Size Matters, the importance of mineralogy and texture in mining porphyry copper deposits: part II

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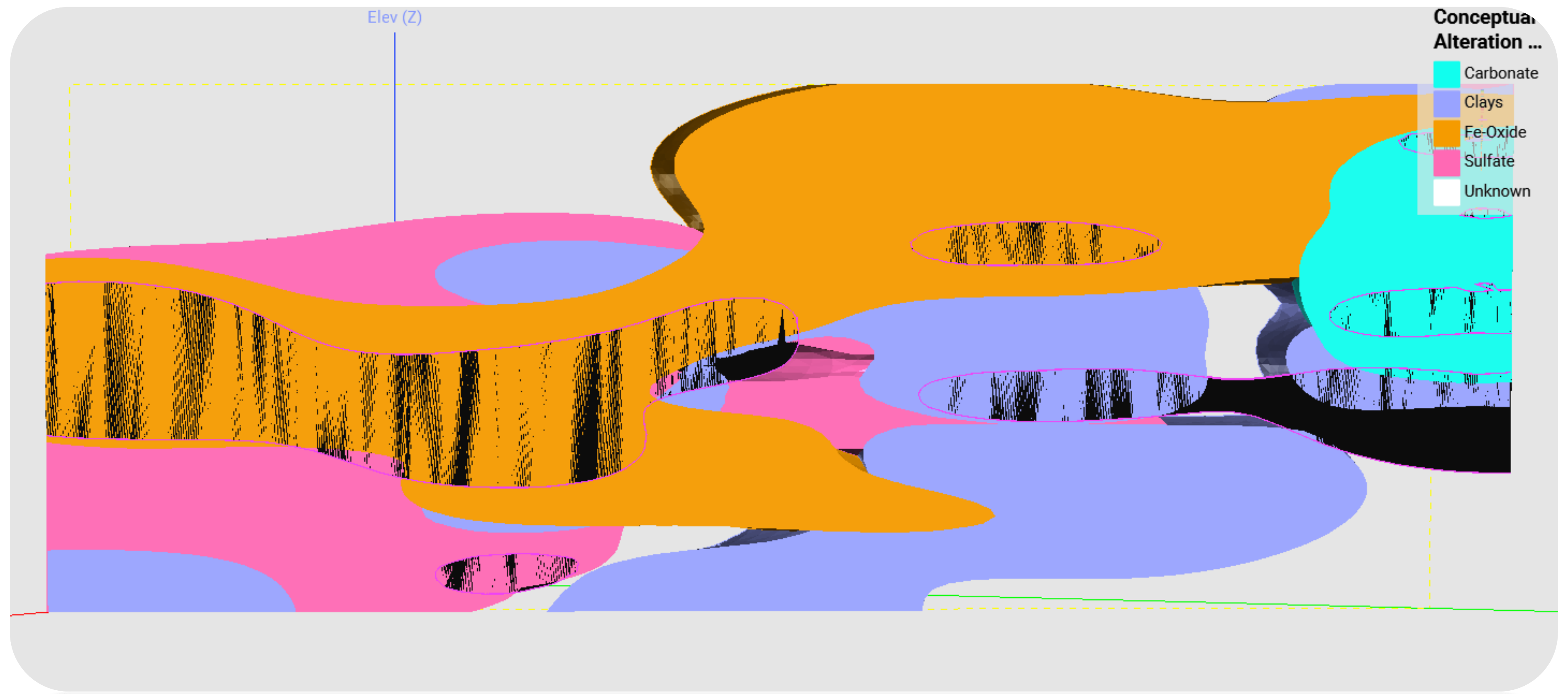
Summary of talk from the workshop

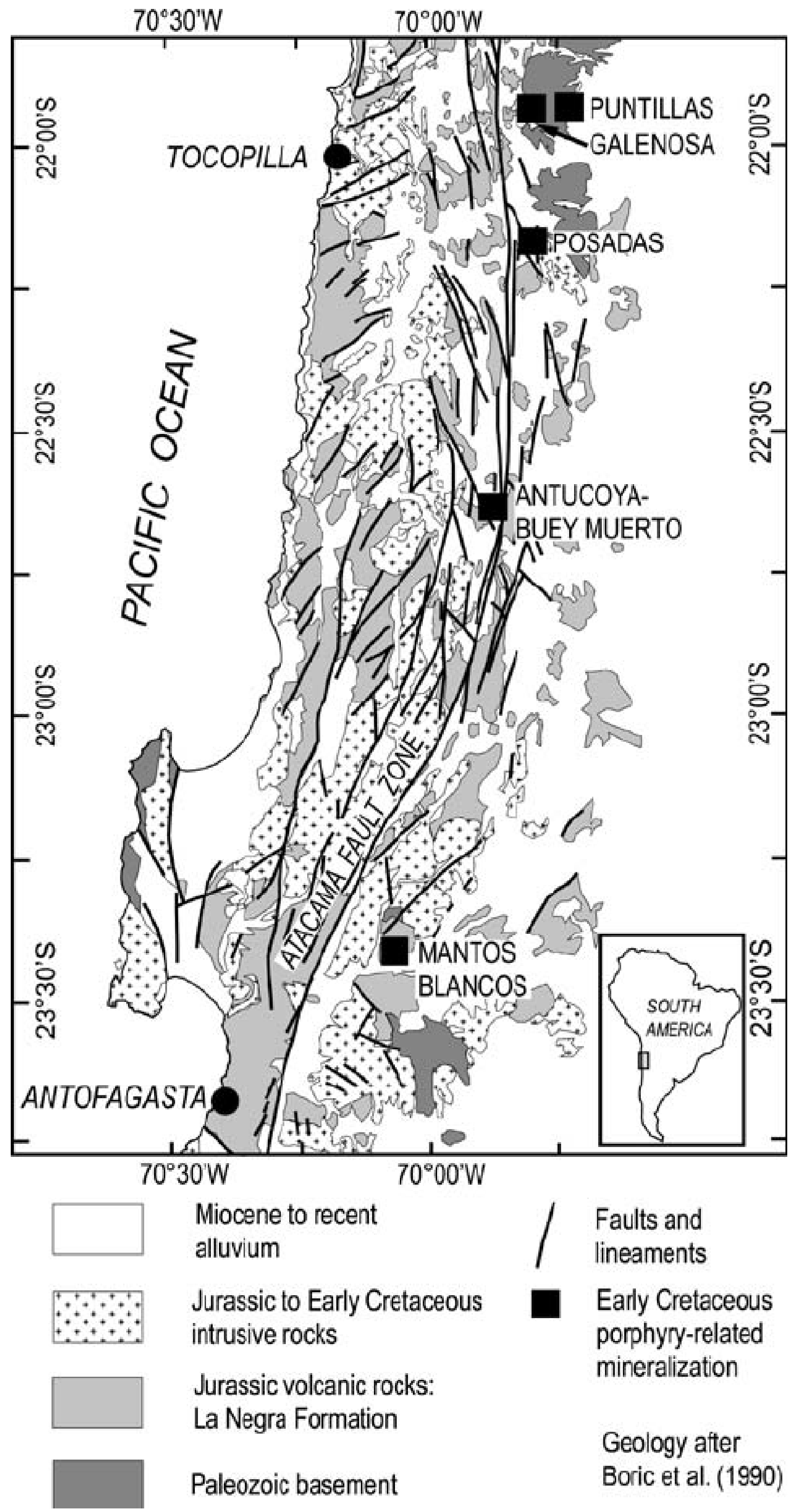
- In the workshop yesterday apart from discussions on the general geology and spectroscopy of the Antucoya Mine, which will be presented following this, we talked about 3D modeling applications of the HSI dataset.

- In this talk we will focus on 3D domain modeling applications of the hyperspectral data and its integration with an acid consumption geometallurgical dataset.



Setting

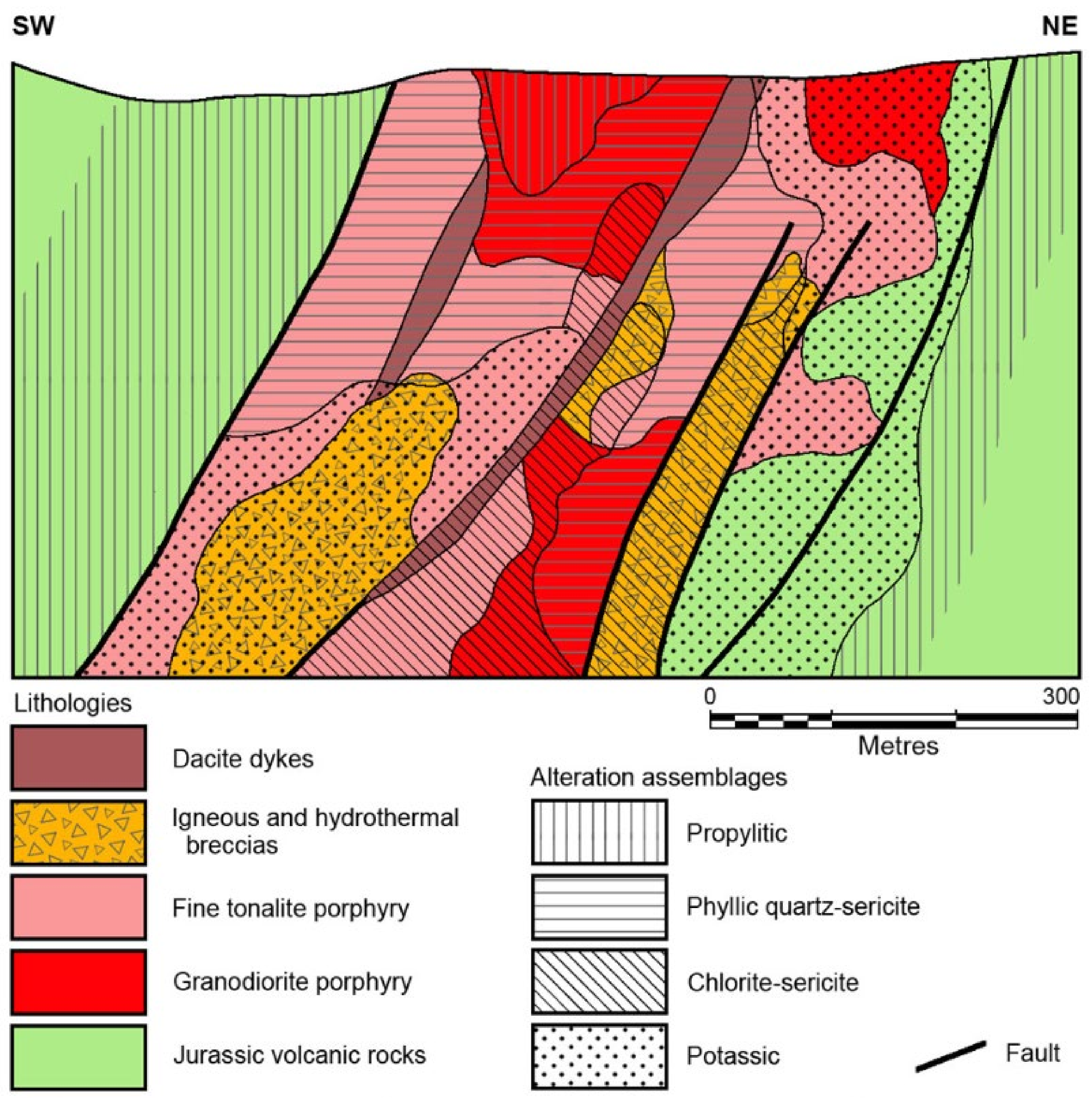
- The Antucoya porphyry copper deposit (PCD) is one of the largest deposits in the poorly studied Early Cretaceous porphyry belt in the Costal Cordillera of northern Chile.
- The complex crystallized at 142.7±1.6 to 140.6±1.5 Ma, which is within a relatively short time span of less than ca. 2 Ma during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

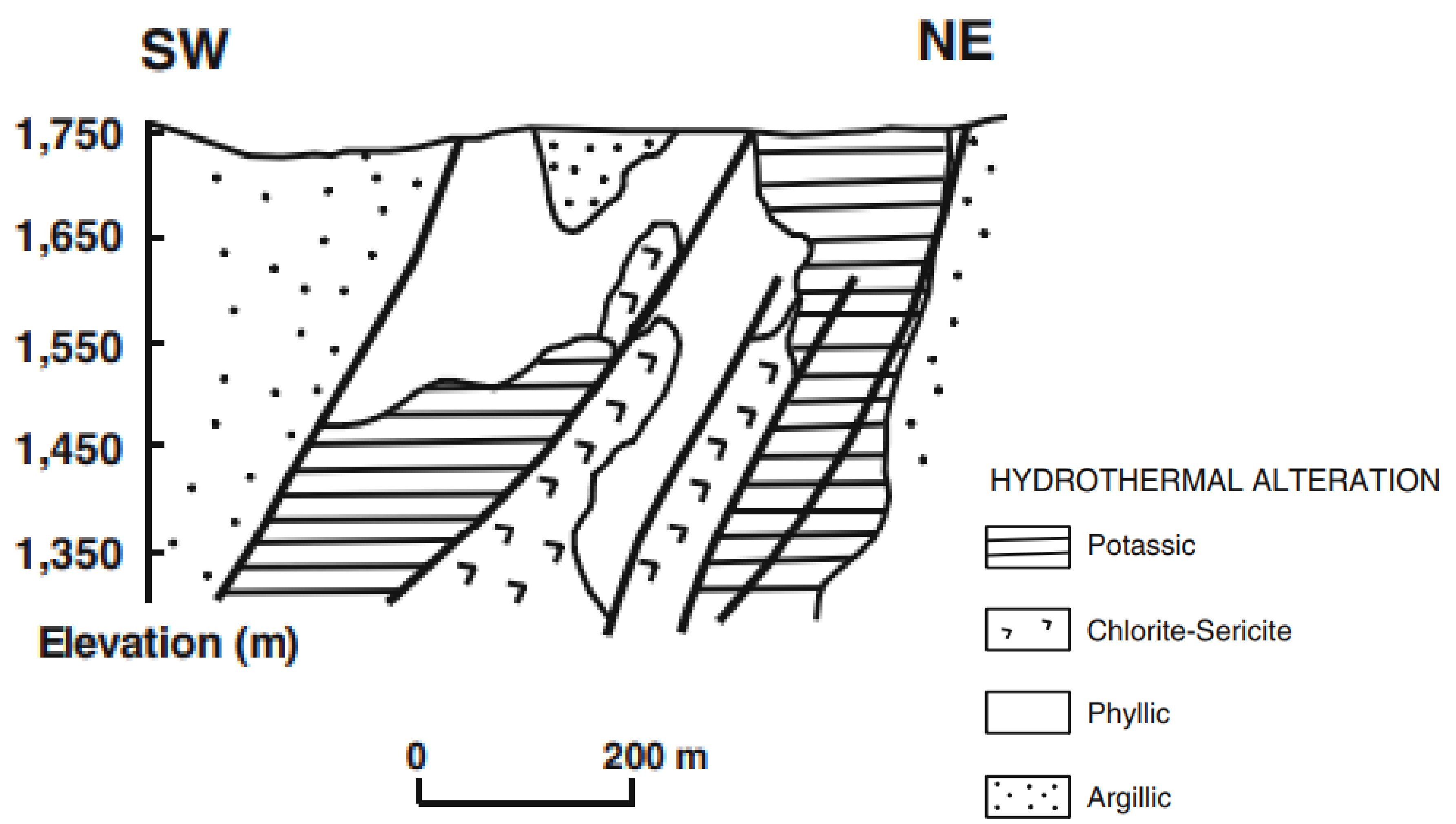


Geological cross section showing the distribution of alteration at the Antucoya porphyry copper deposit, Northern Chile (After: Maksaev *et al.*, 2006).

Maksaev et al., 2006

Alteration style

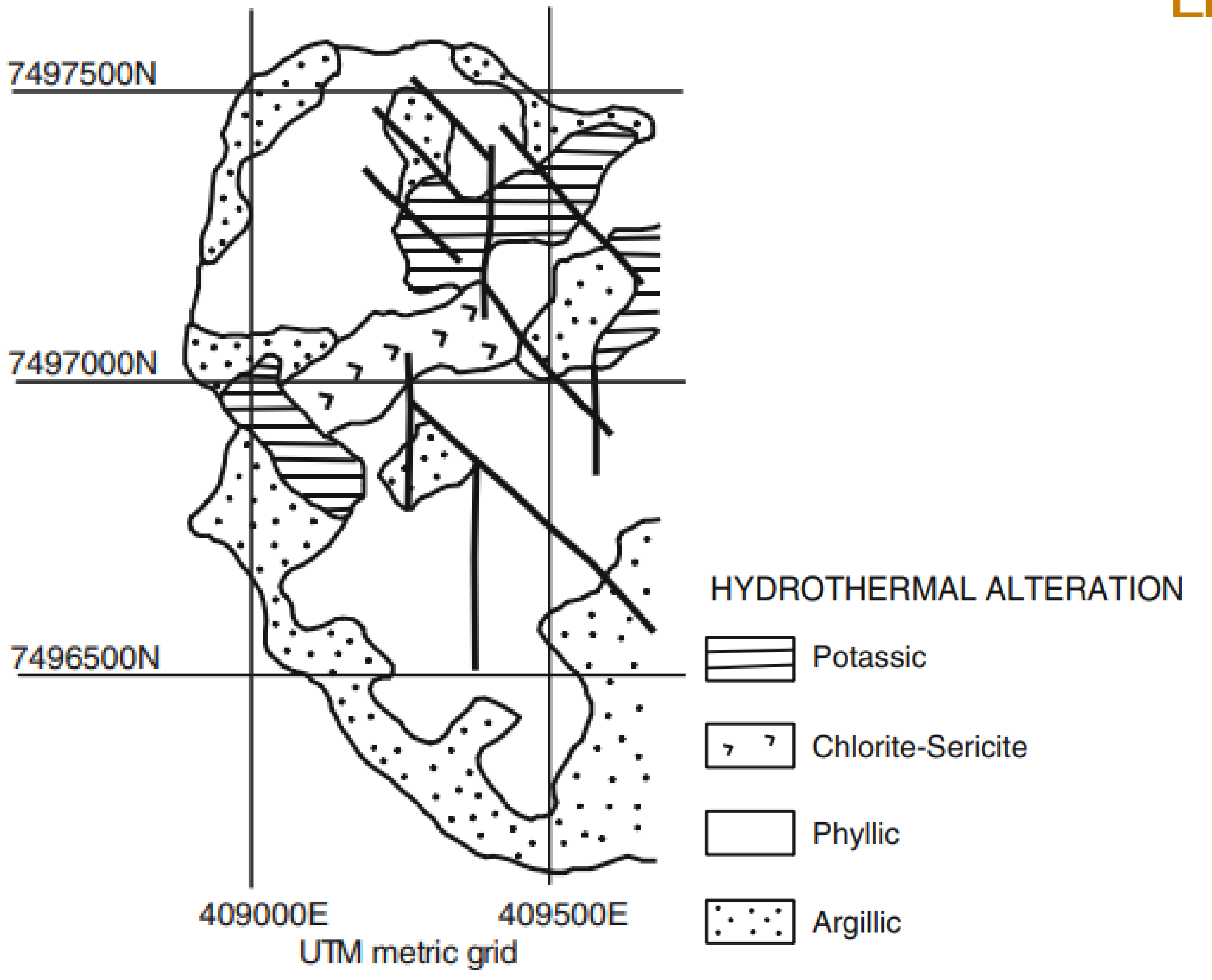
- There are two altered and mineralized porphyry intrusions at Antucoya, the Antucoya porphyry (granodioritic) and the tonalite (fine-grained) porphyry.
- The Antucoya Porphyry is altered to kaolinite, illite, and calcite, with traces of anhydrite and argillized feldspar. It contains a dense stockwork 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 Antucoya deposit from Maksaev et al. (2006).

