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Integrating hyperspectral imaging datasets in 3D alteration and geometallurgical domaining models with case studies

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HSI in mining and mineral exploration

Why is this technology relevant?

- **Accurate mineral detection**: Hyperspectral imaging (HSI) captures data across the electromagnetic spectrum, identifying key minerals like illite, chlorite, montmorillonite, kaolinite, and white mica with precision.
- **Insight into mineral chemistry**: HSI detects subtle variations in minerals, such as changes in white mica composition, which helps vector towards ore zones.

Why is mineralogy from HSI relevant?

- **Understanding alteration and gangue minerals**: minerals like white mica, chlorite, biotite, kaolinite, and smectites provide clues about proximity to ore, but can also impact processing performance.

What is the best way to utilize this data?

- **Real-time updates**: the data integrates quickly into 3D models, allowing for continuous updates as new information is gathered.

This talk is about the *how*

- **How do we get this data into 3D models?**
- **How many ways can we get this data into 3D?**

Two cases, two modeling styles

Fit-for-Purpose 3D Modeling for Different Stages of the Mining Value Chain (MVC)

- **Case Study 1: Ocelot Project, Arizona, USA (Exploration Stage)**
  - Aimed to create a 3D alteration model.
  - Integrated hyperspectral imaging (HSI) and core logging data to model a porphyry copper deposit (PCD).
  - Core logging provided critical mineralogical insights that complement HSI by identifying phases not detectable in VNIR-SWIR bands.

- **Case Study 2: Caspiche Project, Chile (Pre-Feasibility Stage)**
  - Aimed to create an alteration domain model for geometallurgical purposes.
  - Emphasized a data-driven, unsupervised approach, leveraging machine learning techniques to identify natural mineralogical groupings.
  - Prioritized capturing mineral domains (e.g., biotite-amphibole-montmorillonite) over traditional paragenetic considerations.
  - These groupings were modeled in 3D to inform downstream processes.

Case Study 1: Paragenesis

Arizona, USA
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Globe-Miami District, Arizona, USA

Geological Context and Analogue Deposit

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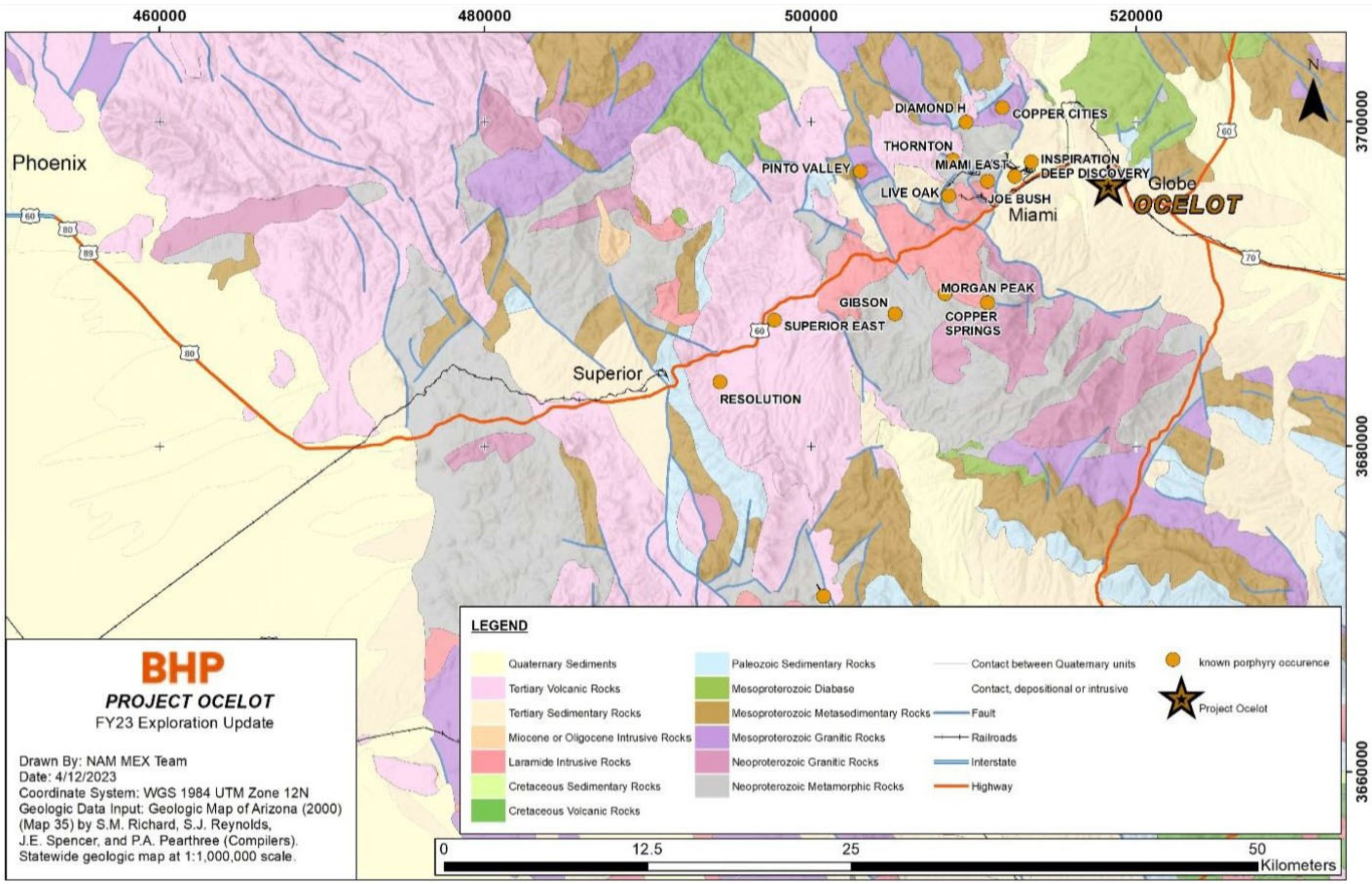

Geology

- The Superior and Globe-Miami districts host an impressive cluster of porphyry copper deposits:

District	Deposit	Historic Cu Production (Mt)	Unmined Cu Reserves (Mt)	Unmined Cu Resources (Mt)	Reference
Globe-Miami	Old Dominion	0.51	-	0.48	Kinnison, 1997
	Miami-Inspiration	9.04	1.47	6.86	Capstone Mining Corp., 2021; Magma Copper Company, 1995; Bird et al., 2020; BHP Billiton PLC, 2004; Wellman et al., 2006
	Copper Cities	0.45	-	0.68	Briggs, 2022; BHP Billiton PLC, 2011
Summit	Copper Springs/Azurite	0.01	-	0.08	Corn, 1990; Gatchalian, 1975
Pioneer	Magma	1.30	0.01	0.06	Magma Copper Company, 1995
	Resolution	-	-	30.06	Rio Tinto PLC, 2021
	Superior East	-	-	1.80	Sell, 1995
Total		**11.3**	**1.5**	**40.0**	

- All deposits are presumed to be associated with the ~61-65 Ma Schultz Granite intrusive complex.
- Post-mineral faulting, in conjunction with younger sedimentary and volcanic units, conceals mineralization in some known deposits, e.g., Resolution & Miami East.
- Resolution was discovered by Magma Copper in 1995 while exploring for additional high-grade vein and carbonate replacement ore for the Magma Mine.
- In 2012, BHP recognized the Old Dominion vein system as a potential analogue for the Magma vein system and began exploring for a proximal center of hypogene porphyry copper mineralization.

