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The Future of Core Logging:
Applications for Hyperspectral Core Imaging

Dr. Cari Deyell-Wurst & Dr. Cassady Harraden

The Big Picture…
The future of mineral exploration and mining

Core Logging

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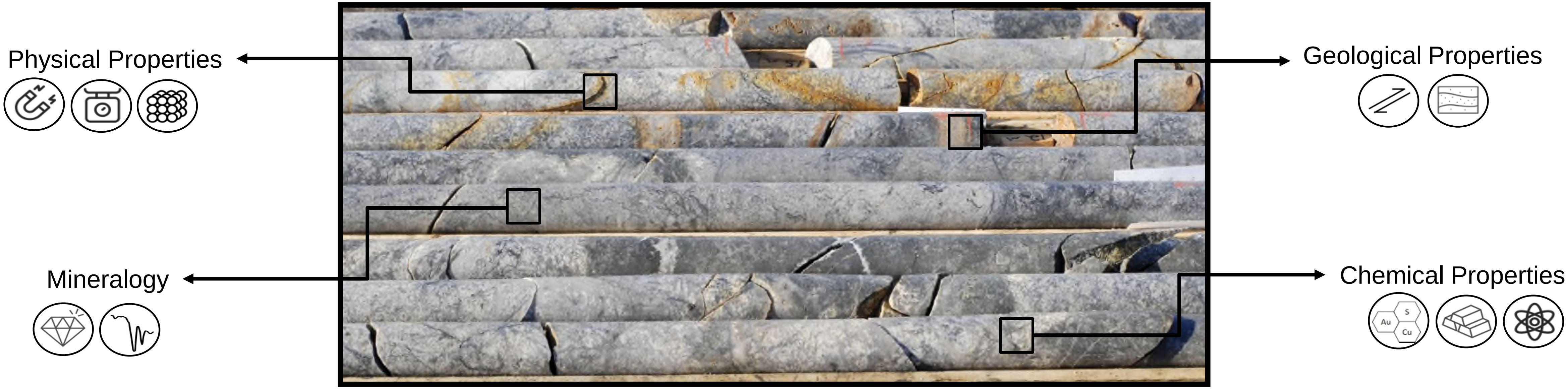


Core Logs: A record of the physical and chemical properties of geological material.

Data collected informs geological, geophysical, geotechnical, geometallurgical and reclamation programs through life of mine.

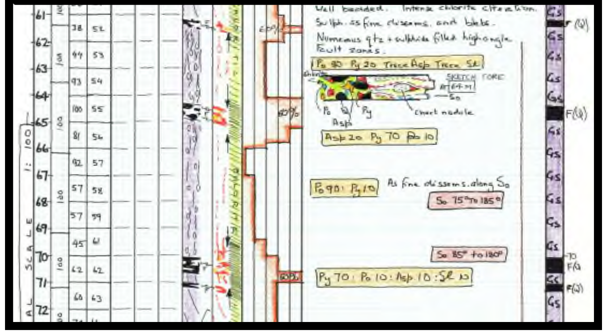
Exploration → ***Discovery*** → ***Development*** → ***Production*** → ***Reclamation***

The Need for Innovation

- Current methods for collecting data from drill core are highly variable:
  - Methods range from manual logging to logging using some combination of analytical techniques and automation
  - Relogging exercises are common as projects mature.
- Challenges with current logging techniques:
  - Subjective - time consuming – inconsistent - labor intensive – incomplete use of data.
- Geoscience workflows are changing – a new range of tools and expertise with increased digitization

How do we get the right data to the right experts at the right time?

Manual Logging



‘Digital’ Logging

Assisted Logging

Automated Logging

New Normal - Automation and Enhanced Analysis

What is the alternative?

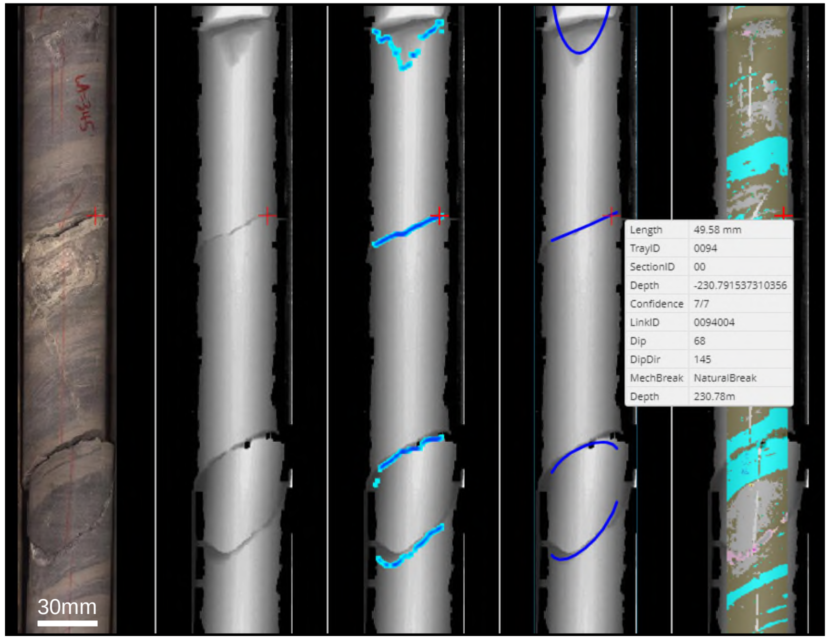
Industry is already incorporating some form of automation as standard practice:

- Decreased reliance on manual data collection (time- and labour-intensive)
- Increased use of accurate, (near) real-time data streams and increased connectivity (direct input into databases).

“Augmented Intelligence” → efficient and effective use of geological expertise and technology for key deliverables

Manual data collection

Automated structural feature detection



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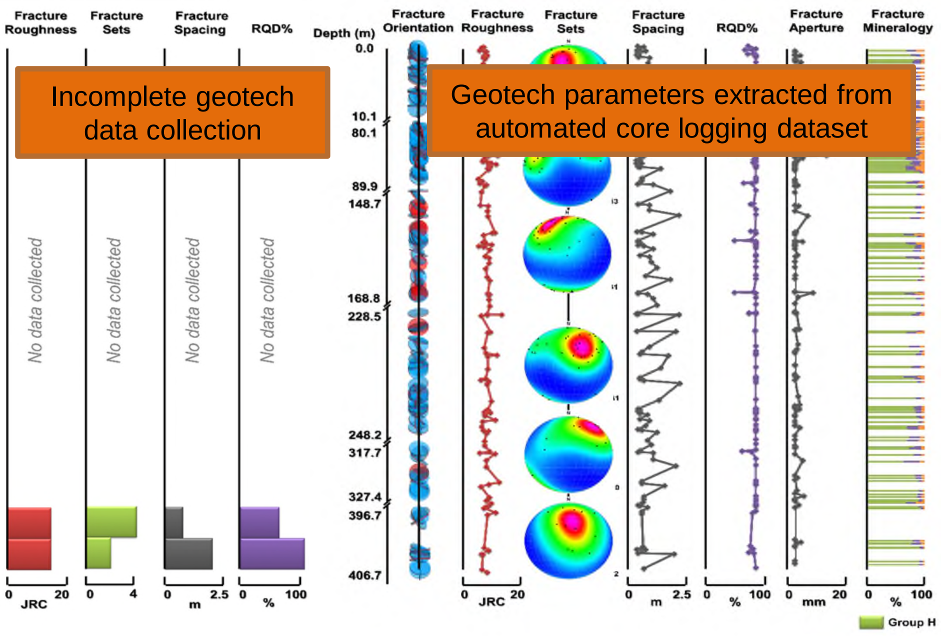
Data integration and predictive analysis



Modified from Harraden et al., 2019

Automated Logging Tools - The Present

A range of different tools are available for specific tasks:

- Mineralogical, geological, petrophysical measurements
- Digitization and connectivity
- AI and deep learning for enhanced rock classification.

a) Point data collection systems:

- XRF, gamma, magnetics, density, hyperspectral.

b) Scanning systems:

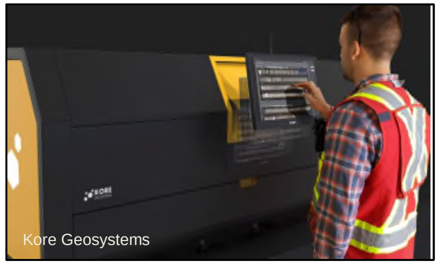
- Single sensor (e.g., digital photography)
- Multi-sensor (integrated scanning systems)

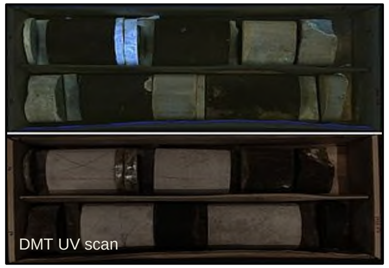
Point Data Instruments


Geometrics MagMapper

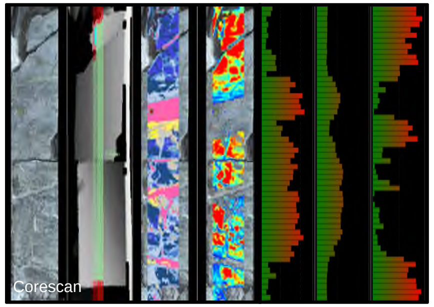

GF instruments

Single Sensor Scanners


Kore Geosystems


DMT UV scan

Integrated Multi-Sensor Systems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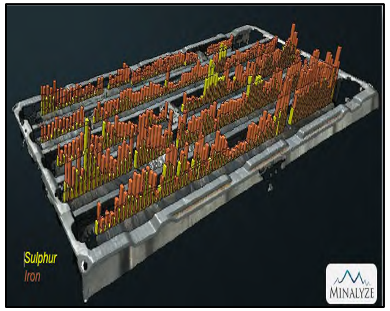
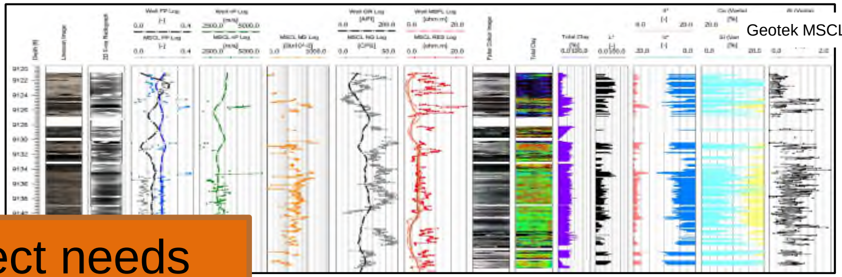



Geotek MSCL

Should be 'fit-for-purpose' and tailored to project needs

Automated Ore Characterization and Monitoring

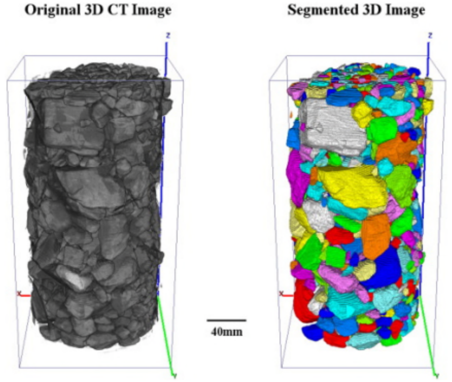
Automated characterization and monitoring tools assist in optimizing ore processing, including:

- Mineral speciation, geometry and association (including metal deportment and tenor)
- Ore versus waste discrimination
- Presence or absence of liberation/recovery-altering minerals (both ore and gangue minerals)
- Monitoring changes in rock mass under mining stress and in tailings/settling ponds.

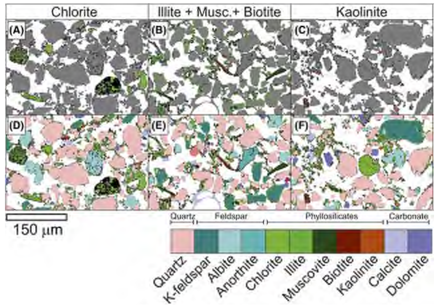
Data collected at various scales:

- Grain and particle characterization systems: MLA/QEMSCAN, micro-CT, X-ray microtomography, micro-XRF, hyperspectral
- Bulk ore characterization systems (on-belt, on-shovel, sorting systems etc.): XRF, LIBS, gamma, magnetics, density, hyperspectral
- Mine-scale monitoring systems: piezometers, load cells, seismometers/accelerometers, LiDAR.

Grain and particle-scale

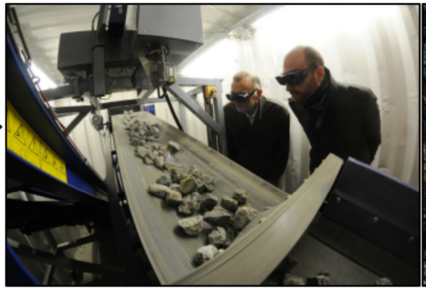


3D micro-CT from Wang and Miller, 2020



QEMSCAN from Griffiths et al., 2019

Bulk ore-scale



LIBS In-Line Grade Scanner (LIGS)

ShovelSense XRF

Mine-scale

Maptek Sentry LiDAR monitoring

Underground seismometers

The Future….

Core logging and mine exploration/development workflows are already experiencing a major shift in standard practice.

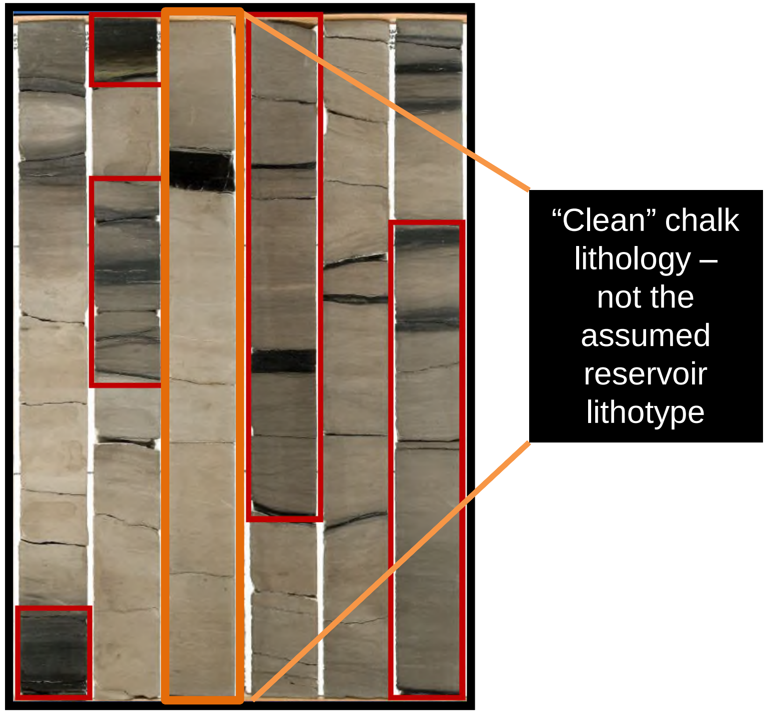
- The future will see an increased automation of core logging tasks and continued digital evolution:
  - Technical advances
  - Integration of technologies across multiple platforms
  - Advances in data handling, integration and application.
- Improvements in mineral processing tools and automation will allow for:
  - Prediction of processing behaviour well in advance of mining
  - Real-time characterization and monitoring for on-the-fly decision-making
  - Preconcentration/separation of similar material for variable ores (may require separate/modified processing circuits).
- Informed decision making for better rock characterization throughout the mining cycle:
  - Risk management
  - Improved efficiency and efficacy.