Alteration style

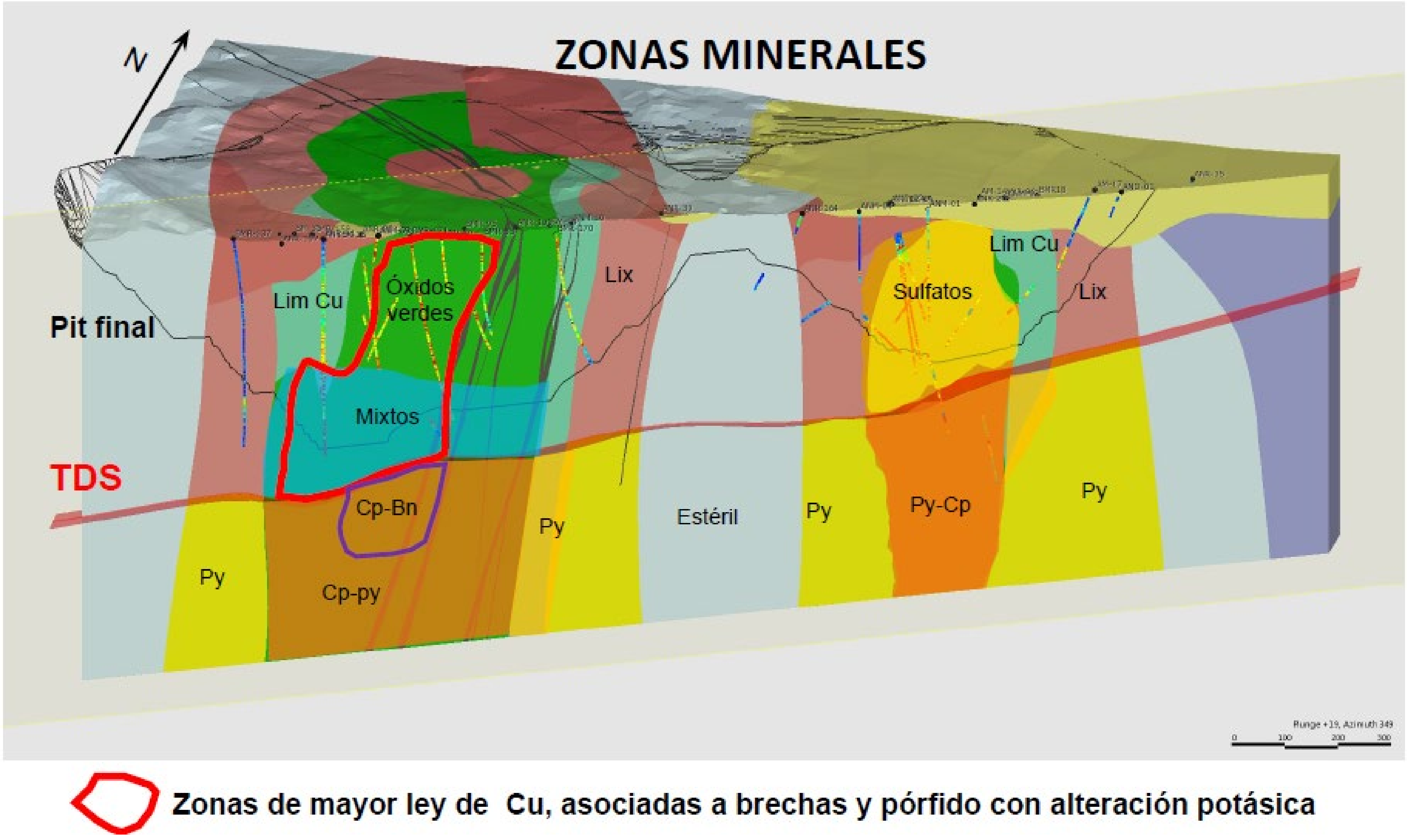
- Four hypogene hydrothermal alteration assemblages are recognized at Antucoya: potassic, chlorite–sericite, quartz–sericite, and propylitic.
  - The first three alteration types affect the porphyries and breccias, whereas propylitic alteration is restricted to the volcanic country rocks.
  - Potassic 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

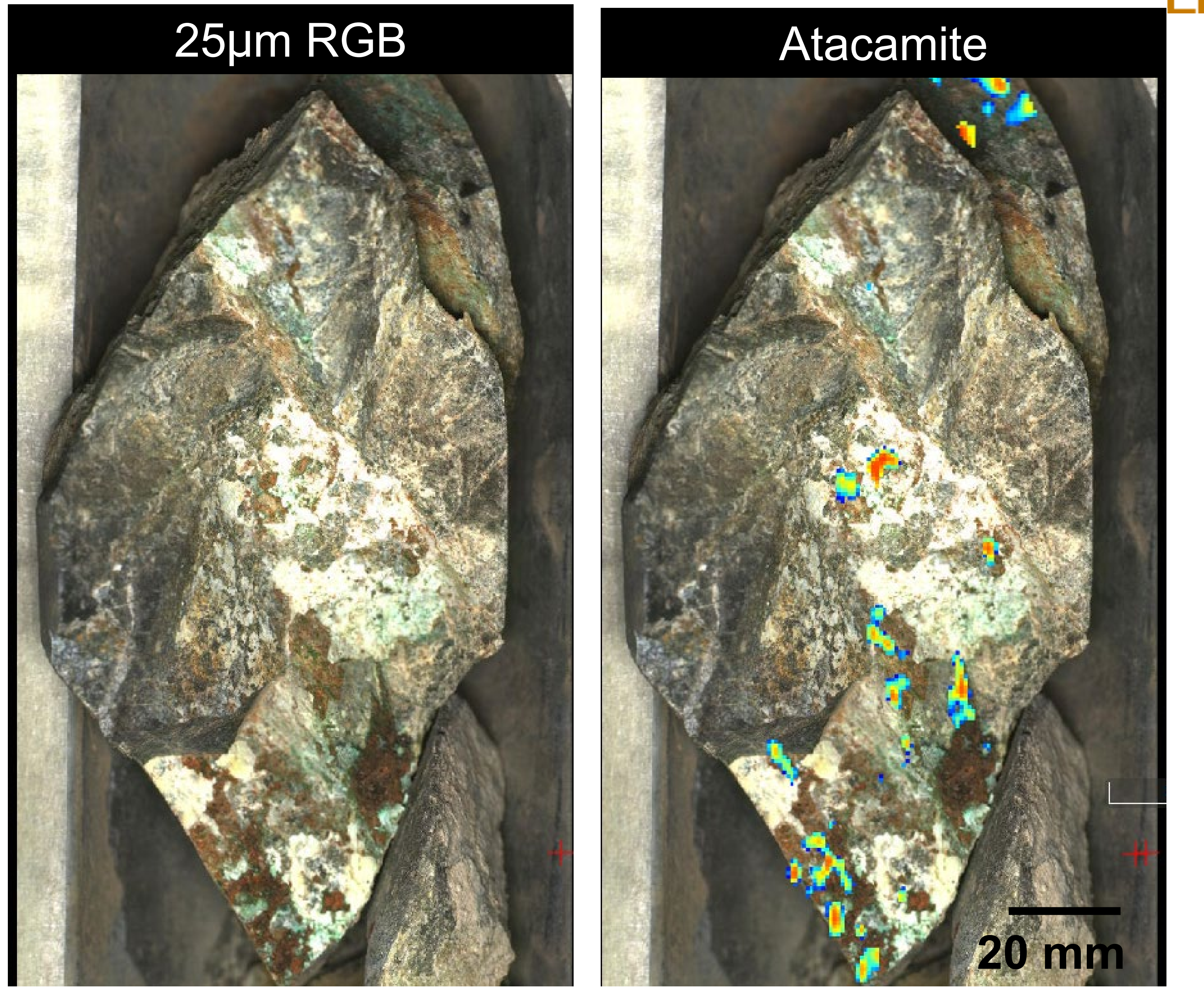
- The majority of the recognized orebody is affected by pervasive supergene argillic alteration (illite, dickite, and kaolinite) and oxidation (atacamite, brochantite, chrysocolla, copper wad, jarosite, and limonite), which extend down to depths of 300 to 350 m from the surface. These alterations are 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.

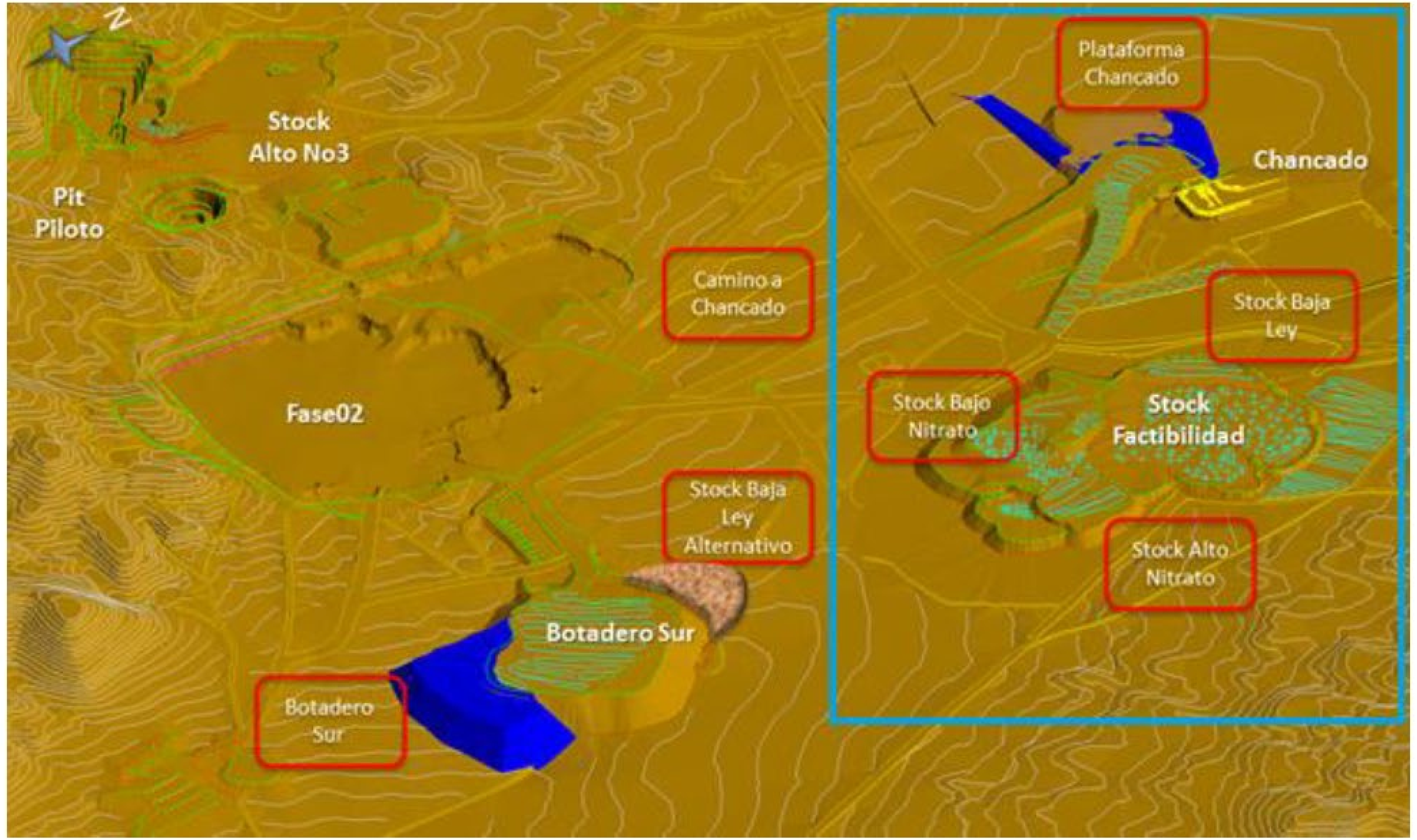


Antucoya Mine

- 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.

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

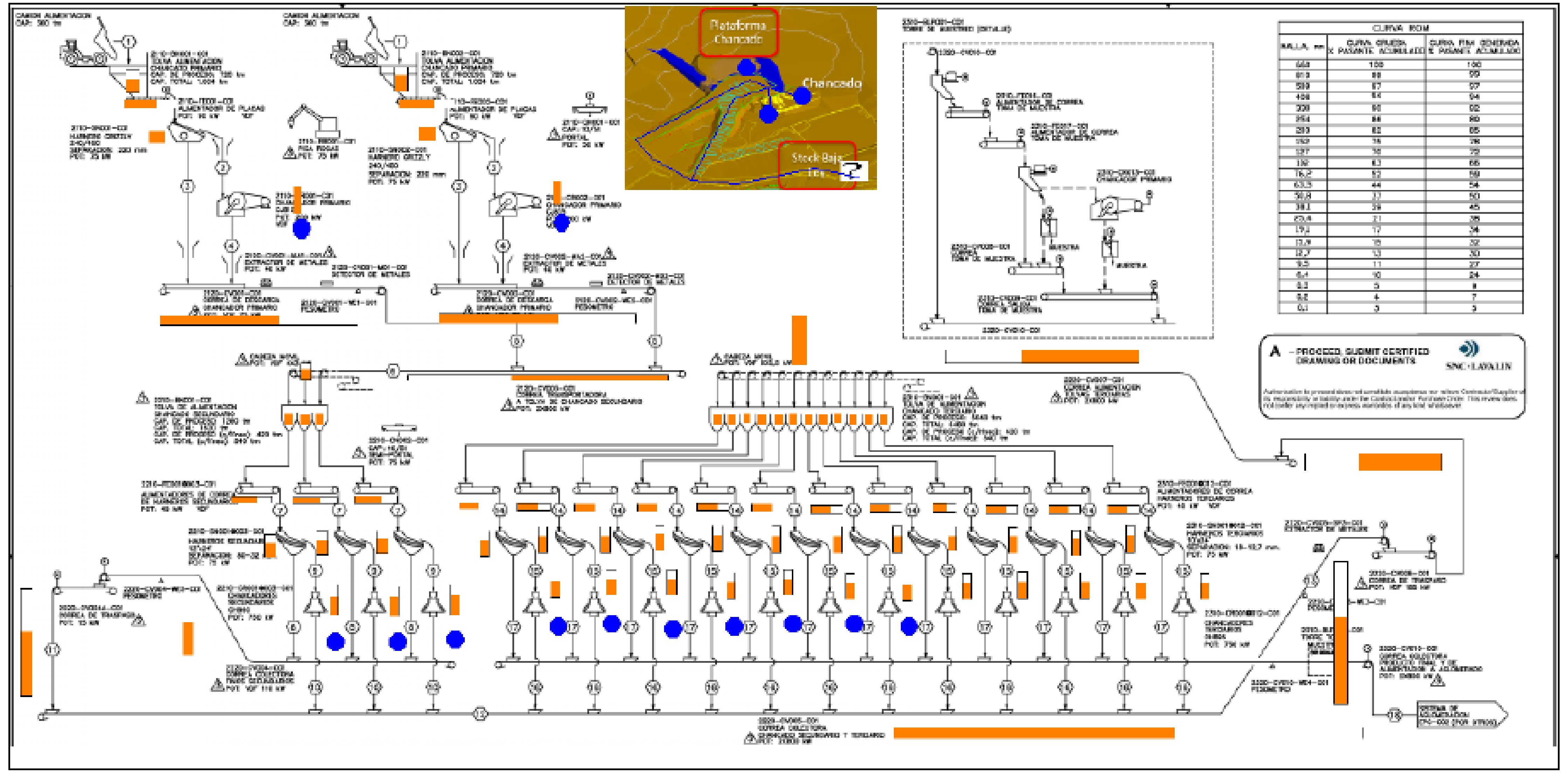
- The majority of the mining at Antucoya is in the oxide resource.
- The resource is comprised of complicated mineralogy that will affect plant performance and leaching.

Workflow Ideas

- Genere un modelo de dominio mineral 3D no supervisado para la selección de trabajos de prueba.
- Cree un modelo de aprendizaje automático para predecir los dominios de consumo de ácido para ahorrar tiempo y dinero en programas futuros para ampliar el modelo de bloques geometalúrgicos.

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.



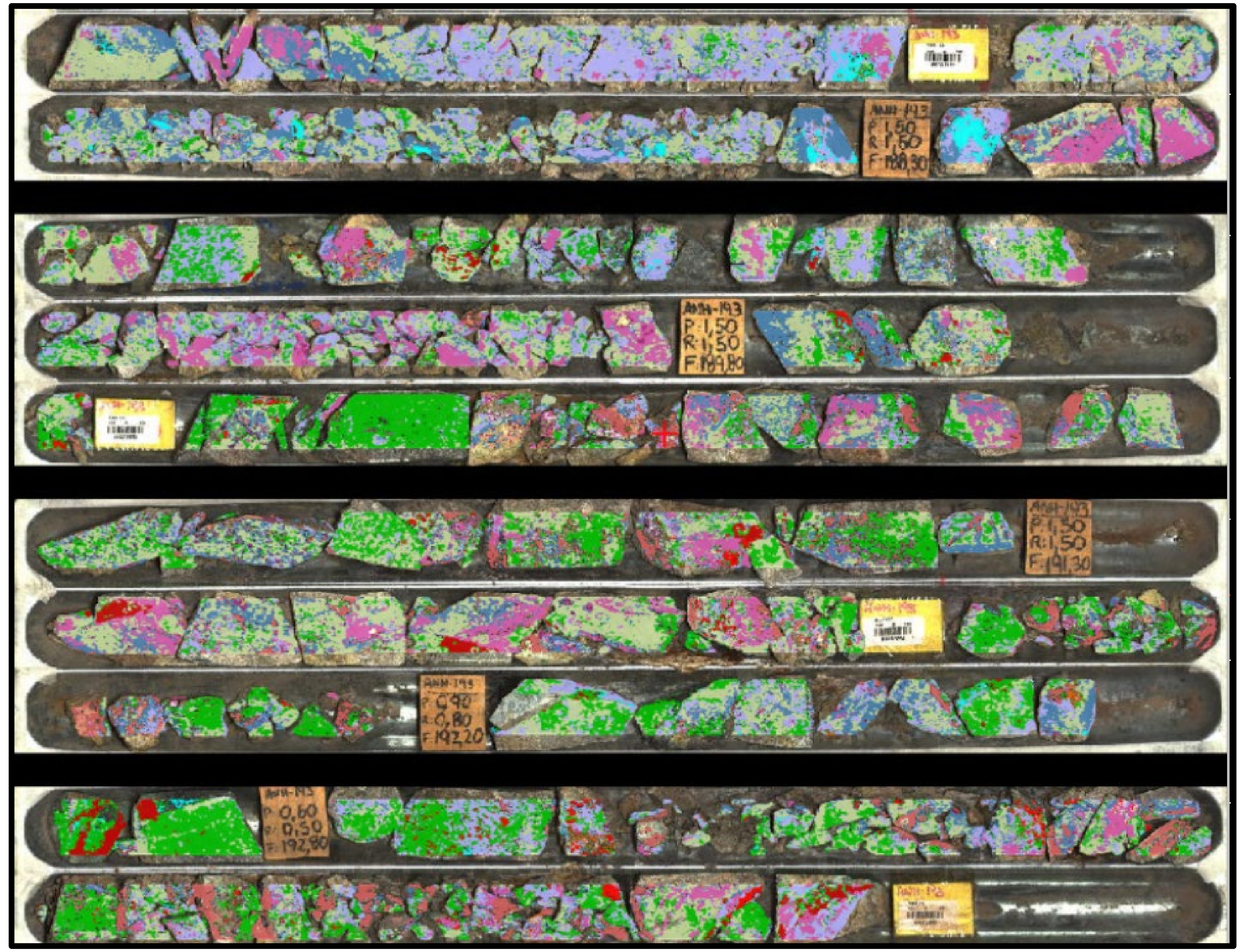
Antucoya milling and processing workflow (López Solar, 2016).