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Old Dominion Vein - Interpretation from underground workings, geological data, state of knowledge prior to 2013 drillhole program

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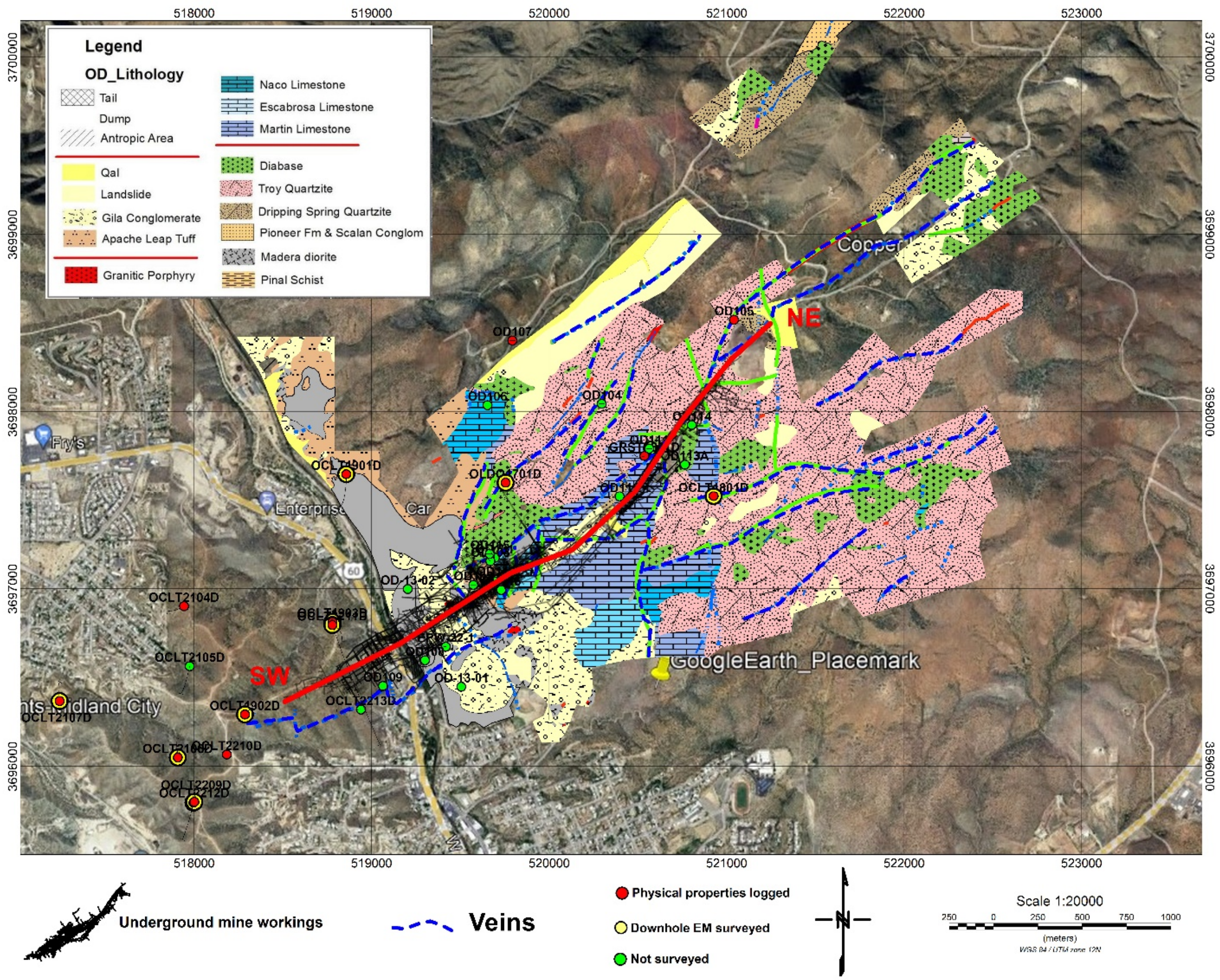
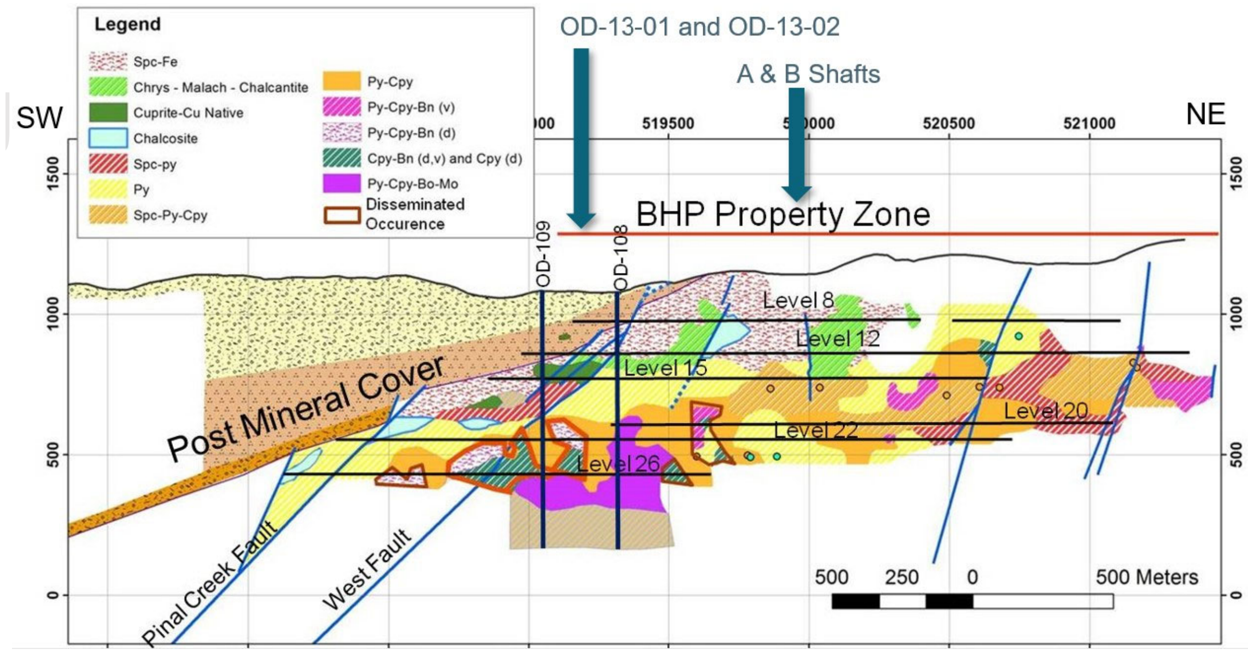




Project Ocelot hosts the Old Dominion vein system that was exploited until 1931 with a total production of 12 Mt at 4.3% Cu (Magma Vein – 198 Mt at 1.4%Cu). Compelling similarities with Resolution triggered an extensive exploration program during 2010's searching for a potential porphyry-related deposit associated with this vein:

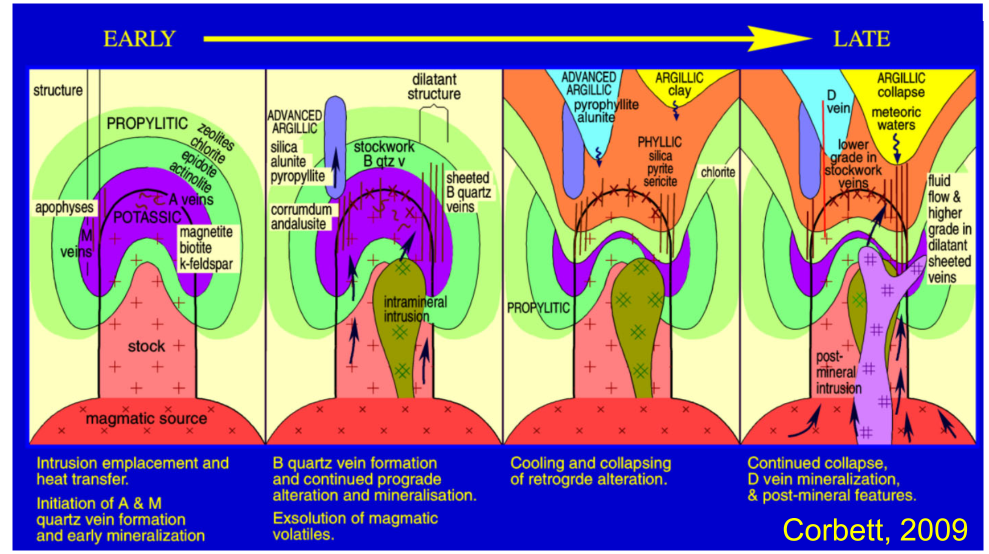
- Integration of recent and historical data.
- Modern geochemistry including ICP and green rocks.
- Geophysical airborne, ground, and downhole surveys.
- Hyperspectral imaging

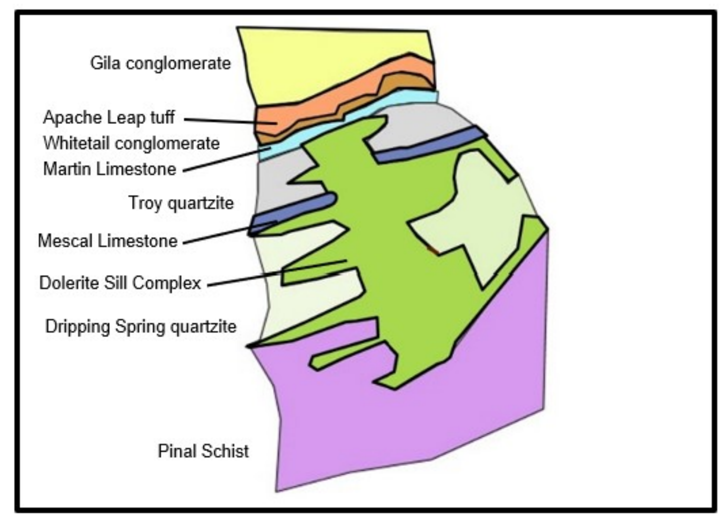
This resulted in significant drill hole intercepts of copper mineralization confirming potential grade and size similar environment to Resolution copper deposit, but at a shallower depth with intercepts starting at 700 m.