High Quality Data Inputs: Vital for Success

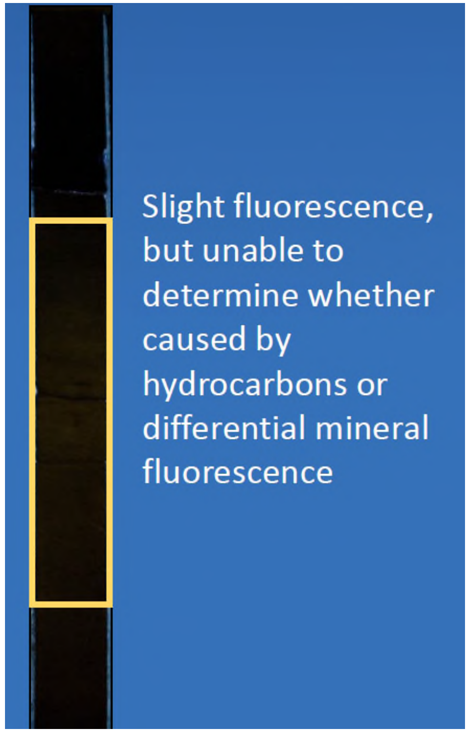
Data-driven workflows are reliant on the quality of data inputs → QC and careful data evaluation a necessity.

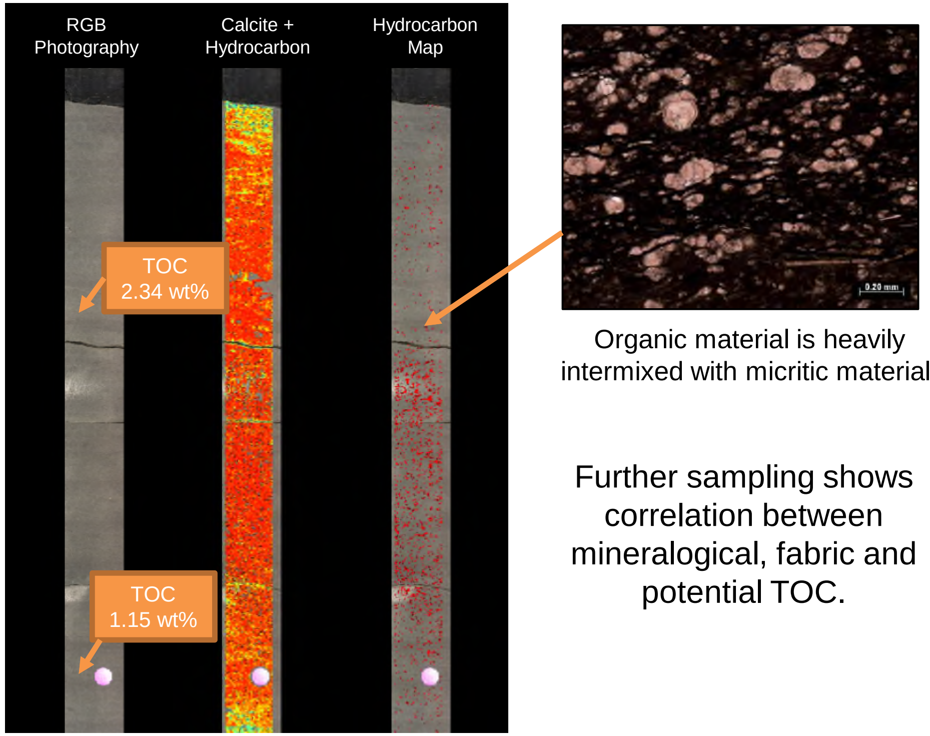
AUSTIN CHALK, Unconventional Oil and Gas Reservoir (USA)

after Hollon et al., 2018



Original sample intervals (red) selected for evaluation based on core photography (circa 2011).





Organic material is heavily intermixed with micritic material.

Further sampling shows correlation between mineralogical, fabric and potential TOC.

Hyperspectral data analysis (2017) is able to identify hydrocarbons during re-assessment of original sampling.

Reflectance Spectroscopy:
Applications in Mining and Mineral Exploration

Reflectance Spectroscopy for Mineral Analysis

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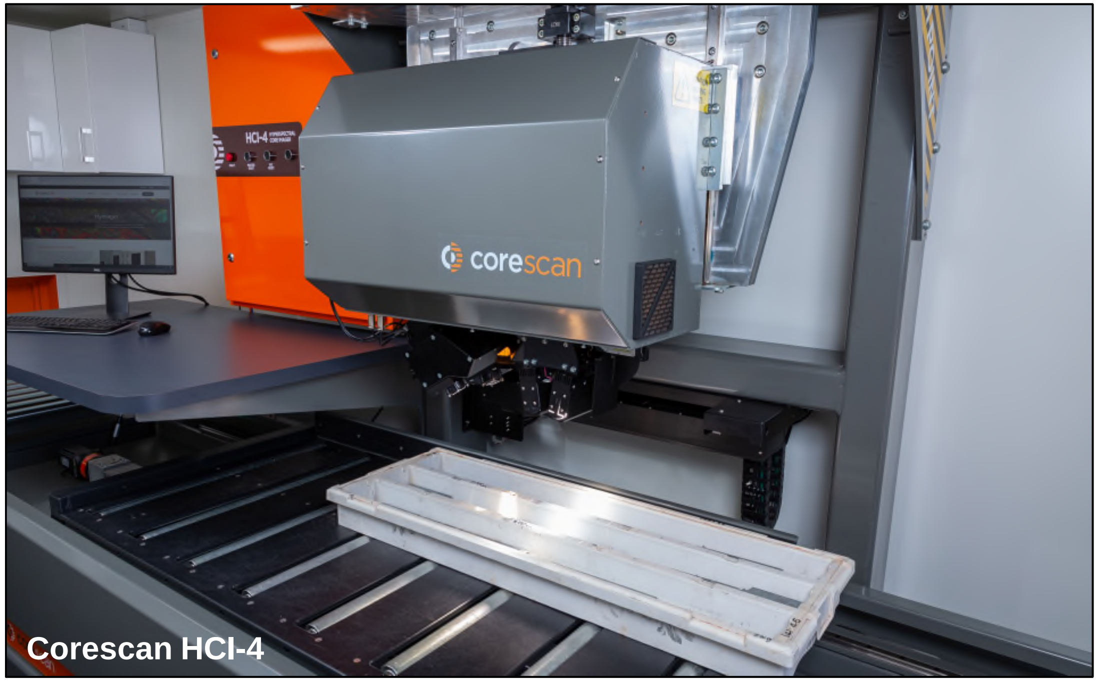
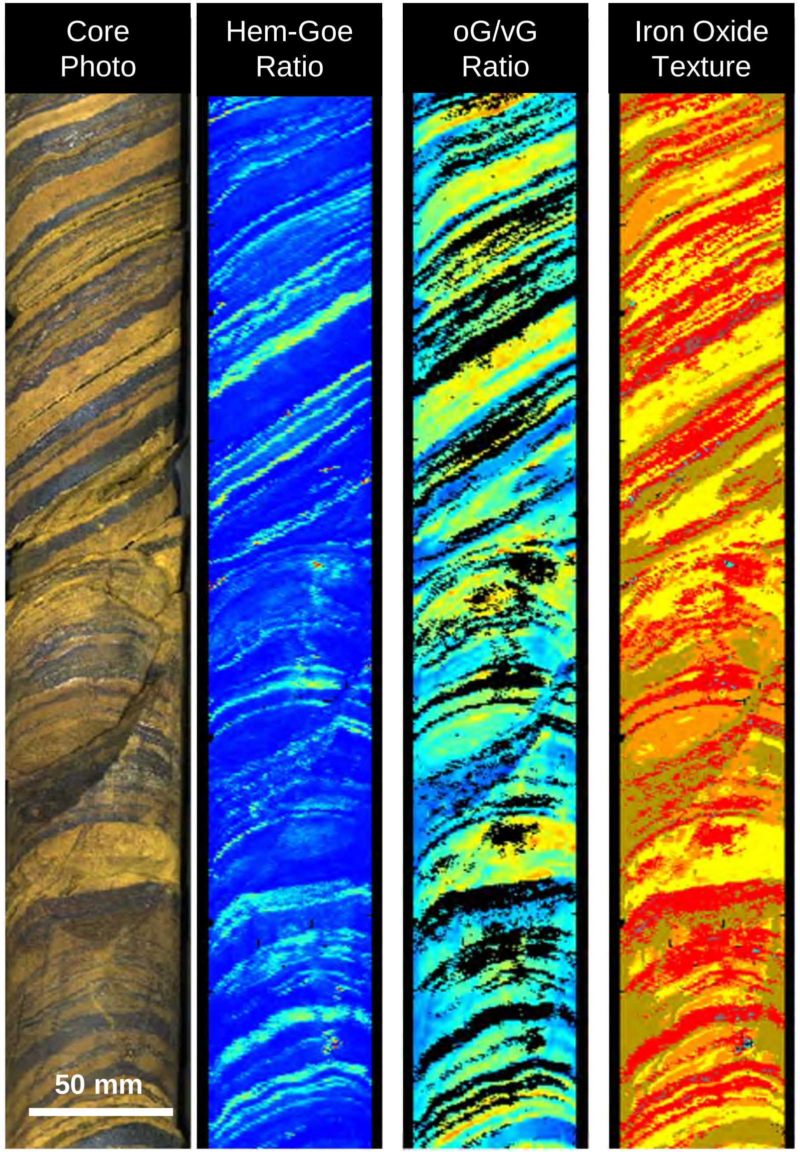
- Reflectance spectroscopy is used to identify and characterize minerals.
- This method can be successfully used on a range of different geological applications.
- Reflectance spectroscopy is a common tool in mining and mineral exploration – and throughout life of mine.



Corescan HCI-4



Example: Corescan HCI-3 photography and mineral imagery for banded iron ore deposit (Australia)

Brown Goethite
Ochreous Goethite
Vitreous Goethite
Martite/Goethite

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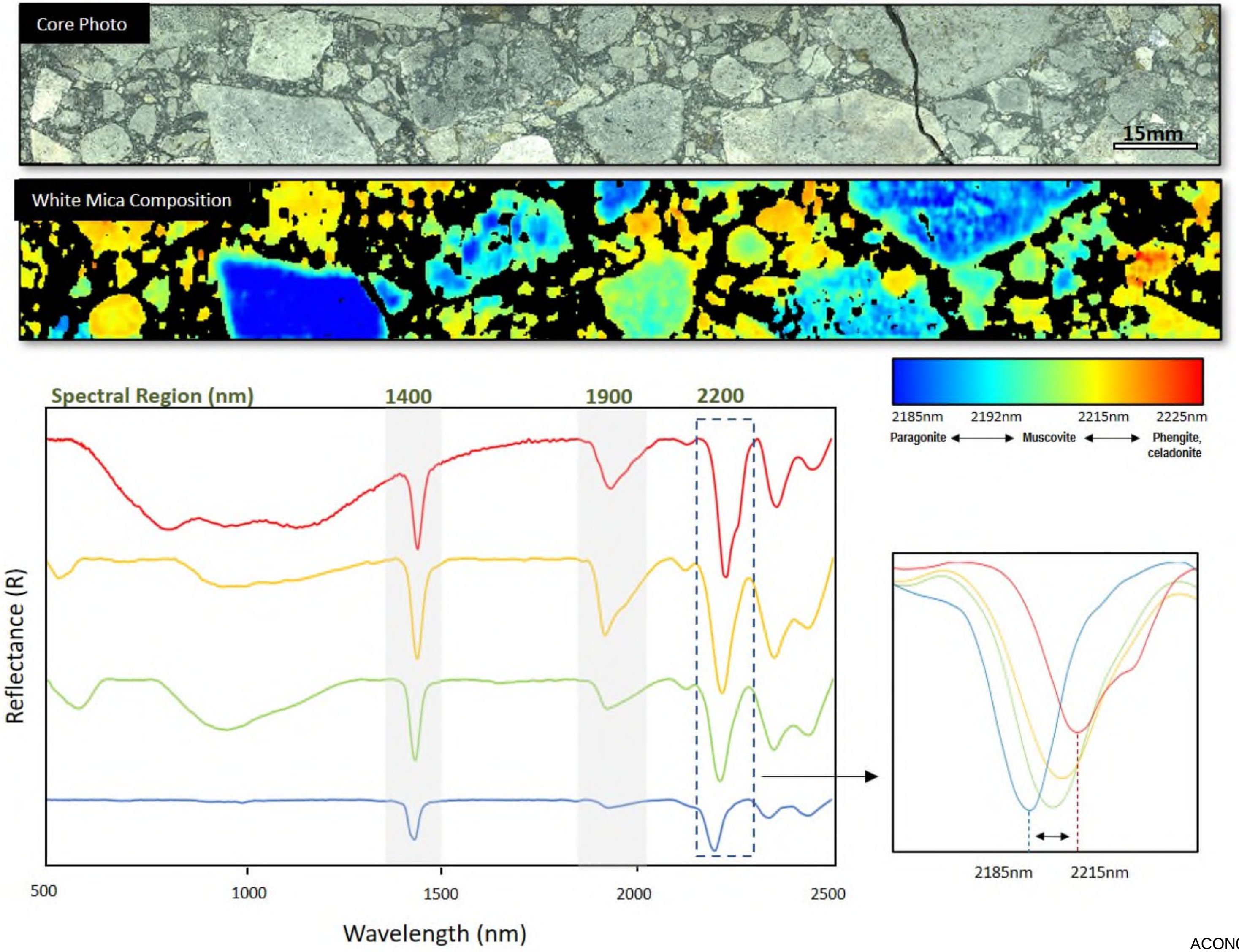
Reflectance Spectroscopy

Why use reflectance spectroscopy in mineral exploration and mining?