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**	

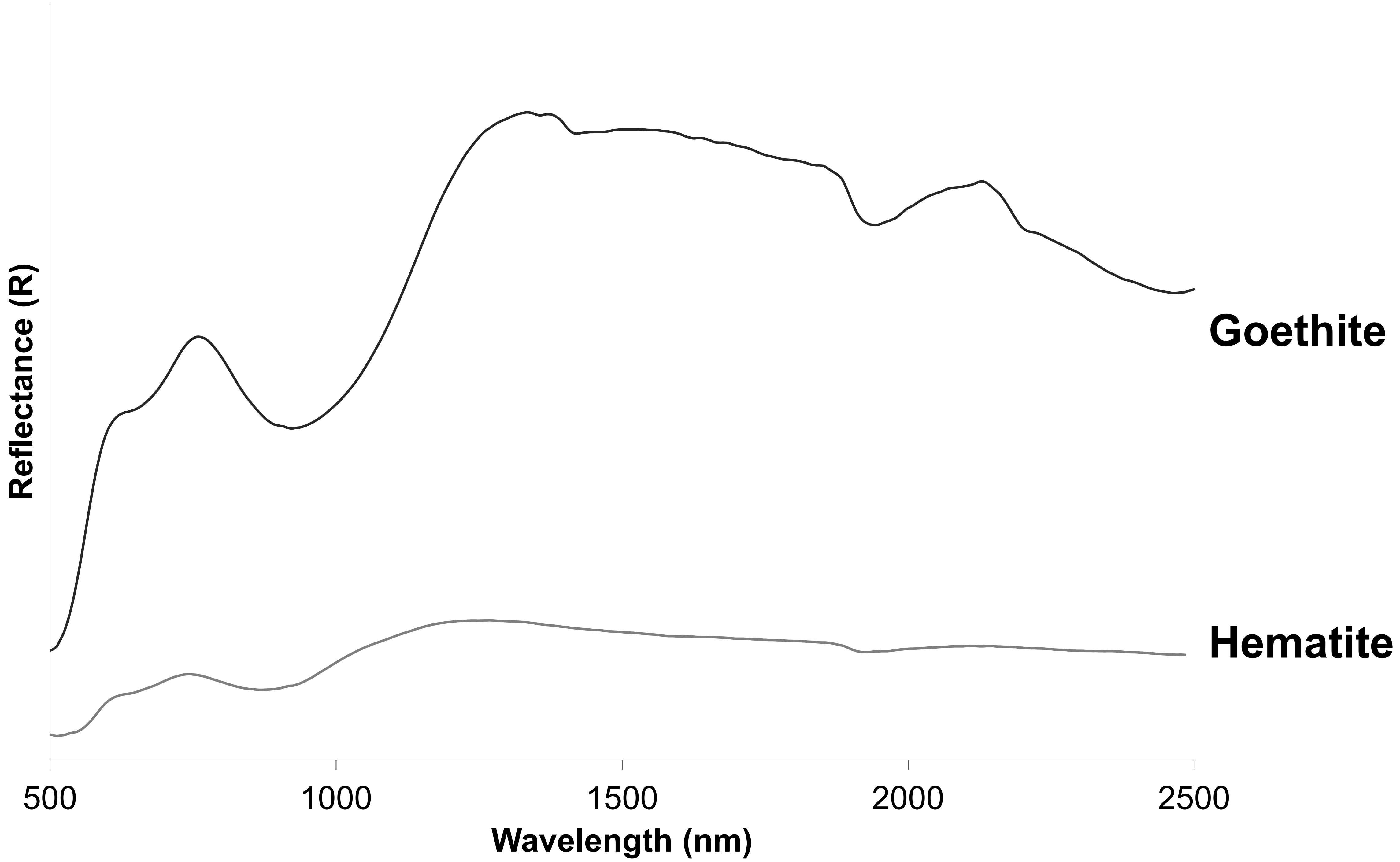
** Featureless Slope Spectra



100 mm

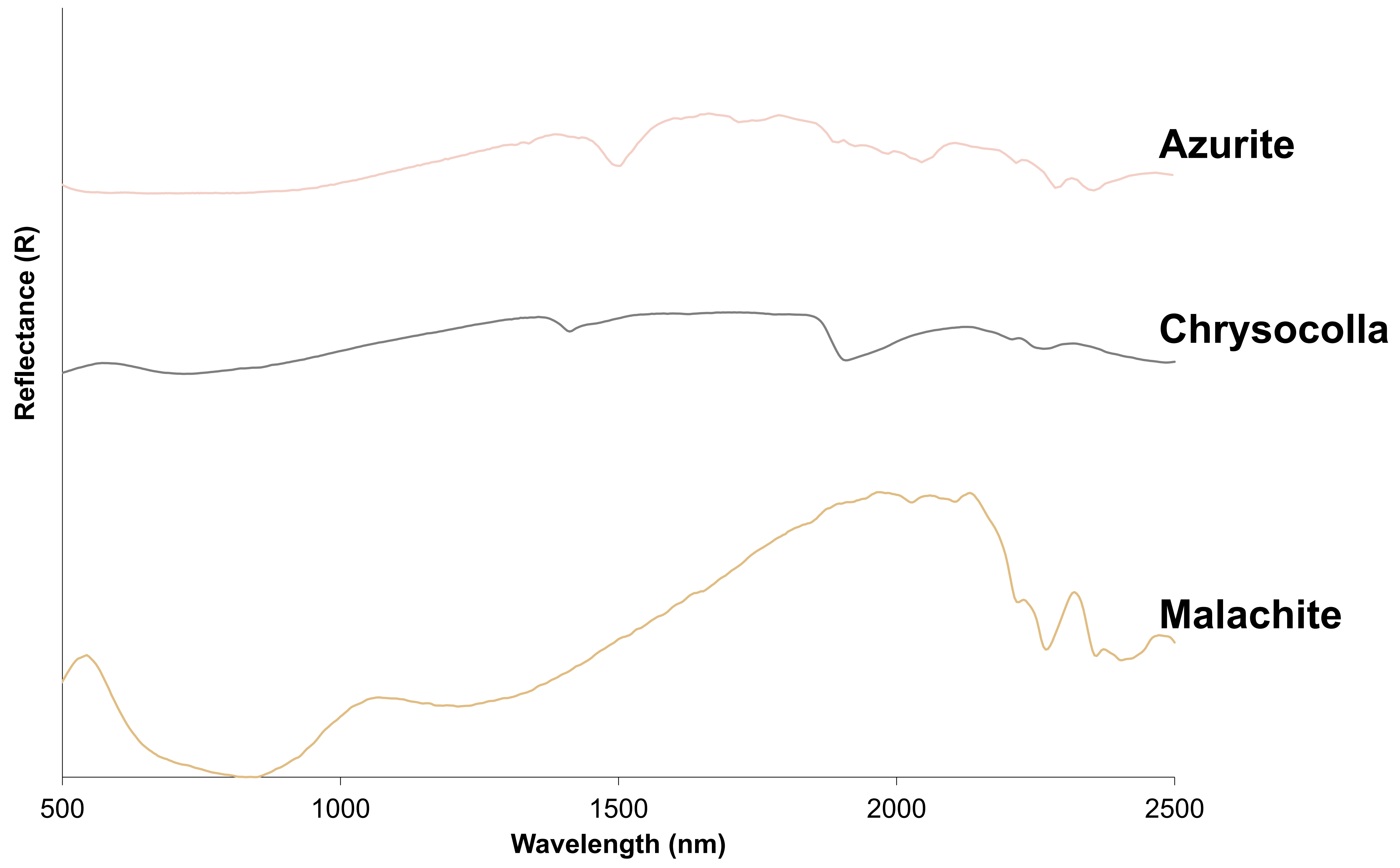
- The Antucoya mineralogy is a complex mixture of carbonates, oxides, sulfates, silicates, and clays.
- In the image at right, there are sulfates, carbonates, clays, and ore minerals complexly intermingled with each other.
- Understanding their distribution is essential for mine planning.

Oxides



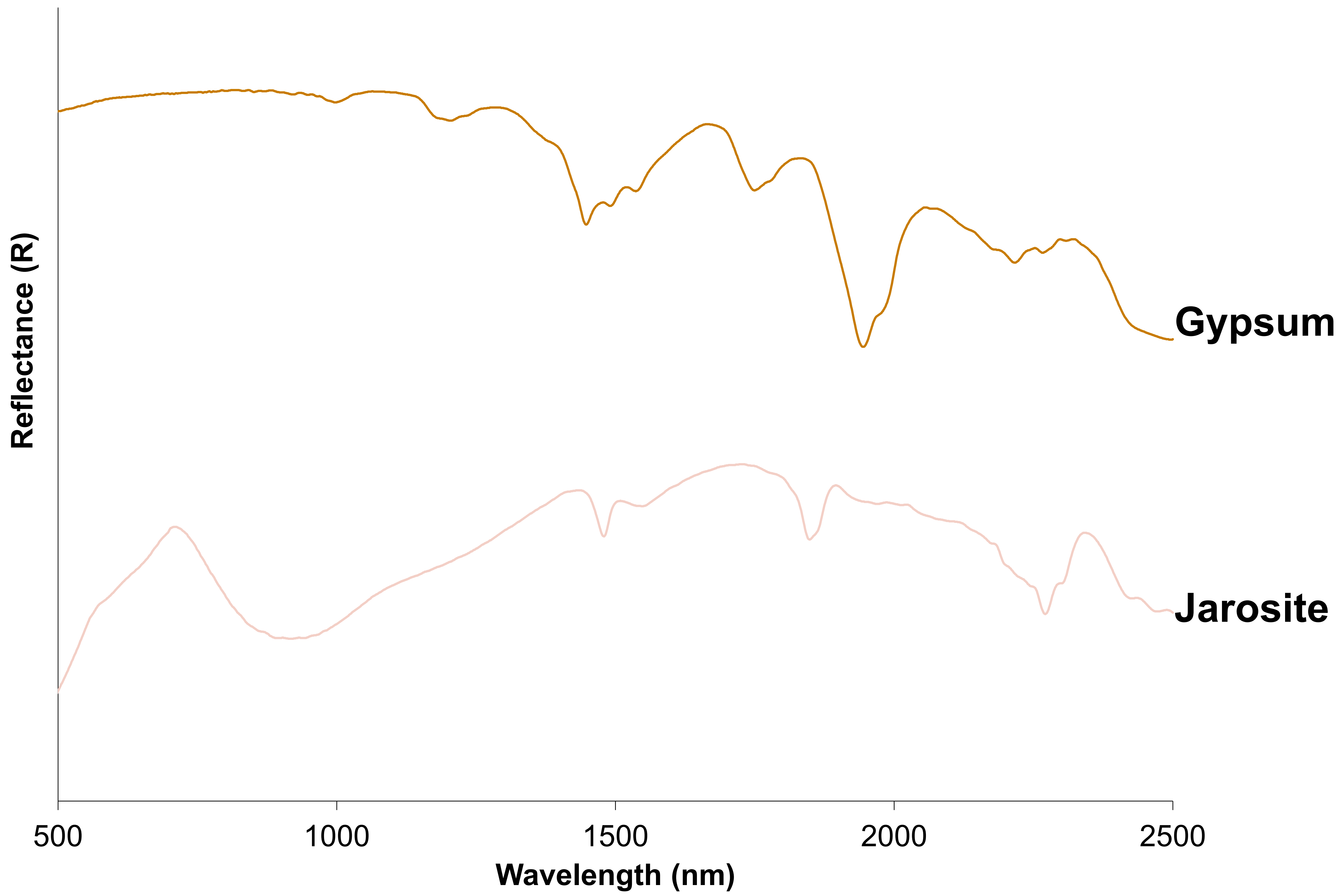
- The oxide zone contains all of the mineralization that is currently mined at Antucoya and represents an ~350m thick column.
- Some of the Fe-oxides contain Cu.

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

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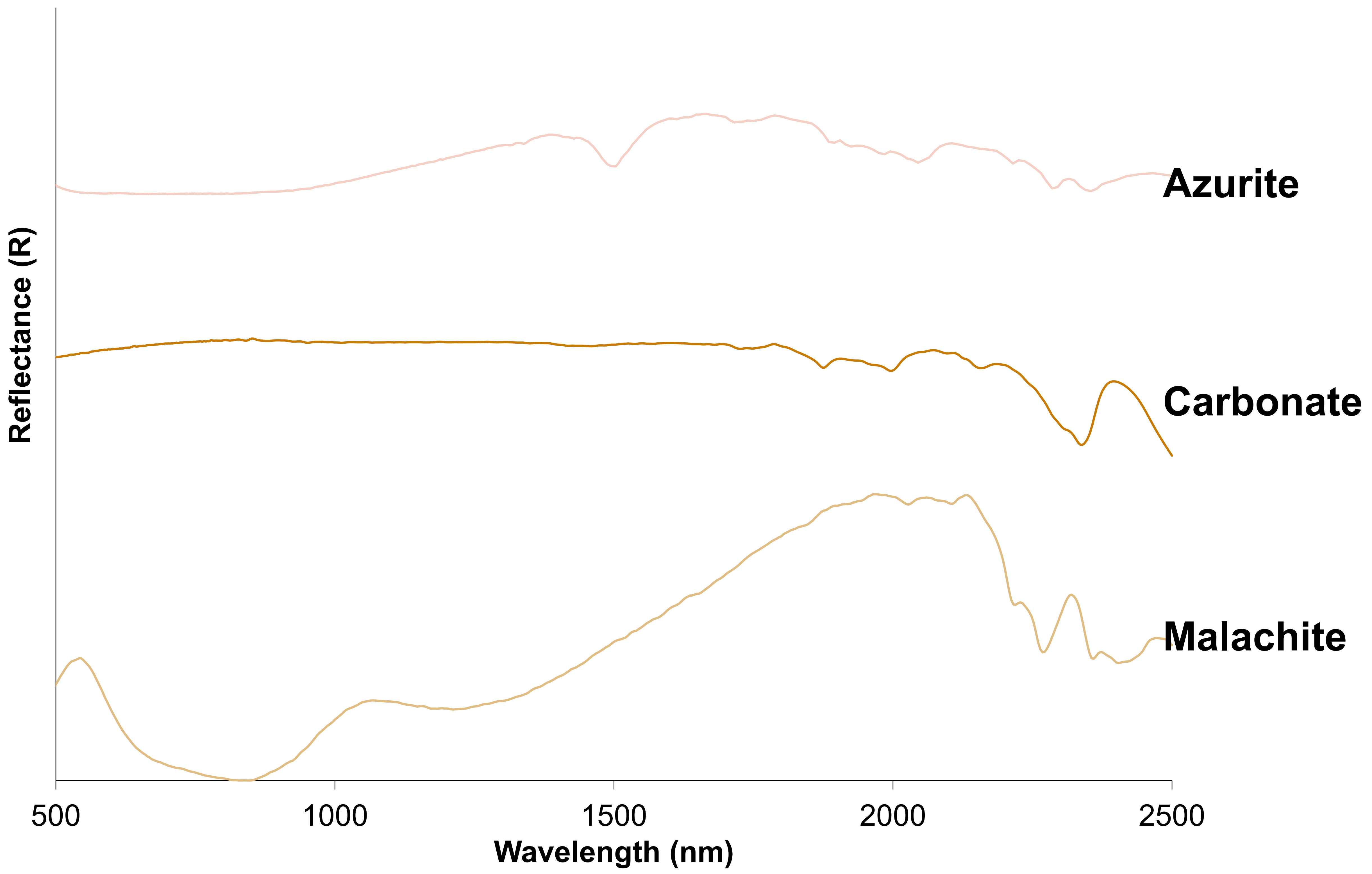
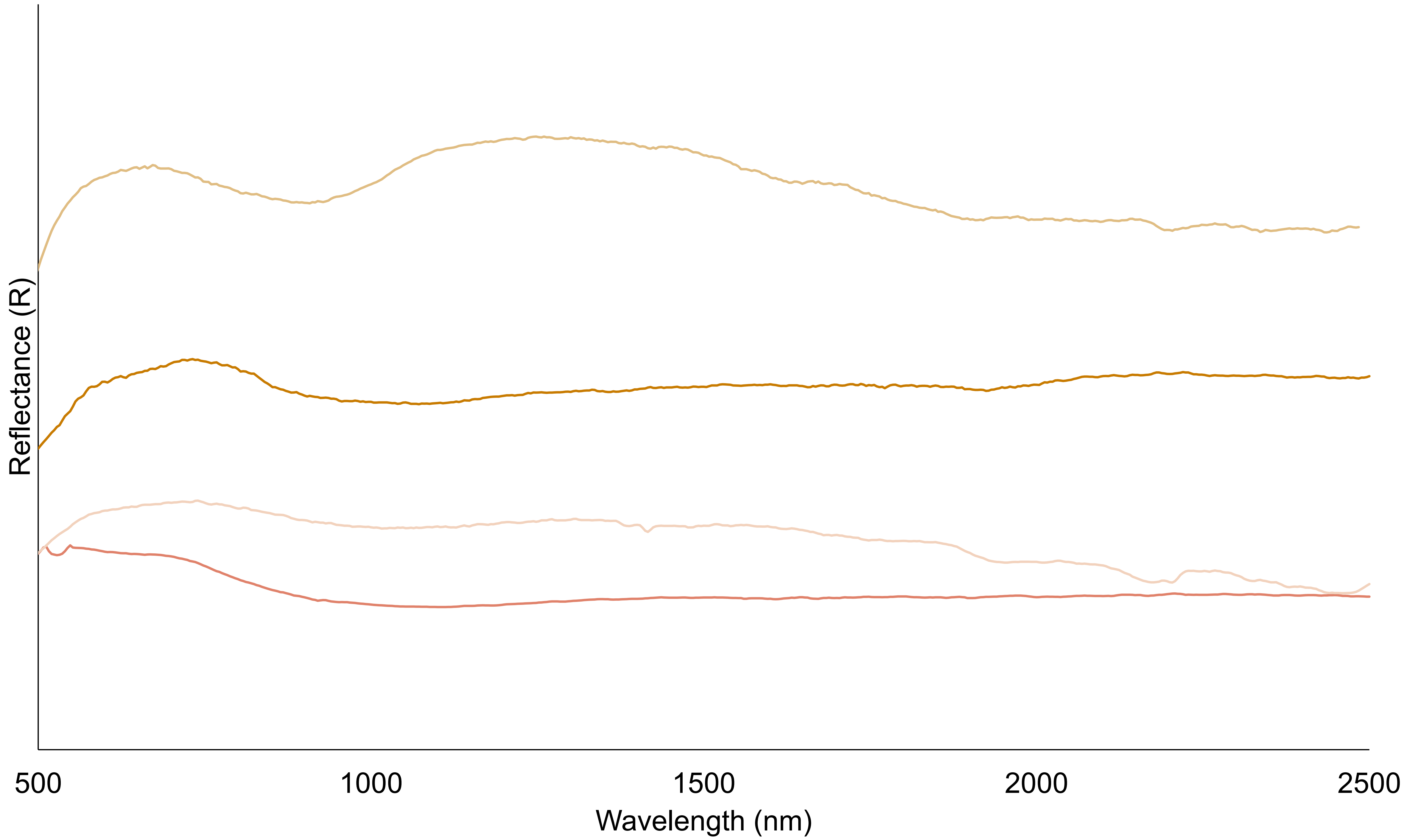
Carbonates



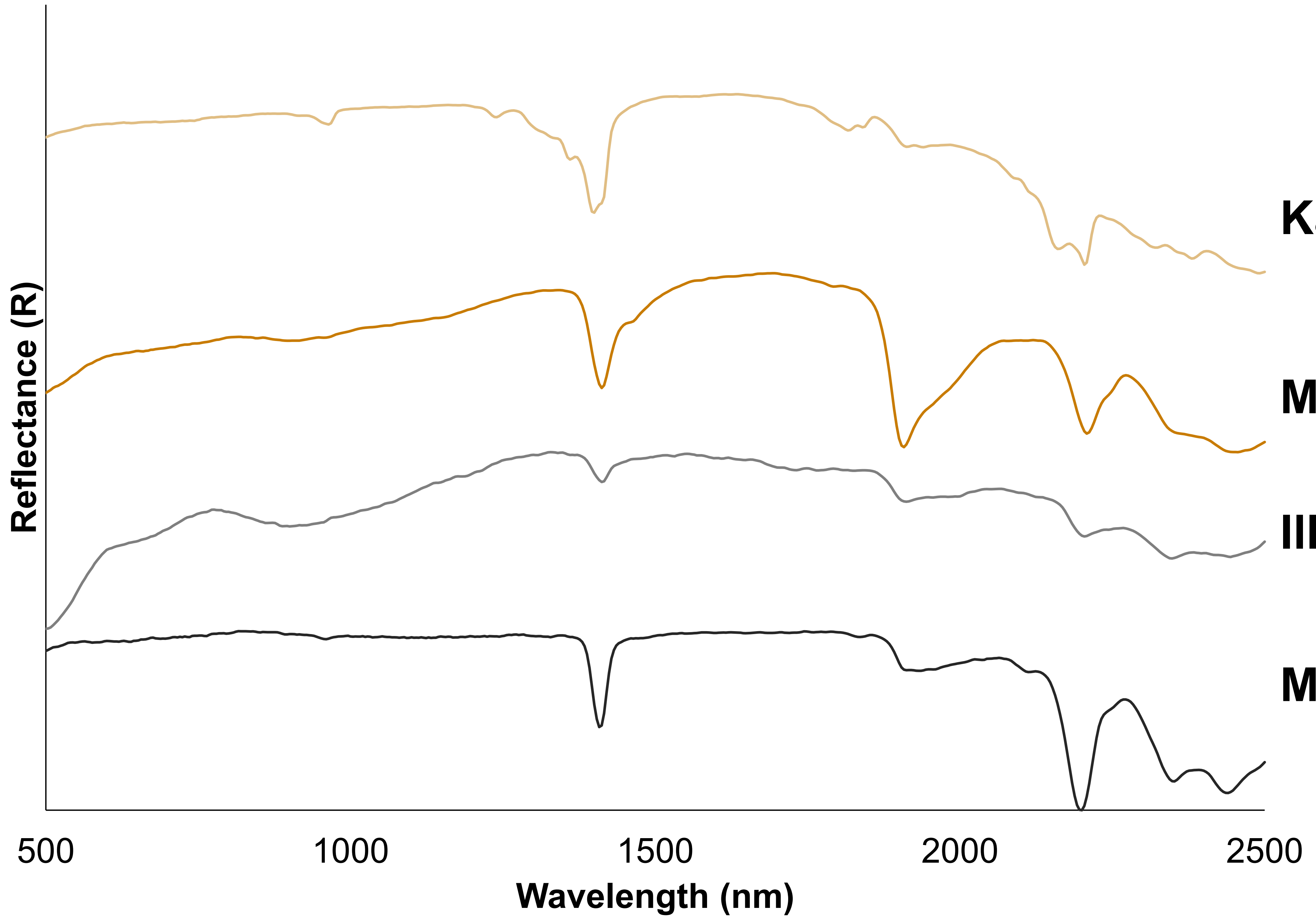
- Similar to the sulfate group of minerals, some of the carbonate minerals at Antucoya are ore-bearing.
- Ore-bearing: malachite
- Understanding carbonate distribution is important because of its acid neutralizing potential for leaching.

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.