Pare, 2024

Reconciling vein PCDs with conceptual models

- The image in the top right shows a conceptual model for a porphyry system, where there is a porphyry stock driving the magmatic-hydrothermal system (Corbett, 2009).
- However, porphyry stocks are volumetrically insignificant at Ocelot (see bottom right; Pare, 2024).
  - Ocelot's mineralization is strongly controlled by permeable and chemically reactive host rocks and is dependent on its proximity to pre- and syn-mineral structures.
  - Additionally, there is hypogene upgrading in parts of the system.
- The challenge is to sort out the porphyry-style alteration halo in this atypical porphyry system.





Globe Miami (Ocelot) Pare, 2024

Building the model: what phases are important?

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HSI Mineral Library

- Alunite
- Calcite
- Chlorite
- Chlorite-Biotite
- Epidote
- Fe-Smectite
- Gypsum
- Kaolinite
- Montmorillonite
- Nontronite
- Phlogopite
- Serpentine
- Talc
- Topaz Mixture
- Tremolite
- Unclassified A, B
- White Mica

Core Logging

- Anhydrite
- Biotite
- Secondary biotite
- Calcite
- Clay
- Chlorite
- Epidote
- Illite
- Kaolinite
- K-feldspar
- Limonite
- Magnetite
- Montmorillonite
- Muscovite
- Quartz
- Sericite

Minerals in Final Model

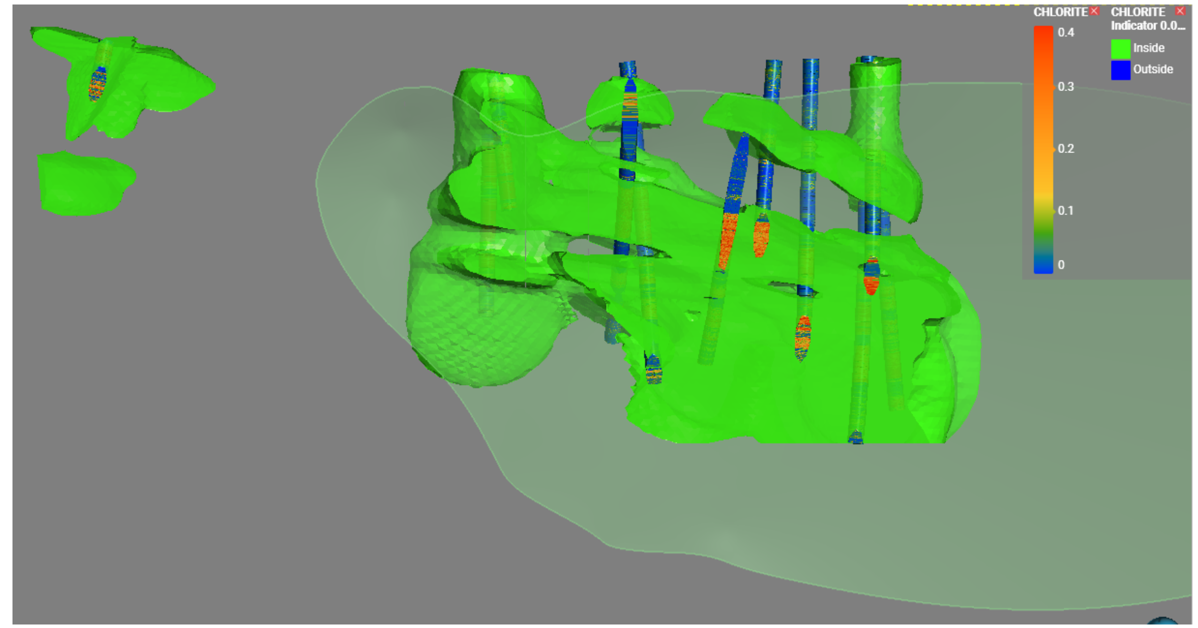
- K-feldspar (logging)
- Biotite (combination HSI, logging)
- Chlorite (HSI)
- White mica (HSI)
- Alunite (HSI)

Additional Datasets

- Structural model
- Structural trends
- Lithological model
- 4-acid geochemistry

