Mining Ores of Northern Chile

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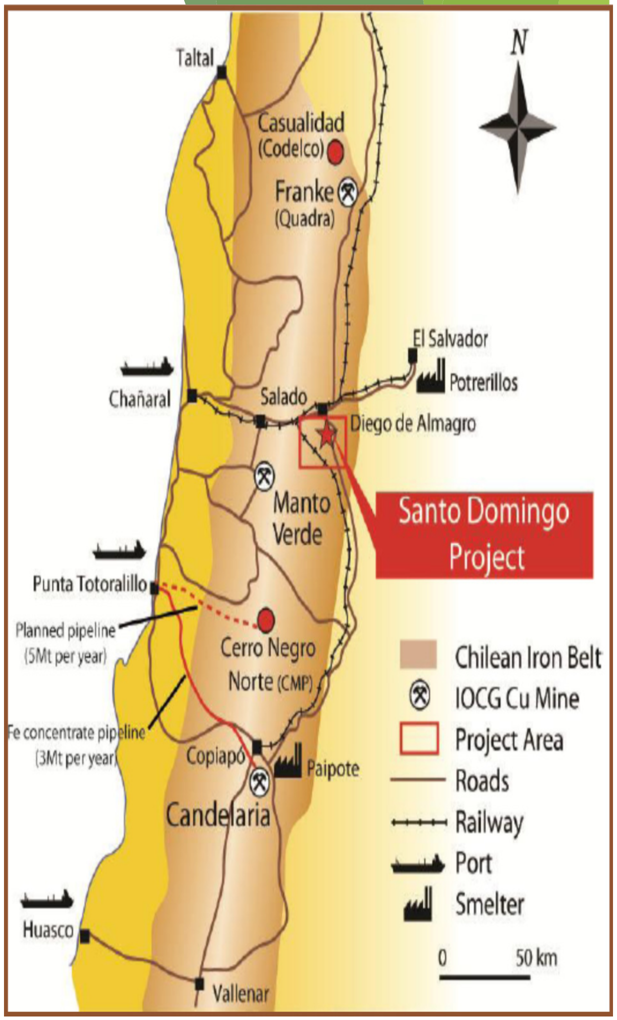
Geology of Northern Chile

- The Chilean Iron Belt
  - mineralization episode during the Andean orogeny.
  - 40 mineral deposits
- Andean orogeny
  - Convergent boundary
  - Paleozoic and Precambrian periods.
- Most of the mineral deposits were created from magmatic hydrothermal activity.
  - The water required to form those deposits derived from the subducted slab of the oceanic crust beneath the Andes.

(Moreno and Gibbons, 2007)



http://blog.ceo.ca/2013/08/08/capstone-acquires-option-on-greenfield-property-in-prolific-chilean-copper-belt/

Location: Candelaria Mine

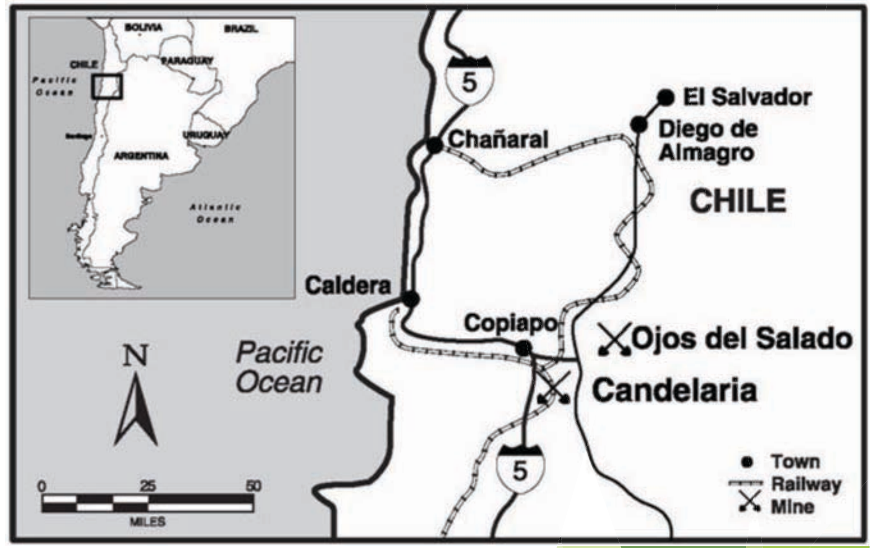
- Located near in the Atacama Region of Copiapó Province, near Copiapó, Chile
- Open pit mining since it opened in 1983
- Composed of Permian to Lower Cretaceous rocks.
- The Candelaria mine is part of the Punta del Cobre formation in the Chañarcillo Group
- Candelaria mine consists of chalcopyrite, magnetite, pyrite, pyrrhotite, and sphalerite.

(SRK Consulting, 2017)

<u>Fun Fact:</u>

Within the next year, suspected yield is 184 kilotons of copper, 105,000 ounces of gold, and 1.8 million ounces of silver

https://www.sec.gov/Archives/edgar/data/831259/000083125914000006/a2013form10-k.htm



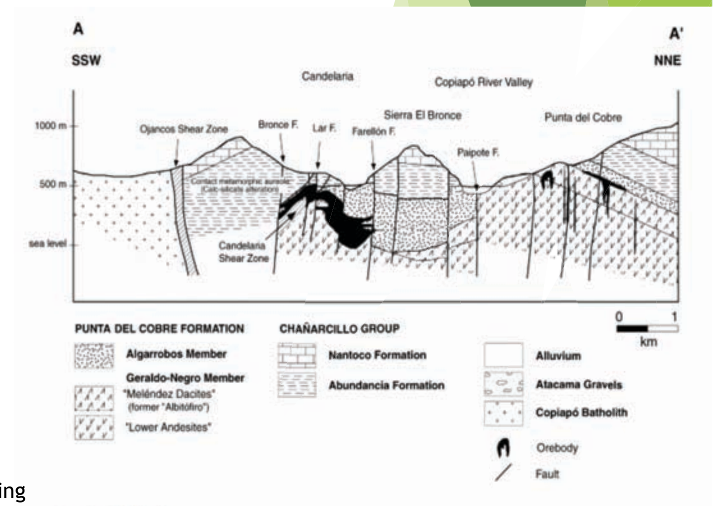


Diagram Credit: SRK Consulting

What are Supergenes?

Supergene: A natural concentration process that gives an unusual abundance of a desired element (typically copper or gold).

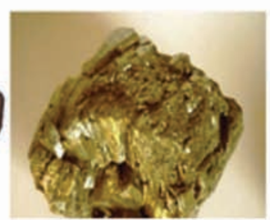
(Harraz. H, 2013)

Why are They Important?

They cause a natural mineral deposit to have greater mineral concentration and higher economic value.

The Very Basic Concept?

leaching of valuable elements from the upper parts of mineral deposits to greater depths where they precipitate and produce higher element concentrations



https://www.rockology.net/shop/copper/michigan-copper-ore-11

Diagram Credit: Aligrah Muslim University

Supergenes – the Basics

- Supergene enrichment is essential for the economic viability of many porphyry copper deposits.
- Surface oxidation produces acidic solutions that leach minerals
- Solution percolates downward until it reaches past the water table.
- Once the water table is reached reducing conditions become more favorable.

(Harraz H, 2013)

Oxidized Zone -> Leaching

Supergene Zone -> Enriched

Protore -> Unaltered Parent Material

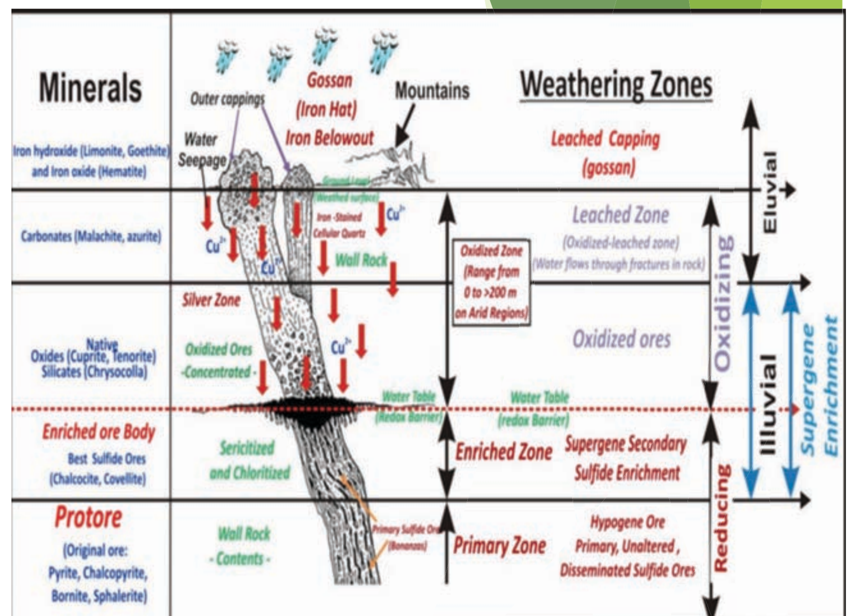
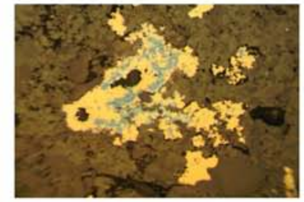