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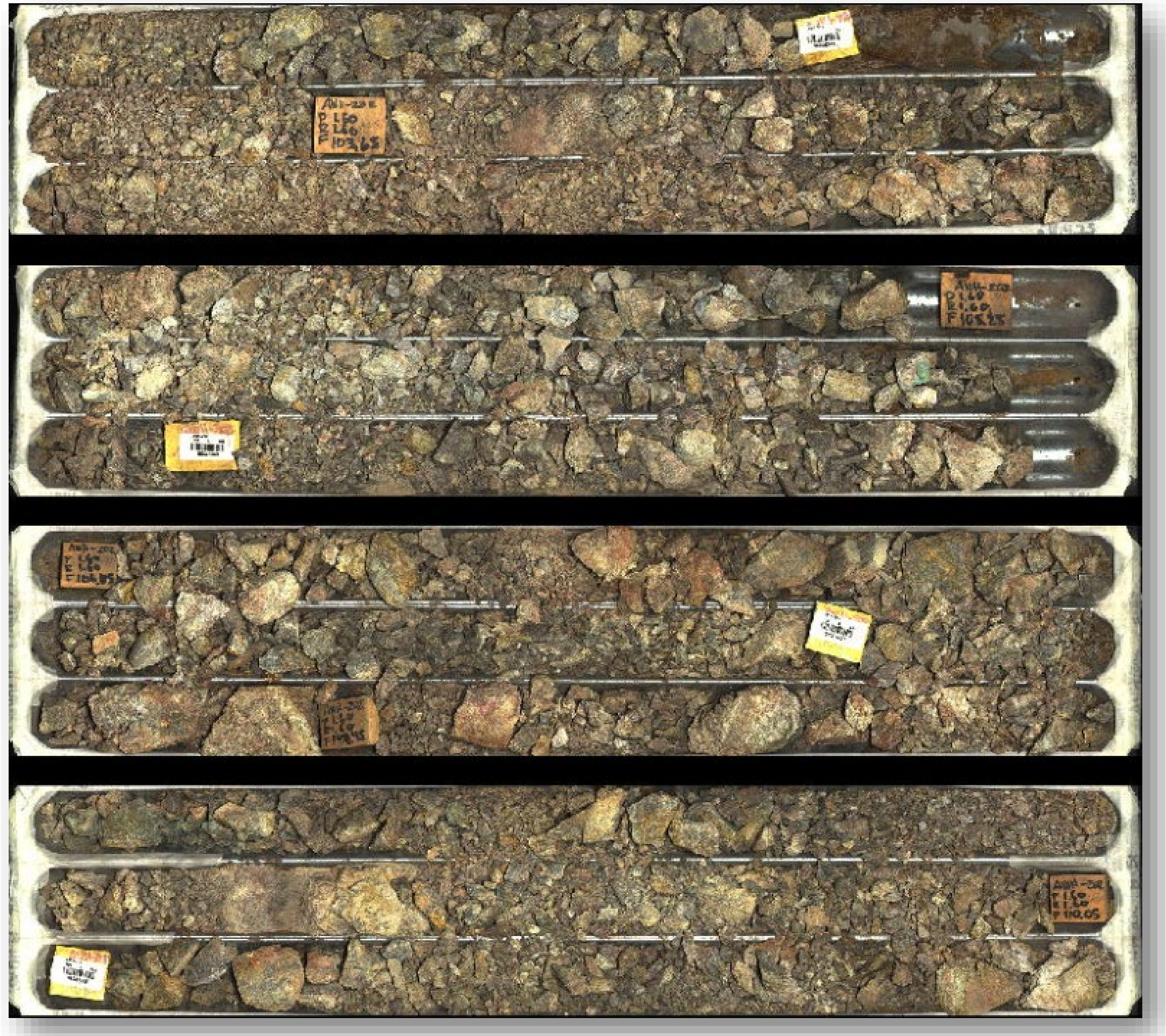
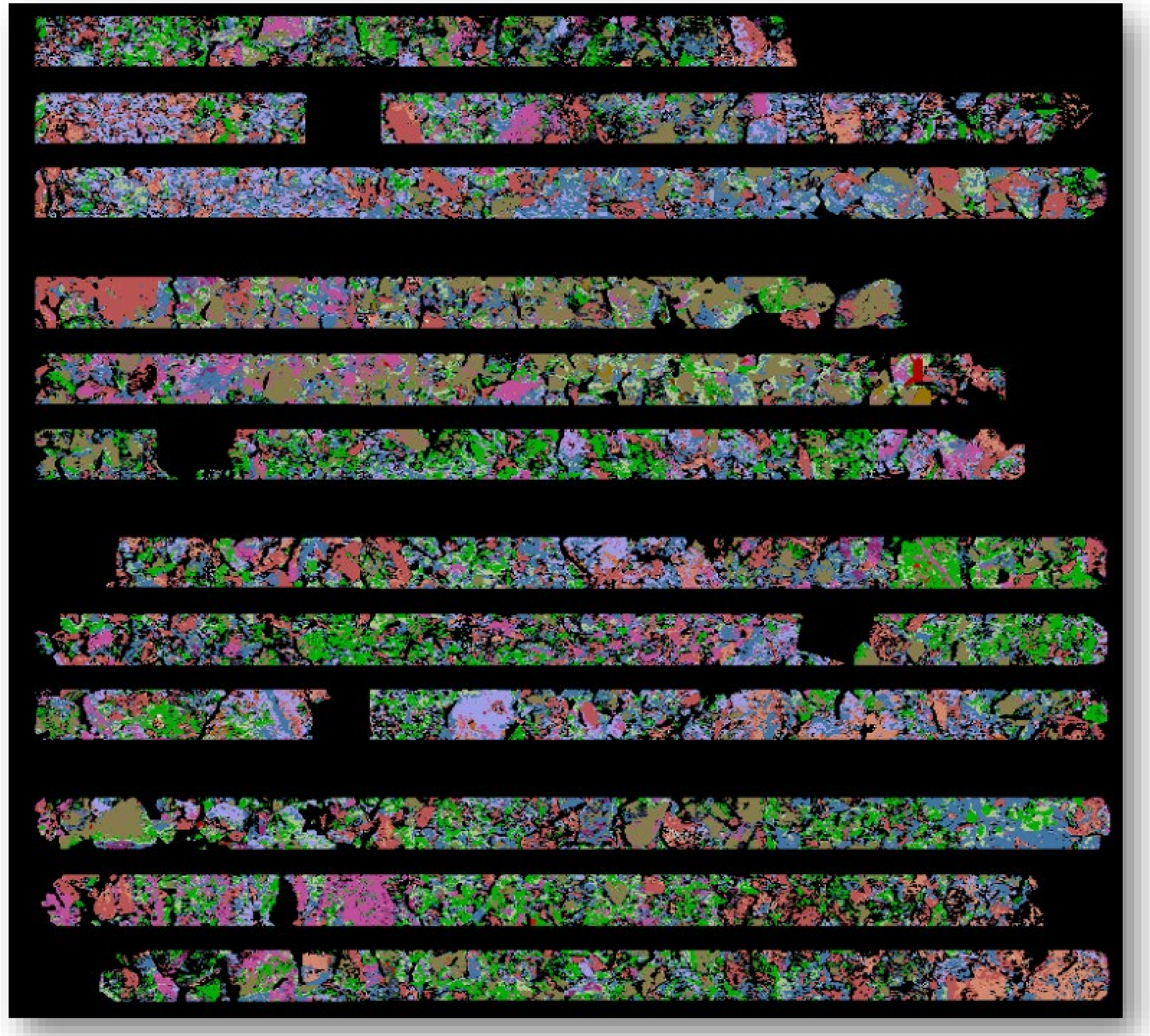
Size matters?

…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).

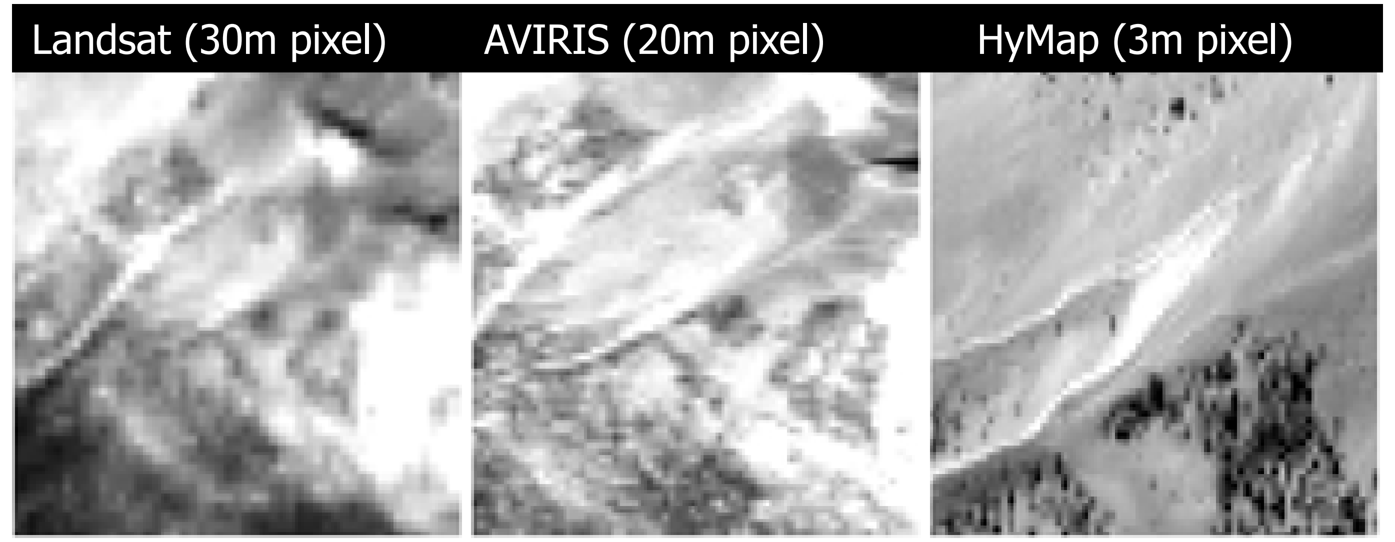
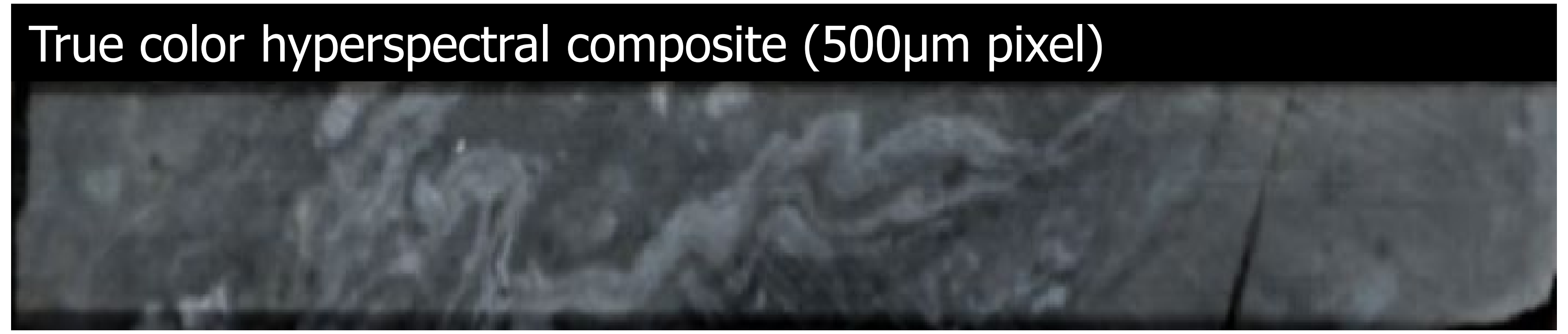


Image credit: Martini et al., 2001.

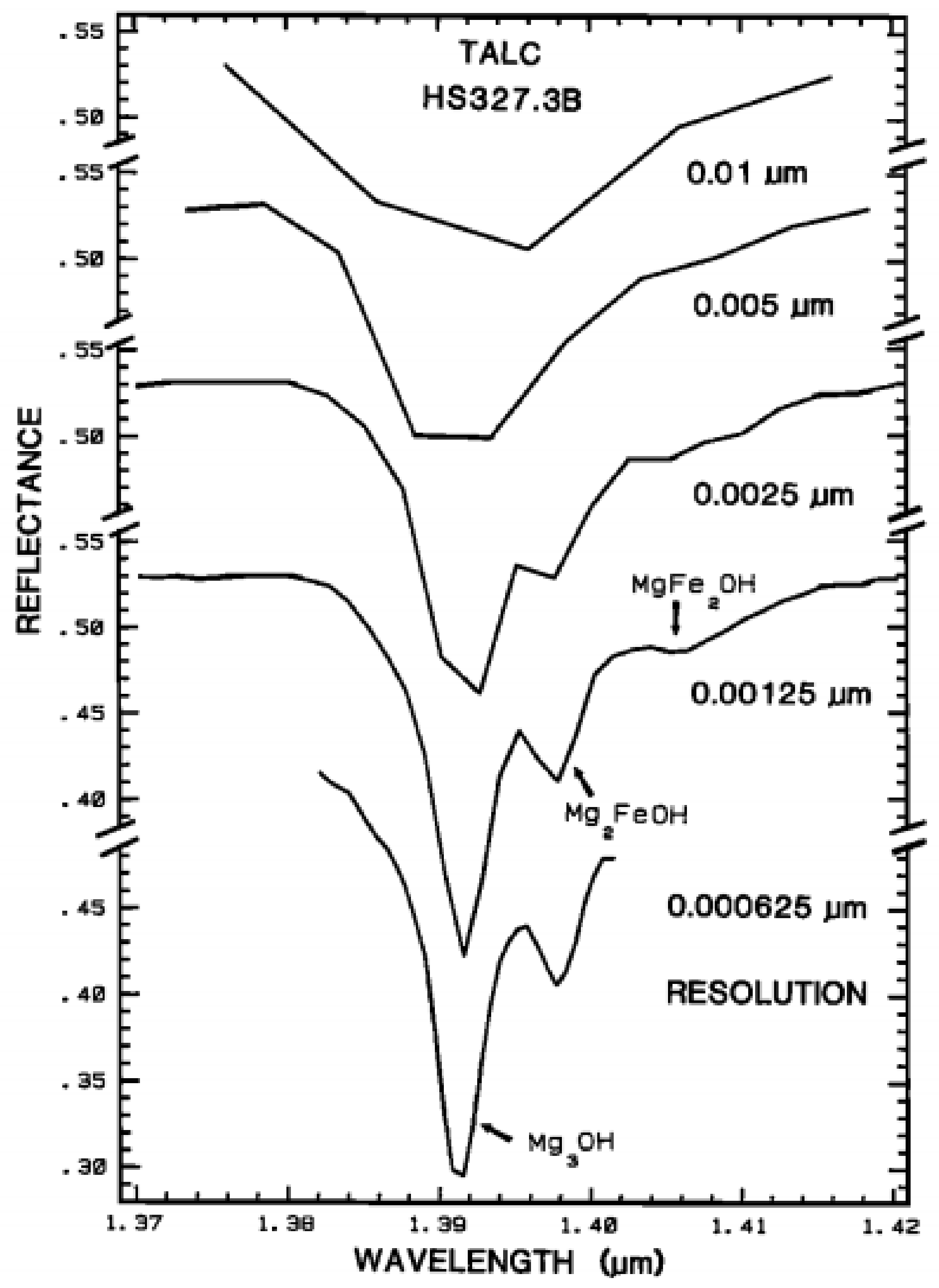


Hyperspectral core imaging data at 500µm. Image credit: Minnesota Department of Natural Resources.

Spectral resolution

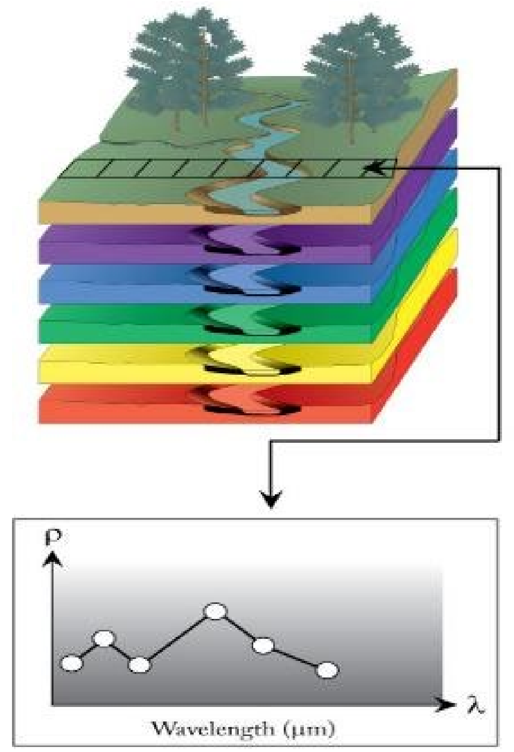
- Spectral resolution describes the wavelength intervals over which each spectral band's measurement is made, and which determines the ability to discriminate fine spectral features.
- It typically refers to how "wide" each band is, or the range of wavelengths covered by a single measurement band.
-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

Reflectance spectra of talc
~1400nm

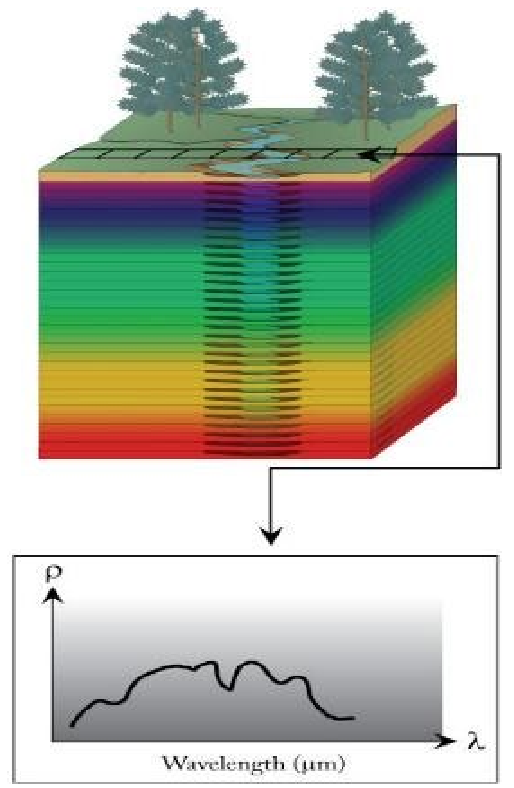


Increasing spectral resolution = more detailed spectral features

(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

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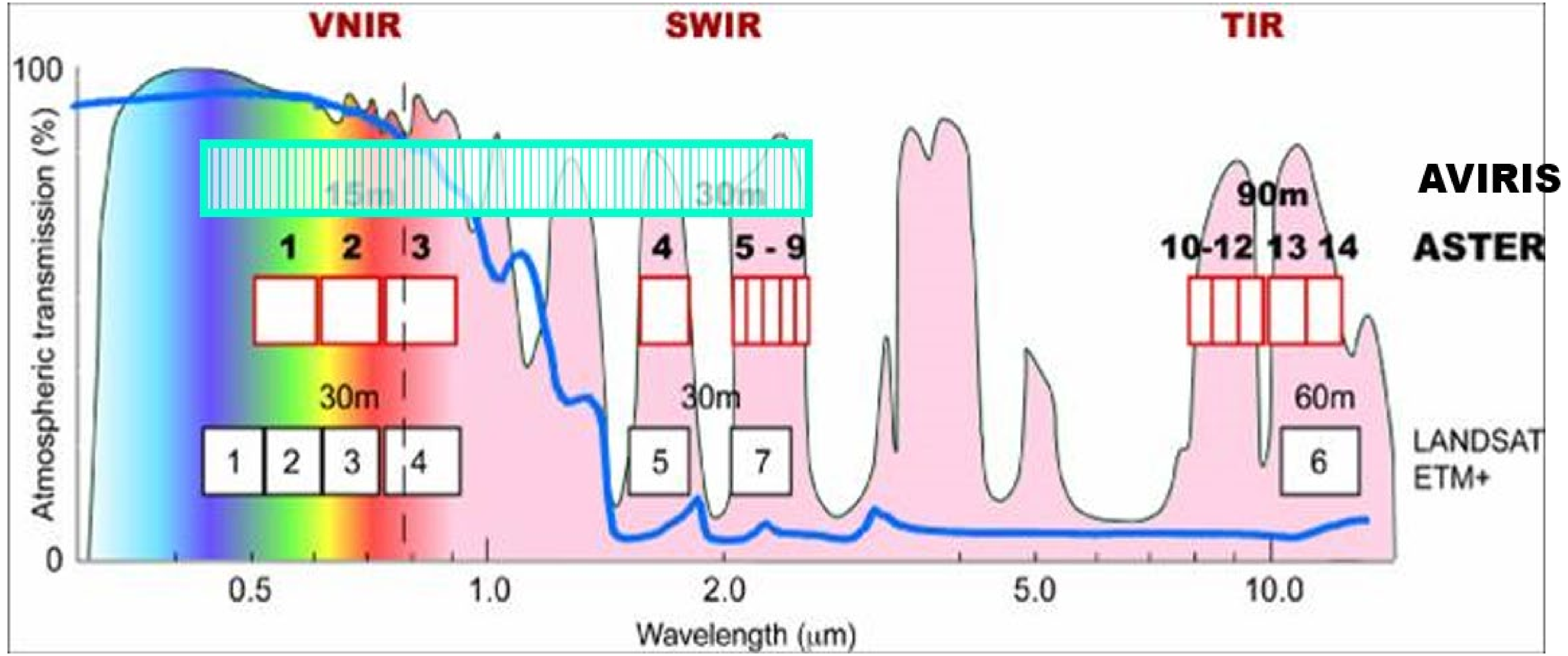
Spectral range, number of bands & band distribution

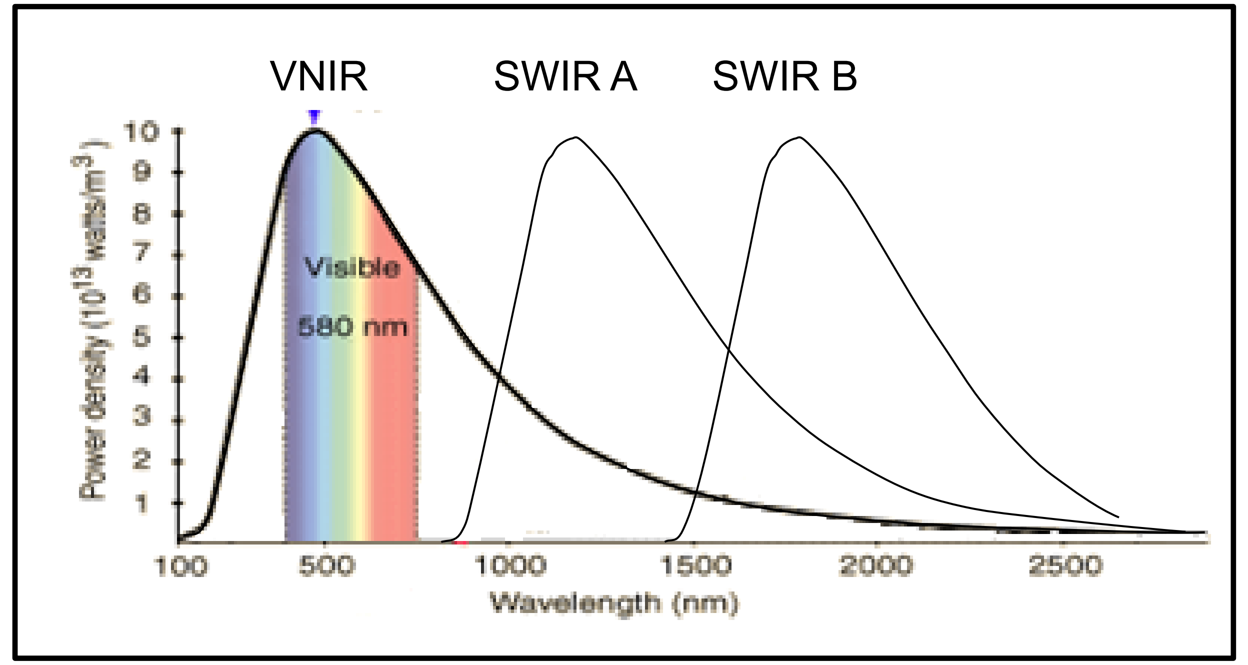
- The spectral range refers to the specific wavelengths measured by a sensor.
- The number of bands (and whether they are contiguous) classifies hyperspectral from multi-spectral, i.e., absolute mineral identifications versus broad mineral classifications.