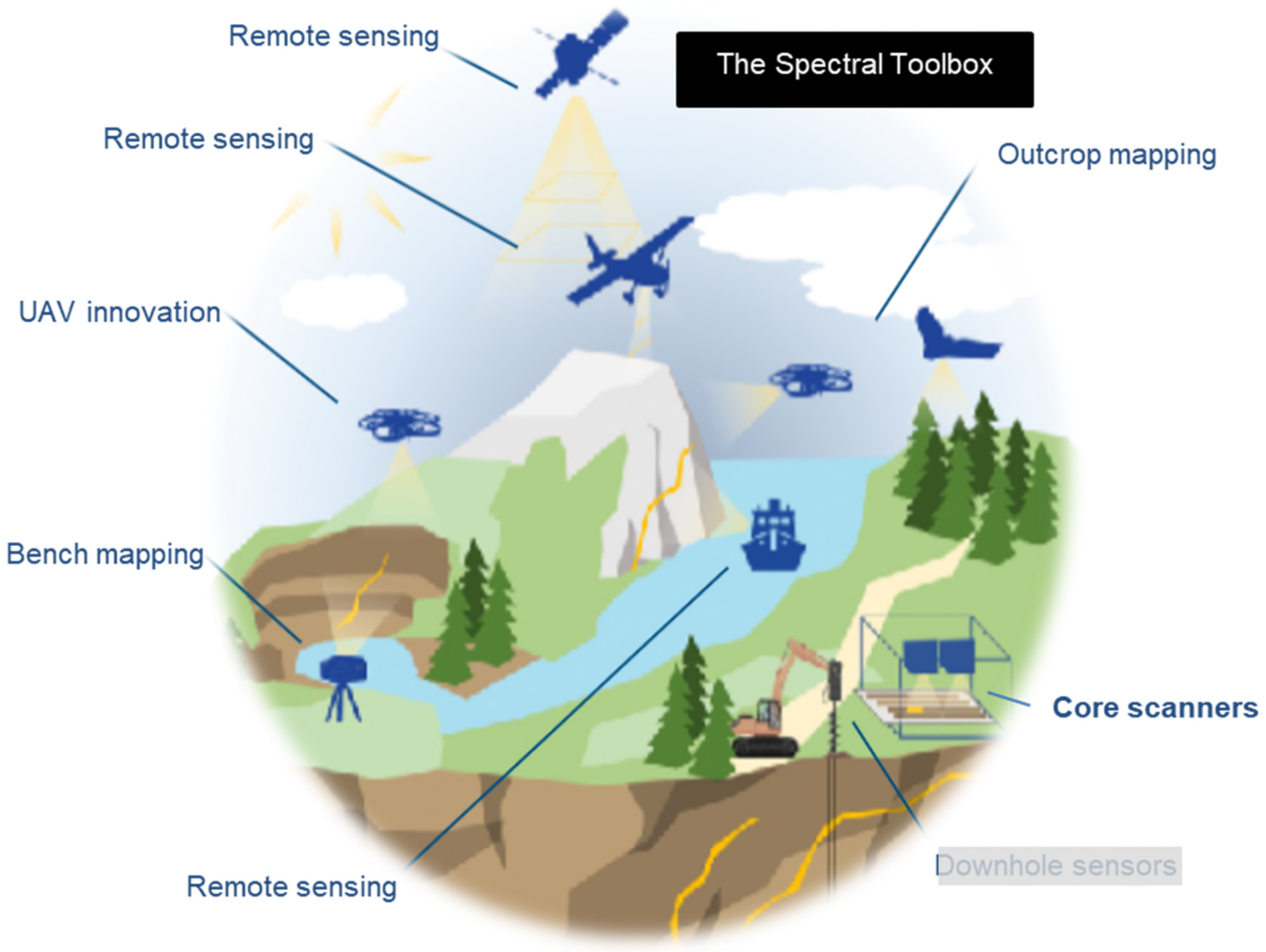
- One of the few techniques that identifies minerals (not elements).
- The method is sensitive to the chemical variations in functional groups (e.g., geochemical substitutions).
- It is a universal technique.
- Ease of use.
- Reflectance spectroscopy is typically fast and easy to acquire and is non-destructive.



Reflectance Spectroscopy: Uses

Why use reflectance spectroscopy in mineral exploration and mining?

- <u>It is universal technique.</u>
- 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 across the entire mining cycle.



(after Jackisch et al., 2018)

Spectroscopy: Minerals, Bonds and Elements

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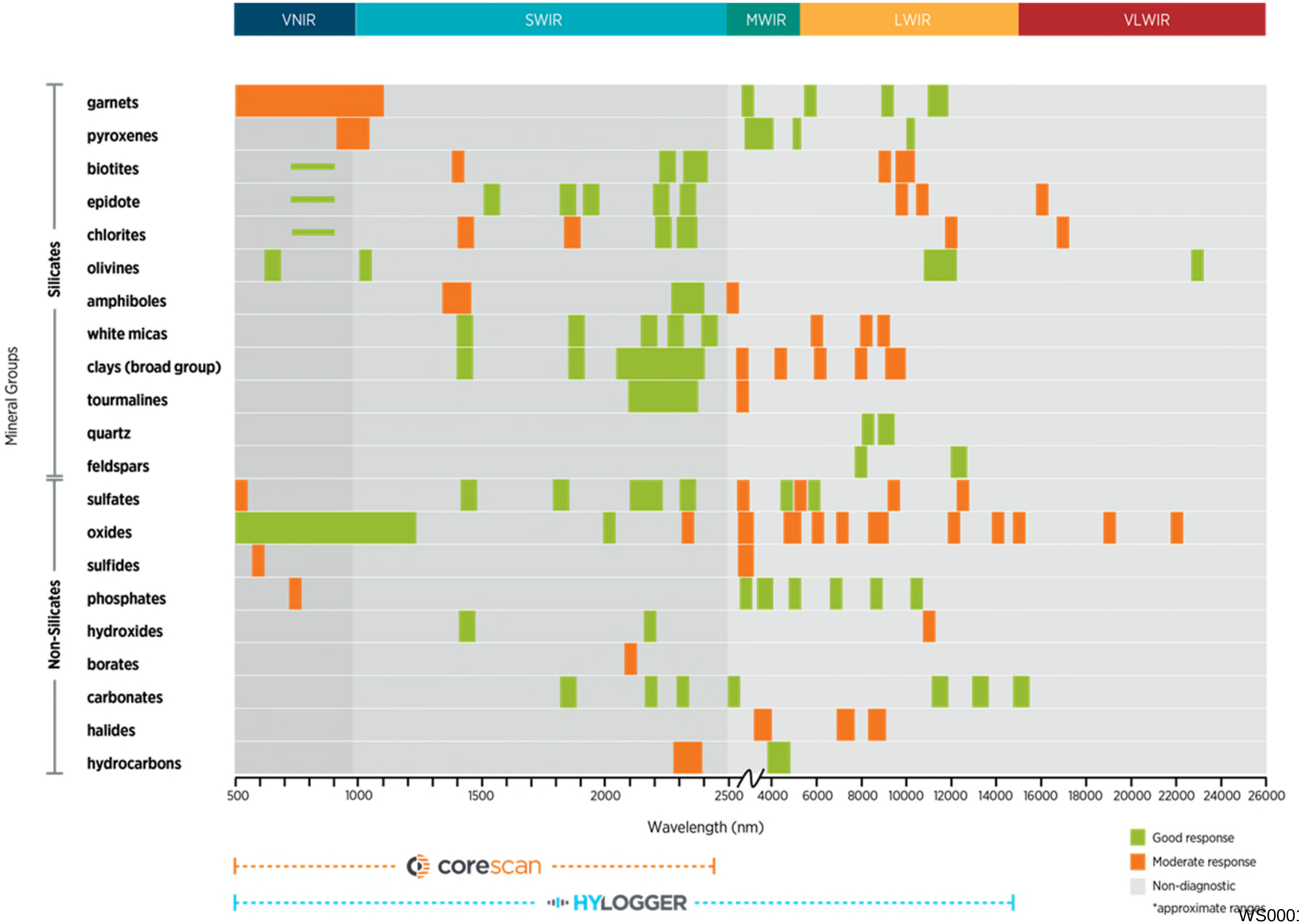
Reflectance spectroscopy directly records information about mineralogy.

- 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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Hyperspectral Core Imaging

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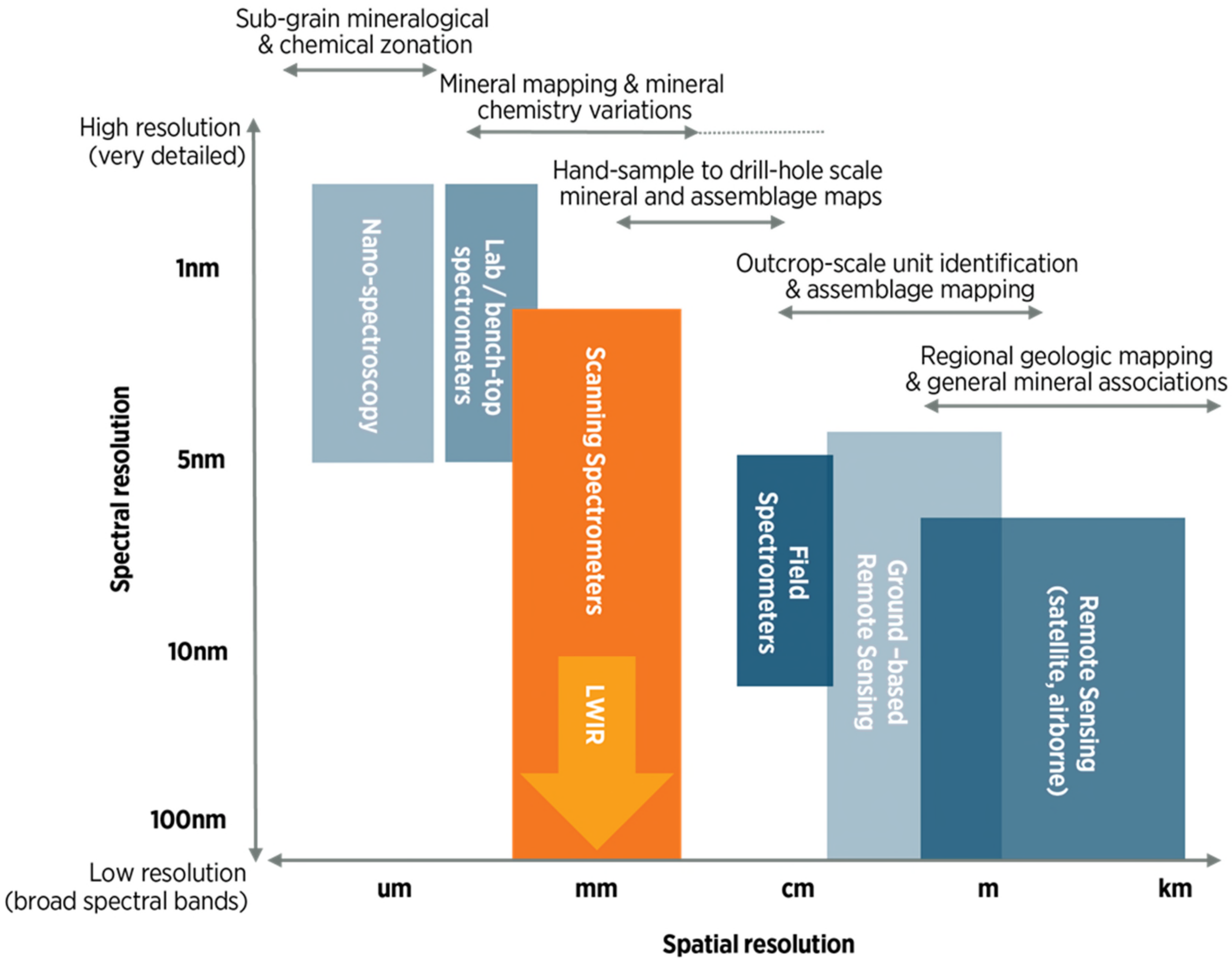
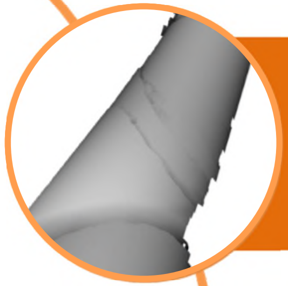
- Hyperspectral imaging is a drill core scanning method with important application to mining and mineral exploration.
- Measures hundreds of contiguous spectral bands at micron to cm scale spatial resolution across the surface of the core.
- Hundreds of thousands of spatially referenced pixels are collected across each meter of core to produce an image of the core surface*.
- Imaging spectroscopy identifies and maps the spatial location, spatial arrangement and assemblage of minerals – TEXTURE.
- Provides the ‘linking’ scale between point instruments and airborne / satellite imaging data.



*Dependent on instrument / system used

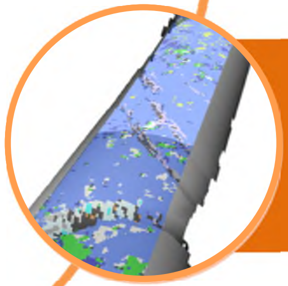
Corescan's HCI System

- Corescan's HCI technology captures three co-registered datasets over the core or sample surface.