Diagram Credit: Harraz H. 2013

Morphology of Zoning

Most common minerals in **Oxidized Zones**:

- Copper: malachite, azurite, Chrysocolla, cuprite
- Gangue Minerals: Quartz, barite, calcite
- Iron: Goethite, hematite, pyrite
- Lead: anglesite, cerussite
- Manganese: pyrolusite
- Nickel
- Silver
- Zinc: Smithsonite

Most common minerals in **Supergene Zones**:

Copper: Chalcocite, bornite, covellite

Lead: Galena

Nickel

Silver

Zinc: sphalerite, wurtzite

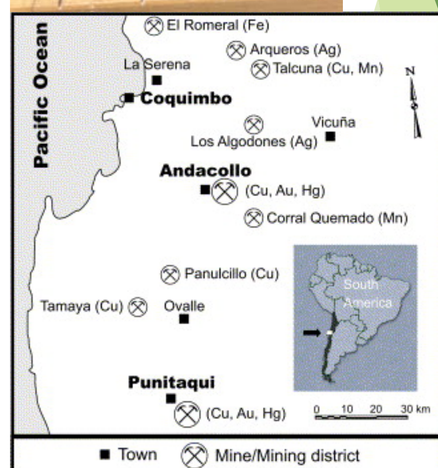







Background: Talcuna Mine

- Northern Chile
- Cu and Mg deposits (Munoz, 1975)
- Stratiform Cu deposits (Talcuna Mine)
  - Confined within strata
  - Hydrothermal deposits (Morales,2005)
  - *Quebrada Marquesa Formation* (Morales, 2005)
  - Low grade metamorphism
- Alteration: chlorite-epidote-calcite-albite, prehnite, zeolite
  (Oyarzun,1998)
- 2 Events
  - Early manganese deposit (Oyarzun, 1998)
  - Late vein deposit (Oyarzun, 1998)

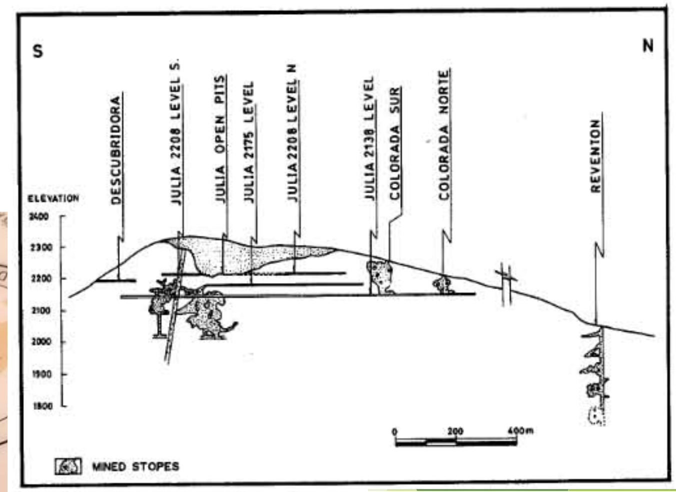


https://www.sciencedirect.com/science/article/pii/S0883292704001039

Background: Montecristo

- Mancilla Plutonic complex
- Iron oxide vein
  - Copper and Iron
- 10 m thick, 1000 m long
- Localized with diabase dykes

(Espinoza Et Al., 1996)



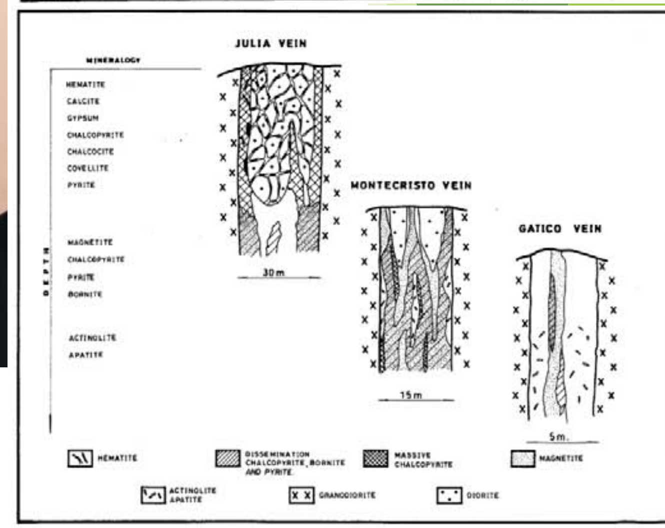
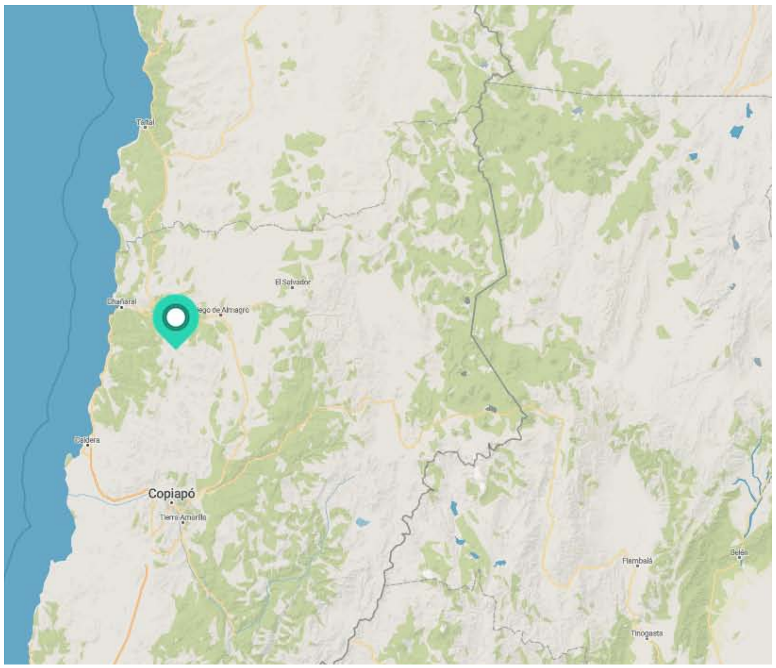
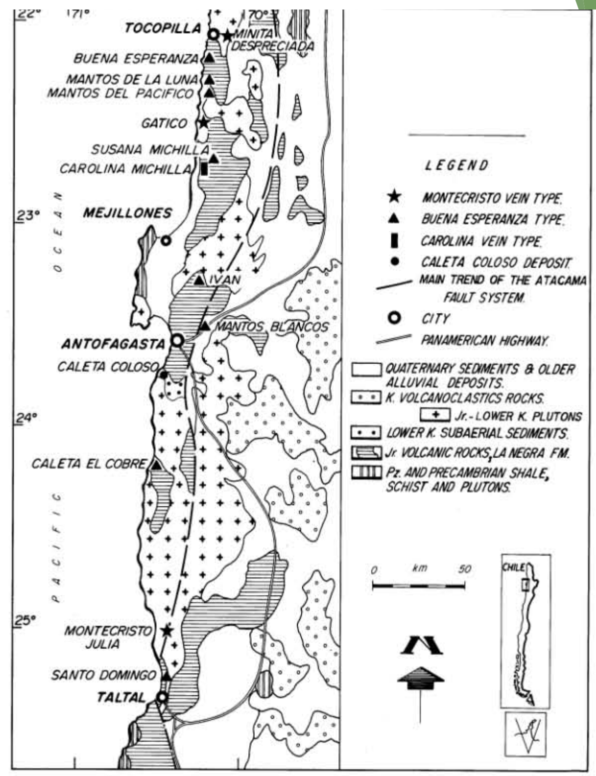


FIGURE 6—Vertical mineralogical zoning and correlation between three Montecristo type veins.

location: Montecristo Mine





Guiding Questions

- Minerology
  - Host rock
  - Ore mineral
- Protolith
  - Copper source
- Geologic story
  - Cause of metamorphism
  - Potential metamorphic facies

Methods: Thin Section

- Cut hand sample to the appropriate length and width to neatly fit on thin section
- "Glue" or use epoxy as a 10:3 ratio and stick the cut rock sample to prepared slide
- Grind sample starting with 400 grit on a glass plate and continue to increasing finer grades (600 grit and 1000 grit)
- Polish sample using 1 micrometer diamond grit and if necessary move down to 0.25 micrometer or even .05 micrometer grit size.

