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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 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.

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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.

Introduction

ALTHOUGH exotic copper deposits have been explored and mined economically for a considerable length of time, understanding of their genesis is limited in terms of their timing, geological controls, mineralogical, and geochemical zoning. Consequently, advances in exploration science are timely, especially those that utilize the wealth of assay data contained in ore reserve databases. Mass-balance analysis, a method that can easily use assay data, is a quantitative means of computing chemical gains and losses of elements and is well-suited to supergene transport processes (Brimhall et al., 1985). The purpose of this paper is to describe how district-scale mass-balance modeling, based on common assay data, can be used as a new practical basis for designing exploration strategies for exotic ores. The modeling both estimates the potential ore metal tonnage, which has economic importance in justifying exploration and designing the project scope, and defines the most prospective corridors. We then present application of this methodology to the discovery of a new exotic deposit in Quebrada Turquesa Norte in the El Salvador district of northern Chile.

Genesis of Exotic Copper Deposits

Recent exploration for exotic deposits, which will extend mine life of porphyry copper deposits in northern Chile, offers new opportunities to study their genesis, especially their relationship with supergene enrichment processes. Besides expanding ore reserves near existing infrastructures, the advantage of exotic deposits includes the relatively inexpensive processing of copper oxide ore by sulfuric acid heap leaching. At El Salvador, Chile, the discovery in 1992 of the exotic copper deposit, Damiana (Rojas and Müller, 1994), which contains 1.8 million metric tons (Mt) of copper, provided an excellent opportunity to study lateral copper transport within the framework of a well-studied porphyry copper deposit (Gustafson and Hunt, 1975).

Existing knowledge of exotic deposits is derived largely from empirical observations. The Exotica or Mina Sur deposit, genetically associated with the world-renowned Chuquicamata porphyry copper deposit, has been the object of much of the early research on exotic deposits (Newberg, 1967; Mortimer, 1977; Fam, 1979). Recently, Münchmeyer (1996) compiled a summary of twelve known exotic deposits in northern Chile and formulated an idealized composite mineralogical section of these deposits, extending from the proximal source of copper to the distal extents of copper mineralization 8 km away.

Past hydrology, present geomorphology

Generally, exotic mineralization occurs in paleodrainage networks leading away from principal porphyry deposits that have undergone supergene enrichment. Acid-oxidizing copper-bearing fluids escaped the supergene enrichment system into the headwaters of the surrounding drainage network and flowed downhill to sites where precipitation of copper oxides occurred.

Exploration for exotic deposits is complicated by the fact that the paleodrainage is today manifested in widespread alluvial gravel fans that partially bury former basement topography defined by paleovalleys and ridges. At different times throughout the Tertiary erosion has episodically modified the landscape. Erosion may have been so severe in some instances that topographic inversion has occurred, exhuming erosional windows and exposing bedrocks in the present valleys (Brimhall and Mote, 1997b). Targeting exotic mineralization is, therefore, difficult because in the El Salvador district it is necessary to decide which of the remnants to prospect of the once-more extensive alluvial fans. Topographic inversion complicates this choice because it is essential to recognize the floors of paleochannels where mineralization would be expected rather than the flanks of buried paleohills.

Key questions

The following key questions must be answered in order to understand deposit genesis and to develop exploration campaigns for these deposits: (1) after being released from the leached zone, why, in certain portions of the enrichment blanket, did copper not reprecipitate but instead coursed on through? (2) what caused the lateral escape of copper from the supergene system? (3) what were the hydrogeological controls on the lateral copper transport? (4) do the known exotic deposits in a district account for all of the missing copper in the source regions? and (5) what is the likely tonnage of copper in any nearby undiscovered deposits?

Mass-Balance Approach

The key questions noted above can only be answered by quantitatively addressing the remobilization of copper from the leached zone into the enrichment blanket, which then continued out to the exotic orebodies, through a district-scale mass balance. Mass-balance budgets provide the only direct method to analyze the redistribution of copper in the entire district and to quantify the magnitude and direction of copper fluxes (source regions), which are the fundamental guide to undiscovered orebodies. District-scale mass-balance analysis has been applied at El Salvador, using the formalism developed earlier at Butte, Montana, by Brimhall et al. (1985) and at Escondida, Chile, by Brimhall et al. (1985) and Alpers and Brimhall (1989). Since hydrochemical remobilization processes must obey the principles of mass conservation, a thorough mass-balance analysis provides direct evidence that the nature of supergene ore-forming processes is a redistributive phenomenon, largely vertical in the region of the enrichment blanket and lateral in the formation of exotic deposits. Mass-balance principles can be applied not only to quantify the copper flux out of the principal deposit but also as an interpretive tool for identifying, describing, and linking the source zones, transport pathways, and sites of deposition, similar to oil field exploration from sources, pathways, to hydrocarbon reservoirs. If source zones that are not correlated with known exotic deposits can be identified, then mass balance offers constraints on the potential size of the undiscovered exotic resources emanating from the source zones and, furthermore, defines the most prospective corridors for exploration.

Geologic Setting

Primary deposit

The El Salvador deposit (Fig. 1) is located in the Indio Muerto district of the Atacama Desert, northern Chile, 800 km north of Santiago. The deposit is on the southern segment of the Domeyko fault system, a trench-linked strike-slip fault system that was active contemporaneously with the emplacement of numerous middle Eocene to lower Oligocene porphyry Cu-Mo deposits in the Andean pre-Cordillera of northern Chile (Cornejo et al., 1997).

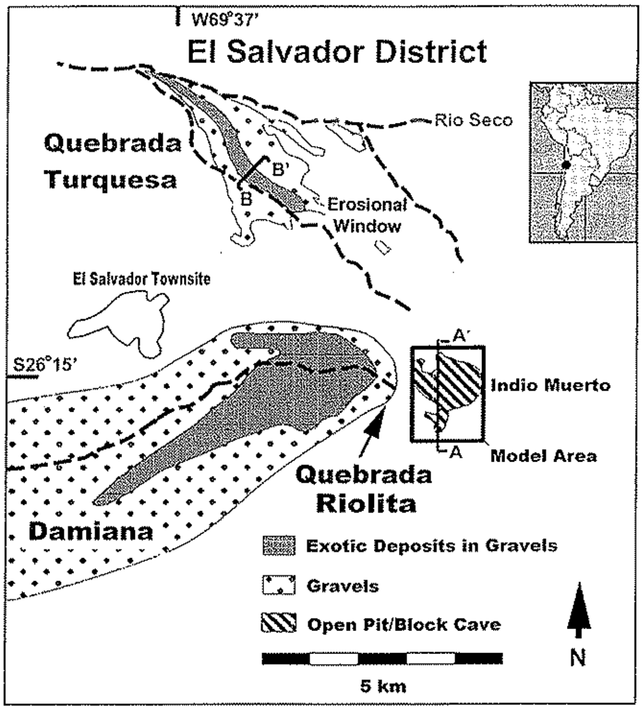

FIG. 1. Plan map of the El Salvador mining district, showing the exotic deposits, Damiana and Quebrada Turquesa, in relationship to the main porphyry copper deposits in the Indio Muerto mine workings and the preserved alluvial fans. Also shown is the region of the mass-balance model area and orientation of cross sections A-A' and B-B'.

The geology of the El Salvador porphyry copper deposit was well characterized by Gustafson and Hunt (1975). Recent work by Gustafson and Quiroga (1995) examined the mineralization and alteration of the deep part of El Salvador, using several deep diamond drill holes. Cornejo et al. (1997) refined the geochronology of the magmatic, mineralization, and alteration history of the district.

El Salvador is the oldest deposit of the Eocene and Oligocene porphyry copper belt in this area. It formed when north-northeast-striking rhyolitic and granodioritic porphyries intruded along the intersection of two major basement faults during a 3-m.y. period (44–41 Ma; Cornejo et al., 1997). Host rock for the ore is an upper Cretaceous-age andesitic volcanoclastic unit. These andesitic rocks are also the principal host of exotic copper mineralization. The main Cu-Mo porphyry intruded the Quebrada Turquesa area of Cerro Indio Muerto during a 1-m.y. period (42–41 Ma). The magmatic history of the system culminated with the intrusion of a latite and/or pebble dike system, at 41 Ma, into district-scale northwest-striking faults, which cut all previous mineralization and alteration but predate supergene processes (Gustafson and Hunt, 1975).

Hypogene mineralization is characterized by a central chalcopyrite-bornite zone in which the bornite/chalcopyrite ratio decreases outward. Surrounding this high-grade zone is a chalcopyrite-pyrite zone in which the chalcopyrite/pyrite ratio decreases outward into a pyritic fringe in which chalcopyrite is absent. This primary zonation is critical to a realistic formulation of the protore grade mode.

Supergene enrichment and formation of exotic deposits

Soon after the emplacement of the hypogene mineralization at the El Salvador deposit, supergene enrichment commenced, spurred by episodic fluctuations of the ground-water table. These fluctuations continued well into the middle Miocene, creating an environment conducive to sulfide oxidation above the ground-water table, enhanced by tectonic uplift coupled with episodic rapid global cooling caused by the growth of polar ice caps and a sea-level drop (Alpers and Brimhall, 1989; Brimhall and Mote, 1997a, b). Oxidation of primary copper-bearing sulfides liberated copper ions in the vadose zone and allowed transportation of copper downward by meteoric water. As copper ions traversed below the ground-water table and passed into reducing conditions, secondary copper sulfides were precipitated by the replacement of primary copper-iron sulfides. An enrichment blanket of chalcocite with lesser amounts of covellite, digenite, and djurleite (identified by XRD) was created (Gustafson and Hunt, 1975).

Supergene enrichment eventually ceased in the middle (Alpers and Brimhall, 1988). During supergene enrichment at the El Salvador deposit a portion of acid copper-bearing fluids acquired a lateral-flow component and copper was transported away from the principal deposit following a hydrologic gradient away from the regional topographic high, Indio Muerto. Beyond the pyritic fringe of the primary deposit the oxidized acidic fluids escaped into gravel-covered paleochannels where they encountered reactive andesite basement containing veinlet calcite in propylitic alteration. Hydrolysis reactions between the acidic supergene fluids and the andesite neutralized the acid and induced the precipitation of copper wad and chrysocolla, forming the exotic ore while still under oxidizing conditions.

Exotic Damiana deposit

Damiana is a recently discovered exotic copper deposit in the El Salvador district (Rojas and Müller, 1994), located in an alluvial fan emanating from the headwaters of Quebrada Riolita on the western face of Cerro Indio Muerto (Fig. 1). The fan deposits contain clasts of rhyolite, pyroclastic rocks, and mineralized porphyry clasts derived from the Cerro Indio Muerto. Grain sizes range from boulders to clay fractions comprising the matrix. Geomorphologic studies correlate the Damiana alluvial fan with the Atacama gravels (Mortimer et al., 1973) fan deposits, forming a regional pediplain surface in northern Chile created during Andean uplift. The morphology of the Damiana fan is largely intact due to desertification (Alpers and Brimhall, 1988), whereby a slow erosion rate of the fan surface indicates it is a preserved part of a Miocene-age fossil landscape (Nishizumi et al., 1998). Münchmeyer (1996) described three distinct zones of mineralization in the Damiana deposit: proximal, intermediate, and distal, all of which occur within the zone labeled exotic deposits in gravels in Figure 1. The proximal zone is the transition from the source of copper to the exotic deposit and is characterized by sooty chalcocite coatings on sulfide in the pyritic fringe. The intermediate zone contains the majority of copper mineralization and occurs at the contact between the gravels and the underlying basement unit. The bottom 5 to 20 m of gravels is cemented with copper wad. The majority of mineralization consists of copper wad-filled fractures within the altered andesite basement unit. Chrysocolla is found in fractures in fresh andesite on the periphery of the main ore zone of copper wad. The distal end of the deposit is characterized by a narrow paleochannel mineralized with copper wad extending up to 6 km from the source of copper. Quebrada Turquesa Norte is a long valley downcutting through a large field of Atacama gravels separated from those surrounding the Damiana deposit and contains the exotic copper deposit discovered in this work.

Mass-Balance Modeling

Intuitive formulation

Applying mathematical models successfully to a natural body as complex as an enriched porphyry copper deposit is difficult. Therefore, we present the modeling as a series of steps. First, we discuss mass-balance analysis intuitively, largely in a geologic manner, and then proceed to develop its application in detail using the requisite mathematical formalism. Intuitively, mass-balance analysis is a budget that compares the total mass of copper contained in an initial or original state to copper distributed in a final chemically differentiated, leached, and enriched state subdivided by the paleoground-water table. If the sum of the copper contained in the supergene system and known exotic deposits is less than the total copper in the protore, there is a good chance that additional exotic deposits may be found.

Copper mass is calculated in the mass-balance budget as the product of three variables: (1) copper grade in weight percent, (2) bulk dry-rock density in grams/cm^3, and (3) volume in cubic meters. The units cancel out to give mass units in grams or tons of fine copper. Assays provide the grade data and bulk densities are measured using the definition of density as mass per unit volume.