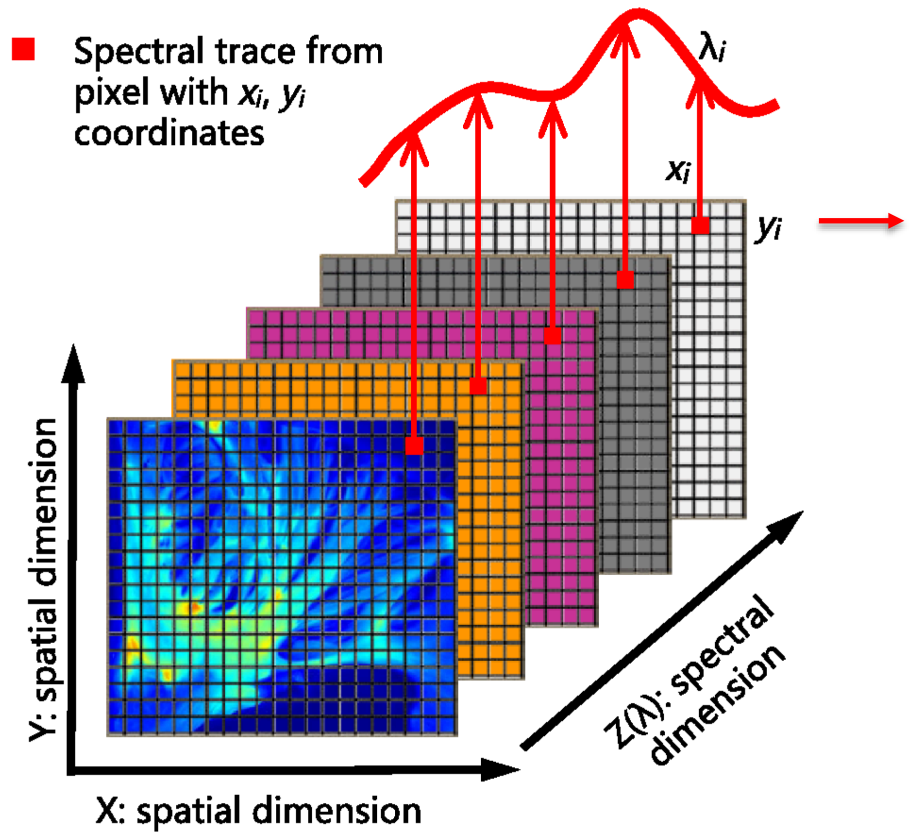


Examples drawn from remote sensing satellite data. Each shows the spectral range of the instrument, as well as how many bands of information are available for interpretation.

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.

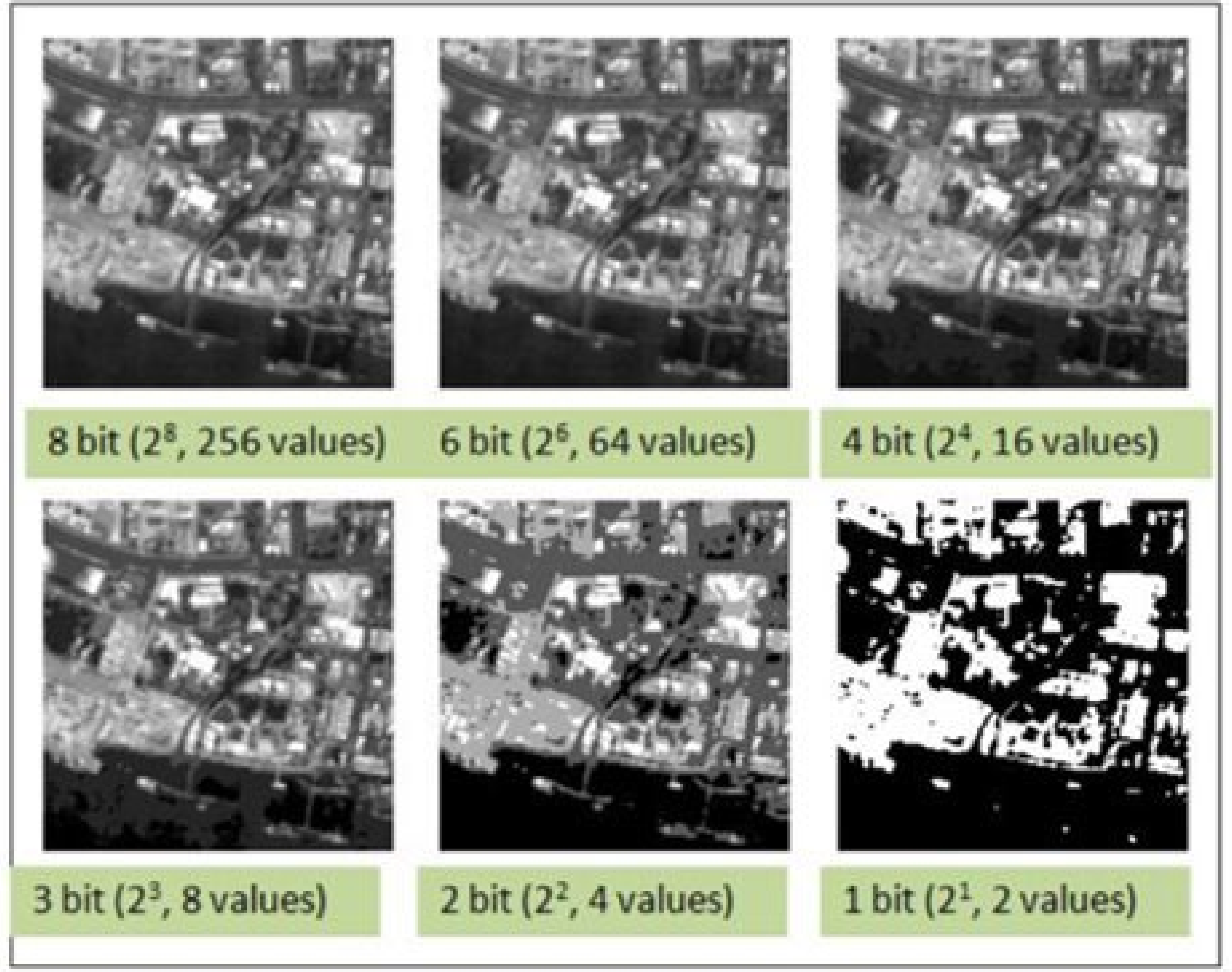
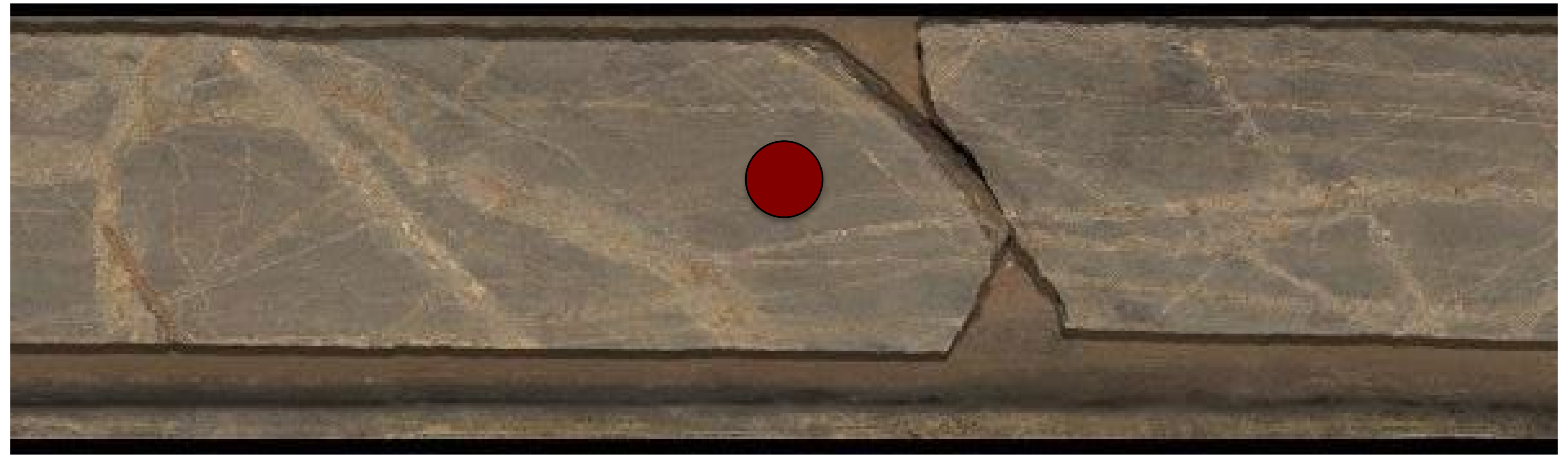


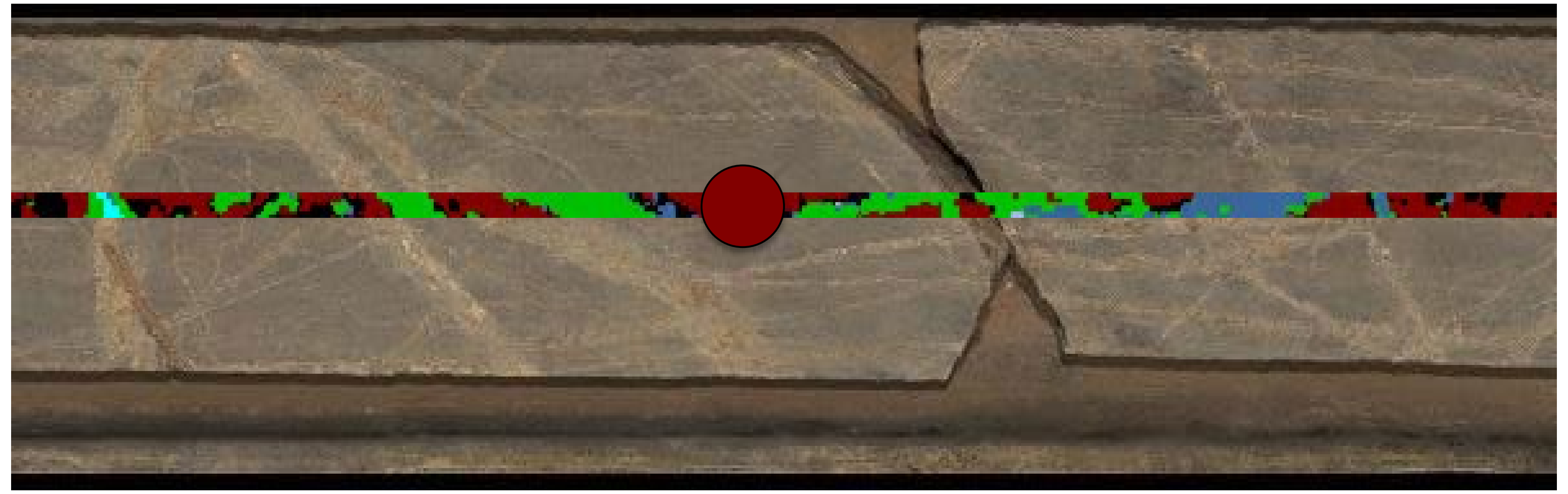
Image credit: Descartes Labs

Increasing counting statistics for data interpretations: point data



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

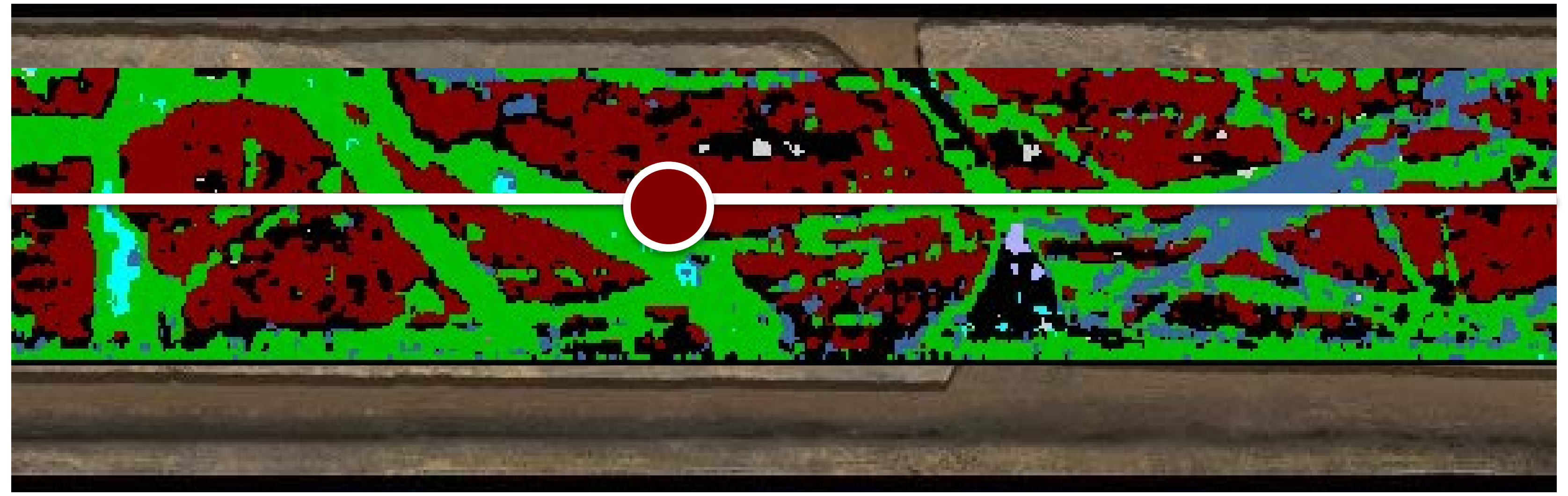
Increasing counting statistics for data interpretations: line scan systems



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

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

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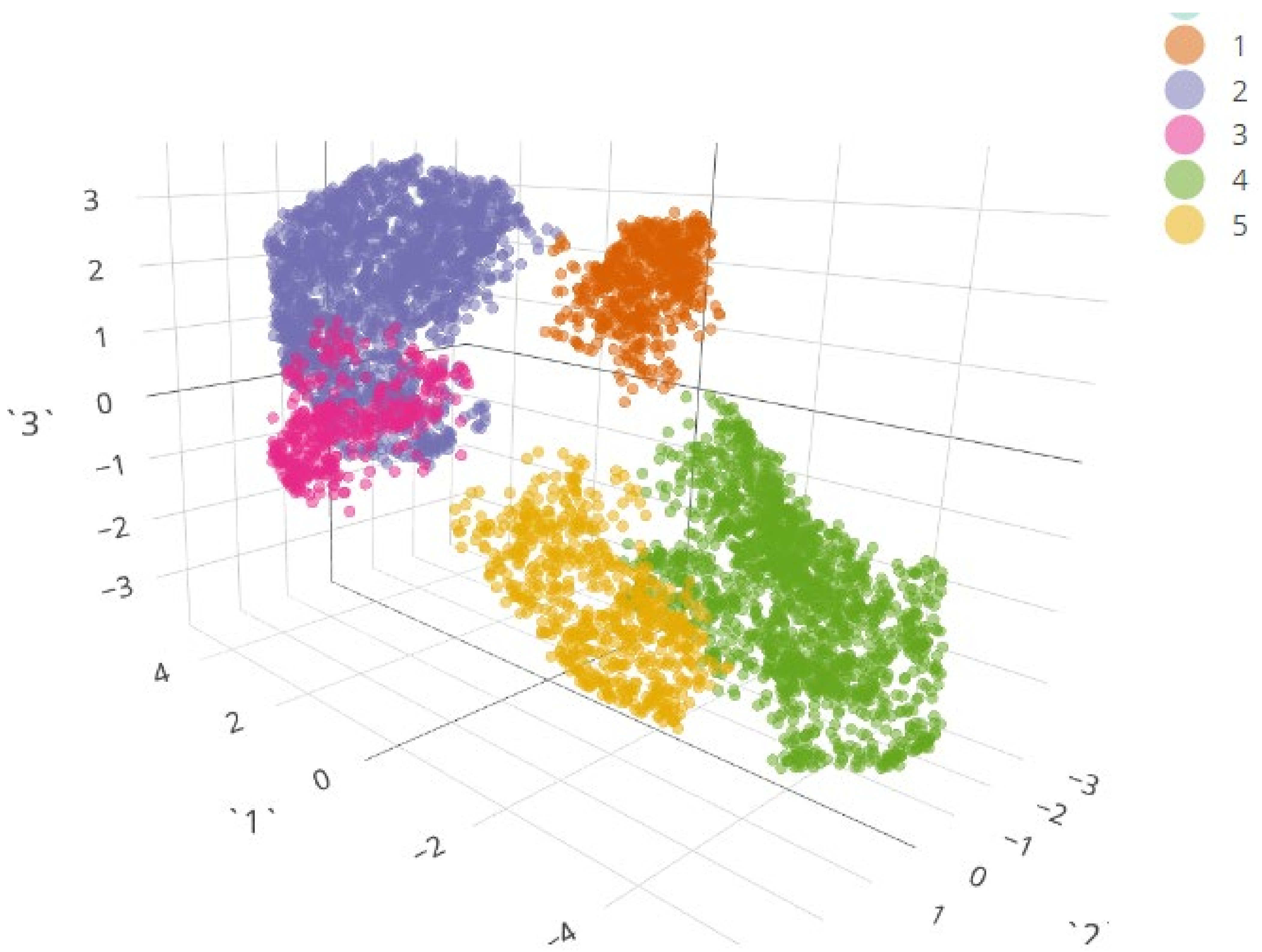
System used in this study

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



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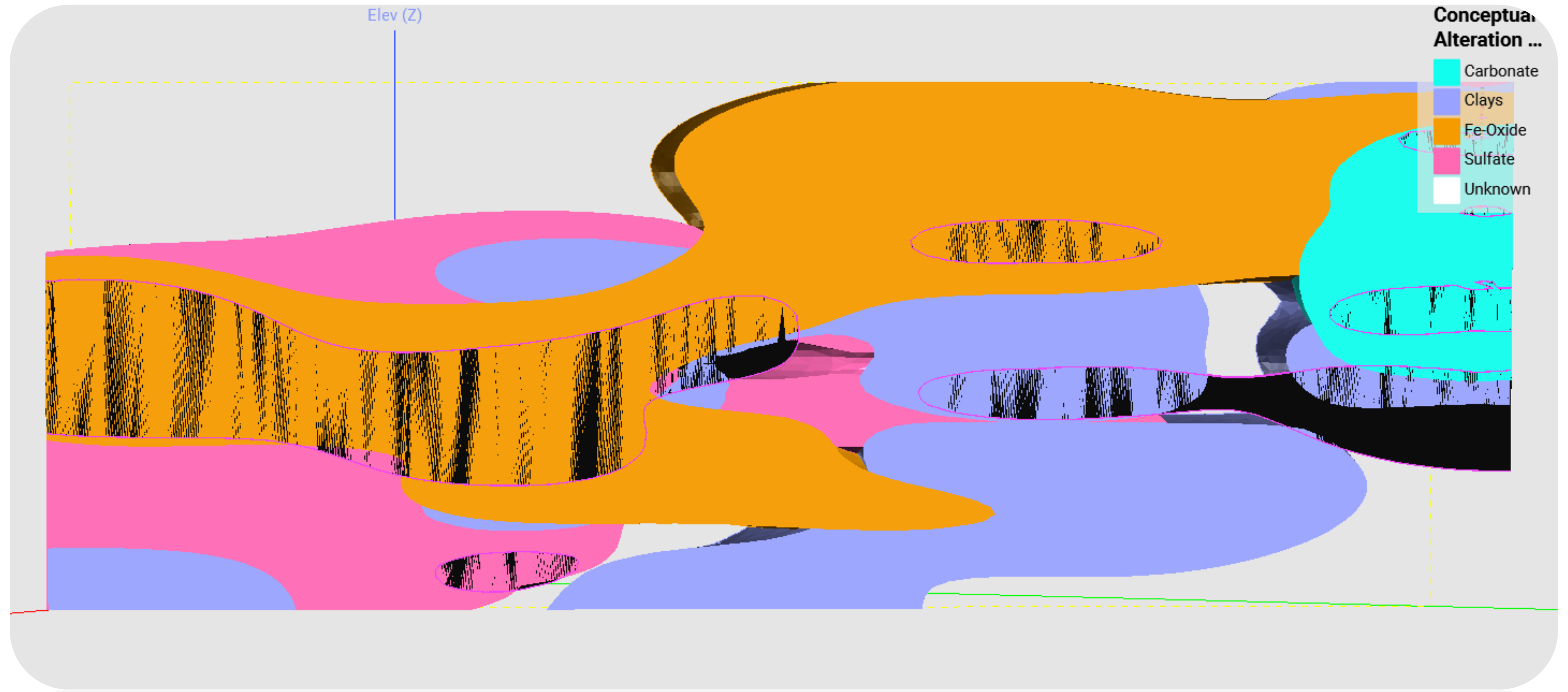
Let’s have a look at the modeling workflow