Epoxy

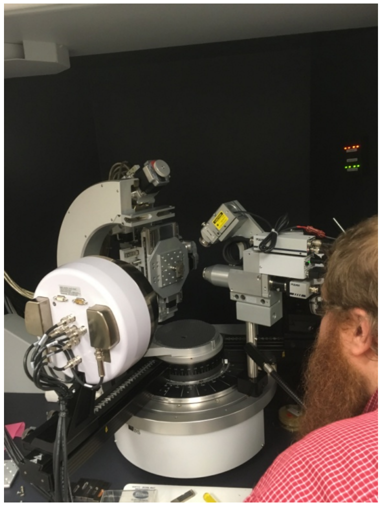
- Similar 10:3 ratio with sample placed in a container for a specific mold size.
- Epoxy sample under went same polishing procedures.

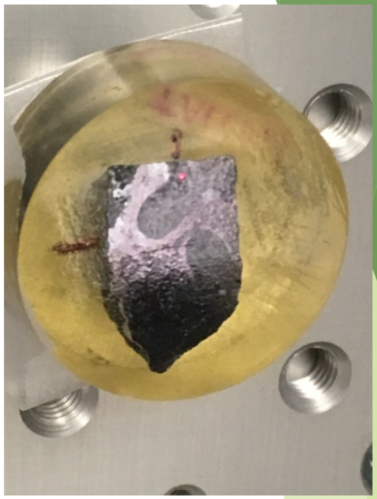
Methods: S.E.M.

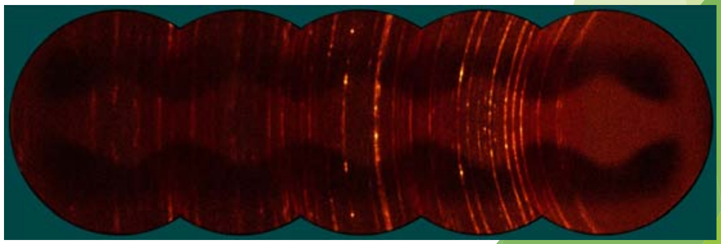
- Preparation
  - Put a Strip of copper on sample (polished section)
  - Coat with Carbon
- JEOLJSM-6490LV SEM_EDS
  - Elemental analysis
- Analysis
  - Test data against theoretical

Methods: Point X-Ray Diffraction

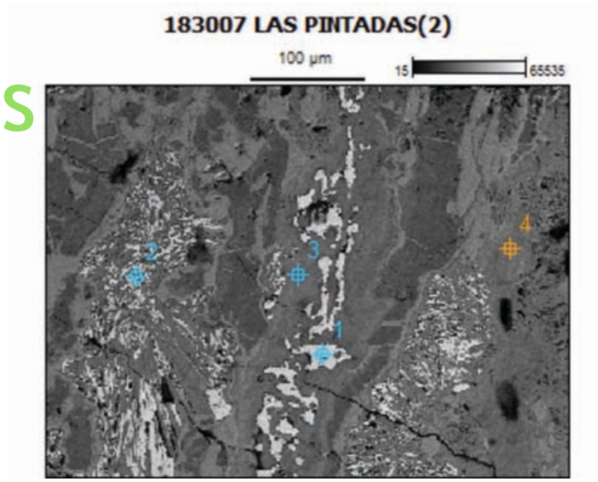
- Preperation
  - Polished section
  - Isolated crystals on slide
- Bruker AXS D8 Discover
  - Point analysis
  - Vertical mount
  - Spin for pattern
- Analysis
  - X'pert
  - Manipulate/match pattern
  - Compare plausible patterns


XRD mount

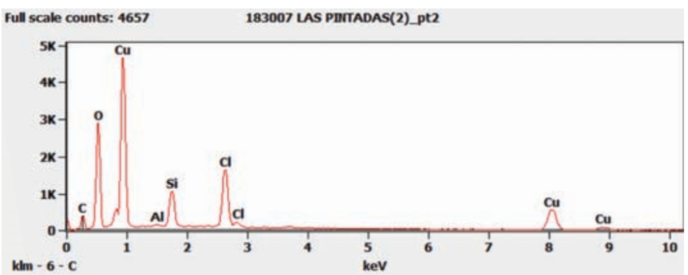

Polished section

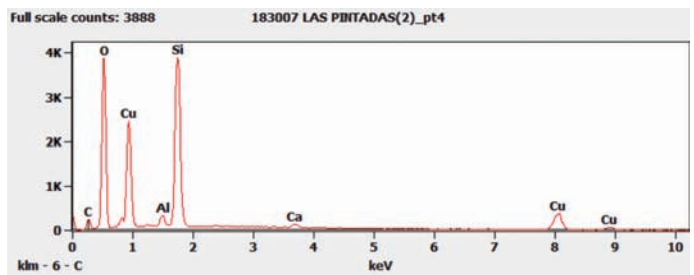

Host XRD pattern

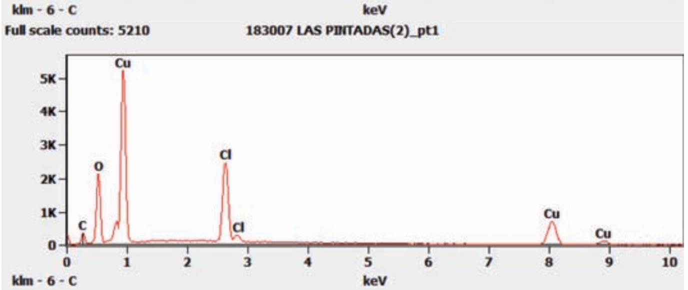
Data: Las Pintadas

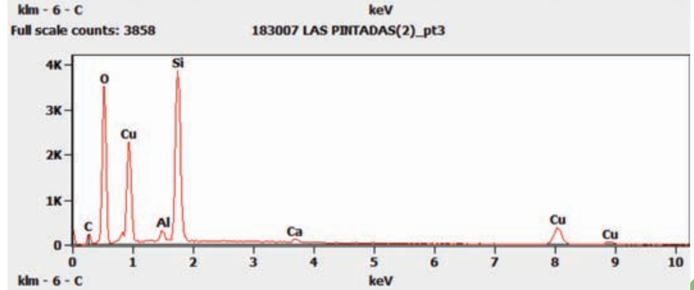


Las Pintadas (2)	Cu (atom %)	Ca (atom %)	Mg (atom %)	Al (atom %)	Cl (atom %)	Si (atom %)	O (atom %)	Suspected Mineral
Point 1	34.6	-	-	-	18.17	-	47.23	Atacamite
Point 2	28.18	-	-	.52	10.94	7.18	53.19	Atacamite
Point 3	15.05	.53	-	1.33	-	24.37	58.72	Chrysocolla
Point 4	15.04	.66	-	1.43	-	23.15	59.68	Chrysocolla
Ideal (Atacamite)	33.33	-	-	-	16.67	-	50	-
Ideal (Stringhamite)	11.11	11.11	-	-	-	11.11	66.67	-
Ideal (Chrysocolla)	15.1					15.1	69.81	-



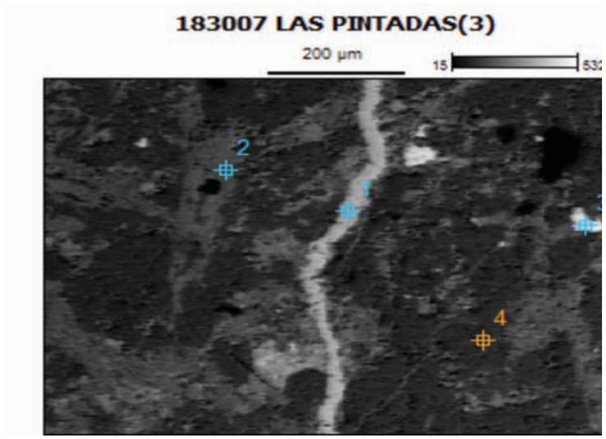




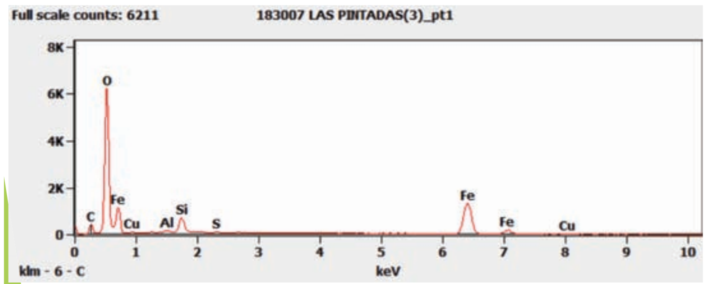


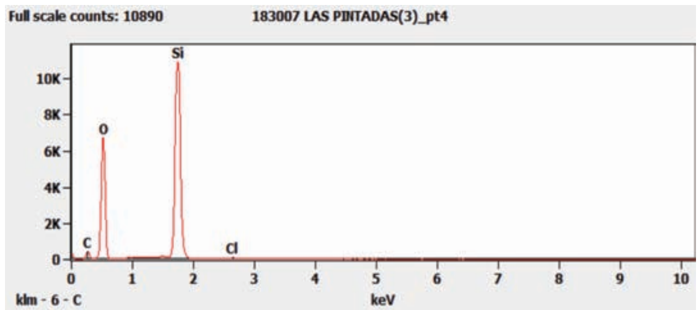
Possible Cl contamination?

