Size Matters, the importance of mineralogy and texture in mining porphyry copper deposits: Part I

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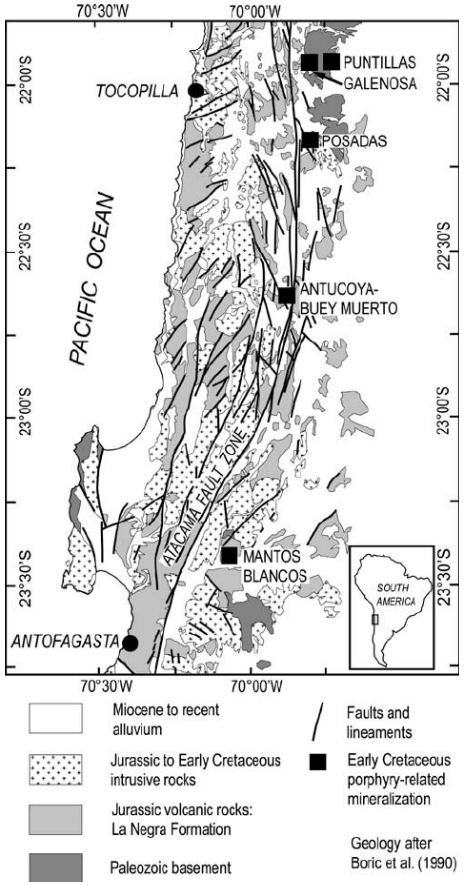
Geologic setting

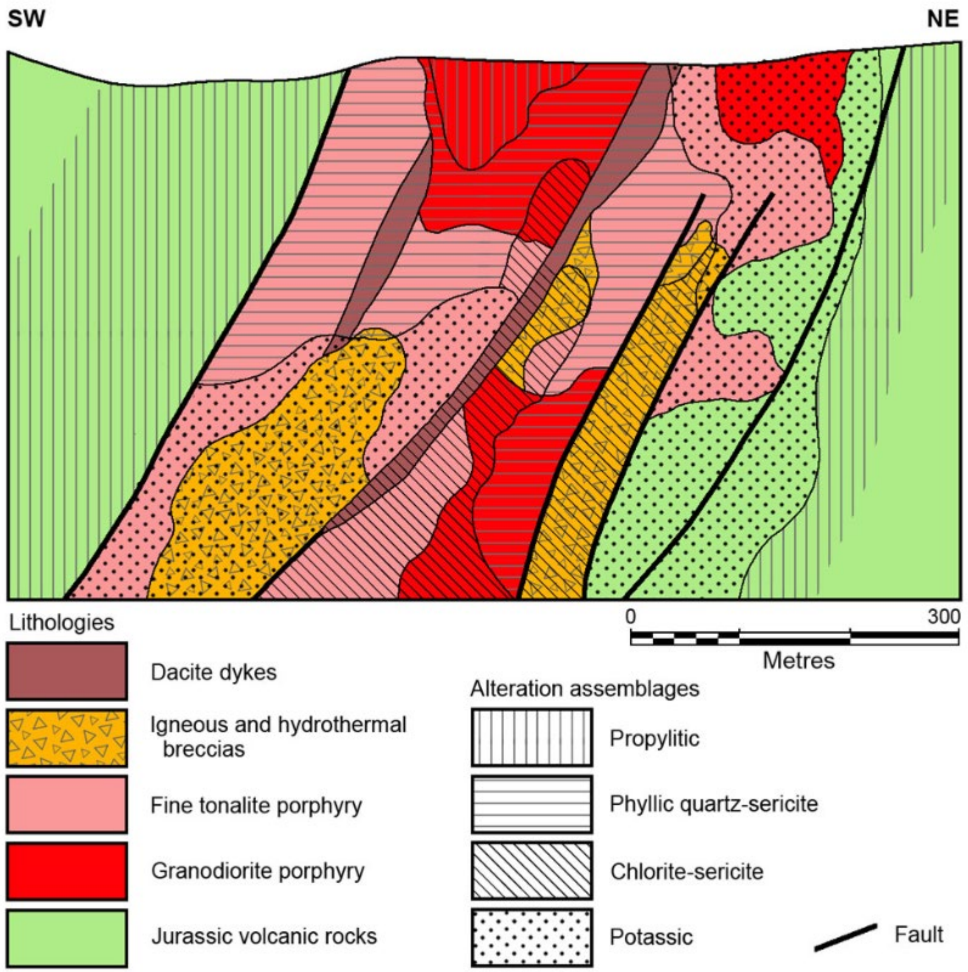
- The Antucoya porphyry copper deposit (PCD) is one of the largest deposits in the poorly studied Early Cretaceous porphyry belt in the Costal Cordillera of northern Chile.
- The complex crystallized at 142.7±1.6 to 140.6±1.5 Ma, which is within a relatively short time span of less than ca. 2 Ma during the earliest Cretaceous.



Maksaev et al., 2006

Background geology

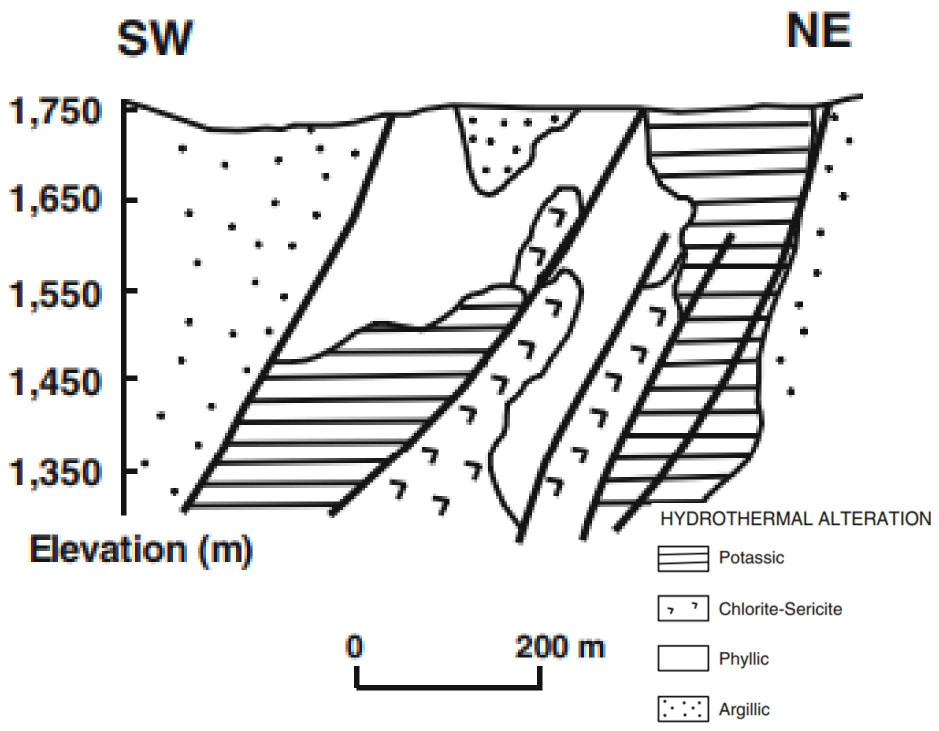
- Antucoya is related to a succession of granodioritic and tonalitic porphyritic stocks and dykes that were emplaced within Jurassic andesitic rocks of the La Negra Formation immediately west of the Atacama Fault Zone (AFZ).
- Copper-bearing ore occurs as stockwork, dissemination, impregnation in altered rocks, and as breccia matrix; it is hosted by the granodioritic and tonalitic porphyries and by magmatic to hydrothermal breccias within a 1.6 x 1 km area.



Geological cross section showing the distribution of alteration at the Antucoya porphyry copper deposit, Northern Chile (After: Maksaev *et al.*, 2006).

Alteration style

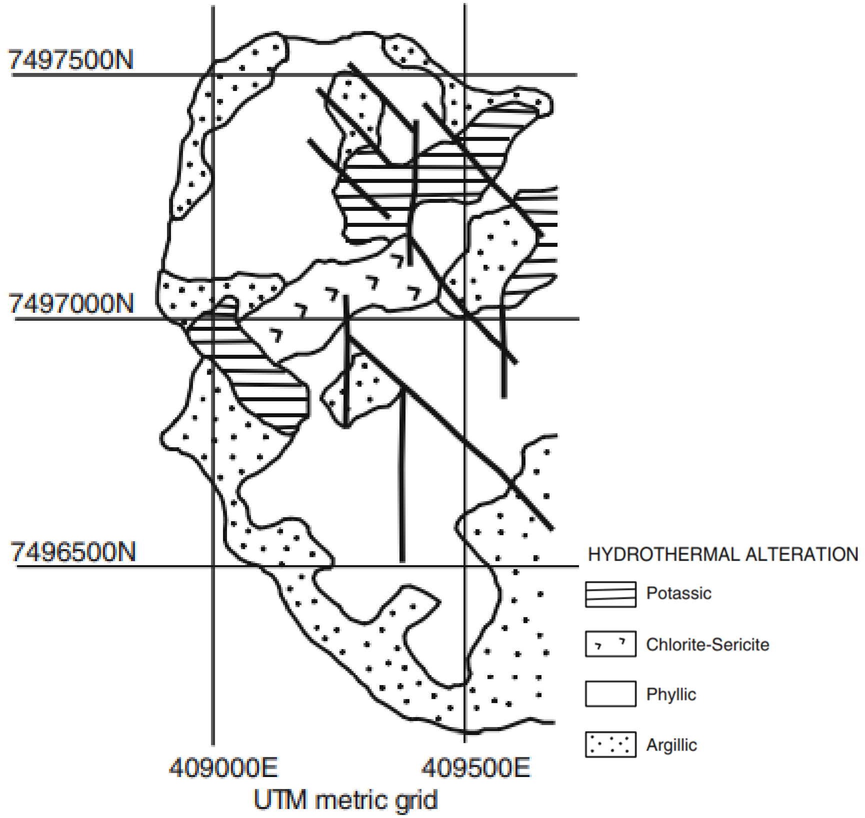
- There are two altered and mineralized porphyry intrusions at Antucoya, the Antucoya porphyry (granodioritic) and the tonalite (fine-grained) porphyry.
- The Antucoya Porphyry is altered to kaolinite, illite, and calcite, with traces of anhydrite and argillized feldspar. It contains a dense stockwork of quartz veinlets, some with oxidized copper minerals, limonites (after sulfides), and some late veins of calcite, anhydrite, and opaque minerals.
- The tonalite porphyry has strong argillic alteration and some calcite replacement.



Alteration cross-section of the deposit from Maksaev et al. (2006).

Alteration style

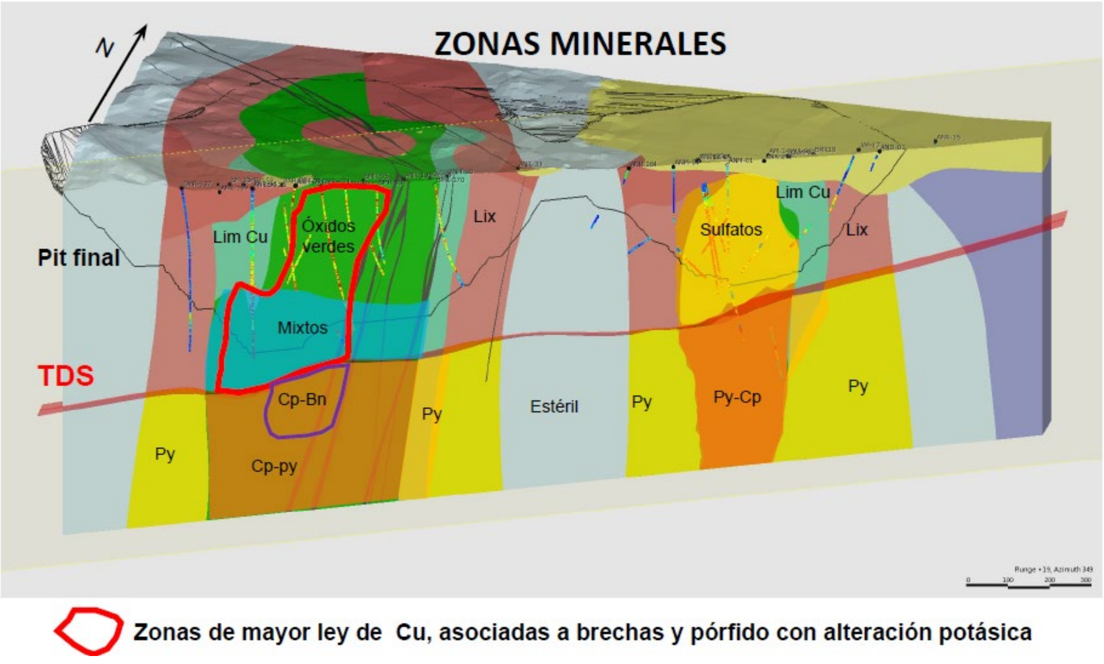
- Four hypogene hydrothermal alteration assemblages are recognized at Antucoya: potassic, chlorite–sericite, quartz–sericite, and propylitic.
  - The first three alteration types affect the porphyries and breccias, whereas propylitic alteration is restricted to the volcanic country rocks.
  - Potassic alteration mainly affects breccia bodies.
  - The tonalitic porphyry is characterized by the biotite, K-feldspar, and quartz assemblage.
  - Whereas, an assemblage of chlorite, sericite, smectite, quartz, pyrite, and chalcopyrite occurs within the Antucoya granodiorite porphyry.



Alteration at the 1,350m level of the deposit from Maksaev et al. (2006).

Alteration & mineralization

- The majority of the recognized orebody is affected by pervasive supergene argillic alteration (illite, dickite, and kaolinite) and oxidation (atacamite, brochantite, chrysocolla, copper wad, jarosite, and limonite), which extend down to depths of 300 to 350 m from the surface. These alterations are overprinted on previous hypogene alteration types.
  - Supergene processes, albeit unconstrained, are thought to have developed during the formation of the Oligocene–Miocene coastal Tarapacá pediplain.

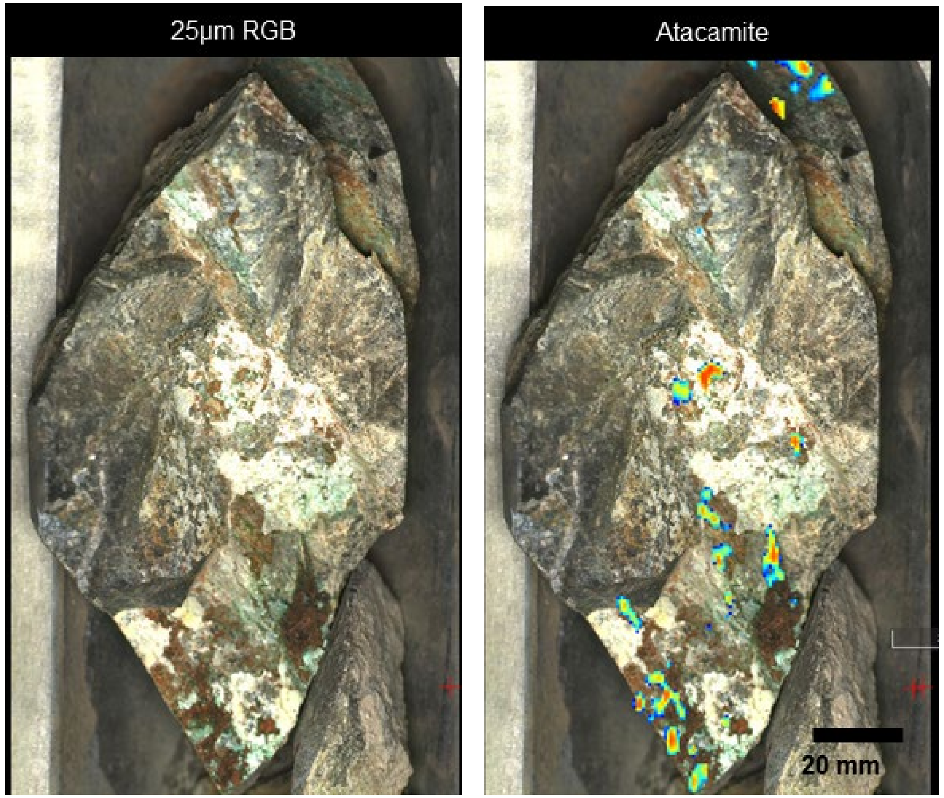


Valiente and Rubio, 2016

Mineralization

- The principal mineralization constitutes a column 350m thick, composed of atacamite, brochantite, Fe-Cu sulfates, Cu-bearing limonite, chrysocolla, and black oxides with rare chalcocite and covellite in a thin supergene enrichment blanket.
- In the underlying hypogene zone, the mineralization is dominated by:
  - Chalcopyrite > pyrite > bornite hosted by A and B veins in potassic alteration
  - C veins on the periphery of the porphyry intrusions
  - The pyrite to chalcopyrite ratio is greater in D veins within a shallow phyllic zone

- Mo distribution is erratic and poorly characterized.

