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Genesis of the Giant, Bonanza San Rafael Lode Tin Deposit, Peru: Origin and Significance of Pervasive Alteration

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Abstract

The San Rafael Sn-Cu deposit, located at lat 14°13'58" S, long 70°19'18" W, on the upper slopes of the Cordillera de Carabaya, northern Puno Department, southeastern Peru, yielded 38,182 t of fine tin in 2001 and, with reserves of 14.460 Mt at 5.14 percent Sn, the main San Rafael Lode constitutes, both at present and historically, the largest-known bonanza-grade cassiterite repository. Sn and subordinate Cu mineralization were confined to laterally and vertically extensive brittle shear zones generated by regional tectonism that transect a small 24.65 ± 0.20 Ma, epizonal stock of strongly peraluminous, Lachlan S-type cordierite-biotite monzogranite and granodiorite. Early, barren, stage I quartz-tourmaline veins and breccias were emplaced at 24.10 ± 0.15 Ma by high-temperature (≤580°C), boiling, saline fluids that plausibly directly exsolved from the granitic melt, whereas both cassiterite (stage II) and, at higher elevations, chalcopyrite (stage III) ores were precipitated from largely nonboiling, cooler (T_h = 215°–420°C), and less saline (0–20 wt % NaCl equiv) fluids at 21.9 to 22.7 ± circa 0.5 Ma.

Only narrow (≤2 m) envelopes of chlorite and weaker sericite and silica are associated with stages II and III veins, but more than 80 percent of the upper 750 m of the San Rafael stock experienced quasipervasive hydrothermal alteration. Early K metasomatism is recorded by widespread replacement of magmatic plagioclase and perthitic alkali feldspar by Na-free orthoclase, while broadly coeval alteration to albite more erratically affected groundmass plagioclase and the rims of alkali feldspar phenocrysts. Despite the intensity of the alkali metasomatism, only minor redistribution of dispersed, magmatic Sn occurred, largely during alteration to orthoclase. Other petrographically similar granitic bodies in the region experienced more intense Na metasomatism, and they host argentian base metal rather than Sn-dominated veins. Superimposed hydrolytic alteration, most intense within 20 to 30 m of the San Rafael Lodes, converted biotite to Fe-rich chlorite and converted alkali feldspar and plagioclase to fine-grained muscovite, but there is no significant dispersed cassiterite or chalcopyrite.

Secondary fluid inclusions trapped in quartz phenocrysts of the granitic rocks range in salinity from 0 to 65 wt percent NaCl equiv and in T_h from 200° to 530°C; fluid boiling is evident in the higher-temperature populations. First-melting temperatures and decrepitate analyses reveal, in addition to NaCl, widely variable concentrations of KCl, $CaCl_2$ (attaining 40 wt % of the solute) and, apparently most abundant in proximity to the lodes, $FeCl_2$. Entrapment pressures are estimated to have fluctuated in the range 150 to 615 bars for much of the hydrothermal history, but fluid overpressuring to at least 2 kbar occurred, probably cyclically, during the evolution of the hydrothermal system. The salinity vs. homogenization temperature range for the phenocryst-hosted inclusions closely matches that of primary inclusions in quartz and cassiterite in the lodes and, remarkably, small clusters of the former record the entire thermal and compositional trajectory of the mineralizing fluids. Early magmatic brines are inferred to have permeated much of the stock whereas, circa 2 m.y. later, Sn- and Cu-rich, lower-temperature, lower-pH fluids were largely channeled along the evolving shear zones where they mixed with cool, nonsaline, tectonically driven ground water. In conjunction with fluid neutralization through hydrolytic alteration, this channeling resulted in catastrophic precipitation of botryoidal and coarsely crystalline cassiterite and, subsequently, chalcopyrite. The hiatus between initial retrograde boiling and ore deposition, a feature documented in several world-class, high-grade lithophile-element deposits, may record protracted storage of metal-rich brines at depth, perhaps in association with small volumes of highly fractionated melt, such as is represented by small bodies of tourmaline leucogranite exposed on the upper margin of the San Rafael stock. However, the parallel evolution in temperature and salinity exhibited by the early nonmineralizing and later fertile hydrothermal fluids may also indicate that Sn and Cu were largely introduced into the subjacent magma chamber at a late stage.

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