In order to characterize the initial state of the system, our analysis must estimate the mass of primary copper contained within the primary hypogene deposit before supergene activity commenced and redistributed copper by coupled leaching and enrichment under oxidizing and reducing conditions, respectively. As a volume, the dimensions of the protore in plan view are easy to ascertain, as is its bulk density. However, the vertical height of the protore is more difficult as its roof, now in the leached cap, may have been partially eroded.

The protore grade model, and especially its height, is thus critically important as subsequent chemical differentiation into a leached zone, blanket, and exotic deposits is gauged against its copper mass given as the product of volume, grade, and density. Assays of the current leached zone and blanket are readily available, but the original protore they replaced must be interpreted also in order to measure the changes in metal content during differentiation. Whereas here we analyze only the present state of the system, chemical fractionation of copper from the protore into the leached and enriched zones was a multistage dynamic process in which both the leached zones and enrichment blanket grew episodically in thickness and evolved into copper grade (Alpers and Brimhall, 1989).

Uncertainties in the protore model and their impact on results

Like all physiochemical models, protore grade reconstruction models are in part based on hard data and in part on inference. Inference stems here from the fact that presently we cannot directly observe the geometrical and mineralogical entirety of the original protore given the consequences of superimposed supergene chemical differentiation and the erosion of its upper reaches. Given this complication, effective use of a geologic model in exploration requires a conservative approach. This approach must yield a numerical result that can be interpreted as rigorously as possible, by knowing if it is lower or upper bound, better on average, its likely error, and which guarantees within reasonable limits that exploration expenditures are proportional to likely discoveries. To not use a conservative approach could mean that the results are difficult or impossible to interpret because of mere model dependency and complexity.

Any protore model is a three-dimensional mineralogical and chemical body and must incorporate primary copper-grade zoning, both lateral and vertical in direction. Lateral protore grades are quite readily calculated from assays at the base of the enrichment blanket and accommodate horizontal variations by subdividing the protore rock volume into a bundle of small vertical columns 50 m wide, each representing the local protore grade. The protore grades, realistically based on the grades directly below the limits of secondary enrichment, are then projected upward, albeit with increasing uncertainty through the upper reaches of the deposit, as far as is warranted by the totality of available grade data for the district, assisted by the distribution pattern of relict sulfide assemblages in the leached capping.

In its lower reaches, assay data availability, especially the depth of drilling below the enrichment blanket into unenriched primary ore, determines how well this protore model can be reconstructed. In particular, deep drilling of the protore can discern the presence or absence of vertical gradients in protore grades and the magnitude of the gradient (copper grades increasing upward or downward) if present (Brimhall et al., 1985). Earlier work (Brimhall et al., 1985) derived analytical solutions to mass-balance models for both constant and variable protore grade models with gradients which have the form of a second-order polynomial. Hence we call the constant protore grade models first order, being fully aware that it is an approximation, and the variable protore grade models second order.

Vertical extent and grade of the protore

Besides the need to characterize the base dimensions and internal zoning of the protore model using assay data, it is also necessary to project primary copper grade upward into regions that have been severely modified by enrichment, leaching, or removed altogether by erosion, thus obscuring original protore characteristics. Hence, the protore-grade model is most accurate where protore still exists, which is generally below the base of enrichment but becomes progressively more interpretive higher in the system.

Three guidelines are considered to constrain protore-grade projections: (1) common verticality of assays and bulk densities contours from deep drilling below enrichment up through the known protore, (2) relict sulfide data up through the leached capping to the premine surface, which qualitatively verifies both lateral and vertical protore sulfide zoning, and (3) published reconstructions of less-eroded porphyry copper deposits, which provide a means to place a given deposit roughly in an appropriate depth of exposure (Dilles and Einaudi, 1992) and hence a large-scale copper-grade profile interval. As far as protore-grade models go, the most useful examples of whole deposit reconstructions up to their paleosurfaces are those that have been modified the least by supergene processes. However, there is variability between deposits, and the lack of enrichment may raise the issue of how representative they are of the processes typical of intensely chemically weathered deposits, because the primary sulfide pattern can clearly influence supergene evolution in terms of acidification, copper mobility, and influence of reactive gangue.

First-order model

In this study, a first-order copper mass-balance analysis was completed, using the geologic database at El Salvador. First order refers to the simple model where hypogene grade within each of the vertical columns is assumed to be constant from the top of the hypogene primary ores at the base of the enrichment blanket up through what today is the leached capping. The first-order model, however, does indeed incorporate horizontal zoning in protore grades, as well as additional geologic complexities. The details of this model are described by Brimhall et al. (1985) as "model 1," the simplest of the geologic models for which analytical mass-balance expressions were derived.

Numerical mass-balance analysis

The two essential features of a copper mass-balance model that must represent geologic reality are a bulk-rock density and copper-grade model and an estimation of the position of the original, preerosion upper extent of hypogene copper-bearing sulfides. Together, these two necessities establish the original total volume, internal grade zonation, and copper mass of the protore affected by oxidative leaching (Brimhall et al., 1985).

Given the limitations of data on the copper-grade model and the preerosion top of sulfide mass balance, modeling is best done as an iterative two-step method (phase I and phase II) based on successive approximations viewed as an initial approximate solution followed by a more geologically realistic refinement. The procedure starts with simple mass conservation and then increases in complexity by imposing additional mineralogical constraints. The methodology, which was developed, tested, and applied to the porphyry copper deposits at Butte, Montana, and Escondida, Chile, is described by Brimhall et al. (1985). Here, in an effort to safely estimate the target size of undiscovered exotic deposits without risking excessive optimism on unworthy exploration targets, we use the most conservative means of modeling that yields a minimum of copper transported laterally. We will see that this conservative approach is accomplished by assuming that the protore grade was constant up through what became the leached cap. The actual discovery of a new exotic deposit using this methodology then provides a tangible means of evaluating the assumptions made about constant protore grade up through the distances involved.

Phase I: Conservative estimate of the original upper surface of hypogene sulfides assuming no lateral flux: $L_T{}^\circ$

The first step in modeling is phase I where an approximation is made of the surface defining the upper and outermost extent of original hypogene copper-bearing sulfides. This is accomplished by using the current distribution of copper in the leached zone defined by the present premine surface, blanket, and protore. In this phase of the iterative model the calculation makes a simplifying assumption that copper transport occurred in a largely downward vertical direction such that excess copper in the blanket was derived only from above by leaching over a total vertical interval of $L_T{}^\circ$.

In its simplest form as given in equation (1), phase I supergene mass balance is the equivalency of copper removed from the leached capping (left-hand side) and the amount of copper added to the enrichment blanket (right-hand side; Brimhall et al., 1985, eq. 4). Copper grades are p (protore), l (leached zone), and b (blanket). Bulk dry-rock densities of these zones are ρ_p, ρ_l, and ρ_b, respectively. Blanket thickness is B, and $L_T{}^\circ$ is the total height of the leached zone.

$$L_T{}^\circ (p\,\rho_p - l\,\rho_l) = B(b\,\rho_b - p\,\rho_p) \qquad [\text{lateral flux} = 0]. \qquad (1)$$

Symbolically, mass balance is a conservation of mass (graphically shown as equivalent-size rectangular areas, Fig. 2). Here, $L_T{}^\circ$ is the total height of the original leached capping before being reduced by erosion and with the assumption of no loss of copper through lateral flux. The superscript "°" denotes no lateral flux. By subdividing the principal mine area into a block model with cells 50 × 50 × 10 m, drill hole

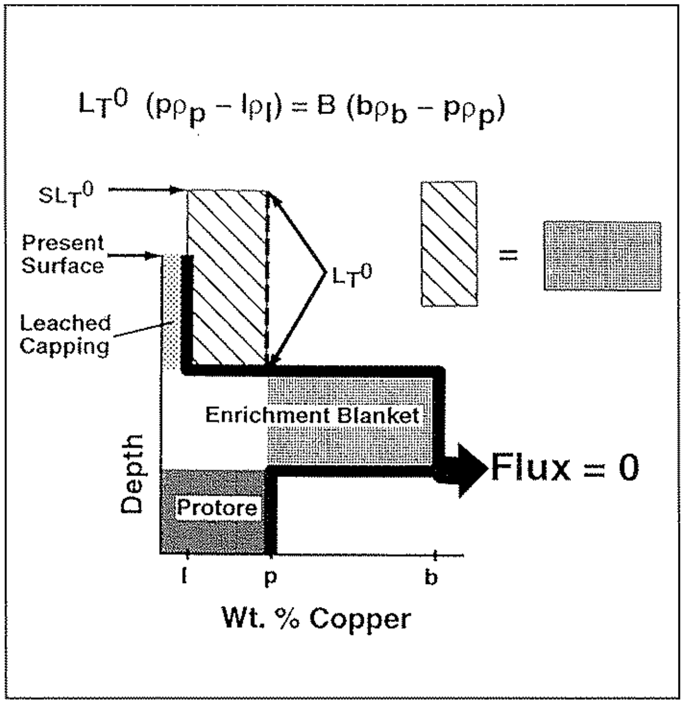

FIG. 2. Graphic representation of the mass-balance calculation: Phase I. The copper leached from the oxidized zone (striped pattern) must equal the metal added to the enrichment blanket (dark gray pattern) above initial protore grade, p, assuming zero lateral flux and complete copper fixation in the enrichment blanket. By solving the only unknown in equation (2), $L_T°$, the height of the copper-bearing sulfides above the current top of enrichment blanket is calculated to determine the upper protore surface, $SL_T°$. Symbols: B = enrichment blanket of thickness; copper grades: l = leached capping, p = protore, b = enrichment blanket; densities: ρ_l = leached zone, ρ_p = protore, ρ_b = enrichment blanket. Note that the protore grade is assumed to be constant in this first-order model.

data including 300,000 individual assay data points sampled at 1.5-m intervals and 100,000 density samples were used to create the initial copper grade and density model. By loading the drill hole data into the Vulcan™ three-dimensional GIS software package (Maptek Inc., Lakewood, CO) individual grade and density values were assigned to each block of the model, using the inverse distance estimation method.

Treating each vertical stack of blocks as an individual 50 × 50-m column, the copper concentration and density within each of the supergene zones (leached capping, enrichment blanket, and protore; Fig. 2) were calculated from individual assay data. The upper and lower bounds of the supergene zones were compiled from serial interpretive cross sections derived from the presence of chalcocite and covellite noted on drill hole logs. Where mineralogical data were lacking, the contacts were picked from a vertical-grade profile, using the assumption that the sharp contrasts in grade are the transitions between the leached capping enrichment blanket and the enrichment blanket protore. The enrichment blanket protore transition is harder to pick because grade in the bottom of the blanket gradually decreases approaching protore grades.

To complete phase I modeling, we solve equation (1) for the only unknown, which is $L_T°$ derived in equation (2):

$$L_T^\circ = B(b\,\rho_b - p\,\rho_p)/(p\,\rho_p - l\,\rho_l). \qquad (2)$$

The mass of copper added to the blanket (the numerator of eq. 2) can be rigorously computed as can the mass of copper extracted from the leached cap (the denominator in eq. 2). It then becomes possible to compute an estimate of the column height of protore leached to yield this same mass of copper fixed below in a blanket of thickness B. This step is necessary in that we cannot simply assume that the existing leached column height up to the premine surface defines the original limit of hypogene copper, because it is a surface that has undergone unkown amounts of erosion.

This calculation was performed for approximately 1,000 separate columns, using Vulcan. Notice that in this model the protore grade is represented by a single value of p for each column. The value of p for each column was determined in the protore immediately beneath enrichment and projected upward at a constant value. A surface was then generated from the computed values of $L_T°$ by adding it to the elevation of the top of the enrichment blanket for each 50 × 50-m block. This surface, called $SL_T°$ (surface of $L_T°$), represents the calculated approximate upper limit of hypogene copper sulfides consistent with a projection of protore grades of constant value and the exact equivalence of copper extracted from the leached zone and than added to the blanket. Figure 3A is a plan map over the model area showing the calculated $SL_T°$ surface and Figure 3B shows the protore grades used in the model. High-grade zones correlate with bornite-rich protore. Clearly the protore-grade model used, in particular its projection up through what is now the leached cap, will influence this result.

Gustafson and Hunt (1975) hypothesized a multistage supergene enrichment history due to mineralogical relationships in the leached capping. They noted perched secondary sulfide blankets preserved in the leached capping and an overprinting of limonite mineralogy. Without careful interpretation, these perched blankets, which represent imperfectly leached former relict stands of the blanket not completely remobilized downward to the present blanket, could cause problems within mass-balance calculations because they lie above the mapped upper extent of secondary sulfide. To eliminate this problem grade profiles in the leached cap were used to identify perched blankets and thus include the copper contained in them in the enrichment blanket zones rather than the leached capping.