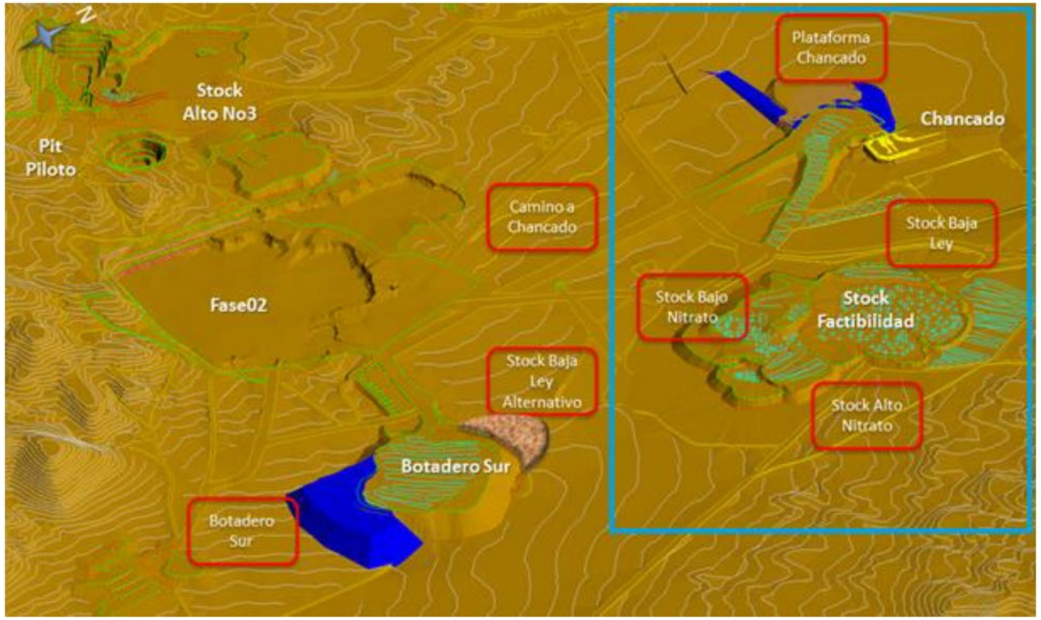


Resource

- Published resource estimates (measured + indicated) from the oxide zone as of 2022 is 1,114.6 Mt at 0.28% Cu plus an inferred resource of 0.3557 Gt at 0.24% Cu.
- The mine is approximately 1.6 km x 1 km.
- This is an oxide resource and includes a large area dedicated to leaching.

Mining process at Antucoya

- Antucoya is an open pit Cu mine that mines and leaches oxide ore using the patented Cuprochlor®-T technology.
- The mine produces copper cathodes using the solvent extraction and electrowinning (SX-EW) process.
    - This involves a two-stage hydrometallurgical process that first extracts and upgrades copper ions from low-grade leach solutions into a solvent containing a chemical that selectively reacts with and binds the copper in the solvent.
    - The Cu is extracted from the solvent with strong aqueous acid which then deposits pure Cu onto cathodes using an electrolytic procedure (i.e., electrowinning).



Antucoya mine plan including the pit, stocks, and leach pads (López Solar, 2016).

Problem Statement & High Impact Model Ideas

Problems

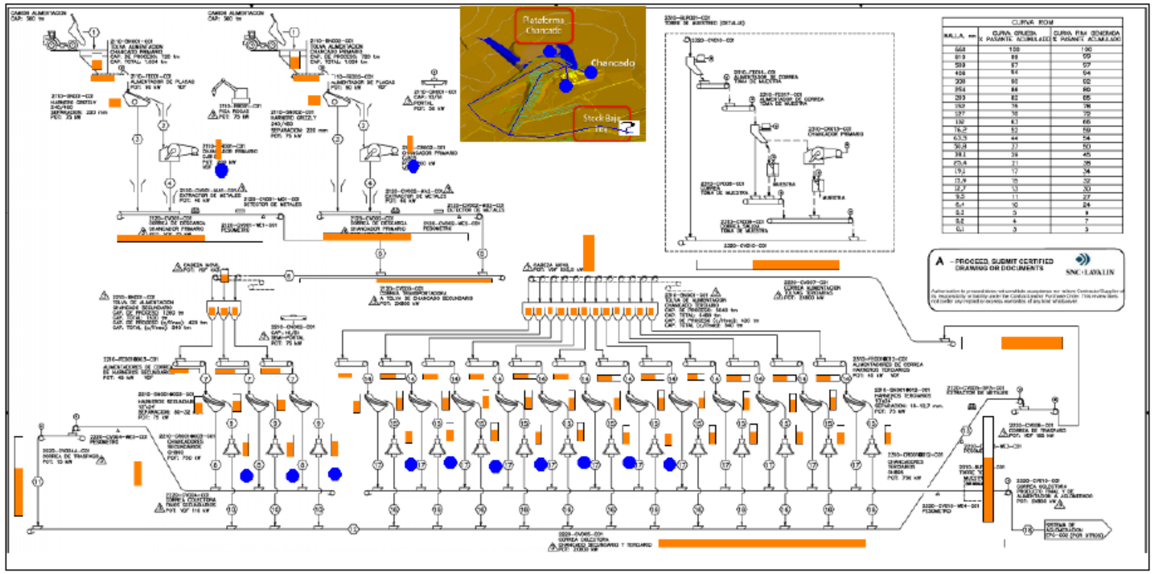
- The majority of the mining at Antucoya is in the oxide resource with about 30% of the ore coming from the sulfate resource.
- The resource is comprised of complicated mineralogy that will affect plant performance and leaching.

Workflow Ideas

- Create a sulfide – oxide – sulfate – carbonate model to help with mine planning.

Impact of using hyperspectral image data

- Can map the required minerals.
- Can continuously update the model in near-real time, as long as core is being scanned.



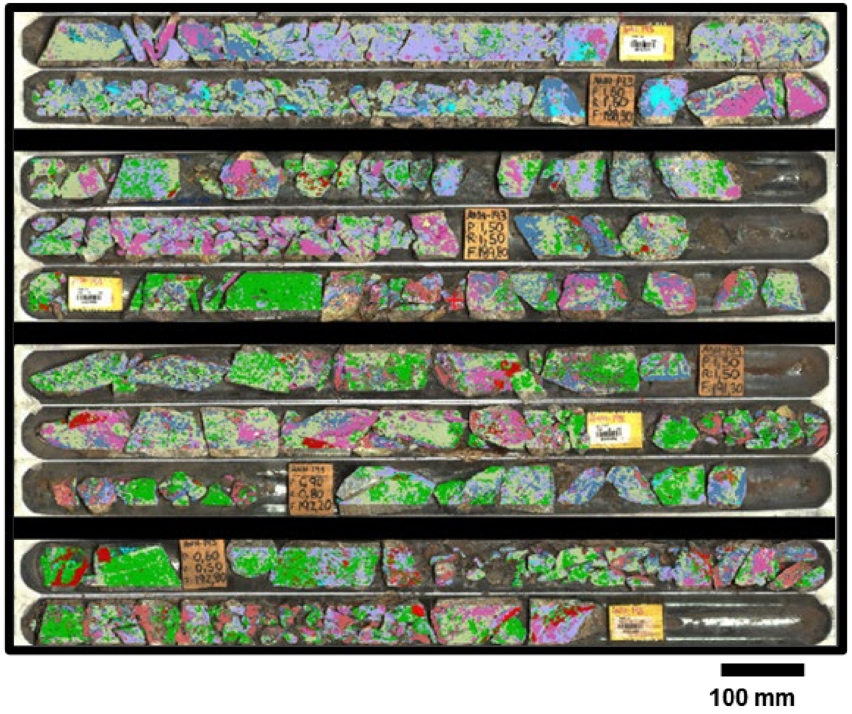
Antucoya milling and processing workflow (López Solar, 2016).

Let’s have a look at the spectral data

The Antucoya hyperspectral mineral library

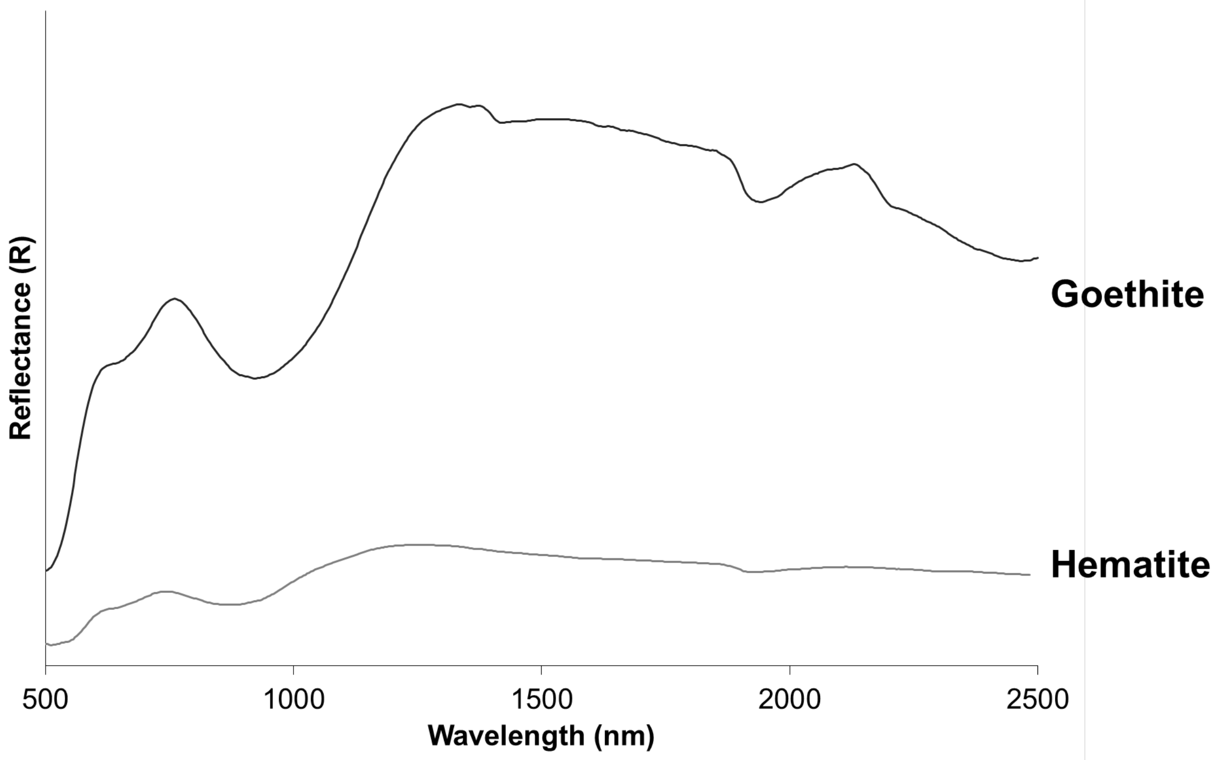
Nombre del Mineral	Color
Malaquita	
Antlerita	
Atacamita	
Cu-Mineral (Sulfate)	
Biotita (grupo)	
Dickita	
Jarosita	
Yeso	
Carbonato	
Sulfato Na-Ca	
Sulfato Fe	
Sulfato Fe-Mg	
Caolinita: Alta X	
Caolinita: Med X	
Caolinita: Baja X	
FLS + Mica Blanca	
Clorita + Mica Blanca	
Mica Blanca: Paragonita	
Mica Blanca: Paragonita-Moscovita	
Mica Blanca: Moscovita	
Mica Blanca: Moscovita-Fengita	
Mica Blanca: Fengita	
Montmorillonita	
Clorita	
Alunógeno	
Cuarzo/Sílice Hidratado	
Cuarzo/Sílice Opalino	
Oxido de Fe (general)	
Featureless Slope (FLS) - Tipo 1**	
Featureless Slope (FLS) - Tipo 2**	

*** Featureless Slope Spectra*



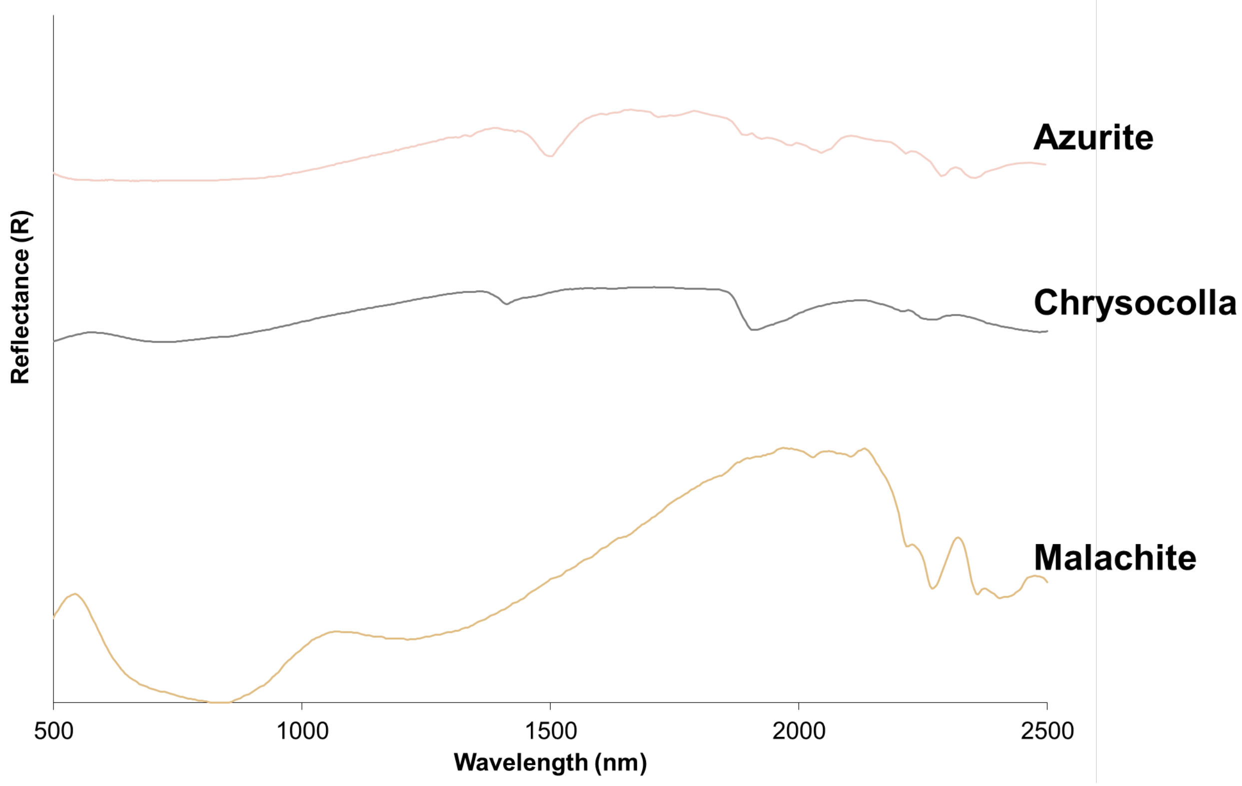
- The Antucoya mineralogy is a complex mixture of carbonates, oxides, sulfates, silicates, and clays.
- In the image at right, there are sulfates, carbonates, clays, and ore minerals complexly intermingled with each other.
- Understanding their distribution is essential for mine planning.

Oxides



- The oxide zone contains all of the mineralization that is currently mined at Antucoya and represents an ~350m thick column.
- Some of the Fe-oxides contain Cu.

Secondary Cu minerals

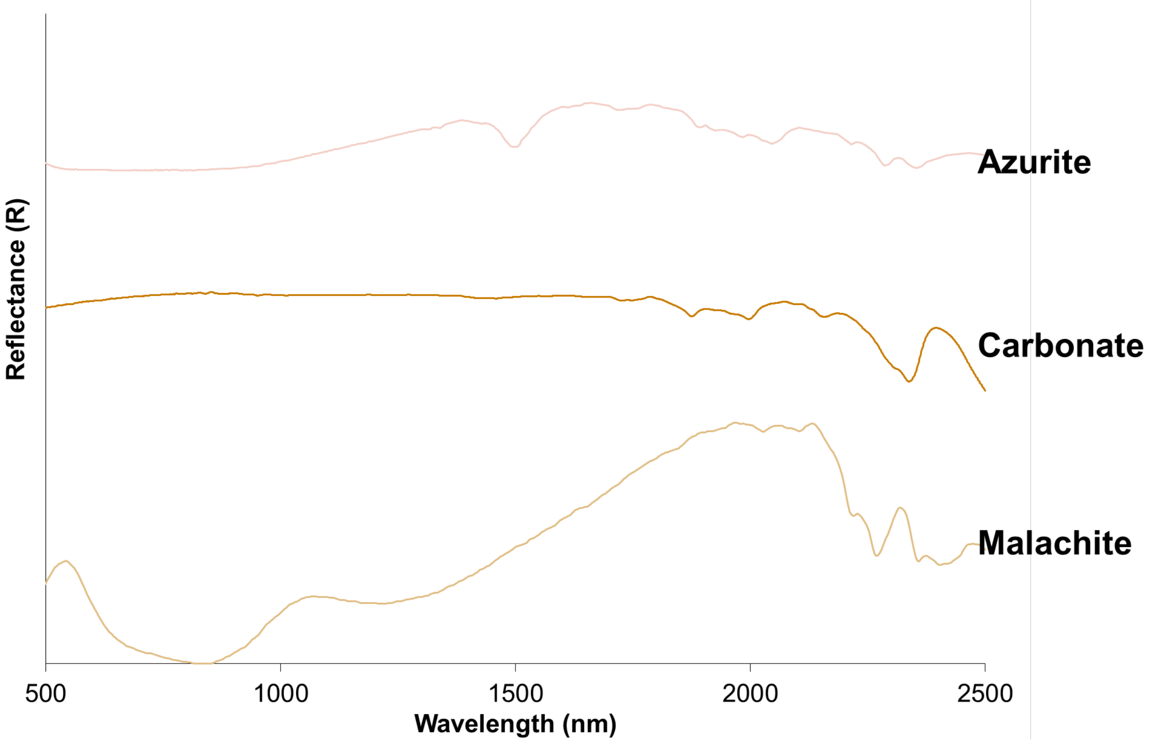


- The principal mineralization is comprised of secondary Cu-bearing minerals including atacamite, brochantite, Fe-Cu sulfates, Cu-bearing limonite, chrysocolla, and black oxides with rare chalcocite and covellite in a thin supergene enrichment blanket.
- At left, are a few of these minerals representing a mixture of carbonates and phyllosilicates.
- This demonstrates that not only is the gangue at Antucoya complex, but the ore mineralogy itself.

