Multiple Centers of Mineralization in the Indio Muerto District, El Salvador, Chile

LEWIS B. GUSTAFSON,†
5320 Cross Creek Lane, Reno, Nevada 89511

WALTER ORQUERA,
CODELCO-Chile, Division Salvador, El Salvador, Chile

MICHAEL McWILLIAMS,
Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115

MARIO CASTRO, OSMAN OLIVARES, GONZALO ROJAS, JUAN MALUENDA, AND MARCELLO MENDEZ
CODELCO-Chile, Division Salvador, El Salvador, Chile

Abstract

The porphyries that formed copper deposits in the Indio Muerto district include both 44 Ma rhyolitic sub-volcanic intrusions and 42 to 41 Ma granodioritic stocks and dikes. All are aligned for 4 km along a north-north-east trend, which is the apparent hinge line of a 58 Ma trap-door caldera. Three separate centers of mineralization were associated with the earlier rhyolites, Cerro Pelado, Old Camp, and probably M Gulch-Copper Hill. Four separate centers were associated with the later granodiorites, M Gulch-Copper Hill, O Nose, Turquoise Gulch, and Sector Granito. Patterns of lithology, structure, mineralization, and alteration in the various centers, which have been documented by systematic mapping partially supported by studies of mineralogy and geochemistry, are presented and compared to the previously described Turquoise Gulch center.

Cerro Pelado is a 750-m diameter rhyolitic volcanic neck, intruding host andesite at the northeast end of the district. Very weak Cu but much stronger Mo mineralization, with analogies to Climax-type deposits, is associated with this intrusion. Surficial sericitic alteration with weak pyrite-(chalcopyrite-bornite)-specularite-gold mineralization shows decreasing sericite, pyrite, Cu, and Au contents downward. This strong vertical zonation grades downward to alkali feldspar-biotite alteration with increasing molybdenite and magnetite content below an abrupt top of quartz veining. The Old Camp is a 250-m diameter, roughly cylindrical body of disseminated chalcopyrite-bornite and quartz veining with K feldspar-biotite alteration, centered within a rhyolitic quartz porphyry dike. This dike was emplaced and mineralized within 1 m.y. of Cerro Pelado. Mineralization zones outward through chalcopyrite-pyrite to pyrite with sericite-chlorite and then chlorite-epidote-albite alteration. A supergene sulfide enrichment blanket has been largely oxidized. M Gulch-Copper Hill was first mineralized in and around quartz porphyry dikes with quartz veining, disseminated chalcopyrite-bornite, and K feldspar-biotite alteration.

Roughly 1 m.y. later, intrusion of a series of feldspar porphyries and igneous breccia displaced the center of the mineralization at M Gulch-Copper Hill. Late-stage hydrothermal activity reworked earlier mineralization and superimposed pyrite-chalcopyrite assemblages with sericite. Aside from some rich D veins containing pyrite-bornite-digenite, economic grade in the M Gulch-Copper Hill pit is mostly due to supergene enrichment. Ore at O Nose was largely supergene chalcocite-covellite on chalcopyrite-pyrite, centered on early QG feldspar porphyry and brecciated and biotized andesite. Subsequent intrusion of intramineral L feldspar porphyry and late hydrothermal activity apparently reworked earlier mineralization. At the contact, this produced a fringing chalcopyrite-pyrite zone in andesite, which is sharply zoned upward to pyrite-bornite-chalcopyrite with higher grade. This is apparently the same L porphyry that intruded the center of the main Turquoise Gulch orebody and controlled transitional and late patterns of alteration and mineralization described previously. The supergene enrichment blanket which makes ore in Sector Granito, to the southwest of Turquoise Gulch, is connected to the main orebody but primary mineralization is spatially separate and related to a different set of intrusions. Although less well known than other centers, a chalcopyrite-bornite core is apparently related to unusually intense, texture-destructive K feldspar alteration in early equigranular X porphyry and later L feldspar porphyry. This core mineralization grades outward to pyrite-sericite and abruptly upward to pyrite-bornite-chalcopyrite with sericite-andalusite-pyrophyllite-diaspore. Extending the trend to the southwest is the barren Granite Gulch feldspar porphyry, emplaced between the two mineralizing periods.

40Ar/39Ar dating demonstrates that two episodes of mineralization associated with the early rhyolitic and later granodioritic intrusions each lasted approximately 1 to 1.4 m.y., from 44.5 to 43.5 and 42.3 to 40.9 Ma, respectively. The barren Granite Gulch porphyry and perhaps the early and equigranular X and O porphyries were intruded between 43 and 42 Ma. Magmatic activity, therefore, occurred episodically over at least 3 m.y. The individual centers are best explained as expressions of different cupolas on a magma chamber, which evolved from granitic to granodiorite to quartz diorite with progressive injection of new magma. Despite our

† Corresponding author: e-mail, lgustaf685@aol.com
best efforts to date 16 carefully selected samples, it was not possible to define the sequence and duration of the partially overlapping centers within each of the larger mineralization periods. The different centers exhibit a wide diversity of characteristics, which mirror variations on the general theme of porphyry Cu-Mo development. Changing hydrothermal input from an evolving and growing magma chamber and major remobilization of early mineralization by both intrusion and hydrothermal activity are major factors in this diversity.

Introduction

The history of discovery and results of more than 80 man years of geologic work, by Anaconda prior to July 1971, were summarized by Gustafson and Hunt (1975). This work was focused on the main, supergene-enriched orebody under Turquoise Gulch, which then comprised the ore reserve for the El Salvador mine. Only minor mention was made of the separate small but high-grade center of mineralization at the Old Camp, some 2 km to the northeast, and the relatively low grade-enriched pyritic mineralization under M Gulch and Granite Gulch was then considered minor and possibly part of the pyritic fringe to the main orebody. Subsequently, CODELCO-Chile not only began mining the large tonnage of primary ore under the main Turquoise Gulch orebody but developed large tonnages of ore in both M Gulch, on the north slope of Cerro Indio Muerto, and below Granite Gulch, on the southwest slope. It became more clear that these represented much more than minor peripheral mineralization around a single center, and in 1993 to 1995, a special project was initiated to document the deep patterns of sulfide and alteration assemblages demonstrated the existence of multiple and independent centers of primary mineralization (Figs. 1–3). A program of 40Ar/39Ar dating was subsequently initiated to investigate time relationships between the centers.

This paper presents the results of these projects and attempts to summarize briefly the geology of the individual centers. Patterns of Cu and Mo grades and hydrothermal vein orientations at 2,600- to 2,660-m elevations are presented (Figs. 4–6) in the context of the rock, mineralization, and alteration patterns (Figs. 1–3). Figure 7 summarizes the time relationships of mineralization relative to the intrusive porphyries in the individual centers. Age data are summarized in Figure 8 and in Tables 1, 2, and 3. The geology of the different centers has been documented to a variable degree by routine mapping and special studies. Of these, only the M Gulch-Copper Hill study has been published (Rojas, 1994). Much information can also be found in university theses by Chelen (1974), Hernandez (1976), Correa (1977), Tobar (1977), Fuster (1983), Godoy (1983), Fuentes (1988), and Olivate (1999). The rest are documented in unpublished internal reports—Cerro Pelado by Olivate (1996–1998) and Castro (1998), Old Camp by W. Galvez (1974) and Castro (1994), O Nose-Zone 295 by Olivate (unpub. data, 1995), and Sector Granito by Maluenda and Mendez (1944–1945). The evolutionary model developed for Turquoise Gulch (Gustafson and Hunt, 1975) remains valid and provides the reference, both in terms of geometric and temporal patterns, for comparison to the other centers and to inferred processes.

