

The background of the slide is a landscape photograph. It shows a range of mountains with several peaks covered in snow. The sky is filled with large, white, fluffy clouds. The foreground consists of rolling hills and valleys with a mix of green and brown vegetation, suggesting a high-altitude or semi-arid environment.

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

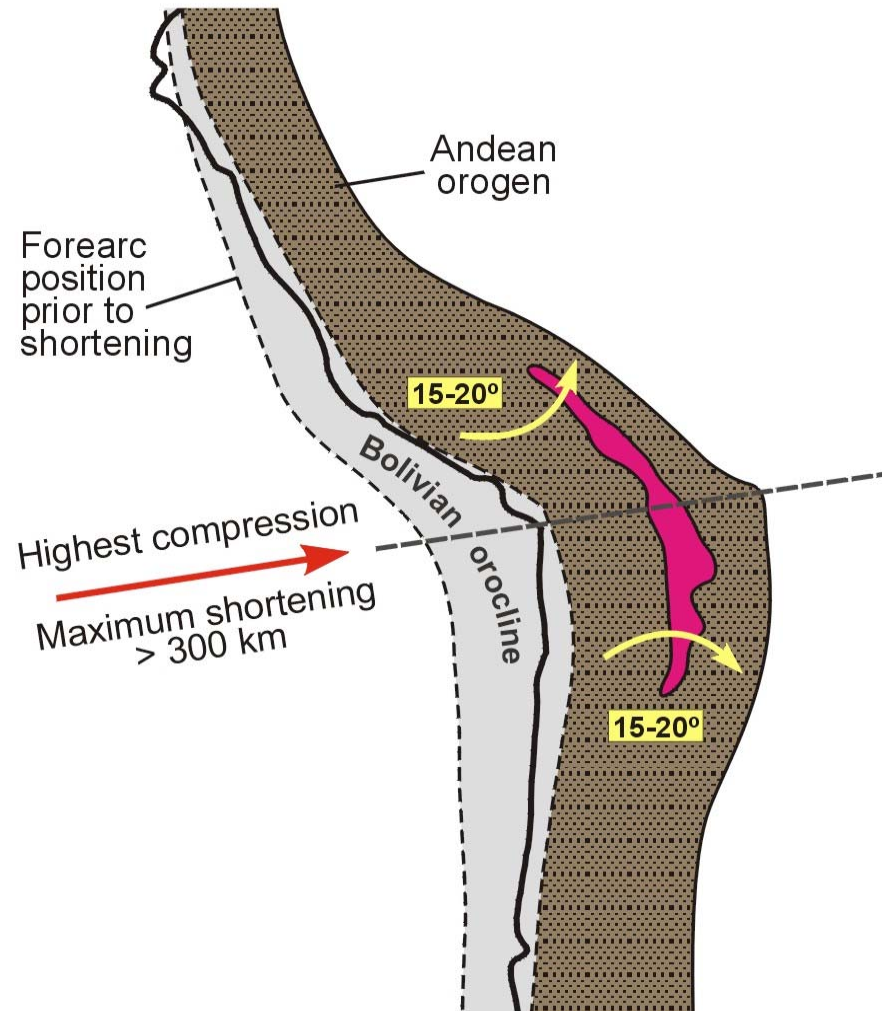
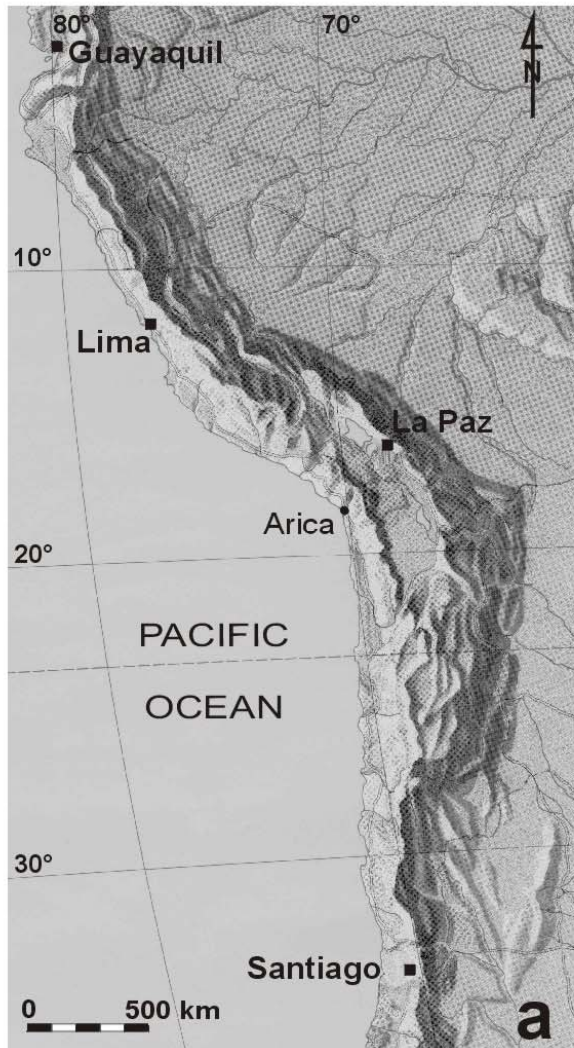
Michael S.J. Mlynarczyk
May 2005

Plan of the presentation

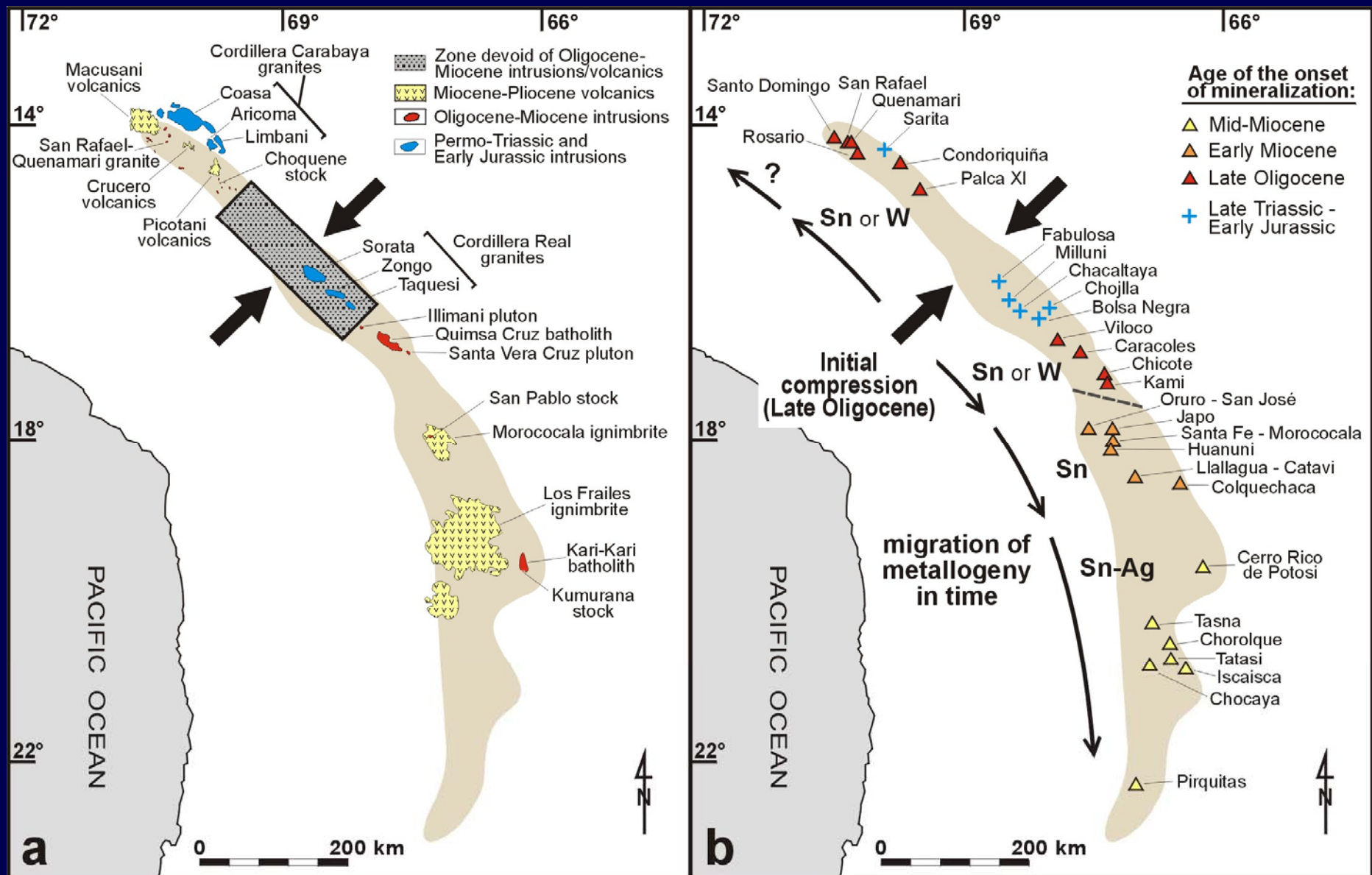
- *Tin metallogeny in the Central Andes*
- *The San Rafael Sn-Cu deposit:*
 - *structural geology*
 - *alteration*
 - *mineralization*
 - *fluid inclusions*
 - *stable isotopes*
- *Genetic model*