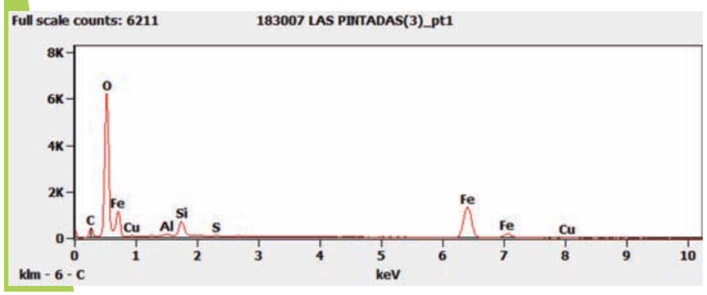
Data: Las Pintadas

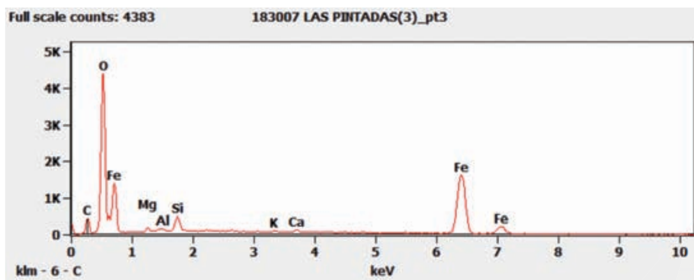


Las Pintadas (3)	Fe (atom %)	Ca (atom %)	Si (atom %)	Al (atom %)	Mg (atom %)	Na (atom %)	O (atom %)	Cl (atom %)	Suspected Mineral
Point 1	30.51	-	3.81	.46	-	-	64.29	-	Goethite
Point 2	6.31	3.37	18.10	2.74	8.34	.26	60	-	Actinolite
Point 3	41.53	.48	2.65	.45	.67	-	53.96	-	Magnetite
Point 4	-	-	33.09	-	-	-	66.78	.13	Quartz
Ideal Goethite)	33.33	-	-	-	-	-	67.66	-	-
Ideal (Magnetite)	42.86	-	-	-	-	-	57.14	-	-
Ideal (Quartz)	-	-	33.33	-	-	-	66.66	-	-

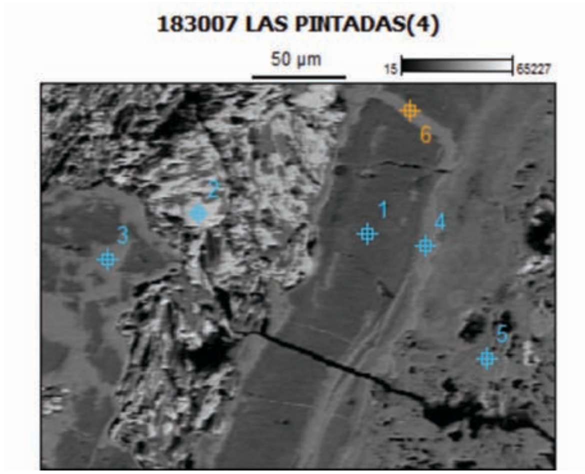




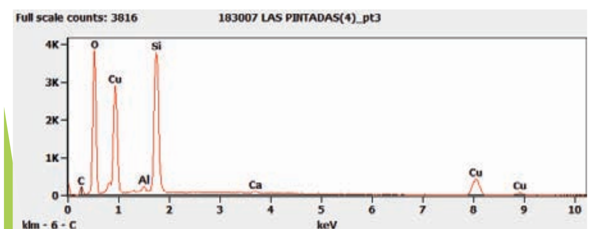


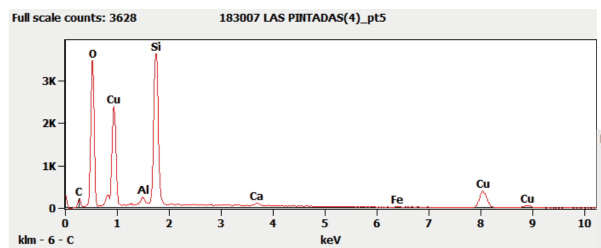


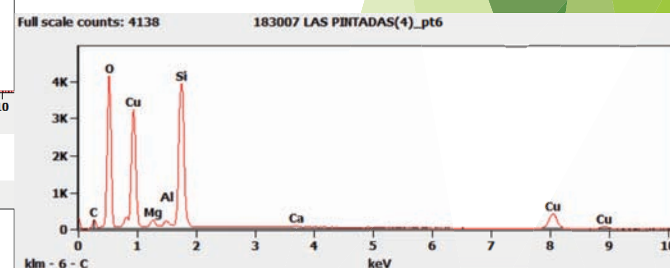
Data: Las Pintadas

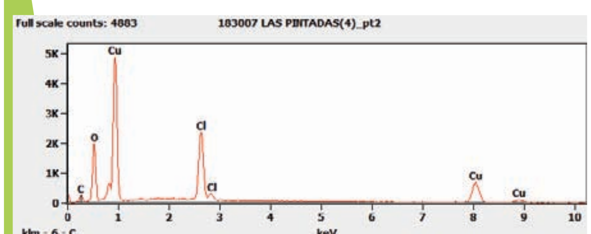


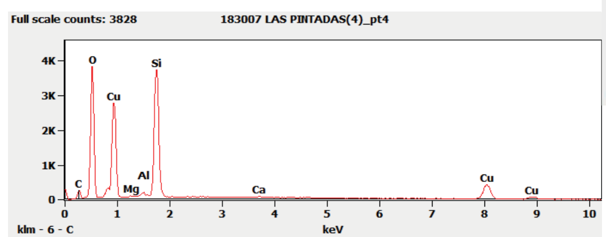
Las Pintadas (4)	Cu (atom %)	Mg (atom %)	Al (atom %)	Cl (atom %)	Si (atom %)	O (atom %)	Suspected Mineral
Point 1	9.79	10.5	.25	-	18.3	61.42	?
Point 2	35.42	-	-	18.84	-	45.74	Atacamite
Point 3	17.91	-	.77	-	23.05	58.26	Chrysocolla
Point 4	17.72	.22	.62	-	23.04	58.26	Chrysocolla
Point 5	16.16		-	-	23.84	58.50	Chrysocolla
Point 6	17.94	1.33	.77	-	22.40	57.55	Chrysocolla
Ideal (Chrysocolla)	15.1	-	-	-	15.1	69.81	-
Ideal (Atacamite)	33.33	-	-	16.67	-	50	-