Not all of the centers have sufficient grade to support mining, although as the operation moves to oxide and lower grade ores, most of these will be mined. The centers are remarkably diverse in the geometry and relative intensity of the intrusion, alteration, and mineralization associated with each. This diversity was widened further by the discovery of the Damiana orebody of exotic copper deposited close to the surface on the lower flanks of Indio Muerto (Rojas and Mueller, 1994). This diversity and the extensive exposure and data this set of deposits affords have made El Salvador an extraordinary school for students of porphyry copper. This has recently been further enhanced by regional mapping by SERNAGEOMIN, at the request of and financed by CODELCO, which has clarified the volcanic and tectonic setting. In particular, the Indio Muerto rhyolite dome complex now appears to be a resurgent feature of an unusual “trap-door caldera,” formed roughly 15 m.y. prior to onset of the magmatic activity which gave rise to the mineralization (Cornejo et al., 1997a, b; unpub. maps and reports by O. Rivera 1995, 1997; and P. Cornejo and C. Mpodozis, 1998). The 44 to 41 Ma mineralized porphyries apparently intruded along the same deep zone of structural weakness, near the intersection of the north-northeast–trending hinge line of the caldera with west-northwest faults at the north edge of the collapse, which guided the emplacement of the earlier rhyolite. The porphyry copper mineralization formed within an active transpressive regime, characterized by felsic volcanism and a system of regional reverse and strike-slip faults (Mpodozis et al., 1994; Tomlinson et al., 1994; Cornejo et al., 1997b). The Sierra Castillo fault, part of the West Fissure or Domeyko fault system, which has apparently localized the Oligocene belt of porphyry copper deposits in northern Chile, passes 10 km east of Indio Muerto. New findings on supergene events and processes are reported in accompanying papers in this volume (Mote et al., 2001a, b).

This paper deals with centers of primary mineralization and does not consider the Damiana orebody, which covers roughly 8 km² lying just off the west edge of Figures 1 through 6 and below the 2,600-m elevation. The 169 million metric tons (Mt) of 0.56 percent Cu is predominantly copper oxides and chrysocolla on fractures and lesser dissemination in bedrock andesites, with smaller tonnages of mineralized surficial gravels. Mineralization extends up to 6 km from the drilled west edge of the sulfide enrichment blanket of the Turquoise Gulch and Sector Granito centers.

Individual Centers

Turquoise Gulch

The main orebody in the district, which supported the initial development of the El Salvador mine in the late 1950s, is located under Turquoise Gulch on the northwest slope of Cerro Indio Muerto. This center of mineralization has been described by Gustafson and Hunt (1975) and Gustafson and Quiroga (1995). The 2,600-m elevation, used for Figures 1 through 6, is the same as that of level maps presented in the former papers. Readers are referred to these papers for details. In summary, roughly two-thirds of the copper in this center was introduced with K feldspar-biotite-anhydrite
alteration and early granular quartz-K feldspar A veins, during intrusion of the K porphyry complex. This followed intrusion of equigranular X porphyry. Central chalcopyrite-bornite is zoned outward to diminishing chalcopyrite with pyrite and removed by the intrusion of the intramineral L and A porphyries. Both are very weakly mineralized except for transitional quartz-molybdenite B veins and late pyrite-bearing D veins with sericitic halos. Advanced argillic alteration and high-sulfidation assemblages formed at high elevations, later in the development of the system. A dynamic model of a magma-dominated early environment was developed, followed by a meteoric water-dominated late environment collapsing inward and downward as the late L porphyry cooled. Figure 7 is a summary to aid readers to keep track of the names and timing of the various porphyries relative to stages of mineralization in the other centers compared to Turquoise Gulch. In none of the other centers has there been as careful mapping and documentation of temporal relationships (veins truncated at intrusive contacts, etc.) as in the original center, so there is some uncertainty in the relationships as shown.

**Cerro Pelado**

Cerro Pelado is a small hill located about 3 km north-northeast of the main Turquoise Gulch orebody. It is a near-circular, steep-walled complex of multiple intrusions of rhyolite porphyry and breccia. These rocks intrude Upper Cretaceous andesitic rocks, which host all of the Tertiary intrusions in the district. Extensive mapping and drilling in the last 5 yr has greatly increased our knowledge of this area (Olivares, unpub. reports, 1996–1998; Castro, unpub. report, 1998).

**Rocks:** Quartz rhyolite porphyry has abundant phenocrysts of sanidine, plagioclase, and quartz, with sparse biotite, in a microcrystalline groundmass of quartz, alkali feldspar, and minor mica and rutile. The texture is variable, with phenocrysts generally <2 mm but with a gradational core of coarser texture in the southeast sector. This coarser intrusion increases with depth and locally intrudes porphyry with finer grained texture. Multiple rhyolite porphyry dikes, with varied texture and relative ages, are crudely radial and circumferential about the central plug.

About two-thirds of the area near the surface is breccia with varied characteristics and formed by multiple brecciation events, simplified in Figure 1 as predominantly rhyolitic or andesitic. All are actually heterolithic, with clast sizes ranging from 5 mm to 1.5 m, and predominantly altered andesite even in most rhyolite breccia. Matrixes are fragmental, with broken quartz and feldspar common. Only minor rhyolitic clasts are present in the andesitic breccia, but microscopic shards and local flow banding are seen in the matrix. Andesitic breccia is cut by dikes of fine-grained rhyolite porphyry and rhyolite breccia and is displaced below 2,600 m by rhyolite porphyry and breccia. In the southwest sector, the rhyolite breccia contains more or less rounded clasts of rhyolite porphyry in a matrix of fragmental (tuffaceous?) rhyolite.

Evidently, this is a shallowly eroded, complex volcanic neck, with magmatic-hydrothermal breccias formed during emplacement of the rhyolite. It probably vented to the surface no more than a few hundred meters above the present surface, although extrusive equivalents cannot be found in the district, unless nearby Rhyolite Hill is a flow rather than a sill.

**Alteration:** At surface, 2,700- to 2,860-m elevations, sericitic alteration is fairly pervasive, with only local residual igneous alkali feldspar in the rhyolite and supergene clay altering residual plagioclase and chlorite in the andesite. At 2,600 m, alkali feldspar is mostly fresh in the rhyolite outside of sericitic veins, biotite is mostly altered to sericite, and plagioclase has gone to sericite and supergene kaolinite. Andesite within and close outside the the rhyolite contact is altered to secondary biotite-albite, with minor actinolite, and more or less overprinted by chlorite-sericite and subsequent supergene kaolinite. Propylitic alteration, chlorite-epidote-calcite-albite, surrounds the center and merges with the larger propylitic halo around the other centers.

**Mineralization:** Copper mineralization here is very weak. A central annular zone of low-intensity (<1% vol) chalcopyrite-pyrite with molybdenite surrounds and partially caps over a weakly pyritic and barren, asymmetrical core in coarser rhyolite porphyry and grades outward to weak pyrite. Copper content is nowhere consistently greater than 0.1 percent, except in a thin supergene chalcocite-covellite enrichment zone. Molybdenite is closely associated with granular quartz veinlets with no alteration halos and only trace pyrite with the molybdenite. Common evidence of segmentation of veins at edges of rhyolite porphyry clinches in breccia, which is in turn cut by more quartz-molybdenite veins and porphyry dikes, clearly proves contemporaneity of multiple pulses of vein formation, porphyry intrusion, and brecciation. The relative age of emplacement of Cu and Mo is hard to determine, as the sulfide is almost all disseminated, but the Mo-bearing veins appear to be early. These veins are more like A veins in the Turquoise Gulch center than B veins.