Analysis of grade variation with depth

Whereas not used here, other more complicated mass-balance model developments in Brimhall et al. (1985) do indeed afford a means to project protore grades that change upward. Ideally the model would reflect copper grades as they vary upward at El Salvador as well, but there were insufficient deep drilling data available to compute gradients in copper grade over the area of interest. A constant protore grade over the vertical distance of the model is therefore assumed. The validity and implications of this assumption can be evaluated.

This first-order phase I model used here, whereas not treating vertical variations in protore copper grades, does in fact treat lateral zoning because each 50 × 50-m column was modeled independently. Adjacent columns were projected upward individually to account for lateral variations in protore

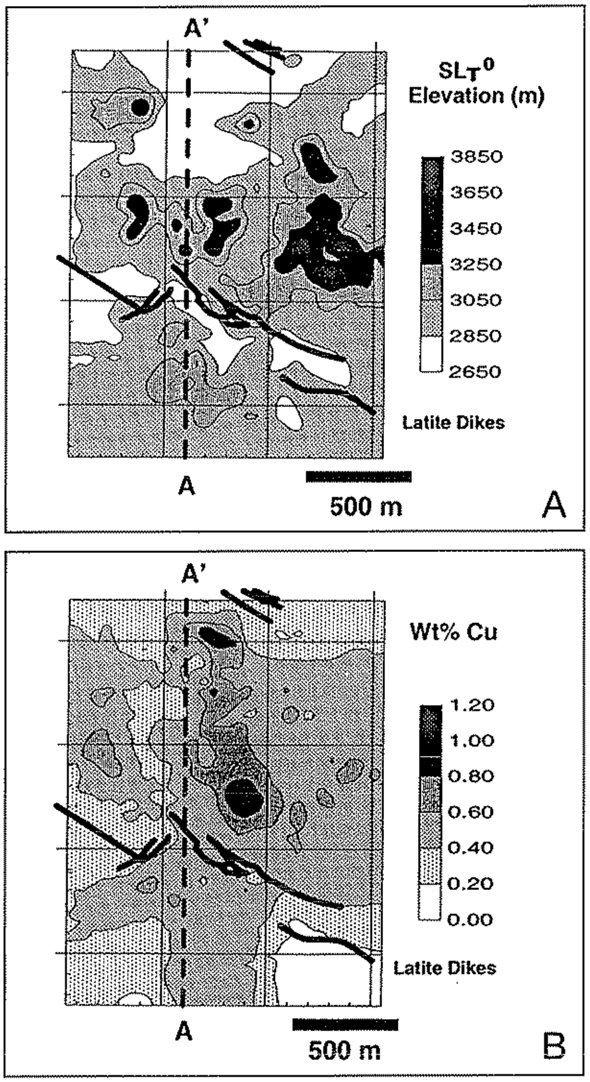

FIG. 3. A. SL$_T$° surface. The calculated upper protore surface assuming zero lateral flux by balancing leached copper with copper enriched in the blanket, contoured over the entire model area (Fig. 1). The latite dikes are shown in black. Notice that near the latite dikes, valleys occur separated by a high area in dark grays. B. Plan map of average protore grade used in the mass-balance analysis contoured over the extents of the model (Fig. 1). High-grade portions correlate with bornite zones.

grade. Figure 3B shows the protore grade averaged for each 50 × 50-m column contoured over the extent of the model.

One major limitation in porphyry copper research, as it pertains to mass-balance studies, is knowledge of the upper and lower portions of the deposits. Because exploration and production target the higher grade parts of these systems the low-grade limbs and bottoms are commonly neglected. Few deposits are exposed in such a way as to display their complete vertical pattern of hypogene grades, and there is most likely to be a significant variation in such profiles between deposits.

Protore-grade gradients

The nature of gradients in protore grade in relationship to the particular local vertical interval represented by the leached cap has received little attention, yet the profile is essential in linking porphyry copper mass-balance models to exploration models. Sillitoe (1973) synthesized a vertical profile of mineralization styles and alteration by piecing together different crustal-level exposures of deposits to make a theoretical mosaic of a complete though synthetic vertical profile. Dilles and Einaudi (1992) contributed in this area by mapping and reconstructing a complete cross section of a porphyry copper deposit exposed by Basin and Range rotational faulting. At the Ann-Mason porphyry copper deposit it was shown that mineralization extends over a 6-km distance vertically.

At El Salvador two deep diamond drill holes double the vertical exposure of the deposit and afford an opportunity to speculate as to the nature of the geochemical profile on a crustal scale as it pertains to vertical variations in copper grade vertically. A detailed description of these holes can be found in Gustafson and Quiroga (1995). Assay data from the deep holes and all other holes intersecting the section were separated into distinct supergene zones and plotted on a vertical profile (Fig. 4). Figure 4 shows a depth versus copper-grade profile of the El Salvador deposit set in a diagrammatic crustal-scale geochemical profile, using the interpretation of Gustafson and Hunt (1975) to fix the deposit at a maximum depth of emplacement at 2 km. The grade increases from crustal abundance levels of 55 ppm (Taylor, 1964) at a depth of 30 km to a local maximum in the ore deposit interval and then diminishes back to crustal abundance levels in the near-surface environment following a hypothetical bell-shaped curve. In Figure 4 the minimum and maximum copper grade of the mineralized wall rock was projected from crustal abundance levels upward to the lower limit of actual drilling. Although Figure 4 shows that protore grade does in fact increase upward, locally, beneath the blanket data (Gustafson and Hunt, 1975; Gustafson and Quiroga, 1995), we were unable to quantify an expression for the gradient of vertical change over the entire extent of the deposit due to the lack of aerially extensive deep drilling, and we, therefore, assume an upwardly constant protore grade within a 500-m vertical interval. Given that the parent porphyry magmas do not typically erupt but rather hydrofracture their wall rocks at depth and circulate hydrothermal fluids by convection, it seems certain that protore grades reach a maximum at some depth and decrease above that point because surface rocks do not commonly have protore-grade copper. Hence, the leached capping is shown here to occur in a region where the protore grade is changing from increasing to decreasing upward, and therefore the assumption of a constant protore grade, although geologically simplified, may be a reasonable estimation as grade must pass through verticality at some depth. What is uncertain is the depth of this maximum in protore copper grade, as is the width, symmetry, and skewness of the curve.

If the protore grade were increasing upward, as suggested by protore data from Gustafson and Hunt (1975) and Gustafson and Quiroga (1995) from deep diamond drill holes portrayed in the box insert in Figure 4, then the results of the mass-balance analysis, which are based on a constant protore grade, would not quantify all of the copper in the system. However, the paleosurface of the earth may have been only about 2 km above and the protore-grade gradient may have

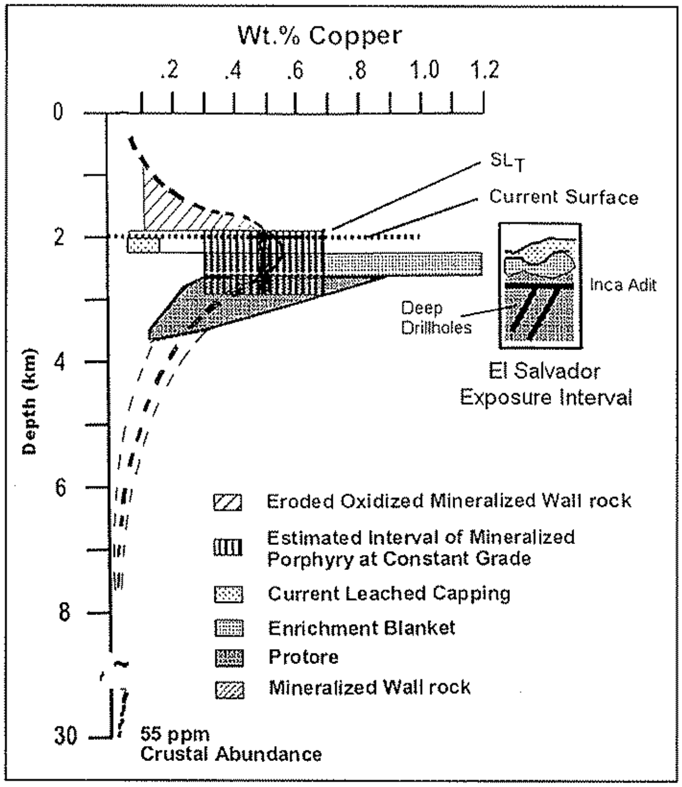

FIG. 4. Schematic crustal-scale geochemical profile, showing protore copper-grade variation with depth for average as well as minimum and maximum estimates vs. depth for a vertical volume of protore in an idealized porphyry copper deposit. This graph applies, for example, to a single 50 × 50-m (in plan) control volume, which is part of a bundled array of such volumes used to calculate the mass of copper contained in each volume. We have inserted actual copper-grade data for the El Salvador deposit, showing two deep drill holes from the Inca adit (Gustafson and Hunt, 1975; insert), as well as the enrichment blanket and current leached capping. The average copper grade increases upwardly from depth at crustal abundance levels of 55 ppm (Taylor, 1964) and reaches a maximum at the base of the enrichment blanket as a hypothetical bell-shaped curve. Minimum through maximum grade values for the current protore, enrichment blanket, and leached capping are derived from assay data and plotted against depth. The current premine surface at El Salvador is tied to the crustal geochemical profile at a depth of 2 km, based on the interpretation of maximum emplacement depth of Gustafson and Hunt (1975). The vertical striped box shows region of influence of the copper-grade range used (minimum to maximum) in relationship to the computed original upper protore surface, SL_T. Note that the assumption of constant grade covers a relatively small vertical interval of the entire crustal geochemical profile and occurs where the gradient is changing from increasing to decreasing grade with elevation. We interpret our first-order constant protore grade model as approximating a vertically integrated average-grade model incorporating both the increasing and decreasing sides of the idealized bell curve shown as the wide vertical grade bar in the middle of the vertical striped box.

been steep and decreased fairly rapidly upward above the current leached cap. We conclude, therefore, that the value of protore grade we used in each column modeled can be reasonably interpreted as a spatially integrated effective average copper grade over the leached column heights calculated (typically 300–400 m) and does approximate, within the limits of available data, the copper contained in the protore column. Therefore at El Salvador, we feel that the assumption of an upwardly constant grade does translate into a quantity of negative flux that is most likely a minimum, resulting in a conservative estimate of copper liberated for lateral transport. The actual mass of copper contained in the protore would depend upon the shape of the geochemical profile, especially its width vertically, symmetry, and skewness, all of which are unknown at this time. In Figure 4 we show in a diagonally ruled pattern a hypothetical model of the protore grade occurring above the present deposit. This area may represent approximately the maximum mass of unaccounted copper in our constant protore-grade model. Compared to the mass of copper remobilized in relationship to our constant protore-grade model, our estimate might in the worst case be low by as much as 100 percent. However, by comparing the mass of copper contained in the Damiana orebody to our calculated source region mass, we will show that our uncertainty is much less.

Phase II: Calculation of lateral flux of copper released from the leached cap but not fixed in the blanket and available for exotic mineralization: Incomplete enrichment anomalies

In phase I, we solved mass-balance equations to find an estimate of the protore column height leached necessary to explain the copper added to the blanket in balanced geochemical profiles.

Perfect fixation would be expected to be the norm given the fact that in water-saturated-reducing conditions chalcocite is very insoluble (Ague and Brimhall, 1989). Nevertheless, exotic deposits are not uncommon. Logically then it follows that there must be anomalous zones in enrichment blankets where fixation was imperfect, and the copper must have escaped. In order to recognize these anomalous poorly enriched areas, we have several possible lines of attack and will apply them now in sequence, using one to confirm another independently.

In phase II, we use additional data to reconstruct the top of protore leached under the likelihood that there are areas in the blanket where copper fixation was perfect (normal areas of complete fixation) and other anomalous areas where copper was not completely fixed and escaped through the blanket, either laterally or below. Phase II is a refinement of the upper protore surface approximated in phase I as balanced geochemical profiles and where we specifically search for anomalous topography. Remember that the upper protore surface is not the paleoland surface but rather it occurred at some subsurface depth approaching 2 km. Unfortunately, today the original upper protore surface has been leached and at least partially removed by erosion, and therefore its position must be inferred, which does not mean assumed. This estimation is an integral part of the model and uses geologic clues to indirectly limit the position of this surface. The use of relict sulfide mapping within the existing leached capping determines both a minimum upper extent, as well as the primary sulfide mineralogy before supergene leaching processes began. This use of relict sulfides as evidence of primary copper sulfide distribution is a new addition to the mass-balance modeling strategy.