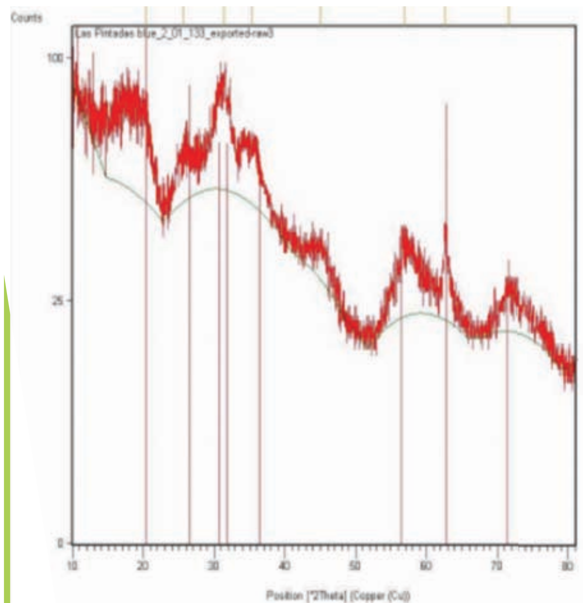


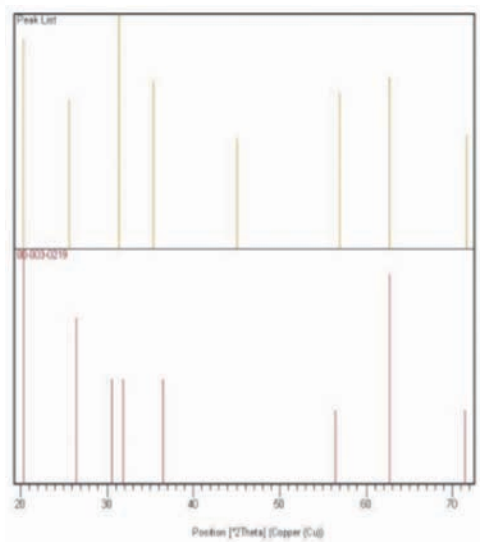


Data: Las Pintadas Mine XRD

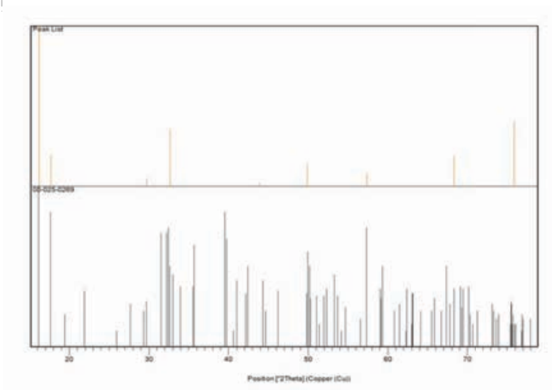
Pos. [°2Th.]	Height [cts]	FWHM [°2Th.]	d-spacing [Å]	Rel. Int. [%]
20.3407	29.33	2.6880	4.36244	79.88
25.5934	14.84	2.3040	3.47777	40.42
31.3892	36.71	2.3040	2.84758	100.00
35.3604	18.74	2.3040	2.53635	51.04
45.0485	8.15	3.0720	2.01083	22.19
56.8603	16.09	2.3040	1.61798	43.83
62.6755	19.45	0.7680	1.48111	52.98
71.6875	8.70	3.0720	1.31545	23.69

Values Generated for Chrysocolla





- Less distinctive XRD pattern due to the nature of the sample
- Sample was rotated throughout the process
- Sample was purposefully oscillated to generate more randomized data
- The oscillation may be extended beyond the crystal surface and started scanning the epoxy instead, which could be the reason for the abnormal trend



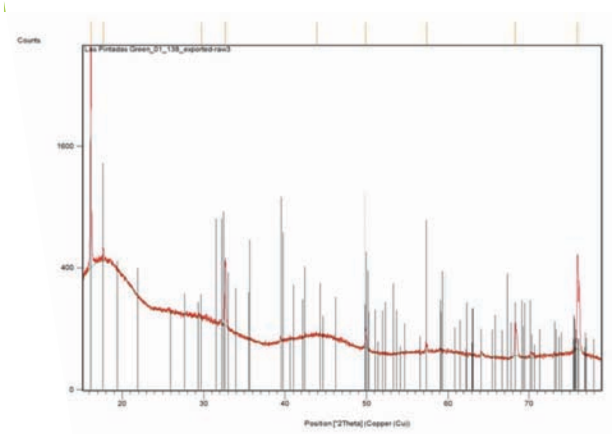
Pos. [°2Th.]	Height [cts]	FWHM [°2Th.]	d-spacing [Å]	Rel. Int. [%]
16.1713	2772.84	0.1082	5.48113	100.00
17.7113	96.26	0.1181	5.00784	3.47
32.6704	347.43	0.0886	2.74104	12.53
44.0176	0.14	2.5190	2.05721	0.00
49.9119	54.63	0.1968	1.82720	1.97
57.3492	17.89	0.2362	1.60667	0.65
68.2957	96.55	0.0960	1.37227	3.48
75.9355	453.17	0.1020	1.25207	16.34
76.1318	272.40	0.0840	1.25244	9.82

Values generated for Atacamite

Much better data match than the previous sample
- This sample only underwent rotation instead of rotation and oscillation

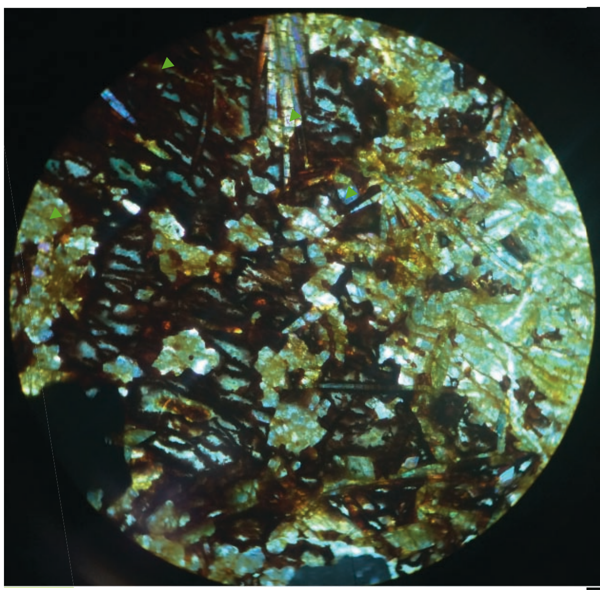
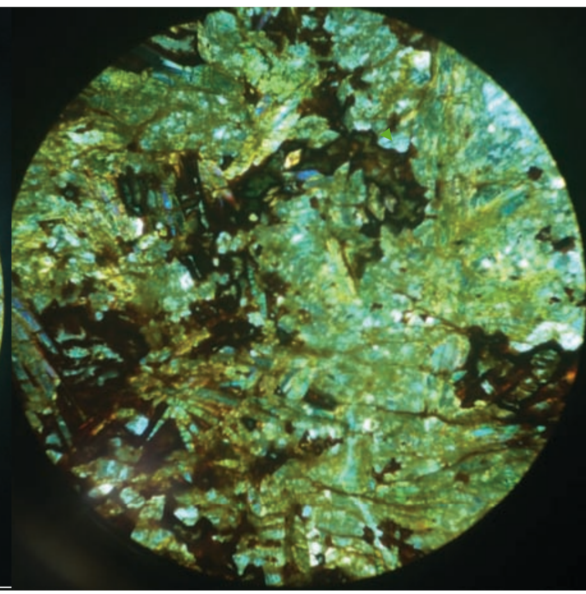
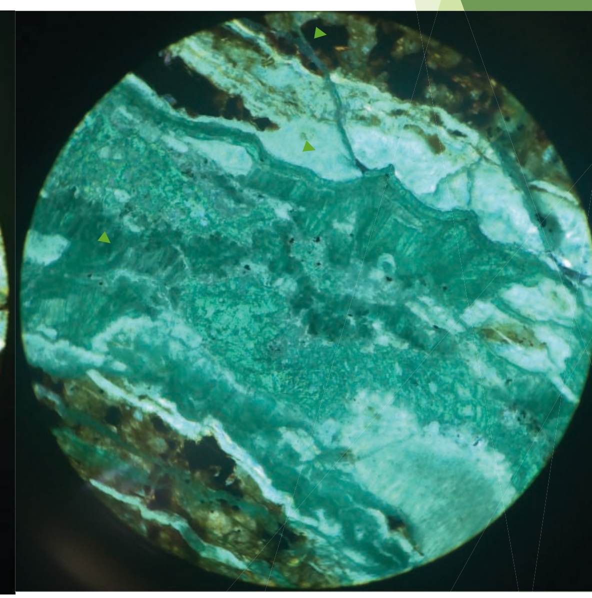
Strong peak match for Atacamite, but there is still strong variation because this was a crystal sample and not a powdered sample

The XRD standard for Atacamite was actually taken from the same province as my sample in Chile!