Building on the workshop model

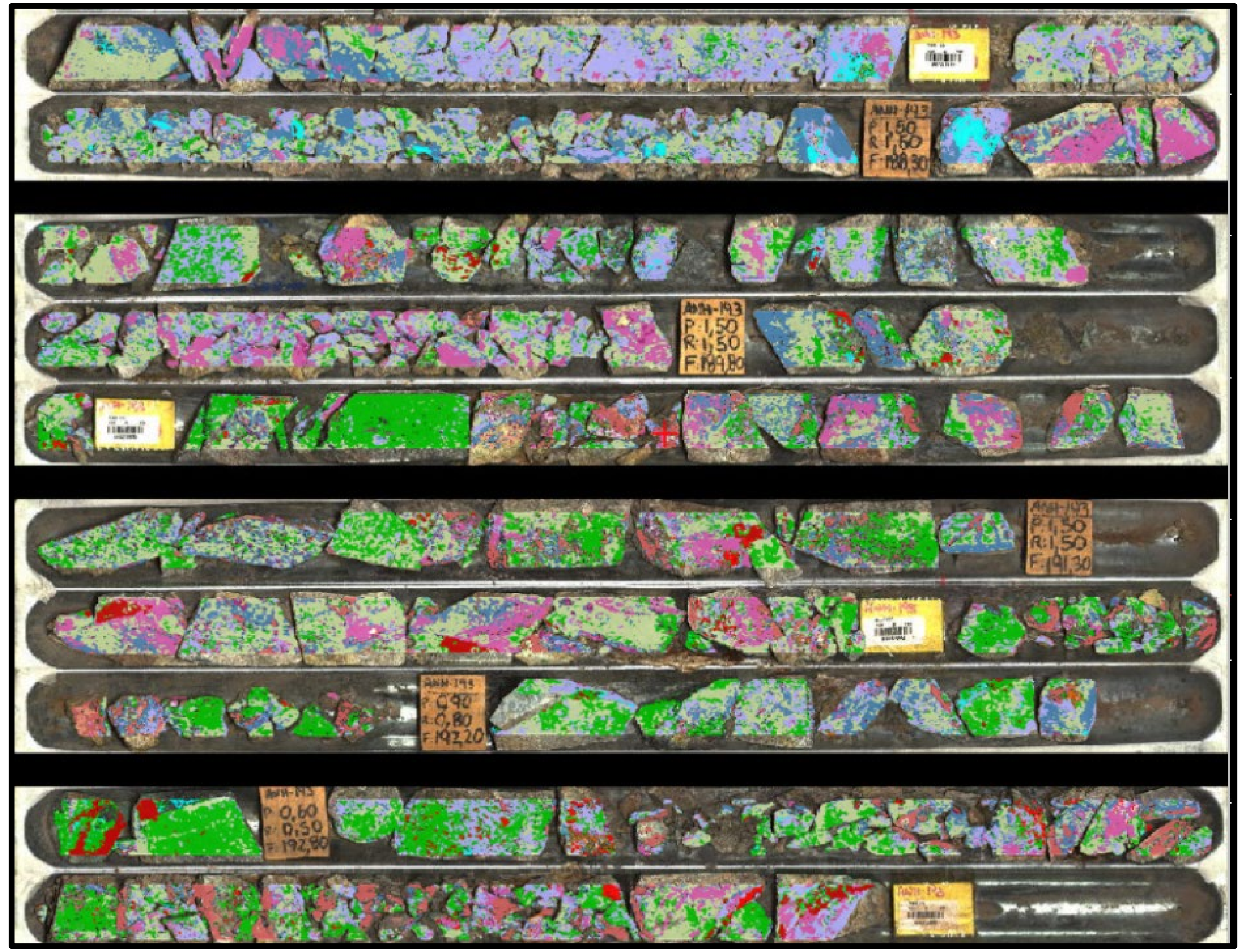
- The model built in the workshop was highly supervised.
- It focused on our knowledge of the mineralogy and the layers that we wanted to build based on known metallurgical problems:
  - Sulfates
  - Carbonates
  - Clays
- Another way to approach a geometallurgical model is to come at it from an unsupervised approach, whereby we only select the mineralogical inputs based on statistical continuity and system knowledge.



Data inputs: hyperspectral mineralogy

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

- Mineralogy criteria:
  - Must be continuous
  - Amount must be statistically significant
  - Do not select minerals that are highly correlated

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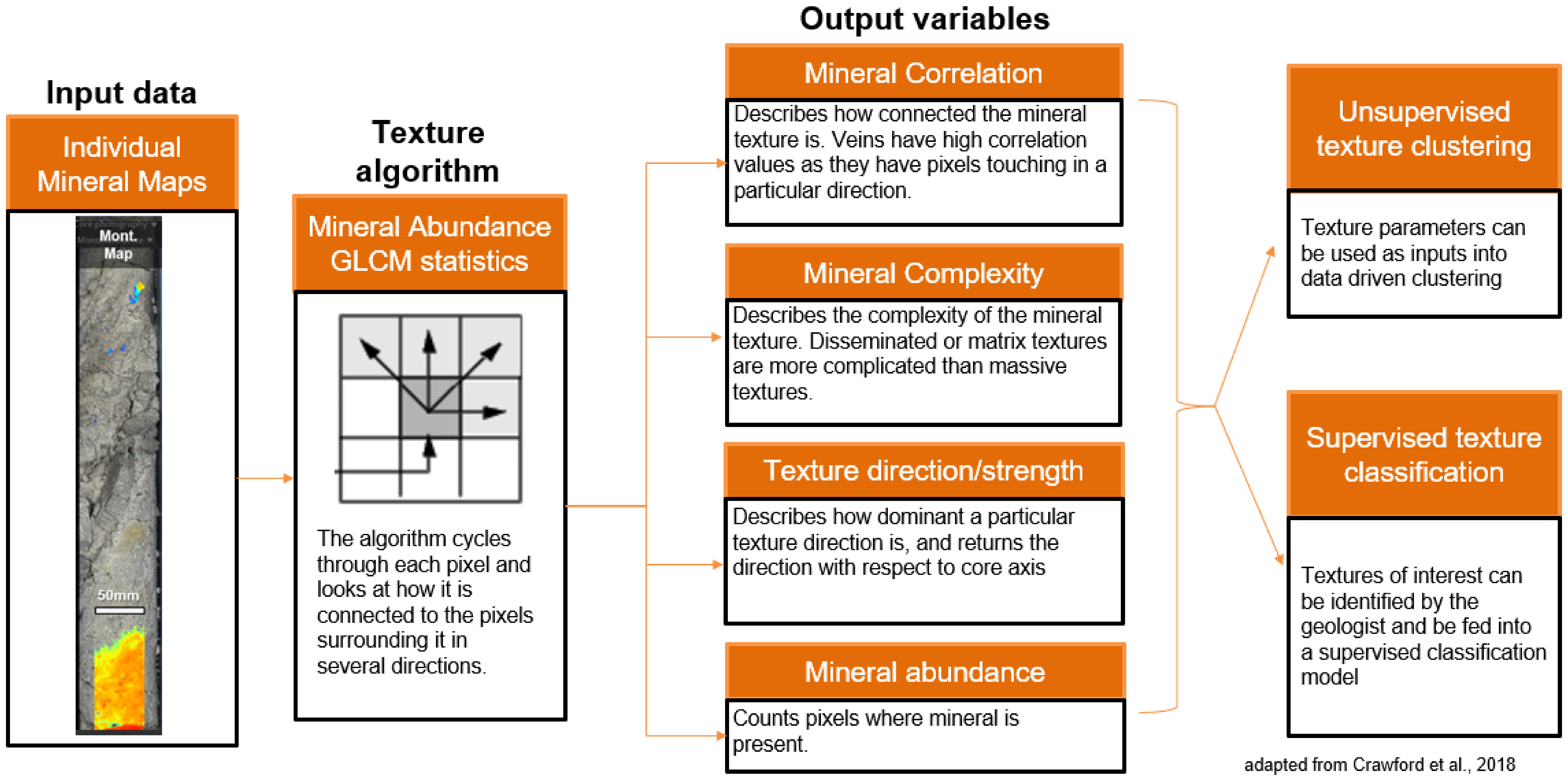
Data inputs: image textural data

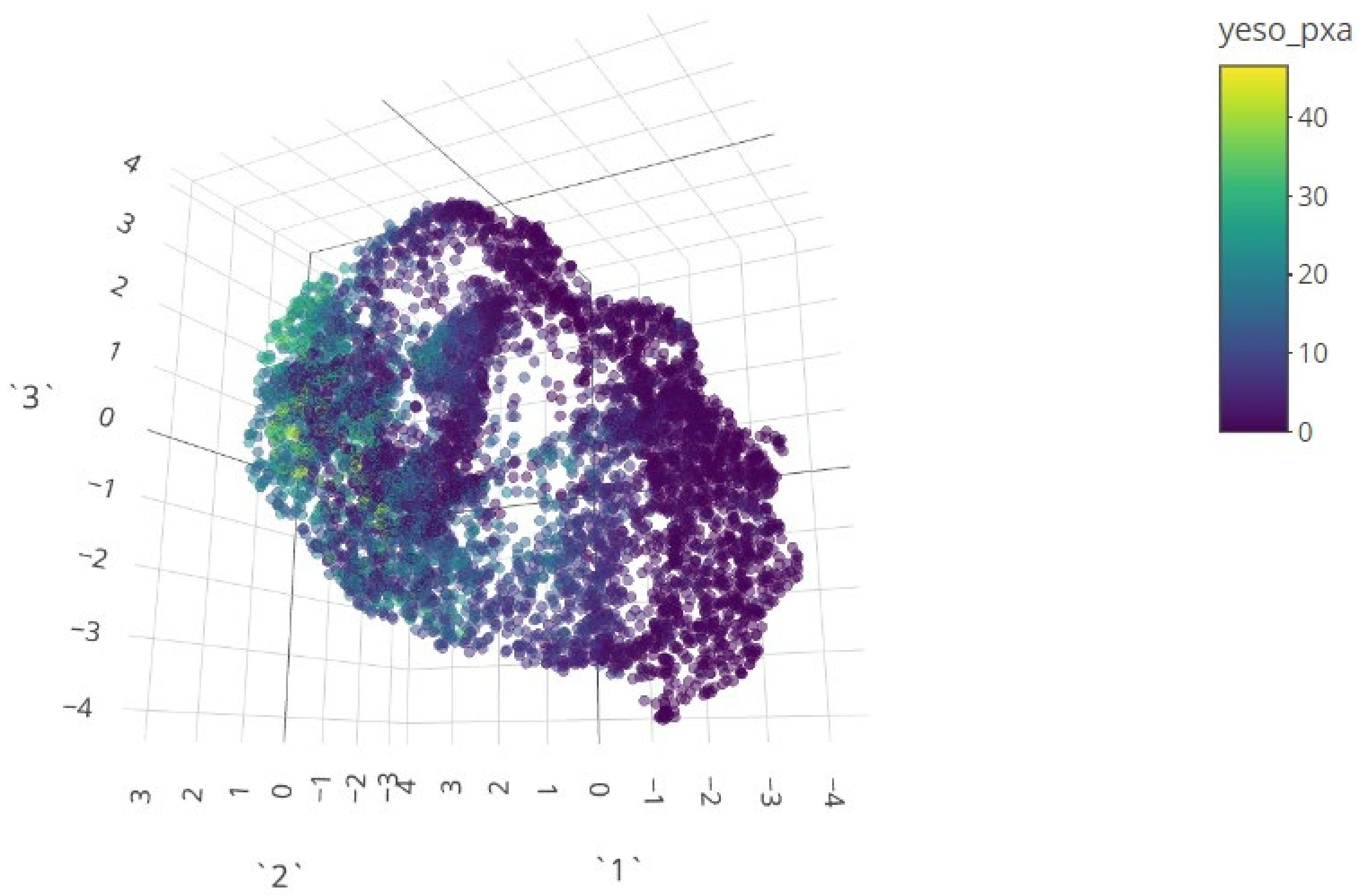
- Textural data extractions from the image data:
    - By looking at the statistics of how pixels are connected and spatially distributed, it is possible to extract some statistical measures of mineral texture from HSI mineral maps.
    - These statistics can then be used to classify mineral texture in both supervised classification and clustering applications (this study).
    - Example techniques include: Gray Level Co-Occurrence Matrix (GLCM) and Convolutional Neural Networks (CNN).

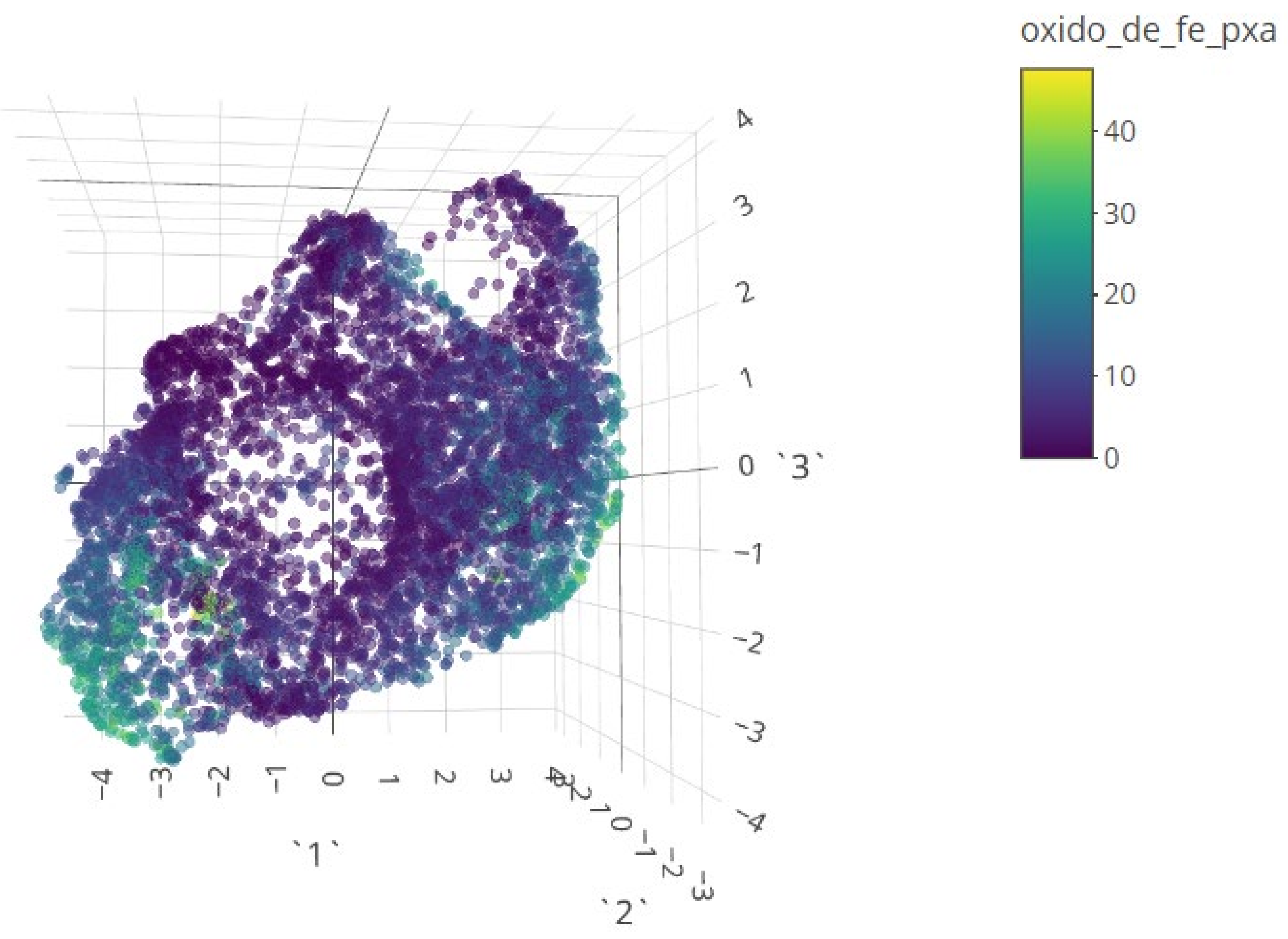


adapted from Crawford et al., 2018

Mineral selection and dimensionality reduction

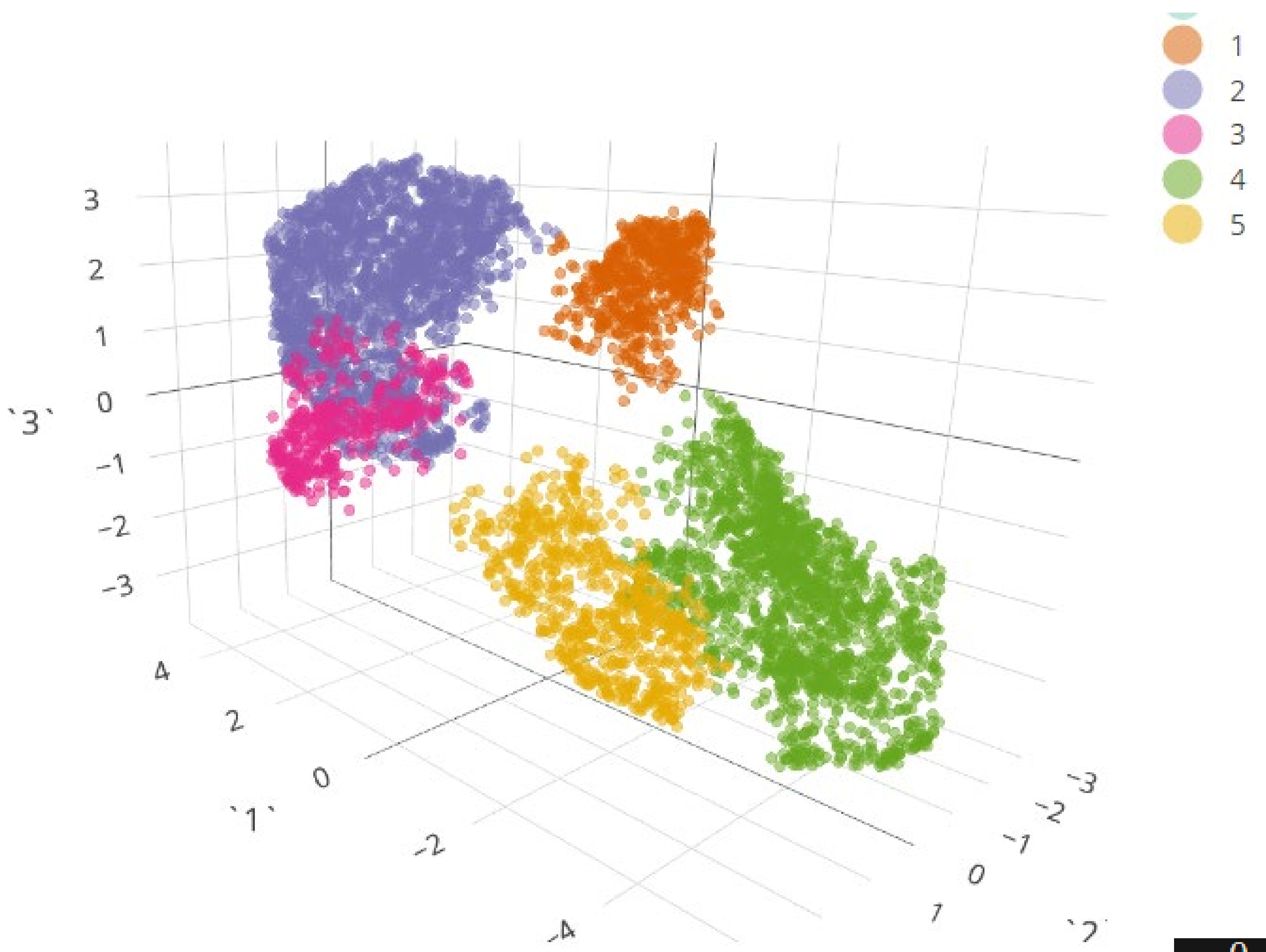
- A UMAP is a dimensionality reduction technique not dissimilar in principle to a PCA or tSNE.
- The idea is to take a lot of variables (too complex for us to see all at once in a model) and reduce them to an amount that is both more manageable and easy to model in 3D.





Clustering

- After we reduce these variables to distinct domains or clusters (see right), we can look at the composition of these clusters and model them.
- This UMAP and DBScan presented a five cluster solution.
- Clusters 2 and 4 are much larger than 1, 3 and 5 – it would be interesting in the future to look at these separately and in more detail.



