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Application of Mass-Balance Modeling of Sources, Pathways, and Sinks of Supergene Enrichment to Exploration and Discovery of the Quebrada Turquesa Exotic Copper Orebody, El Salvador District, Chile

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Abstract

A computerized district-scale copper mass-balance analysis at the El Salvador porphyry copper deposit was completed, using all available assay data to address the genesis of exotic copper deposits and their relationship to the enrichment blanket. Of special importance was identifying the controlling geologic factors useful in exploration for defining prospective corridors leading to undiscovered exotic ores to extend mine life, and providing an estimate of the mass of copper most likely to be discovered. In principle, our metal sources, pathways, and sinks approach is analogous to the oil field strategy of identifying hydrocarbon source rocks, migration pathways, and final reservoirs, except that here we discover these component parts of the system and their spatial linkages, not by organic biomarkers but rather by geochemical mass-balance calculations involving assays, densities, and spatial geometry, which define volumes of the interrelated subsystems. A district geochemical model was created on the Vulcan three-dimensional GIS program consisting of the protore, enrichment blanket, and leached capping in terms of grade and bulk-rock density distribution. The copper assay, density, and volume mass-balance equations from Brimhall et al. (1985) were programmed in Vulcan and solved in a two-step computational procedure. The first step is an approximation to set a rough position of the effective original top of protore containing significant values of copper. This is necessary because some of the leached cap has been eroded. The second step incorporates relict sulfide mineralogy in the existing portion of the leached cap to verify and refine the position of the preerosional surface of contributory protore mineralization from which oxidation mobilized significant copper. The numerical protore model reflected primary copper-grade zoning calculated from assays at the base of the enrichment blanket and accommodated lateral variation by subdividing the protore rock volume into a bundle of 50-m^2 vertical columns. Grade values in each column of the bundle were then projected upward through the higher reaches of the deposit into the leached capping. Mass balance during coupled leaching and enrichment was computed on each column separately. Overall flux of copper in each column was computed to determine whether all of the copper liberated from the leached cap was fixed in the blanket column below as a balanced geochemical profile or whether some of it escaped, as well as to ascertain the magnitude of the copper lost from the negative flux zones. Where the flux is zero, all of the copper extracted from the leached capping was reprecipitated in the blanket as secondary sulfide mineralization. Over much of the areal extent of the blanket copper fixation was indeed nearly perfect. Sulfide mineral textures in these areas show extensive replacement of the primary by secondary sulfides as rims and along cracks. However, two sizable separate regions were identified as negative flux or source zones totaling 2.3 million tons (Mt) of copper where the flux was negative, indicating that fixation of copper released from the leached cap was quite imperfect in these areas of the enrichment blanket. Here, primary sulfides are hardly replaced by chalcocite, indicating the passage of significant copper out through the blanket. Hence, these zones were interpreted as clearcut cases of source zones for copper that continued to migrate downward and laterally beyond the limits of the enrichment blanket and out into the surrounding hydrologic flow regime. Factors identified here contributing to the imperfect fixation, limited replacement of primary sulfides, and escape of copper include: (1) high structural permeability along latite dike and/or fault systems serving as conduits, (2) fluid movement inferred to be so rapid as to minimize the residence time required for chalcocite replacement of primary sulfides, and (3) locally unreactive sericite-kaolinite alteration gangue minerals. One of the negative flux source zones is positioned along a pathway to the previously

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sourceless Damiana exotic orebody, thus resolving its origin and copper source and lending credence to the practicality of exploration based on mass-balance modeling. Buoyed by this result, attention turned to the second source region that was similarly aligned along regional latite dike and/or fault systems. Motivated by the sizable estimate of potential exotic copper to be found, drilling focused along the corridor extending from the second depositless source zone, and a new exotic copper orebody, preserved under the Atacama gravels in Quebrada Turquesa northwest of El Salvador, was discovered. District-scale multielement geochemistry supplements the Cu-based mass-balance analysis and shows that like copper, Mn, K, and Co were also transported from the leached capping and were precipitated within the surrounding paleodrainage network as copper wad and cryptomelane.

This study offers some insight into the requirements of numerical model-based exploration, as well as highlights areas in ore deposit models where future research might profitably focus to support the future use of modeling in exploration. The genetic linkages established between the two copper source regions and their respective exotic orebodies in Damiana and Quebrada Turquesa generally verify the integrity of the projections in protore characteristics up through the leached capping, which involves increased certainty upward where supergene modification of the protore was most severe and initial grade estimates are more speculative. Given the relative scarcity of deep-drilling data to define gradients in protore copper grade that are useful in upward projection through the blanket and leached cap, the primary copper grade within each column was modeled to be constant upward. Because the modeling was intended to motivate and guide exploration, we purposely chose to be conservative in projecting protore copper grade upward at constant values. Also, we were necessarily concerned to avoid overestimating the potential size of undiscovered exotic resources and, therefore, calculated a minimum of copper transported laterally.