In graphic form, in terms of areas to represent copper mass (Fig. 5), the area of leached protore was found in phase I (hatchered) and, therefore, the value of SL_T°, which exactly matched the area of the copper, added to the enrichment blanket (fine dots). In symbolic form lateral flux is defined by

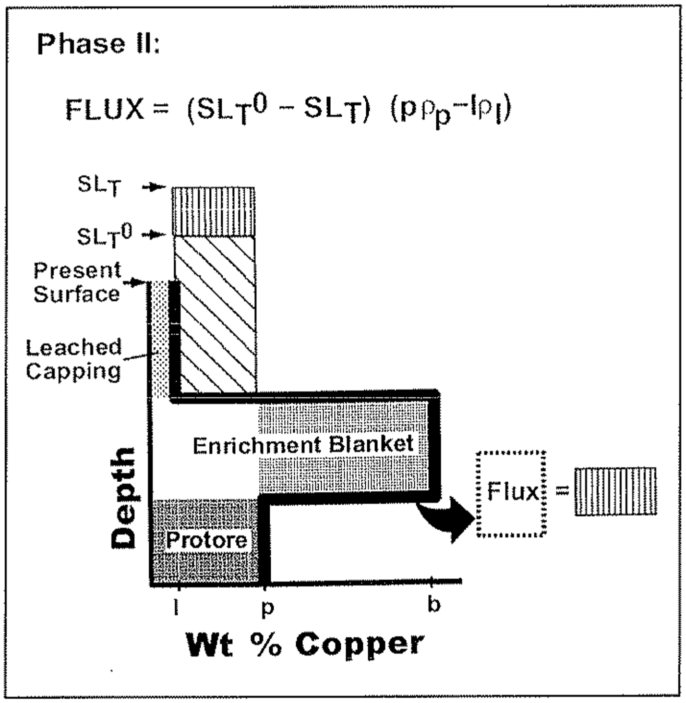

FIG. 5. Graphic representation of the flux calculation: Phase II. The quantity of lateral flux is equal to the difference between the calculated top of copper-bearing sulfide surface, $SL_T°$, and the estimated protore surface, SL_T, multiplied by the difference in grade between the leached capping and the protore, modified by density terms. Refer to Figure 2 for symbol definitions.

the imbalance of leached and fixed copper and is expressed as the mass flux given in equation (3) (Brimhall et al., 1985, eq. 11), where L_T is the actual original height of copper-bearing sulfides above the enrichment blanket (not $L_T°$, which assumed no lateral flux).

$$\text{Flux} = B\,(b\,\rho_b - p\,\rho_p) - L_T\,(p\,\rho_p - l\,\rho_l). \tag{3}$$

By substituting equation (1) into equation (3), we solve the lateral flux problem with reference to the difference between the calculated height, $L_T°$, assuming zero lateral flux, and the original height, L_T, of copper-bearing sulfides above the leached capping, using average protore grade, p:

$$\text{Flux} = (L_T° - L_T)\,(p\,\rho_p - l\,\rho_l), \tag{4}$$

because $L_T°$ and L_T column heights have equivalent $SL_T°$ and SL_T surface elevations— found simply by adding them to the current top of the enrichment blanket:

$$L_T° - L_T = SL_T° - SL_T \tag{5}$$

is used and substituted into equation (4) to solve flux-using surfaces:

$$\text{Flux} = (SL_T° - SL_T)\,(p\,\rho_p - l\,\rho_l). \tag{6}$$

Equation (6) is an expression of lateral flux equal to the difference between the calculated $SL_T°$, assuming no lateral flux, and the original SL_T top of the copper-bearing sulfide surface multiplied by the copper mass removed from the leached capping over that distance (Fig. 5). Graphically then we can see in Figure 5 that the mass flux (represented as an area over the thickness of the blanket) is equal to a mass of protore leached in excess of that needed for balancing the leached cap and blanket. In other words, the flux is proportional to the difference in elevation between the actual top of leached protore (SL_T) and $SL_T°$. Hence, regions in the blanket where copper was not fixed quantitatively will be represented as recognizable zones where $SL_T°$ is anomalously low in phase I.

To complete phase II and solve the lateral flux problem, the value of $SL_T°$ from phase I and the estimation of SL_T from phase II for each column in the model is substituted into equation (6). Because the estimation of the original protore surface SL_T (with an integrated average copper grade approximately equal to the average value used, p) directly affects the magnitude of lateral flux calculated, it is vital to make the best geologic estimation through use of numerous constraints to fix the surface height.

Relict sulfide constraints on SL_T

Critical to the estimation of the original upper and outer protore surface (SL_T) is interpretation of the relict sulfide mapping on the current surface. Relict sulfides from the surface of the leached capping today indicate the presence of a hypogene sulfide mineral assemblage that once occupied the area. A map was made showing the original boundaries of the bornite, chalcopyrite, and pyrite zones on the surface (Fig. 6). In places where the original Anaconda sampling was scarce the surface was resampled and the relict sulfides were recounted modally, using a reflected light petrographic microscope.

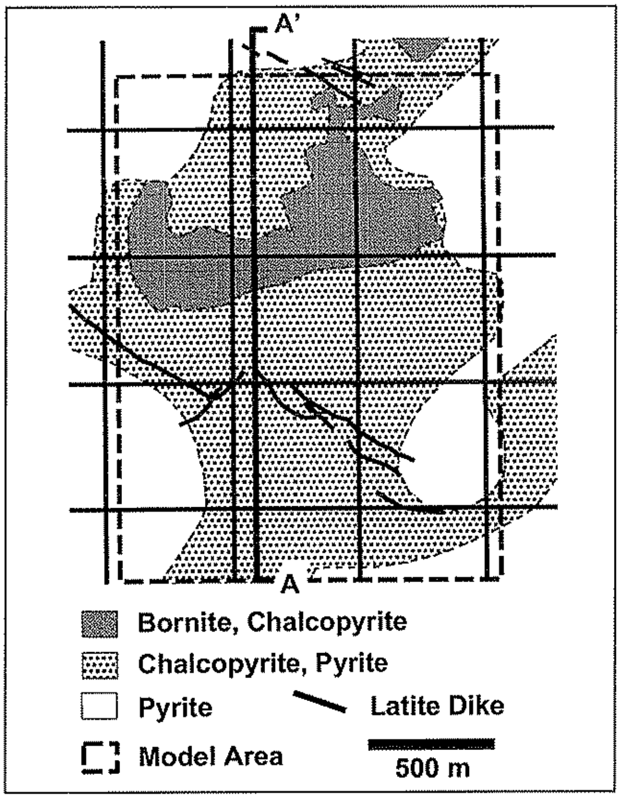

FIG. 6. Plan map of relict sulfide mineralogy on the current surface of Indio Muerto over the model area (Fig. 1). Taken largely from Anaconda Company reports and augmented by new sampling.

Figure 7A is a north-south cross section that illustrates an excellent correlation between the relict sulfide boundaries and the mapped sulfides at depth. Although today the leached capping is essentially barren of copper, the relict sulfide map suggests that at one time copper mineralization (inside the pyritic fringe) continued from the current protore at the base of the enrichment blanket to the current surface or higher with nearly vertical mineralogical contacts. This is a critical point of the model as it places a minimum height for the estimation of the original top of copper-bearing sulfide surface, SL_T, as being at least as high as the current premine land surface and not below that elevation.

"No lateral flux" portions of the supergene system

Figure 7B (Fig. 3A: plan view) shows the calculated top of the copper-bearing sulfide surface, SL_T°, across the north-south section. In some areas of the model the SL_T° surface is beneath the current topography, yet copper-bearing chalcopyrite and/or bornite relict sulfides have been mapped continuously across the premine topography (Fig. 7A). Such areas (shown in a cross-hatched pattern) are the anomalous source zone for the copper described above. In contrast, other areas of the model show the SL_T° surface reaching heights of >200 m above the current topography (Fig. 7B). These areas where the SL_T° is above or coincides with the present surface where copper-bearing relict sulfides occur indicate that the protore once extended above the current surface. These are normal leached protore zones. The copper leached below these regions has been essentially fixed in the enrichment blanket below and we refer to them as "no lateral flux" zones. Homogeneous porphyry lithologies at depth (Fig. 7C) support a relatively simple protore-grade profile in these zones.

Refinement of the position of the upper protore surface (SL_T)

In zones where the calculated SL_T° surface is at or above the present surface where we have found copper-bearing relict sulfides, we can assert rigorously that the mass-blance profile is balanced and that there is no evidence of missing copper. Erosion could have removed some of this zone. This assertion is proven in a later section by showing that the primary sulfides are largely replaced by secondary sulfides, indicative of perfect copper fixation. The calculated upper protore surface, SL_T°, is coincident within the original SL_T in these areas (Fig. 7D).

In contrast, where the calculated SL_T° surface is below the present premine land surface where we have found copper-bearing relict sulfides, we can assert rigorously that some copper in the mass-balance budget is missing and while it was leached from the capping, it was not quantitatively fixed in the blanket below. We refer to these zones as source zones for copper. Using approximately 10 serial cross sections and SL_T° surfaces as guides, the SL_T surface was interpolated as shown in a cross above a hatched pattern in Figure 7D.

The original protore surface, SL_T, (inferred to represent a vertically integrated average copper grade of p for each column in the bundle calculated) was inferred across the model by using the elevation of the calculated SL_T° within the no lateral flux zones and the relict sulfide mapping as guides. The copper-bearing relict sulfides define the minimum surface

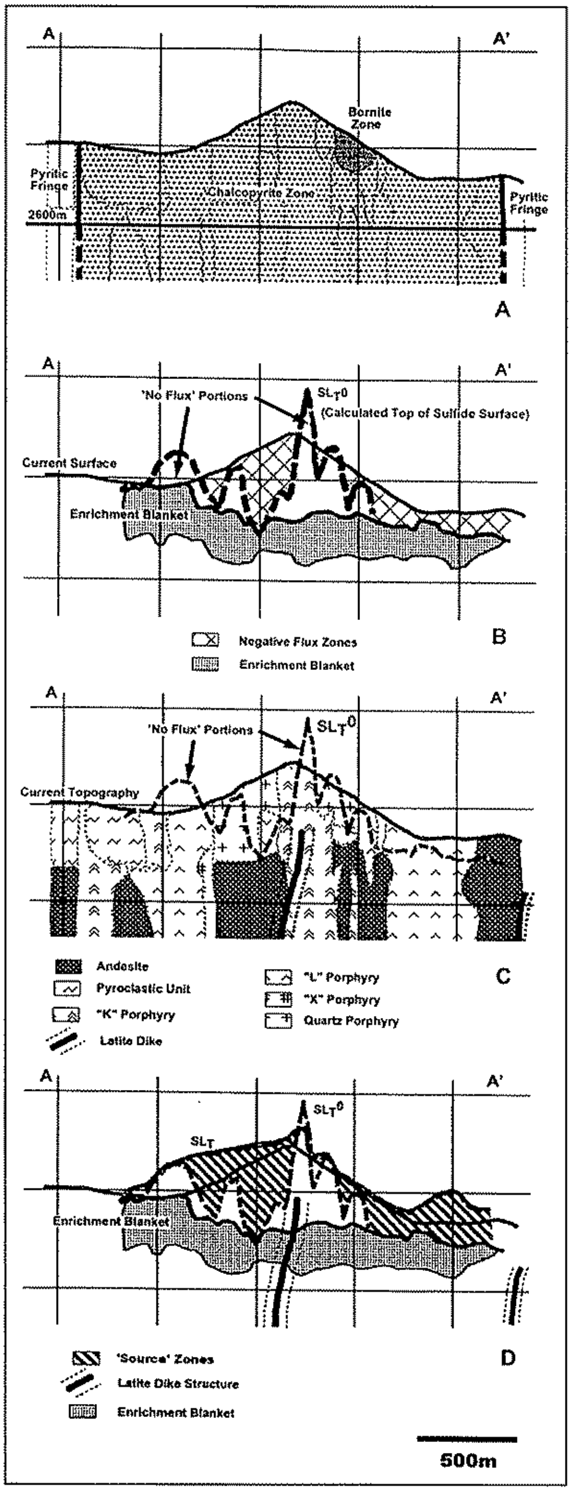

FIG. 7. North-south cross section A-A' (looking west). A. Protore sulfides distribution up through the leached capping constructed by relict sulfide mapping on the surface. B. The calculated, protore surface assuming no lateral copper flux, SL_T° (dashed) and portions of the enrichment system interpreted as no lateral flux in a crossed pattern. The average height where SL_T° is above the current surface in the no lateral flux portions of the model is 125 m. C. Lithology and SL_T° surface. The no lateral flux zones are over homogeneous rock types. D. Source zones as defined by the difference between the calculated zero flux protore surface, SL_T° (dashed), and the refined stage II protore surface using relict sulfides, SL_T (gray). Notice the coincidence between the source zones and the two latite dikes at depth.

that SL_T must lie above. Within the no lateral flux zones, $SL_T°$ is about 125 m above the current topography in section A-A' (Fig. 7B). We used this distance as a guide to estimate SL_T across the section. The relict sulfide mapping was used to define the horizontal boundaries of copper-bearing sulfides. Iteration of this process on orthogonal serial sections generated the SL_T estimation over the entire model.