Modeling HSI data

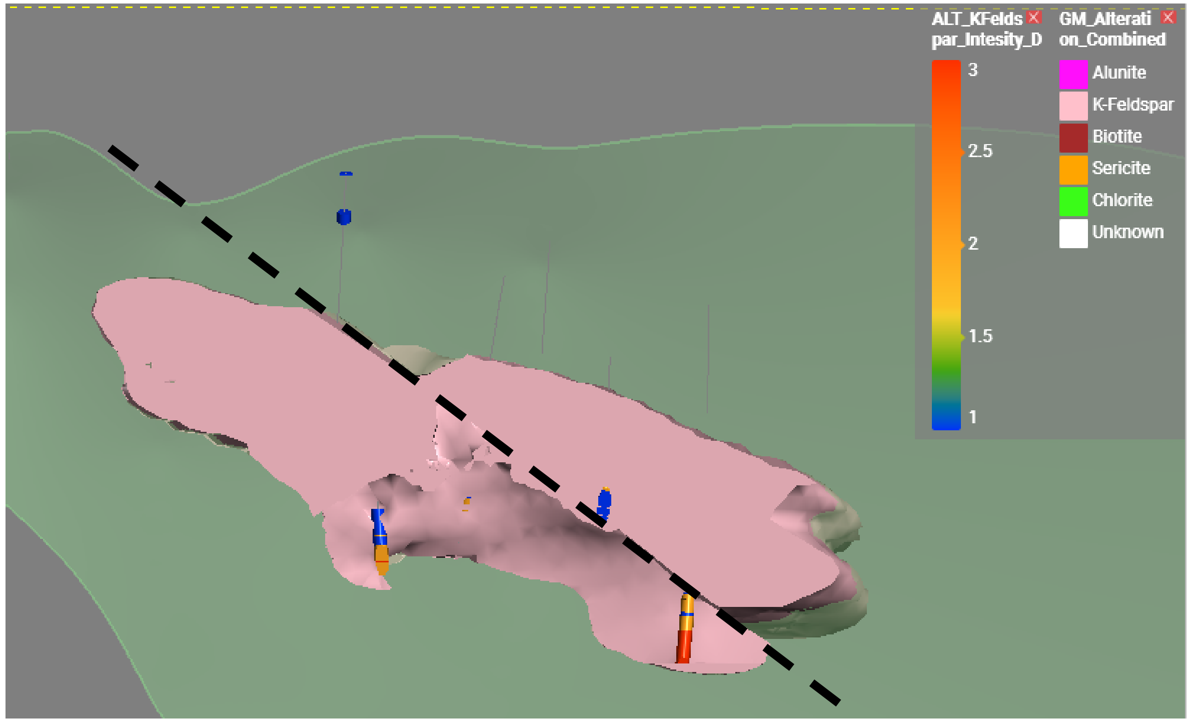
FROM_FT	TO_FT	ALUNITE	CALCITE	CHLORITE	CHLORITEBIOTITE	EPIDOTE	FESMECTITE	GYPSUM	KAOLINITE	MONTMORILLONITE	NONTRONITE	PHLOGOPITE	SERPENTINE	TALC	TOPAZMIXTURE	TREMOLITE	UNCLASSIFIEDA	UNCLASSIFIEDB	WHITEMICA
0	10	0.03	0	0.01	0	0	0.06	0	0.04	0.24	0.04	0	0	0	0.01	0	0.08	0.05	0.43
10	20	0.02	0.01	0.05	0	0	0.15	0	0.01	0.13	0.07	0	0.01	0	0	0.01	0.1	0.02	0.43
20	30	0.03	0.01	0.03	0	0	0.13	0	0.01	0.11	0.07	0	0	0	0	0	0.16	0.03	0.42
30	40	0	0	0.05	0	0	0.06	0	0	0.01	0.06	0	0	0	0	0	0.65	0	0.15
40	50	0.01	0	0.04	0	0	0.05	0	0	0.03	0.07	0	0	0	0	0	0.69	0	0.1
50	60	0.01	0	0.06	0	0	0.02	0	0	0	0.05	0	0	0	0	0	0.77	0.01	0.08
60	70	0	0.01	0.09	0	0	0.02	0	0	0.01	0.06	0	0	0	0	0	0.67	0	0.14
70	80	0	0.01	0.09	0	0	0.01	0	0	0	0.06	0	0	0	0	0	0.67	0	0.14
80	90	0	0.01	0.09	0	0	0.01	0	0	0	0.07	0	0.01	0	0	0	0.7	0	0.11
90	100	0	0.02	0.23	0	0	0.04	0	0	0.08	0.09	0	0.02	0	0	0	0.35	0	0.15
100	110	0	0.01	0.11	0	0	0.04	0	0	0.24	0.37	0	0.01	0	0	0	0.15	0.02	0.04
110	120	0	0.02	0.18	0	0	0.05	0	0	0.25	0.3	0	0.02	0	0	0	0.15	0.01	0.02
120	130	0	0.03	0.19	0	0	0.1	0	0	0.19	0.35	0	0.02	0	0	0	0.1	0.01	0.02
130	140	0	0.03	0.24	0	0	0.09	0	0	0.2	0.28	0	0.02	0	0	0	0.11	0.01	0.03
140	150	0	0.03	0.42	0	0	0.08	0	0.01	0.01	0.01	0.03	0	0	0	0	0.07	0	0.33
150	160	0	0.03	0.42	0	0.01	0.12	0	0.01	0.01	0.01	0.04	0	0	0	0	0.09	0	0.26
160	170	0	0.04	0.6	0	0	0.03	0	0	0	0.01	0.04	0.01	0	0	0	0.1	0	0.15
170	180	0	0.04	0.5	0	0	0.12	0	0	0.04	0.07	0.03	0.01	0	0	0	0.12	0	0.07
180	190	0	0.04	0.47	0	0	0.12	0	0	0.05	0.09	0.02	0.02	0	0	0	0.11	0.01	0.08
190	200	0	0.05	0.36	0	0	0.1	0	0	0.09	0.16	0.03	0.03	0	0	0	0.1	0	0.06
200	210	0.01	0.03	0.26	0	0	0.06	0	0	0.15	0.21	0.02	0.05	0	0	0.01	0.12	0.01	0.07
210	220	0	0.03	0.23	0	0	0.03	0	0	0.18	0.28	0.02	0.05	0	0	0.01	0.09	0.01	0.06
220	230	0	0.03	0.25	0	0	0.04	0	0	0.17	0.24	0.02	0.06	0	0	0.01	0.1	0.01	0.05
230	240	0	0.02	0.13	0	0	0.11	0	0	0.29	0.25	0	0.04	0	0	0	0.1	0	0.05
240	250	0	0.03	0.29	0	0	0.09	0	0	0.13	0.15	0.08	0.02	0	0	0.01	0.14	0.01	0.06
250	260	0.02	0.01	0.31	0	0	0.05	0	0.02	0.04	0.03	0.07	0.01	0	0	0	0.18	0	0.26
260	270	0.02	0.01	0.32	0	0	0.03	0	0.03	0.01	0.01	0.08	0	0	0	0	0.16	0	0.33
270	280	0.01	0.01	0.39	0	0	0.05	0	0.02	0.02	0.02	0.07	0	0	0	0	0.16	0	0.26
280	290	0.01	0.01	0.28	0	0	0.03	0	0.01	0.01	0.06	0.07	0	0	0	0	0.31	0.01	0.19
290	300	0.02	0.02	0.42	0	0	0.04	0	0.01	0.01	0.02	0.07	0	0	0	0	0.24	0	0.16
300	310	0.04	0.01	0.29	0	0.01	0.02	0	0.03	0	0.01	0.08	0	0	0	0	0.2	0	0.3
310	320	0.05	0.01	0.21	0	0.01	0.02	0	0.04	0	0.02	0.08	0	0	0	0	0.22	0	0.34
320	330	0.07	0.01	0.16	0	0.01	0.01	0	0.04	0	0.01	0.08	0	0	0	0	0.2	0	0.4
330	340	0.04	0.01	0.13	0	0.01	0.03	0	0.05	0.01	0.01	0.09	0	0	0	0	0.25	0	0.37
340	350	0.02	0.01	0.09	0	0	0.07	0	0.04	0.03	0.04	0.06	0	0	0	0	0.22	0.01	0.4
350	360	0.02	0	0.04	0	0	0.07	0	0	0.11	0.13	0.02	0	0	0	0	0.23	0.05	0.31
360	370	0.01	0	0.02	0	0	0.03	0	0	0.32	0.09	0.01	0	0	0	0	0.15	0.16	0.19
370	380	0.02	0	0.05	0	0	0.06	0	0.01	0.16	0.1	0.02	0	0	0	0	0.17	0.09	0.31
380	390	0.02	0	0.01	0	0	0.01	0	0	0.32	0.08	0	0	0	0	0	0.14	0.24	0.17
390	400	0.02	0	0	0	0	0.01	0	0	0.33	0.12	0	0	0	0	0	0.1	0.17	0.24
400	410	0.03	0	0	0	0	0.06	0	0.01	0.2	0.08	0	0	0	0	0	0.29	0.13	0.19
410	420	0.05	0	0	0	0	0.01	0	0	0.24	0.09	0	0	0	0	0	0.27	0.2	0.13
420	430	0.1	0	0	0	0	0.02	0	0.02	0.15	0.07	0	0	0	0	0	0.25	0.09	0.29
430	440	0.06	0	0.01	0	0	0.01	0	0	0.01	0.04	0	0	0	0	0	0.61	0.11	0.15
440	450	0.1	0	0.01	0	0.01	0.02	0	0.12	0.05	0.03	0.01	0	0	0	0	0.22	0.03	0.41
450	460	0.1	0	0.01	0	0	0.02	0	0.23	0.14	0.03	0.01	0	0	0	0	0.14	0.01	0.29
460	470	0.09	0.01	0.11	0	0	0.18	0	0.07	0.16	0.03	0	0	0	0	0	0.12	0.01	0.21
470	480	0	0.02	0.25	0	0	0.24	0	0	0.14	0.1	0	0.01	0	0	0	0.2	0.01	0.02
480	490	0	0	0.04	0	0	0.13	0	0	0.34	0.4	0	0.01	0	0	0	0.05	0.01	0.02
490	500	0	0	0.04	0	0	0.07	0.01	0	0.3	0.44	0	0.01	0	0	0	0.04	0.02	0.06
500	510	0	0.01	0.05	0	0	0.14	0	0	0.3	0.4	0	0.02	0	0	0	0.04	0.02	0.03
510	520	0	0	0.03	0	0	0.12	0	0	0.44	0.32	0	0.01	0	0	0	0.03	0.02	0.03
520	530	0	0	0.01	0	0	0.05	0	0	0.52	0.32	0	0	0	0	0	0.04	0.02	0.02
530	540	0	0	0.03	0	0	0.06	0	0	0.45	0.36	0	0.01	0	0	0	0.05	0.02	0.02
540	550	0	0.01	0.05	0	0	0.06	0	0	0.32	0.47	0	0.02	0	0	0	0.06	0.01	0.02
550	560	0	0.01	0.08	0	0	0.11	0	0	0.37	0.31	0	0.02	0	0	0	0.08	0.01	0.02
560	570	0	0	0.03	0	0	0.05	0	0	0.33	0.51	0	0.01	0	0	0	0.04	0.01	0.02
570	580	0	0	0.02	0	0	0.05	0	0	0.49	0.35	0	0	0	0	0	0.05	0	0.03
580	590	0.01	0.01	0.16	0	0	0.13	0	0	0.12	0.07	0.02	0.01	0	0	0.01	0.29	0.01	0.16
590	600	0.04	0.02	0.22	0	0	0.14	0	0	0.02	0.03	0.03	0.01	0	0	0.02	0.21	0.02	0.24
600	610	0.02	0.02	0.29	0	0	0.1	0	0	0.01	0.03	0.05	0.02	0	0	0.02	0.33	0.01	0.09
610	620	0.03	0.01	0.09	0	0	0.01	0	0	0	0.01	0.02	0.02	0	0	0.04	0.77	0.01	0.02
620	630	0.03	0.01	0.05	0	0	0.02	0	0	0	0.02	0.01	0.02	0	0	0.01	0.79	0.01	0.02
630	640	0.03	0.01	0.06	0	0	0.02	0	0	0	0.02	0	0.03	0	0	0.01	0.76	0.03	0.02
640	650	0.05	0.02	0.18	0	0	0.04	0	0	0	0.01	0.01	0.04	0	0	0.04	0.54	0.02	0.03
650	660	0.03	0.02	0.24	0	0	0.08	0	0	0	0.03	0.01	0.05	0	0	0.03	0.47	0.02	0.02



The 0.05 indicator RBF interpolant for chlorite created from the HSI export. These models are automatically updated with any new data appended to the HSI file in the Drillhole section of the project tree. Old Dominion Fault shown in light green.

