

Magmatic-Hydrothermal Redox and Sulfur Evolution in the Grasberg Porphyry Cu-Au Deposit, Indonesia: Insights from Mineral Chemistry and Sulfur Isotope Analysis

Adi Sulaksono¹, Yasushi Watanabe², Antonio Arribas³, Takuya Echigo², Keiko Hattori⁴

¹PT Geo Fix Indonesia, South Jakarta, Indonesia, ²Akita University, Akita, Japan, ³University of Texas at El Paso, El Paso, USA, ⁴University of Ottawa, Ottawa, Canada

Recent research on the Grasberg porphyry Cu-Au deposit suggests that decreasing melt fO_2 during syn-mineral magmatism may drive large-scale sulfur degassing and that the subsequent evolution of fO_2 and sulfur plays a key role in metal precipitation. Here, we present melt fO_2 estimates from zircon and amphibole and reconstruct fO_2 -sulfur evolution using apatite, anhydrite, and sulfur isotopes.

Zircon ($n = 20$) and low-Al amphibole ($n = 95$) from the Main Grasberg Intrusion (Syn-Mineral Intrusion I) record high oxidation states, with average fO_2 of FMQ+4.8 ($Ce^{4+}/Ce^{3+} = 519$) and FMQ+3.4, respectively. In contrast, zircon ($n = 21$) and low-Al amphibole ($n = 61$) from the Early Kali Intrusion (Syn-Mineral Intrusion II) record lower fO_2 values of FMQ+4.2 ($Ce^{4+}/Ce^{3+} = 248$) and FMQ+2.7. In Syn-Mineral Intrusion II, low-Al amphibole rims high-Al amphibole, with the latter ($n = 49$) recording a low fO_2 of FMQ+1. Consistent with the decrease in fO_2 , apatite in Syn-Mineral Intrusion I records higher melt S concentrations (46 ppm; $n = 29$) than apatite in Syn-Mineral Intrusion II (31 ppm; $n = 37$).

Magmatic anhydrite ($n = 38$) differs from hydrothermal anhydrite ($n = 49$), showing higher FeO (0.018 vs. 0.009 wt.%), but lower SrO (0.19 vs. 0.34 wt.%). Anhydrite-sulfide pairs from veins yield $\delta^{34}S$ values indicating SO_2 -derived sulfate/sulfide molar ratios of ~ 4 at $>550^\circ C$, decreasing to ~ 1 at $<550^\circ C$.

The decrease in melt fO_2 in the upper-crustal magma chamber likely reflects the injection of more reduced magma. This decrease destabilized anhydrite formed during Syn-Mineral Intrusion I, producing SO_2 -rich volatiles during emplacement of Syn-Mineral Intrusion II. The released SO_2 disproportionated to sulfate and sulfide, and the SO_2 -derived sulfate was subsequently reduced to sulfide during cooling through reactions with wallrock. Consistently, lower Fe contents in hydrothermal anhydrite reflect the lower fO_2 of the hydrothermal system relative to the source magma.