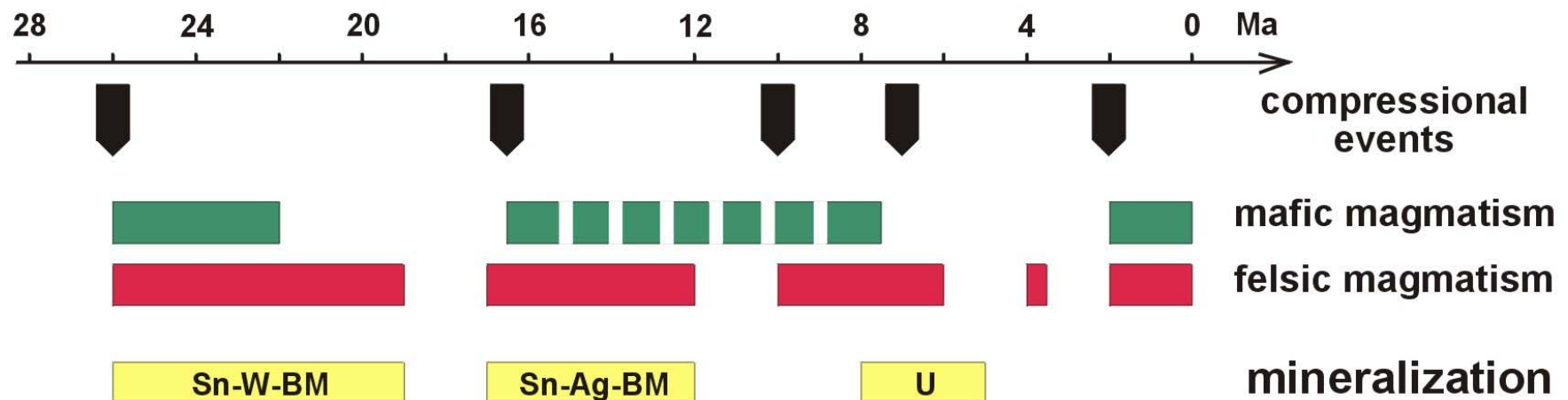
The metallogeny of the Central Andes



Tertiary magmatism and metallogeny

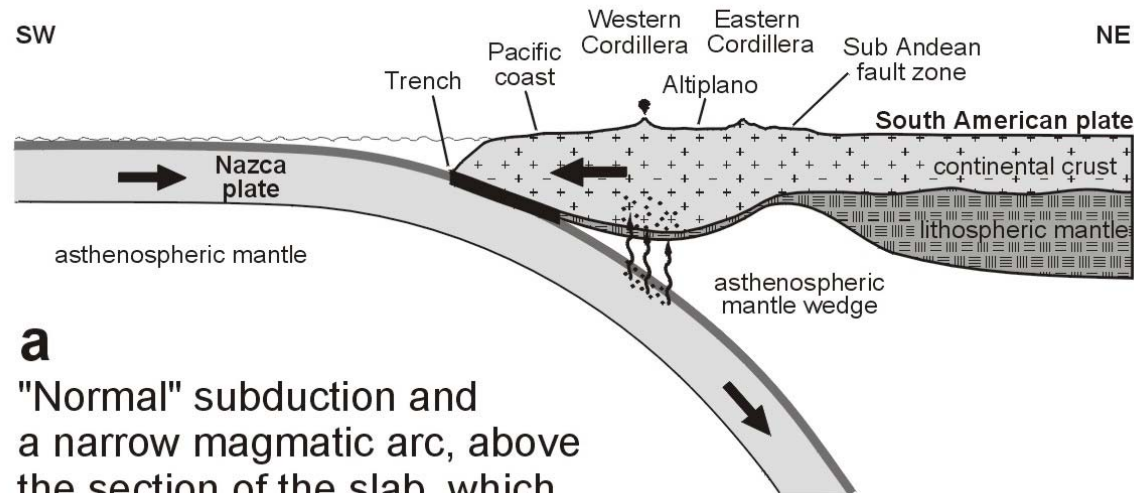


Concurrent timing of mineralization and compressional pulses



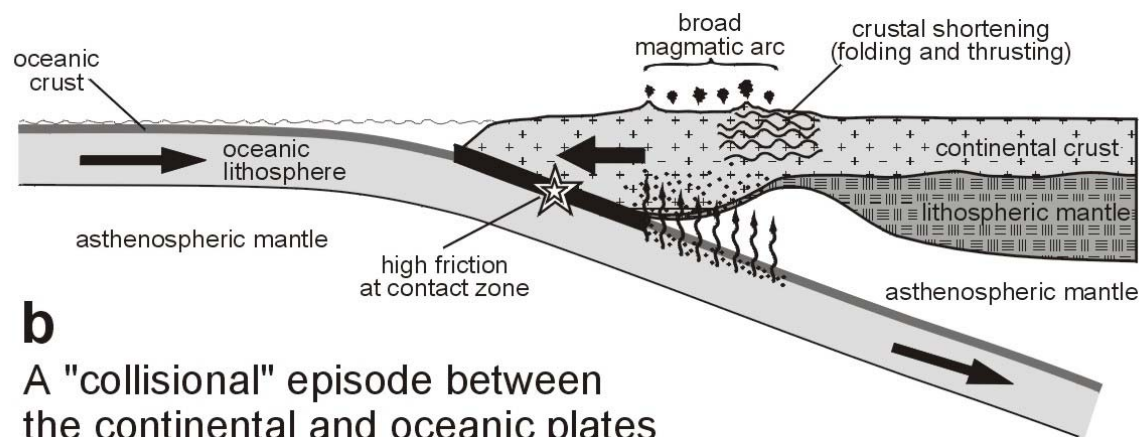
→ Collisional tectonics - a trigger for tin metallogeny ?

A "collisional" model for tin metallogeny



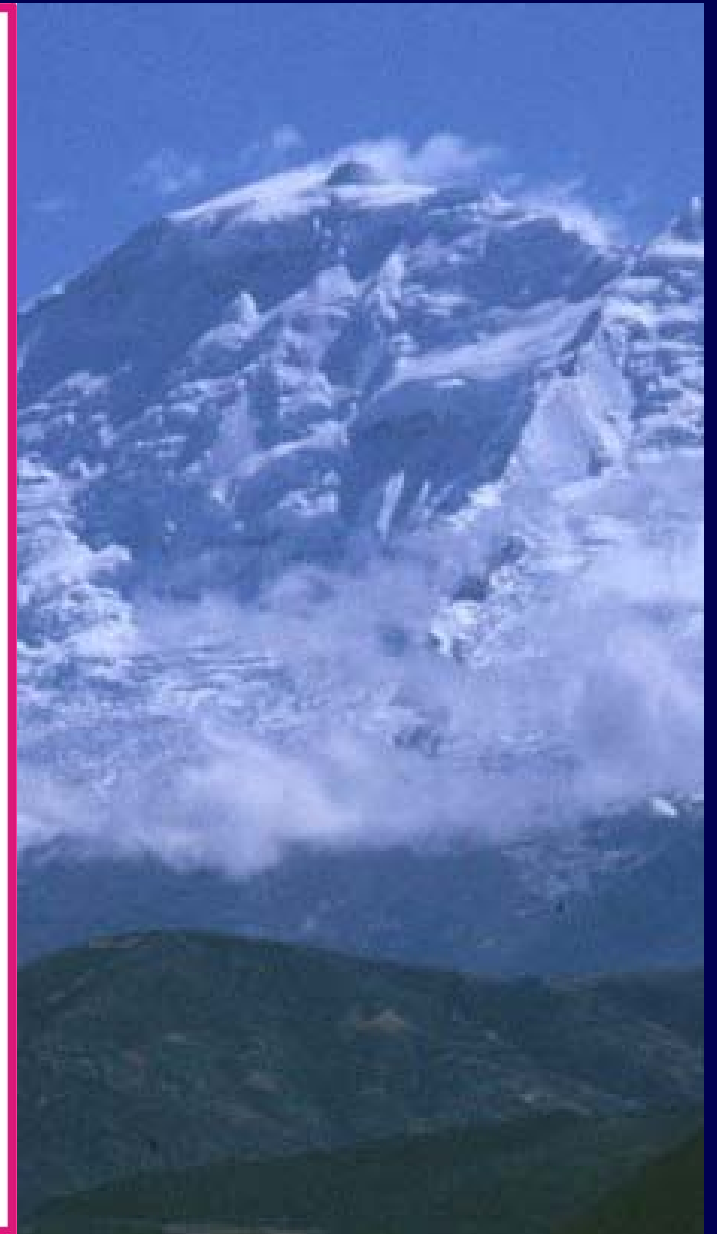
a

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



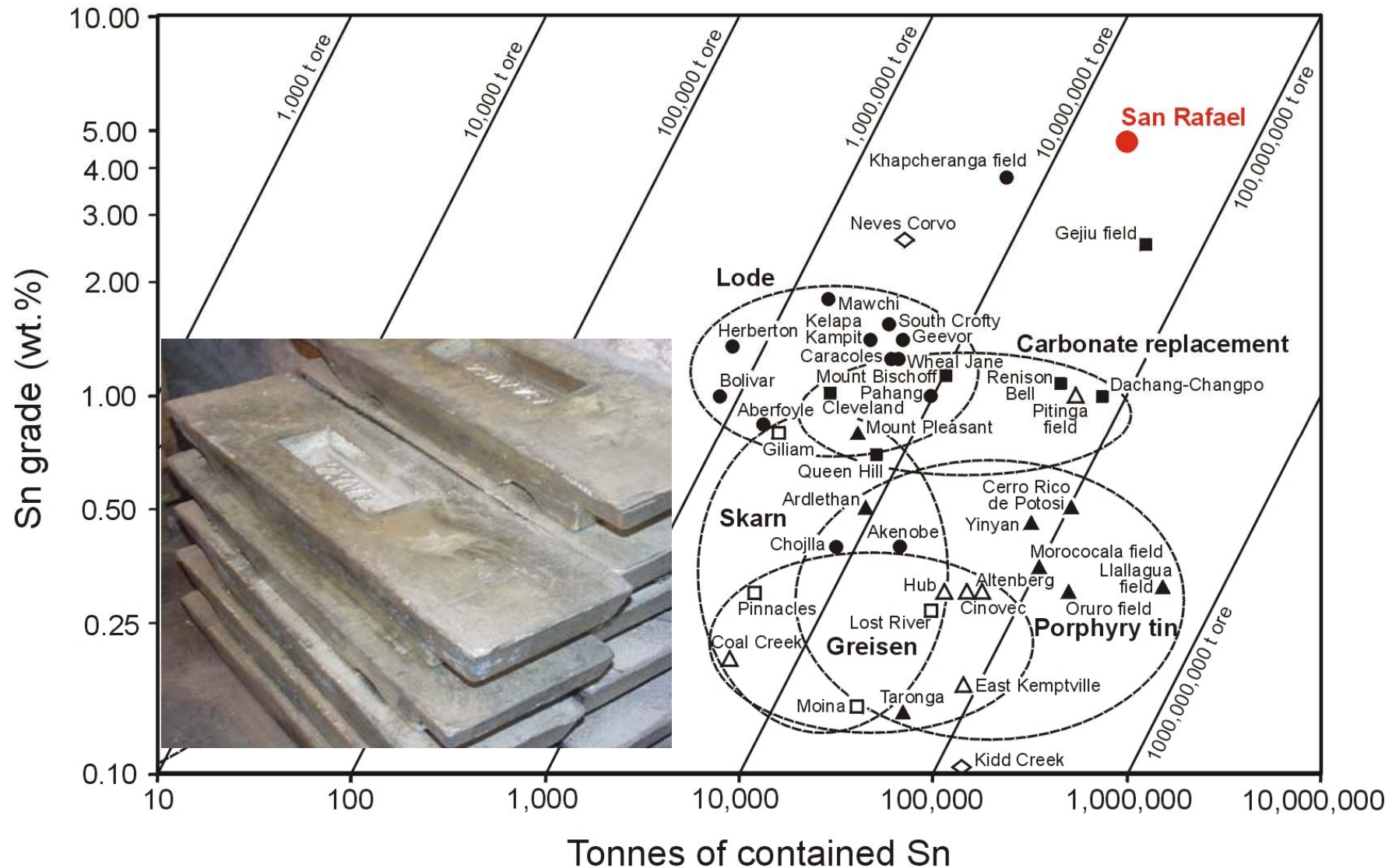
b

A "collisional" episode between the continental and oceanic plates leads to shallower subduction, crustal shortening and magmatic arc broadening