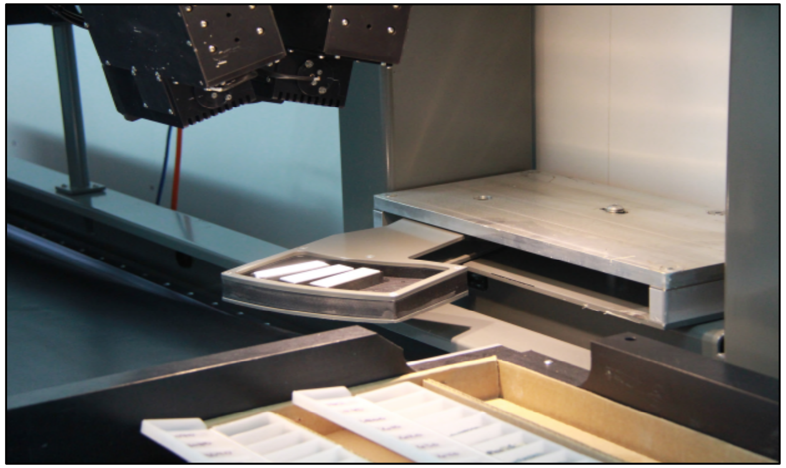


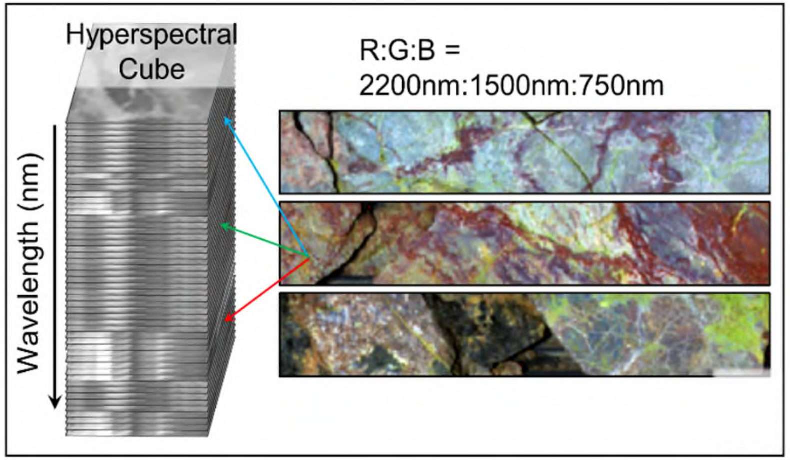
3D Core Morphology
Automated geotechnical measurements
* 500µm spatial resolution / 20µm height resolution

High Resolution Core Photography
* 50µm pixel (whole of deposit ~hand lens scale photos)



InfraRed Spectrometers (VNIR, SWIR-A, SWIR-B)
* 500µm spatial resolution, ~4nm spectral resolution





* HCI-3 specifications

VNIR-SWIR Spectroscopy
Applications to Mining and Exploration

Applications of Mineral Spectroscopy

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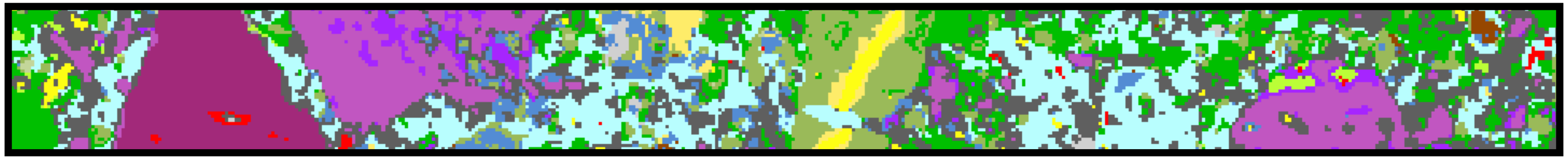
MINERALOGY ACROSS THE MINE CYCLE



Anthophyllite | Hornblende | Chlorite | Carbonate | Prehnite | White Mica | Aspectral

Exploration
- Surface reconnaissance
- Surface sampling
- Prelim. technical report
- Exploration drilling

Evaluation
- Pre-feasibility
- Scoping study
- Feasibility
- Resource drilling

Development
- Construction
- Pre-production
- Condemnation
- Exploration drilling

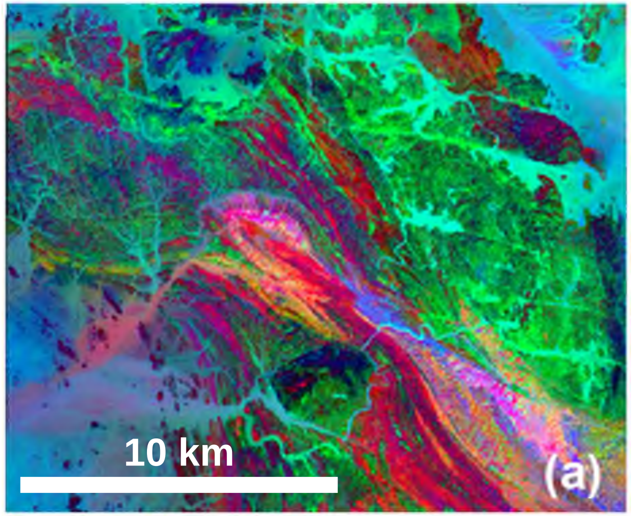
Production
- Pre-production
- Commercial production
- LOM extensions

End of Production
- Mine closure
- Remediation

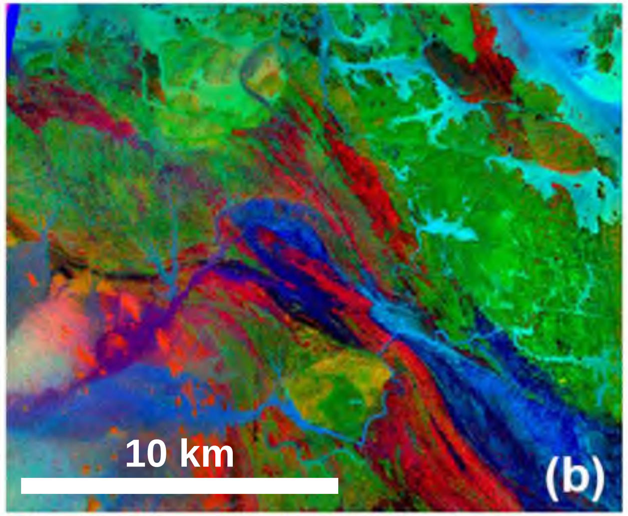
~2-10yrs | ~3-6yrs | ~2-4yrs | ~10-50yrs | ~1-10yrs

Application: District-Scale Alteration Mapping

- ASTER satellite imagery is used to map alteration in the El-Hoteib area, SE Desert, Egypt

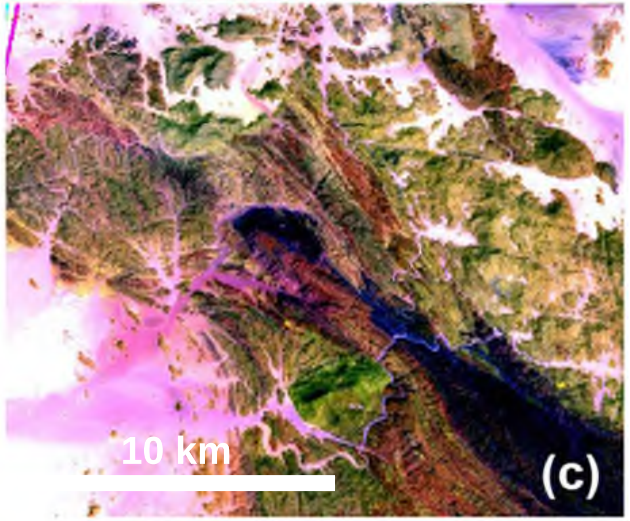


(a) composite image:
Red = 2205nm/2330nm
Green = 1650nm/2165nm
Blue = 660nm/1650nm

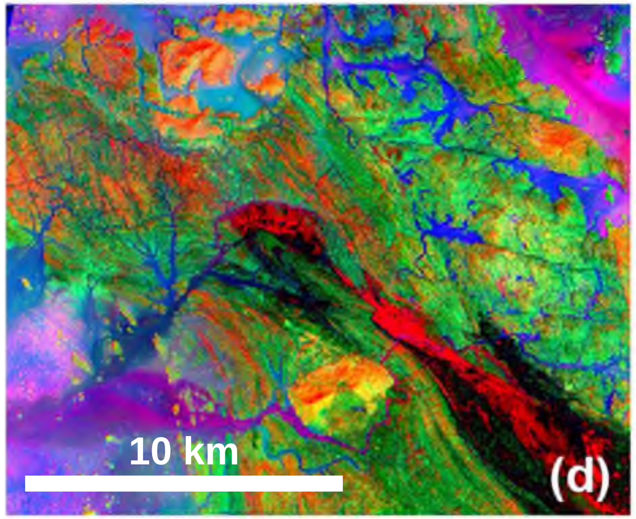


(b) composite image:
Red = 560nm/1650nm
Green = 800nm/1650nm
Blue = 2165nm/660nm

NOTE: wavelengths approximate – ASTER is a multi-spectral system with wide but variable spectral bands (~10-80nm)



(c) composite image:
Red = 2 + 1650nm/800nm
Green = 5 + 2260nm/2205nm
Blue = 7 + 2395nm/2330nm



(d) composite image:
Red = 2 + 1650nm/2205nm
Green = 7 + 2230nm/2395nm
Blue = 1650nm/2260nm

(from Gabr et al., 2015)

Application: Deposit-Scale Mineralogy Mapping

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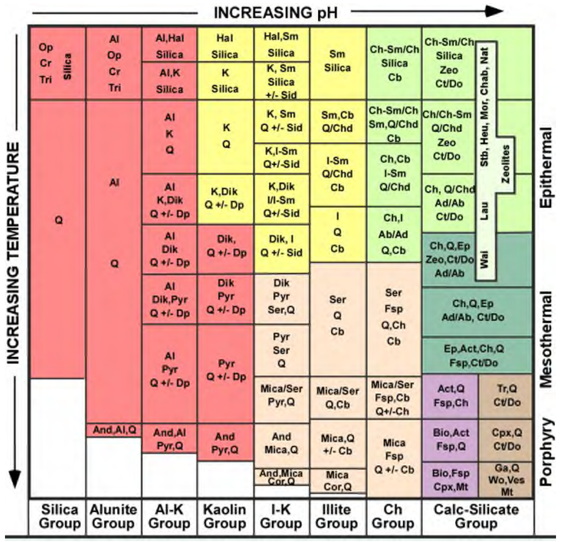
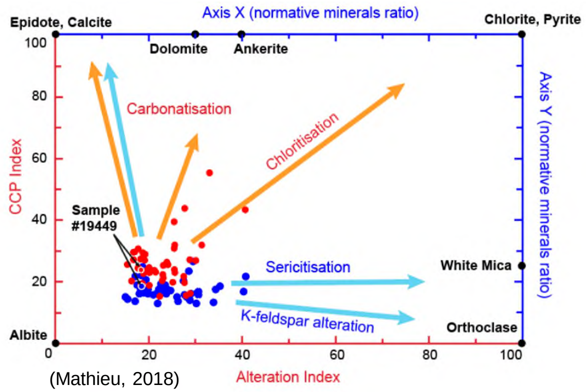
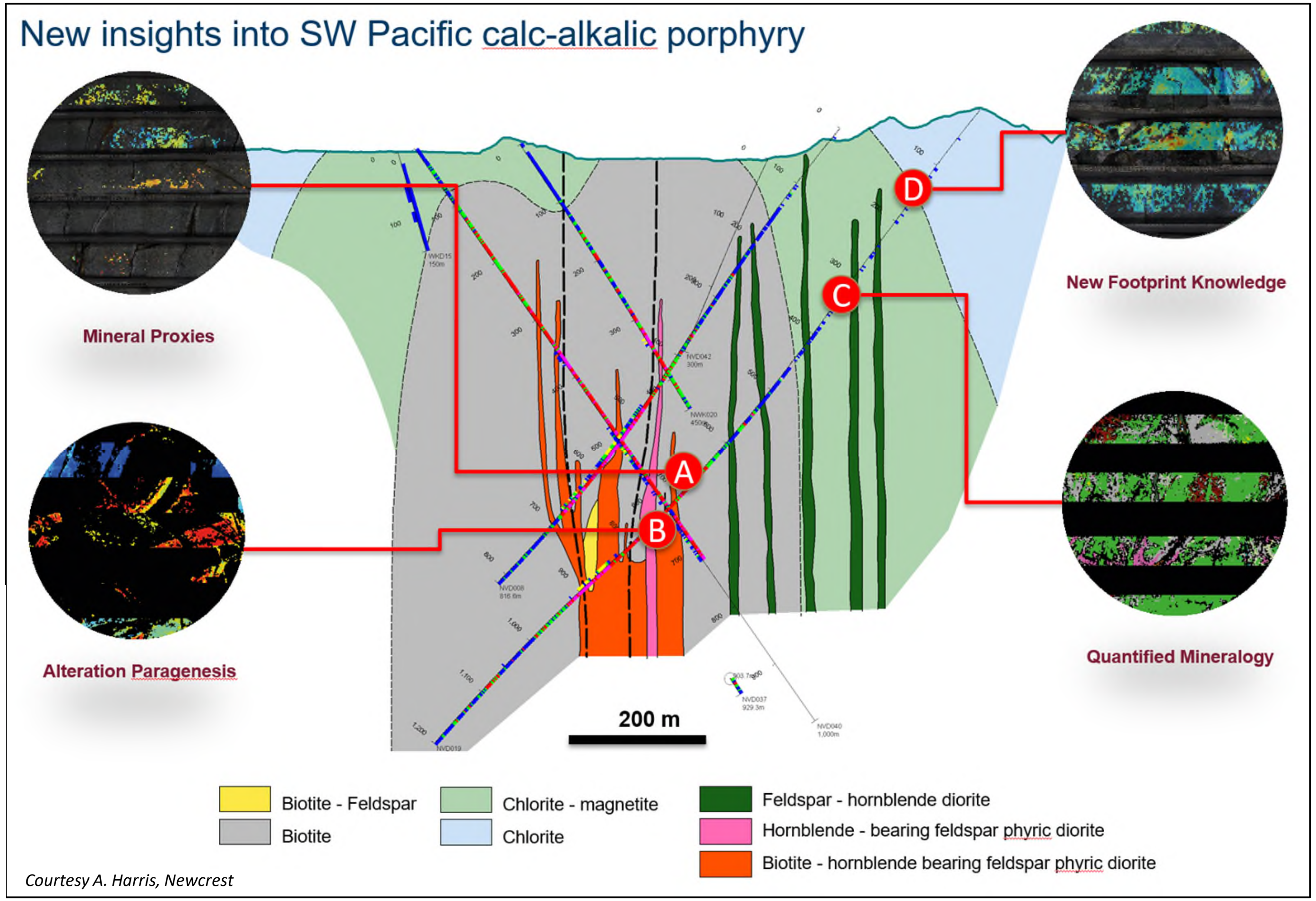


(modified from Leach, 1995)



(Mathieu, 2018)