Integrating core logging data

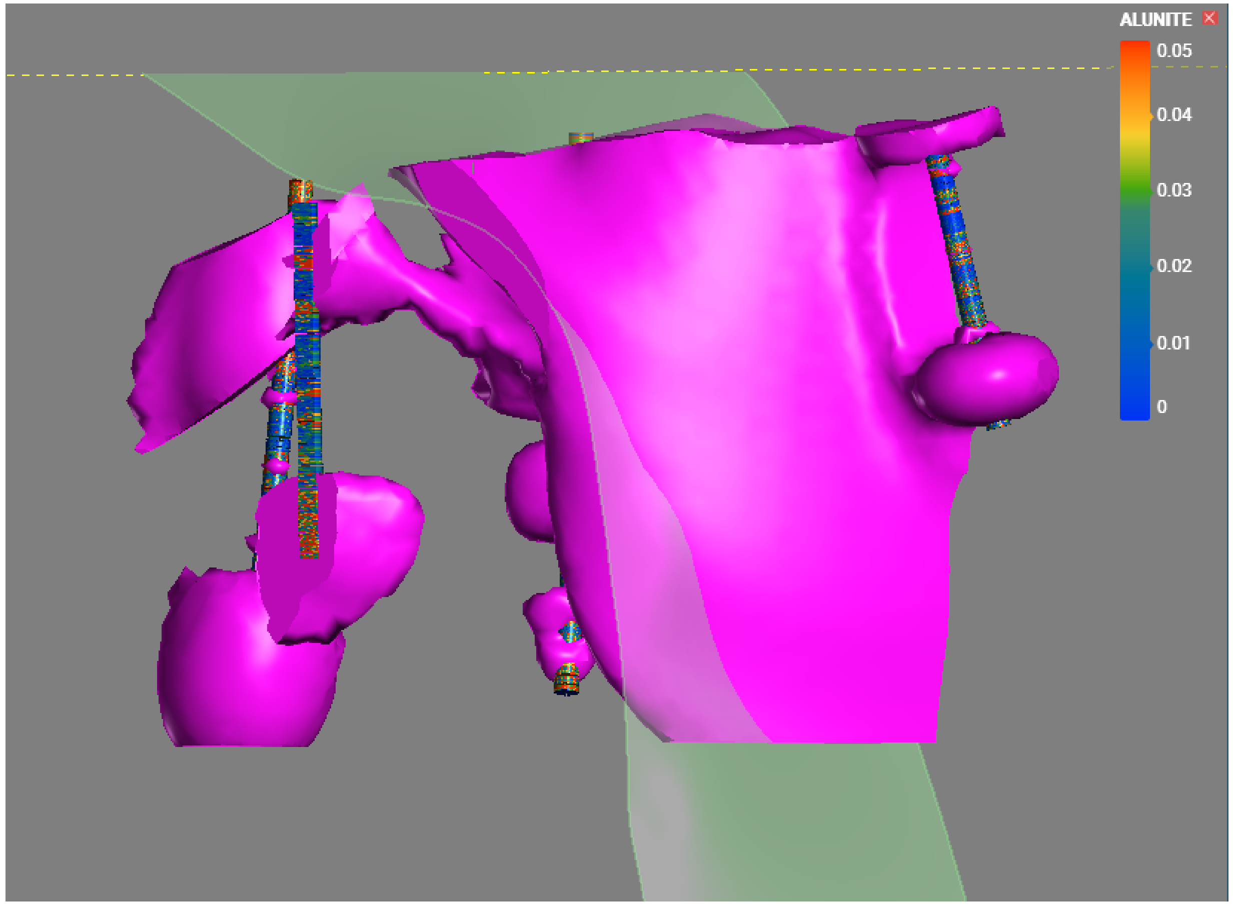
- Not only did we integrate K-feldspar and secondary biotite from the core logging data, but we also:
    - Utilized the structural trends from the Pioneer Formation (Yp) – Dripping Springs Quartzite (Yds) Contact, as well as the diabase (Yd) and Pinal Schist (Xp);
    - Modeled the HSI differently for the different structural zones; here you can see the offset from the Pinal Creek Fault.



The 2.0 indicator RBF interpolant for K-feldspar created from the alteration logging (minerals and intensities) export. Similar to the HSI numerical models, these models are automatically updated with any new data appended to the alteration file in the Drillhole section of the project tree. Old Dominion Fault shown in light green.

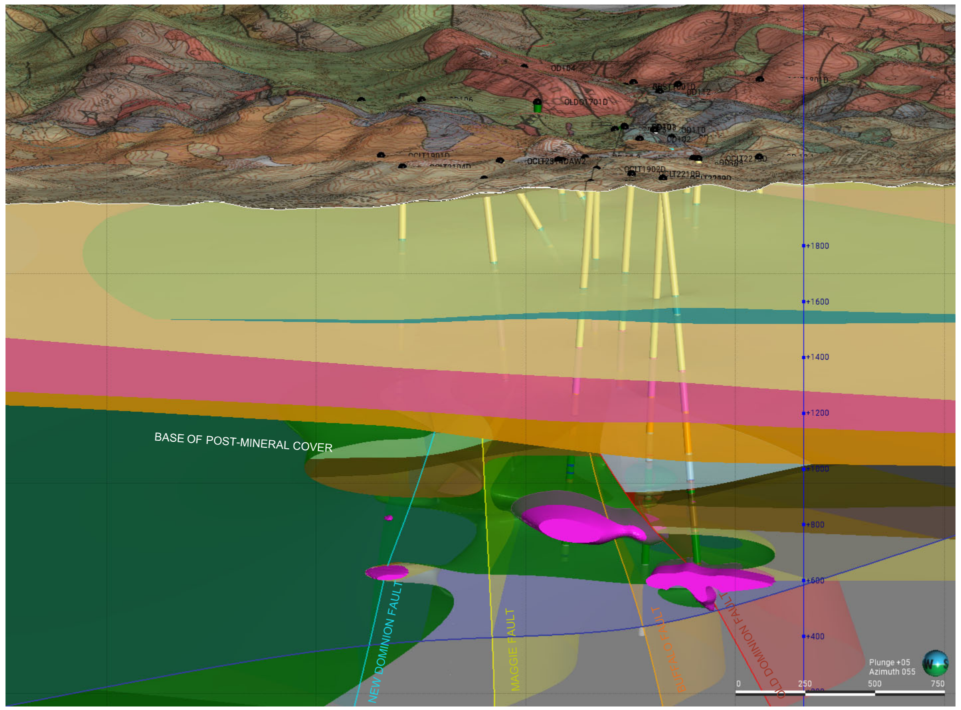
Hypogene upgrading

- An important facet of this model was to map where there is evidence of alteration coincident with hypogene upgrading.
- Topaz and alunite were identified by HSI.
- The interpretation was that high sulfidation fluids moved through the vein system, such as Old Dominion featured in the image at right (light green).
    - From a modeling perspective, structural trends from the veins were used to instruct construction of this shell.