Vertical zonation is pronounced. Cu decreases downward to less than 100 ppm at about 2,250 m, where magnetite is abundant, especially in andesite and andesitic breccia. Mo is greater than 200 ppm at this depth, extending upward to a rather abrupt drop in grade at just below 2,600 m in the eastern sector and 2,800 m in the west. The 2,600-m elevation of Figures 4 and 5 is largely below the chalcocite enrichment and intersects the top of molybdenite. The deep sulfide and grade patterns at Cerro Pelado shown in Figures 2, 4, and 5 are poorly defined by sparse drilling and are largely schematic. The quartz veins develop local drusy centerlines and top out only a few meters above the abrupt decline in their molybdenite content. Sulfides in the uppermost 150 m appear to be dominantly pyrite-chalcopyrite-spalerite-bornite, judging from relict sulfides and high-level sulfide intersections. Gold values in oxidized rock near surface and in this uppermost sulfide zone are significant, 0.1 to 1 g/t Au in the eastern sector, but less than 0.3 g/t Au at the top of sulfide and these values do not persist in depth. Specular hematite rather than magnetite occurs near surface and is particularly abundant in the northeast andesitic breccia.

Late sulfide veins are rare in the intrusive plug but abundant and relatively continuous peripheral to it. Figure 6 shows the larger D veins, 2 to 20 cm of limonite (after pyrite) with sericitic halos, as mapped on surface but plotted 100 to 200 m below on the 2,600-m level. The pattern of predominantly west-northwest–striking veins, which deviate to curve around the outside of the plug, is strongly influenced by the intrusive center.
Fig. 1. Indio Muerto district lithology, showing rock types (2,600- to 2,660-m elev).
MINERALIZATION, INDIO MUERTO DISTRICT, EL SALVADOR, CHILE

BACKGROUND SULFIDE ASSEMBLAGE
- Molybdenite-Pyrite-Chalcopyrite
- Low Intensity, Pyrite-Bornite-Chalcopyrite
- Low Intensity, Molybdenite-Pyrite-Chalcopyrite-Magnetite
- Chalcopyrite-Bornite
- Low Intensity Chalcopyrite-Bornite
- Chalcopyrite-Pyrite
- Low Intensity Chalcopyrite-Pyrite-Chalcopyrite-Magnetite
- Molybdenite-Pyrite-Chalcopyrite
- Pyrite-Chalcopyrite (>5:1 py:cp)
- Trace Sulfide
- No Background Sulfide (Latite)
- Air-beyond 2600m contour

INDIO MUERTO DISTRICT SULFIDE ZONING
2600 - 2660 ELEVATION

CODELCO CHILE DIVISION SALVADOR
SUPERINTENDENCIA DE GEOLOGIA

INDIO MUERTO DISTRICT SULFIDE ZONING

Fig. 2. Indio Muerto district sulfide zoning, showing background sulfide assemblage (2,600- to 2,660-m elev).
Fig. 3. Indio Muerto district alteration zoning, showing background alteration assemblage (2,600- to 2,660-m elev).
Fig. 4. Indio Muerto district, showing copper grade (2,600- to 2,660-m elev).
Fig. 5. Indio Muerto district, showing molybdenum grade (2,600- to 2,660-m elev).
Fig. 6. Indio Muerto district, showing trends of D veins (2,600- to 2,660-m elev).
operation, is this resource scheduled for development. Turquoise Gulch (Perry, 1960). Only now, after 40 yr of mine
by the higher grade supergene enrichment blanket under
0.91 percent Cu, but this limited tonnage was soon eclipsed
and penetrated 437.4 m of primary mineralization averaging
third drill hole at El Salvador in 1951 was drilled at Old Camp
ploration interest in this district during the 1950s. Anaconda’s
2 km north-northeast of Turquoise Gulch, was the focus of ex-
sterisk.

teripple mineralization responsible for most of the copper in each center is marked by an as-
types in other centers is also discussed in the text. The stage(s) of mineral-
Cerro Pelado are more like A than B veins. Uncertainty of timing of vein
and late stages of mineralization, respectively. Quartz-molybdenite veins at
Gulch center (Gustafson and Hunt, 1975) and characterize early, transitional,
characteristics between centers are discussed in the text. Textural and timing
Uncertainties of correlation of porphyries with similar texture and timing

<table>
<thead>
<tr>
<th>Center</th>
<th>Pre-mineral</th>
<th>Syn-mineral</th>
<th>Late intra-mineral</th>
<th>Post-mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerro Pelado</td>
<td>qtz rhyolite &amp; breccia</td>
<td>qtz vns ___ *</td>
<td>(Mo) D vns *</td>
<td>(Au)</td>
</tr>
<tr>
<td>Old Camp</td>
<td>qtz porphyry</td>
<td>A vns ___ *</td>
<td>late qtz porphyry B vns .... D vns ----</td>
<td></td>
</tr>
<tr>
<td>M Gulch</td>
<td>qtz porphyry &amp; f.g. fsp. porph. A vns ___ *</td>
<td>L porphyry igneous breccia A porphyry B vns .... D vns ---- *</td>
<td>R porphyry Latite</td>
<td></td>
</tr>
<tr>
<td>O Nose</td>
<td>qtz porphyry</td>
<td>O porphyry porphyry A vns ___ *</td>
<td>igneous breccia L porphyry A porphyry B vns .... D vns ---- *</td>
<td>Latite</td>
</tr>
<tr>
<td>Turquoise Gulch</td>
<td>qtz porphyry</td>
<td>X porphyry K porphyry A vns ___</td>
<td>L porphyry A porphyry B vns .... D vns ---- *</td>
<td>Latite</td>
</tr>
<tr>
<td>Sector Granito</td>
<td>qtz porphyry</td>
<td>X porphyry K porphyry G porphyry apite A vns ___</td>
<td>L porphyry (?) A porphyry (?) B vns .... D vns ---- *</td>
<td>Latite</td>
</tr>
<tr>
<td>Granite Gulch</td>
<td>Granite Gulch porphyry</td>
<td>Granite Gulch porphyry</td>
<td>Granite Gulch porphyry</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Summary of timing of mineralization relative to intrusive por-
phries in the individual centers. Porphyry units are those shown in Figure 1. Uncertainties of correlation of porphyries with similar texture and timing characteristics between centers are discussed in the text. Textural and timing characteristics of A, B, and D vein types are those defined in the Turquoise Gulch center (Gustafson and Hunt, 1975) and characterize early, transitional, and late stages of mineralization, respectively. Quartz-molybdenite veins at Cerro Pelado are more like A than B veins. Uncertainty of timing of vein types in other centers is also discussed in the text. The stage(s) of mineralization responsible for most of the copper in each center is marked by an asterisk.

Old Camp

Outcropping high-grade oxide copper, on a small hill about
2 km north-northeast of Turquoise Gulch, was the focus of explora-
tion interest in this district during the 1950s. Anaconda’s third drill hole at El Salvador in 1951 was drilled at Old Camp and penetrated 437.4 m of primary mineralization averaging 0.91 percent Cu, but this limited tonnage was soon eclipsed by the higher grade supergene enrichment blanket under Turquoise Gulch (Perry, 1960). Only now, after 40 yr of mine operation, is this resource scheduled for development.

Rocks: Most ore here is hosted by quartz porphyry and is composi-
tionally much closer to Cerro Pelado rhyolite than the granodioritic porphyries in and around Cerro Indio Muerto. Quartz porphyry has prominent phenocrysts of plagioclase, quartz, biotite, and rare K feldspar in an abundant and very fine grained groundmass of microcrystalline quartz with minor sericite. The sericite is derived from biotite and minor K feldspar, which is increasingly abundant in the groundmass at depth. Biotized hornblende phenocrysts are rare. This porphyry has a variable but distinctive texture, characterized by equant, composite-crystal plagioclase, and variably abundant 5- to 10-mm quartz eyes, making it recogniz-able across the district.