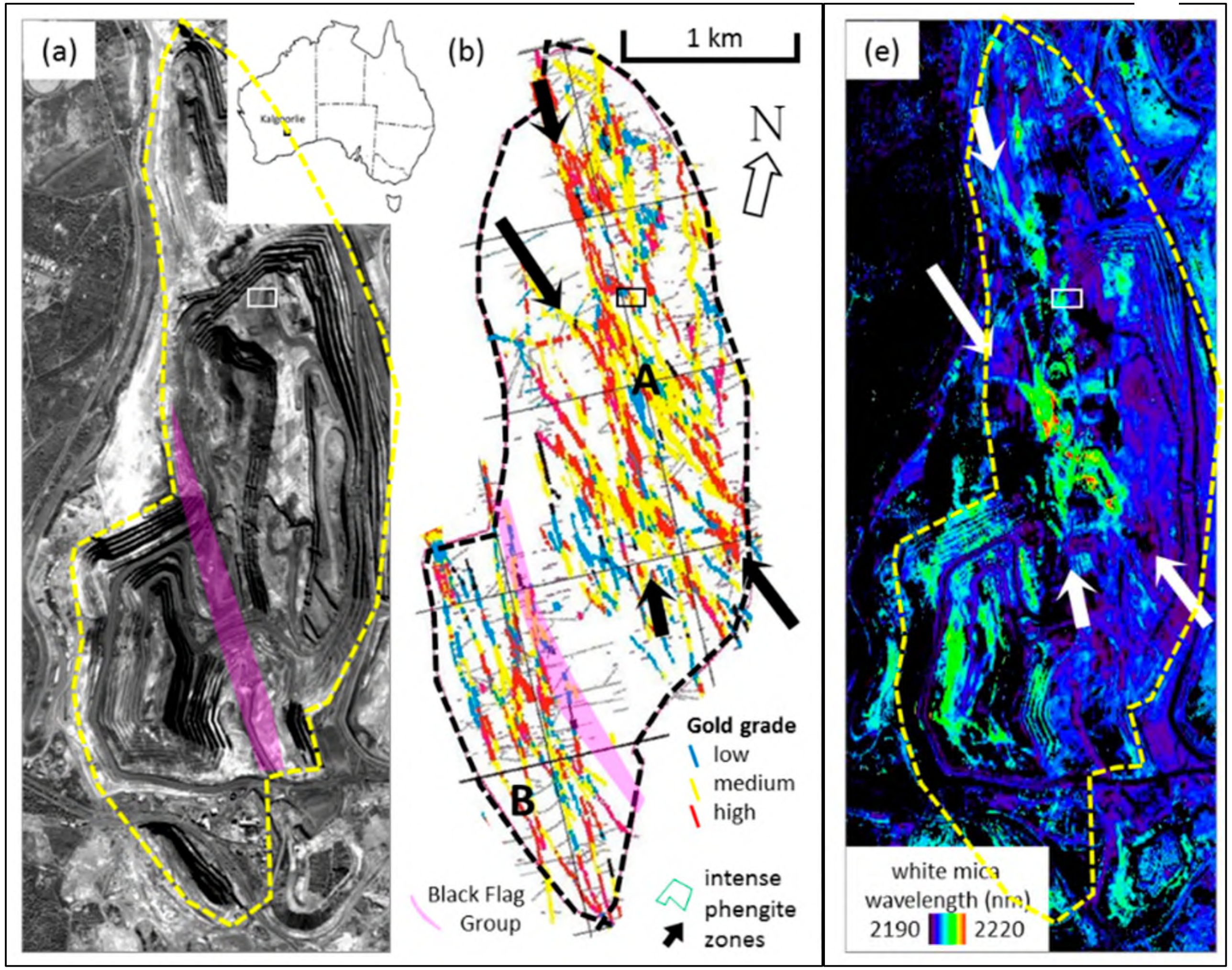


- Porphyries and epithermal deposits ideally suited to hyperspectral analysis.
- Direct genetic relationship between fluids responsible for mineralization and alteration.
- Fluid-rock interactions occur at depths and/or temperatures that result in range of VNIR-SWIR detectable minerals.

Spectroscopy is an exploration TOOL - best used in combination with geological knowledge, geochemistry, geophysics.

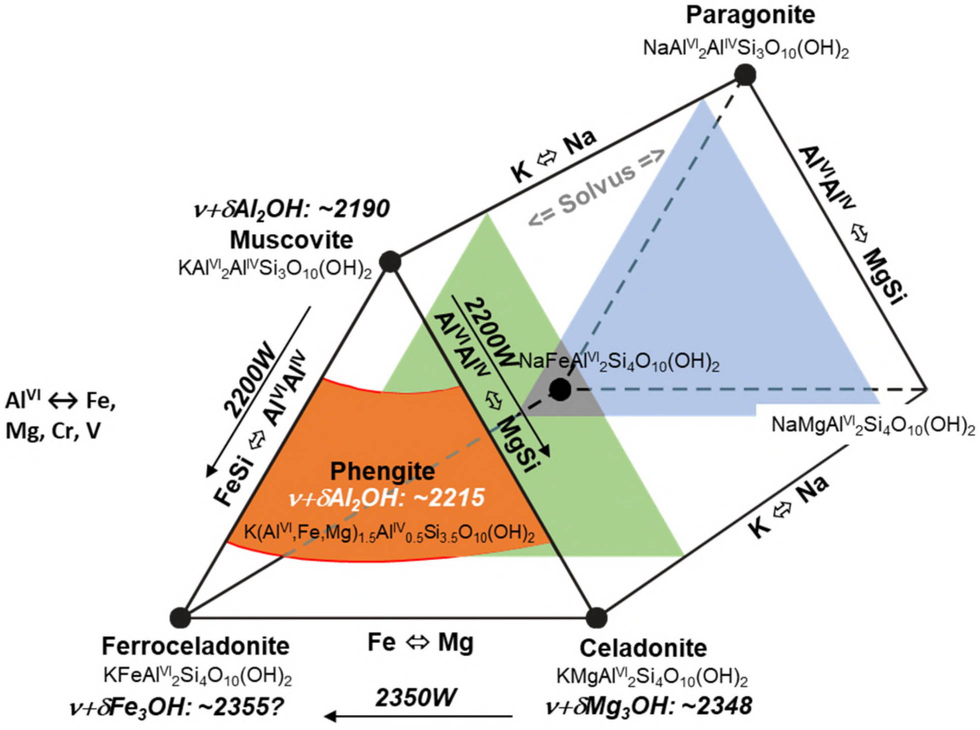
Application: Deposit-Scale Mineralogy Mapping

Kalgoorlie Superpit, Western Australia with mapped Au grade (middle) and white mica compositions (right). Major linear zones of phengite are highlighted by white arrows.



(from Cudahy, 2016)

- Hyperspectral mineral mapping at the Kalgoorlie Superpit (Western Australia) where spectral variations in white micas (wavelength variations) have been recognized as effective vectors to mineralization.



(Laukamp, 2011)

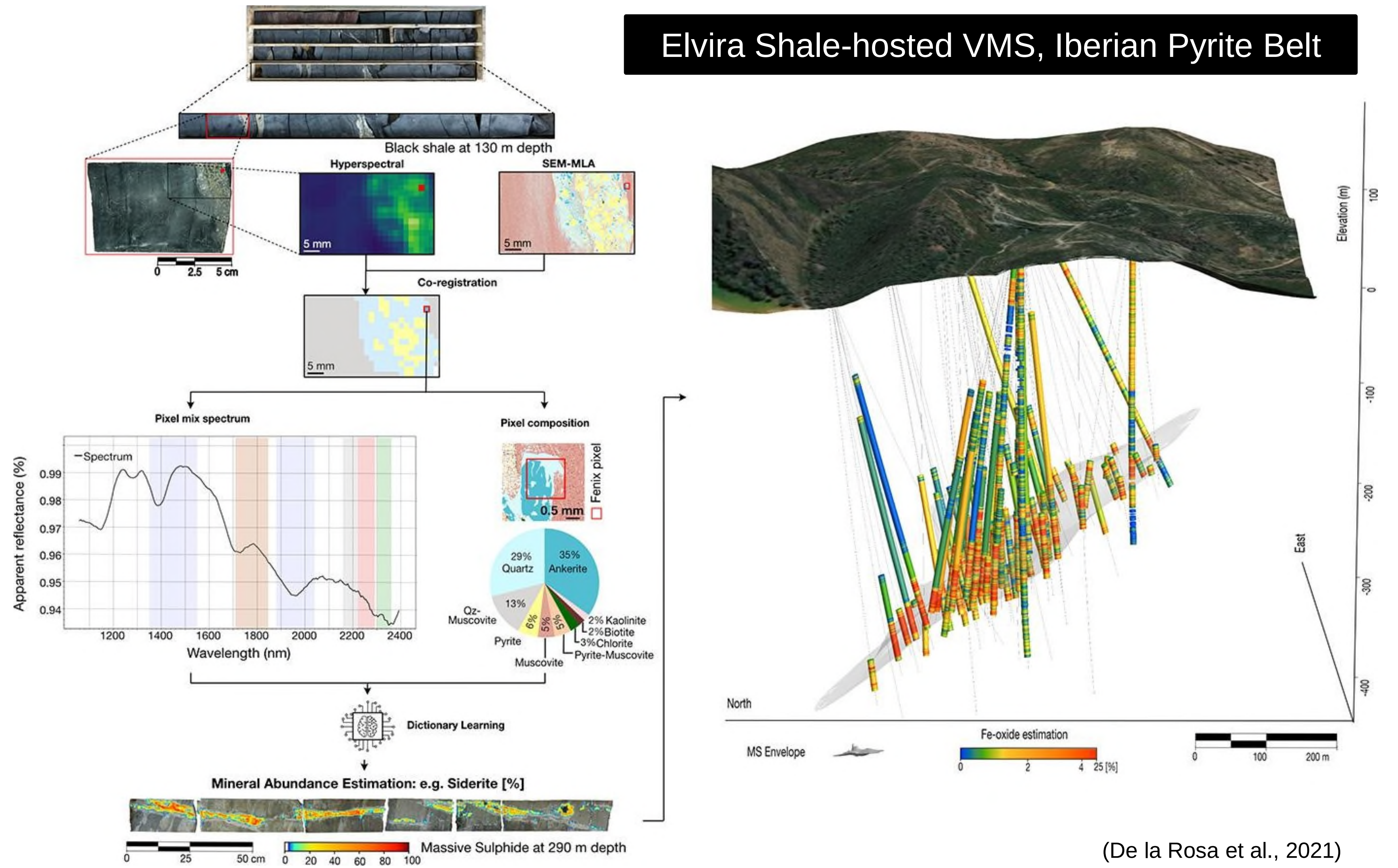
Application: Deposit-Scale Mineralogy Mapping

- Integration with other datasets (e.g., mineral assay data) can show correlations between alteration (gangue) mineralogy and mineralization
- Consistent & clear zonation trends → effective vectors to ore

VMS deposits generally show relationship between abundances of certain minerals/mineral groups and/or chemical compositions and proximity to the massive sulphide ore.

Key mineral groups:
White micas, chlorite (Fe vs Mg), and carbonates

Elvira Shale-hosted VMS, Iberian Pyrite Belt



(De la Rosa et al., 2021)

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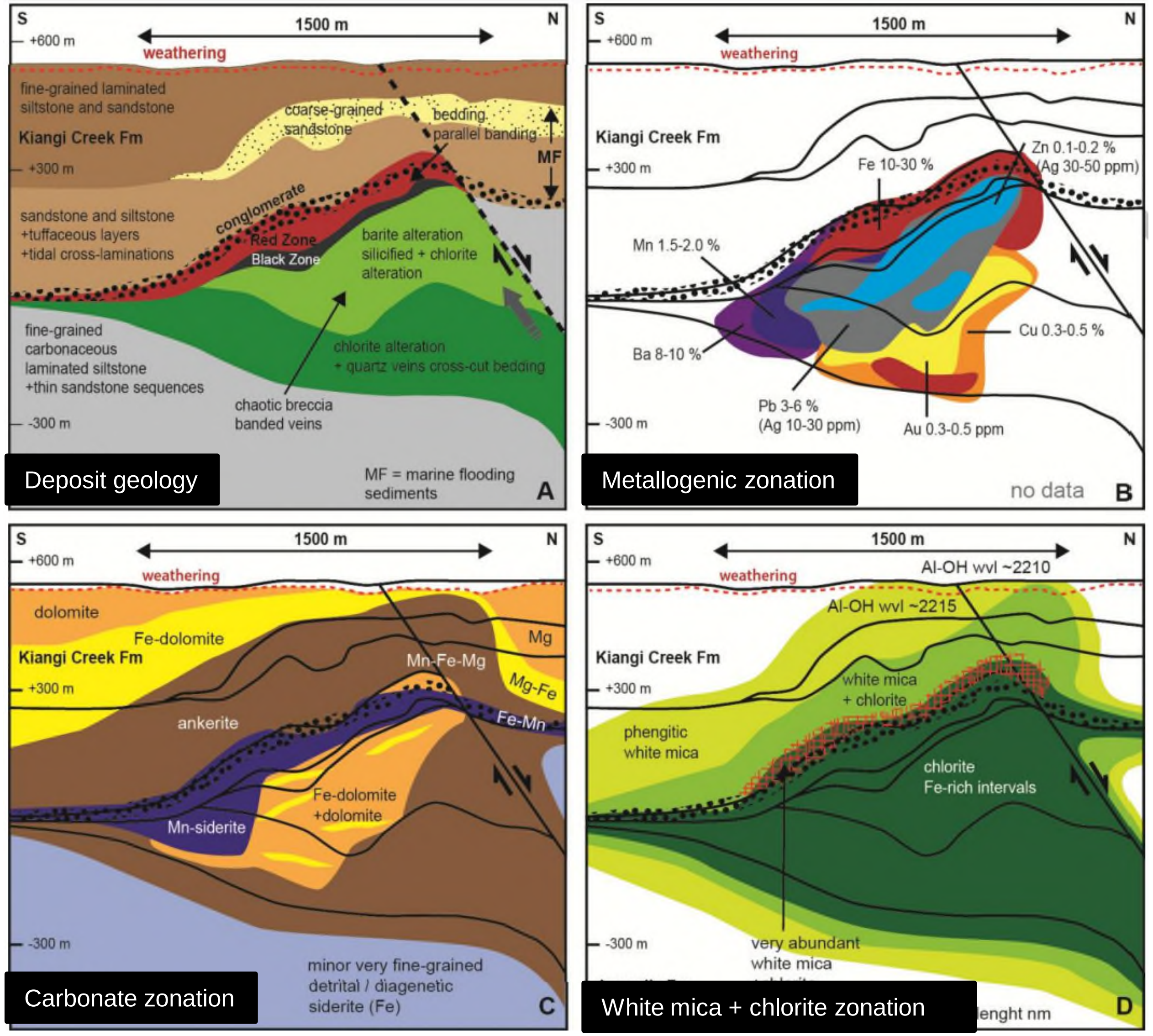
Application: Deposit-Scale Mineral Vectors

- Compared to igneous systems, sedimentary-hosted deposits can be complex:
  - Mineralogical and chemical compositions reflect hydrothermal alteration AND diagenesis or metamorphism (or detrital components)
  - PLUS impacts effects of weathering.
- SEDEX mineral signatures from SWIR-active phases can be subtle but zonation in carbonate, white micas, and chlorite can provide effective vectoring tools.