The distance that SL_T is above $SL_T°$ directly determines the quantity of lateral flux (eq. 6). Consequently, the calculation of $SL_T°$and the estimation of SL_T are integral parts in the mass-balance analysis and also in the uncertainty of the results. One must realize that both of these surfaces are based on assumptions of an upwardly constant protore-grade model and no lateral flux portions of the blanket. The assumption of constant protore grade was addressed in a previous section and the validity of the no lateral flux zone assumption will be addressed in a later section by analysis of sulfide replacement textures.

Lateral flux zones: the source for copper in exotic deposits

By using both the calculated $SL_T°$ and the original SL_T for individual columns the calculation of lateral flux was completed using equation (6). Where SL_T is beneath $SL_T°$ the value for lateral flux is negative and therefore corresponds to areas where copper has been laterally transported, defined as source zones (Fig. 7D).

The lateral flux of copper from the leached capping computed for each 50 × 50-m column was contoured in a plan map (Fig. 8). This is the single most important diagram in this work because it portrays the areas of the enrichment blanket where copper was not quantitatively fixed, escaped the supergene system to migrate laterally, and formed exotic deposits. Note that much of the area has a lateral copper flux near zero. However, two very distinct copper depletion belts where the flux is negative (as much as –3 t of copper/m^2), indicative of a copper source region, are shown in dark gray. Note that both copper source zones are either coincident or near latite dikes intruding fault structures striking northwest-southeast in the principal mine area. These belts are interpreted as two distinct exotic copper source zones, one southern and one northern, separated by a zone of predominately vertical supergene enrichment with little or no net lateral flux of copper. Summing the lateral flux times the surface area, a total mass flux of 1.6 and 0.7 Mt is estimated from the southern and northern zones of copper, respectively.

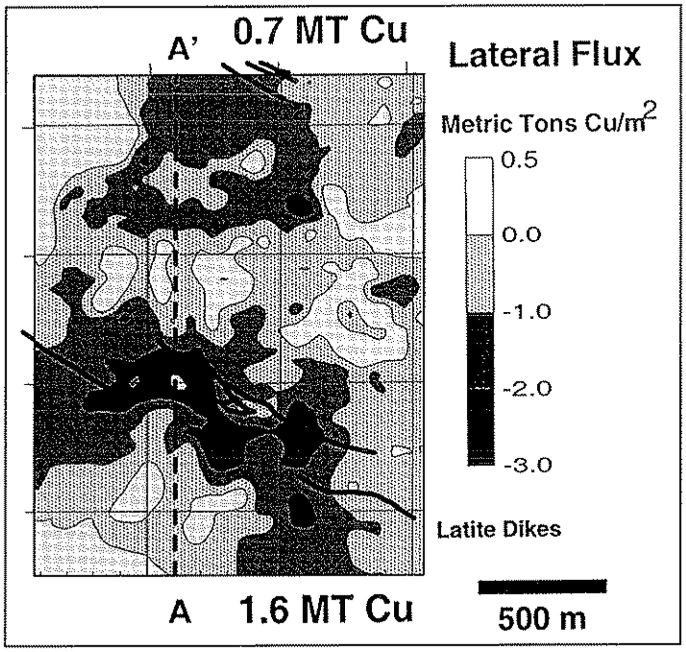

FIG. 8. Plan map of lateral flux of copper (tons/m^2) contoured on 50 × 50-m blocks over the model area. Note the coincidence of the latite dikes with the large negative flux zones (source zones). The integration of the total negative flux from the southern source zone gives 1.6 Mt of copper. The northern source zone indicates 0.7 Mt of copper. Note the jog of the latite dike mimicked by the pattern of greatest negative flux.

The most southern copper depletion belt and associated latite dike system trend northwest into the headwaters of Quebrada Riolita (Fig. 1). We feel that the source of copper for Damiana is therefore adequately explained by this source zone, as Damiana lies in the drainage of Quebrada Riolita (Fig. 1). The similarity of the actual tonnage of copper in Damiana and the calculated flux in its source (1.6 vs. 1.8 Mt of copper) is surprisingly close. Hence, the constant protore grade projection as a local approximation to a relevant part of a much larger but unknown bell-shaped curve does seem warranted and in fact serves a useful purpose until crustal-scale protore models are actually devised. The northern copper depletion belt occurs on the north side of the main mine area of Indio Muerto and follows the trend of the latite dikes into the headwaters of Quebrada Turquesa. This result suggested that another exotic orebody or bodies emanating from the northern source zone would be expected and this realization led to the discovery of the Quebrada Turquesa exotic deposit discussed below.

Analysis of source regions

In order to confirm the conclusion concerning the interpretation of no lateral flux zones and source zones as being parts of the enrichment blanket where copper fixation is perfect and imperfect, respectively, we present spatial correlations with blanket thickness, copper flux, and copper grade within the leached capping, blanket, and protore in the same cross section (Fig. 9A). Figure 9 is cross section A-A' from Figure 1, showing variations in the model parameters across the southern source zone, the no lateral flux zone, and the northern source zone. The grade of the leached capping (l) is relatively constant across this section, indicative that the overall leaching of copper was nearly complete. Although the protore grade (p) varies from 0.25 to 0.7 wt percent copper across this section, it has no apparent correlation with the magnitude of flux. However, there is a positive correlation between the blanket grade (b) and the magnitude of lateral flux. The lower the blanket grade (b) the greater the negative lateral flux. Consequently, it is apparent that in the source zones, downward-migrating copper was not fixed in the enrichment blanket and escaped into the surrounding paleodrainage network. Low blanket grades correspond to the source zones, whereas in no lateral flux zones, we assert from mass-balance considerations that all of the mobilized copper was fixed making blanket grades higher.

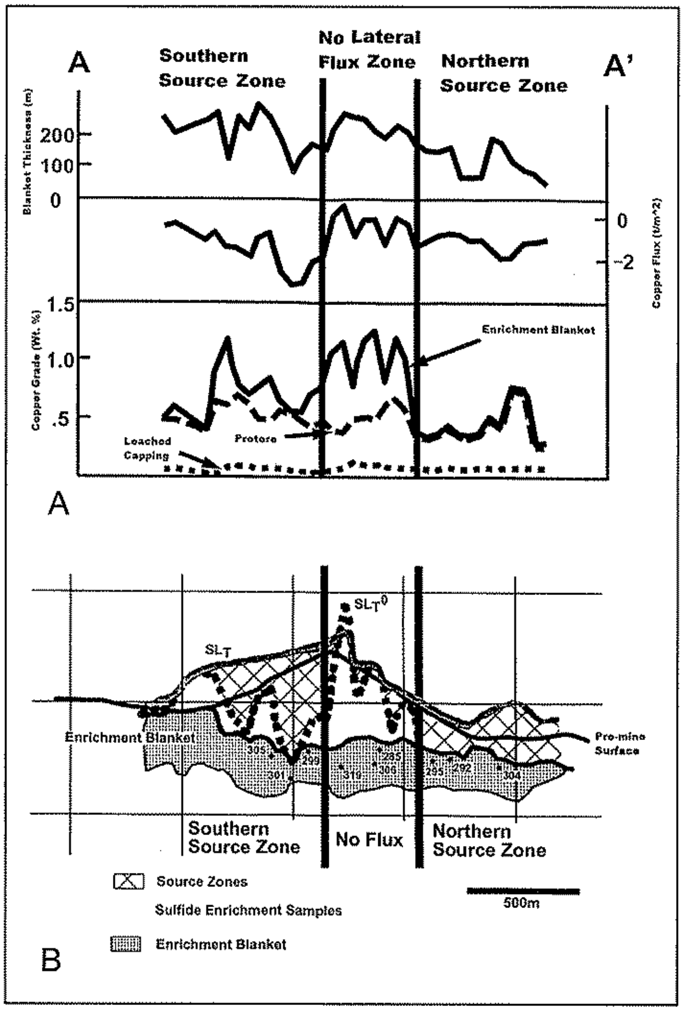

FIG. 9. North-south cross section A-A'. A. Variation of leached capping grade (l), enrichment blanket grade (b), protore grade (p), blanket thickness (B), and magnitude of flux. Notice the correlation between the lower blanket grades and higher negative flux zones, implying that the source zones for laterally escaping copper have deficiencies in fixation of copper within the blanket. The no lateral flux zone has a blanket with grades well above the protore grades for this section. Sharp decreases in the thickness of the blanket also coincide with source zones. B. Location of samples for optical microscopy of sulfide textures. Three samples were taken from the enrichment blanket within each of the three zones: southern source, no lateral flux, and northern source.

Across the section the thickness of the blanket (B) has a slight correlation with lateral flux, the thickest parts of the blanket correspond to no lateral flux zones and the thinner parts correspond to source zones. The spatial correspondence of blanket grade and thickness with source zones suggests that incomplete blanket development, in terms of both grade and thickness, is related to lateral transport of copper. The differential development of enrichment in the source versus the no lateral flux zones can be proven by examining sulfide replacement on a microscopic scale. Three core samples were taken for each of the two source zones and the no lateral flux zone within the enrichment blanket along the north-south section A-A' (Fig. 9B). These samples were polished and analyzed in reflected light for their sulfide mineralogy, habit, and texture, with particular attention to supergene sulfide replacement of primary sulfides.

The northern source zone (Fig. 10A) has only very minor replacement of primary chalcopyrite, bornite, and pyrite by secondary sulfides. This implies that all the copper in solution may not have been fixed. The no lateral flux zone (Fig. 10B) shows thorough replacement of chalcopyrite by chalcocite and substantial replacement of pyrite by chalcocite, which implies that much if not all of the available copper in solution was fixed in this zone. The replacement textures in this zone are representative of a well-enriched supergene blanket because secondary sulfide tends to replace protore sulfides, thereby using available sulfide rather than reducing aqueous sulfate to nucleate new sulfide crystals. The southern source zone (Fig. 10C) is rich in pyrite with minor chalcopyrite and bornite blebs. In this zone chalcocite has replaced pyrite only as thin rims and fractures. Where primary sulfides exist covellite is replacing them.

Structural control of copper source regions

The two copper source zones are centered on the latite dikes in the north and south (Fig. 8). The latite dikes are indications of major district-scale structures that magmas intruded, as the dikes are coincident with contacts of older lithologies at depth (Gustafson and Hunt, 1975). The latite dikes and numerous pebble dikes in the source zones are presumed to be late intrusions along faults that may have increased the permeability of these zones to ground-water flow. This increase in permeability is thought to have increased the velocities of supergene fluids and therefore decreased the residence time of copper ions in contact with the primary sulfides; hence allowing solutions to escape the primary deposit with aqueous copper in solution before it was fixed by protore sulfide replacement.

The no lateral flux zones are characterized by lack of major crosscutting structures (i.e., latite dikes) and are thought to have lower overall permeability. This slowed the copper-bearing fluids enough to allow thorough replacement of primary sulfides.

Primary mineralization control

Comparison of the positions of source zones (Fig. 8) and the protore sulfide mineral assemblages on mine level 2600 (Fig. 11A) shows that both source zones are centered in areas where pyrite is >75 percent of the sulfide and total sulfides reach 6 percent of the rock volume. These zones continued upward with chalcopyrite and bornite mineralization as shown by the relict sulfides on the surface (Fig. 6). The occurrence of a pyritic protore is an important mineralogic control on the lateral transport of copper. The pyrite/chalcopyrite ratios in these zones, when oxidized will produce acid and sustain a low pH geochemical environment suitable to copper transport (Anderson, 1982). In addition, as chalcocite and covellite more readily replace chalcopyrite and bornite than pyrite, a pyritic protore is less effective in fixing copper from supergene solutions (Fig.10A, C).