The very irregular, arcuate dike that hosts the orebody ap-
pears to be a partial ring dike around the Cerro Pelado cen-
ter. The interpretation that quartz porphyry is closely related to the early rhyolitic volcanism of Cerro Pelado is supported by their similar composition and geometric characteristics, which contrast with the younger granodioritic intrusions (Gustafson and Hunt, 1975), and by dating (see below). This quartz porphyry merges with a discontinuous and irregular dike extending south to Copper Hill and O Nose. More than one intrusive pulse is probably involved, but only in one place has an intrusive contact separating quartz porphyries with dif-
ferent stages of alteration been mapped, and textural differ-
ences cannot be consistently mapped elsewhere. Irregular bodies of tourmaline breccia are more or less associated with contacts of quartz porphyry.

Mineralization: The +0.7 percent Cu primary orebody is an elongate, downward-tapering conical zone cored by disseminated chalcopyrite-bornite with no pyrite outside of late, superimposed D veins and sericitic halos. This zone is sur-
rounded by chalcopyrite-pyrite, which passes outward to pyrite with less than a 1:3 ratio of chalcopyrite:pyrite. The orebody has a diameter of 250 m at the 2,600-m elevation and extends vertically downward for at least 300 m but with decreasing sulfide abundance and grade. Early, granular quartz veins are abundant within the central zone. They are similar to A veins in the Turquoise Gulch orebody but have little K feldspar and are more of an east-west sheeted zone than a stockwork. Their abundance generally increases downward, as disseminated magnetite and hematite-rutile after ilmenite appear disseminated in the porphyry groundmass. The as-
semblage pyrite-bornite is seen only in D veins, which also contain minor molybdenite. Detailed mapping has not yet documented the structural pattern of these veins. Tourmaline breccias contain only barren pyrite.

A strong but laterally restricted supergene enrichment zone, near the present surface and mostly above the 2,600-m elevation (Fig. 4), has largely been oxidized in place to an ore-
body of mostly brochantite, chrysocolla, and Cu wad.

Alteration: The central quartz veined zone is altered to K
feldspar-biotite-rutile, with minor anhydrite at depth. This grades outward to sericite-chlorite with rare anhalite, which fades into the propylitic assemblage of chlorite-epidote-al-
bite-calcite. Sericitic halos on D veins cut all zones. Sup-
gene clay alteration (kaolinite and montmorillonite) and alu-
nite associated with sulfide enrichment and oxidation is variably abundant at surface.

M Gulch-Copper Hill

The open pit in M Gulch is located at roughly 20,500 to
21,500N, 7,750 to 8,400W (local coordinates) in the western part of the composite mineralization center defined in Fig-
ures 2 and 4. It was developed to mine enriched sulfides with grades greater than 1 percent Cu. Anaconda had just begun to explore this area (Hunt, unpub. report, 1965), but the ge-
ology has since been documented by mapping of drill core and pit benches. A special project to document the sulfide
and alteration patterns on the 2,600-m elevation revealed the unity of mineralization in M Gulch, Copper Hill (to the east), and Zone 295 area (to the southeast) as a single center (Castro, 1993; Rojas, 1994). Most recent efforts here have been directed to extending the pit eastward to exploit shallow oxide ore resources in Copper Hill.

Rocks: A steep, northeast-dipping Cretaceous sequence of interbedded andesitic sandstone and lava flows strikes southeast into the area, where biotitic alteration obliterates original textures. Quartz porphyry in two irregular dikes within the pit are clearly cut by L and A felspar porphyry dikes emanating from the intrusive complex of Copper Hill. In both these dikes and the larger body of quartz porphyry east and south of Copper Hill, there is considerable textural variation that could indicate multiple pulses of intrusion, but no definitive contacts have been found. Because of similarities in texture to quartz porphyry at Old Camp, irregular dike shape, and a relative age older than all granodioritic porphyries, this quartz porphyry is considered to be contemporaneous with rhyolites at Cerro Pelado and Old Camp. An extension of the earliest fine-grained O porphyry extends discontinuously from O Nose to Zone 295. Within the felspar porphyry mass mapped as L porphyry, there is considerable textural variation that has not been documented but appears very analogous to that of L porphyry in Turquoise Gulch (Gustafson and Hunt, 1975). Although it is always hazardous to correlate between completely separate intrusive bodies, the similarities in texture, intrusive sequence, mineralization and/or alteration, and age with L porphyry (Tables 2 and 3, Fig. 8) are so close that the dominant porphyry in Copper Hill is probably the same as L porphyry or a very closely related intrusive unit. There is also some finer grained felspar porphyry that is better mineralized, probably older than the main mass, and analogous to K porphyry in Turquoise Gulch. This fine-grained porphyry is cut by dikes of igneous breccia and A porphyry, but clear contacts with L porphyry have not been seen (Olivares, unpub. report, 1995), and this rock is lumped in with L porphyry in Figure 1. A minor component of the Copper Hill mass is mapped as A porphyry. It has textural variations similar to A porphyry in Turquoise Gulch, largely characterized by afeldsparic groundmass with small plagioclase laths and biotite but no K feldspar. A porphyry clearly cuts L porphyry in numerous small dikes not shown in Figure 1, and the bulk of the A porphyry occurs as the matrix to the igneous breccia with L porphyry clasts.

The large, clast-supported M Gulch breccia in the western part of the pit has angular to subrounded clasts of andesite, up to several meters across. The matrix consists of coarse pyrite and chlorite (after biotite) in deepest exposures. A very late age is confirmed by D veins in clasts truncated by matrix and by postmineral Latite dikes that cut the breccia but also appear to be fragmentated by it. On the lowest benches, the breccia is intruded by a distinctive porphyry called R porphyry, which contains only trace pyritic mineralization and is probably responsible for the formation of the breccia. The breccia appears to have been formed by collapse and accompanying hydrothermal activity. R porphyry is superficially similar to L porphyry, with plagioclase, hornblende, and rare biotite phenocrysts in an aplitic groundmass. However, there is an abundance of ±1-mm diameter round quartz grains in the groundmass, and it is younger than mineralization.

Mineralization: The northwest edge of >0.2 percent Cu (Fig. 4) is chalcopyite precipitated on extremely low grade pyritic protore. Better protore grades are confined to chalcopyrite-pyrite and chalcopyrite-bornite areas, which correspond to quartz porphyry and adjacent andesite and fringe the feldspar porphyry complex that has a very low sulfide content. Early A quartz veins are abundant in the quartz porphyry and adjacent andesite in the pit and to a lesser extent in the quartz porphyry dikes to the east and southeast. They also occur locally in fine-grained feldspar porphyry. These veins are locally truncated by L and A porphyry dikes and are virtually absent, as are the accompanying sulfides, in the L and A porphyry of the Copper Hill complex. Probably the earliest veins in granodioritic porphyry are veinlets of actinolite-magnetite with minor quartz, pyrite, chalcopyrite, chlorite, and K feldspar, which are fairly common in O porphyry. These are not seen in other porphyries, but definitive truncation by younger intrusion has not been reported. Except for rare, barren quartz-K feldspar and actinolite veins similar to those seen in L porphyry in Turquoise Gulch, the only veins in L and A porphyries and the igneous breccia are transitional B quartz-molybdenite veins and late D veins. These are clearly intramineral intrusions that have removed much of the original center in a manner analogous to the Turquoise Gulch center (Gustafson and Hunt, 1975). Good grade extends to depth in the quartz porphyry in the zone 295 area to the south, but unfortunately, recent drilling of the bornite zone on the east side of Copper Hill has revealed mostly pyritic waste, especially closer to the surface. Relict bornite grains locked in quartz reveal the continuity of the original bornite zone and indicate that copper has been leached by late hydrothermal activity around the cooling feldspar porphyry.