Abra sediment-hosted Pb-Zn-Cu-Au deposit (Western Australia)

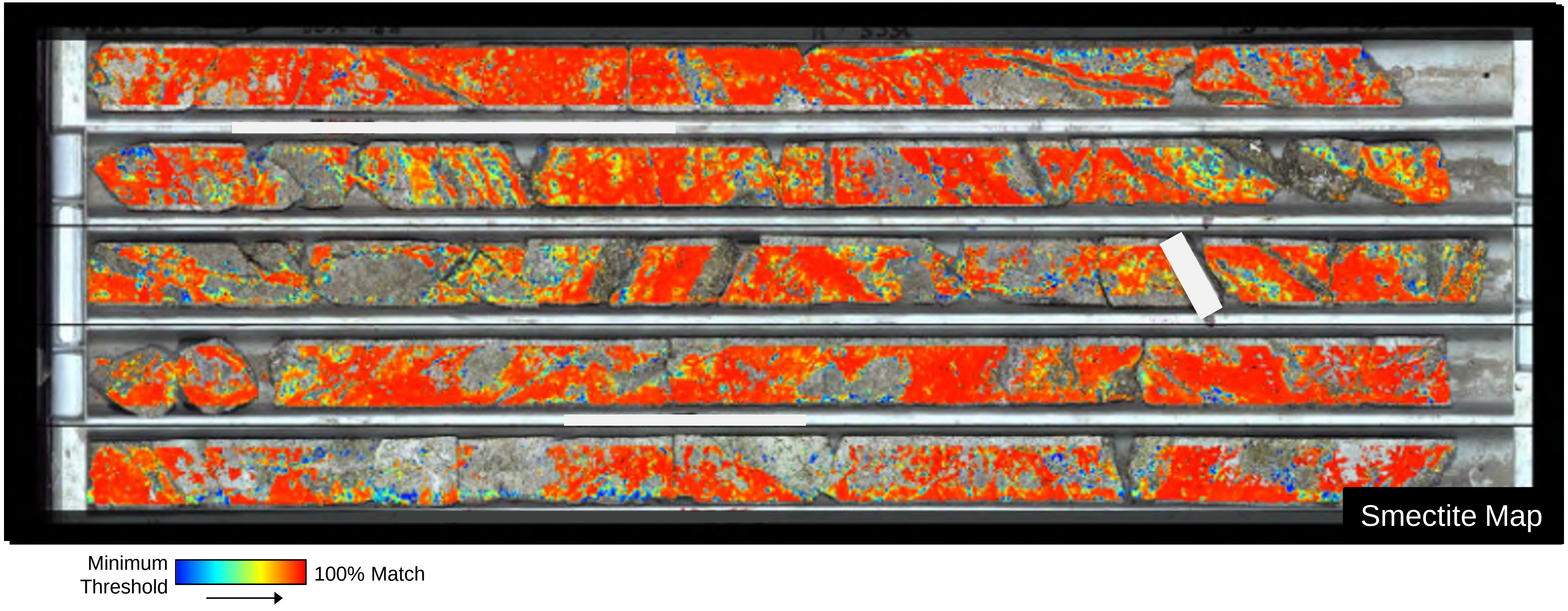
Surficial mineral footprint linked to deposit below using hyperspectral mineralogy.

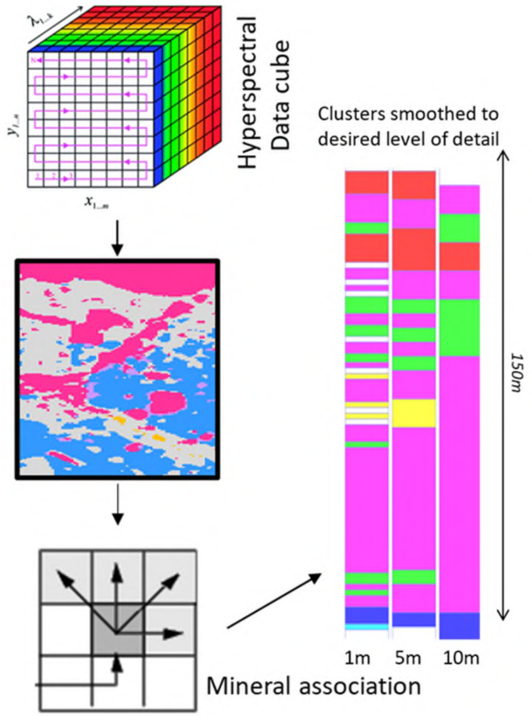
(Lampinen et al., 2018)

Application: Logging in the Core Shack / Shed

- Hyperspectral imaging systems consistently and reliably map mineralogy while simultaneously capturing mineral textures (paragenesis).
- Reflectance spectroscopy can be used in core logging for the characterization of alteration and alteration zonation, lithological domaining, and ultimately deposit modelling.

World-class Peruvian Cu-Zn skarn



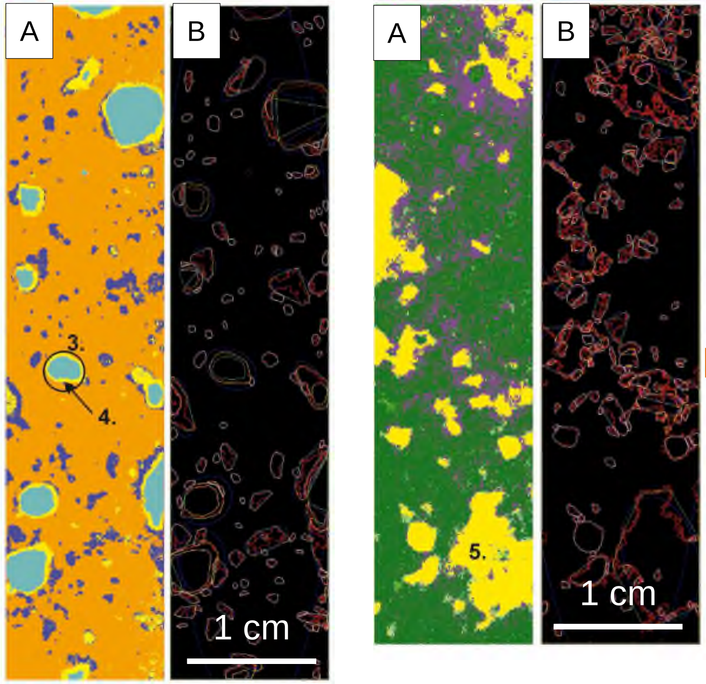


(Modified from Jorguera et al., 2018)

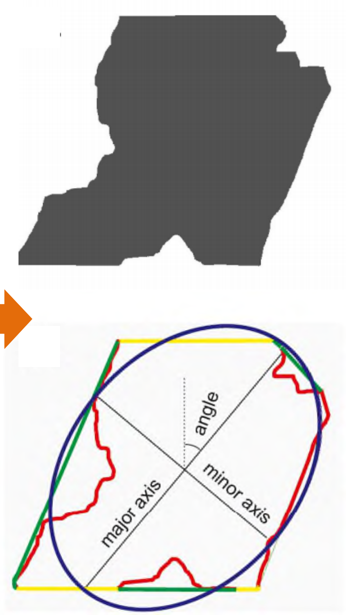
Application: Detailed Mineral Analysis and Texture

- Textural data derived from hyperspectral core imaging provides critical information on the spatial distribution of different mineral phases (micro- and macro-scale relationships).

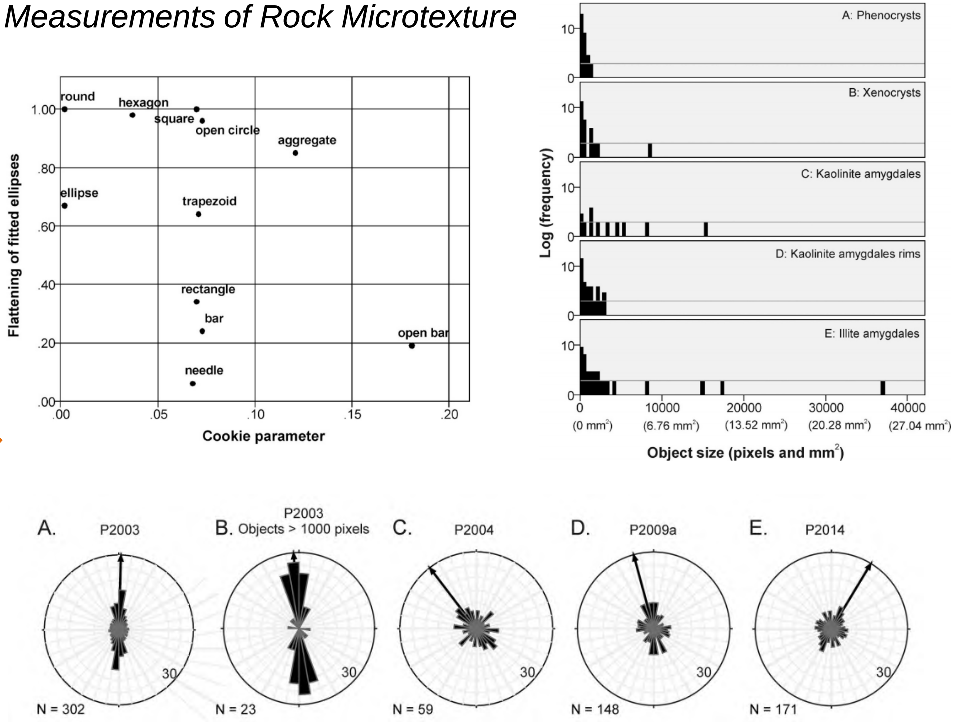
Hyperspectral Mineral Map (A) & Object Parameter Image (B)



Shape Parameters of Image Objects



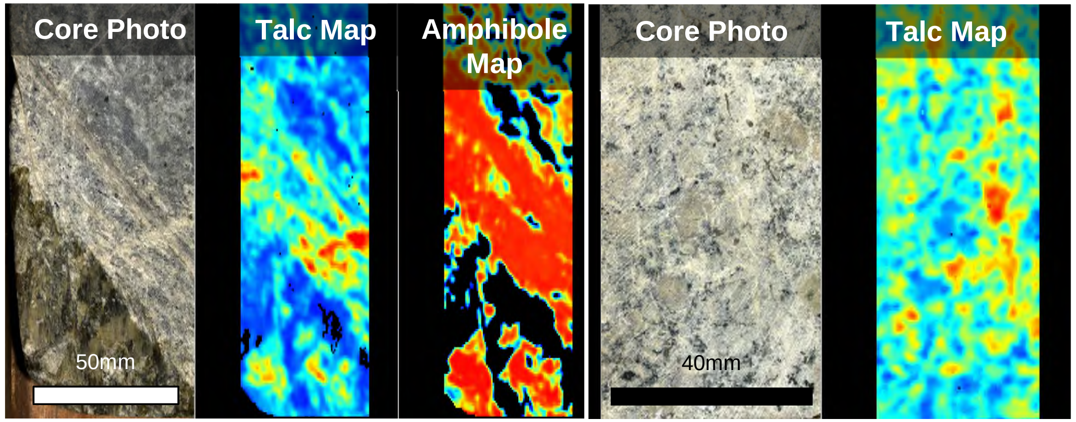
Measurements of Rock Microtexture



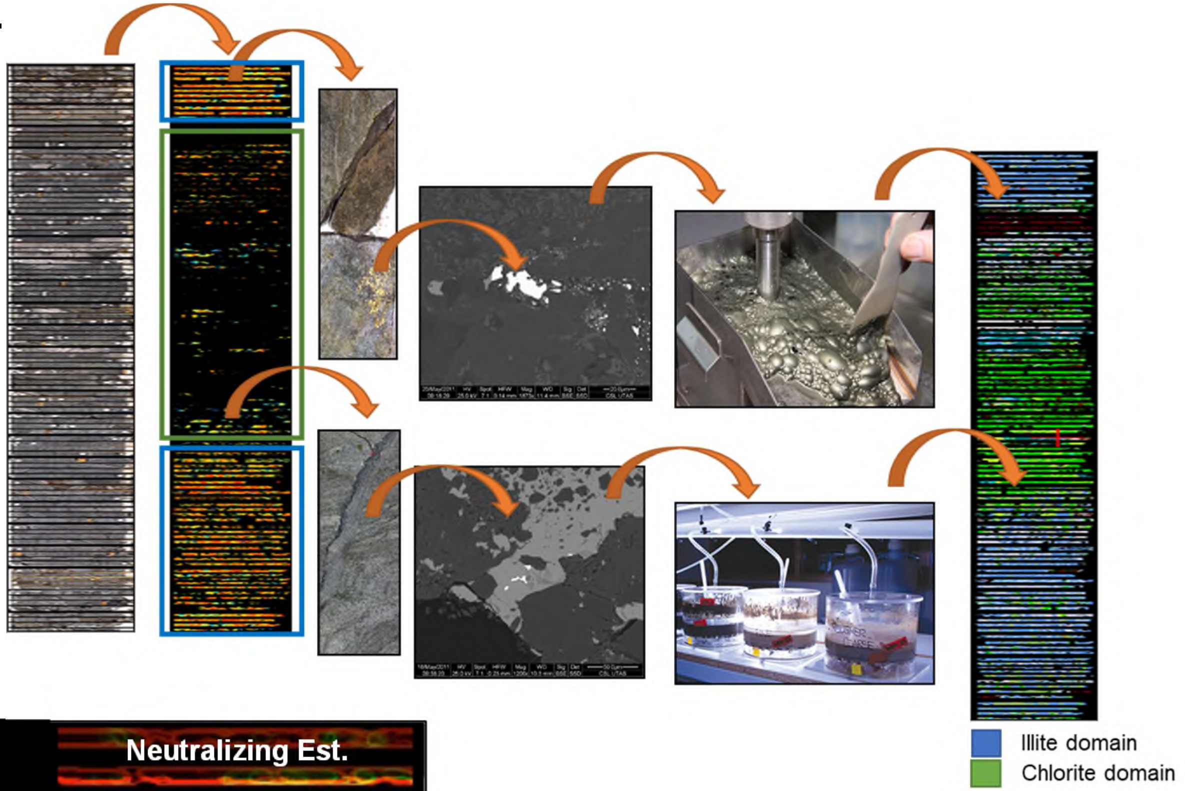
(Van Ruitenbeek et al., 2019)

Application: Geometallurgical Assessment

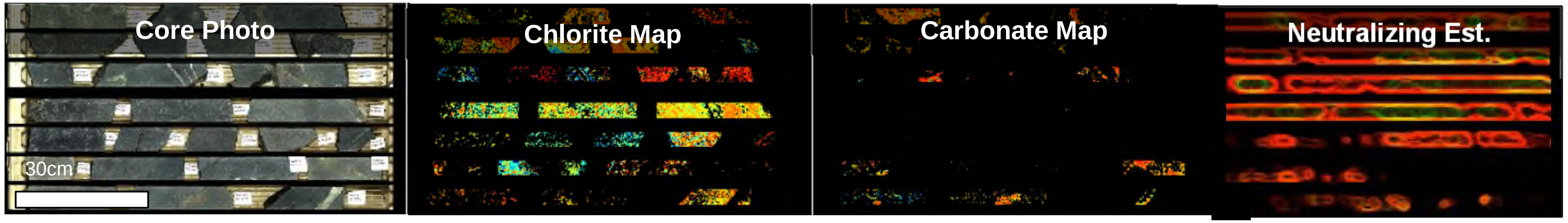
- Consistent hyperspectral imaging data can be applied to geometallurgical assessments to determine texture, grain size, mineral speciation, with <u>increased sampling statistics</u>.



