineral library, communicate with your providers what deposit type you have – this will help to focus the minerals they look for.
3. Provide any supplementary mineralogy data you have – thin section analysis, XRD, etc. – this will improve their interpretation.
4. Your champion should be in constant contact, hyperspectral is interpretative and it benefits from your champion working closely with the interpreter.
5. Are there particular products that will help for vectoring or with geomet? Ask your vendor!
6. As you continue to scan new material, new minerals will likely be uncovered. No one logging is a 'bad' geologist, take this opportunity to be excited! This is what ore body knowledge is all about.

7. Long-term implementation

New technology is A LOT of work

- Require a project champion
- Define study objectives
- Goals
- Follow through on action items
- Integration with other datasets
- Workflow implementation

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How to construct meaningful hyperspectral studies and implement programs with actionable deliverables…

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I want to say that I could make a slide on how you can perfectly implement your program.

But I can't.

For 100 reasons, **EVERY** project is so **unique**.

But what I do know, is that if you can understand the basics of some very complicated physics, understand the business opportunities, select a project champion (and support them), and ensure that after your orientation study you still think that this is both the right technology and vendor for your project… you can follow well established implementation workflows within your own company to make this as successful as any other technology implementation.

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