Several large D veins, with strike lengths greater than 100 m and widths up to 1.5 m, cut the feldspar porphyries. They contain high-grade pyrite-bornite-digenite, which with supergene enrichment and lateral migration during oxidation has made significant tonnages of oxide ore. The veins occupy a strong north-south to north-northwest structural trend (Fig. 6), which does not fit either the radial pattern shown by the D veins in Turquoise Gulch or the regional northwest and northeast trends.

Alteration: Andesite near the quartz porphyry was intensively altered to biotite-albite-quartz-anhydrite and the porphyry altered to strong K feldspar-quartz with quartz veining. The older fine-grained feldspar porphyry was similarly altered. Secondary biotite after hornblende is also developed in L and A porphyries, but the intensity of alteration is much less in these rocks than in adjacent andesite and quartz porphyry, a fact not evident in Figure 3. There is practically no secondary K feldspar in either L or A porphyries, and at greater depth residual hornblende and sphene are preserved. Hornblende in R porphyry was also not biotitized but was largely replaced directly by chlorite. Sericite-chlorite accompanies the surrounding pyrite, with minor andalusite and tourmaline, and gives way outward to propylitic alteration defined by epidote and calcite with the chlorite. Sericite halos accompany late D veins, and clay alteration is associated with supergene enrichment and oxidation at higher elevations.
Fig. 8. Summary geochronology diagram for the Indio Muerto district. The $^{40}$Ar/$^{39}$Ar results are from this study (Table 2). The $^{40}$Ar/$^{39}$Ar age shown (●) is the isochron age with ±1σ error bars. Comparable dates from Cornejo et al. (1997b, Table 3) are also shown. K-Ar ages (♦) are plotted here with ±1σ error bars. U-Pb ages (—) are concordia intercept ages. Also plotted are unpublished Re-Os dates on B vein molybdenite (★) from Watanabe et al. (1999). Within each center, samples are plotted in the order of decreasing geologic age based on field relationships.
O Nose

The O Nose ore zone lies within the north-central portion of the main Turquoise Gulch porphyry body, but it was developed for production only after Anaconda's departure and was not described by Gustafson and Hunt (1975). An early study by Eckstrand (unpub. company report, 1969) was based on limited drill core and surface exposures, but because of lack of geologic continuity and operational priorities during the years following 1971, and subsequent loss of access, it remains the best description available. The patterns presented in Figures 1 through 6, however, are interpreted from subsequent routine mapping and sampling of mine workings.

 Rocks: Quartz porphyry forms a thick sill at the unconformity between Cretaceous andesite and pyroclastic rocks at the base of the overlying rhyolitic dome sequence, well above the 2,600-m level. It is cut by a fine-grained, equigranular porphyry called O porphyry, with a texture similar to X porphyry. O porphyry occupies a similar position as the earliest of the granodioritic intrusions and is lumped with X porphyry in Figure 1. A distinctive porphyry forms the approximate center of mineralization in O Nose. It is characterized by a relatively coarse grained aplitic groundmass of quartz and perthitic K feldspar, which usually contains abundant small (±2-mm) quartz phenocrysts. It is named quartz grain, or QG porphyry. It is well mineralized and clearly intruded by L porphyry. Although A quartz veins are less abundant than in K porphyry of Turquoise Gulch, QG porphyry is similar and was mapped as "late K" during development of the mining blocks. However, Eckstrand (1969) has documented on surface a B quartz vein in QG porphyry truncated at the contact of L porphyry. As B veins, in both Turquoise Gulch and M Gulch-Copper Hill centers, evolved only after intrusion of L porphyry, this B vein is probably related to an earlier center of mineralization—probably in O Nose and related to QG porphyry itself. A large body of igneous breccia contains fragments of andesite, quartz porphyry, QG porphyry, and L porphyry. The matrix is a mafic-rich, feldspathic groundmass porphyry similar to A porphyry, but several dikes of A porphyry cut the igneous breccia and older rocks.

Brecciation is abundant in andesite at the contact of the igneous breccia, L porphyry, and northwest-trending structural zones cutting the intrusions. One larger breccia dike has a vuggy matrix with drusy quartz, coarse pyrite, variable chalcopyrite, and local specular hematite. A small tourmaline breccia pipe cuts O porphyry to the northeast. A series of Latite dikes occupy northwest-trending faults between O Nose and M Gulch. As described and interpreted in Gustafson and Hunt (1975), these are postmineralization and were emplaced into the surficial hot spring that produced advanced argillic alteration and was the final phase of the porphyry copper system. The Latite dikes are responsible for the formation of pebble dikes. They are really andesite by petrographic criteria, but the name Latite has been used for more than 40 yr and has been retained to preserve continuity. Similar swarms of discontinuous Latite dikes occupy northwest fault zones between Copper Hill and Old Camp and between Turquoise Gulch and Sector Granito.

Mineralization: Chalcopyrite with outwardly increasing pyrite forms two zones of highest primary grade. These are centered on the QG porphyry and the brecciated andesite at the intrusive contacts. Only traces of bornite are seen in chalcopyrite of O Nose itself, but a low-intensity bornite-chalcopyrite zone is located to the west in contact andesite, under the old Red Hill orebody, and extending into L porphyry (Fig. 2). An outer chalcopyrite-pyrite zone wraps around the L porphyry contact and connects Red Hill with O Nose. Vertical zonation is very abrupt and strong in Red Hill. Pyrite increases upward, producing pyrite-bornite-chalcopyrite with "reaction textures" (Gustafson and Hunt, 1975, fig. 25). This primary zonation combined with strong supergene chalcocite enrichment produces high grades over very low grade protore. Similar vertical zonation is evident but not as well developed in O Nose itself, where strong supergene enrichment also made low-grade protore economic. Quartz veining is sparse in O Nose, mainly B quartz-molybdenite veins that also cut the L and A porphyries. D veins locally contain quartz and are relatively abundant. Minor enargite, both in D veins and breccias, is more abundant here than in all but the south-eastern part of the Turquoise Gulch orebody. The radial pattern of D veins continues across both O Nose and Turquoise Gulch ore zones, with an apparent center in L porphyry at 20,320N to 8440W (Fig. 6). This is also one of two centers of the radial-concentric pattern of pebble dikes on surface (Langerfeld, unpub. report, 1964; Gustafson and Hunt, 1975, fig. 4A). The other pebble dike center is in the south-east lobe of the L porphyry at 19,820N to 8035W.

Alteration: K feldspar-biotite alteration is well developed in QG porphyry and andesite is intensely biotized. In late L and A porphyries, this alteration is weak and evidenced primarily by biotite replacement of hornblende. Chlorite-sericite and sericite are strongly developed as outer zones and along structures. Andalusite occurs with sericite in the highly pyritic fringe developed in O porphyry and andesite, adjacent to ore in the andesite contact breccia. Vertically above and in structural zones cutting the sericite-andalusite, pyrophylilite and diaspore with local coarse-grained primary alunite are developed. There is a strong overprint of kaolinite, fine-grained alunite, and minor montmorillonite associated with supergene sulfide enrichment. Andalusite is altered to diaspore and amorphous material.