Sulfates

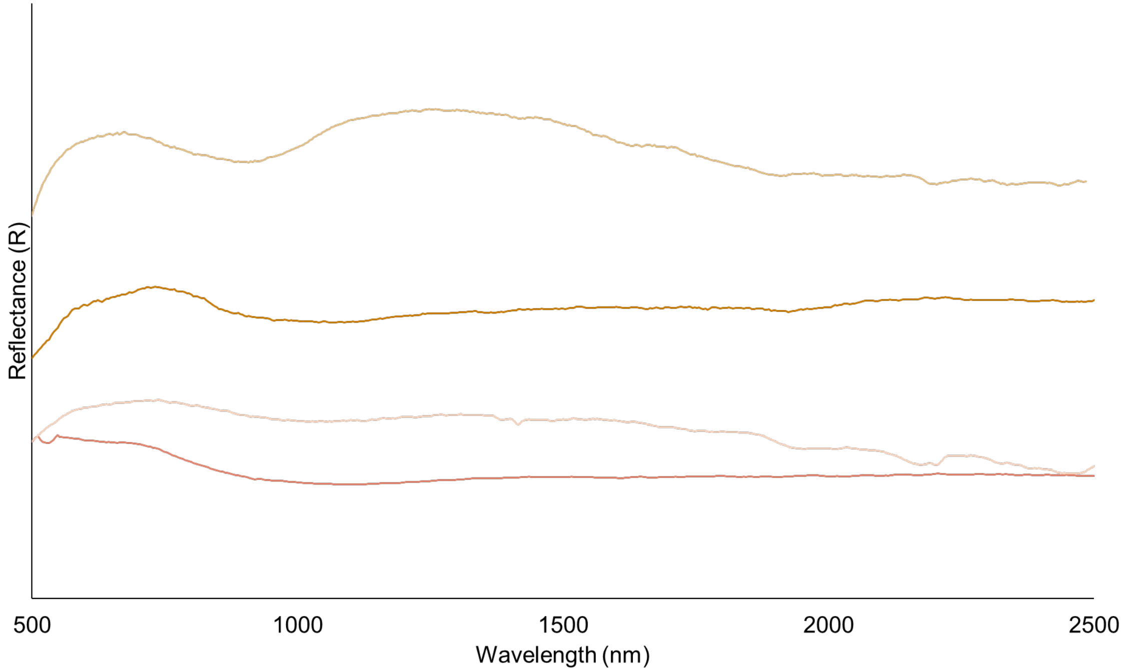
- At Antucoya there are a variety of sulfates, some of which are ore bearing.
- Ore-bearing: antlerite, Cu-mineral, brochantite
- Others: alunogen, jarosite, gypsum, Na-Ca, Fe, and Fe-Mg

Carbonates



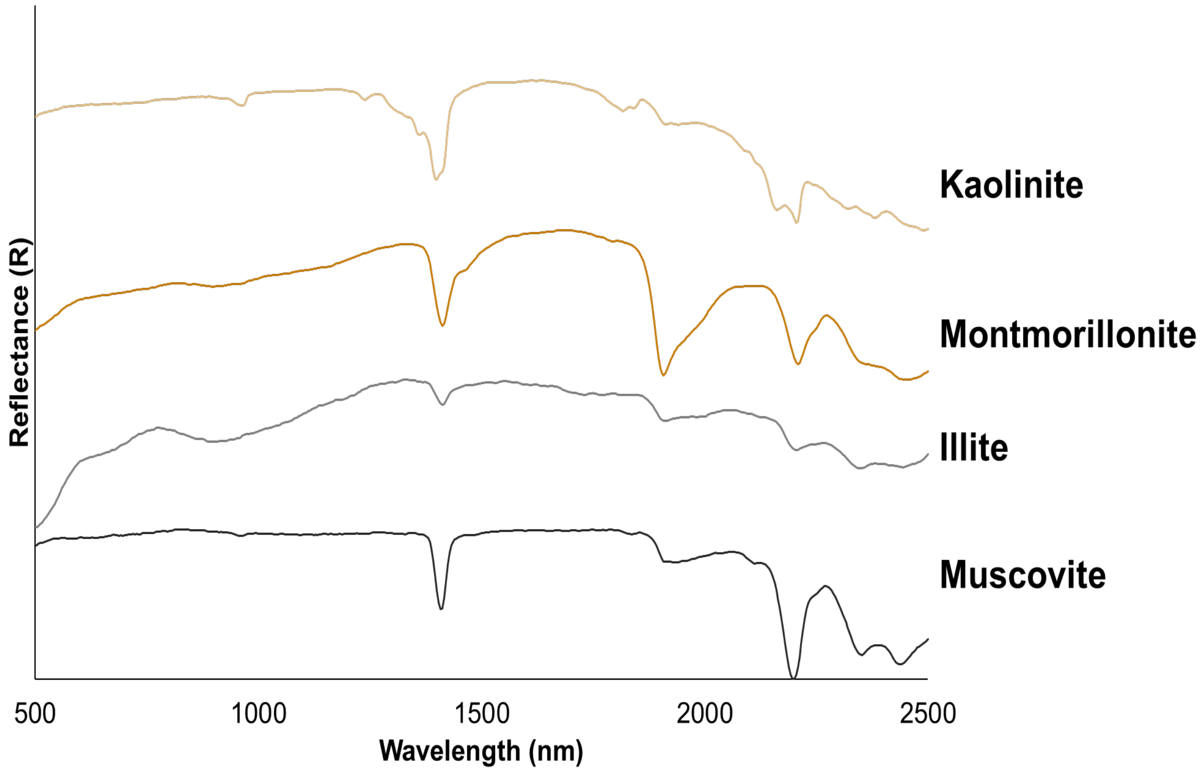
- Similar to the sulfate group of minerals, some of the carbonate minerals at Antucoya are ore-bearing.
- Ore-bearing: malachite
- Understanding carbonate distribution is important because of its acid neutralizing potential for leaching.

Sulfides



- Iron sulfides (e.g., pyrite, chalcopyrite) lack diagnostic spectral absorption features in the VNIR-SWIR range.
- However, the overall shape of the spectral signatures (plus texture – veined, massive, etc.) may allow for general discrimination and identification, particularly for coarser grained materials.

Gangue

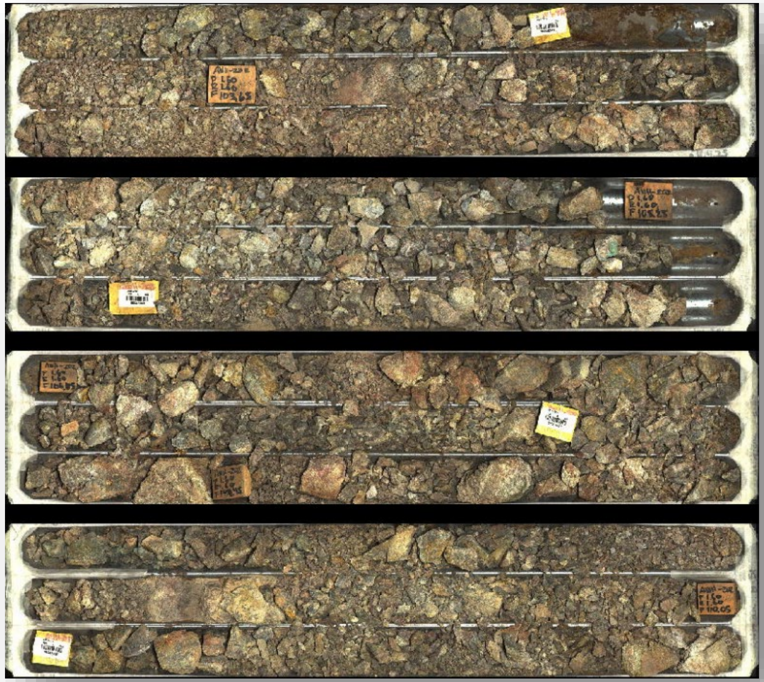


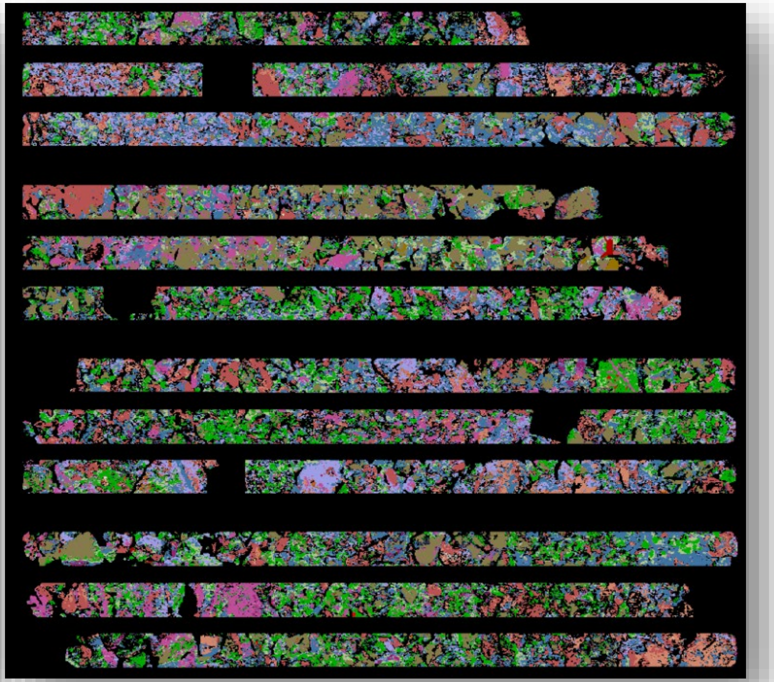
- Phyllosilicate minerals are comprised of tetrahedral (T) and octahedral (O) layers.
- This structure is inherently linked to behaviors in all aspects of mining (e.g., the ability of T-O-T structure to accommodate water and cause swelling behavior).
- Consider Antucoya:
  - Grinding: clays can increase mill residence time and clog milling equipment.
  - Leaching: clays have the capacity to absorb reagents, thereby increasing consumption.

Size matters?

…of course it does.

Facets of size





- Spatial resolution
- Spectral resolution
- Spectral range
- Amount / quality of spectrometers
- The amount of pixels

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).

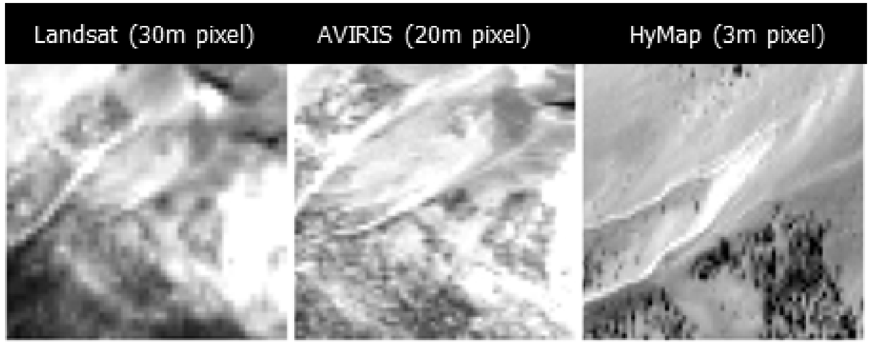


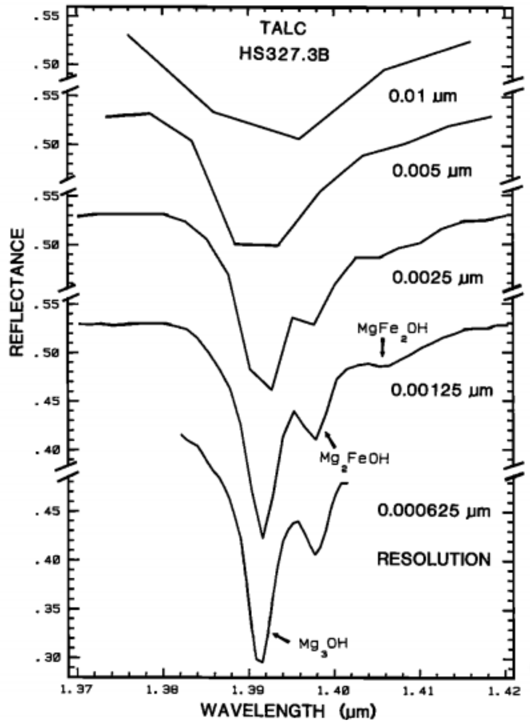
Image credit: Martini et al., 2001.

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

Spectral resolution

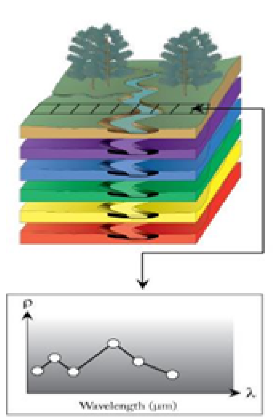
- Spectral resolution describes the wavelength intervals over which each spectral band's measurement is made, and which determines the ability to discriminate fine spectral features.
- It typically refers to how "wide" each band is, or the range of wavelengths covered by a single measurement band.
-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

Reflectance spectra of talc ~1400nm

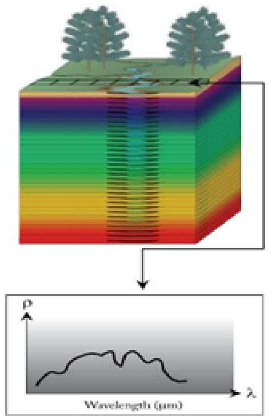


Increasing spectral resolution = more detailed spectral features

(from Clark et al.,1990)



Example multi-band:
0.5µm or 500nm

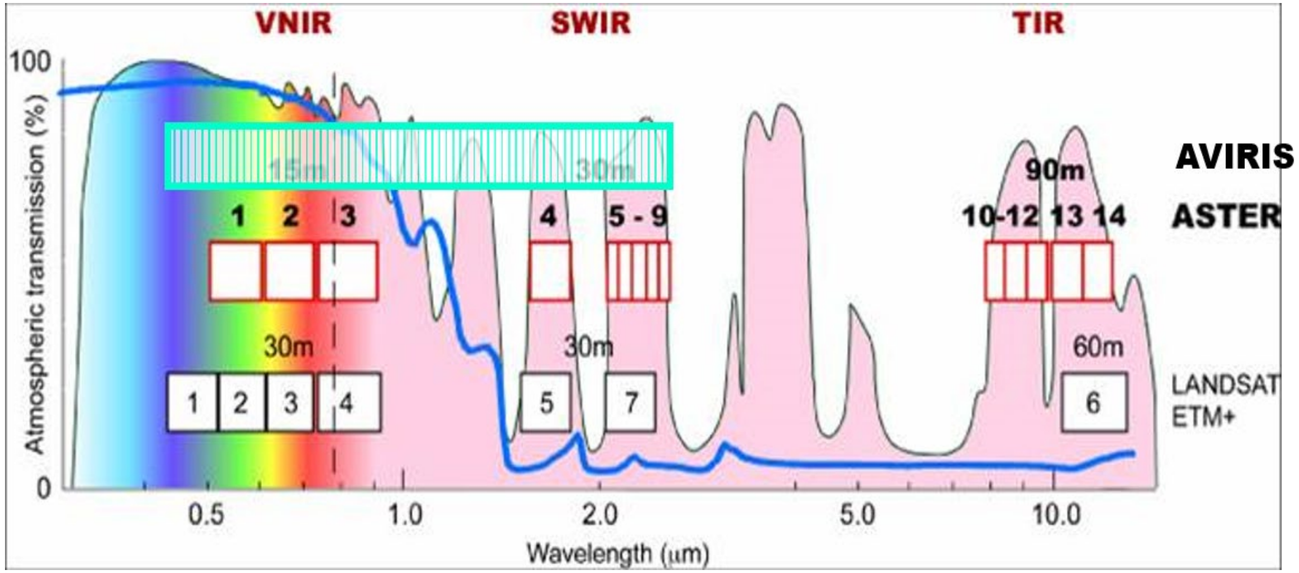


Example hyperspectral:
0.004µm or 4nm

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

Spectral range, number of bands & band distribution

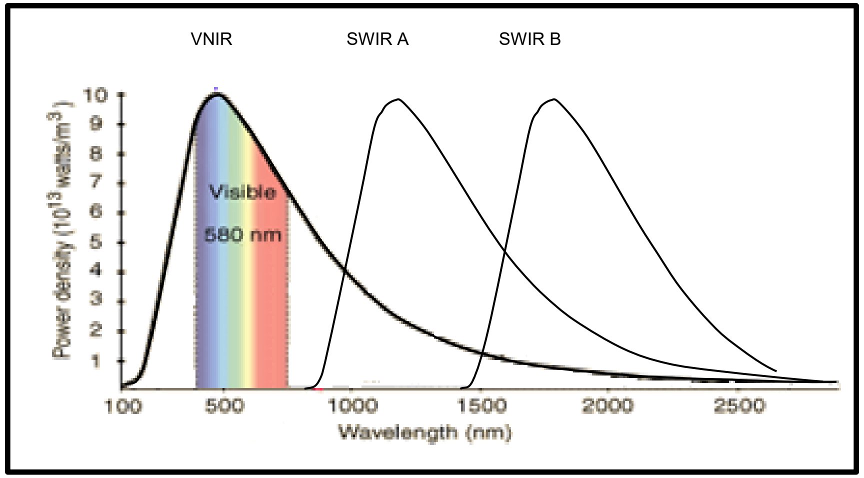
- The spectral range refers to the specific wavelengths measured by a sensor.
- The number of bands (and whether they are contiguous) classifies hyperspectral from multi-spectral, i.e., absolute mineral identifications versus broad mineral classifications.

