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Atacama Caliche Mining: A Planetary Regolith Mining Analog

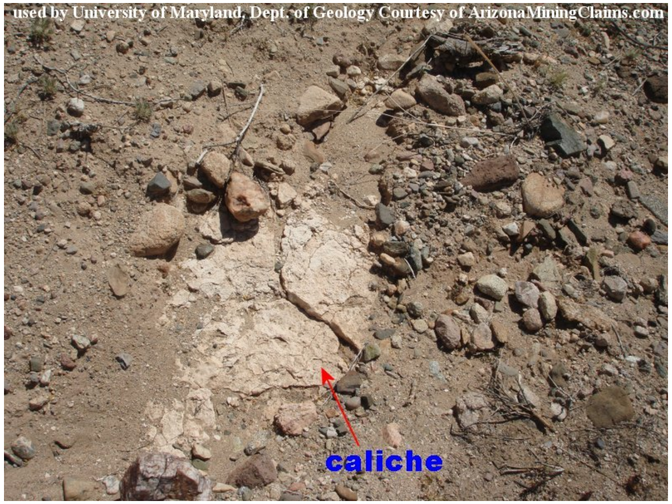
Location/History

- northern Chile
- caliche mined in Peru since the 1600’s as nitrate source
- first shipped to Europe in 1830
- nitrate history
  - explosives
  - fertilizer
  - social ramifications of both boom and bust

Simon et al., 2005

Caliche – Basic Information

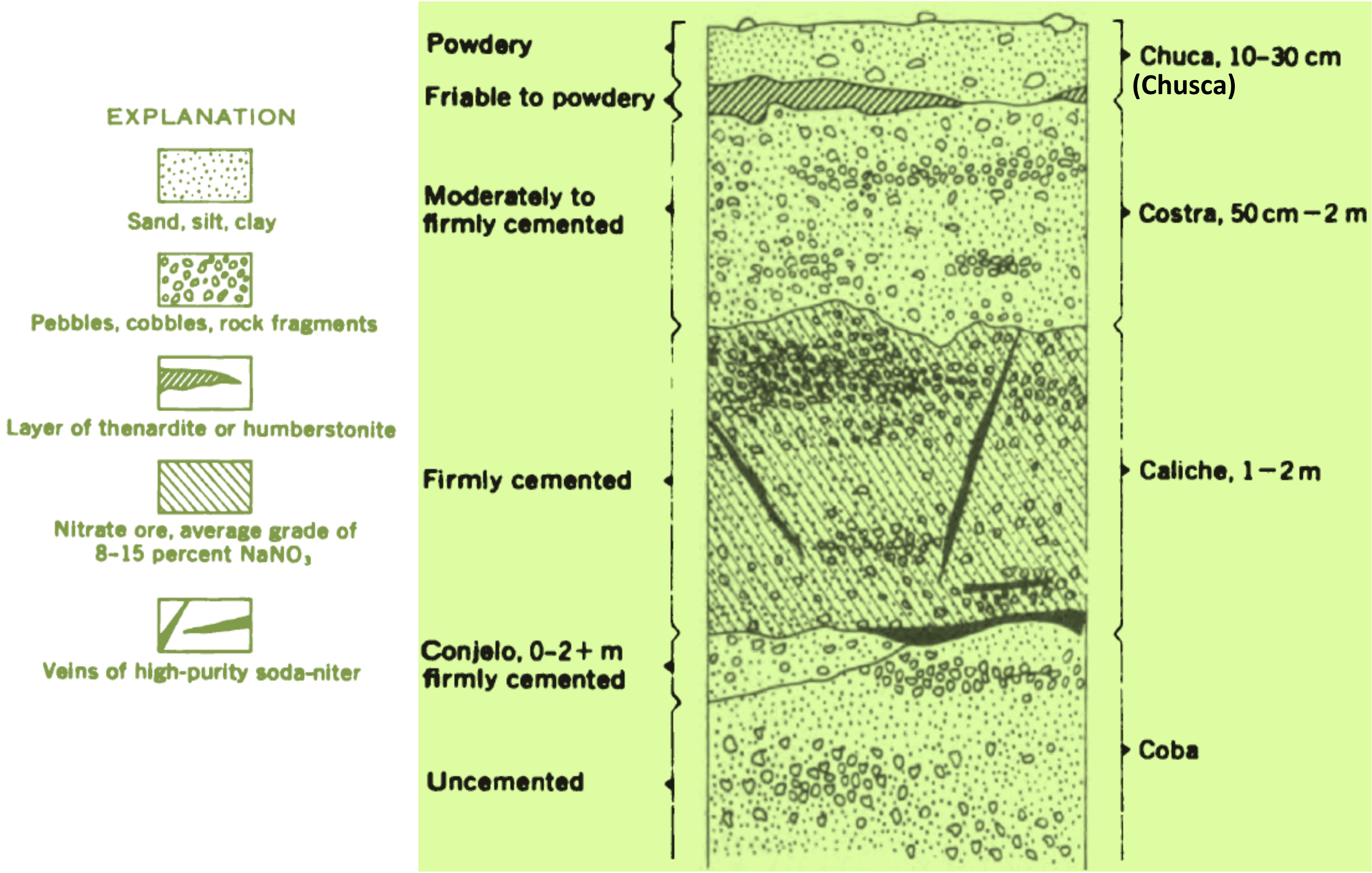
- Deposit Formation
  - evaporative conditions
  - microbial denitrification of atmospheric aerosols
  - colluvium
- Uses:
  - source of nitrates, sulfates, and iodine
  - building stone