Sector Granito

Before 1976, only weak chalcocite enrichment had been found developed on the high elevation top of sulfide south of the main Turquoise Gulch orebody. By 1978, enough +1 percent Cu ore had been developed to open a new extension of the mine, named Sector Granito because it underlies the north end of Granite Gulch (Quiroga, unpub. report, 1978). The name Granite Gulch is reserved for the intrusive center exposed even farther southwest in Granite Gulch itself. Although high-elevation chalcocite enrichment connects Sector Granito with the main orebody, it is clearly a separate center of mineralization. This is best illustrated by the patterns of intrusion, sulfide, and alteration zoning (Figs. 1–3). The center is also clearly shown by the Cu pattern (Fig. 4) and partially flanked by anomalous Mo (Fig. 5). Because the lowest elevation in Sector Granito with mine workings and abundant drill penetration is 2,660 m, these maps are extended southward at this elevation. Rock and alteration types are rather
different from those established in the main orebody, and careful mapping supported by petrography and X-ray diffraction that is required to resolve many of the questions has yet to be completed.

Rocks: Rhyolitic pyroclastic rocks, which are the basal part of the Paleocene Indio Muerto dome complex overlying Cretaceous andesite, occur at the 2,660-m elevation here (Fig. 1), the result of gentle southwest tilting of the section during the late stages of caldera formation (Cornejo and Mpodozis, 1998). Several irregular feeder dikes for the overlying rhyolitic dome complex also occur in the area. The large mass of rock mapped as X porphyry, extending south from Turquoise Gulch, has a varied texture and could comprise different intrusive units, but definitive contacts have not been seen. Biotite X porphyry has a fine-grained equigranular texture with euhedral plagioclase, biotite, and (biotized) hornblende phenocrysts in a coarse mosaic matrix of K feldspar, quartz, and biotite. Granite X porphyry usually has less euhedral phenocrysts, only about 5 volume percent biotite compared to 15 to 20 percent for biotitic X porphyry, and perthitic K feldspar replacing both plagioclase and biotite. Several bodies mapped as aplite are unique to Sector Granito. They are white, equigranular alkali feldspar-quartz rocks, mostly perthitic orthoclase with only traces of biotite. They are more or less altered to sericite, andalusite, cordum, rutile, and trace fuchsite and green tourmaline (E. Tidy, pers. commun., 1998). Aplite is cut by dikes of feldspar porphyry but appears to have gradational contacts with X porphyry. It may be a separate intrusion or a product of extreme alteration of X porphyry.

A variety of feldspar porphyries occur with a range of textures very similar to L and K porphyries in the main orebody but with different timing relative to mineralization. Rock mapped as K porphyry has texture and intensity of A quartz veining and K feldspar-biotite alteration similar to relatively late K porphyry intrusions in the southeast part of the main orebody. An irregular porphyry body to the south looks superficially like L porphyry but has more abundant A veins and more intense K feldspar-biotite alteration and disseminated mineralization than the K porphyry. It is more or less central to the zonal pattern and has been named G porphyry. Isolated dikes of nearly fresh and unmineralized porphyry, indistinguishable from L and A porphyries elsewhere in the mine, are also seen. A series of more or less continuous Latite dikes occupy northwest-trending faults at the northeast edge of this area.

Mineralization: The familiar zonal pattern of disseminated chalcopyrite-bornite grading outward to chalcopyrite-pyrite and then to pyrite is well developed within the mine workings. However, closure has not been documented to the south, where grades appear to be lower. The pattern is centered on the zone of K feldspar-biotite alteration in G and X porphyries and aplite, where early A quartz veins are abundant. Transitional B quartz-molybdenite veins, with no alteration halos and late D veins with sericitic halos and pyritic sulfide assemblages, are well developed. Primary grades and intensity of supergene enrichment is rather variable, with controls poorly understood. Pyrite abundance increases markedly upward in assemblages of pyrite-bornite-chalcopyrite or pyrite-bornite-digenite with reaction textures. As elsewhere at high elevations above the main orebody, sulfide intervals are locally overwhelmingly pyritic, whereas tiny sulfides locked in quartz in these intervals and as relict sulfide in adjacent oxidized intervals have a much higher ratio of copper sulfides to pyrite. This situation is commonly seen in rhyolitic rocks altered to advanced argillic assemblages and was interpreted by Gustafson and Hunt (1975) as partial hypogene leaching of primary copper from these areas. Ore grades in this center are due almost entirely to supergene enrichment. The elevations of the top of sulfide and the bottom of strong enrichment are widely variable across the area.

Alteration: The most distinctive feature of Sector Granito is the intensity and variability of K feldspar-biotite alteration in the different intrusions. Although not studied in detail, the gradation between biotitic and granitic X porphyry in at least some areas is due to early hydrothermal alteration rather than to magmatic variation. Where most intense, perthitic K feldspar replaces plagioclase and biotite and results in a rock that resembles an aplite. Why this alteration is accompanied by abundant disseminated chalcopyrite-bornite in some areas but only trace sulfide in others remains a puzzle. Similar texture-destructive alteration affects rhyolitic intrusions and pyroclastic rocks, and at high elevations andalusite is commonly part of this assemblage. Less intense early alteration of the feldspar porphyries preserves texture and is manifested by replacement of hornblende by biotite and minor K feldspar replacement of plagioclase. Sericitic alteration, mostly without chlorite, is associated with late pyritic veining and surrounds and overlies the central zone. At higher elevations, pyrophyllite and diaspore are abundant, apparently formed by the replacement of sericite and andalusite.

Granite Gulch

The granodioritic porphyry intrusion cropping out in Granite Gulch looks very similar to the variant of L porphyry with relatively little aplite groundmass. It is a fresh rock, practically devoid of mineralization. Even though biotite alteration of andesite a few meters wide occurs at its contact, hornblende in the porphyry is not biotized. It lies beyond the southern limit of effects of the Sector Granito center of mineralization. Unfortunately, age relationships from the few contacts penetrated by diamond drilling between this Granite Gulch porphyry and X porphyry have not been determined. Radiometric age dating indicates that this is the oldest granodioritic intrusive center.

Radiometric Dating

Mineralization centers at Old Camp and Turquoise Gulch were first dated at about 46 and 41 Ma, respectively, by K-Ar and Rb-Sr (Gustafson and Hunt, 1975). In this study we have attempted to define more closely the sequence and duration of the individual events with 40Ar/39Ar geochronology. Sample locations and descriptions are given in Table 1. Age spectra and isochron diagrams for all samples are presented in the Appendix; ages are reported at ±1σ. Concurrent district mapping by SERNAGEOMIN geologists was supported by an extensive program of K-Ar and U-Pb geochronology throughout the region. Comparable ages for magmatic and alteration events at El Salvador from this program are summarized in Table 3 and Figure 8. Not included in this table are ages of older volcanic events (Cornejo et al., 1997b), which indicate...
that the rhyolitic dome complex on Cerro Indio Muerto was emplaced at 58 to 60 Ma, about 10 m.y. prior to the previous 50 Ma Rb-Sr date (Gustafson and Hunt, 1975).

Procedures:

Samples for this study were selected by Gustafson and Orquera to provide optimum geologic control and thin section evaluation. Mineral separations were done at the El Salvador laboratory, using procedures used by Marsh et al. (1997), which contains a detailed discussion of the techniques of sample preparation, analytical methods, and data analysis.

The ages listed in Table 2 include the following:

1. Total fusion age: The age calculated by summing all the gas fractions released during stepwise heating. Total-fusion ages approximate the conventional K/Ar age that might be expected from the same sample.

