

The San Rafael tin district, comprising the underground San Rafael deposit and the Quenamari and other prospects, is located in southern Peru, and represents the northernmost expression of the Andean tin belt. The ore mostly occurs as NW-SE trending veins dipping NE or SW, mainly hosted by Late Oligocene cordierite-bearing granitic rocks (24.6 ± 0.2 Ma at the San Rafael deposit) and Late Ordovician shales and quartzites.

Three of the four mineralization stages defined by other authors at San Rafael have been recognized at surface in the Quenamari prospect during the present work. Stage I is observable as small veins (< 3 cm wide) of fine-grained quartz and tourmaline in the Ordovician host rock. The main cassiterite stage II, also containing abundant quartz, muscovite, and chlorite at San Rafael, does not crop out at Quenamari, but the results of the present study favor the possibility of its presence at depth. The mineral association of polymetallic stage III consists of chalcopyrite, sphalerite, needle-tin cassiterite, galena, pyrite, marcasite, pyrrhotite, rhodonite, rhodochrosite and sulfosalts (including kobellite $(\text{Cu,Fe})_2\text{Pb}_{11}(\text{Bi,Sb})_{15}\text{S}_{35}$, tetrahedrite-freibergite $\text{Cu}_6[\text{Cu}_4(\text{Fe, Zn})_2]\text{Sb}_4\text{S}_{13}$ - $\text{Ag}_6[\text{Cu}_4\text{Fe}_2]\text{Sb}_4\text{S}_{13-x}$, and canfieldite Ag_8SnS_6). The late stage IV is characterized by narrow (< 20 cm wide) barren quartz dominant veins. Mineralogy of the polymetallic veins in the Santo Domingo prospect, located 20 km to the west of San Rafael and also studied in the present work, are similar to the stage III in San Rafael and Quenamari and contain chalcopyrite, sphalerite, needle-tin cassiterite, galena, pyrite, marcasite, pyrrhotite, arsenopyrite and late carbonate.

Mapping at a scale 1:2000 at Quenamari has revealed generally NW-SE trending mineralized veins showing good continuity (> 1 km) and considerable width (up to 3 m thickness) emplaced in faults with normal displacement. Alteration is non-pervasive and is restricted to the vicinity of veins, except for pinitization of cordierite, which seems to affect all outcropping granites and in places the formation of Na-rich plagioclase haloes rimming K-feldspars. Stage I quartz-tourmaline is accompanied by sericitic alteration (quartz-sericite-pyrite), whereas stage III is spatially associated with chloritization and minor silicification.

Tourmaline of stage I and in granite dykes shows a color and compositional evolution from orange-brown (intermediate composition between dravite and schorl) to blue tourmaline (0.03 Mg apfu and 2.36 Fe apfu), similar to that described at San Rafael, and indicating a decrease of temperature. Colorless tourmaline veins (dravite pole (1.9 Mg apfu and 0.19 Fe apfu), seem to be post orange-brown tourmaline which, if confirmed, would imply a hotter pulse. Microprobe analysis of sphalerite indicates that a strong correlation between color and iron content. Opaque sphalerite has up to 11.36 wt. % Fe and orange-yellow sphalerite under microscope down to 3.3 wt. %. Manganese content can rise up to 3.08 wt.% in opaque sphalerite. Cadmium contents are relatively high in all sphalerite color groups (≈ 0.25 -0.3 wt. %).

At Quenamari, microthermometric analyses performed on liquid-vapor fluid inclusions occurring in quartz interpreted to be slightly later than sphalerite and in quartz intergrown with chalcopyrite of stage III, and in liquid-vapor fluid inclusions in quartz of stage IV, indicate that salinity and homogenization temperatures for stage III range from 1.2 to 9.4 wt% NaCl eq. and 248 to 324 °C respectively (with values from 7.3 to 9.5 wt% NaCl eq. and 248 to 295 °C for sphalerite, 4.6 to 7.9 wt% NaCl eq. and 253 to 283 °C for quartz syn to post sphalerite, and 1.3 and 5.8 wt% NaCl eq. and 283 to 324 °C for quartz intergrown with chalcopyrite). Regarding stage IV, salinities for quartz-hosted fluid inclusions lie between 0.7 and 0.9 wt% NaCl eq. while homogenization temperatures range between 170°C and 217°C. The minimum pressure of entrapment for stage III is 103 bar and for stage IV 16 bar.

At Quenamari, stable isotope analyses performed on tourmaline (stage I), quartz, and chlorite (stage III and IV) give $\delta^{18}\text{O}_{\text{V-SMOW}}$ values ranging from 11.3 to 12.0 ‰ for tourmaline and 10.6 to 17.8 ‰ (stage III) and 8.6 to 9.8 ‰ (stage IV) for quartz. For chlorite, the range is from 4.8 to 6.2‰ for stage III and 0.7‰ for stage IV. $\delta\text{D}_{\text{V-SMOW}}$ values range from -79.6 to -70.4 ‰ for tourmaline and from -76 to -59.2 ‰ and -90.1‰ for chlorite, from stage III and IV, respectively. At Santo Domingo, $\delta^{18}\text{O}_{\text{V-SMOW}}$ values are 14.4 and 15.7‰ for quartz, and 7.3 and 8.4‰ for chlorite. $\delta\text{D}_{\text{V-SMOW}}$ values for chlorite are -67.1 and -62.2 ‰. Values for tourmaline are clearly magmatic; chlorite values are very close to the magmatic range and those of stage III suggest a vapor phase, and quartz $\delta^{18}\text{O}_{\text{V-SMOW}}$ values decrease with time. The quartz-chlorite geothermometer gives two temperatures for stage III at Quenamari: 270 °C and 290°C.

The results achieved in Quenamari are comparable with previous findings at the San Rafael mine, suggesting that the Quenamari prospect is the upper part of a steep system similar to the one that formed the San Rafael tin deposit. Stable isotope data are indicative of magmatic fluids during stage I formation. Precipitation during stage III is dominated by mixing between a, possibly magmatic, fluid (≥ 9.5 wt.% NaCl eq. and $\leq 250^\circ\text{C}$) and a low-salinity fluid of higher temperature (≤ 2 wt.% NaCl eq. and $\geq 340^\circ\text{C}$). Taking in account the stable isotope results, this second fluid could correspond to condensated magmatic vapor or, less likely, to isotopically equilibrated and heated meteoric fluids. Stable isotope and fluid inclusion data indicate that in stage IV ingression of meteoric fluids was strong and they dominated the fluid budget.

The fact that at comparable altitude above sea level, similar mineral paragenesis, fluid inclusion characteristics, and stable isotope ratios are found, strongly suggests that the magmatic roots of the mineralizing system at Quenamari are located at a similar depth than at San Rafael. This, together with the lateral extension and width of the mineralized veins revealed by the detailed surface mapping of the present work, points to an important potential at depth for Sn mineralization at the Quenamari prospect.