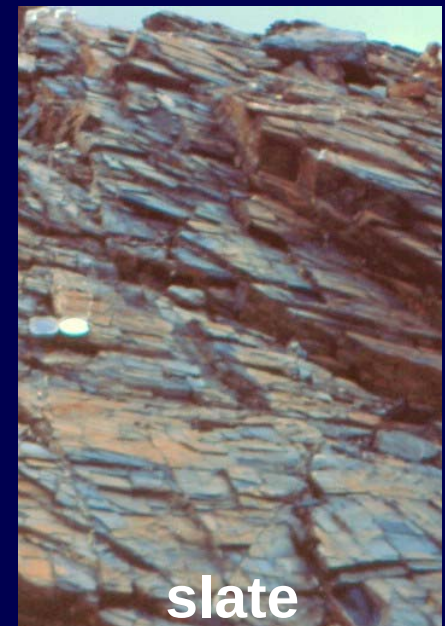
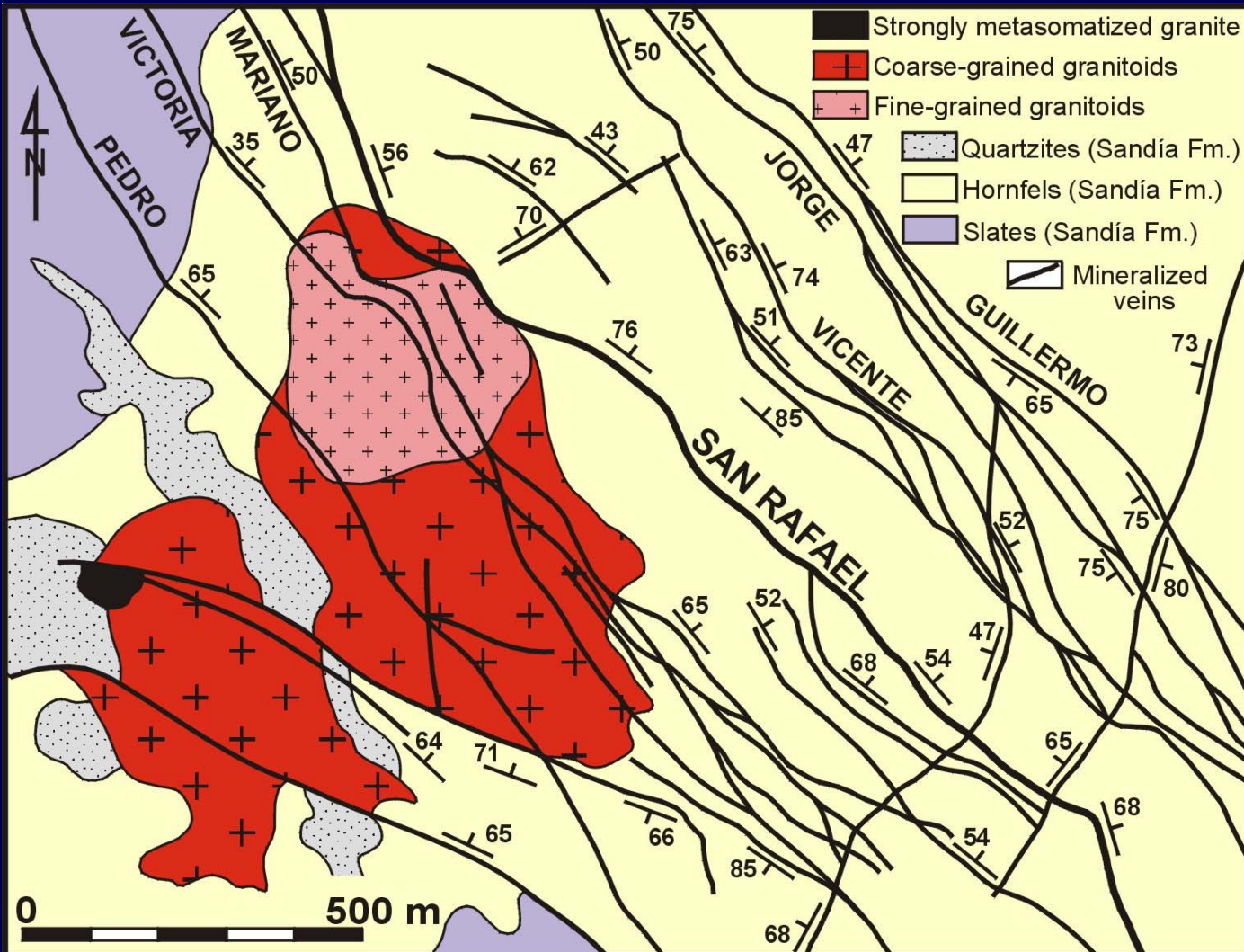


The San Rafael tin deposit

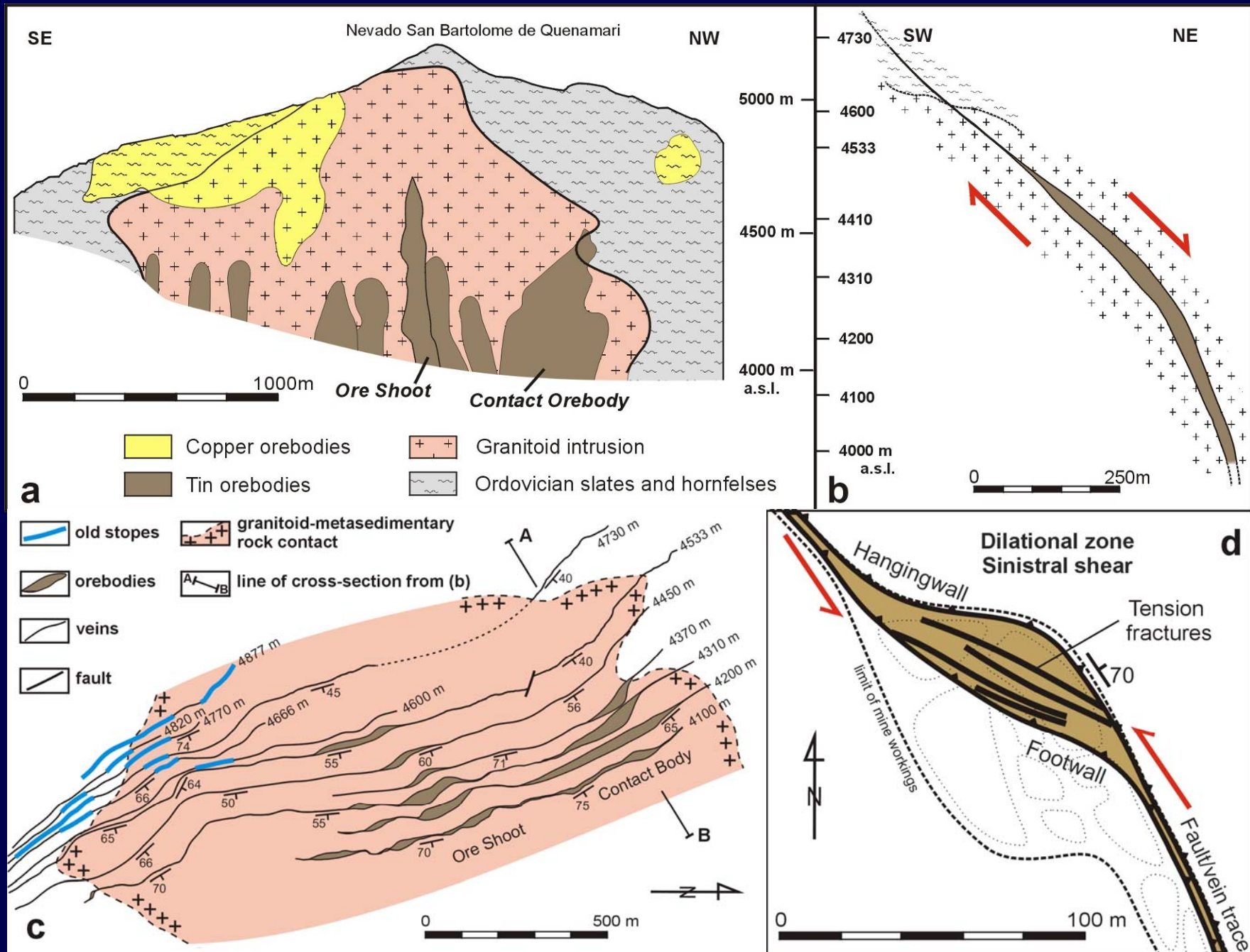
~ 1,000,000 tonnes Sn metal, average grade ~ 5 wt.% Sn



Geology of the San Rafael area

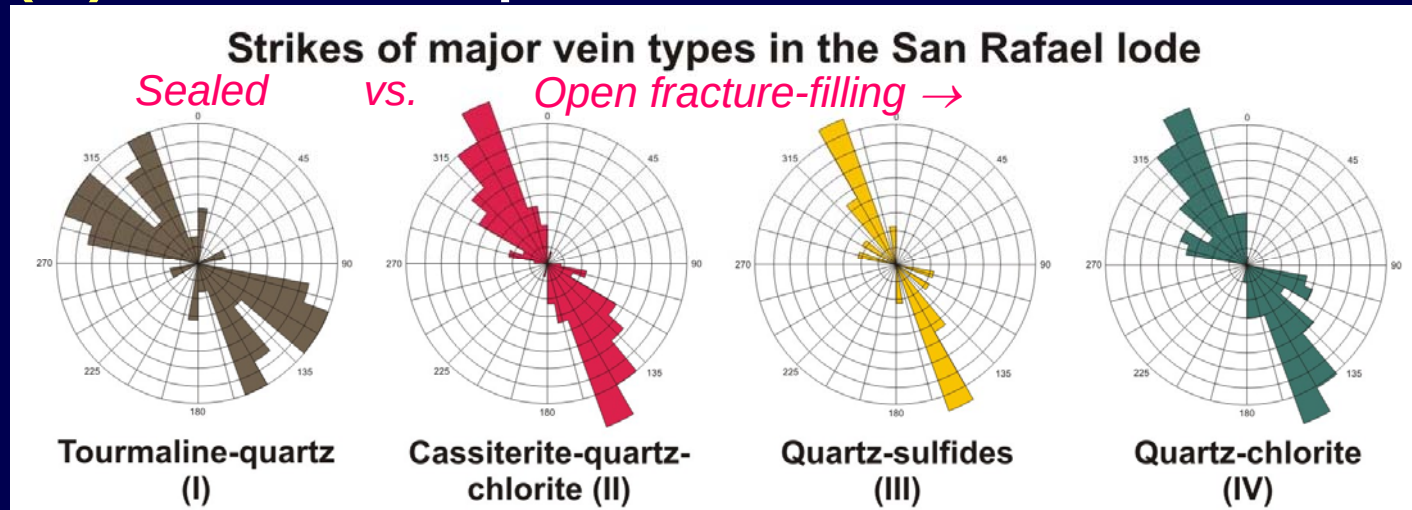
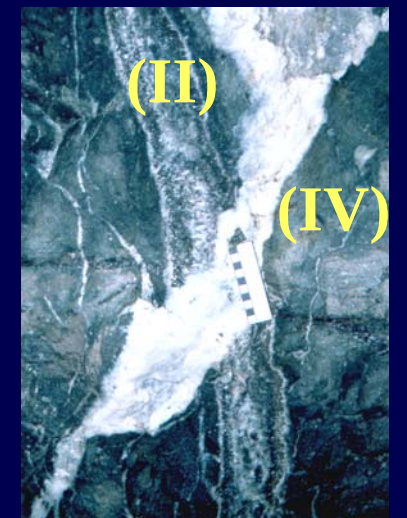


One major vein-breccia system (the San Rafael lode)

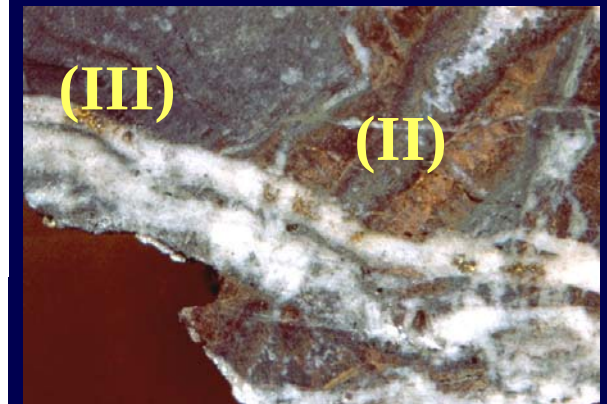
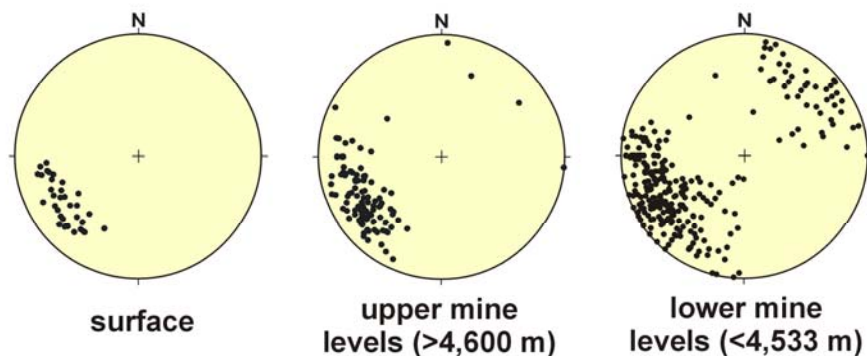


