

# Nukundamite ( $\text{Cu}_{3.38}\text{Fe}_{0.62}\text{S}_4$ )-Bearing Copper Ore in the Bingham Porphyry Deposit, Utah: Result of Upflow through Quartzite

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## Abstract

Nukundamite is an important ore mineral in a geologic resource of approximately 90 million metric tons (Mt) of 0.8 wt percent Cu in quartzite on the northeast contact of the Bingham stock. In contrast with other deposits, where nukundamite occurs as a minor phase in relatively low temperature, sericitic assemblages, nukundamite at Bingham is widespread in higher temperature, potassic assemblages. The coexistence of this high-sulfidation sulfide with potassic assemblages suggests an unusual evolutionary path for magmatic-hydrothermal fluids in quartzite wall rocks.

Nukundamite-bearing copper ore, restricted to a 240-m-thick quartzite unit of the Pennsylvanian Bingham Mine Formation, extends 170 m from the northeast margin of the mineralized stock along the strike of beds and plunges 1 km down the dip of beds ( $30^\circ$  NNW). The quartzite unit is cut off at depth by a thrust fault, below which beds of the Bingham Mine Formation are vertical and cut by abundant northeast-striking, steeply dipping faults, dikes, and isoclinal folds, the Fortuna zone.

Ore-forming hydrothermal assemblages in quartzite can be classified as Main and Late stage. Main-stage minerals are predominantly disseminated quartz + phlogopite  $\pm$  K feldspar, with nukundamite replaced by chalcopyrite and bornite, and no pyrite. Replacement of nukundamite by chalcopyrite and bornite reduced its abundance from possibly as high as 90 to 10 vol percent of total sulfides at the end of the Main stage. Late-stage assemblages consist of quartz + sericite  $\pm$  kaolinite with abundant pyrite, lesser amounts of bornite, digenite, enargite, and traces of nukundamite.

Based on experimental data and retrieved thermodynamic properties, nukundamite is stable within a highly limited range of  $a_{(\text{Fe}^{+2})}/a_{(\text{H}^+)^2}$ ,  $f_{\text{S}_2}$ , and  $f_{\text{O}_2}$  at temperatures between  $501^\circ$  and  $223^\circ\text{C}$  at very high sulfidation states. Values of  $a_{(\text{Fe}^{+2})}/a_{(\text{H}^+)^2}$  in the nukundamite field are also appropriate for the stable assemblages chalcopyrite + bornite and chalcopyrite + pyrite, but nukundamite requires higher values of  $f_{\text{S}_2}$  and  $f_{\text{O}_2}$  than the latter, more common, assemblages. Phase equilibria indicate that nukundamite-bearing sulfide assemblages of the Main stage are metastable (supersaturated with respect to pyrite).

We hypothesize that early brine and vapor, known to be of magmatic origin on the basis of isotopic and fluid inclusion evidence, traveled upward through several kilometers of quartzite along the stock contact and the Fortuna zone and then up to the south-southeast along bedding. At its source region the brine had  $\text{SO}_{2(\text{g})}/\text{H}_2\text{S}_{(\text{g})} \geq 1$ , typical of degassing magmas of intermediate composition. On cooling, and due to lack of redox buffers in quartzite, the brine became increasingly oxidized and evolved to  $\text{SO}_{2(\text{g})}/\text{H}_2\text{S}_{(\text{g})} \cong 0.1$  at  $450^\circ\text{C}$  at constant  $f_{\text{S}_2}$ . Precipitation of nukundamite with K feldspar + phlogopite at temperatures below  $400^\circ\text{C}$  ( $\text{SO}_{2(\text{g})}/\text{H}_2\text{S}_{(\text{g})} \cong 0.01$ ) was possible due to relatively high concentrations of S and K in the brine ( $\Sigma\text{S}_{(\text{aq})} = 0.2\text{ m}$ ,  $[\text{K}^+] = 0.5\text{ m}$ ), also resulting from lack of exchange reactions with quartzite.

Subsequent replacement of nukundamite by bornite + chalcopyrite during the late Main stage required a different fluid at lower sulfidation and oxidation states, and slightly higher  $a_{(\text{Fe}^{+2})}/a_{(\text{H}^+)^2}$ . We suggest that this late Main-stage fluid, rising within the faulted northeast margin of the stock, had been enriched in iron and depleted in sulfur during Main-stage potassic alteration and ore deposition in the stock.