- Typical Properties
  - basic properties
    - unit weight = 19.4 ± 1.9 kN/m^3
    - porosity = 25.7 ± 4.8%
  - strength & deformability
    - UCS = 5.4 ± 2.4 MPa (others measure 2-60 MPa)
    - Schmidt rebound = 28.6 ± 7.1
    - Shore hardness = 12.9 ± 5.0
    - P-wave velocity = 790 ± 367 m/s
    - point load index = 1.17 ± 0.42
    - Young's modulus = 590 ± 370 MPa
  - physical and chemical properties highly variable
    - matrix vs. inclusions

Dinçer et al., *2008*

Caliche – Structure & Classes



Erickson & Mrose, 1972

Aguas Blancas Mine

- lat 24°8′S, long 69°53′
- 970 - 1,230 m elevation
- 38,200 hectares
- average temp 5-28°C
- average daily evaporation 13 mm
- draws 120-180 liter/sec water from two aquifers
  - some purified for drinking
- supplies & services from
  - Antofagasta (300 km)
  - Santiago (1,600 km)

- permanent camp on-site
  - offices, living quarters
  - mechanical & electrical workshops
  - telephone, internet
  - on-site electricity generation

Simon et al., 2005

Exploration

- trenching
- drillholes
- sampling
- sample tests


trench in unmined ground


exploration drilling


trench in old waste rock dump

Simon et al., 2005

Sampling


cyclone collecting sample during drilling

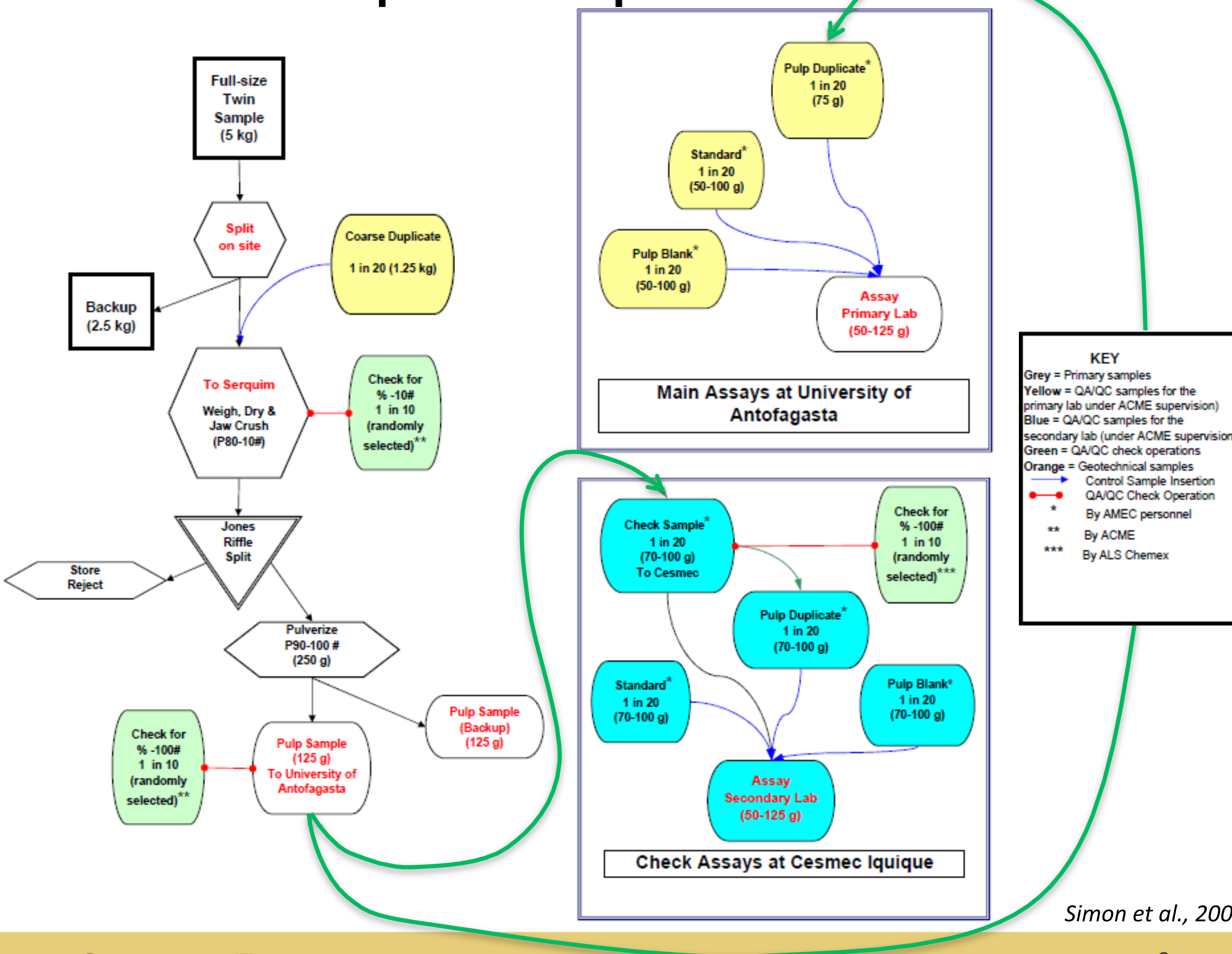

cyclone close-up showing sample bag


splitting the sample


geochemical analysis of sub-samples

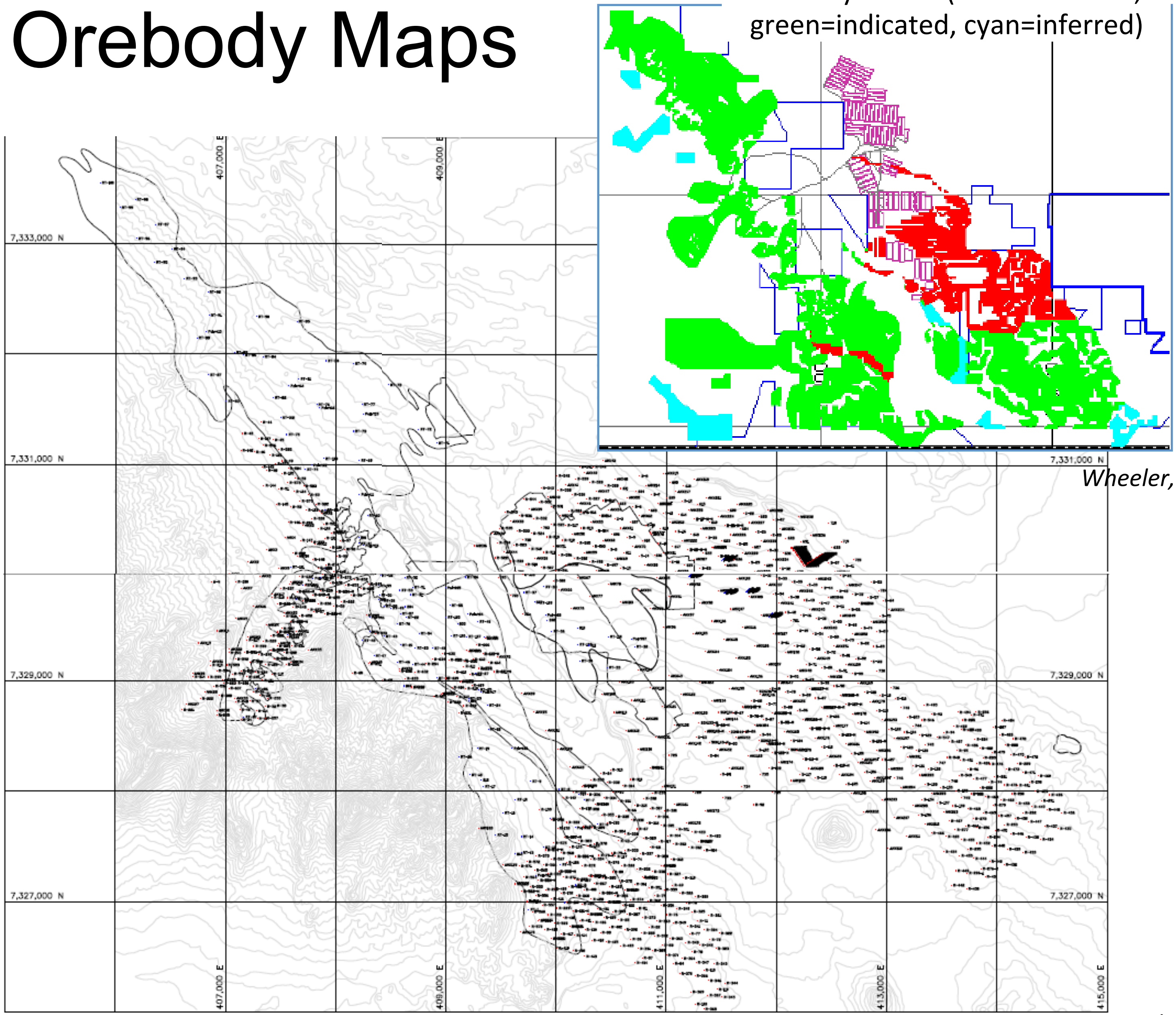
Simon et al., 2005

Sample Prep Flowchart



Simon et al., 2005

Orebody Maps



Simon et al., 2005

orebody model (red=measured, green=indicated, cyan=inferred)

Wheeler, 2010

Previous Mining Methods

- Underground mining of high-grade veins
  - done in the initial, high-grading phase
- Surface mining of lower-grade disseminated ore:
  - exploration – shallow pits dug on 100-300m grid, infilled to 50m where high grade
    - observe color of sparks from pulverized material spread on burning wick