In contrast the no lateral flux zones are centered over the high-grade chalcopyrite-bornite zone of the protore where pyrite is absent and total sulfide generally comprises 0.5 to 2.0 vol percent of the rock. The chalcopyrite-bornite zones provide

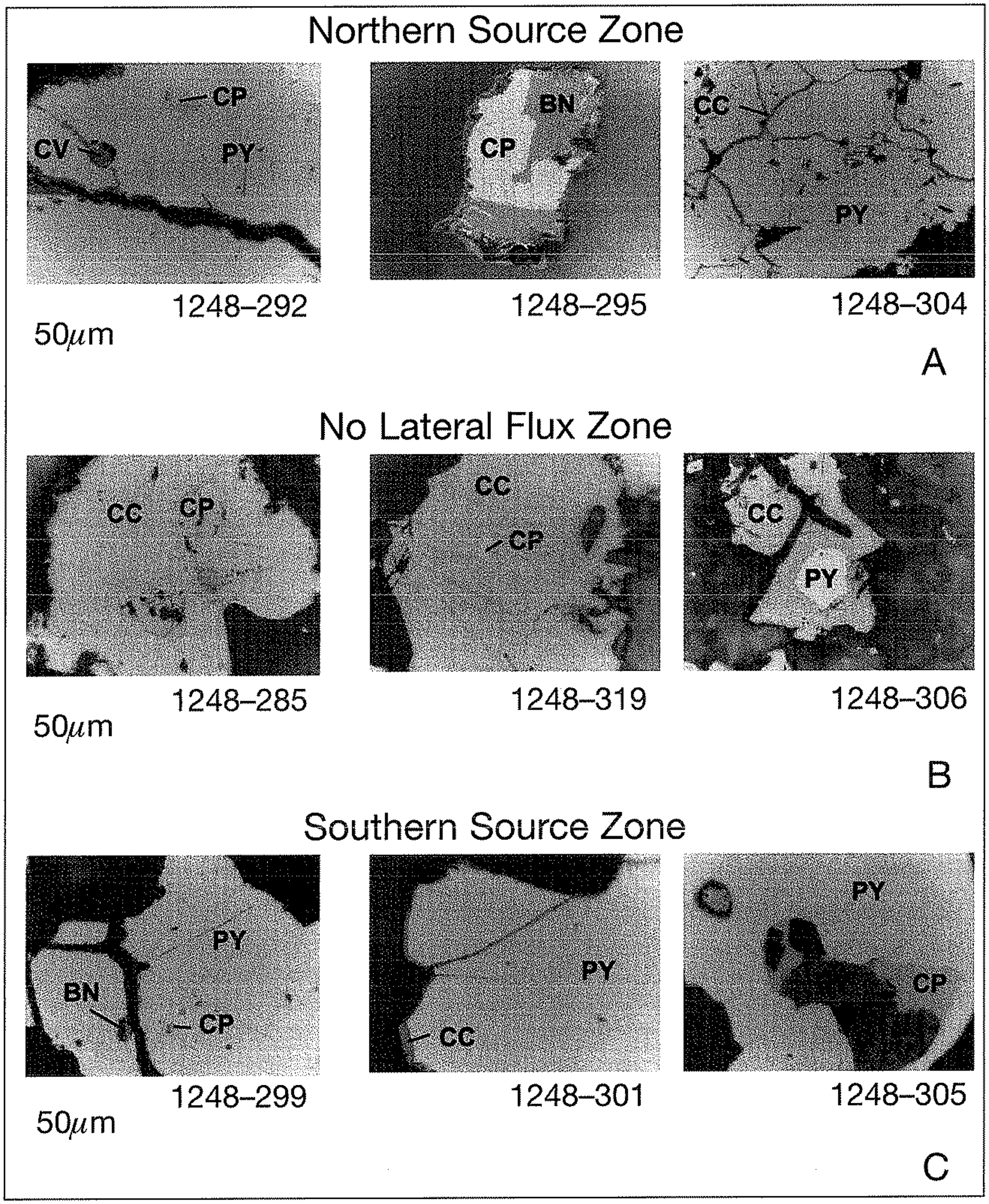

FIG. 10. Photomicrographs of sulfide replacement. Abbreviations: BN = bornite, CC = chalcocite, CP = chalcopyrtie, CV = covellite, PY = pyrite. A. Northern source zone samples. This zone has a high PY/CP ratio. The secondary enrichment is seen as weak replacement rims on PY by CC and selective replacement of CP blebs by CV and CC. Even where CP and BN are dominant the replacement by CV and CP is weak. This zone shows an overall deficiency in enrichment. B. No lateral flux zone samples. This zone has lower PY/CP ratios than the source zones (Fig. 11A, C). Textures show nearly complete replacement of CP by CC. PY is apparently being thoroughly replaced by CC. Sulfide replacement textures are similar to well-developed high-grade enrichment blankets. C. Southern source zone samples. This zone has a high PY/CP ratio. The secondary enrichment is seen as weak replacement rims on PY by CC and selective replacement of CP blebs by CV and CC. This zone shows an overall deficiency in enrichment.

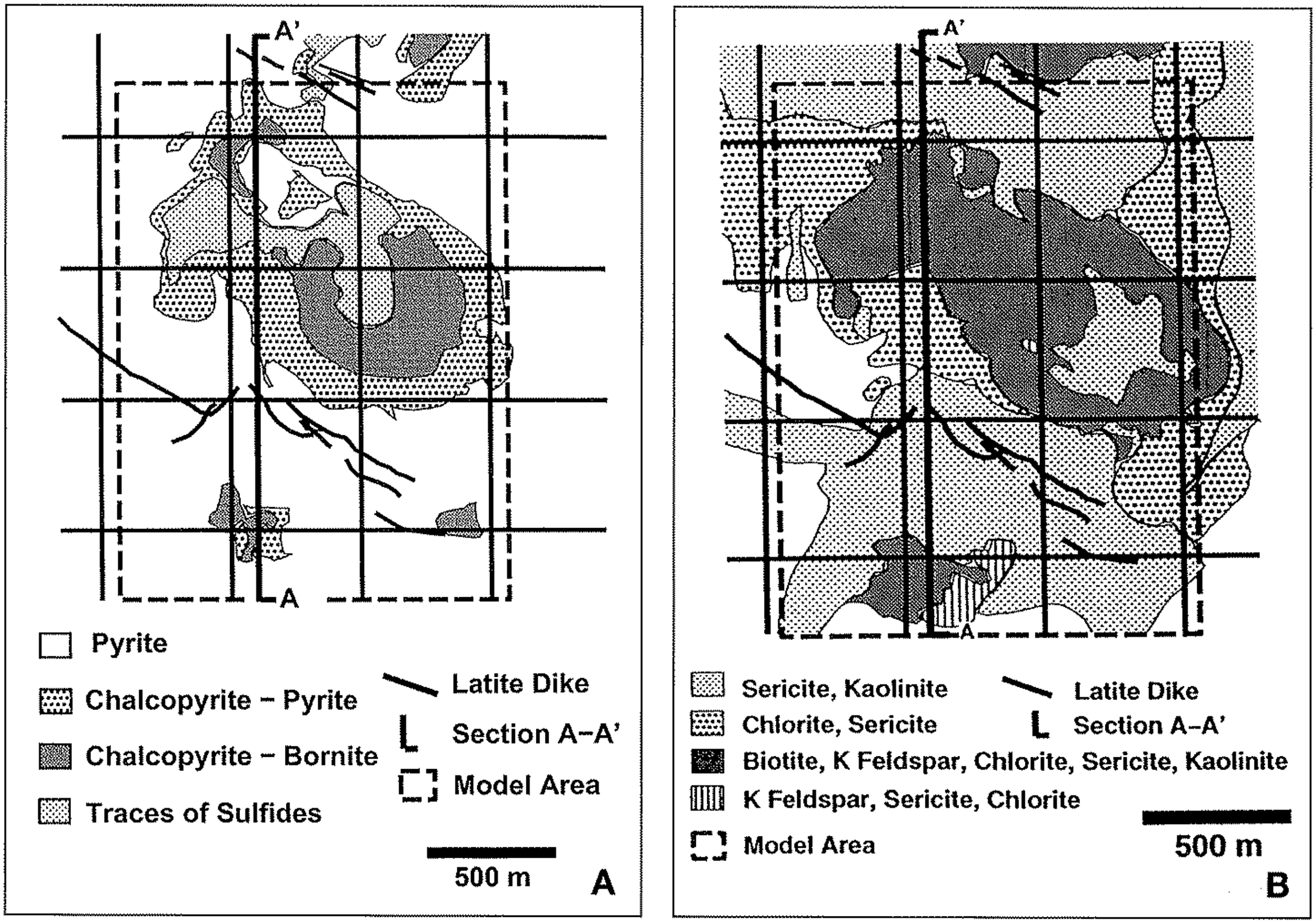

FIG. 11. A. Plan map at mine level 2600, showing hypogene sulfide zones of pyrite, chalcopyrite-pyrite and chalcopyrite-bornite zones of hypogene sulfides. Pyrite zone: pyrite >75 percent of total disseminated sulfide, which comprises from 0.5 to >6 percent of the rock volume. Chalcopyrite is the principal minor sulfide. Chalcopyrite-pyrite zone: pyrite/chalcopyrite proportions decreasing inward from 3/1 to 0, bornite is absent, total sulfide generally comprises 0.75 to 2.5 percent of the rock volume. Chalcopyrite-bornite zone: chalcopyrite/bornite proportions range from infinity to 0 and decrease inward, with chalcocite present in a high bornite zone, pyrite is absent; total sulfide is generally 0.5 to 2.0 percent of the rock volume. B. Rock silicate alteration minerals. The source zones are centered above sericite-kaolinite-rich alteration, which is an inadequate buffer for copper-bearing fluids because they lack either plagioclase or K feldspar, which would otherwise begin hydrolysis reactions and neutralize acidic supergene fluids. The no lateral flux zones are above biotite and K feldspar alteration.

excellent replacement sites for secondary chalcocite to precipitate and have less acid-generating potential, which enhances the development of well-enriched secondary blankets (Fig. 10B).

Alteration control on copper source regions

The ability of alteration assemblages to neutralize supergene acid is a critical factor in determining the fixation of copper in the enrichment blanket (Locke, 1926). Figure 11B shows the alteration assemblages mapped on mine level 2600. Analysis of the two copper source zones shows sericite-kaolinite alteration centered in these areas. These zones are essentially inert as they now lack plagioclase or K feldspar to neutralize acidic supergene fluids and provide no geochemical barrier to trap copper from the escaping copper-rich fluids. In contrast the no lateral flux zones have potassic feldspar-bearing alteration mineral assemblages that, as reactive gangue, are strong acid neutralizers which leads to the retention of copper in these zones (Blanchard, 1968).

Analysis of Transport Pathways

Guided by the correlation between the spatial association of source zones and the latite dike systems field mapping was focused in specific areas to find evidence of acidic fluids leaving the supergene system. This type of mapping is quite unique as it was completely guided by the mass-balance results, essentially beginning in the computer laboratory and extending into the field.

The upper extent of Quebrada Riolita is a transition zone between the supergene system and the exotic mineralization (Fig. 12). Here, exposed by a road cut, there is a network of faults filled with fine-grained porcelaneous supergene alunite and jarosite. Both of these potassium-bearing hydroxy sulfates are interpreted to have precipitated from low pH fluids

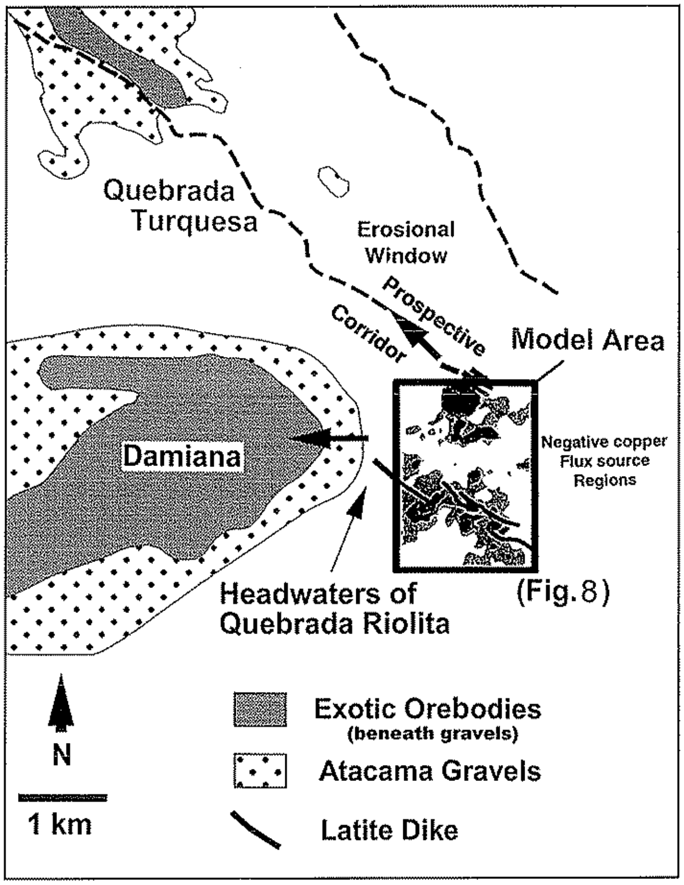

FIG. 12. Plan map of lateral copper flux (Fig. 8) in relationship to the El Salvador district geology. Notice the correlation between the strike of the southern set of latite dikes and the headwaters of Quebrada Riolita where the exotic mineralization in Damiana begins. In the transition zone between the principal deposit and the exotic deposit in the headwaters of Quebrada Riolita there is evidence of supergene fluid escape manifested as laminated jarosite, goethite, and alunite veins. The northern set of latite dikes leads off into Quebrada Turquesa and controls fluid migration from the northern source zone into Quebrada Turquesa Norte. The alluvial fans there are an erosional remnant of a much larger fan, which extends toward the northern source zone. Erosion of the intervening fan produces a window into andesite basement, leaving small patches of gravels and much lag gravel behind.

draining down the hydrologic gradient into the Damiana exotic orebody from the principal deposit where these veins reached the surface. Crosscutting relationships of alunite veins imply there was multigeneration faulting and multiple fluid escape events in this area (Mote et al., 2001). Pebble dikes, the brecciated shallow expression of the latite dike system (Langerfeld, 1964), observed on the surface are presumed to have caused increased permeability.