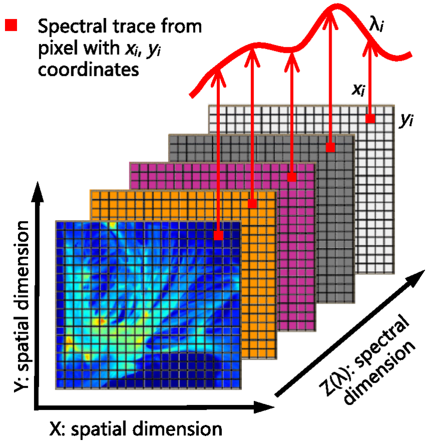


Examples drawn from remote sensing satellite data. Each shows the spectral range of the instrument, as well as how many bands of information are available for interpretation.

Number of spectrometers

- Due to optical performance constraints, core scanning hyperspectral systems are designed with more than one spectrometer to cover the spectral range, typically a VNIR and a SWIR spectrometer. However, some systems have more than two spectrometers, for example:
  - VNIR spectrometer: ~400nm to 1000nm
  - SWIR-A spectrometer: ~800nm to ~1700nm
  - SWIR-B: spectrometer: ~1600nm to ~2500nm
- These overlapping spectrometers help to prevent noise both in the overlapping regions and extend the signal further out in the SWIR, where a lot of important minerals (e.g., mafic minerals and carbonates) have important absorption features





Importance of co-registration: The spectral response across all spectrometers must be sampled from the same location (pixel) on the core surface for accurate and reliable mineral interpretation.

Signal to Noise Ratio (SNR)

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

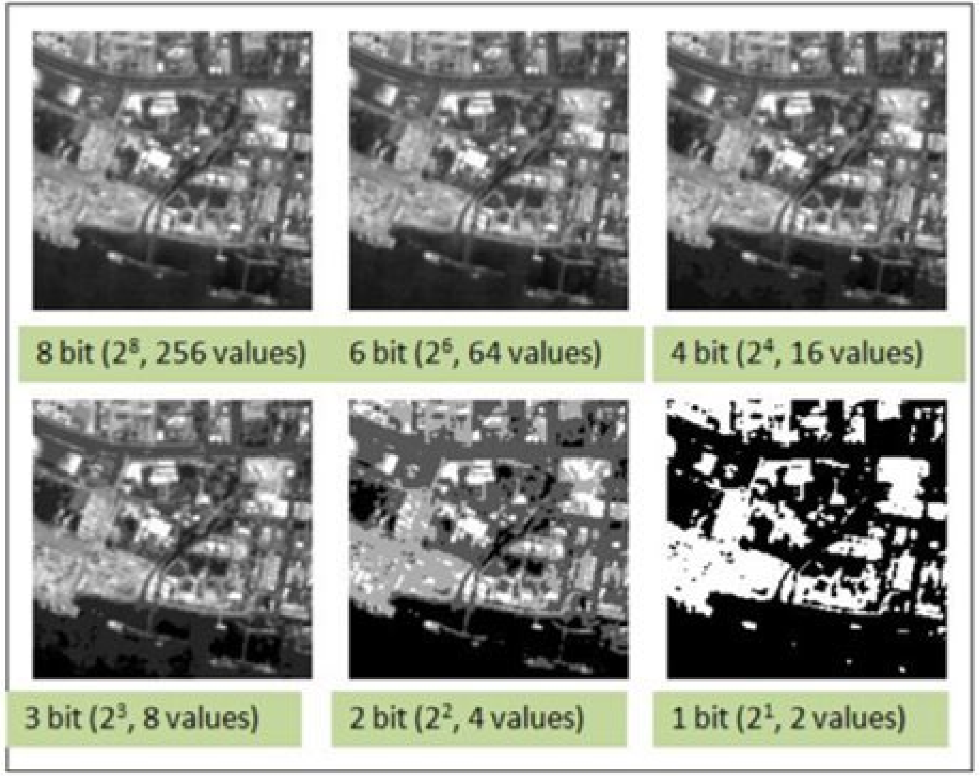
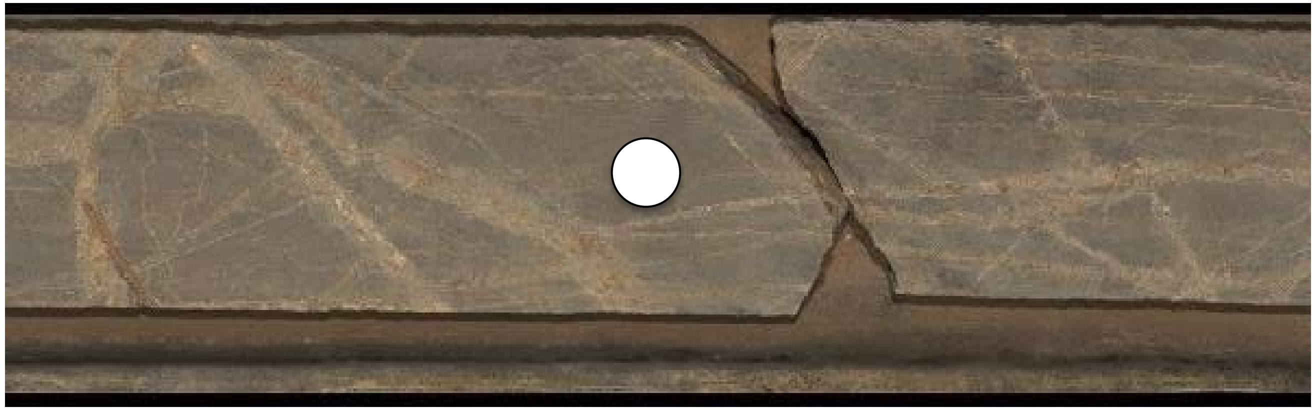


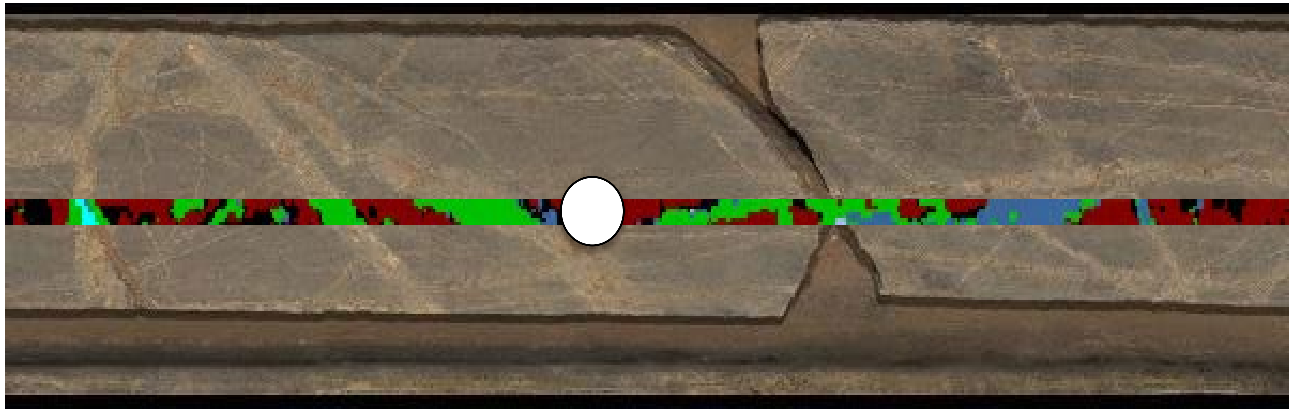
Image credit: Descartes Labs

Increasing counting statistics for data interpretations: point data



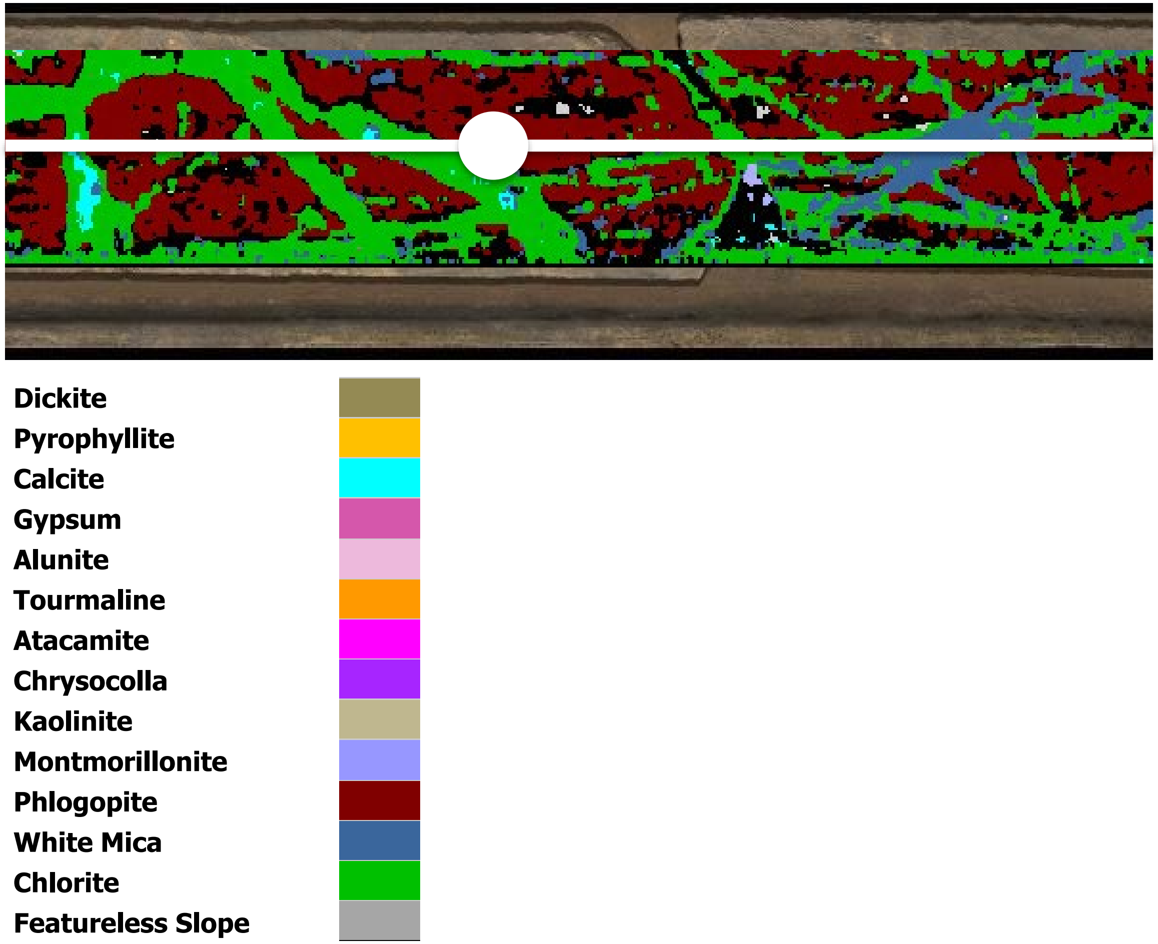
Mineral	Mineral % (Point)
# Spectra	1
Calcite	
Chlorite	
Kaolinite	
Montmorillonite	
Phlogopite	100
Tourmaline	
White Mica	

Increasing counting statistics for data interpretations: line scan systems



Mineral	Mineral % (Point)	Mineral % (Line)
# Spectra	1	20
Calcite		0.006
Chlorite		31.9
Kaolinite		0
Montmorillonite		0
Phlogopite	100	48.6
Tourmaline		0
White Mica		0.083

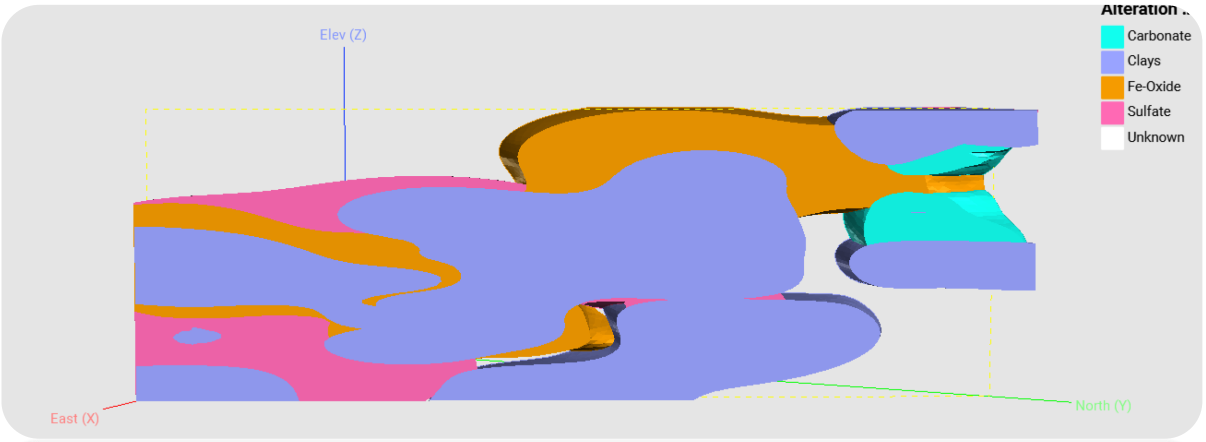
Increasing counting statistics for data interpretations: imaging systems



Mineral	Mineral % (Point)	Mineral % (Line)	Mineral % (Image)
# Spectra	1	20	55,000
Calcite		0.006	0.005
Chlorite		31.9	27.6
Kaolinite		0	0.002
Montmorillonite		0	0.03
Phlogopite	100	48.6	37.6
Tourmaline		0	0.01
White Mica		0.083	26.9

System used in this study

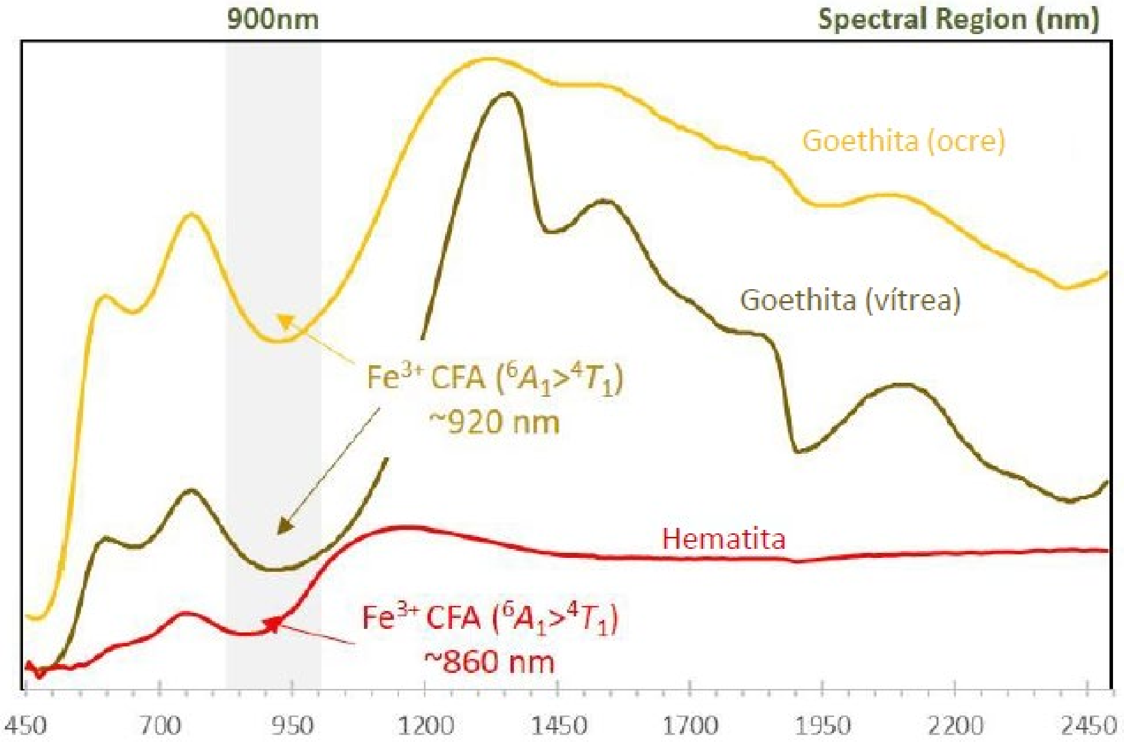
IR System Specification	Corescan HCI-4.1
Sensor type	Imaging
Spectrometer modules	3
Spectral range – VNIR (nm)	450 – 1,000nm
Spectral range – SWIR (nm)	1,000 – 2,500nm
Spectra per meter (1000mm x 60mm)	240,000
Spatial resolution	250µm
Spatial sampling	500µm
Spectral resolution	2nm