  - extraction –
    - manual or explosive fragmentation
    - haulage to heated tanks of water
  - processing
    - crystallization in evaporation ponds
    - scraping and loading for shipment

Current Mining Method

- open pit with single 2-4m high bench
- chusca (0.5m thick) stripped by dozer to sides of mining block
- blastholes drilled to bottom of caliche layer
- broken ore removed from mining block
  - front-end loaders
  - 22-m^3 trucks
  - hauled 6 km
- heap leaching
  - 420 m^3/hr outflow
  - iodine content 0.26-0.30 g/l
  - recoveries:
    - 58% iodine
    - 30% $NaNO_3$
    - 10% $Na2SO_4$

loading haul truck to go to heap

Simon et al., 2005

The Heaps

loaded haul truck

shaping the heap

haul truck climbing heap

heap pads under construction

Simon et al., 2005

Processing

- Reduction in agitated leach tanks
  - iodate brine from heaps mixed with iodide solution to produce iodine
  - extracted with air in blow-out tower
  - treated with NaOH solution in absorption tower
  - concentrated by recirculation until reaches 100 g/l iodine
  - accumulated, then sent onward
- Crystallization in evaporation ponds
- Preparation of iodide solution in absorption tower
  - iodate in separate brine stream reduced to iodide with SO_2 injection
- SO_2 production
  - sulfur burned in combustion furnaces
  - particulates eliminated
  - water-cooled

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Processing

the processing plant

SO_2 production tower

crystallization ponds

pelletized metallic iodine

Simon et al., 2005

New Processing Approach

- Agitation leaching
  - ore is ground in a semi-autogenous grinding mill to minus-12 mesh (<1.68mm)
  - crushed ore is run through agitation leaching tank using counter-current decantation
  - iodine is recovered by the same iodate-iodide process