Adjacent to the latite dike approximately 200 m north, there is a distinct laminated jarosite and goethite outcrop, where each band is interpreted to be the result of a different fluid escape event with a pH distinctive to alternating jarosite or goethite precipitation (Alpers and Brimhall, 1989). Goethite-cemented gravels are also apparent in many nearby places in Damiana and are evidence of supergene fluids moving through these areas and flowing out onto the surface as paleosprings.

Figure 13 shows the average bulk dry-rock density of the leached capping contoured over the model area. A high-density zone correlates with the southern source zone and the latite dikes. This density high is interpreted to be caused by escaping iron-rich but reduced exotic fluids moving through this zone, which upon oxidation, precipitates transported goethite and K sulfates, jarosite, and alunite in veins and ferricretes. The absence of the density anomaly in the northern source zone is probably due to increased erosion and paucity of preserved leached capping in the area (Fig. 7B).

Translocation (migration) of iron in many soils is very limited because hydroxy oxides of Fe, e.g., goethite, are generally insoluble. In spodozols, however, chelation of iron occurs making it mobile (Birkland, 1984). Spodozols are exactly analogous to miniature supergene systems because they have an iron-leached zone above an iron-enriched zone and a protore or protolith beneath (Brimhall and Dietrich, 1987). This result, using simple gravimetric data, offers yet another possible means of recognizing copper source regions at the level of the exposed leached capping and relatively higher density areas. This can be used as another direct exploration tool for exotic orebodies.

Analysis of Sites of Copper Deposition

The Damiana orebody (Fig. 12) with its exotic mineralization lying near the contact between the bedrock and overlying alluvial fan is proof that copper in solution escaped Indio Muerto in Quebrada Riolita, surfaced in the paleosprings, flowed downhill, and deposited as exotic copper oxides. By

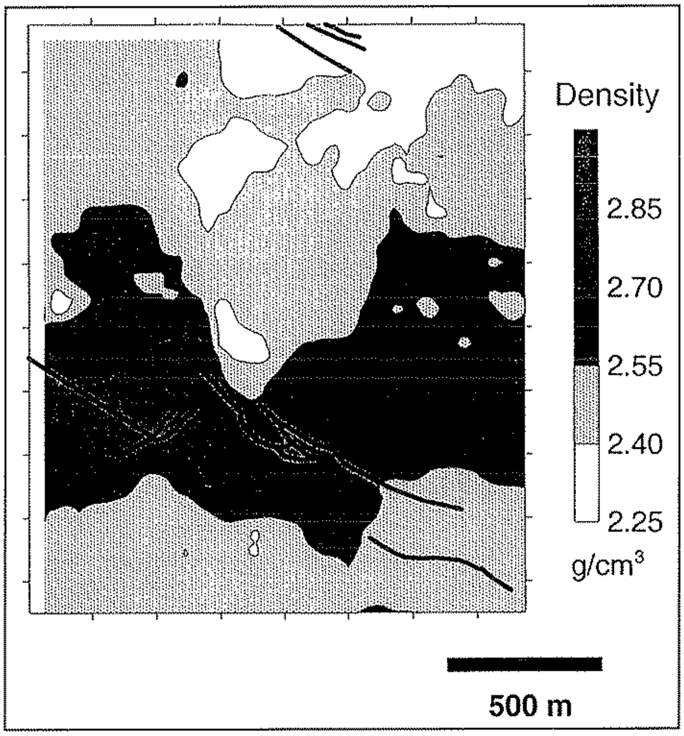

FIG. 13. Plan map of the bulk dry-rock density of the leached capping across the model extent. This figure shows a density high that correlated with the southern latite dike system. We interpret this to be due in part from transported iron into this highly permeable zone seen as jarosite and goethite in surface outcrops.

relating the copper tonnage in known exotic deposits to the quantified lateral negative flux in the correlated source region, copper can be accounted for in the entire system. The ore reserve calculation of the Damiana exotic deposit reports 1.8 Mt of copper (Rojas and Müller, 1994), which is remarkably close to the calculated integrated negative flux of 1.6 Mt of copper from the southern source zone. It is therefore interpreted that Damiana is directly linked to this southern source zone.

The northern source zone has a negative flux of 0.7 Mt of copper and implies that another, though smaller, exotic deposit could exist beyond this area along the trend of the northern swarm of latite dike and/or faults.

Exploration Driven by Mass-Balance Modeling

The results of the mass-balance model correlate the Damiana orebody with the southern source zone in terms of remobilized copper and its transport direction, linking the source and sink zones. We recognize that the northern source zone (Fig. 12) and its quantity of 0.7 Mt of laterally transported copper had not been reconciled with any known exotic deposit at the time of our modeling. Combining the newly gained knowledge of lateral copper transport processes with the mass-balance results, we explored the possibility of exotic deposits associated with the northern latite dike system. Starting at the northern source zone, we followed the northwest-trending latite dike outward to create a target for exotic copper deposition under the alluvial fan in the Quebrada Turquesa area.

In the northern source zone the strike of the latite dike structure is traced northwest into the headwaters of Quebrada Turquesa. Historically, Quebrada Turquesa has been known for copper oxide showings, hence the name. The ancient Inca workings in this area were helpful in the discovery of the El Salvador deposit by the late William Swayne of Anaconda in 1954 (Gustafson and Hunt, 1975). In the headwaters of Quebrada Turquesa there is ample evidence that acidic, copper-bearing fluids having moved through this area, precipitating supergene alunite veins, jarosite, chrysocolla, and copper wad in the altered andesite basement rock.

Guided by the northwest strike of the latite dikes the alluvial fan system was explored downslope for mineralization in a prospective corridor extending from the northern flux zones. The surface expression of distal Quebrada Turquesa is an erosional remnant of an incised valley down through an alluvial fan (Fig. 1). The fan consists of polymictic gravel clasts derived from erosion of Cerro Indio Muerto, Sierra Miranda, and Cerro Amarillo. The gravels are easily recognized in the field and in both colored air photographs and satellite images enhanced the revelation of clays and iron oxides. Lithologically, the gravels represent numerous sources and include clasts of several of the oxidized mineralized porphyries mapped underground at El Salvador. The polymictic gravels once completely covered much of the area northwest of the mine and are bounded by ridges (topographic highs) on the north and west to form a wedge shape. These gravels filled and covered a network of smaller channels flowing northwest.

Subsequent differential erosion removed a large portion of the gravels and incised many younger channels into the fan. The gravels nearest the mineralization center have been eroded away leaving a "ventana," an erosional window, of exposed fresh andesitic bedrock (Brimhall and Mote, 1996). Traces of lag gravels can still be found on ridges leading back to the mineralization centers through this area. Latite dike outcrops are present in this ventana area. Numerous occurrences of chrysocolla and copper oxide are present in fractured andesite bedrock leading down from the headwaters of Quebrada Turquesa.

Discovery of the Mineralized Paleochannel in Quebrada Turquesa

Differential erosion within the Quebrada Turquesa alluvial fan system has created a topographic inversion effect where gravel-covered paleochannel deeps are now topographic highs. The interpretation that mineralized paleochannel deeps should still be perserved under these gravels led Brimhall to define this area as a drilling target. Brimhall initially recommended two drill holes (G.H Brimhall, 1996, pers. commun.) and later recommended nine more exploration holes to be drilled in the thickest central part of this fan remnant after field mapping had progressed (Brimhall and Mote, 1997b) and mapping of the trenches revealed the dip direction of the paleochannel wall pointed toward the valley deeps. The first hole drilled hit copper wad at the gravel-andesite contact. By January, 1998, 68 holes were drilled, defining a mineralized paleochannel 4 km long perserved under the fan (Fig. 1) and containing 0.4 Mt of copper.

The mineralization in Quebrada Turquesa is mostly copper wad occurring in fractures of altered andesite. In the peripheral extent of the mineralization, where the acid fluids have not altered the host rock entirely, chrysocolla is dominant. A clay-altered andesite unit occurs at the contact between the andesite and the gravel and reaches several meters of thickness. This is evidence of vast quantities of low pH fluids passing through this zone. Figure 14 shows a northwest cross section B-B' (Fig. 1) looking down gradient through the central part of the Quebrada Turquesa gravels, perpendicular to flow direction of the preserved paleochannel. The andesite-gravel contacts, observed in the trenches, dip away from the current channels toward the preserved paleochannels (Brimhall, 1997) and provide vivid evidence of topographic inversion.

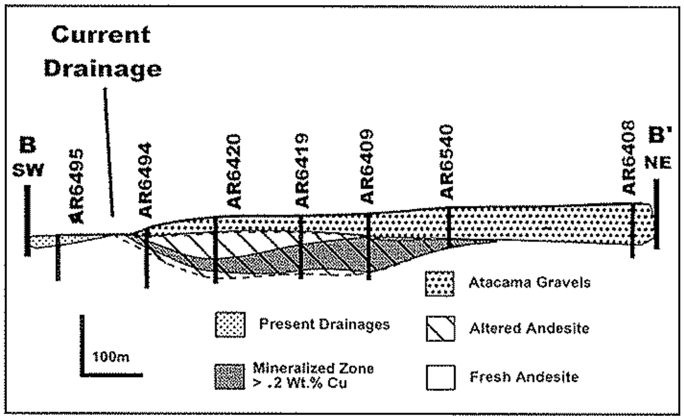

FIG. 14. Cross section B-B' (Fig. 1) across the mineralized paleochannel of Quebrada Turquesa. Topographic inversion has preserved the paleochannel under a covering of the Atacama gravels. Notice the mineralization dipping away from the current channel.

The mineralization in Quebrada Turquesa is very similar to the distal portion of Damiana, confined to a narrow paleochannel (Fig. 1). If we assume that the two deposits formed similarly, a portion like that of the intermediate part of Damiana, containing most of the copper reserve, would have existed in the ventana area. It is possible that the increased erosion has mechanically transported this zone northwestward over the top of the remnant gravels. This introduces a possible target for mechanically transported exotic mineralization beyond the current limits of the fan.

Differential Development of Enrichment Blanket Copper Grade

At El Salvador deficiencies in copper fixation within certain permeable portions of the blanket are correlated with lateral copper transport into exotic orebodies. Using the flux model to calculate an apparent deficit of copper grade from the blanket, the geologic validity of the SL_T estimation can be directly addressed.

Deficit blanket grade: Delta b

Delta b (or change in blanket grade b) calculates the deficit in copper grade within the enrichment blanket due to lateral flux by using the assumptions and estimations from phases I and II of the mass-balance calculation. Delta b differs from the flux function in that it represents a simple change in blanket grade, whereas the flux represents a total mass of missing copper and is dependent on grade, density, and thickness of the blanket. No lateral flux portions will have a delta b of 0 regardless of protore grade, because they are portions of the blanket where enrichment has been assumed to be complete. Delta b is defined as the following: (see Mass Balance Section for explanation of symbols).

$$\text{Delta b} = (SL_T - SL_T{}^{\circ})\,(p\,\rho_p - l\,\rho_l)/(B\,\rho_b). \tag{7}$$

Equations (6) and (7) are combined to solve delta b in terms of flux as shown in equation (8):

$$\text{Delta b} = -\text{flux}/B\,\rho_b. \tag{8}$$

Figure 15 is the delta b function contoured over the model extents and shows a direct correlation between the latite dikes and the loss of grade from the blanket, with a general loss of about 1.0 wt percent of copper around the latite dikes.

Normal blanket grade b^*

Taking the delta b function and adding it to the actual grade of the blanket (b) yields the grade in the blanket if no lateral transport had occurred and if all copper had been fixed in the existing blanket. This function is termed b^* and is defined in equation 9:

$$b^* = \text{delta b} + b. \tag{9}$$

Function b^* allows the validity of the model to be checked in terms of realistic enrichment blanket grades. If the estimation of SL_T or the grade model is too high or too low, values for b^* maybe geologically unrealistic when compared to empirical-grade distribution models of supergene ore at other deposits.

Figure 16 shows the b^* function over the extent of the model. The overall changes in the b^* function are subdued as

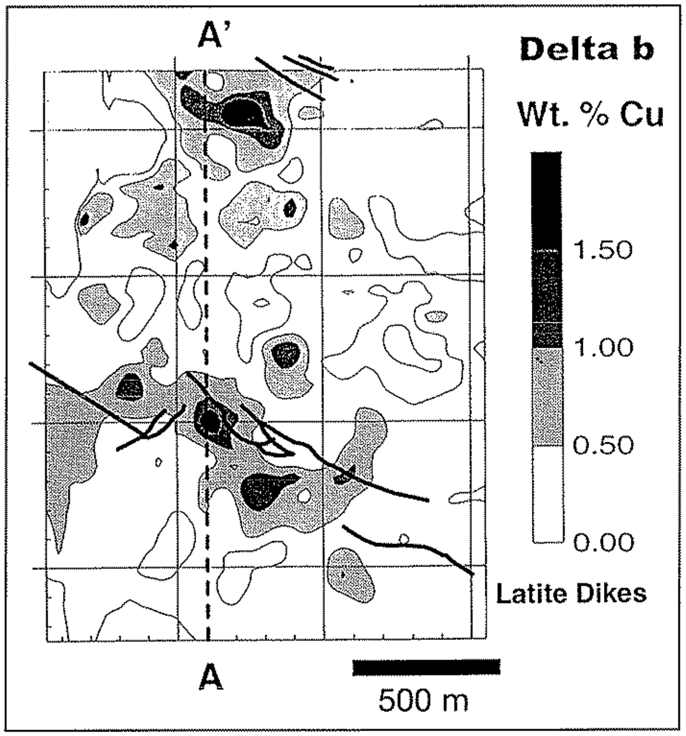

FIG. 15. Plan map of the delta b function contoured over the model area. The delta b function highlights the estimated loss of grade from the enrichment blanket. Notice the correlation between delta b and the latite dikes.