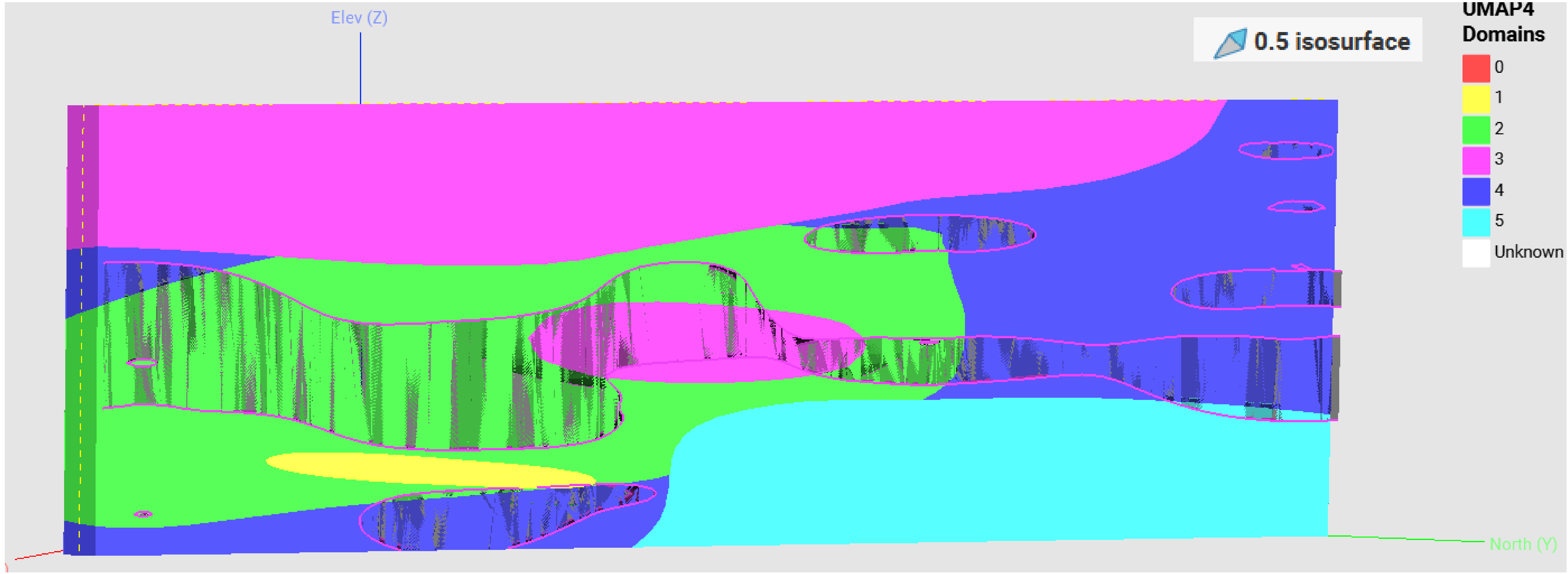
0	1	2	3	4	5
614	602	1951	428	1604	652

Mineralogic domains

Row Labels	Average of unclassified_pxa	Average of caolinita_pxa	Average of carbonato_pxa	Average of clorita_pxa	Average of cuarzo_hidratado_pxa	Average of montmorillonita_pxa	Average of oxido_de_fe_pxa	Average of silice_opalina_pxa	Average of sulfato_Fe_Mg_pxa	Average of sulfato_Fe_pxa	Average of yeso_pxa
1	4.15	9.23	0.33	13.78	0.00	7.39	8.00	1.05	1.61	2.40	11.91
2	10.22	4.77	0.28	9.86	0.11	11.40	7.96	1.83	4.03	4.46	11.72
3	12.23	0.01	0.31	17.76	0.25	22.66	7.74	2.51	2.56	4.90	9.37
4	10.25	4.14	2.14	28.04	0.01	23.47	8.22	0.19	0.00	0.03	1.55
5	11.31	0.60	2.02	27.82	0.11	22.75	7.59	0.95	0.00	0.04	5.19

Cluster	Mineralogic Composition
1	Kaolinite, Fe-Oxide, Gypsum
2	Unclassified, Fe-Oxide, Gypsum, Fe-Mg Sulfate, Fe-Sulfate, Kaolinite, Opaline Silica
3	Chlorite, Montmorillonite, Gypsum, Hydrated Quartz, Fe-Mg Sulfate, Fe-Sulfate, Opaline Silica
4	Chlorite, Montmorillonite, Carbonate, Fe-Oxide, Kaolinite, Fe-Oxide
5	Chlorite, Montmorillonite, Carbonate

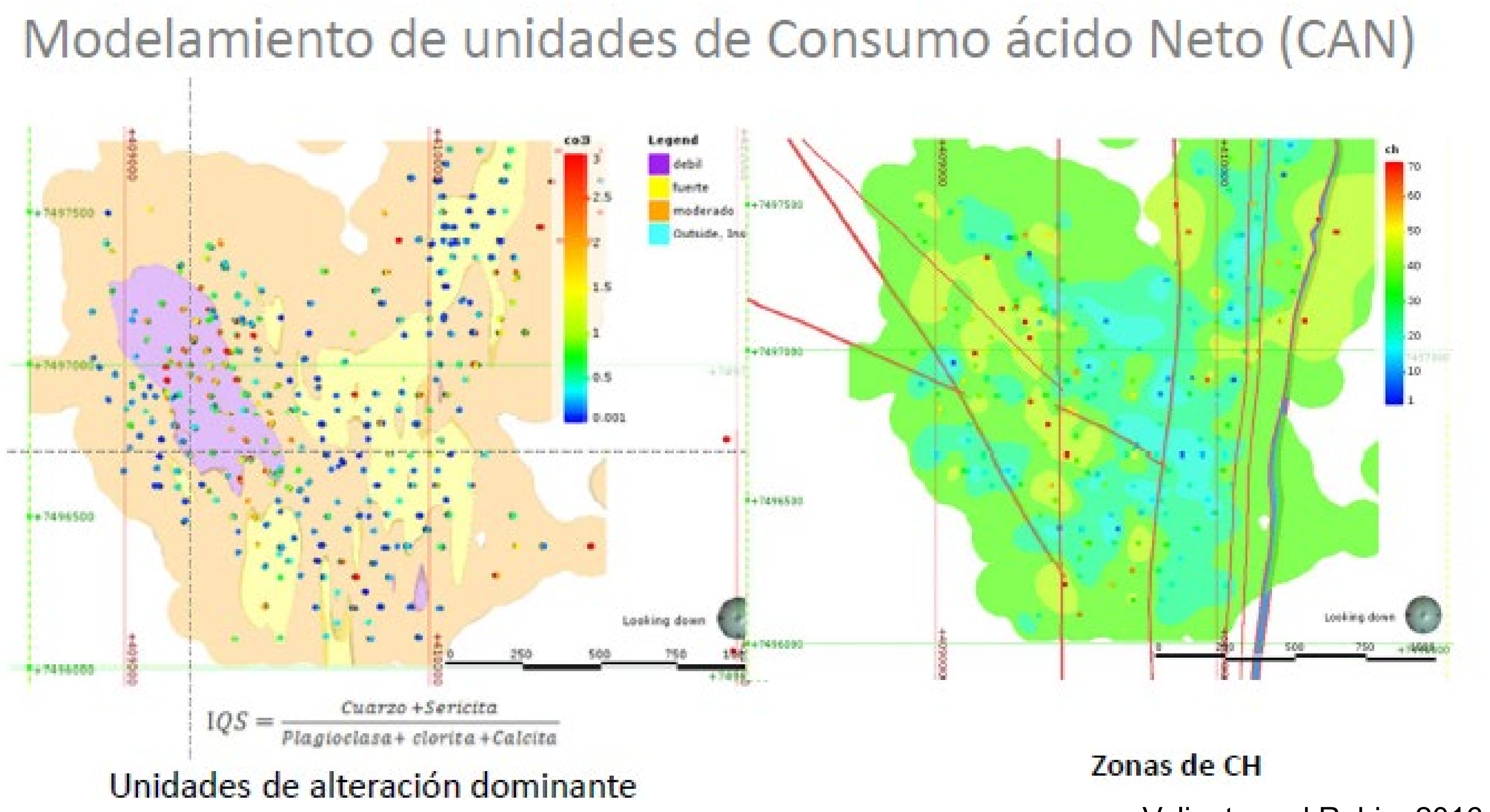
Domain model



- Models such as this can be used to understand mineralogic domains (separate from paragenesis), as well as to help select geometallurgical testwork samples to understand these mineralogically and texturally similar domains.

Current acid consumption model

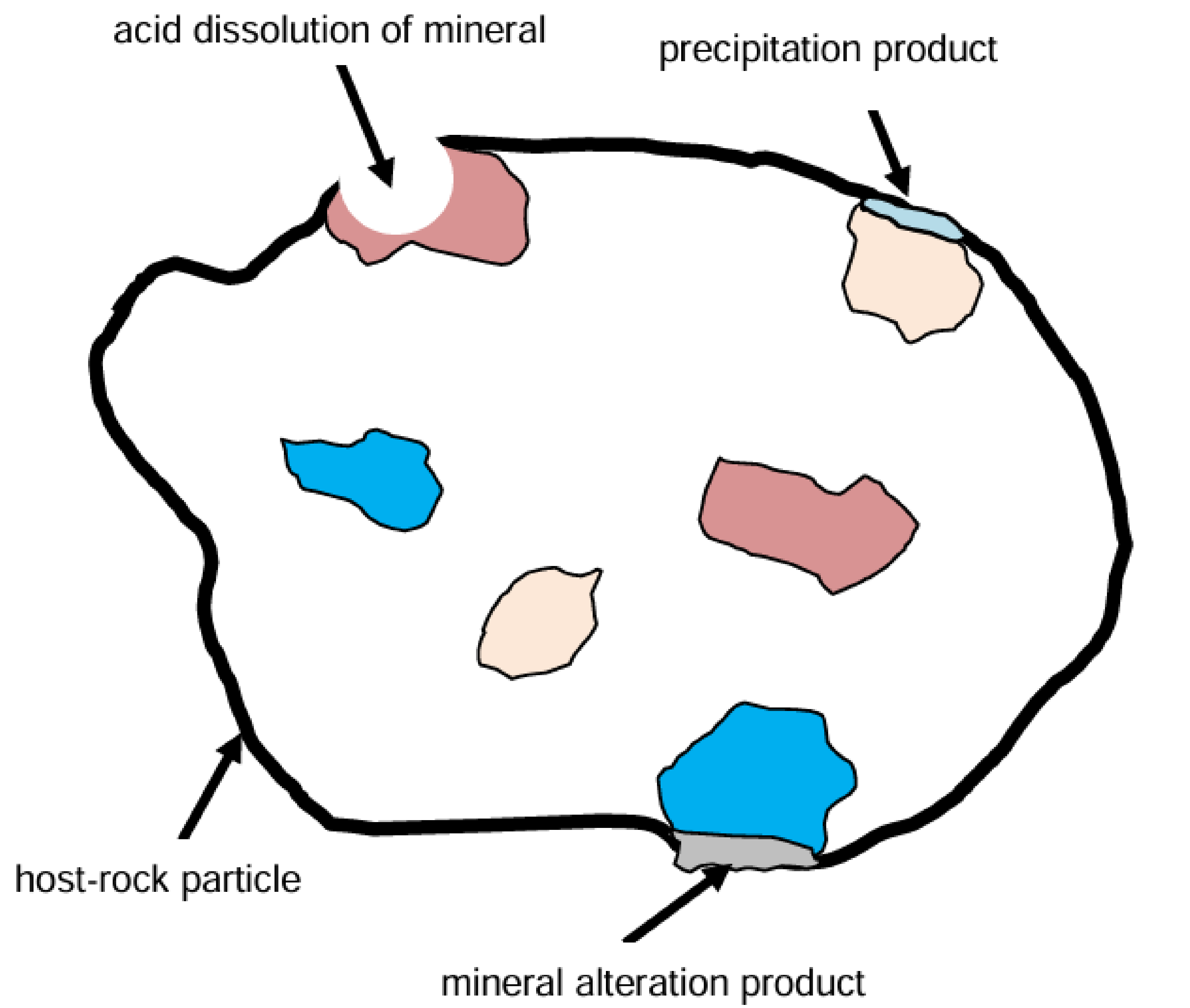
- Antucoya possesses an acid consumption model that is based on their alteration types and intensities.
- Overall it is shown that the early alteration zones consume more acid than the late stage events.
- In this case study we are going to look at another way to apply and model HSI data.
- Herein we are going to explore regression models and how a consistent and continuous dataset like HSI can help save money over time.



Valiente and Rubio, 2016

What is acid consumption

- Acid consumption can determine whether or not a project is economically and technically feasible because copper recovery is directly related to it.
- Factors that play a role in determining acid consumption:
  - The minerals present in the ore, including gangue minerals (some gangue minerals undergo alterations that cause additional precipitate formation).
  - Solution pH
  - Rate of acid application
  - Particle size
- Ores that consume large quantities of acid often present substantial technical challenges for copper recovery.
- Some acid consuming minerals dissolve, some dissolve then rapidly form precipitates at the surface that restricts further leaching, and other acid-consuming minerals gradually transform into secondary minerals during the leaching process.
  - It is possible for by-products to restrict acid consumption as well as release acid, thereby altering the acid balance.



Free, 2010

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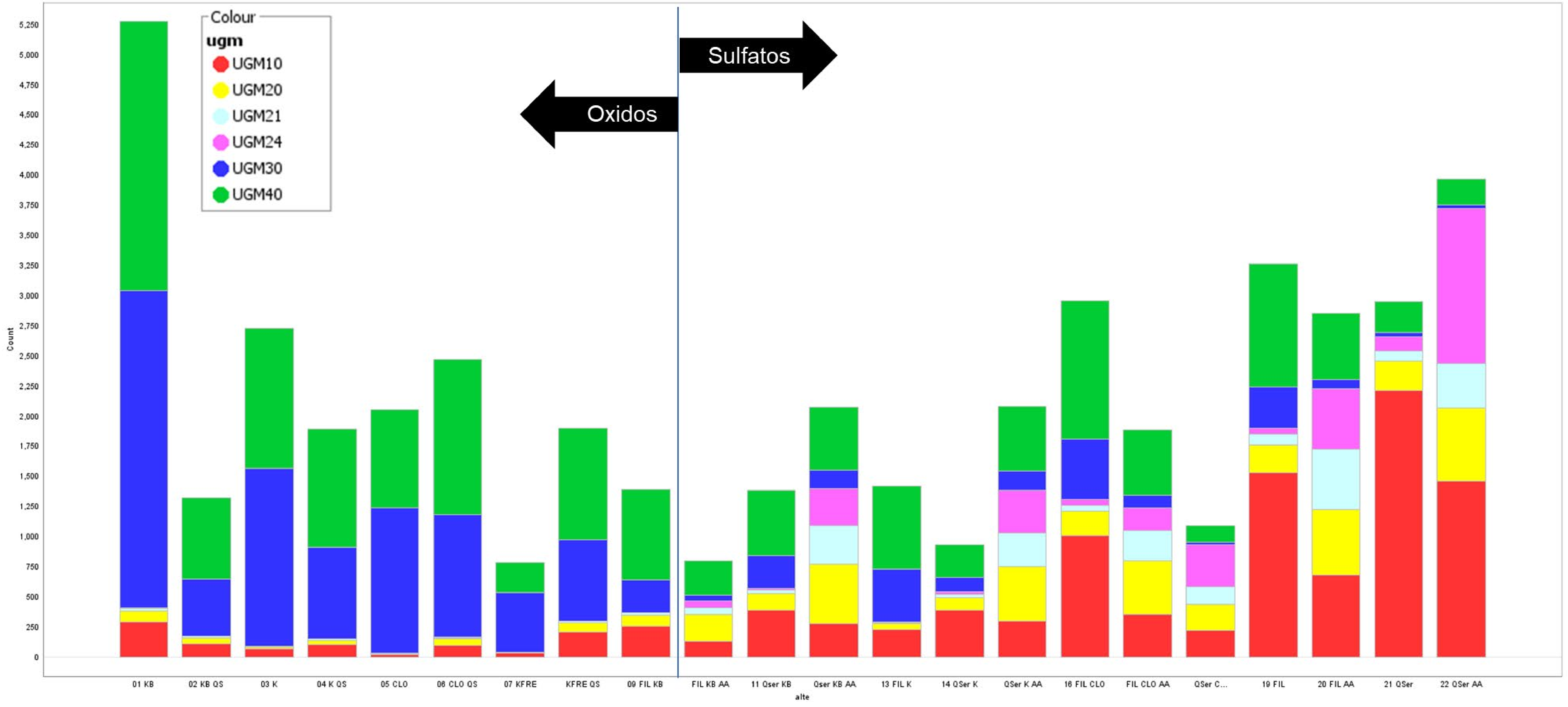
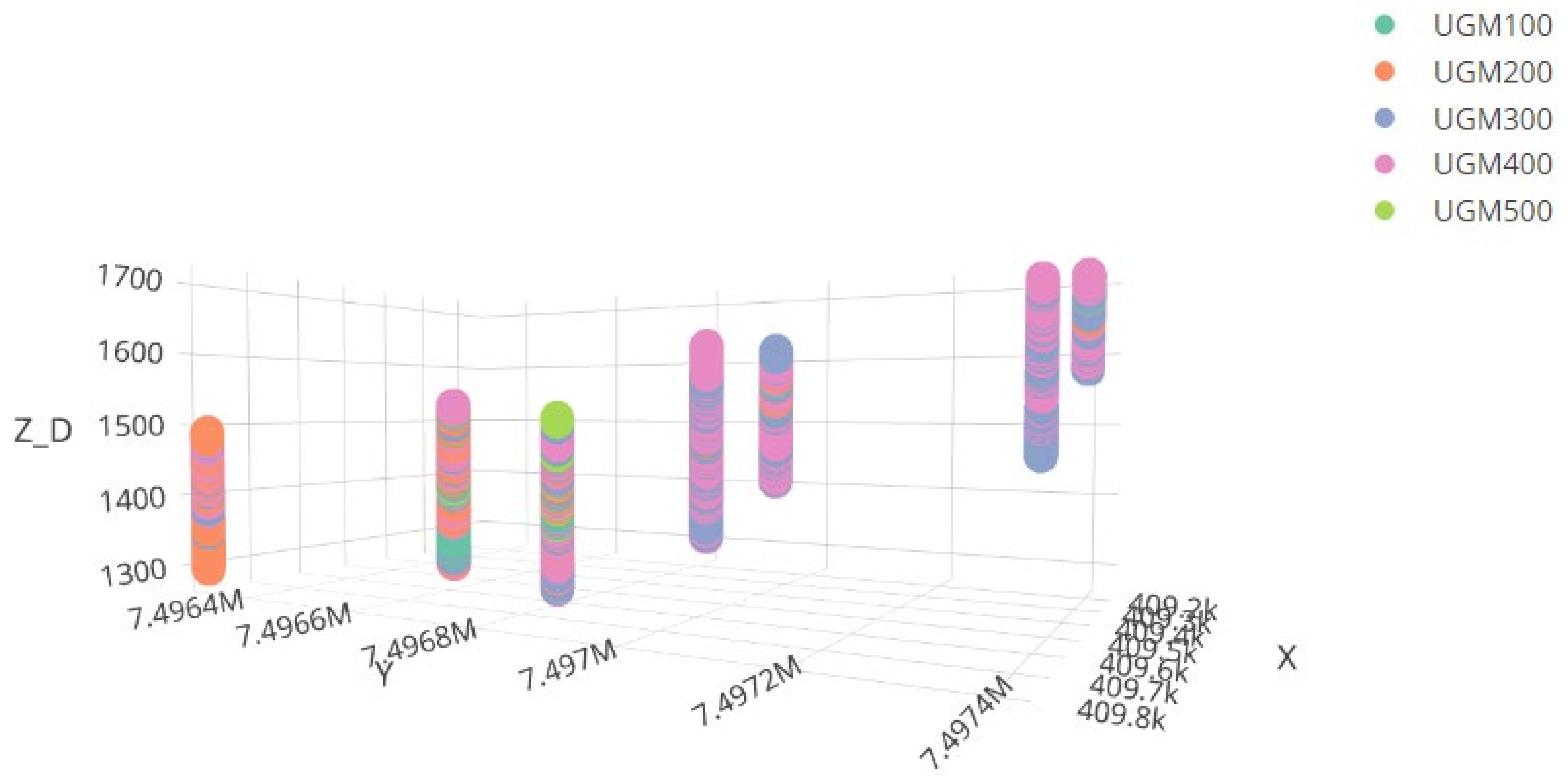
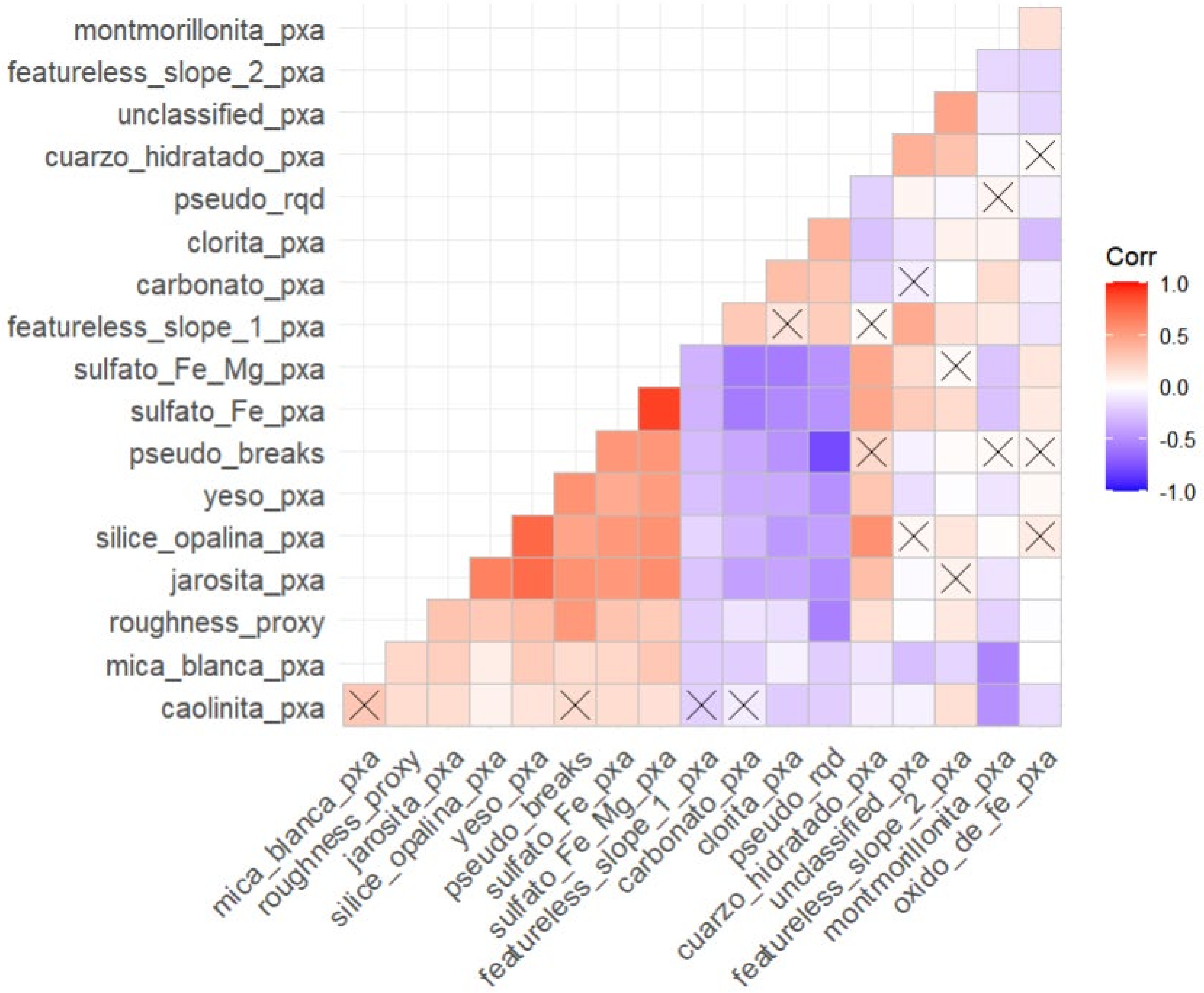
Feeding the plant is a delicate balance

- The different geometallurgical units (UGM) ensure that the plant is constantly being filled by the correct balance of sulfates to oxides.
- There's no need with another technology to re-build all this work, however, an underlying consistent and continuous dataset like HSI would allow for the construction of a variety of prediction and classification algorithms.
- In this case, we could rapidly classify the geometallurgical domain as soon as the core is scanned.
- For this we are going to use an XGBoost ML Model.