Vein paragenesis

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



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:

 fresh granite and granodiorite

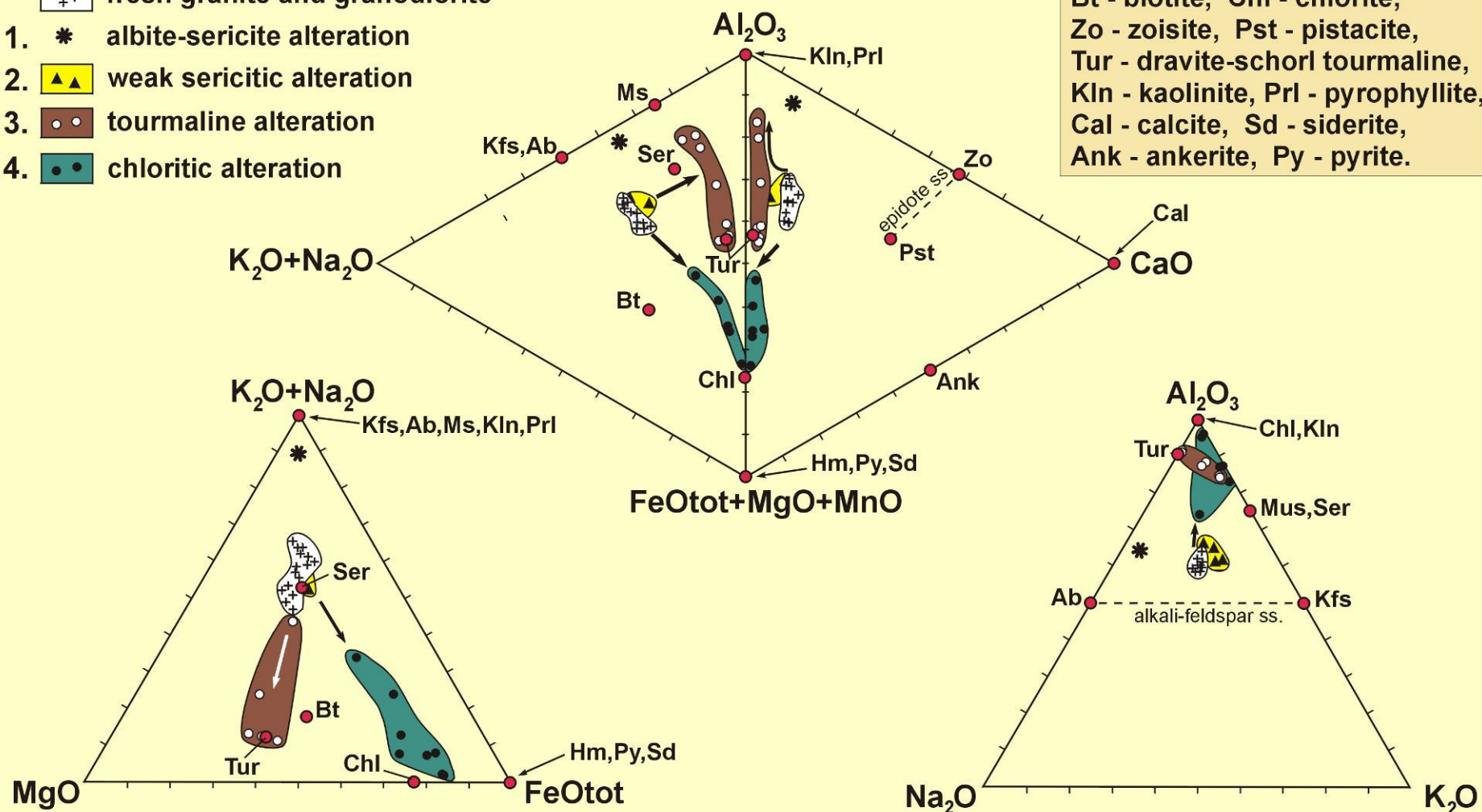
1. * albite-sericite alteration

2.  weak sericitic alteration

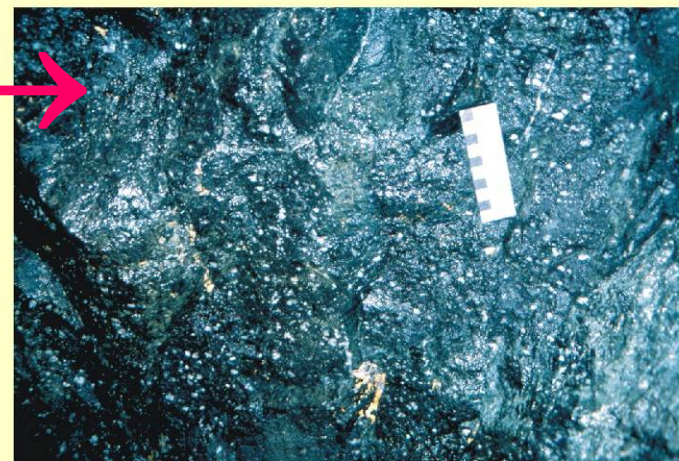
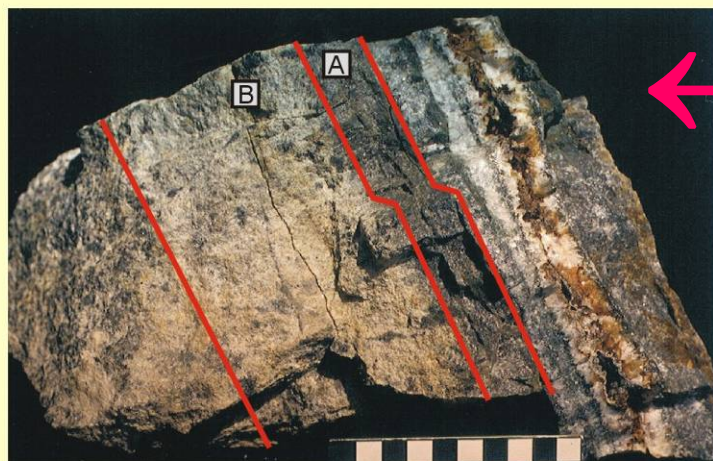
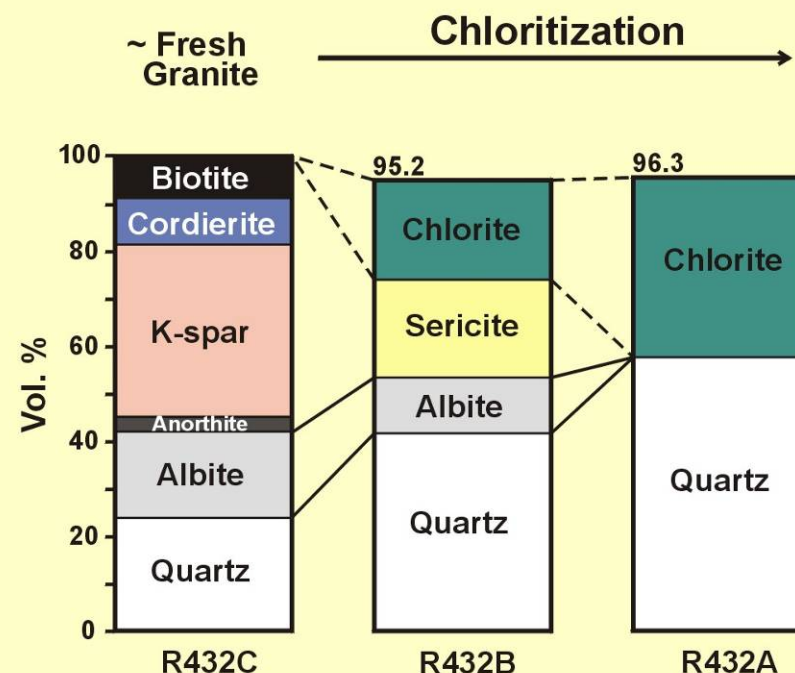
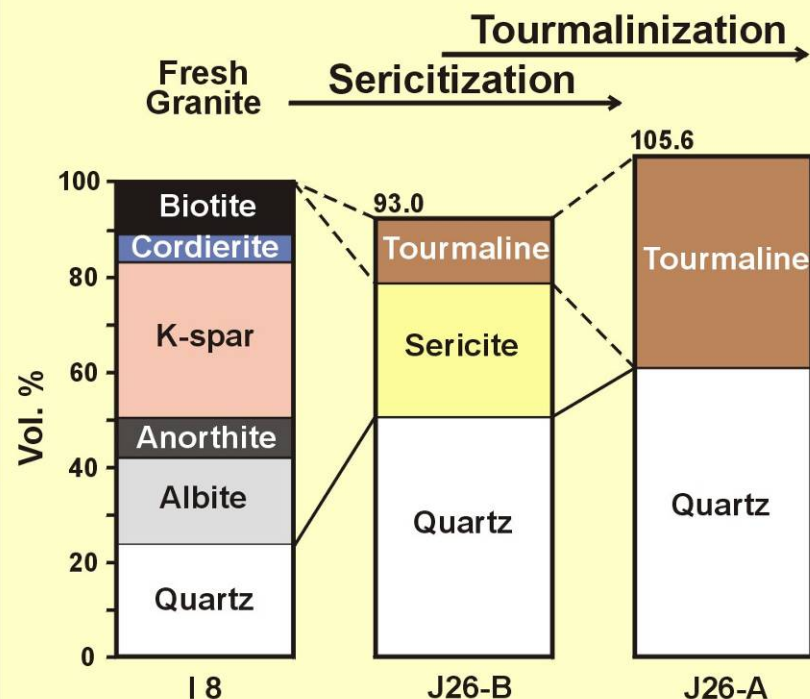
3.  tourmaline alteration