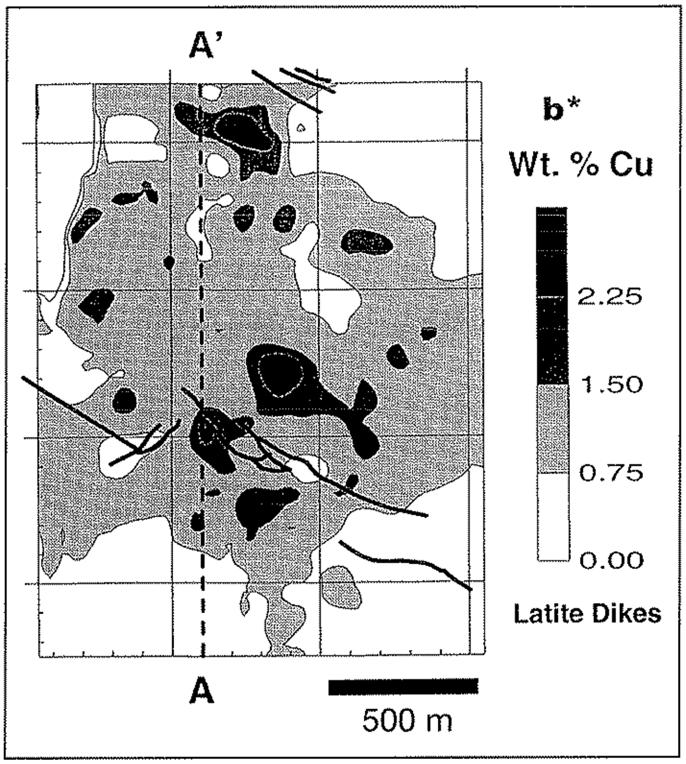

FIG. 16. Plan map of the b^* function contoured over the model area. The b^* function estimates the grade of the blanket had no lateral flux occurrence. The b^* function shows a subdued surface with blanket copper grades greater than 1.5 wt percent in localized areas, corresponding to high-grade bornite zones (Figs. 4B, 12A).

one might expect from a disseminated hypogene deposit having undergone supergene enrichment only in the vertical direction. The grade distribution is realistic and supports the validity of our assumptions as the overall b° grade is generally between 0.5 and 1.5 wt percent, only reaching a value greater than 2.0 wt percent in areas of the model with high-grade protore due to bornite mineralization (Figs. 3B, 11A).

Cu, Fe Mn, Co, and K Geochemistry Within Exotic Ore Systems

Multielement chemical analyses were performed on a sample suite of protore, enrichment blanket, leached capping, exotic ore, and exotic host rock to understand the geochemical processes involved in the source of the elements Mn, Co, and K found in the copper wad. The reconnaissance analysis here supplements the more comprehensive copper study and addresses the redistribution of other elements in the system. Refer to Mote (1999) for a complete multielement chemical analysis. A total of 49 samples were taken along a cross section. Samples from the protore and enrichment blanket where extracted from diamond drill hole assay pulps over a representative distance. The leached capping samples were compiled from drill holes assay pulps and surface samples. Exotic ore samples were taken from three reverse circulation drill holes. Fresh outcrops of andesite provided samples of the exotic ore host rock.

The samples were crushed to a <¼-in diam and pulverized to 100-g splits. The samples were analyzed by ICP-AES at Chemex Laboratories, Reno, NV. Samples were run in order from lowest to highest grade to minimize memory effect and cross-sample contamination.

Fractionation factors

Figure 17 plots the averaged chemical concentration data as fractionation factors defined as ratios of the concentration of an element in zones of the hypogene, supergene, exotic system to a previously unmineralized unit. The ratios include the leached capping/protore, enrichment blanket/protore, and exotic ore/andesite. The fractionation factors highlight the enriched or depleted elements from the leached capping, the enrichment blanket, and the exotic ore. Fractionation factors for each element are plotted across the periodic table as a function of group in order to reveal systematic trends (e.g., Brimhall, 1987). This technique takes advantage of the intrinsic chemical order within the periodic table as groups of elements often behave similarly due to similarities in the electronic configuration of the atoms. Enrichment factors near 1 imply that there has been relatively little change in concentration of the element between the two respective states (>1 indicates gain, <1 indicates loss). This technique only estimates mobility or immobility of an element because it does not take into account changes in bulk-rock density (Brimhall et al., 1991).

The leached capping with respect to the protore shows apparent depletion of K, Mn, Co, and Cu based upon enrichment factors less than 1.0. Fe was relatively immobile in the leached cap. Analysis of the enrichment blanket/protore ratios shows that of all the elements depleted from the leached capping, the blanket fixed only Co and Cu, whereas K and Mn passed through the blanket in discharging fluids. In fact Mn and some K are depleted from both the leached capping and enrichment blanket. It is important to note that while elements are fixed when crossing the oxidation-reduction boundary from the leached capping into the enrichment blanket, all elements do not necessarily behave this way and may require another geochemical barrier to precipitate. Taking the elements depleted from both the leached capping and enrichment blanket we surmise that exotic fluids containing Cu, K, Mn, and Co escaped the supergene system and followed hydraulic gradients into the andesite-based paleochannels. Enrichment of the andesite from the exotic fluids shows that Cu, K, Mn, and Co were all fixed in the andesite by ratios greater than 1.0 (Fig. 17).

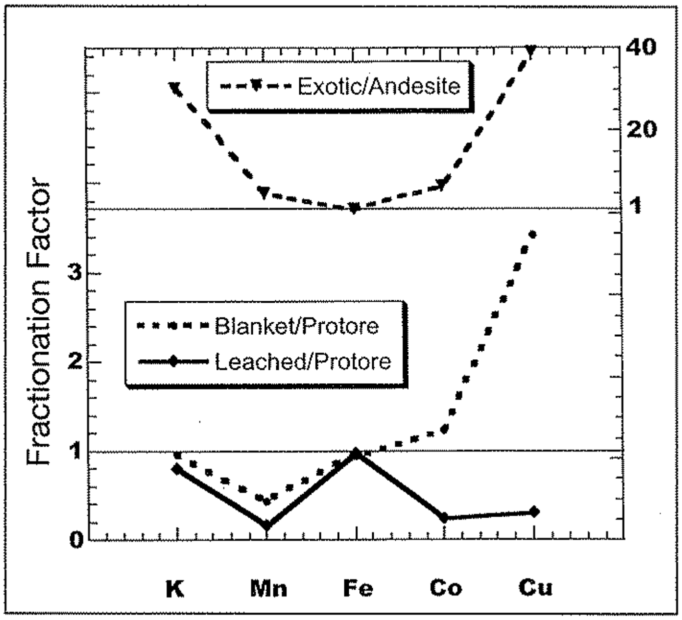

FIG. 17. Fractionation factors for K, Mn, Fe, Co, and Cu within the supergene, exotic system. Fractionation factors are defined as the ratio of concentration of an element between final and initial states in genetically linked zones. The ratios shown here are leached capping/protore, enrichment blanket/protore, and exotic ore/andesite host. Values greater than 1 imply enrichment, values less than 1 imply depletion. For example, copper is depleted from the leached capping yet enriched in the enrichment blanket compared to the protore.

Although Fe is not fractionated to the degree of Mn or Cu (Fig. 17), it is surprisingly mobile in this system under oxidizing conditions. Minor remobilization does occur showing that Fe was removed from the leached capping and precipitated in the paleospring transition zone before reaching the exotic deposit. Evidence of this Fe mobility is the locally abundant jarosite and goethite in the upper reaches of the system. Figure 13 emphasizes the effect of Fe mobility on leached capping density, showing the pattern of its redistribution with respect to transport pathways for escaping supergene fluids where dry-rock bulk densities increase from about 2.4 to 2.7 g/cc, an increase of some nearly 20 percent.

Conclusions

A simplified first-order mass-balance analysis of the El Salvador porphyry copper deposit, using constant protore grade projections upward, was sufficiently accurate to identify and quantify two significant source zones where copper escaped fixation by enrichment in the blanket and was transported laterally from the principal deposit into the surrounding paleodrainage networks. The southern source zone near Quebrada Riolita has an aerially integrated negative flux of 1.6 Mt of copper and the northern source zone on the northern flank of Indio Muerto has a negative flux of 0.7 Mt of copper. Both of these copper source zones are coincident with a different set of district-scale northwest-trending latite dike and/or faults that directed the lateral transport of copper into the headwaters of the surrounding paleodrainage network. Copper from the southern zone flowed downslope to become the Damiana exotic orebody and copper from the northern source flowed into Quebrada Turquesa Norte where a new exotic orebody was discovered. The discovery of the latter orebody was guided by the trend of the latite dikes leading away from the northern source zone and the genetic sources and pathways deposit model developed for Damiana. These results show that the mass-balance analysis is an effective tool for assessing copper redistribution and defining exotic mineralization targets on a district scale.

District-scale mass-balance analysis, using all available assay data, provides a practical tool to guide district-scale exploration for exotic deposits by defining prospective corridors and providing an estimate of the ore metal mass most likely to be found. Mass-balance analysis, using the sources and pathways deposit methodology, also helps focus the use of independent methods to verify the conclusions of mass balance and assures that a district-scale analysis is made to integrate and assess all relevant information.

We conclude that weak fixation of copper within source region portions of the supergene blanket, which allowed escape of copper, is due to a combination of structural, alteration, and mineralogical controls. Microscopic analysis of sulfide replacement textures showed only weak replacement rims on bornite, chalcopyrite, and pyrite in these source zones. In these regions it is thought that the latite dikes increased permeability, thereby allowing higher than normal fluid-flow velocities through this zone. This increased fluid velocity may have hampered the replacement of hypogene sulfides by reducing the residence time of interaction copper ions with the primary sulfides. These portions of higher pyrite/chalcopyrite ratios were also zones of acid generation that kept copper soluble and transportable. Compounding this effect, the fluids were unable to effectively reduce or neutralize supergene fluids by reactions with the wall rock because the alteration assemblage of kaolinite and sericite is relatively unreactive gangue. The combination of these controls creates an ideal system for lateral copper transport and explains the sizable exotic deposits found at El Salvador.

Besides focusing laboratory study, the mass-balance results also guided field mapping on the surface and brought attention to the headwaters of Quebrada Riolita where we identified evidence that exotic acid copper-bearing fluids had escaped the principal supergene system and flowed outward into a paleospring environment. It is an unusual occurrence when a theoretical model completed in the laboratory has successfully guided field mapping. The goethite-jarosite laminate deposit and the crosscutting relationships of alunite veins in the Quebrada Riolita area show that multiple, episodic events of fluid escape have taken place. Paleospring deposits provide the very best samples for dating supergene and exotic ore-forming processes.

Even at the well-drilled El Salvador deposit, a need exists for deeper drilling of the protore as the mass-balance model was limited to a first-order approach, using a conservative assumption of an upwardly constant copper grade. General knowledge of variations in copper grade within uneconomic portions is desirable to complete robust mass-balance calculations and infer the total copper budget within a district, which can lead to new discoveries of exotic orebodies. The most useful way to interpret the protore-grade projections in our first-order model, where they are constantly upward, is a vertically integrated average copper grade.

A valuable area of future research that could improve modeling capabilities is a better definition of the protore grade model variations in unenriched porphyry copper deposits. It is argued here that crustal-scale protore-grade functions of vertical columns will approximate a bell-shaped curve. A constitutive mass-balance equation could then be derived, which would accommodate not only a gradient in protore grade as in existing second-order models (Brimhall, et al., 1985) but also a change in the derivative of grade with elevation so that a maximum representing the protore as a crustal-scale geochemical anomaly could be modeled. The width of the bell-shaped curve, its symmetry, and skewness remain to be determined as does variability among porphyry copper deposits. In the meantime, by incorporating relict sulfide mineralogy of the leached cap, we have added a useful tool to the overall mass-balance approach that does help refine estimates of the original preerosion copper protore surface. The existence of relict sulfides from the leached capping is proof of the minimum extent of contributory mineralization before leaching commenced. By using the minimum protore surface to constrain the estimation of the original extent of copper-bearing sulfides, the mass-balance model is brought closer to geologic reality.

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