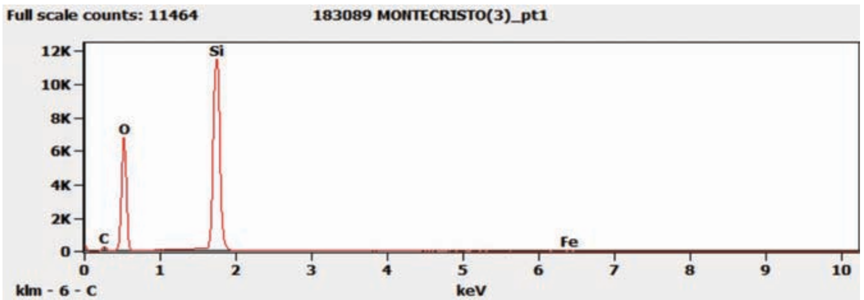


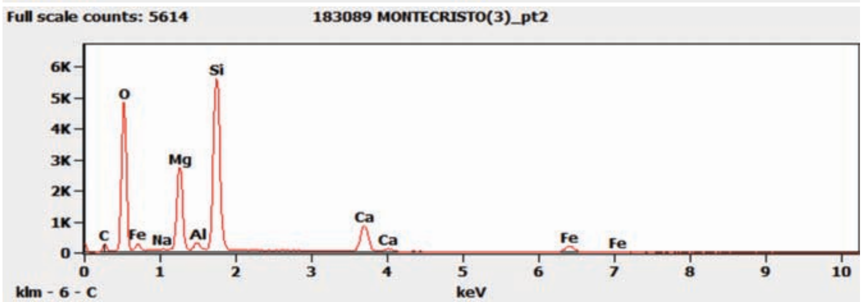
Thin Section (FoV 5mm)

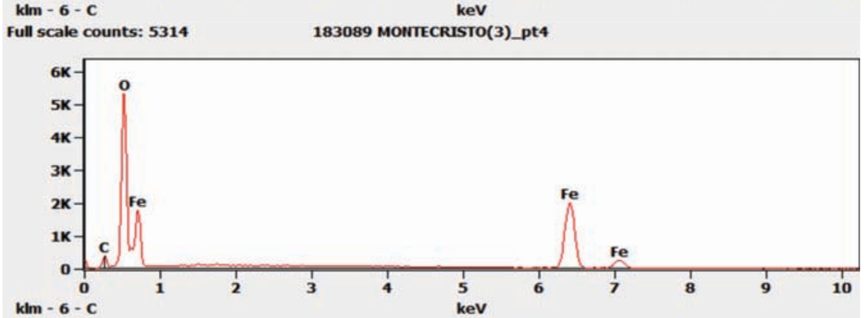
Minerals found in thin section:
Goethite
Actinolite
Iron Oxide
K-spar
Quartz
Atacamite
Calcite
Magnetite

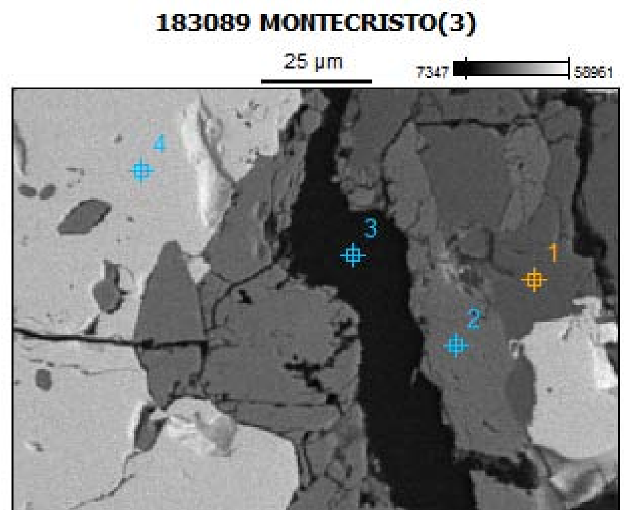




Data: Montecristo S.E.M



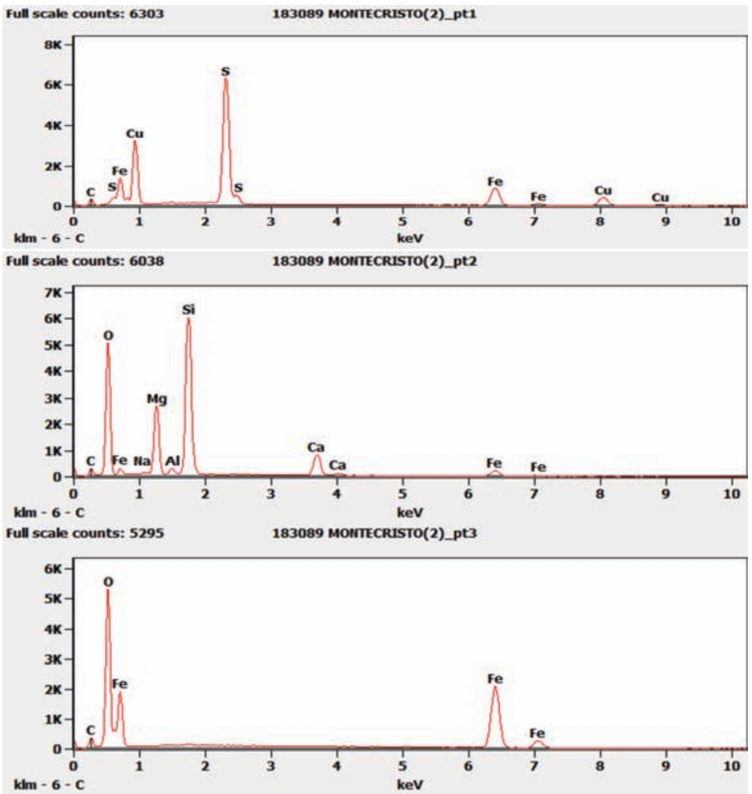


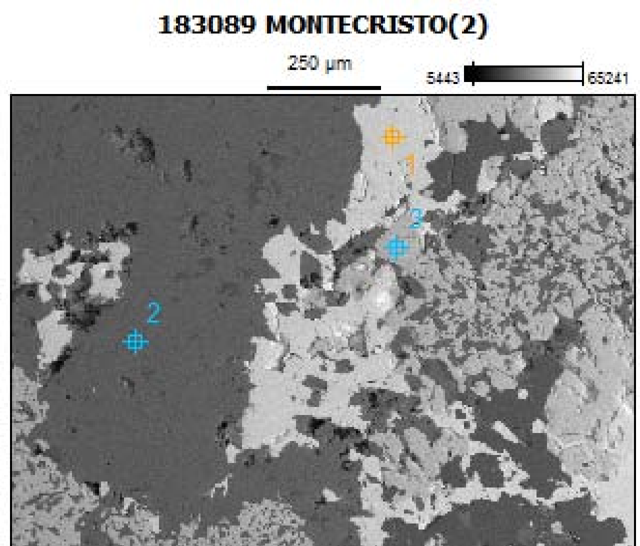




	Pt1A	Pt2A	Pt3A
O	65.61	60.45	54.42
Na	0	0.12	0
Mg	0	9.98	0
Al	0	0.59	0
Si	34.18	21.15	0
S	0	0	0
Ca	0	4.55	0
Fe	0.21	3.15	45.58
Cu	0	0	0

Data: Montecristo S.E.M.





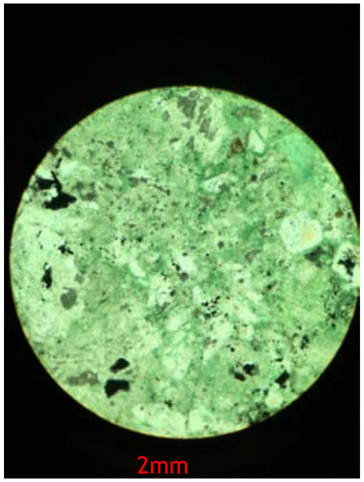
	Pt1B	Pt2B	Pt3B
O	0	60	54.17
Na	0	0.15	0
Mg	0	10.59	0
Al	0	0.77	0
Si	0	20.45	0
S	46.06	0	0
Ca	0	4.89	0
Fe	23.01	3.16	45.83
Cu	30.94	0	0

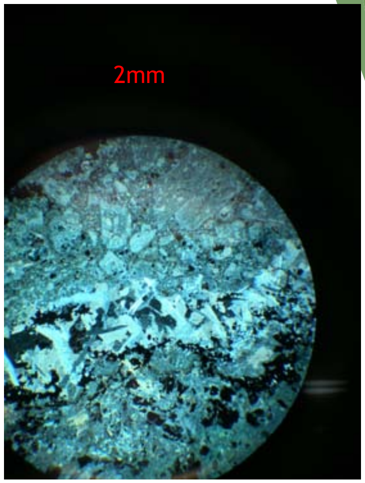
Data Talcuna: Thin Section

Common
- Chlorite
- Albite (vein)
- Barite

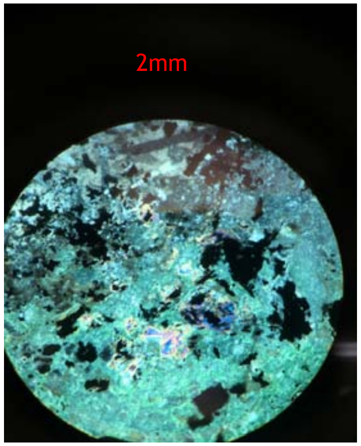
Less Common
- Olivine
- Epidote
- Calcite