4.  chloritic alteration

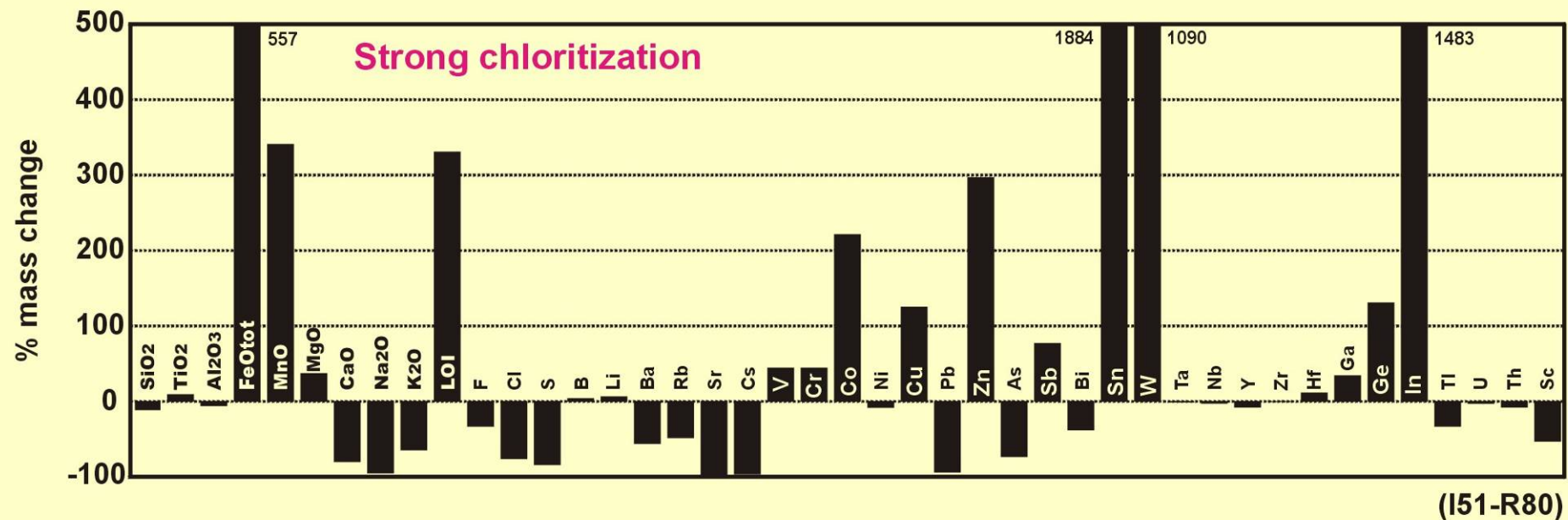
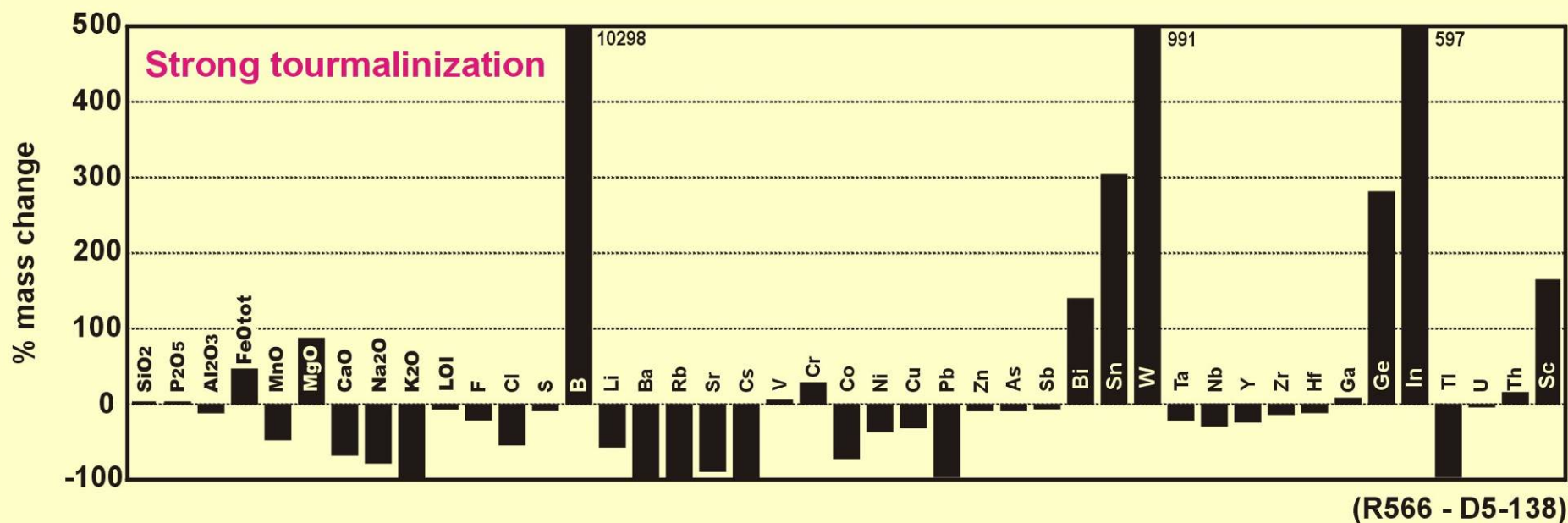
Kfs - K-feldspar, Ab - albite,
Ms - muscovite, Ser - sericite,
Bt - biotite, Chl - chlorite,
Zo - zoisite, Pst - pistacite,
Tur - dravite-schorl tourmaline,
Kln - kaolinite, Prl - pyrophyllite,
Cal - calcite, Sd - siderite,
Ank - ankerite, Py - pyrite.



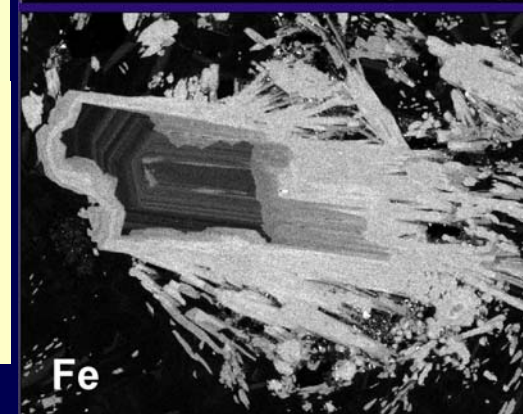
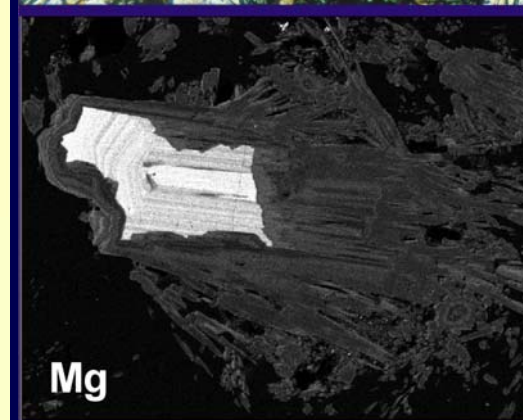
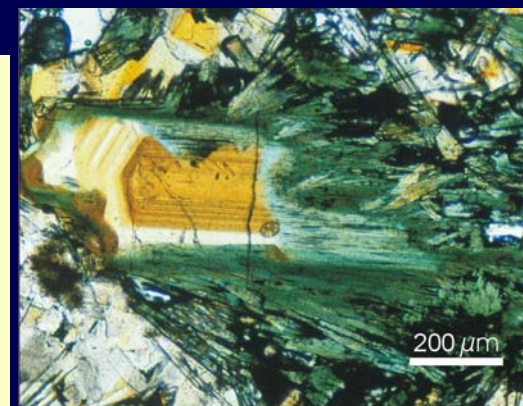
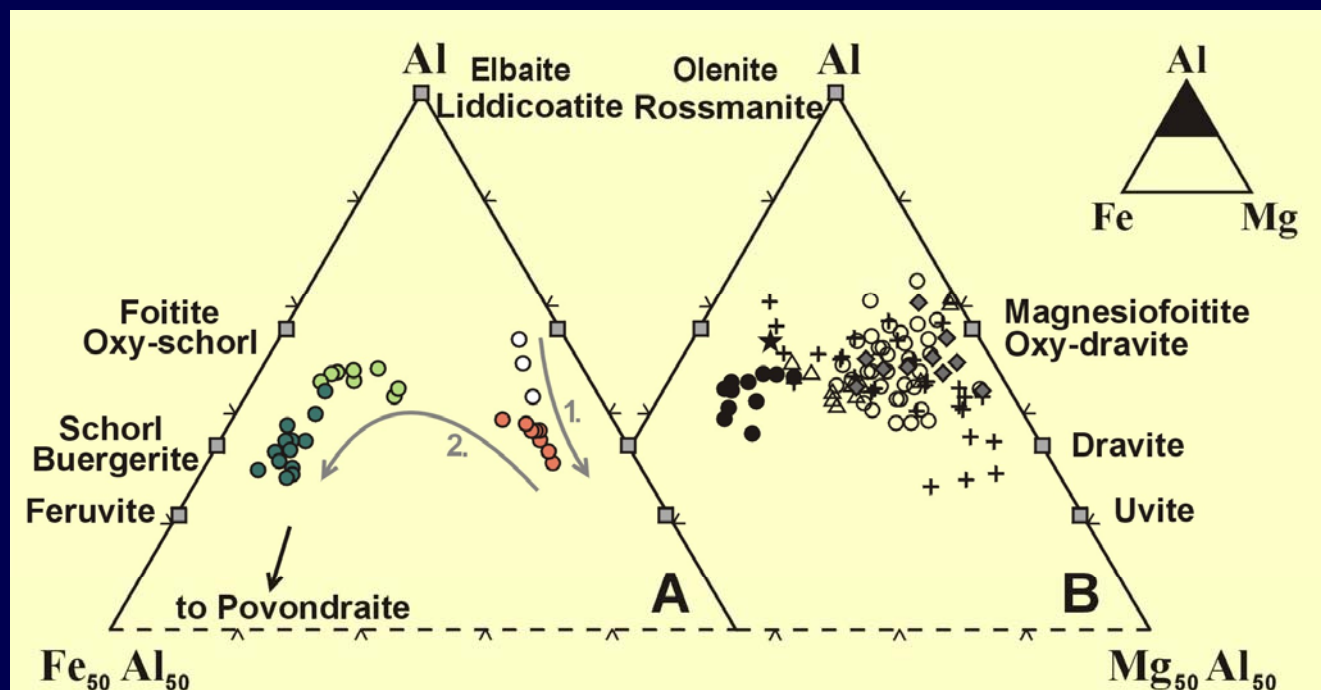
Variation in normative mineralogy: early sericitic and tourmaline alteration versus main-stage chloritization



