Constraints on the genesis of lode-style tin mineralization: evidence from the San Rafael tin-copper deposit, Peru

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Plan of the presentation

• *Tin metallogeny in the Central Andes*

• **The San Rafael Sn-Cu deposit:**
  - structural geology
  - alteration
  - mineralization
  - fluid inclusions
  - stable isotopes

• **Genetic model**
The metallogeny of the Central Andes
Tertiary magmatism and metallogeny

Legend:
- Zone devoid of Oligocene-Miocene intrusions/volcanics
- Miocene-Pliocene volcanics
- Oligocene-Miocene intrusions
- Permo-Triassic and Early Jurassic intrusions

Age of the onset of mineralization:
- △ Mid-Miocene
- ▲ Early Miocene
- ▲ Late Miocene
- ▲ Late Triassic - Early Jurassic

Initial compression (Late Oligocene)

Migration of metallogeny in time

Map showing locations such as:
- Macusani volcanics
- San Rafael-Quenamari granite
- Crucero volcanics
- Sorata Zongo Taquesi
- Illimani pluton Quimsa Cruz batholith
- Santa Vera Cruz pluton
- Los Frailes ignimbrite
- Kari-Kori batholith
- Kumurana stock
- Cerro Rico de Potosí
- Tasna Chorolque Tatasi Iscaisca Chocaya
- Pirquitas

Geographic coordinates and scale:
- 0 to 200 km
- 14°, 18°, 22°, 66°, 69°, 72°
Concurrent timing of mineralization and compressional pulses

→ Collisional tectonics - a trigger for tin metallogeny?
A “collisional” model for tin metallogeny

a
"Normal" subduction and a narrow magmatic arc, above the section of the slab, which undergoes dehydration and triggers lower crustal melting

b
A "collisional" episode between the continental and oceanic plates leads to shallower subduction, crustal shortening and magmatic arc broadening
The San Rafael tin deposit
~ 1,000,000 tonnes Sn metal, average grade ~ 5 wt.% Sn
Geology of the San Rafael area

- Strongly metasomatized granite
- Coarse-grained granitoids
- Fine-grained granitoids
- Quartzites (Sandia Fm.)
- Hornfels (Sandia Fm.)
- Slates (Sandia Fm.)
- Mineralized veins

granite

slate
One major vein-breccia system (the San Rafael lode)
Vein paragenesis

(I) Early, barren tourmaline-quartz,
(II) Main-stage cassiterite-quartz-chlorite,
(III) Main-stage quartz-sulfides-\(\pm\) cassiterite-chlorite,
(IV) Late, barren quartz-chlorite.

Strikes of major vein types in the San Rafael lode

Sealed vs. Open fracture-filling

Stereonet plots of main- and late-stage veins at different elevation
Alteration styles at San Rafael
and associated changes in rock chemistry

Chronology of alteration:

1. * albite-sericite alteration
2. ▲▲ weak sericitic alteration
3. brown tourmaline alteration
4. green chloritic alteration

Variation in normative mineralogy: early sericitic and tourmaline alteration versus main-stage chloritization

Fresh granite → Tourmalinization → Sericitization → Chloritization

- Fresh Granite
- Tourmaline
- Sericite
- Quartz

Vol. %

Biotite
Cordierite
K-spar
Anorthite
Albite
Quartz

I8 J26-B J26-A R432C R432B R432A

Vol. %

Biotite
Cordierite
K-spar
Sericite
Albite
Quartz

Fresh granite
Gains and losses of major / trace elements during alteration

**Strong tourmalinization**

![Graph showing gains and losses of major / trace elements during strong tourmalinization.]

**Strong chloritization**

![Graph showing gains and losses of major / trace elements during strong chloritization.]

(R566 - D5-138)

(I51-R80)
Chemical zoning of hydrothermal tourmaline: from early dravite (Mg) to ore-stage schorl (Fe)

**A- single vein**
- colorless tourmaline (1st gen.)
- orange tourmaline (2nd gen.)
- green tourmaline (3rd gen.)
- dark green tourmaline (4th gen.)

**B- entire deposit**
- magmatic tourmaline
- tourmaline from microbreccia
- very early, alteration tourmaline
- early alteration tourmaline
- vein tourmaline
- late overgrowths on earlier tourmaline
Physico-chemical conditions of chloritic alteration associated with main-stage cassiterite deposition

- **A**
  - $T=380^\circ C$
  - $P=300$ bar
  - Qtz saturation
  - $a_{H_2O}=0.744$ (20wt. % NaCl eq.)
  - pH=5
  - $a_K/aH^+=10^{2.4}$
  - $a_{Na}/aH^+=10^{3}$
  - $a_{Schorl}=0.4$

- **B**
  - $T=300^\circ C$
  - $P=300$ bar
  - Qtz saturation
  - $a_{H_2O}=0.873$ (20wt. % NaCl eq.)
  - pH=4
  - $a_K/aH^+=10^{1.7}$
Ore mineralogy and metal zoning

- **Upper zone:** sulfides dominate, complex mineralogy
  
  \[(\text{chalcopyrite, pyrite, arsenopyrite, sphalerite, galena pyrrhotite, needle-tin cassiterite, quartz, chlorite})\]

- **Lower zone:** oxides/silicates dominate, simple mineralogy
  
  \[(\text{massive cassiterite, quartz, chlorite ± wolframite})\]
Fluid inclusion studies

→ Ore fluids of moderate $T$ (360-230°C) and fluctuating salinity (21-0 wt.% NaCl eq.)

Homogenization temperature (°C)

Total salinity (wt.% NaCl eq.)
Stable isotope studies

δ^{34}S_{V-CDT} (‰)

δ^{18}O_{V-SMOW} (‰)

Arrenopyrite

Chalcopyrite

Pyrrhotite

Pyrite

Sphalerite

Galena

Tourmaline

Quartz

Chlorite

Cassiterite

Wolframite

δ^{18}O_{V-SMOW} (‰)

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Isotopic evolution of hydrothermal fluids at San Rafael

Calculated values of δ¹⁸O and δD for water in equilibrium with the different ore and gangue minerals (at the temperature of their formation), exhibit a clear paragenetic trend of δ¹⁸O decrease.
Mineral stability relationships for the tin stage (II) and the copper stage (III) of the San Rafael paragenesis.
Effect of cooling and mixing of magmatic and meteoric fluids on the oxygen isotope composition of precipitating quartz (A) and cassiterite (B)

Only a scenario of mixing of a hot brine with a cooler, dilute fluid can reproduce the range of oxygen isotope compositions of quartz and cassiterite from the deposit.
A genetic model for San Rafael

- **Early stage:** lithostatic conditions, hot magmatic brines produce strong sericite + tourmaline alteration and sealed, barren, tourmaline-quartz veins.

  \[ \Rightarrow \text{Tectonic activity reopens the vein system} \rightarrow \text{transition to hydrostatic conditions} + \text{influx of heated meteoric waters.} \]

- **Main ore stage:** mixing of magmatic brines and meteoric waters in the fault-jogs \(\rightarrow\) oxidation, dilution, cooling, and acid neutralization of the ore fluids \(\rightarrow\) massive precipitation of cassiterite as localized, high-grade ore shoots.

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**Diagram:**

- **Fluid mixing in the fault jogs:**
  - Hangingwall
  - Sinistral shear
  - Tension fractures
  - Footwall
  - Fault vein
  - Ore Shoot
  - Contact Orebodies
  - Copper orevbodies
  - Tin orevbodies
  - Granitoid intrusion
  - Ordovician slates and hornfelses

**Image:**

- **cas**
- **qtz**
Thank you for your attention...