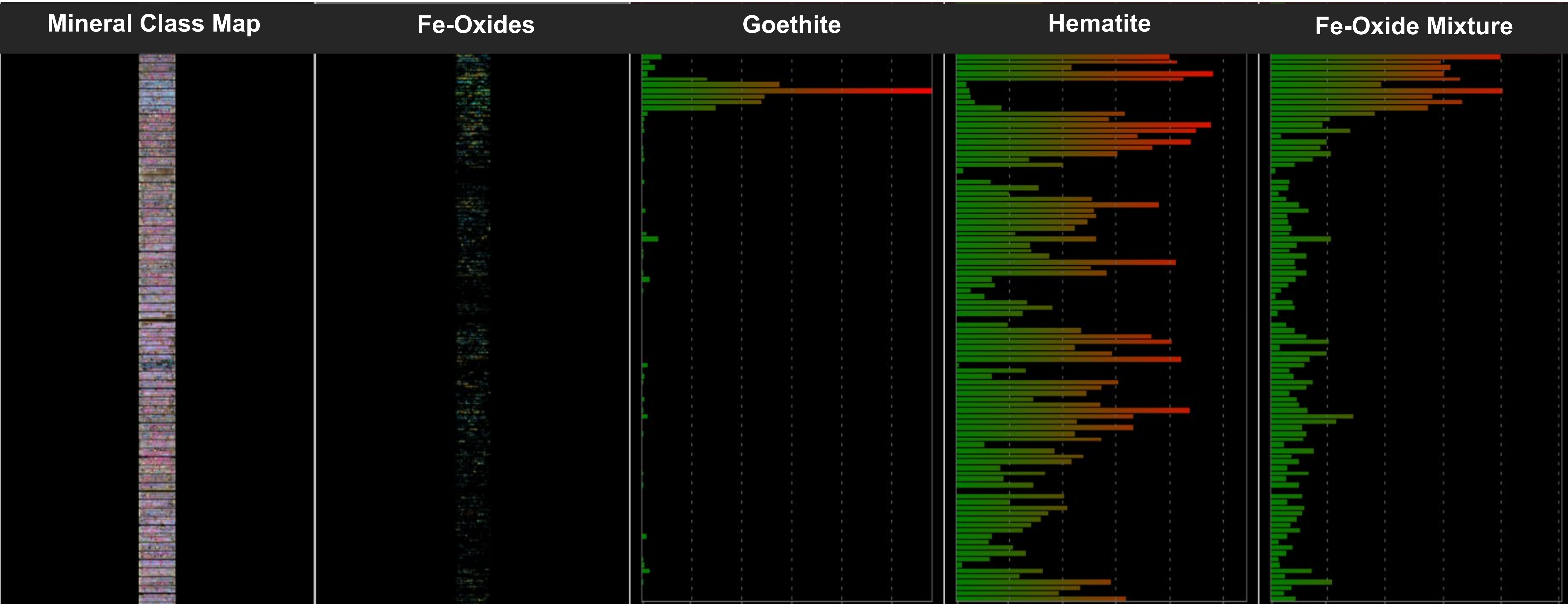
Small programs with large impacts

The oxide zone, what we're mining

- As we saw in the prior section, Fe-oxides are easily mapped in the VNIR with well-defined absorption features.
- These absorption features are due to crystal field absorptions (CFA) and are related to Fe.
- In addition to mapping the general group, Fe-oxides can be speciated into hematite and goethite based on their wavelength position:
    - Fe^{3+} (hematite): ~860nm
    - Fe^{2+} (goethite): ~920nm

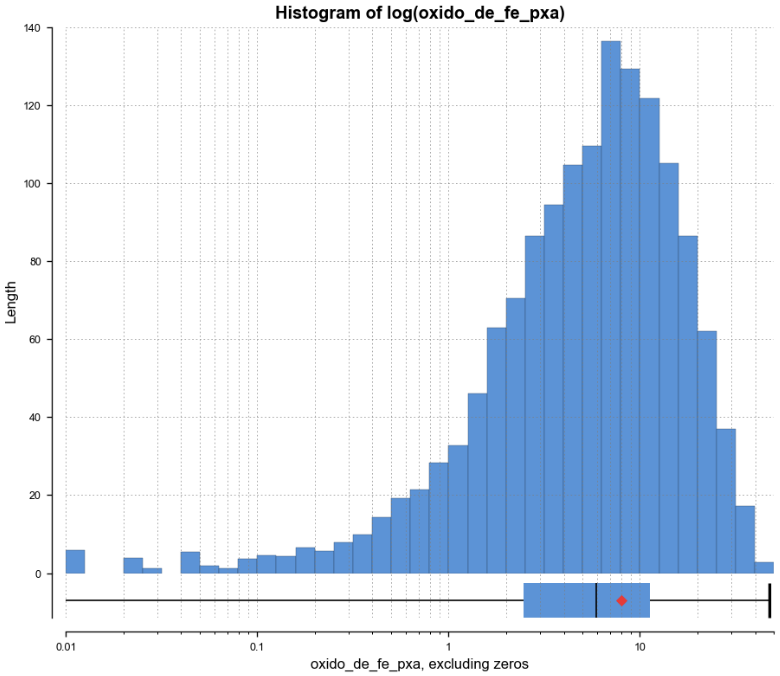


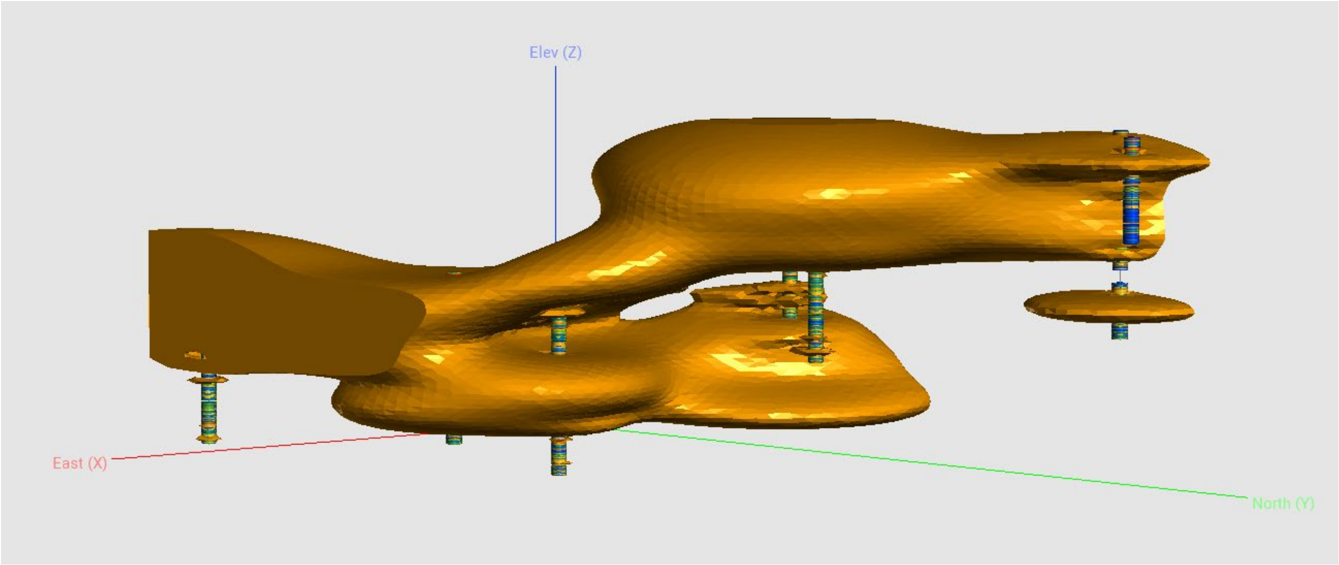
Distribution of Fe-oxide species



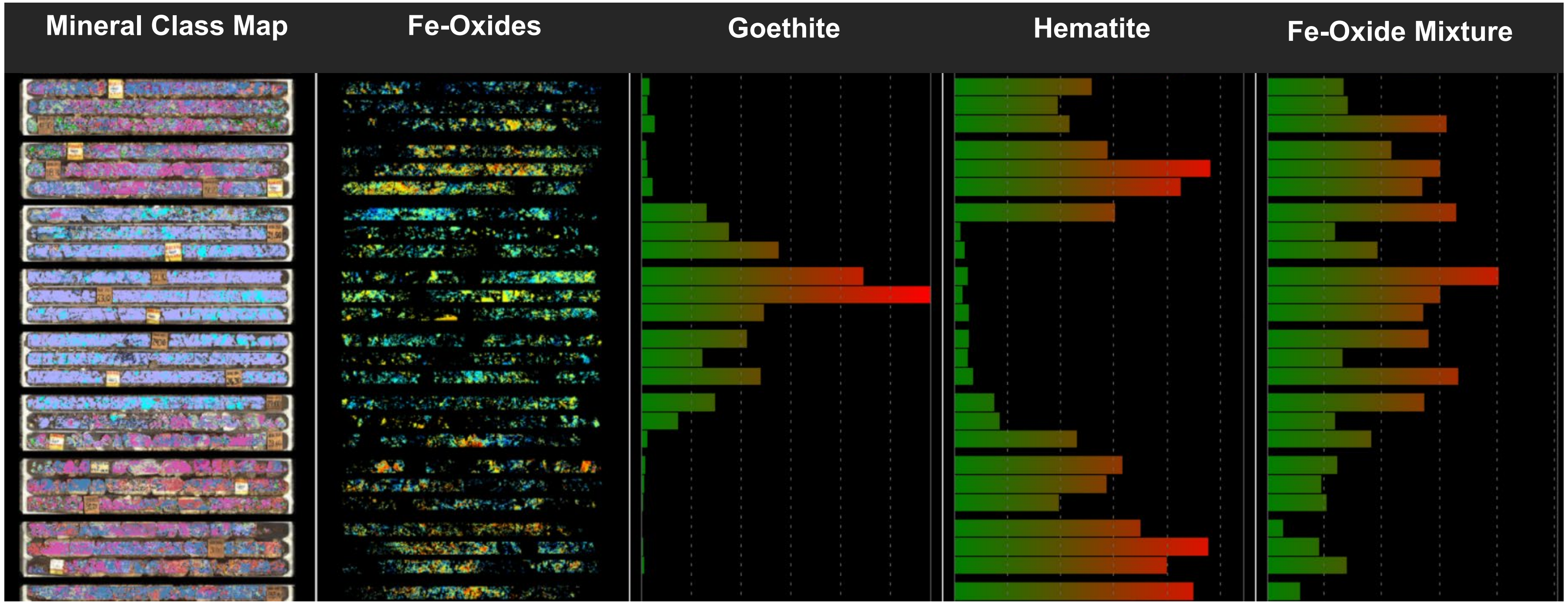
Oxide zone in 3D

- Indicator RBF Interpolant cut-off for model selected based on the median value of the data: 5%.





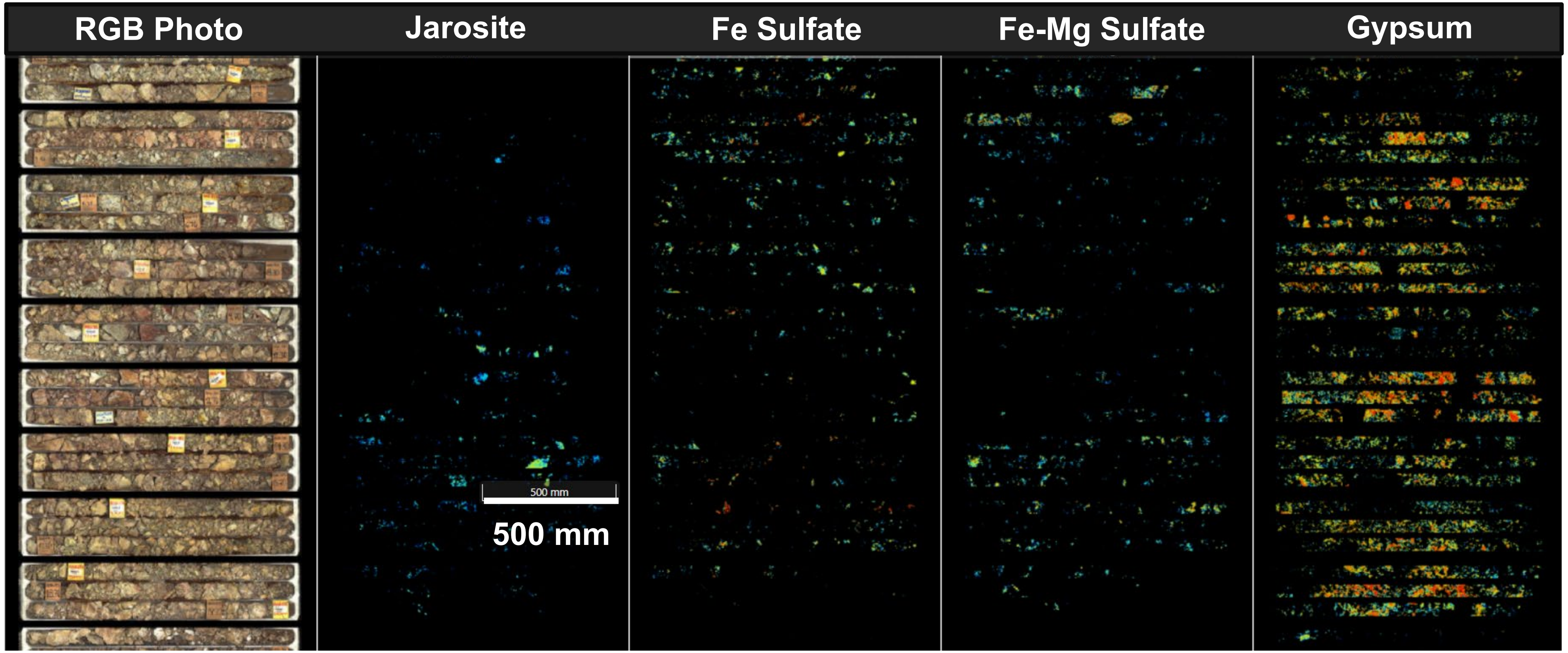
The oxide zone… it’s complicated



Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	
White Mica	
Montmorillonite	
Fe-Oxide (General)	
Chlorite	
Carbonate	

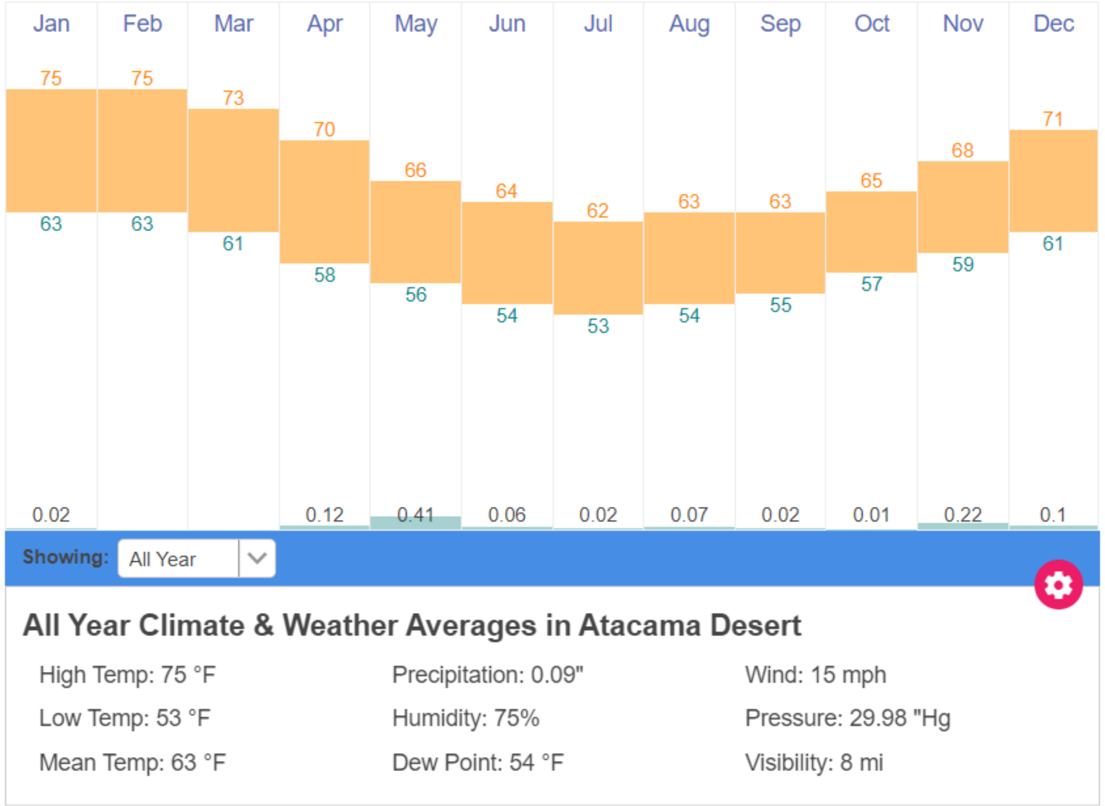
Sulfate, a permeability issue

- Antucoya's mine is completely based on mining the oxide resource and leaching the Cu from the oxide and sulfate ore.
- However, when there is too much sulfate on the leach pad, things become problematic.