2. Weighted mean plateau age: The weighted mean of three or more contiguous and concordant ages measured during stepwise heating, whose collective 39Ar represents at least 50 percent of the total 39Ar released. The steps defining the plateau are shaded on the age spectrum plots (App.).

---

### Table 1. Location and Description of 40Ar/39Ar Samples

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D489-91m</td>
<td>20,110N, 8291W, 2,710 m</td>
<td>O Nose feldspar porphyry (L), secondary biotite and books</td>
</tr>
<tr>
<td>D1203-147.6</td>
<td>22,160N, 7075W, 2,577 m</td>
<td>Old Camp quartz porphyry, biotite books</td>
</tr>
<tr>
<td>D2371-193m</td>
<td>20,850N, 7462W, 2,750 m</td>
<td>M Gulch, biotized andesite adjacent to quartz porphyry</td>
</tr>
<tr>
<td>ES12604</td>
<td>19,301N, 8172W, 2,658 m</td>
<td>Kporphyry, sericite alteration, leached capping</td>
</tr>
<tr>
<td>ES12582</td>
<td>19,700N, 7850W, 2,430 m</td>
<td>Kfeldspar-biotite altered M Gulch quartz porphyry, fresh biotite books</td>
</tr>
<tr>
<td>ES12152</td>
<td>19,705N, 8420W, 2,660 m</td>
<td>Kfeldspar-biotite altered M Gulch quartz porphyry</td>
</tr>
<tr>
<td>ES12158</td>
<td>21,185N, 7911W, 2,640 m</td>
<td>Kfeldspar-biotite altered M Gulch quartz porphyry, fresh biotite books</td>
</tr>
<tr>
<td>ES12471</td>
<td>22,955N, 6665W, 2,810 m</td>
<td>Sericite halo in County Pelado rhyolite porphyry</td>
</tr>
<tr>
<td>ES12162</td>
<td>21,128N, 7916W, 2,640 m</td>
<td>Sericite halo in M Gulch quartz porphyry</td>
</tr>
<tr>
<td>ES12163</td>
<td>21,128N, 7916W, 2,640 m</td>
<td>Sericite halo in M Gulch quartz porphyry</td>
</tr>
<tr>
<td>ES12165</td>
<td>22,955N, 6665W, 2,510 m</td>
<td>Sericite halo in County Pelado rhyolite porphyry</td>
</tr>
<tr>
<td>ES12470</td>
<td>19,215N, 7850W, 2,675 m</td>
<td>Sericite halo in M Gulch quartz porphyry, fresh biotite books</td>
</tr>
</tbody>
</table>

Coordinates are local mine coordinates shown in Figures 1 through 6

1 Denotes surface sample, other samples are from underground workings and drill holes

---

### Table 2. El Salvador 40Ar/39Ar Ages

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>Description</th>
<th>TFA (Ma)</th>
<th>WMPA (Ma)</th>
<th>WMA (Ma)</th>
<th>IA (Ma)</th>
<th>40Ar/39Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>D489-91</td>
<td>Biotite</td>
<td>O Nose feldspar porphyry (L)</td>
<td>40.60 ± 0.18</td>
<td>40.80 ± 0.18</td>
<td>40.80 ± 0.18</td>
<td>285 ± 17</td>
<td></td>
</tr>
<tr>
<td>D1203-147.6</td>
<td>Biotite</td>
<td>Old Camp quartz porphyry, biotite books</td>
<td>43.82 ± 0.32</td>
<td>44.53 ± 0.14</td>
<td>43.83 ± 0.19</td>
<td>266 ± 69</td>
<td></td>
</tr>
<tr>
<td>D2371-193</td>
<td>Biotite</td>
<td>M Gulch biotized andesite</td>
<td>41.39 ± 0.42</td>
<td>41.54 ± 0.42</td>
<td>41.43 ± 0.44</td>
<td>357 ± 69</td>
<td></td>
</tr>
<tr>
<td>ES12604</td>
<td>Sericite</td>
<td>Turquoise Gulch sericite K porphyry</td>
<td>40.04 ± 0.87</td>
<td>40.84 ± 0.46</td>
<td>40.92 ± 0.51</td>
<td>294 ± 4</td>
<td></td>
</tr>
<tr>
<td>ES12471</td>
<td>Hornblende</td>
<td>Granite Gulch feldspar porphyry</td>
<td>42.10 ± 0.14</td>
<td>42.26 ± 0.12</td>
<td>42.32 ± 0.24</td>
<td>293 ± 7</td>
<td></td>
</tr>
<tr>
<td>ES12152</td>
<td>Biotite</td>
<td>Granite Gulch feldspar porphyry</td>
<td>43.12 ± 0.12</td>
<td>42.98 ± 0.09</td>
<td>42.86 ± 0.14</td>
<td>298 ± 7</td>
<td></td>
</tr>
<tr>
<td>ES12470</td>
<td>Sericite</td>
<td>Crystaline, in quartz-alunite altered rhyolite</td>
<td>35.51 ± 1.70</td>
<td>35.85 ± 1.59</td>
<td>34.57 ± 3.69</td>
<td>307 ± 13</td>
<td></td>
</tr>
<tr>
<td>ES12162</td>
<td>Sericite</td>
<td>Crystaline, in quartz-alunite altered rhyolite</td>
<td>35.4 ± 16.6</td>
<td>43.9 ± 1.3</td>
<td>43.5 ± 3.7</td>
<td>305 ± 101</td>
<td></td>
</tr>
<tr>
<td>ES12471</td>
<td>Sericite</td>
<td>Crystaline, in quartz-alunite altered rhyolite</td>
<td>35.51 ± 1.70</td>
<td>35.85 ± 1.59</td>
<td>34.57 ± 3.69</td>
<td>307 ± 13</td>
<td></td>
</tr>
<tr>
<td>ES12152</td>
<td>Sericite</td>
<td>Crystaline, in quartz-alunite altered rhyolite</td>
<td>35.51 ± 1.70</td>
<td>35.85 ± 1.59</td>
<td>34.57 ± 3.69</td>
<td>307 ± 13</td>
<td></td>
</tr>
<tr>
<td>ES12471</td>
<td>Sericite</td>
<td>Crystaline, in quartz-alunite altered rhyolite</td>
<td>35.51 ± 1.70</td>
<td>35.85 ± 1.59</td>
<td>34.57 ± 3.69</td>
<td>307 ± 13</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: TFA = total fusion age, WMPA = weighted mean plateau age, WMA = weighted mean age,IA = isochron age; errors ±1 σ; altd. = altered, books = euhedral phenocrysts, porph. = porphyry, qtz. = quartz, 40Ar/39Ar = trapped 40Ar/39Ar ratio calculated from least mean square linear isochron fit; air is 295 ± 16

1 El Salvador mine sample identification
3. Weighted mean age: The conditions which define a formal plateau age are not met in samples where steps comprising what would otherwise define a plateau age represent less than half the total 39Ar released or where one or more steps are not concordant. In these cases we have calculated a weighted mean age from the shaded steps in the release spectra presented in the Appendix.

4. Isochron age, the age calculated by fitting a straight line through the points which define the plateau (as described above) on a plot of 36Ar/40Ar versus 39Ar/40Ar. The 39Ar/40Ar intercept can be used to estimate the age, whereas the 36Ar/40Ar intercept can be used to estimate the isotopic composition of the trapped nonradiogenic Ar. Values of 39Ar/40Ar significantly greater than 295.5 (air) suggest the presence of excess 40Ar. Whereas the isochron ages invariably have less precision than the weighted mean plateau ages, they are more accurate (if less precise), we have plotted only these in Figure 8 and use them in our discussion, unless otherwise noted.