Selecting variables to predict our acid consuming domains

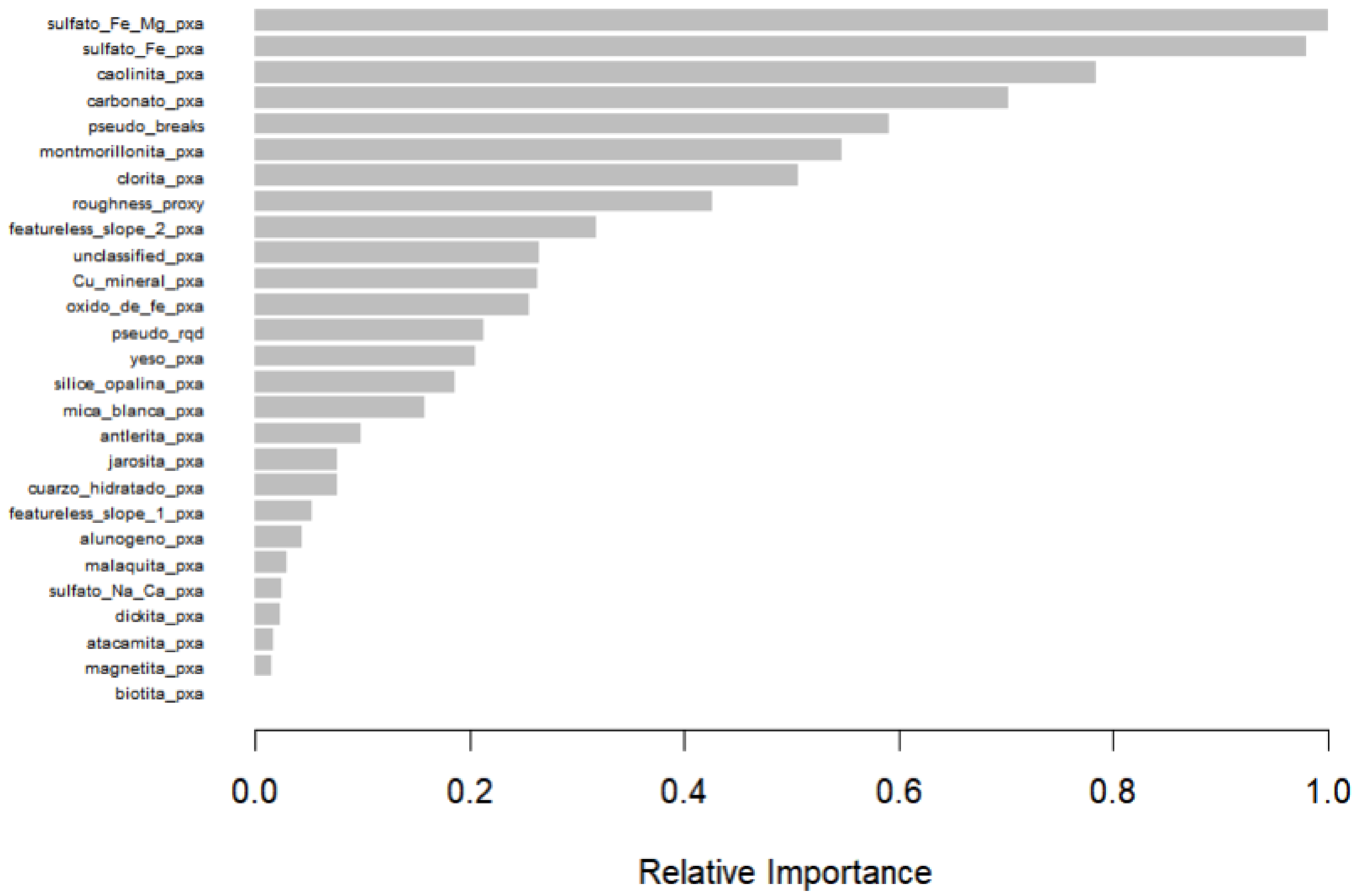




Our classification model

- Wherever we have this HSI data, we can construct our Acid Consuming Domains.
- It's important to perform model maintenance, especially when entering new areas that the model is not familiar with.
- This represents a testwork cost savings and time saving solution for future geometallurgical domain additions to their block model.
- The principles presented here can be used to predict hardness, grade; classify other domains, lithologies.

Variable Importance Plot



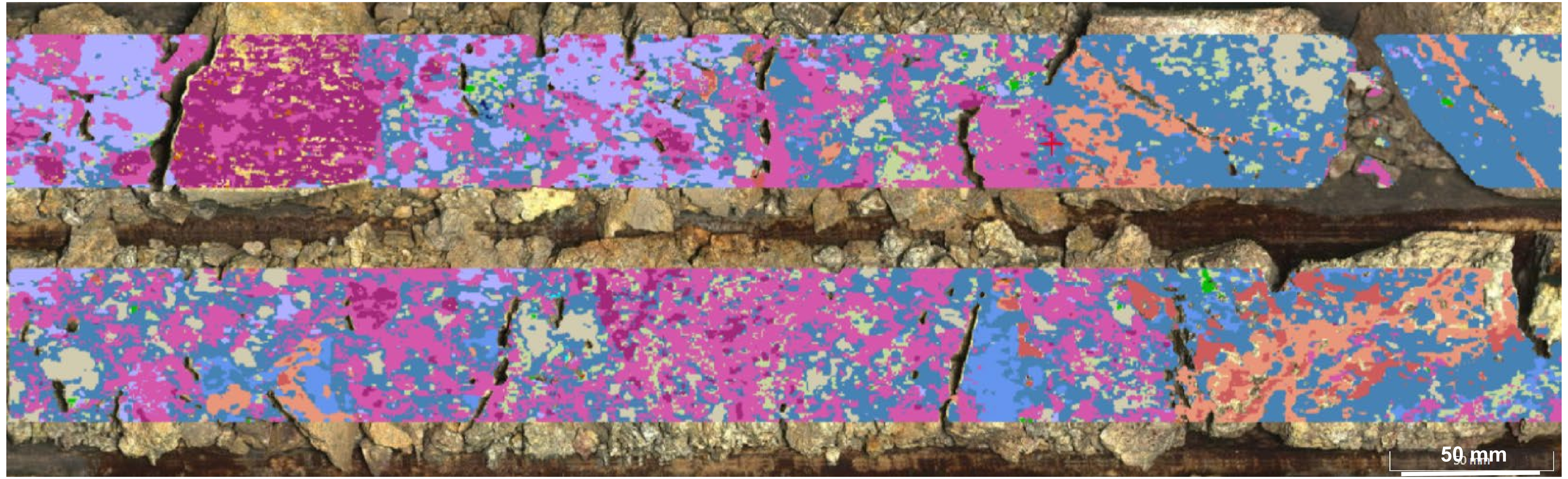

```
Confusion Matrix and Statistics

          Reference
Prediction UGM100 UGM200 UGM300 UGM400 UGM500
    UGM100      0      2      0     14      0
    UGM200      1     20      0     27      0
    UGM300      8     19     99     98      0
    UGM400     15     66     15    350      1
    UGM500      0      0      0      0      0

Overall Statistics

               Accuracy : 0.6381
                 95% CI : (0.6022, 0.6729)
    No Information Rate : 0.6653
    P-Value [Acc > NIR] : 0.9448

                  Kappa : 0.3272
```

Size matters?

…of course it does.

Why did size matter: spectral resolution

- The ability to map subtle changes in mineralogy, such as Fe-Mg Sulfate, Jarosite, Fe Sulfate that may have impacts on the way acid is consumed during leaching.



Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	

White Mica	
Kaolinite	
Montmorillonite	

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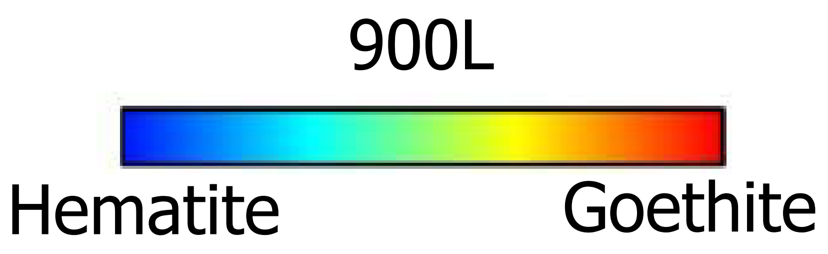
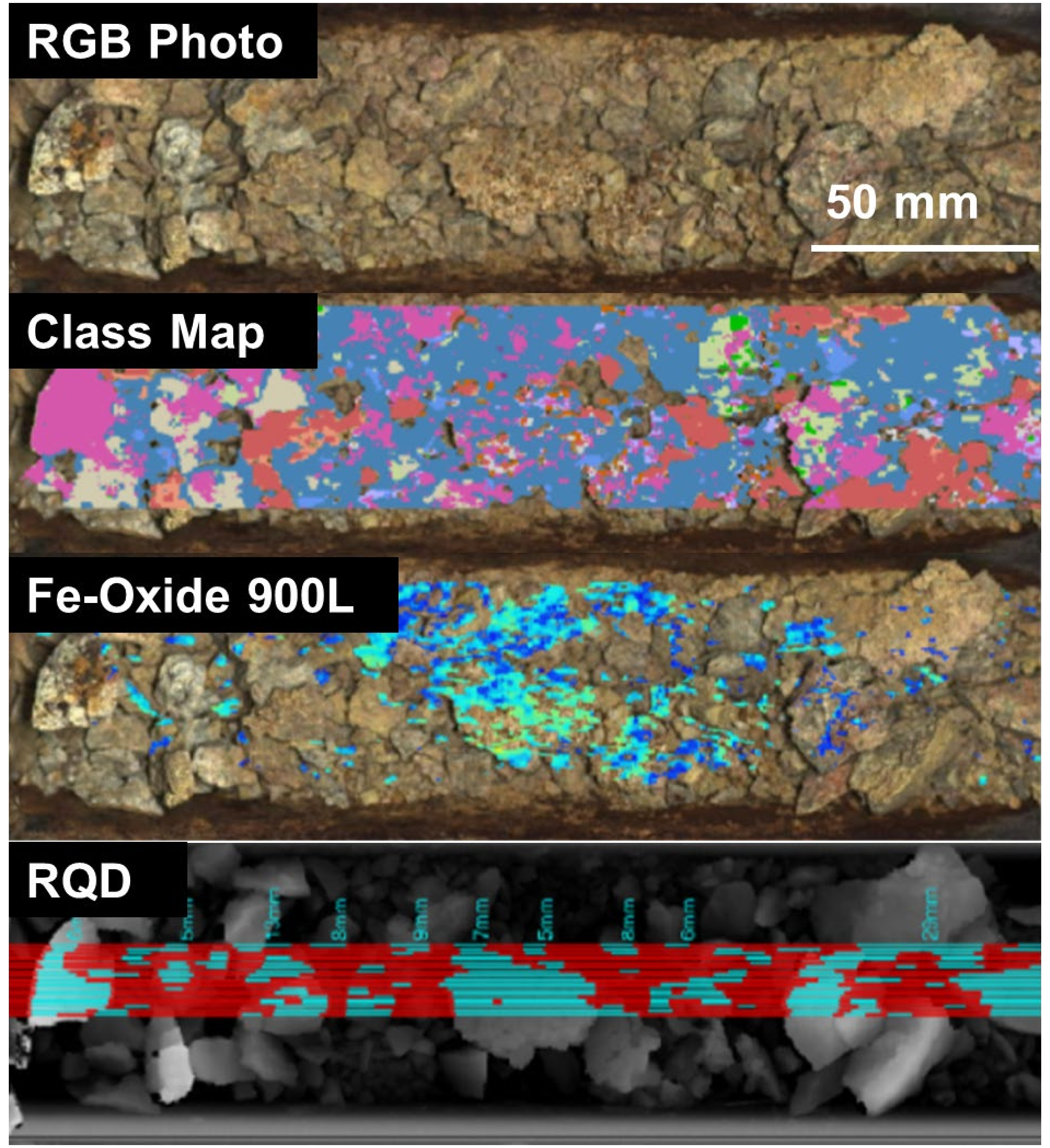
Why did size matter: spatial resolution

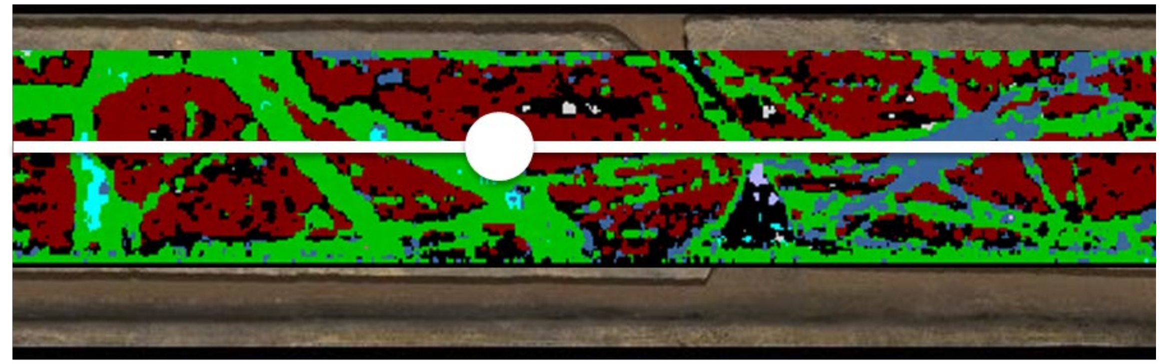
- Able to map spectral parameters and complex mixtures in areas where the core is highly degraded.



Jarosite	
Fe-Mg Sulfate	
Fe Sulfate	
Gypsum	
White Mica	
Kaolinite	



Why did size matter: number of pixels

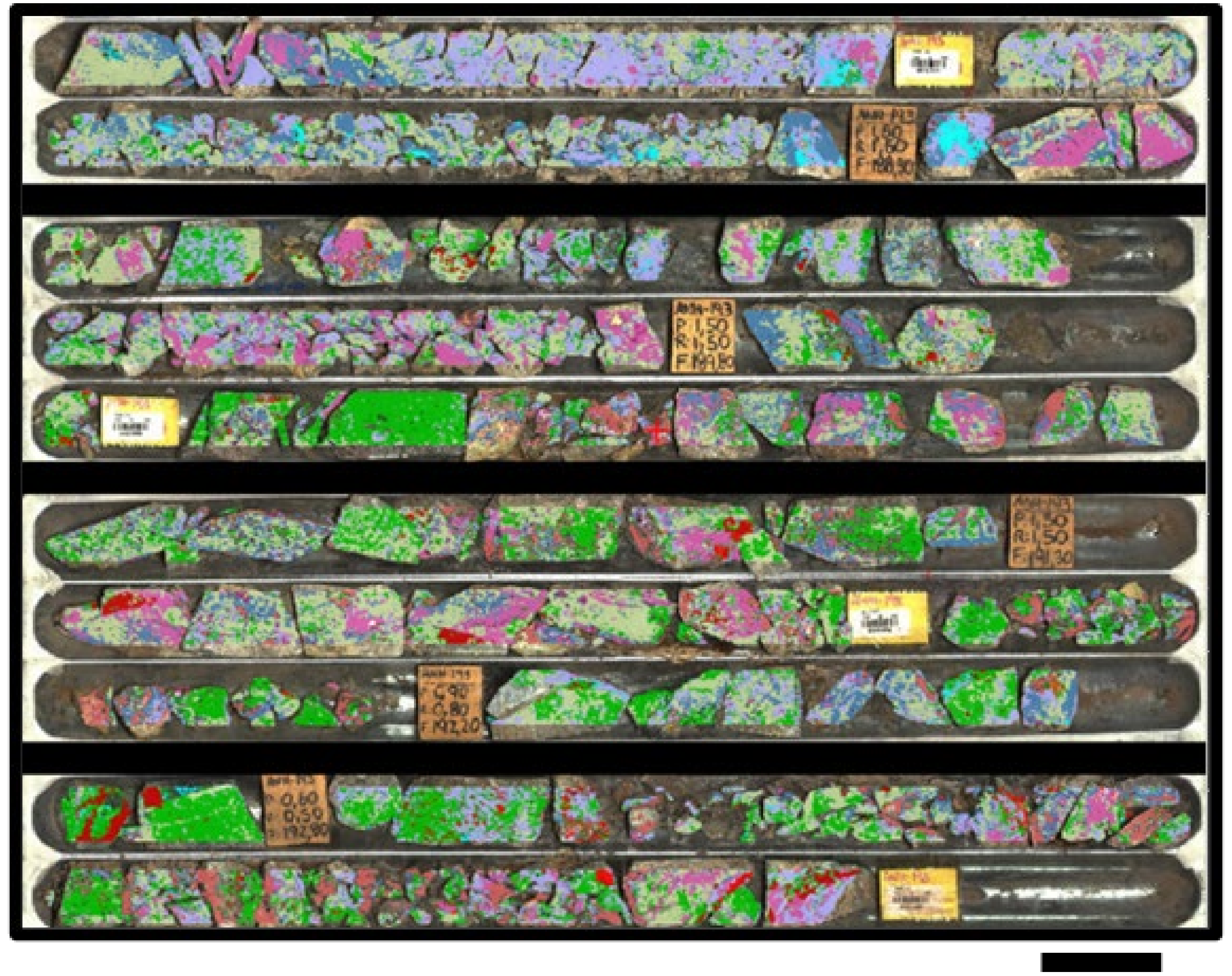


- Dickite
- Pyrophyllite
- Calcite
- Gypsum
- Alunite
- Tourmaline
- Atacamite
- Chrysocolla
- Kaolinite
- Montmorillonite
- Phlogopite
- White Mica
- Chlorite
- Featureless Slope

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/Silice Hidratado	
Cuarzo/Silice Opalino	
Oxido de Fe (general)	
Featureless Slope (FLS) - Tipo 1**	
Featureless Slope (FLS) - Tipo 2**	

** Featureless Slope Spectra



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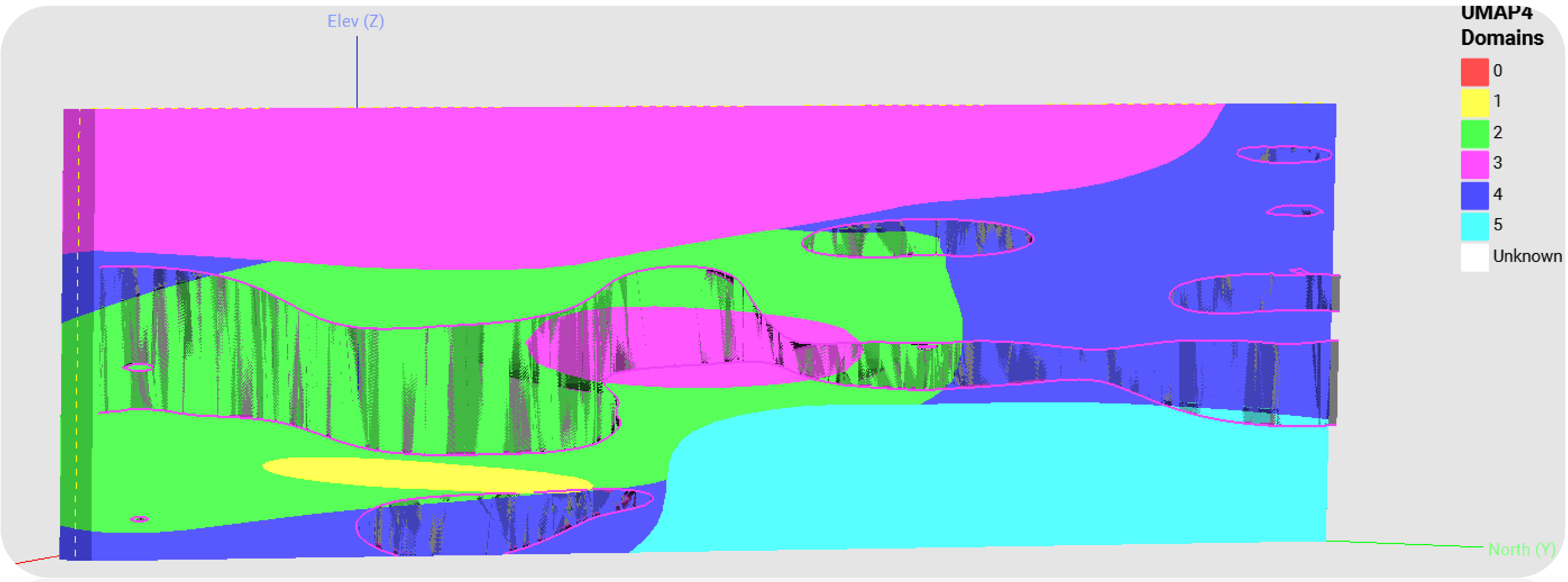
Why did size matter: counting statistics

- Continuous dataset to use as the backbone for any ML models to predict or classify parameters.
- Continuous dataset to use as a backbone for the domaining model:
    - Texture
    - Mineralogy



Size Matters, the importance of mineralogy and texture in mining porphyry copper deposits: part II

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