  - sodium sulfate is recovered from the iodine plant brine, using recycled sodium chloride and sodium sulfate
  - the brine is evaporated in an evaporation pond and the bottom salts are recycled
  - magnesium sulfate is precipitated
  - nitrate is produced by evaporation in a nitrate lagoon
- Advantage
  - higher iodine recovery (64% → 85%)
  - lower water use
- Being implemented now

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Recent Production History

	2011	*2010*	*2009*	*2008*
kilotons mined	4,488	3,804	3,203	2,592
iodine grade (ppm)	581	623	570	659
iodine produced (tons)	1,122	1,256	1,096	844
iodine sold (tons)	1,134	1,244	1,086	861

- 2,000 tons iodine production planned for 2012
- potential additional products:
  - K nitrate
  - Na sulfate
  - Mg sulfate

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Conclusions

- How good is the analogy?
  - similarities:
    - thin, near-surface deposits
    - the matrix is the ore
    - weak to moderate strength
  - differences:
    - formation processes & geologic histories
    - components, chemistry, & weathering
    - microstructures and deposit structure (layering)
- Knowledge gaps
  - map ice-regolith deposits
  - sample ice-regolith deposits
    - characterize *in situ* and in Mars lab and in Earth lab
  - characterize ice-regolith deposits in situ
    - texture & porosity, strength & stiffness, excavatability, process effectiveness
    - 3D variations
    - indicative features

Recommendations

- Reduce ISRU-supported architecture risk:
  - identify terrestrial mineral deposits as analogs for similar situations on the Moon and Mars
  - study the associated mines and mining methods
  - adapt the findings for use on lunar, martian, and asteroidal bodies
- Next steps:
  - exploration – determine what is there
  - product selection – determine what is to be mined

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