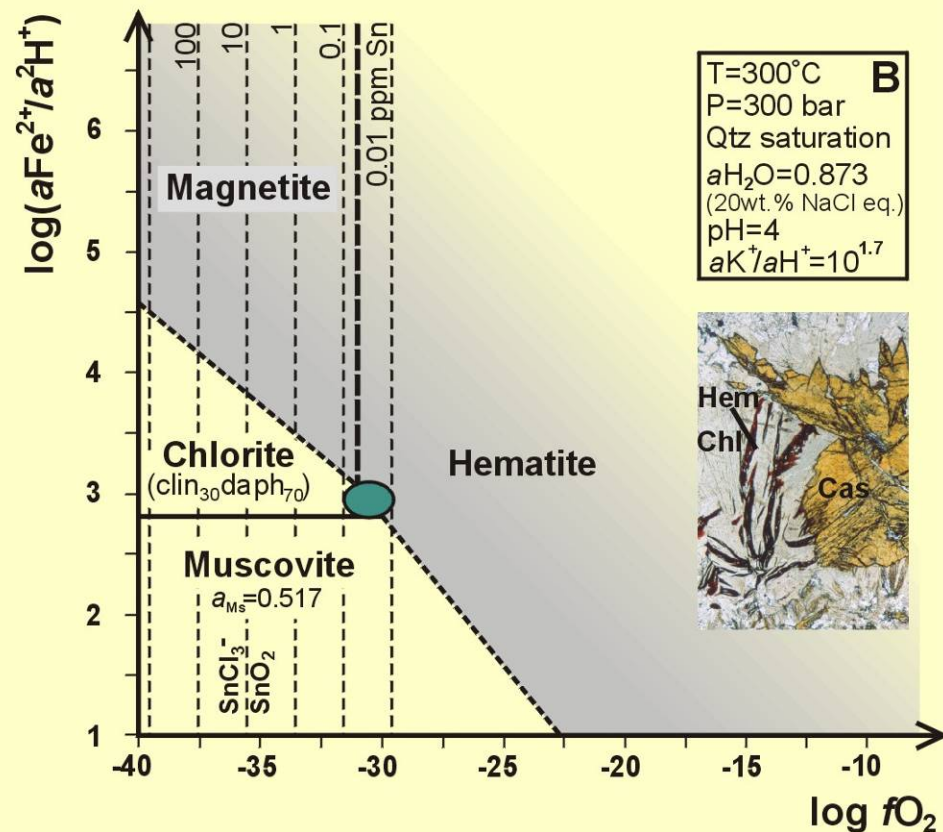
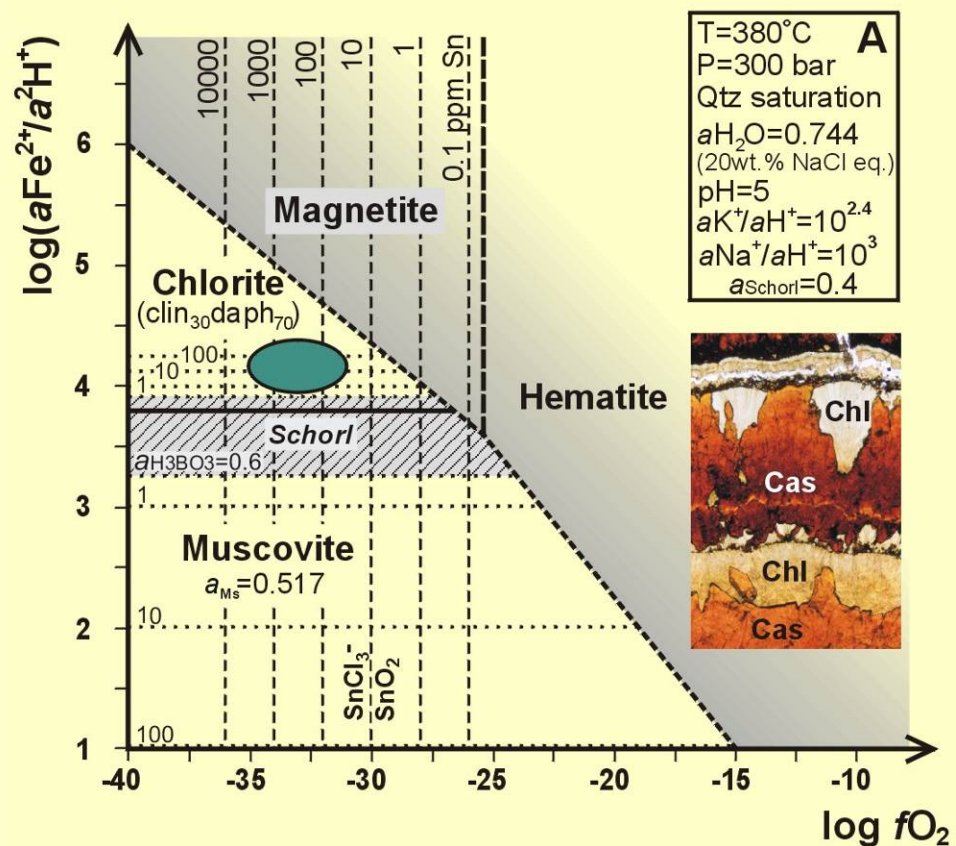
Gains and losses of major / trace elements during alteration



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

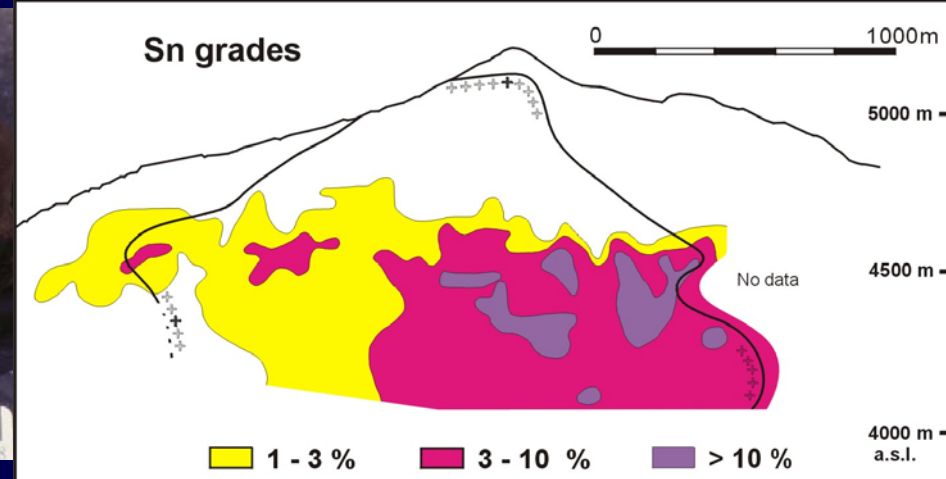
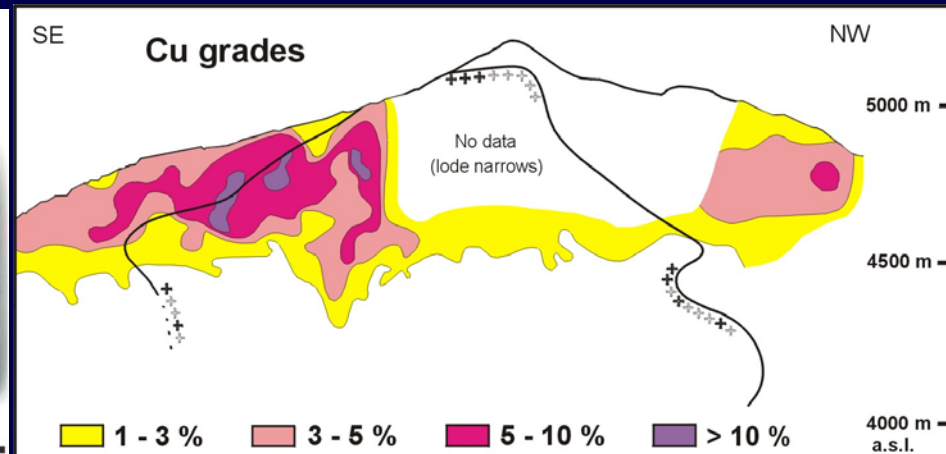
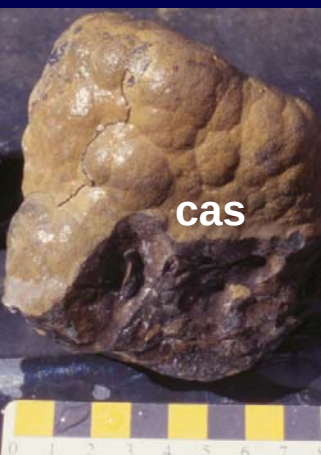
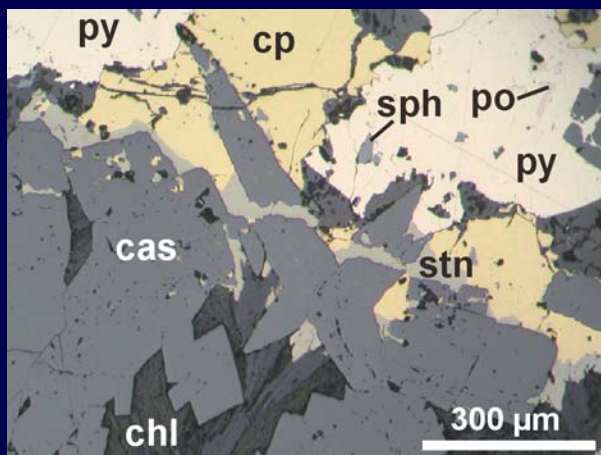
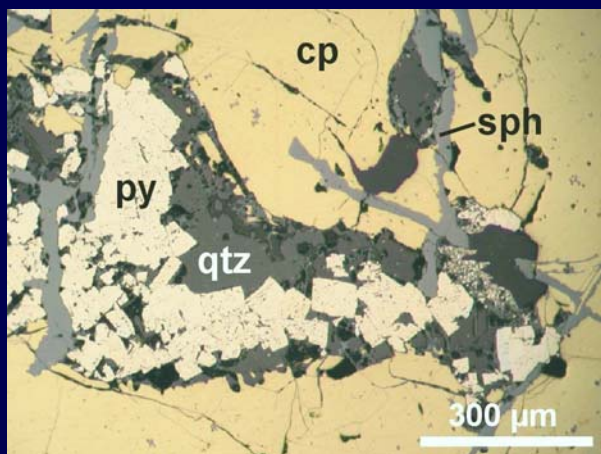


Physico-chemical conditions of chloritic alteration associated with main-stage cassiterite deposition