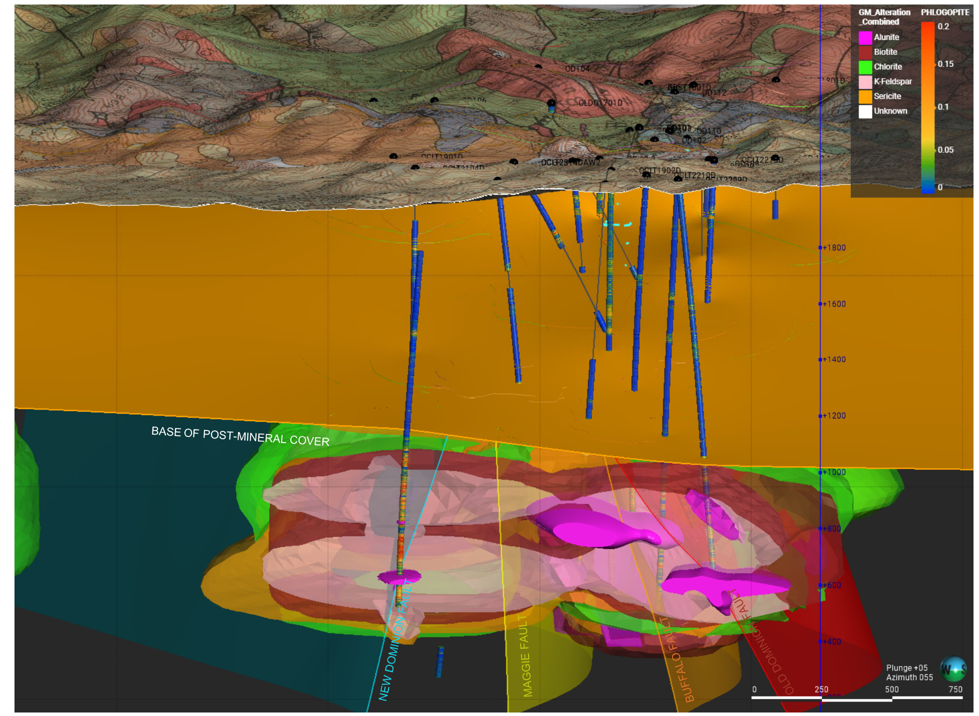
The 0.03 indicator RBF interpolant alunite created from the HSI export. These models are automatically updated with any new data appended to the HSI file in the Drillhole section of the project tree. Old Dominion Fault shown in light green.

Integrated 3D alteration model



3D Alteration Model Incorporates:

- **Observations from detailed core logging**
- **Multi-element geochemistry**
- **Continuous XRF scanning**
- **Mineral proportion maps from hyperspectral imaging**



INPUT (to determine boundaries & trends) : Lithostructural Model

OUTPUT (for vectoring & characterization): Alteration Model

Case Study 2: Domaining

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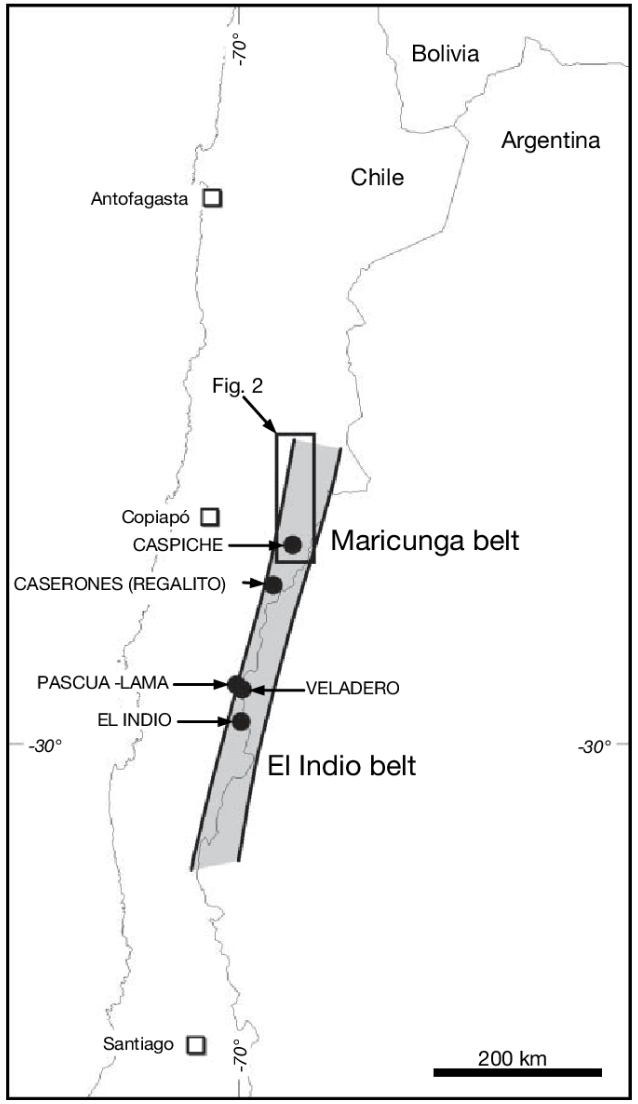
Caspiche-Casale District, Atacama, Chile

Geologic context

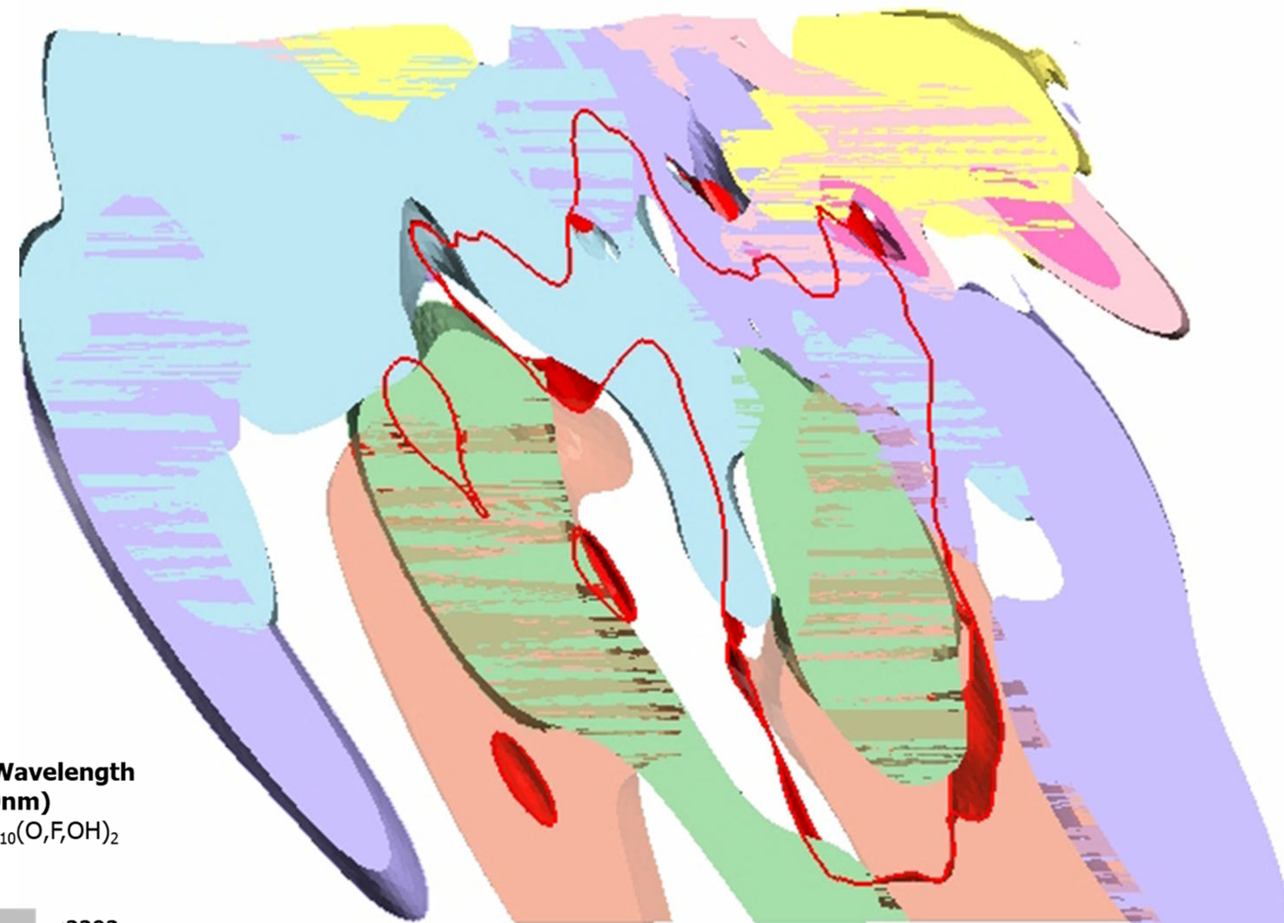
- Caspiche is a Au-Cu porphyry located in Maricunga belt of northern Chile.
- The deposit is characterized by a central gold-copper zone and is hosted in diorite to quartz diorite porphyry stocks.
- The alteration system is documented extensively:
  - Potassic, potassic-calcic, chlorite-sericite, propylitic, and advanced argillic (Sillitoe et al., 2013)
  - However, being onsite from 2018-2019, I know it to be aggressively overprinted by multiple hydrothermal events, both ore bearing and late stage argillic.



Location of the Caspiche porphyry Au-Cu deposit (Sillitoe et al., 2013).

Mapping individual minerals versus domaining

- The goal of creating a geometallurgical alteration domain model with HSI data is to improve geometallurgical testwork selection:
    - Capture complex, multi-mineral and textural zones,
    - Identify key mineral variations that may impact processing to ensure representative samples,
    - Deliver unbiased data across a large dataset.