Chlorit
e (PPL)





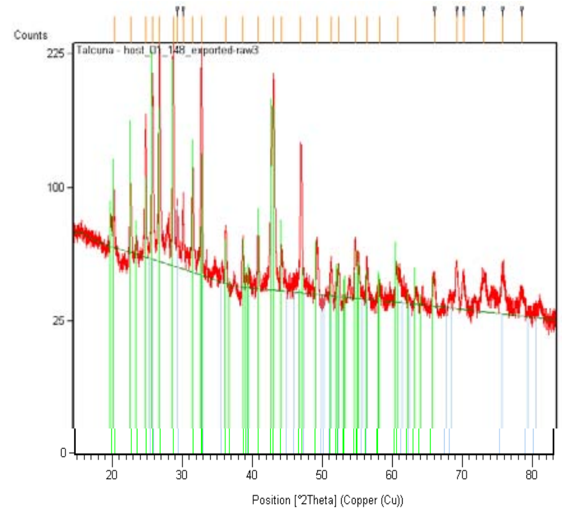
Albite
(XPL)



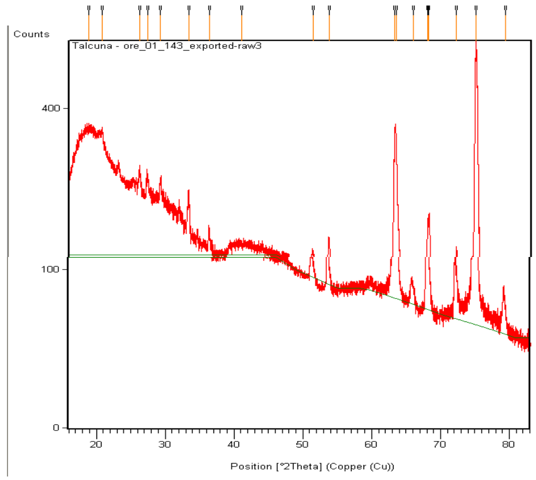
Epidote (XPL)

Data Talcuna: X Ray Diffraction

Host Rock: Point XRD
•Experimental
•Barite XRD pattern

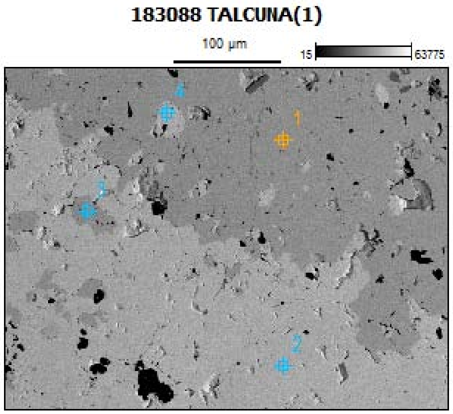


Ore: Point XRD
•Inconclusive



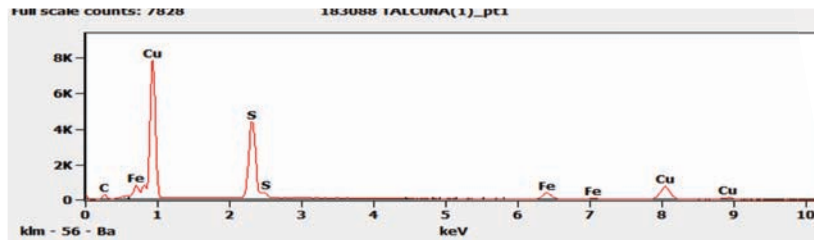
Data: Talcuna Mine S.E.M.

Results: SEM Location

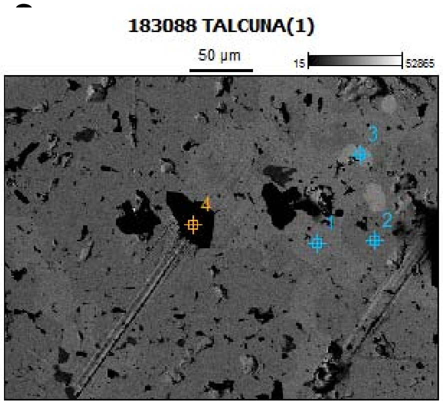


Location 1

	O	S	Fe	Cu	Sr	Ba	Total	Mineral
Point 1		35.76	8.59	55.65			100	Bornite
Point 3		35.99	8.19	55.83			100.01	Bornite
Bornite Theoretical		40	10	50				
Point 2	66	16.87			1.4	15.72	99.99	Barite
Point 4	66.05	17.05			0.68	16.21	99.99	Barite
Barite Theoretical	66.6	16.7				16.7		

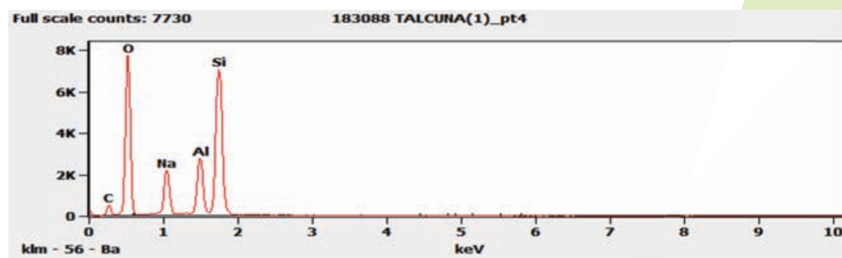


Results: SEM Location



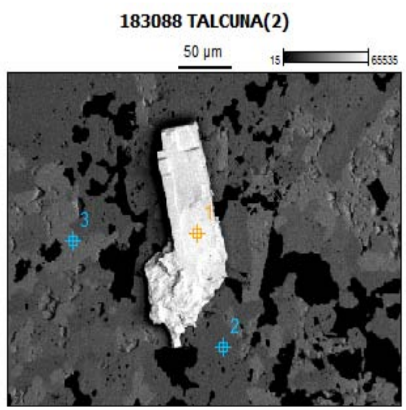
Location 2

	O	Na	Mg	Al	Si	S	Fe	Cu	Zn	Sb	Total	Mineral
Pt1						29.85	0.58	69.57			100	Bornite
Pt2						35.65	8.73	55.63			100.01	Bornite
Bornite Theoretical						40	10	50				
Pt4	62.96	8.03		7.4	21.61						100	Albite
Albite Theoretical	61.54	7.69		7.69	23.08						100	
Pt3			2.7			39.86		41.38	4.61	11.45	100	?



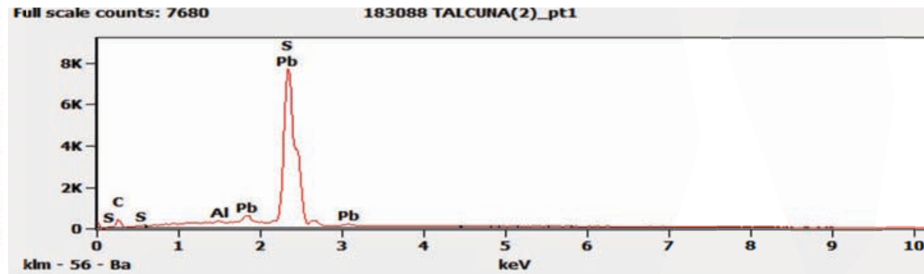
Data: Talcuna Mine

Results: SEM Location 3

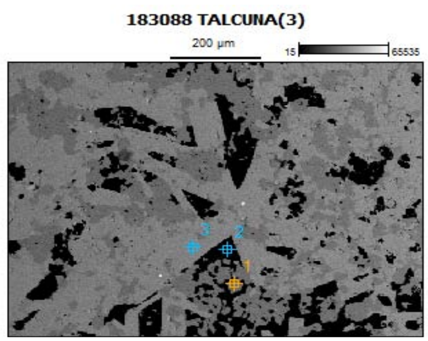


Location 3

	O	Al	S	Fe	Cu	Sr	Ba	Pb	Total	Mineral
Point 1		0.45	51.3					48.25	100	Galena
Galena Theoretical			50					50	100	
Point 2			35.88	8.51	55.61				100	Bornite
Bornite Theoretical			40	10	50				100	
Point 3	65.87		17.14			0.63	16.36		100	Barite
Barite Theoretical	66.6		16.7				16.7		100	