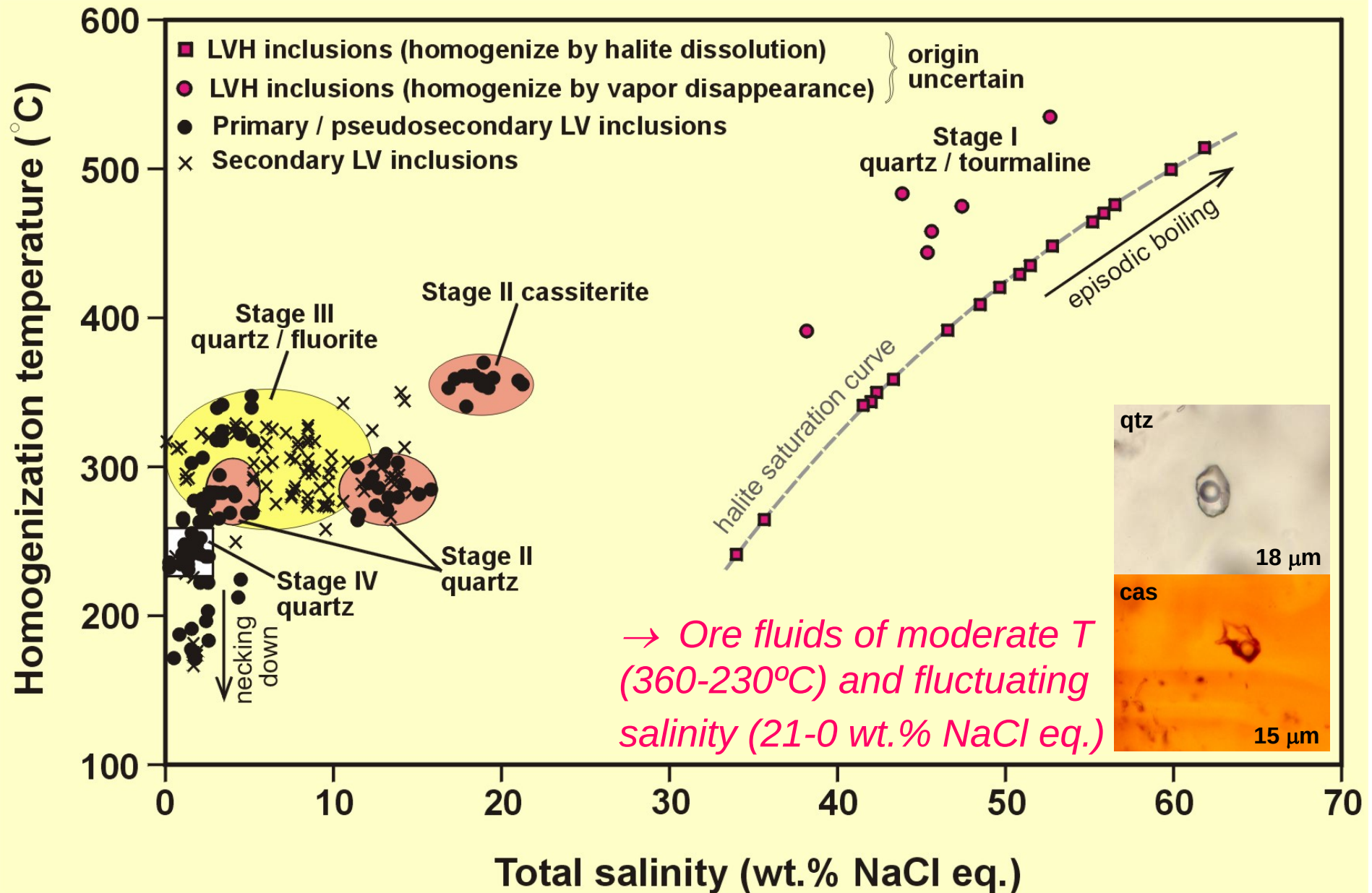


Ore mineralogy and metal zoning

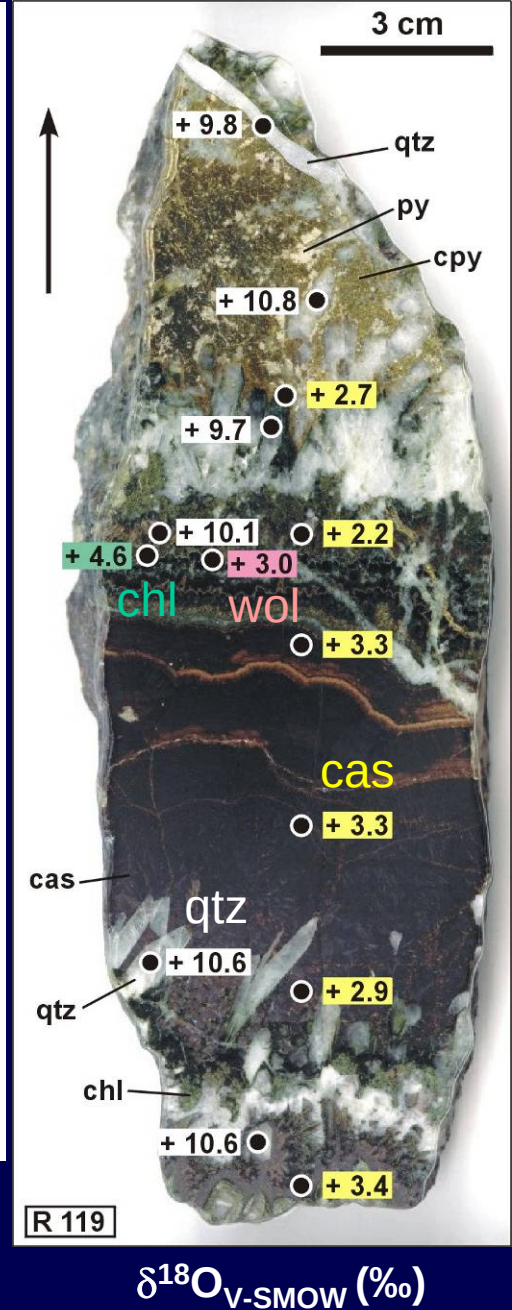
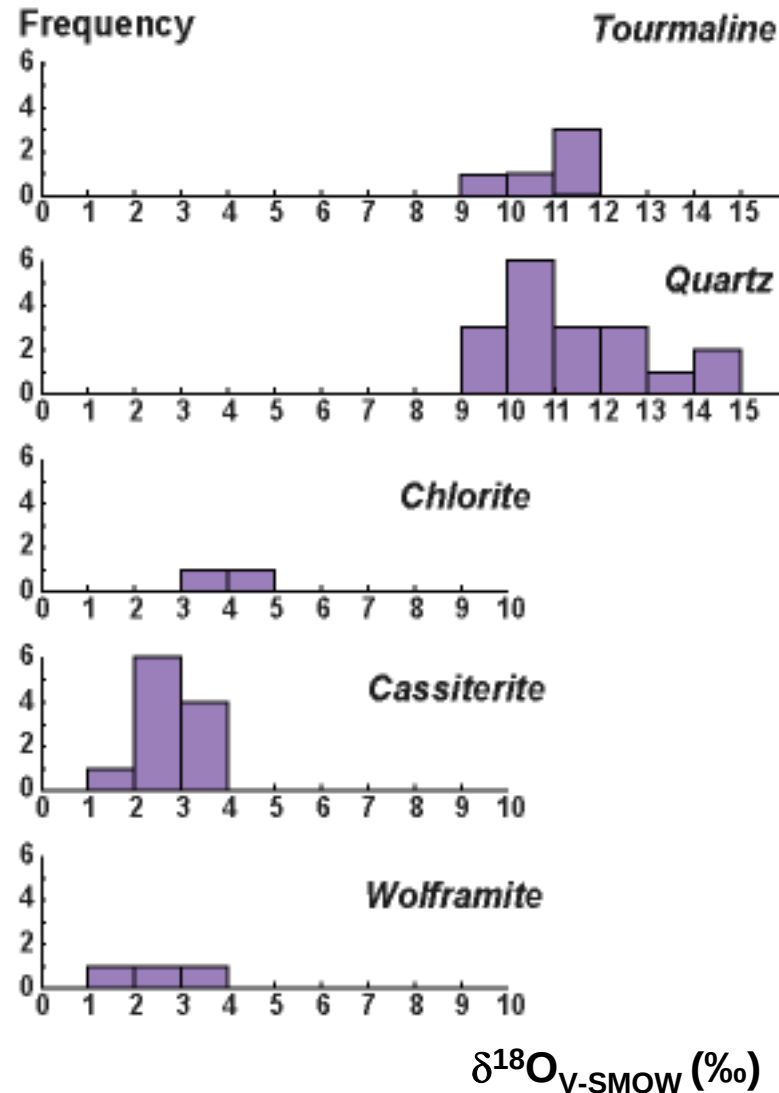
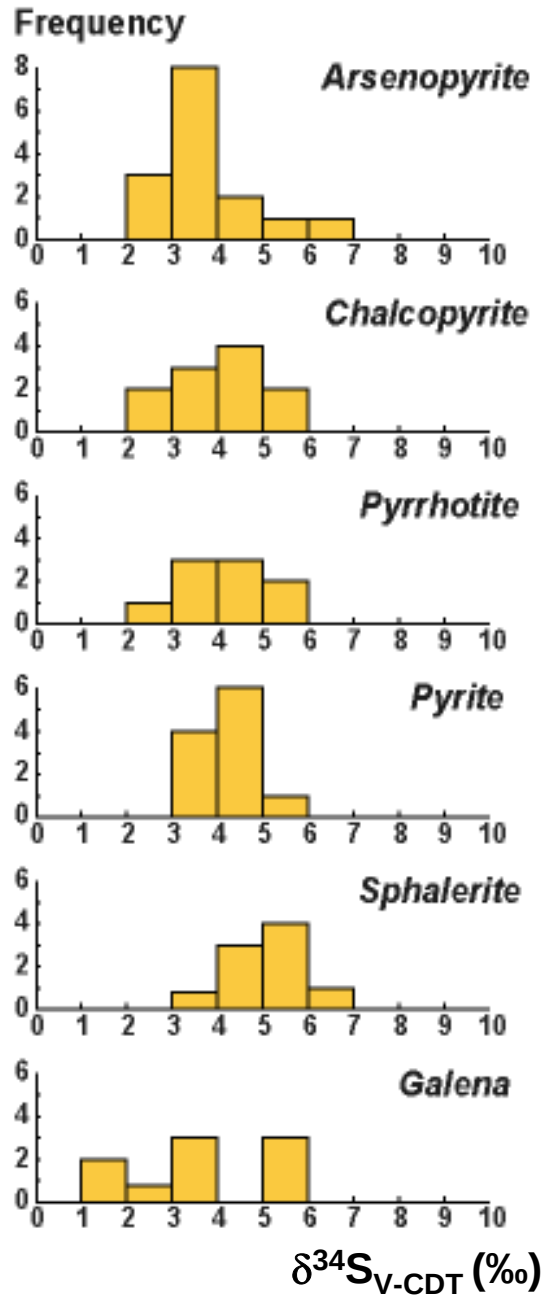
- Upper zone: sulfides dominate, complex mineralogy
(*chalcopyrite, pyrite, arsenopyrite, sphalerite, galena pyrrhotite, needle-tin cassiterite, quartz, chlorite*)
- Lower zone: oxides/silicates dominate, simple mineralogy
(*massive cassiterite, quartz, chlorite ± wolframite*)