Speciation, grain size, texture of both hard and clay minerals → can relate to crushing/grinding testwork → proxy development (reagent consumption + swelling + viscosity changes)



Informed metallurgical and bench-scale testwork sample selection



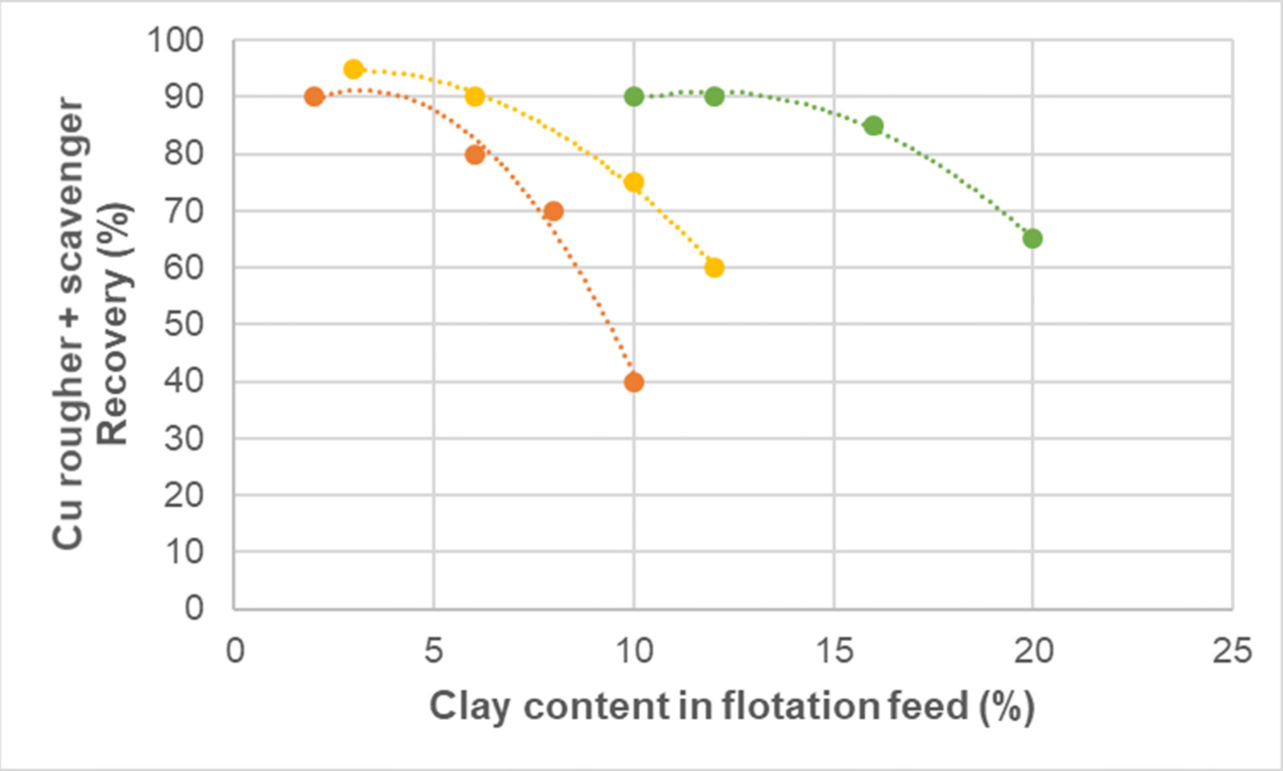
(Modified from Jackson at al., 2017)

Acid neutralizing potential + Acid Rock Drainage index domaining

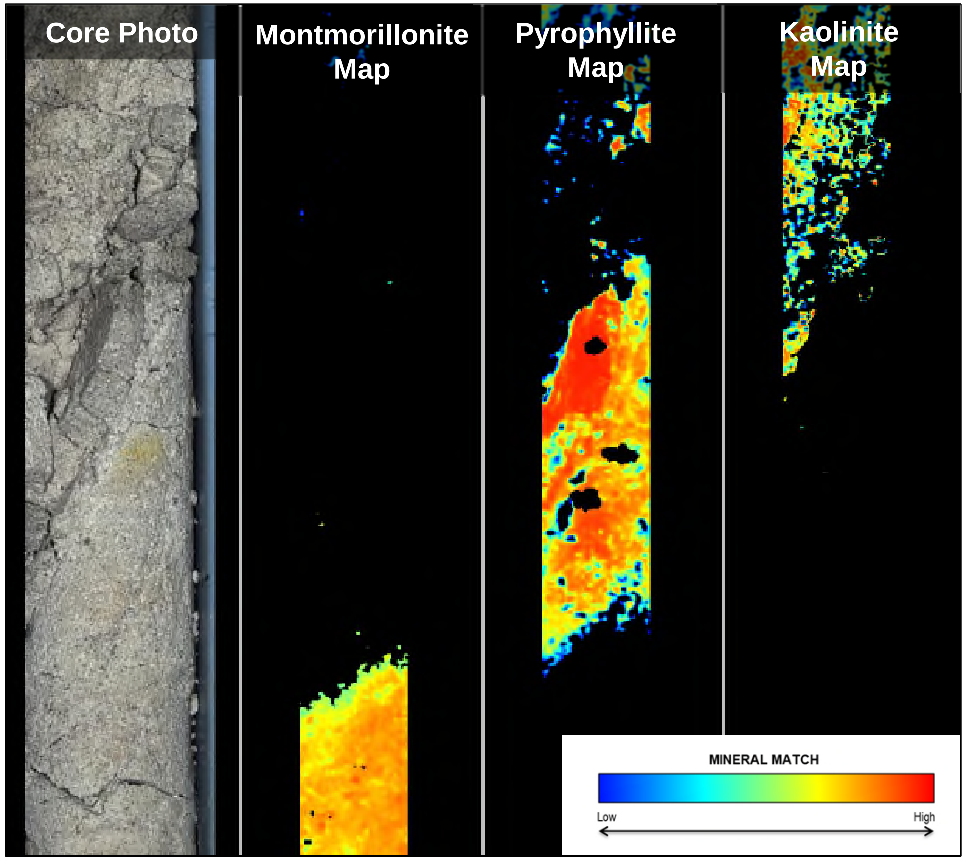
Minimum Threshold → 100% Match

Application: Processing Proxies and Modelling

- When testwork results can be linked to mineralogical/textural properties, proxies can be developed and calculated over entire hyperspectral imaging datasets
- Predictive processing behavior models can be developed

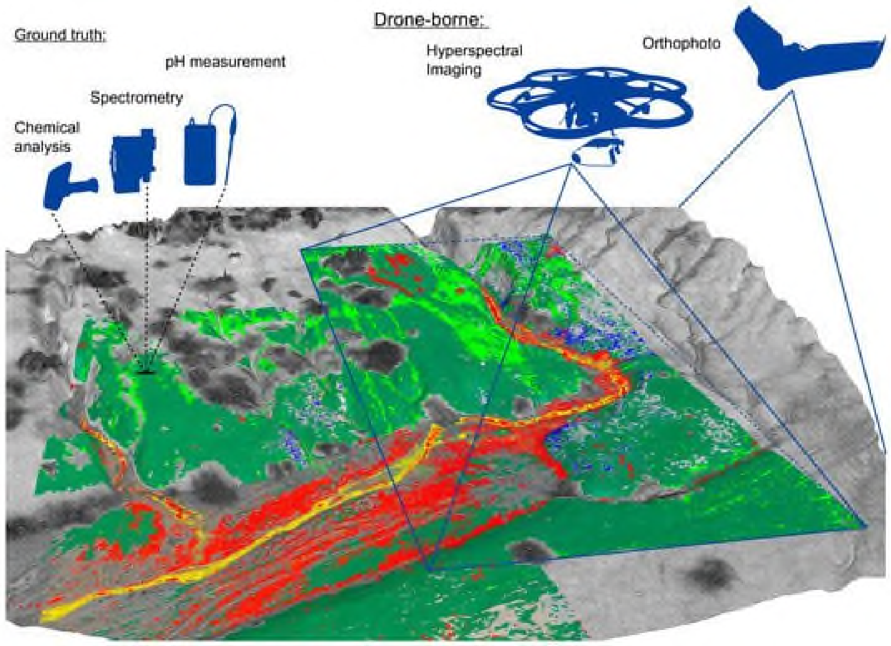


re-plotted from Bulatovic, Wyslouzil and Kant, 1999

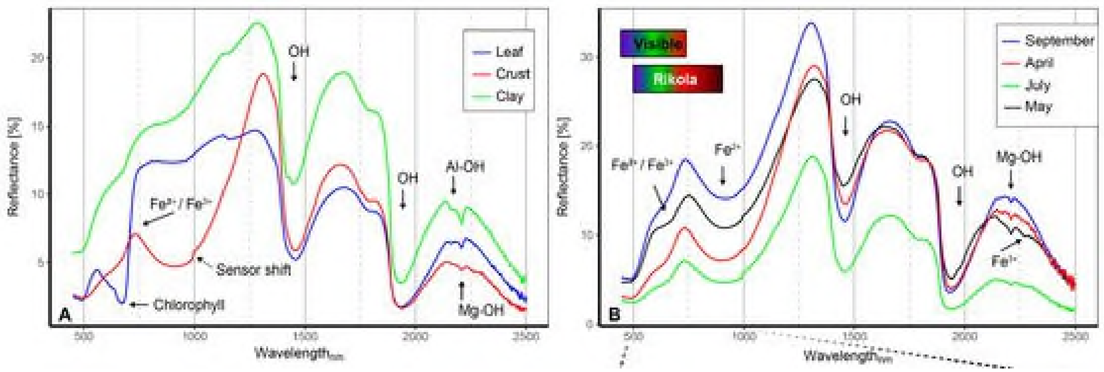


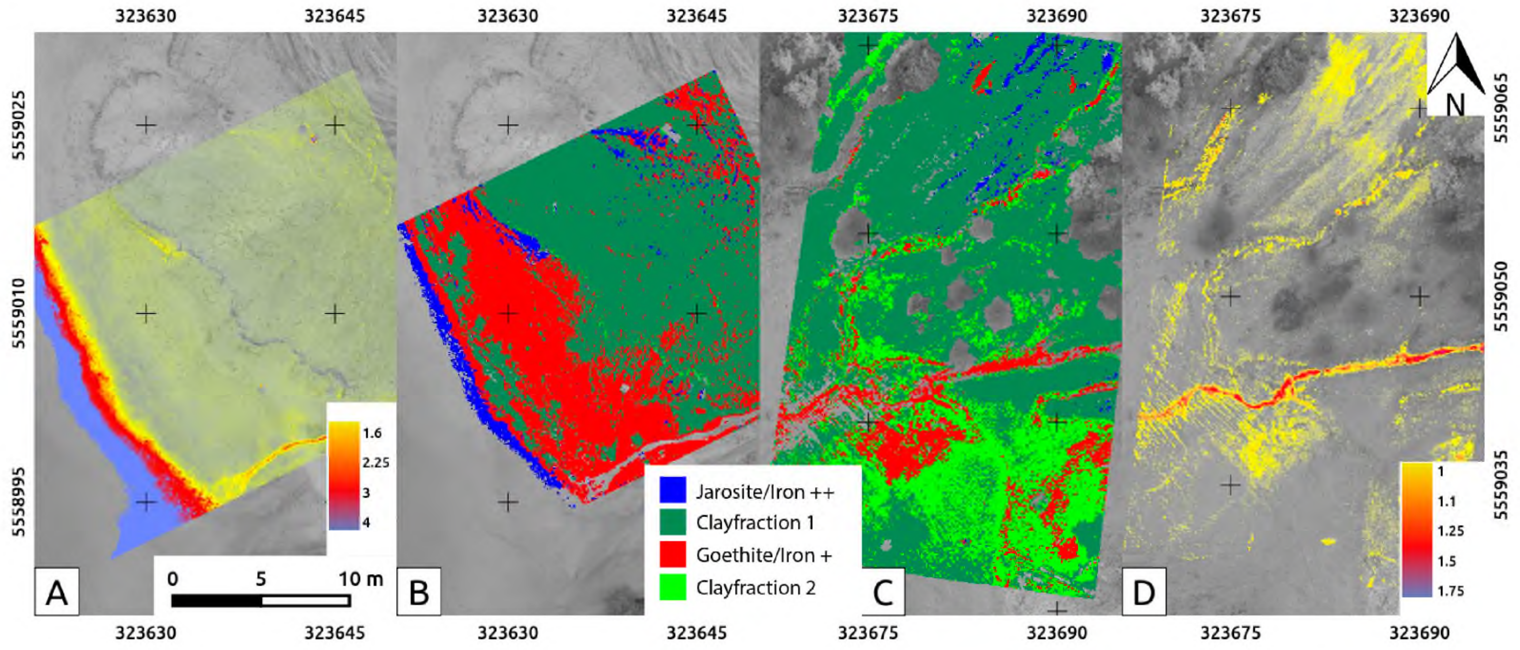
Application: Remediation and Monitoring

- Hyperspectral imaging for the monitoring of acid mine drainage is being conducted in the Sokolov lignite district of the Czech Republic.



UAS-based data acquisition and the ground validation using hand-held instrumentation.

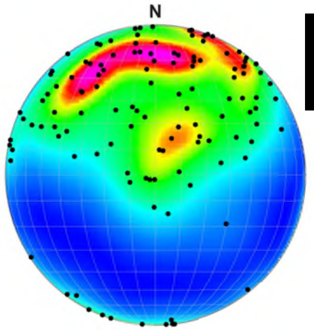




(from Jackisch et al., 2018)

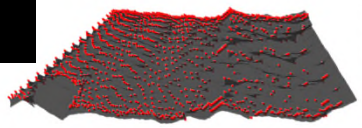
Application: Geotechnical Data Collection

- Hyperspectral imaging technology – combined with 3D profiler data – allows for collection of high volumes of consistent drill core information that can applied to geotechnical assessments.