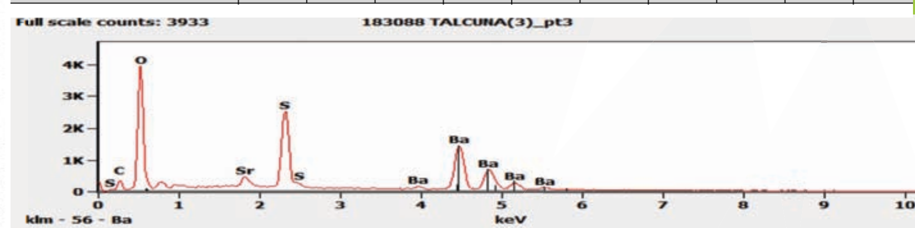


Results: SEM Location



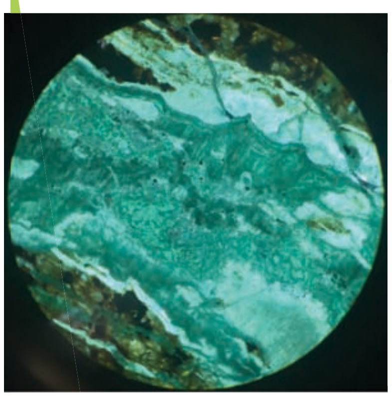
Location 4

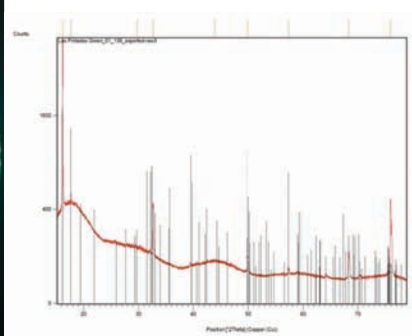
	O	S	Ca	Mn	Fe	Cu	Sr	Ba	Total	Mineral
Point 1		35.95			8.42	55.63			100	Bornite
Bornite Theoretical		35.88			8.51	55.61			100	
Point 2	74.33		25.23	0.43					99.99	Calcite?
Calcite Theoretical (minus carbon)	60		20						80	
Point 3	65.89	17.13					1.6	15.38	100	Barite
Barite Theoretical	66.6	16.7						16.7	100	



Discussion: Candelaria Mine

- The SEM data, XRD, and Thin Section all have strong levels of atacamite present.
- Strange because atacamite can only form in highly saline fluids, whereas supergene enrichment is formed as a result of slightly acidic rainfall water. (Eion et al. 2006)

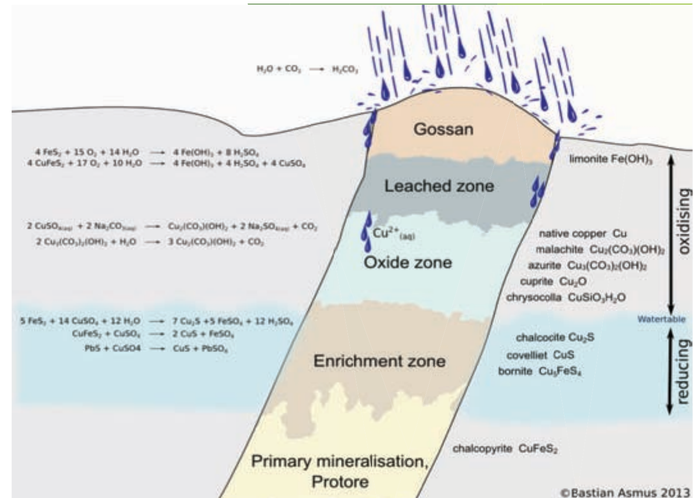




Las Pintadas (2)	Cu (atom %)	Ca (atom %)	Mg (atom %)	Al (atom %)	Cl (atom %)	Si (atom %)	O (atom %)	Suspected Mineral
Point 1	34.6	-	-	-	18.17	-	47.23	Atacamite
Point 2	28.18	-	-	.52	10.94	7.18	53.19	Atacamite

Proposed Theory

- The original supergene formed and deposited material 44 to 9 Ma.
  - During a period of arid environment where there was just enough rainwater to supply the process. (Eion et al. 2006)
- The atacamite actually formed much more recently (< 2 Ma).
- Current Hypothesis: the saline, Chlorine rich water necessary for formation is the result of sedimentary rocks.
  - Brought up from tectonics
  - Dissolved salts from these rocks mixing with the evaporating meteoric water to create hyper-saline water. (Eion et al. 2006)
- This only occurs along fault zones filled with porphyry rock.



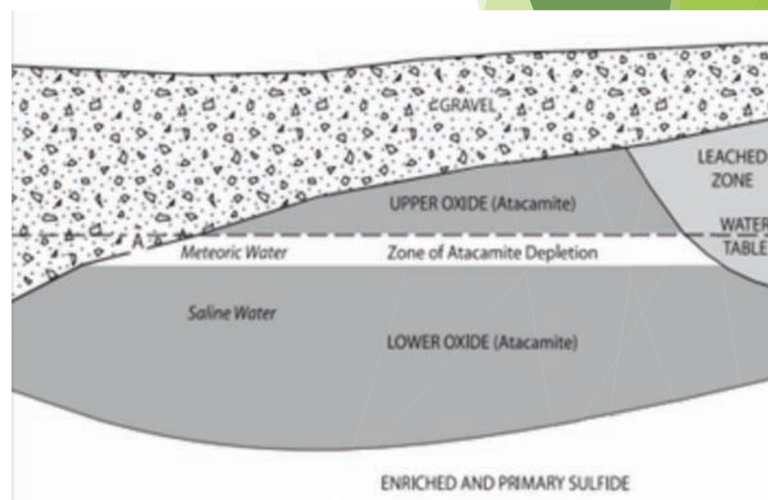


Photo Credit: Bastian Asmus of http://en.archaeometallurgie.de/gossan-iron-cap/

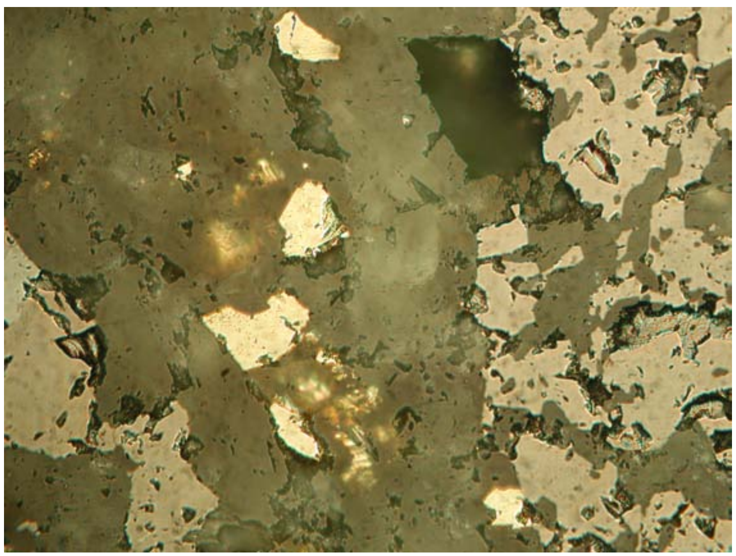
Photo Credit: Reich, M. et al., 2009

Discussion: Talcuna Mine

- Host Rock
  - Barite
  - Chlorite
  - Epidote
  - Albite (vein)
  - **Greenschist Facies** (Wilson, 2016)
- Ore Material
  - Bornite
  - Galena

Discussion: Montecristo

- Magnetite
- Chalcopyrite
- Edenite
- Quartz



Magnetite	Ideal	Experimental	
	Fe_3O_4	Pt3A	Pt3B
Fe	42.8	45.58	45.83
O	57.1	54.42	54.17
Chalcopyrite			
$CuFeS_2$	ideal	Pt1B	
Cu	25	30.94	
Fe	25	23.01	
S	50	46.06	
Edenite			
$NaCa_2(Mg, Fe)_5AlSi_7O_{22}(OH)_2$	Ideal	Pt2A	Pt2B
O	46	60.45	60
Na	2.5	0.12	0.15
Mg	14.5	9.98	10.59
Al	3.5	0.59	0.77
Si	23.5	21.15	20.45
Ca	9.5	4.55	4.89
Fe	0	3.15	3.16
Quartz	Ideal	Experimental	
SiO_2		Pt1A	
Si	33	34.18	
O	66	65.61	

Conclusion

Michael

- Sulphide ore mineral was generally replaced by Copper Chloride atacamite within the past 2 million years

Joel

- Low grade metamorphism
- Greenschist Facies
- Ore: Bornite

Joey

- Ore: Magnetite, Chalcopyrite and Edenite
- From the Montecristo vein

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- The assistance of Dr. Eidukat for sample preparation and project guidance
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- NDSU electron microscopy center

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