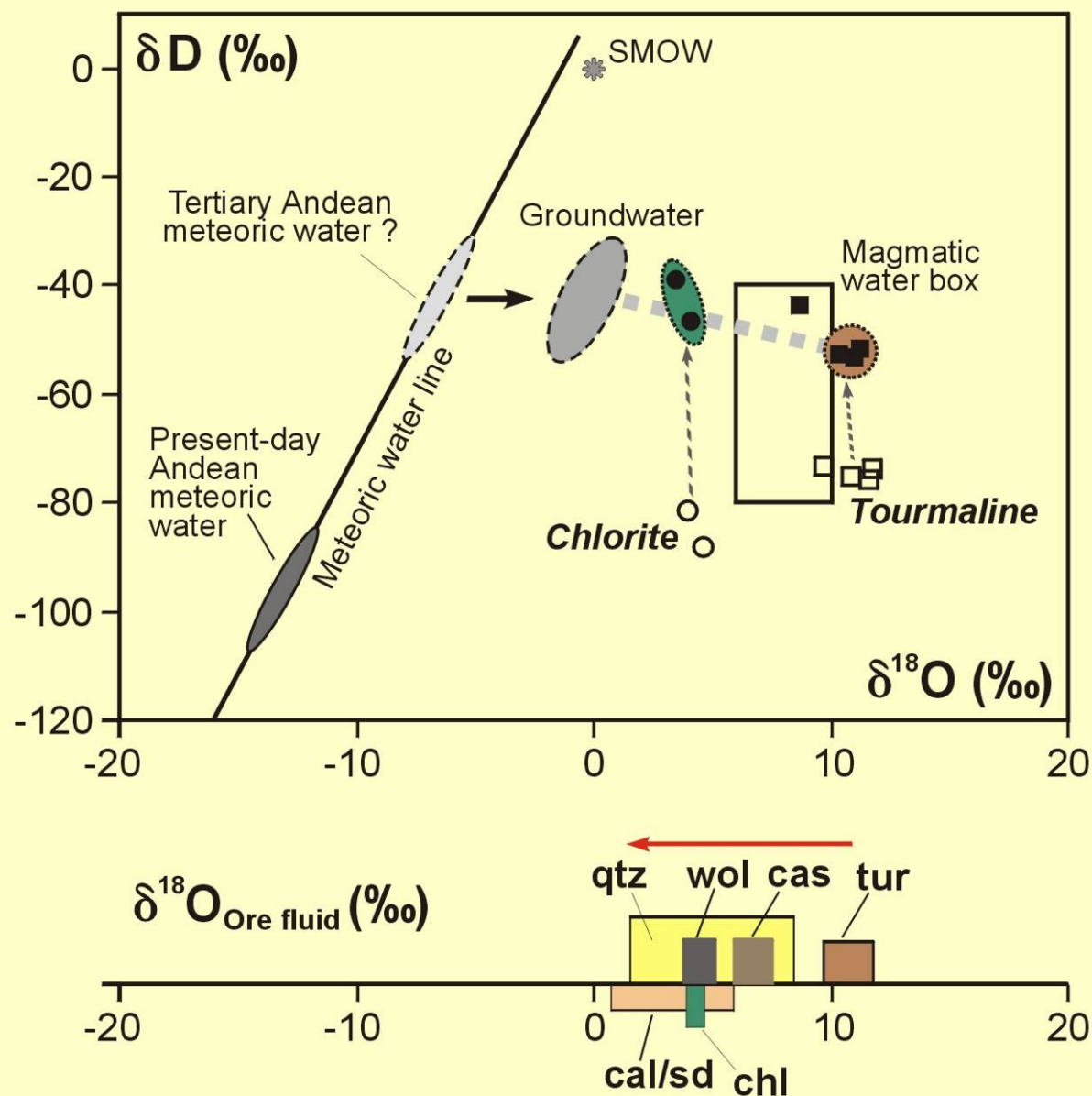
Fluid inclusion studies



Stable isotope studies



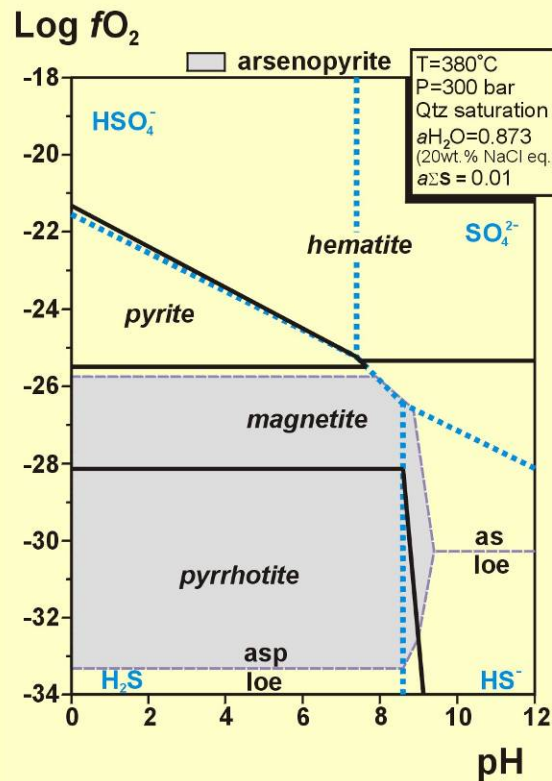
Isotopic evolution of hydrothermal fluids at San Rafael



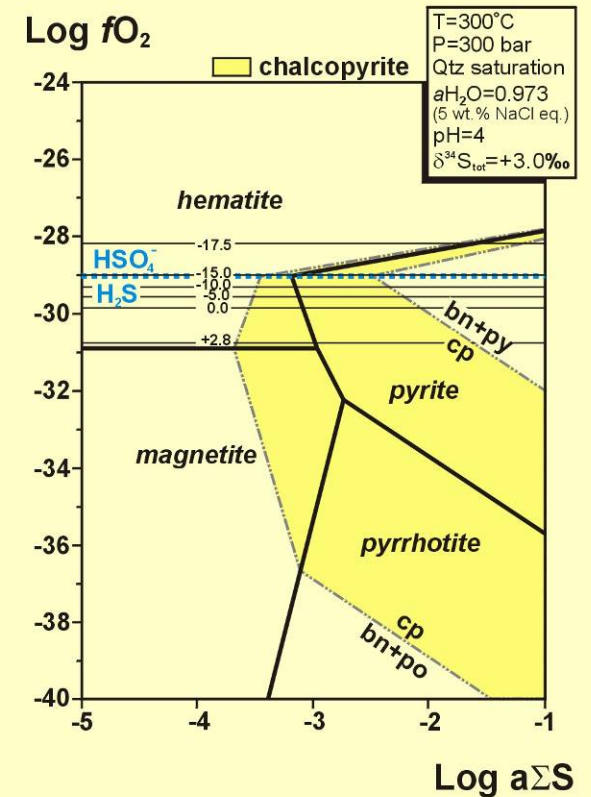
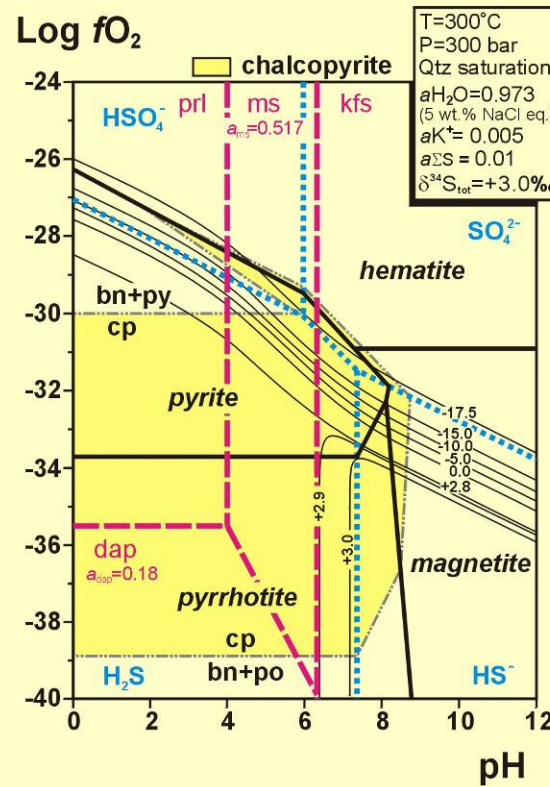
Calculated values of $\delta^{18}\text{O}$ and δD for water in equilibrium with the different ore and gangue minerals (at the temperature of their formation), exhibit a clear paragenetic trend of $\delta^{18}\text{O}$ decrease.

Mineral stability relationships for the tin stage (II) and the copper stage (III) of the San Rafael paragenesis

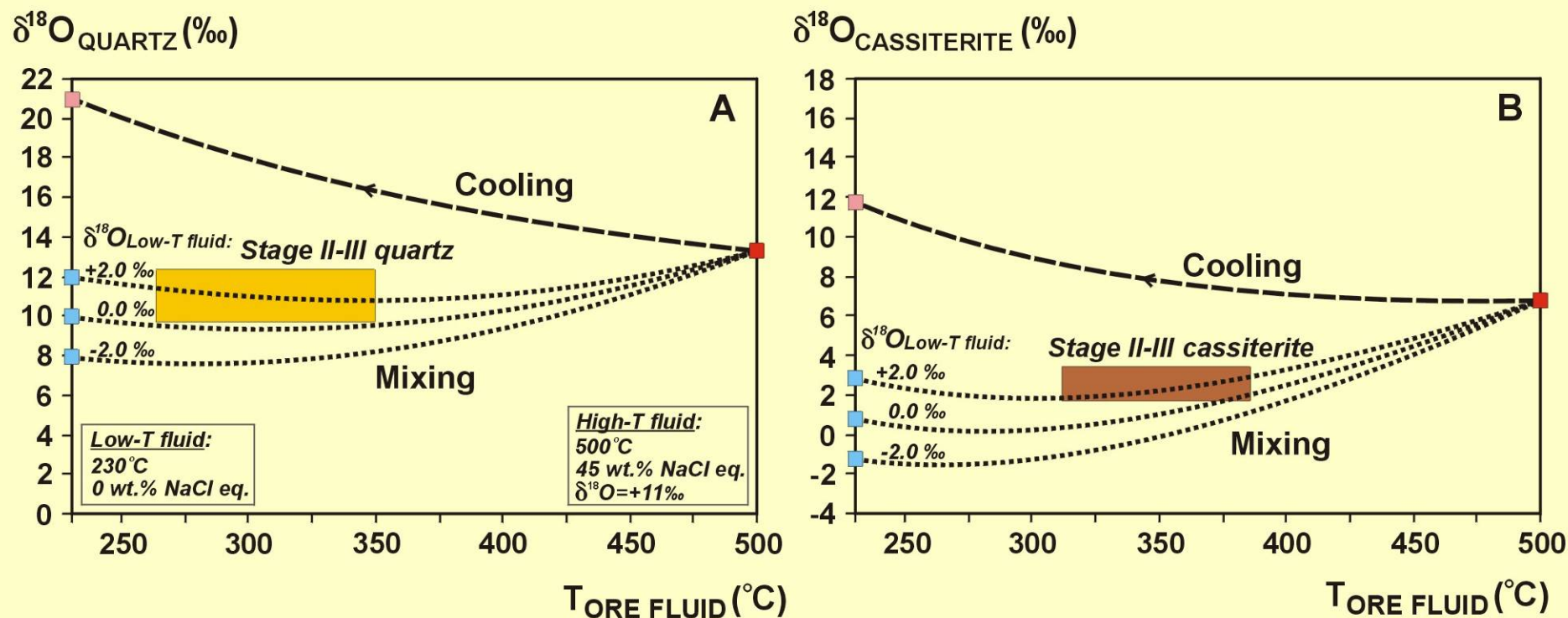
Stage II (tin deposition)



Stage III (copper deposition)



Effect of cooling and mixing of magmatic and meteoric fluids on the oxygen isotope composition of precipitating quartz (A) and cassiterite (B)



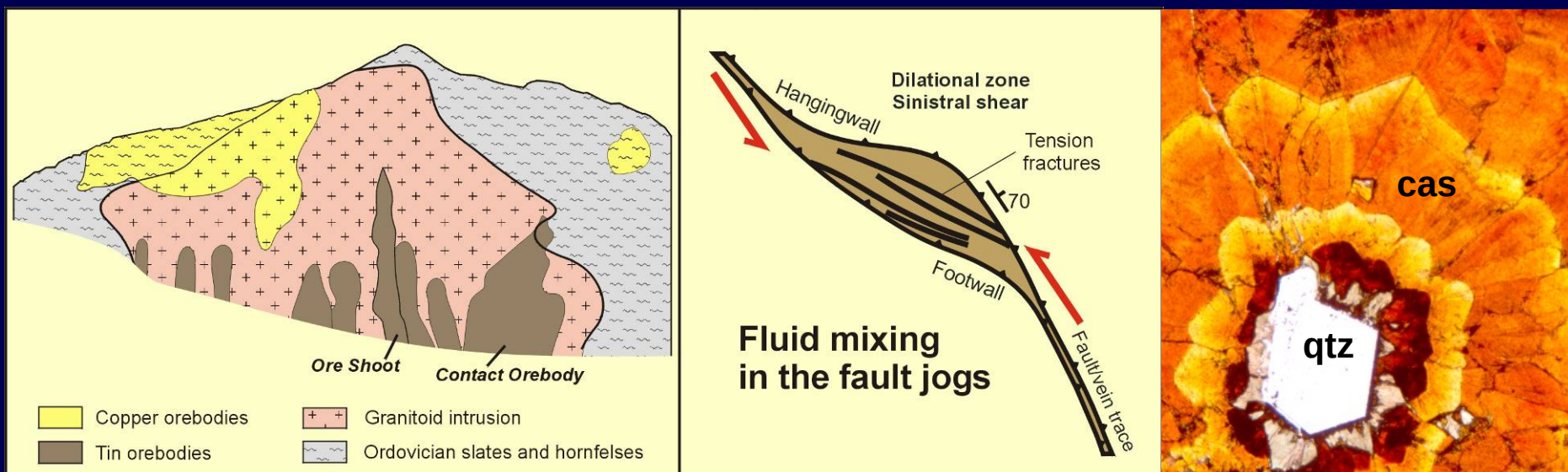
→ Only a scenario of mixing of a hot brine with a cooler, dilute fluid can reproduce the range of oxygen isotope compositions of quartz and cassiterite from the deposit

A genetic model for San Rafael

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

⇒ *Tectonic activity reopens the vein system → transition to hydrostatic conditions + influx of heated meteoric waters.*

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





Thank you for your attention...