Let's talk about the Atacama Desert

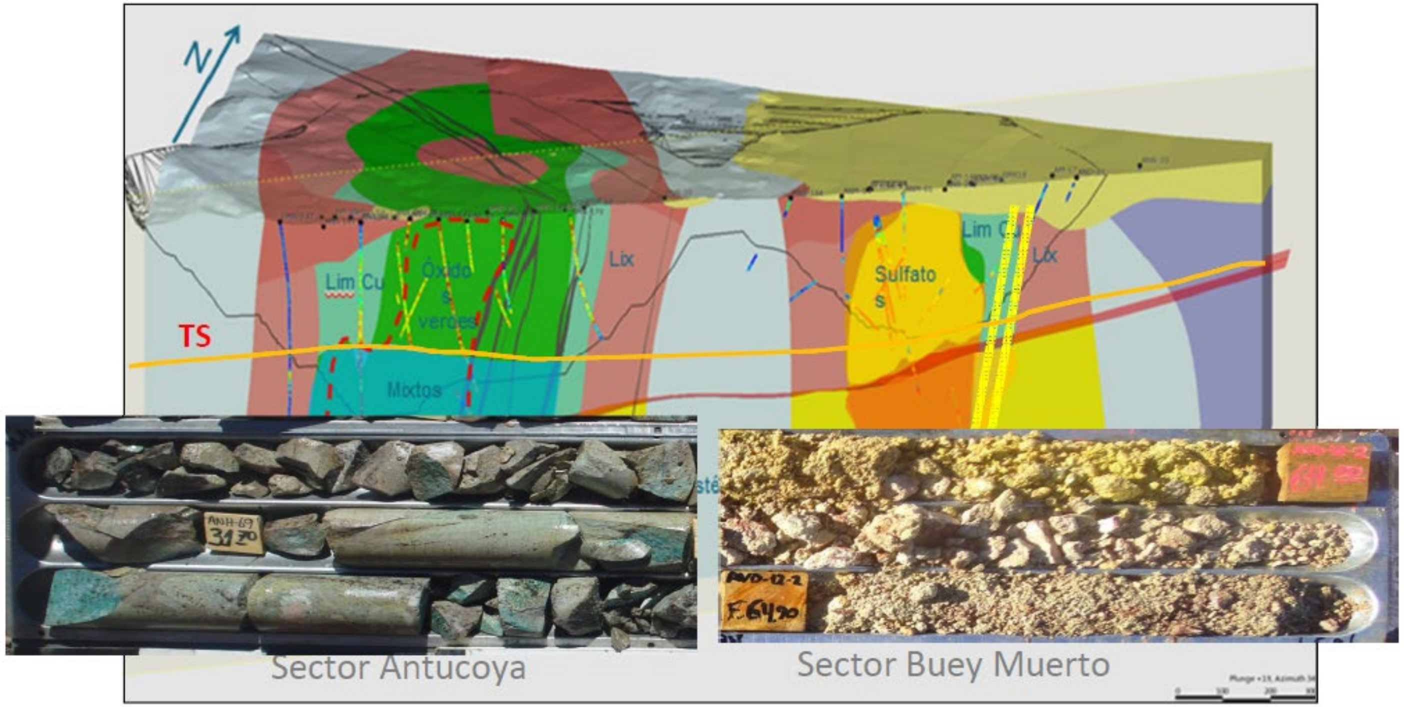
- The Atacama Desert is the driest desert on Earth.
- Interestingly, the Atacama Desert is a fog desert, a type of desert where fog drip supplies the majority of moisture needed by animal and plant life.
- The humidity in the foggy air is above 95%.
- The average temperature in the Atacama Desert in the Antofagasta Region can be seen at right. Importantly, it is sufficiently cold at night for the sulfate liquid in the heap leach to crystallize, forming an impermeable layer below the leach.



This graph is based on weather reports collected during 1992 to 2021 from Antofagasta, Chile; this city is ~125km southwest from Antucoya Mine (link).

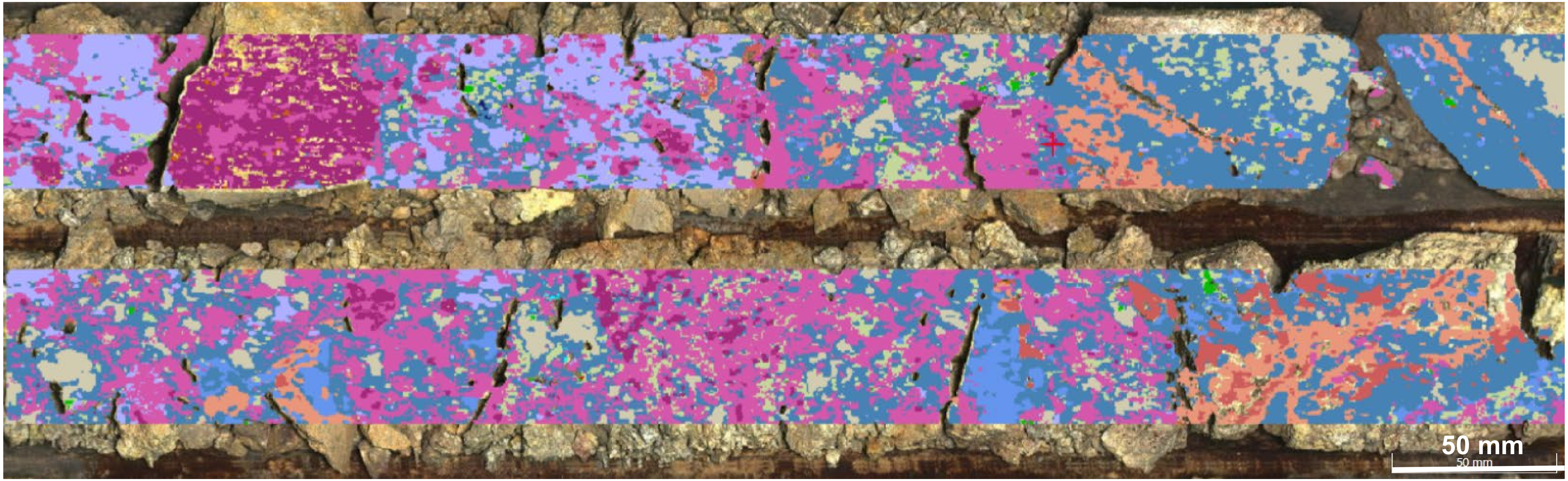
Understanding the sulfate distribution

- Understanding the sulfate distribution is crucial to successfully mine the Antucoya resource.
- These next few slides are dedicated towards looking at these different sulfates and appreciating them at the 500um scale.
- Also, appreciating how intermixed they are with the oxide resource.



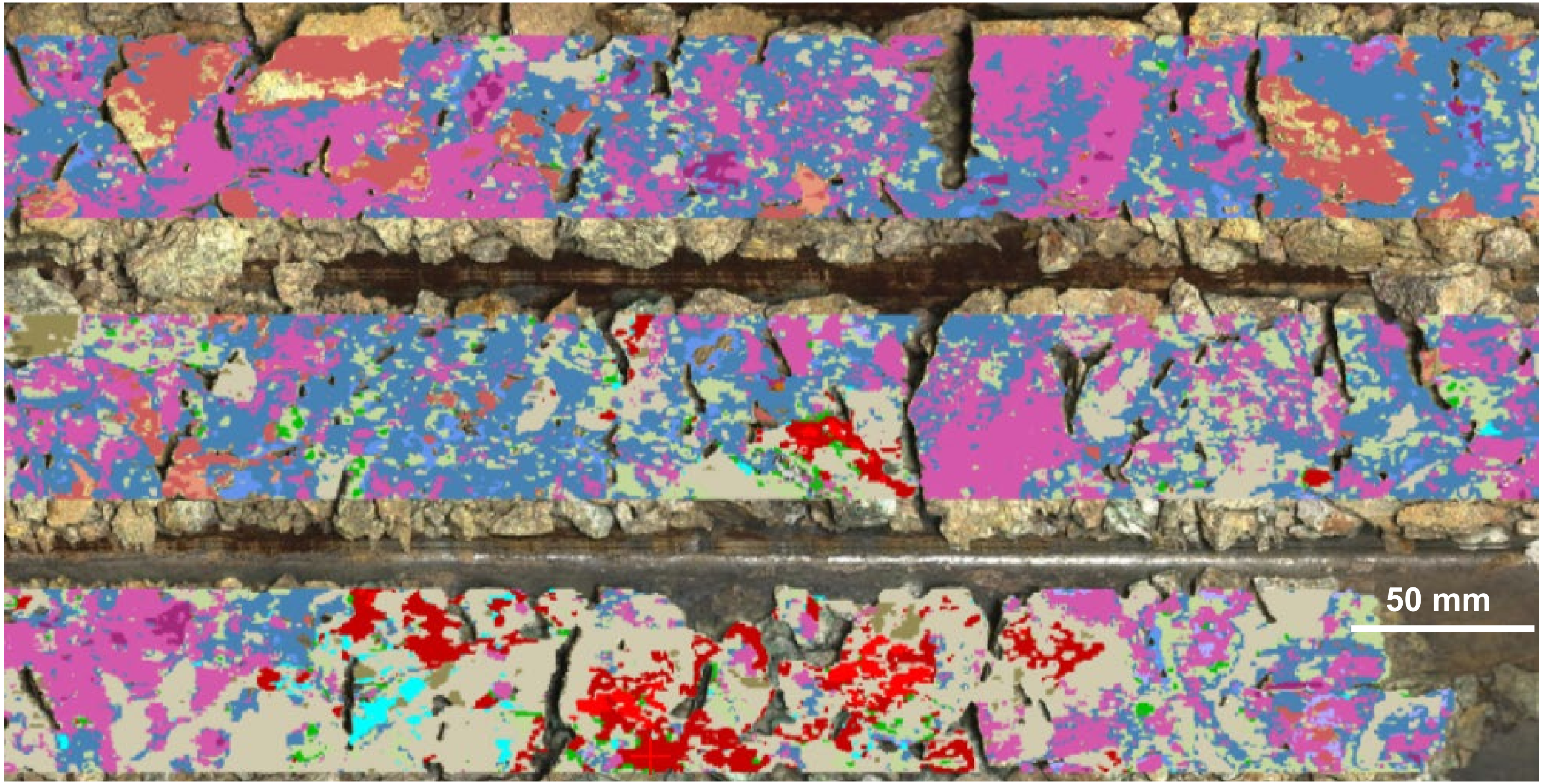
Valiente and Rubio (2016)

Sulfates in an oxide geometallurgical domain



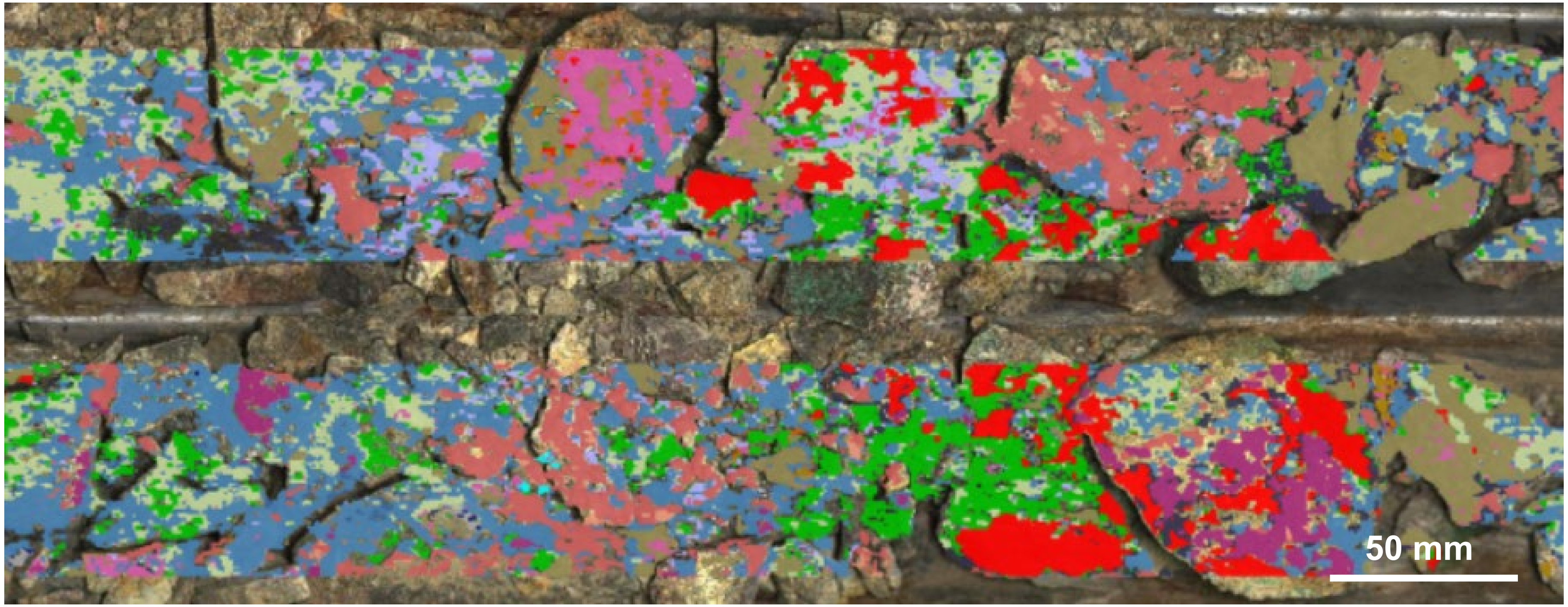
Jarosite		White Mica	
Fe-Mg Sulfate		Kaolinite	
Fe Sulfate		Montmorillonite	
Gypsum			

Sulfates in the quartz-sericite-pyrite + sulfate domain



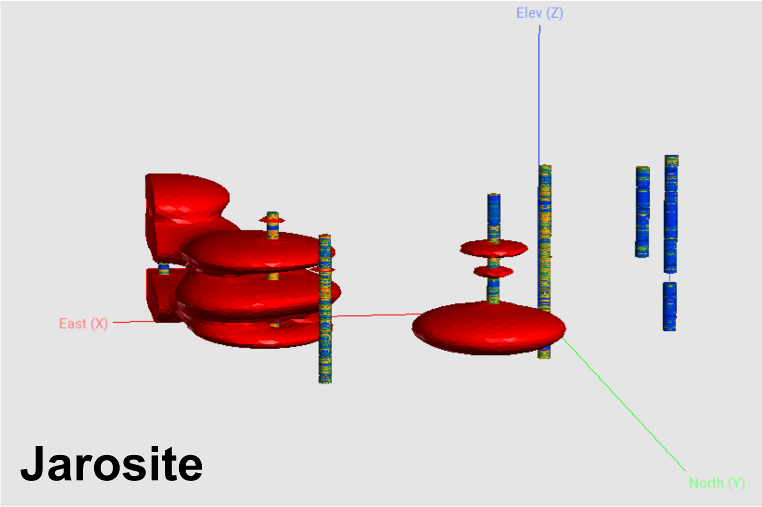
Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	
White Mica	
Kaolinite	
Cu Mineral (Sulfate?)	
Antlerite	
Carbonate	

Sulfates in quartz-sericite-pyrite domain

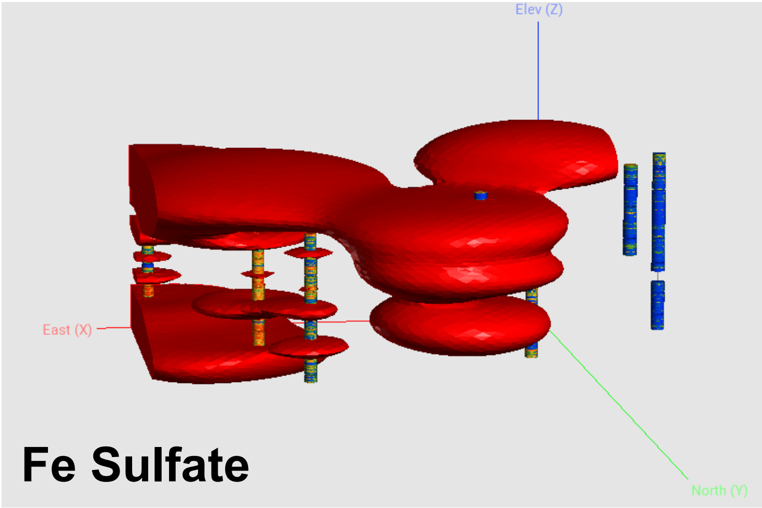


Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	
White Mica	
Kaolinite	
Chlorite	
Antlerite	