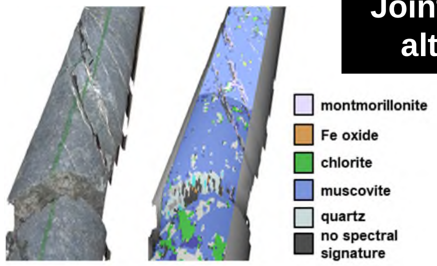


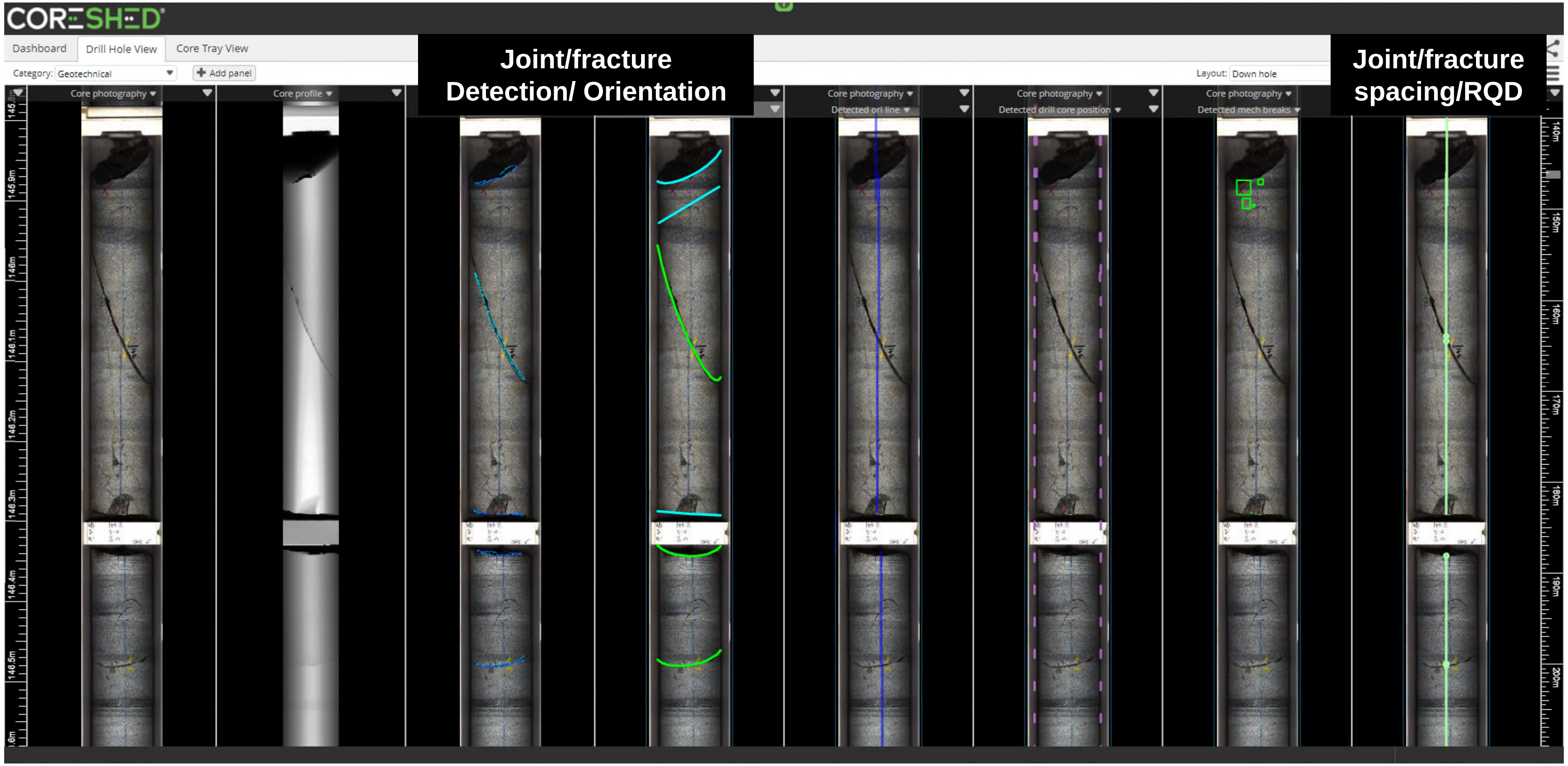
Joint/fracture sets

Joint/fracture roughness



Joint/fracture alteration





Joint/fracture Detection/ Orientation

Joint/fracture spacing/RQD

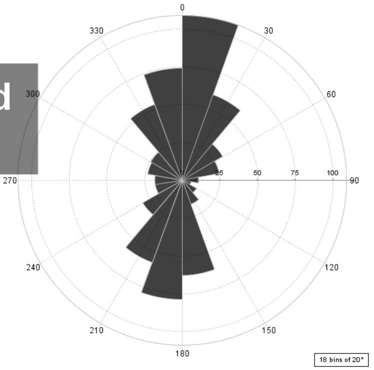
Low density of fracture pixels

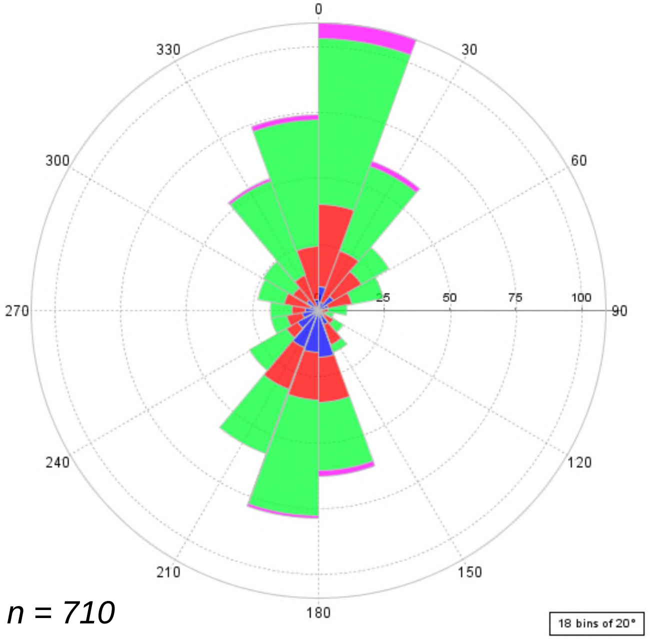
High density of fracture pixels

Application: Structural Data Collection

- For automated core imaging systems where hyperspectral mineralogy is co-registered with profiler data, the mineralogy of structures (e.g. joints, veins, faults) can be integrated with the automatically measured orientation values.

Undifferentiated mineralogy





n = 710

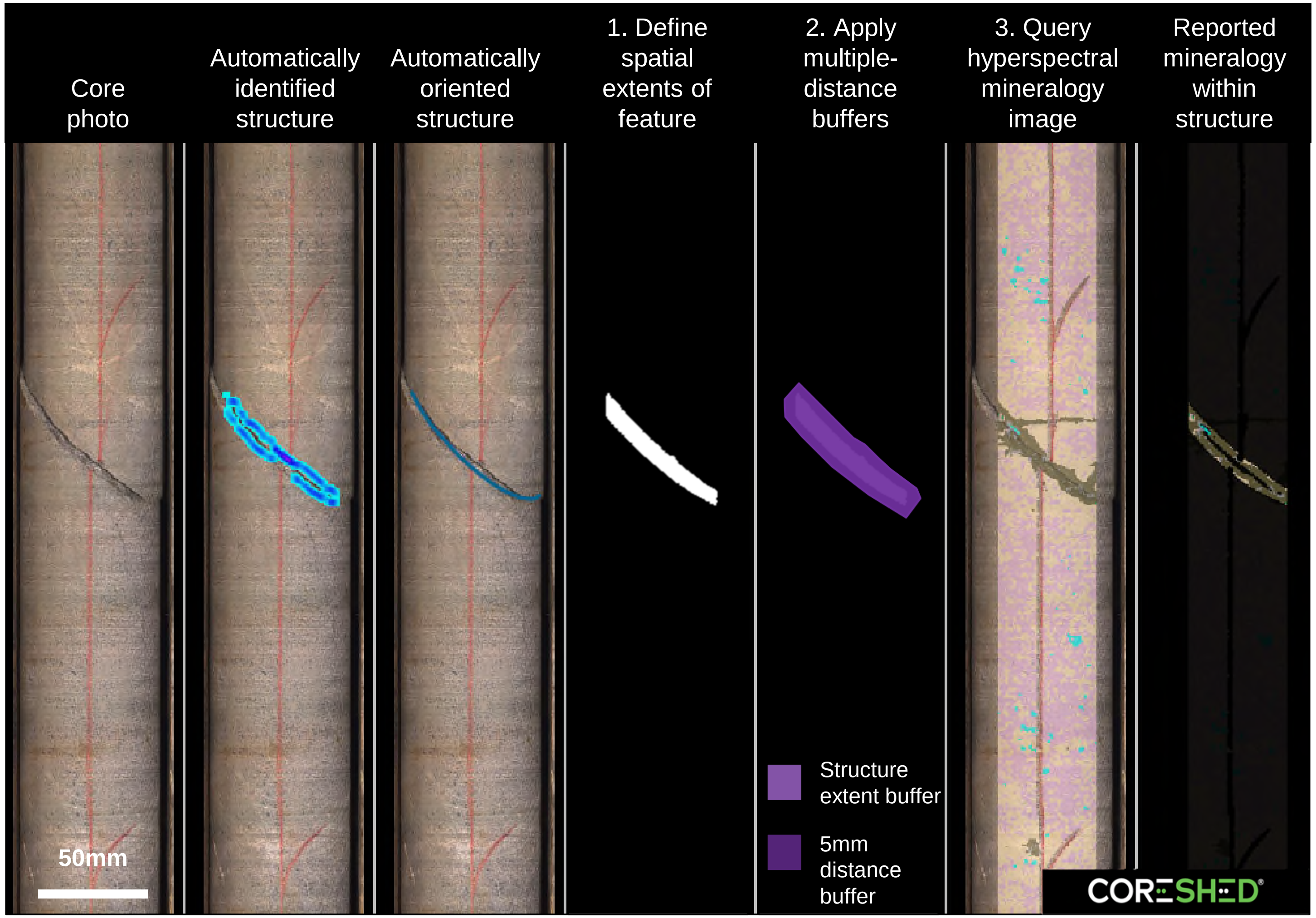
Chlorite

Carbonate

Featureless Spectrum

Montmorillonite

Colored by primary mineralogy within fracture



Kaolinite

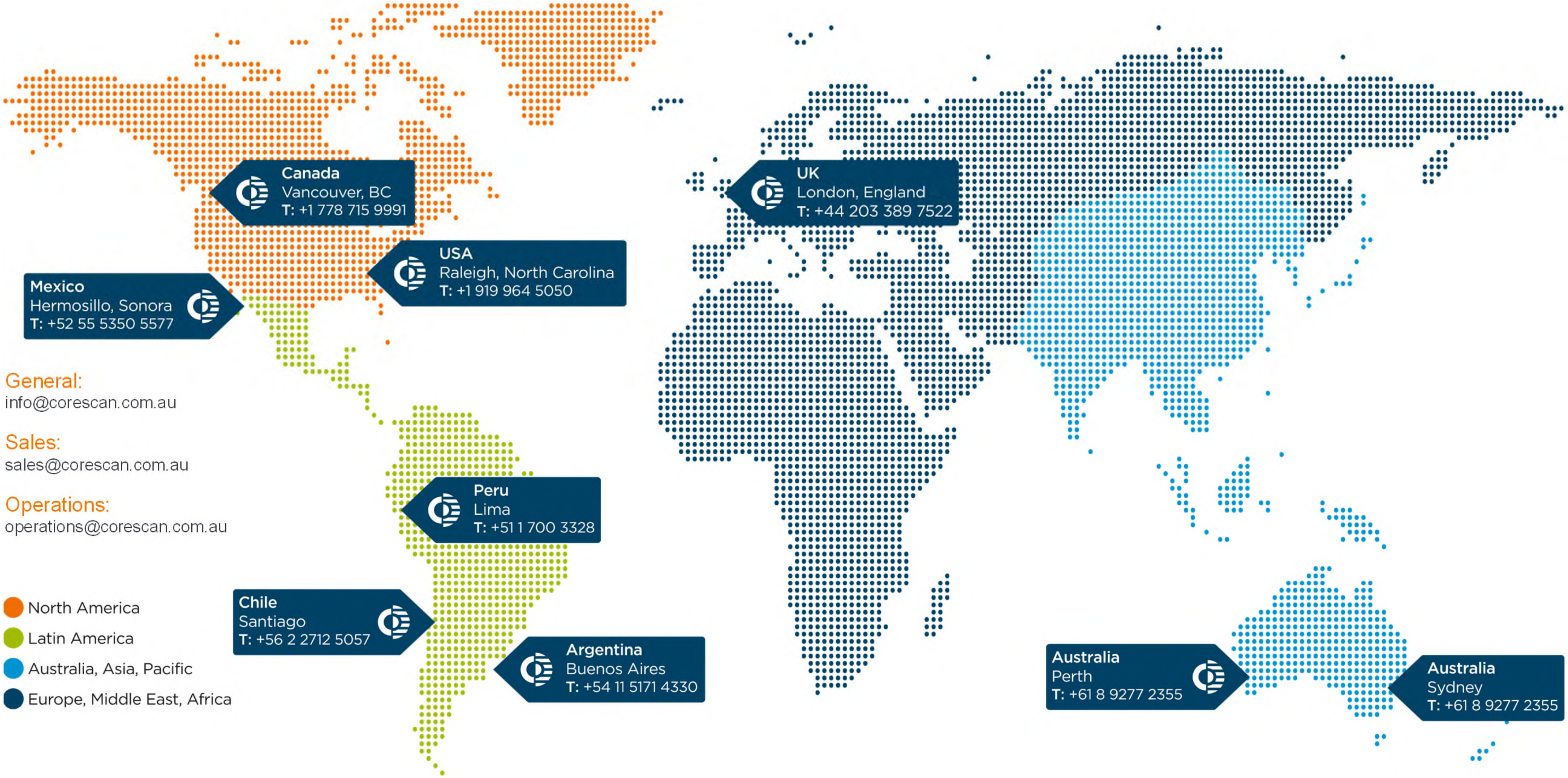
White Mica

Kaolinite + White Mica

Carbonate

ACON0014

Contact Us



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The Future of Core Logging: Applications for Hyperspectral Core Imaging

Dr. Cari Deyell-Wurst & Dr. Cassady Harraden