Illite
Muscovite
Biotite
Amphibole
Pyrophyllite

White Mica Wavelength (2200nm)
$AB_{2-3}(X,Si)_4O_{10}(O,F,OH)_2$

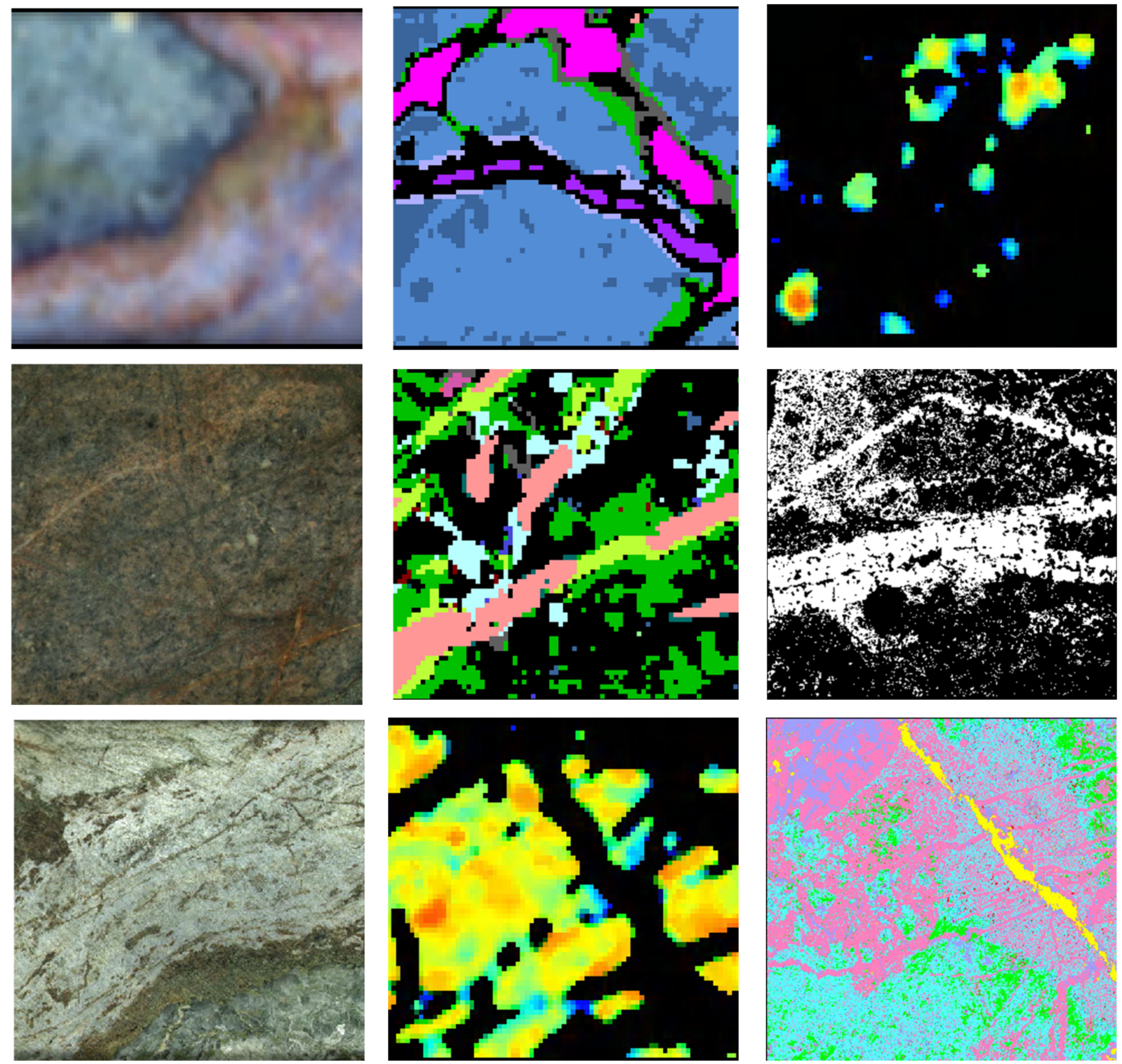
A: Na substitution
B,X: Al substitution
A: K substitution
B: Fe, Mg substitution
X: Si substitution

<2202nm
2202-2204nm
2204-2207nm
2207-2210nm
>2210nm

Cu > 0.2 wt%

Hyperspectral image data workflows

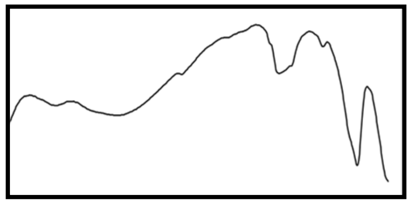
- Images are data!
- After curating set of depth registered “clean” images several different types of analysis can be performed:
    - **Image classification**
        - Lithological classification
        - Texture classification
    - **Image segmentation**
        - Object detection
        - Object segmentation (physical grains)
            - Geological object segmentation
                - (veins, laminations, foliations, physical grains)
    - **Extraction of descriptive statistics**
        - Texture statistics



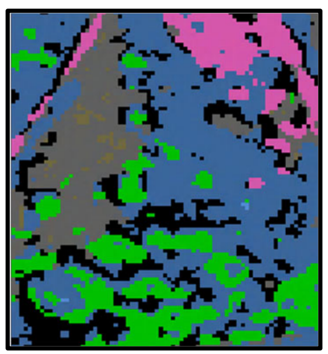
Upscaling and domaining hyperspectral data

Raw Data

Spectra at 500µm

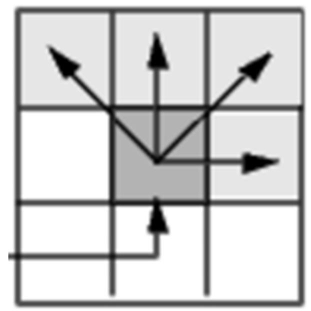


Mineral class maps



Generation of descriptive statistics

Mineral association

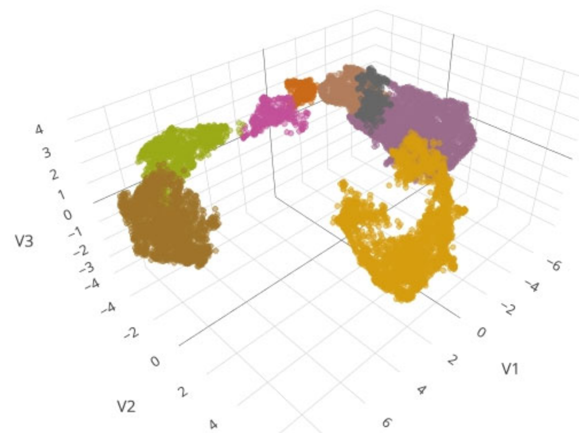


Mineral proportion

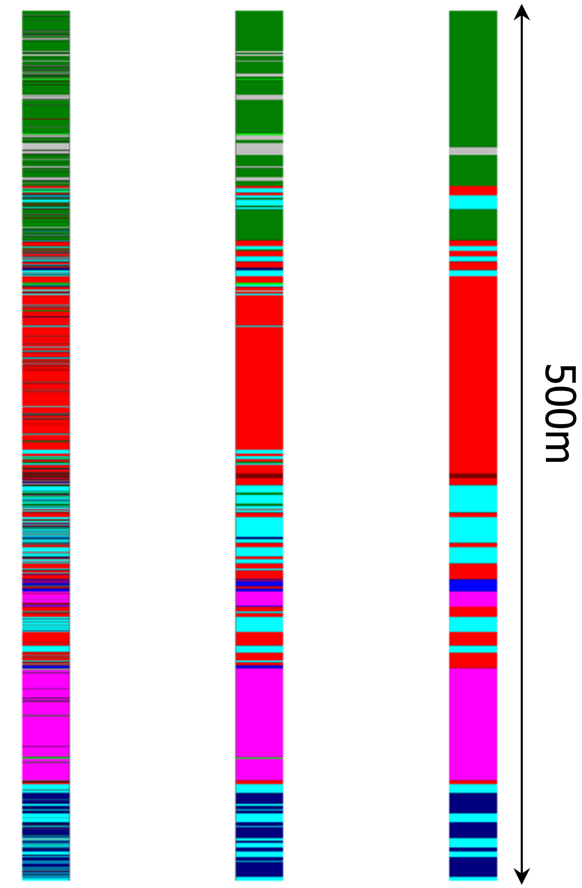
aspectral_	biotite_pxa	carbonate_pxa	chlorite_pxa	epidote_pxa
0.045	0	0.125	0.404	0.391
0.089	0.001	0.095	0.392	0.138
0.083	0.002	0.155	0.409	0.278
0.022	0.018	0.215	0.403	0.452
0.002	0.002	0.203	0.536	0.56
0.027	0.004	0.263	0.516	0.3
0.036	0	0.046	0.113	0.761