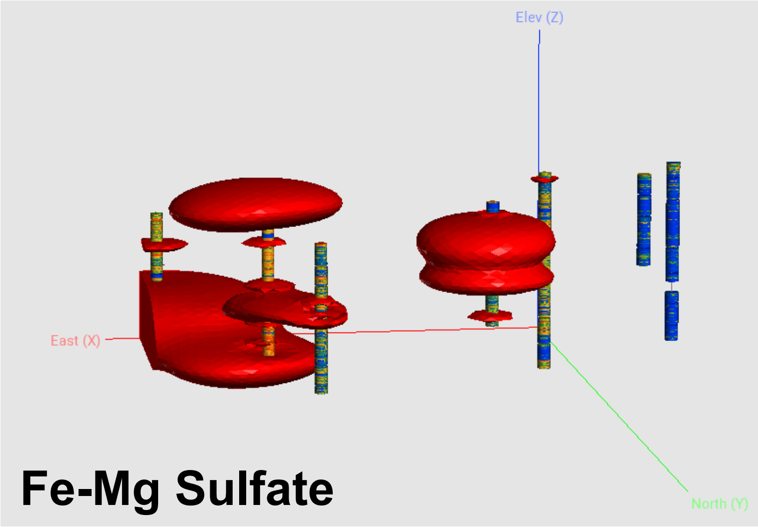
Quantifying these images



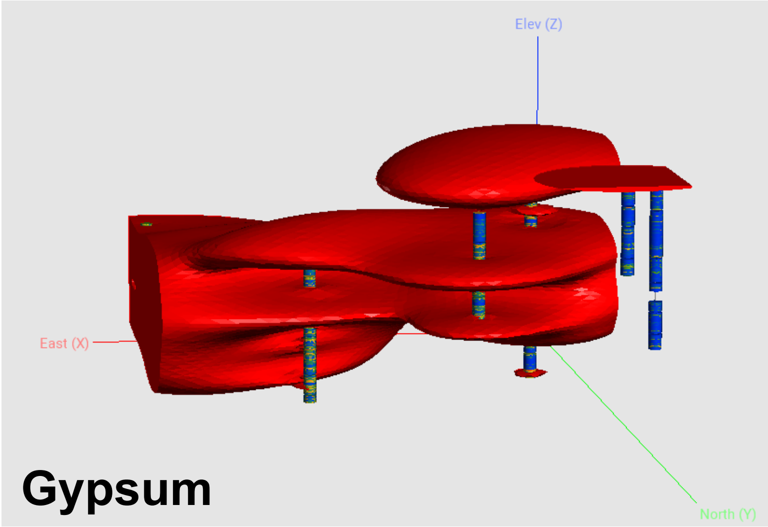
Jarosite



Fe Sulfate

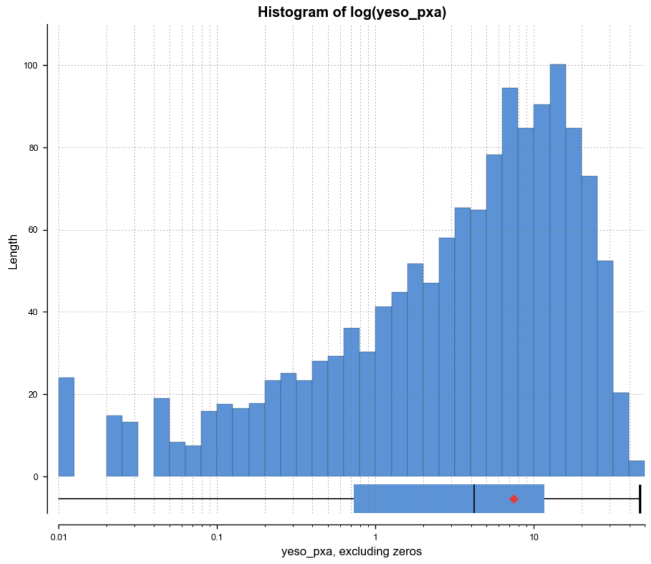


Fe-Mg Sulfate

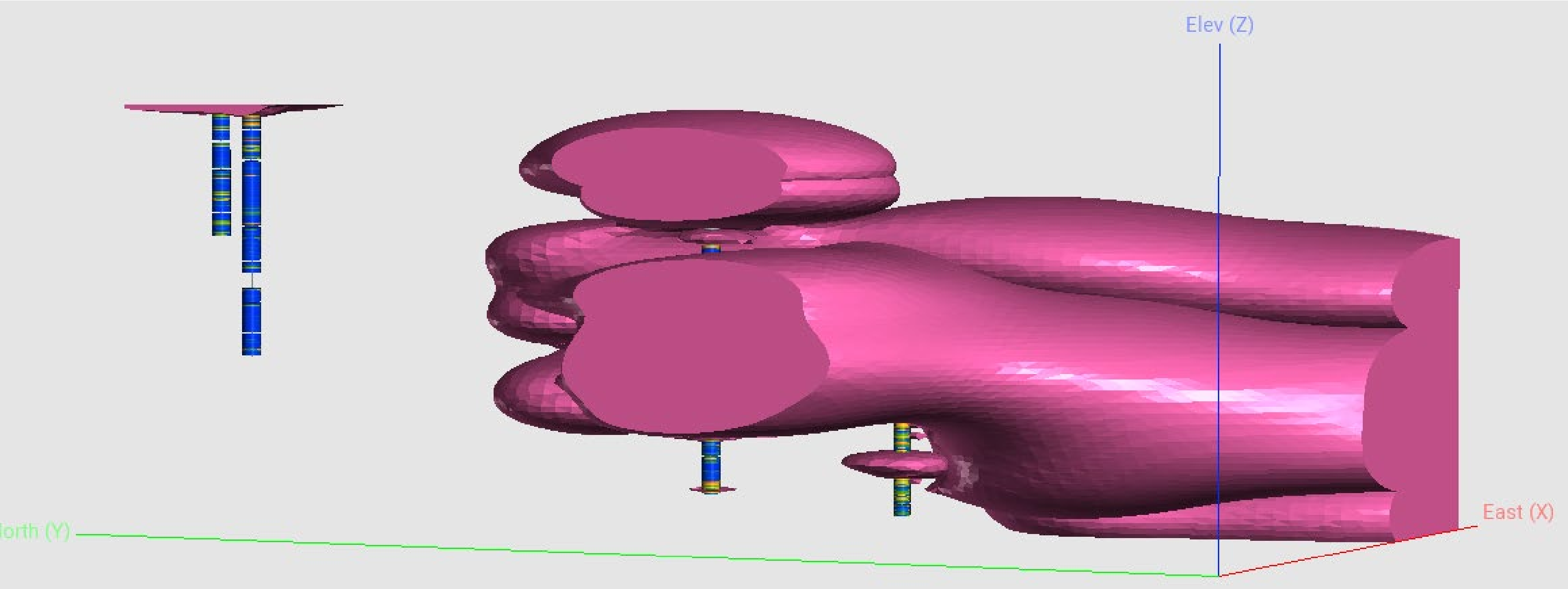


Gypsum

- Indicator RBF Interpolant cut-off for model selected based on the median value of the data.



Quantifying these images



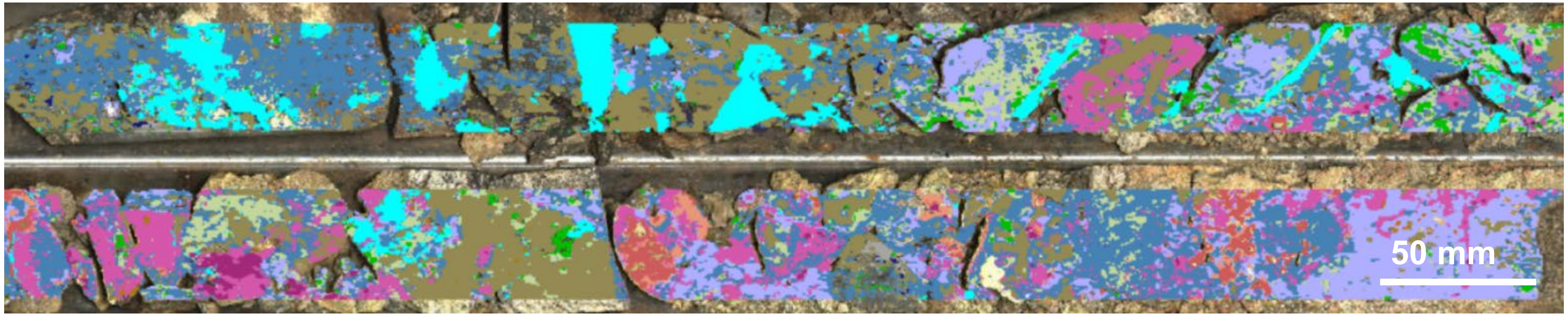
- Next step is to work with tools such as XRD and geochemistry to calibrate this sulfate shell.

Let’s build on this model: carbonates

- Carbonates present a problem for heap leaching operations.
- Strong acids are used to leach the Cu from the ore. At Antucoya they maintain a pH of 1.5.
- Carbonates are natural buffers to acid solutions.
- At the micron scale, carbonates are intermingled with the ore.
- Furthermore, some of the ore mineralogy is carbonate.

Malachite: $Cu_2CO_3(OH)_2$

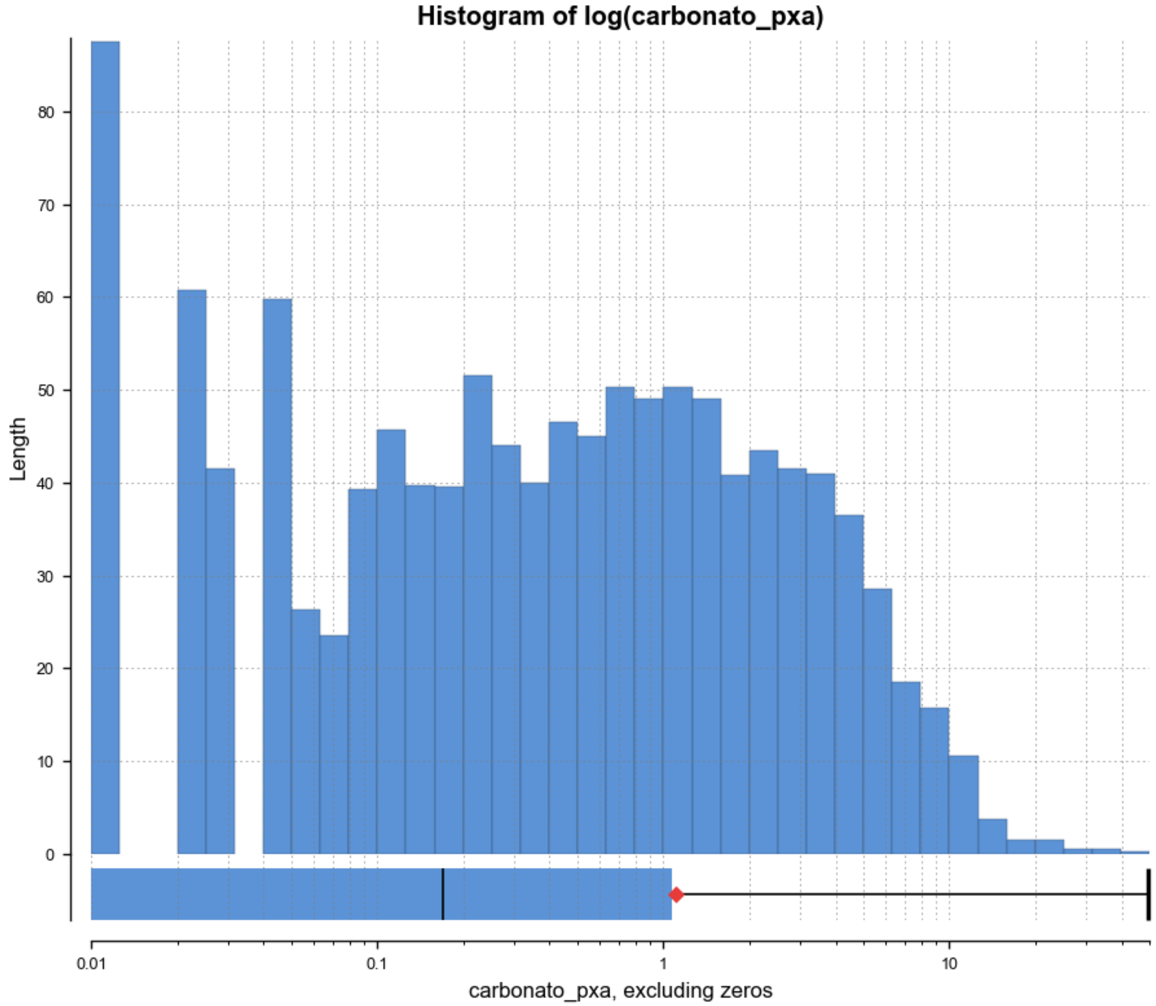
Carbonate at the 500µm scale



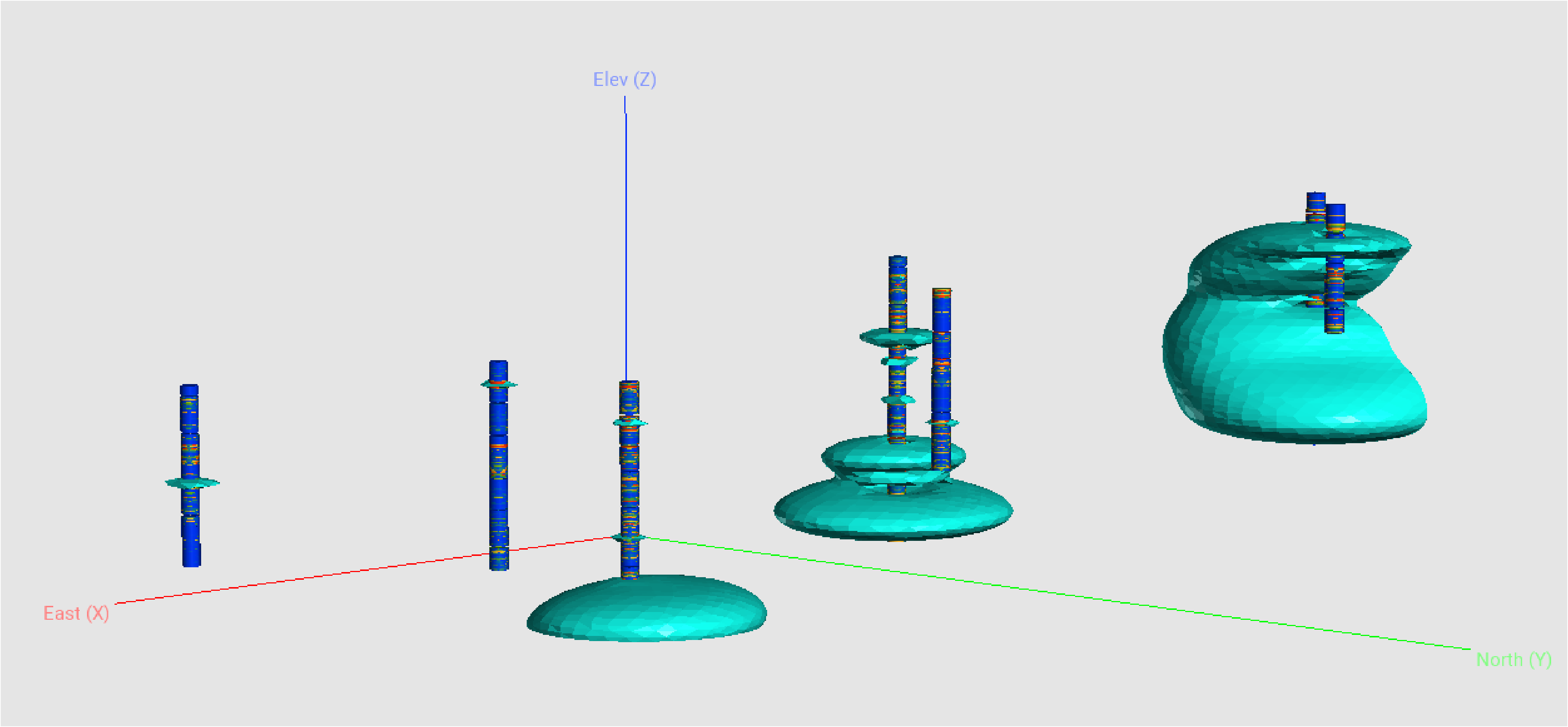
Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	
White Mica	
Kaolinite	
Carbonate	

Carbonate distribution

- Indicator RBF Interpolant cut-off for model selected based on the median value of the data: 0.5%.
- This does not reflect a significant carbonate percentage for issues with acid buffering.



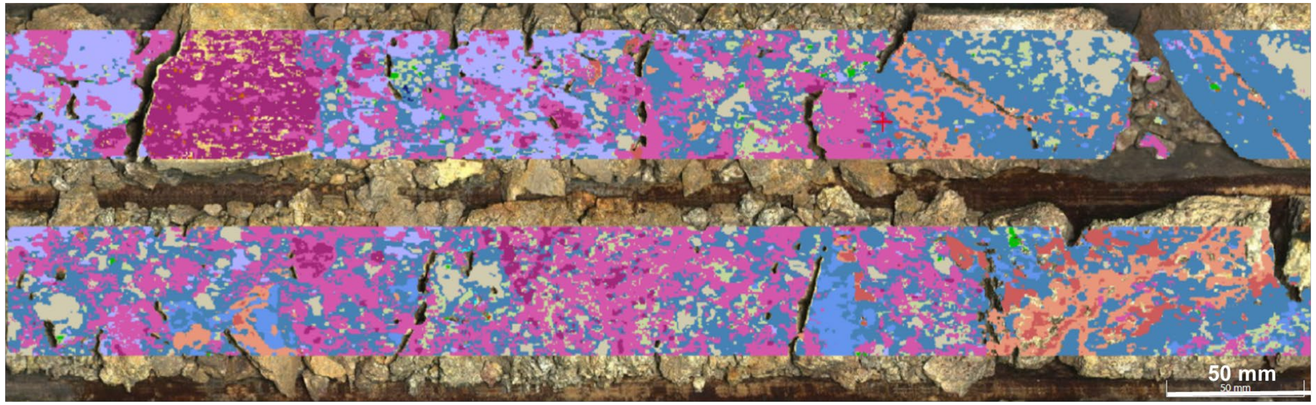
Carbonate model



Carbonate-oxide-sulfate model

Clays, always a potential complication

- Throughout the images thus far we have seen white mica (illite), montmorillonite, and kaolinite.
- Estimated by the geometallurgists at Antucoya unless there is >10% clays, there should not be an issue in the heap leach or in the mill during crushing.
- Understanding their distribution is important so that proper testwork can be conducted.



Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	

White Mica	
Kaolinite	
Montmorillonite	

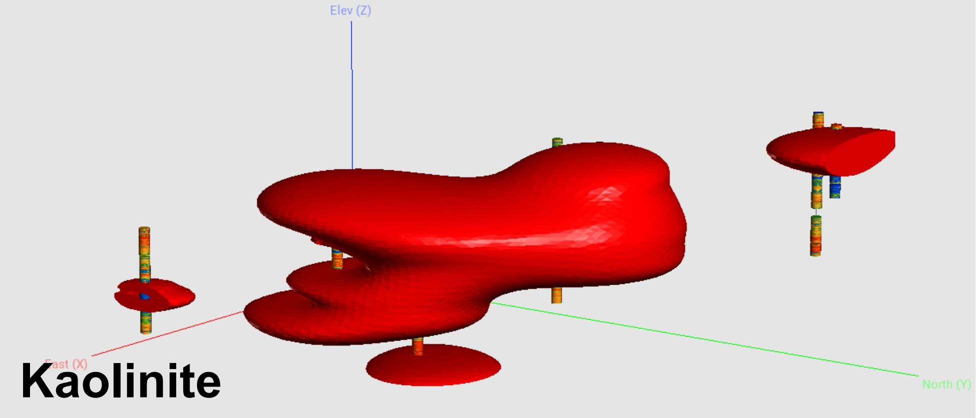
Clays, a closer look

- During comminution (i.e., crushing and grinding) material high in clay has the potential to increase mill residency time.
- Clays have the capacity to absorb reagents (e.g., cyanide), thereby increasing consumption of an expensive resource.

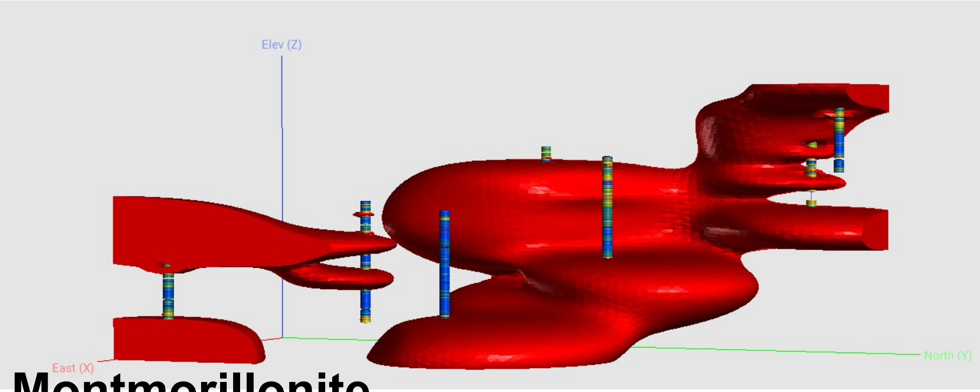
Table 4. Examples of clay minerals and potential processing problems (cf. Cruz et al. 2013; Farrokhpay et al. 2016).

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

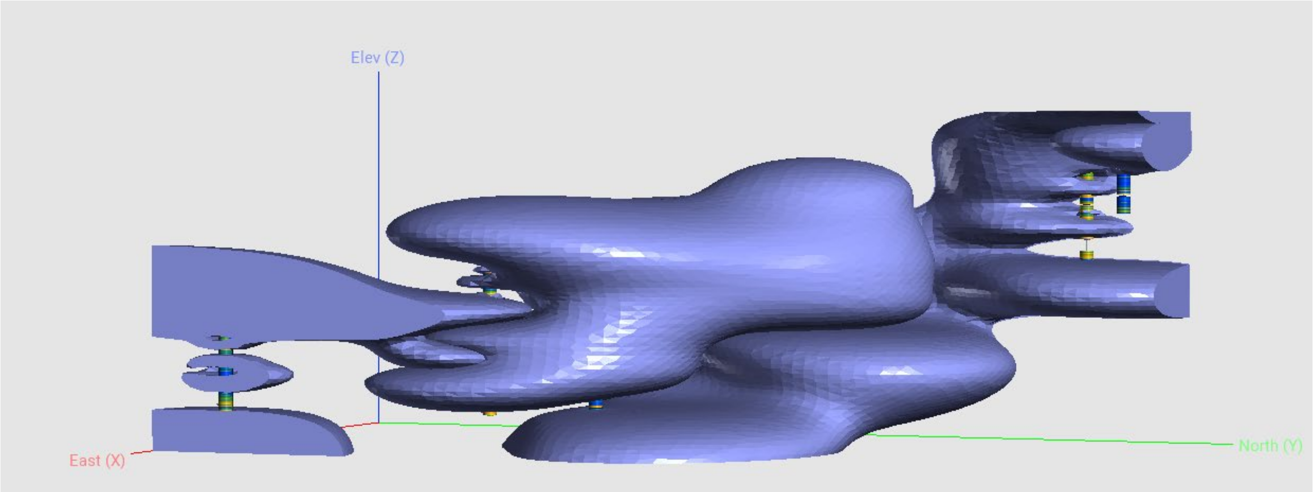
Clays in 3D



Kaolinite

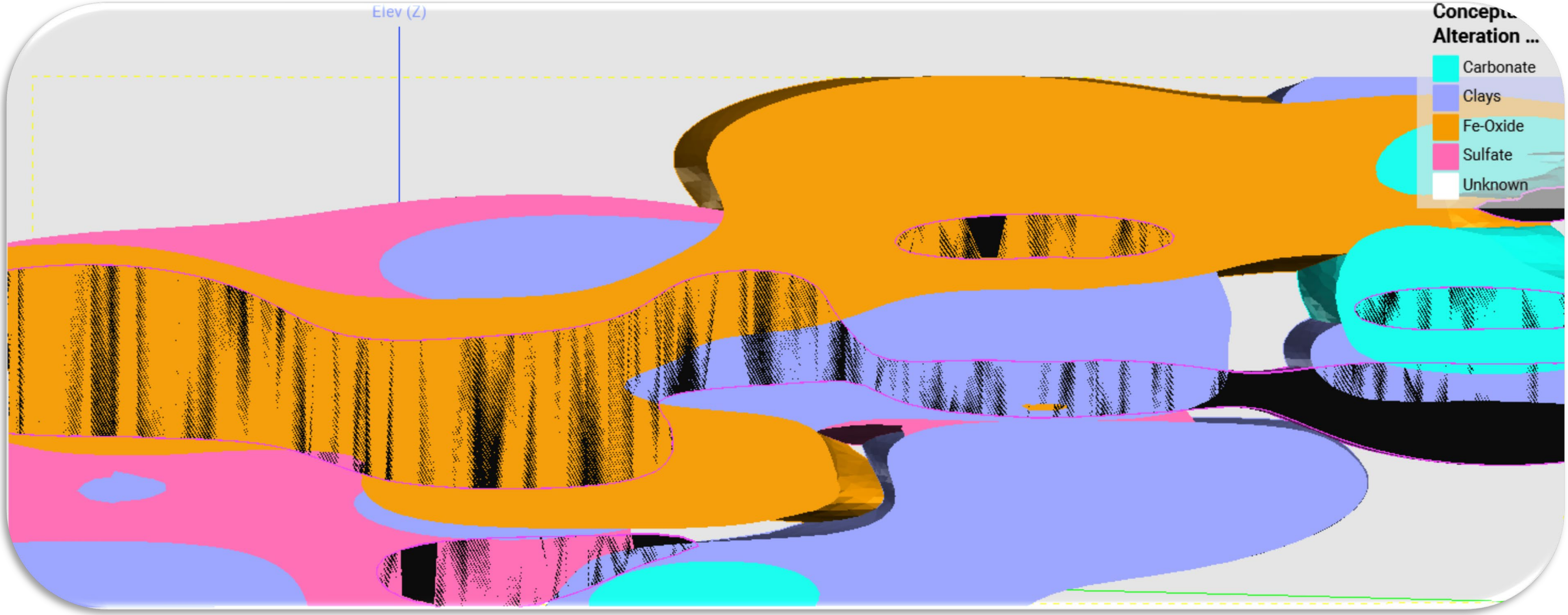


Montmorillonite



Combined Clay Mineral Shell

Integrated Alteration Model

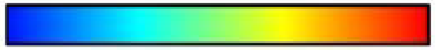


Size matters?

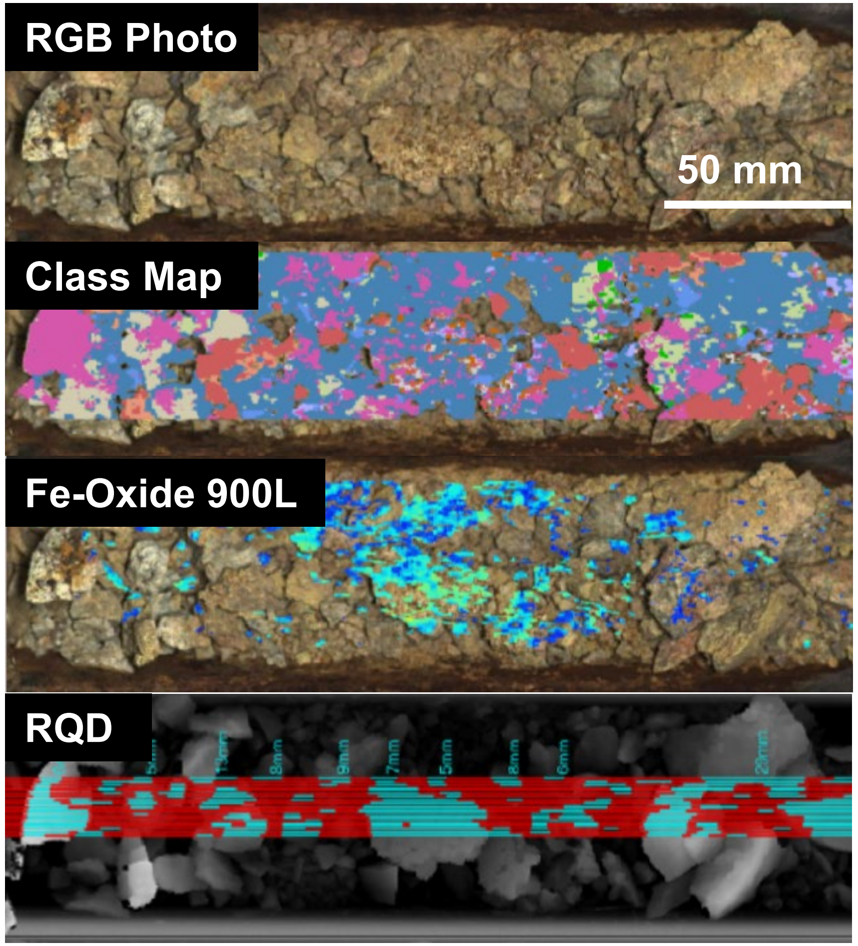
…of course it does.

Why did size matter: spatial resolution

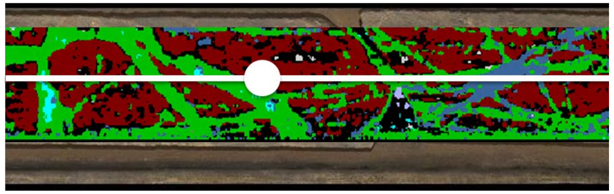
- Able to map spectral parameters and complex mixtures in areas where the core is highly degraded.



Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	
White Mica	
Kaolinite	



Why did size matter: number of pixels

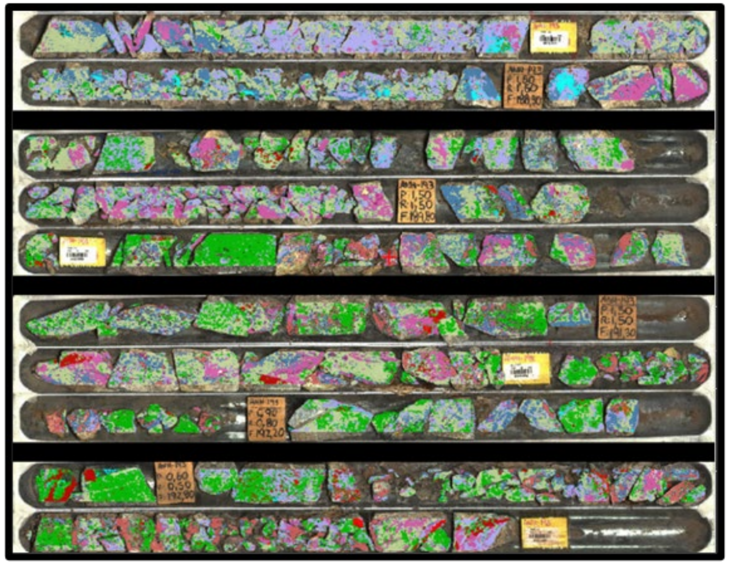


Dickite
Pyrophyllite
Calcite
Gypsum
Alunite
Tourmaline
Atacamite
Chrysocolla
Kaolinite
Montmorillonite
Phlogopite
White Mica
Chlorite
Featureless Slope

Mineral	Mineral % (Point)	Mineral % (Line)	Mineral % (Image)
# Spectra	1	20	55,000
Calcite		0.006	0.005
Chlorite		31.9	27.6
Kaolinite		0	0.002
Montmorillonite		0	0.03
Phlogopite	100	48.6	37.6
Tourmaline		0	0.01
White Mica		0.083	26.9

Nombre del Mineral	Color
Malaquita	
Antlerita	
Atacamita	
Cu-Mineral (Sulfate)	
Biotita (grupo)	
Dickita	
Jarosita	
Yeso	
Carbonato	
Sulfato Na-Ca	
Sulfato Fe	
Sulfato Fe-Mg	
Caolinita: Alta X	
Caolinita: Med X	
Caolinita: Baja X	
FLS + Mica Blanca	
Clorita + Mica Blanca	
Mica Blanca: Paragonita	
Mica Blanca: Paragonita-Moscovita	
Mica Blanca: Moscovita	
Mica Blanca: Moscovita-Fengita	
Mica Blanca: Fengita	
Montmorillonita	
Clorita	
Alunógeno	
Cuarzo/Sílice Hidratado	
Cuarzo/Sílice Opalino	
Oxido de Fe (general)	
Featureless Slope (FLS) - Tipo 1**	
Featureless Slope (FLS) - Tipo 2**	

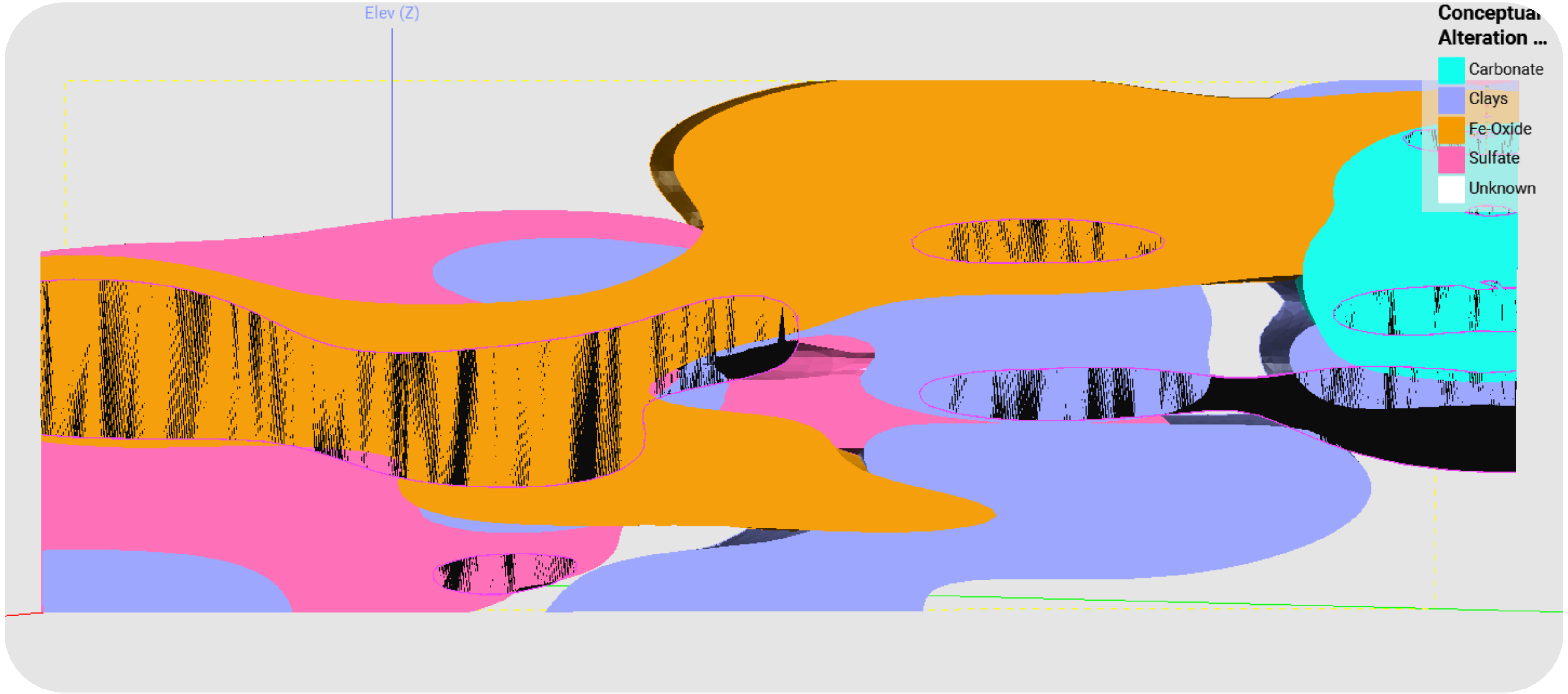
*** Featureless Slope Spectra*



100 mm

Why did size matter: counting statistics

- Continuous dataset to use as a backbone for this model.



Size Matters, the importance of mineralogy and texture in mining porphyry copper deposits: Part I

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