Clustering of multivariate signature + validation

Plotting of similarity metric in low dimensional space to assess clustered solution



Clusters are smoothed to desired level of detail



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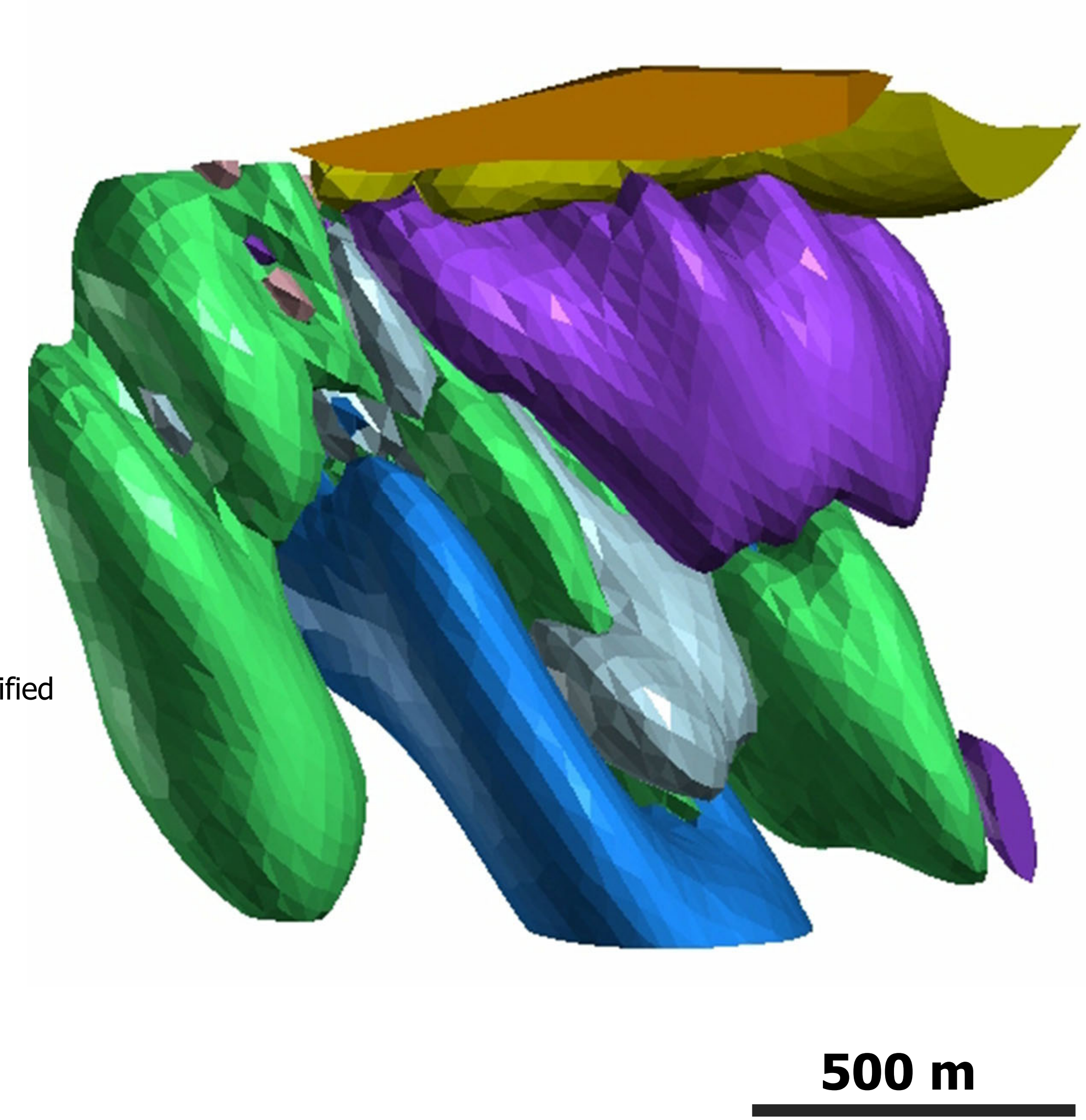
Modeling Caspiche HSI data in 3D

- How do we look at where the minerals coexist?
- How do we look at 35 minerals simultaneously?
- How do we incorporate their texture and style of occurrence?
- Importantly, have we effectively domained our orebody?



- 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

Proposed Workflow for Geometallurgical Testwork Sampling

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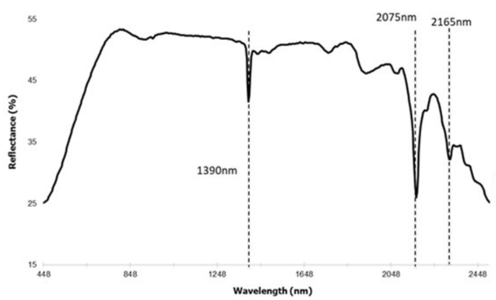
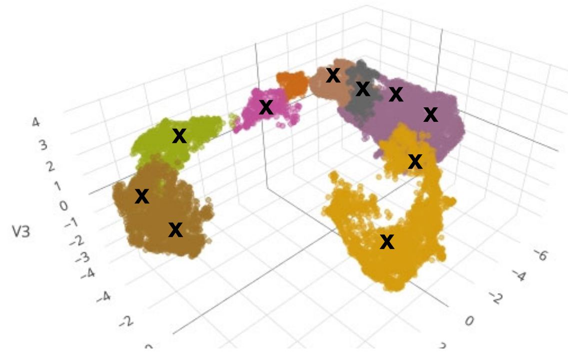
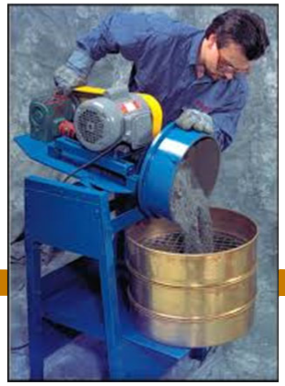


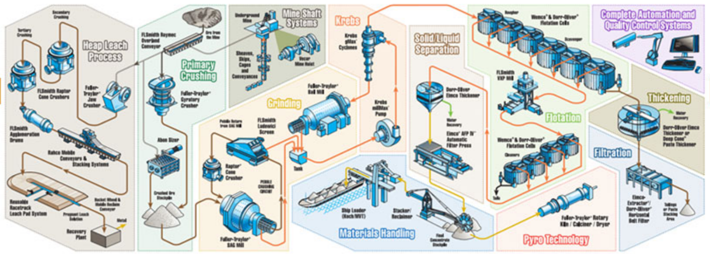
Recognize Mineral Presence



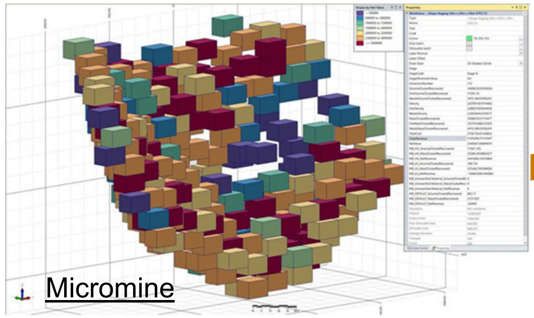
Domain Mineralogy & Textures for Specific Testwork



Perform Appropriate Testwork



Optimize Flowsheet



Improved Resource Model

Multiple approaches to modeling HIS data

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- **Fit-for-purpose models**: the two case studies demonstrate that HSI data can be easily integrated into modeling software, but also that different modeling techniques are suited to different stages of the MVC:
  - **Exploration stage**: a traditional alteration-focused approach, integrating HSI with core logging and geochemistry.
  - **Pre-feasibility stage**: a data-driven approach using unsupervised machine learning to define mineralogical domains using the mineralogy, as well as textural information in order to optimizing resource understanding.

- **Both approaches are valuable**: whether prioritizing geological processes (paragenesis) or focusing on mineral domains for operational efficiency, both methods provide critical insights.

- **Future modeling styles**: how can we continue to improve our understanding of mineral systems to enhance decision making? How do *you* model your HSI data?

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Co-authors, BHP, Norte Abierto, the organizing committee, &
everyone here at 16:30 on Thursday…

Thank you!