Discussion

44 Ma events: The fine-grained quartz rhyolite porphyries of Cerro Pelado and the coarser quartz porphyry that extends from the Old Camp to Turquoise Gulch have long been interpreted as related to the same volcanic period. The partial ring dike and radial dike form of the Old Camp quartz porphyry closely link it structurally and compositionally to the ap proximately equivalent lithologic sequence adjacent to the large quartz porphyry dike southeast of M Gulch (samples ES12163 and ES12604) and secondary biotite in andesite adfams from quartz porphyry dikes in M Gulch (samples ES-12163 and ES12604) and secondary biotite in andesite adjacent to the large quartz porphyry dike southeast of M Gulch.

Table 3. Comparable Dates Reported by Cornejo et al. (1997b) for comparative purposes

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Description</th>
<th>Method</th>
<th>Date (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerro Pelado</td>
<td>Quartz-sandstone rhyolite porphyry</td>
<td>Zircon, U-Pb</td>
<td>43.1 ± 1</td>
</tr>
<tr>
<td>IT-3</td>
<td>Quartz-sandstone rhyolite porphyry</td>
<td>Sanidine-(altered plagioclase), K-Ar</td>
<td>45.3 ± 1.0</td>
</tr>
<tr>
<td>ES-7458</td>
<td>Quartz-sandstone rhyolite porphyry</td>
<td>Whole rock, K-Ar</td>
<td>42.1 ± 0.6</td>
</tr>
<tr>
<td>IP-11</td>
<td>Sericite-sandstone rhyolite porphyry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Old Camp</td>
<td>Quartz porphyry</td>
<td>Zircon, U-Pb</td>
<td>43.1 ± 1 or 42.3 ± 1.3</td>
</tr>
<tr>
<td>IT-5</td>
<td>Quartz porphyry</td>
<td>Whole rock, K-Ar</td>
<td>43.9 ± 0.8</td>
</tr>
<tr>
<td>IP-10</td>
<td>Whole rock, K-Ar</td>
<td>Sericite, K-Ar</td>
<td>42.1 ± 1.3</td>
</tr>
<tr>
<td>IP-6025B</td>
<td>Quartz porphyry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M Gulch-Copper Hill</td>
<td>Feldspar porphyry (L)</td>
<td>Biotite, K-Ar</td>
<td>41.3 ± 0.7</td>
</tr>
<tr>
<td>ES-12337</td>
<td>Feldspar porphyry (L)</td>
<td>Biotite, K-Ar</td>
<td>41.2 ± 0.7</td>
</tr>
<tr>
<td>ES-12338</td>
<td>Feldspar porphyry (L)</td>
<td>Biotite, K-Ar</td>
<td>41.3 ± 0.7</td>
</tr>
<tr>
<td>IP-45</td>
<td>Feldspar porphyry (A)</td>
<td>Biotite, K-Ar</td>
<td>43.5 ± 0.6</td>
</tr>
<tr>
<td>ES-6136</td>
<td>Cu Hill feldspar porphyry (A)</td>
<td>Biotite, K-Ar</td>
<td>41.6 ± 0.9</td>
</tr>
<tr>
<td>Turquoise Gulch</td>
<td>X porphyry</td>
<td>Zircon, U-Pb</td>
<td>41 ± 2 or 41.8 ± 2.3</td>
</tr>
<tr>
<td>IT-10</td>
<td>X porphyry</td>
<td>Biotite, K-Ar</td>
<td>41.6 ± 0.6</td>
</tr>
<tr>
<td>IT-9</td>
<td>X porphyry</td>
<td>Zircon, U-Pb</td>
<td>41 ± 2</td>
</tr>
<tr>
<td>IT-9</td>
<td>L porphyry</td>
<td>Biotite, K-Ar</td>
<td>41.2 ± 0.6</td>
</tr>
<tr>
<td>ES-3256</td>
<td>L porphyry</td>
<td>Sericite, K-Ar</td>
<td>41.9 ± 0.5</td>
</tr>
<tr>
<td>ES-4269</td>
<td>L porphyry</td>
<td>Biotite, K-Ar</td>
<td>42.0 ± 0.5</td>
</tr>
<tr>
<td>Granite Gulch</td>
<td>Granite Gulch porphyry</td>
<td>Hornblende, K-Ar</td>
<td>43.2 ± 1.3</td>
</tr>
<tr>
<td>ES-3853</td>
<td>Granite Gulch porphyry</td>
<td>Biotite, K-Ar</td>
<td>43.1 ± 0.6</td>
</tr>
<tr>
<td>ES-3853</td>
<td>Granite Gulch porphyry</td>
<td>Biotite, K-Ar</td>
<td>43.1 ± 0.6</td>
</tr>
</tbody>
</table>

Originally reported ±2σ errors converted to 1σ for comparative purposes

1 Recalculated dates from Gustafson and Hunt (1975)
(sample D2371-193m) were expected to give a similar age but instead yielded all different and significantly younger ages (Table 2, Fig. 8). This quartz porphyry was intruded by the L porphyry complex yielding 41 to 42 Ma ages (samples D2371-193m, ES12337, and ES12338). Even though there is no evidence in the age spectra, we interpret these $^{40}\text{Ar}^{39}\text{Ar}$ ages to have been reset by temperatures greater than 300° to 325°C because of their proximity to the massive feldspar porphyry intrusion and hydrothermal alteration of the main 41 to 42 Ma period. Such evidence would not be expected from biotite as it is not a feldspar-like geochronometer with different diffusion domains. Our failure to find quartz porphyry outside of Old Camp yielding a similar age means that the interpretation of a single period of intrusion and mineralization of quartz porphyry is suspect, in that it relies primarily on petrographic evidence and relative age relationships, which are nondefinitive. Further dating is required to resolve this question.

Sericitic from an alteration halo in a D-type goethite vein at the surface of Cerro Pelado (sample ES12165) yielded an age of 43.94 ± 0.75 Ma and appears also to have been formed during this same event. A similar conclusion that D veininge at Cerro Pelado is closely timed relative to intrusion was reached by Gustafson and Hunt (1975), based on an Rb-Sr date of 46.1 ± 0.5 Ma on sericite. However, other Rb-Sr dates on Indio Muerto rhyolite domes appear to have been seriously affected by younger alteration (Cornejo et al., 1997b), and this age is not reliable. The whole-rock K-Ar age of 42.1 ± 0.8 Ma on sericite-altered Cerro Pelado rhyolite (IP-11, Table 3) indicates that sericite was also formed this far north during the 42 to 41 Ma period of hydrothermal events farther south.

Sericitic alteration of quartz porphyry at Old Camp apparently also occurred in the 41 to 42 Ma interval. The high-temperature heating steps of sample ES6010 (Fig. 8, Table 2, App.) yield an isochron age of 41.56 ± 0.32 Ma with a somewhat anomalous $^{40}\text{Ar}^{39}\text{Ar}$ ratio. The low-temperature steps yield a 42.60 ± 0.87 Ma isochron but with a very high $^{40}\text{Ar}^{39}\text{Ar}$ ratio, indicating the presence of excess $^{40}\text{Ar}$. The combination indicates that the sericite formed at about 41.6 Ma in an older rock from which radiogenic Ar was not completely expelled. Also, the 43.04 ± 0.78 Ma age of a sericite alteration biotite contributed to the dated sample, so the 41.54 ± 0.45 Ma probably dates alteration of L porphyry rather than intrusion or alteration of the main-mineralizing QG porphyry.

Watanabe et al. (1999) have obtained Re-Os ages of 42.0 ± 0.2 and 42.2 ± 0.2 Ma on two samples of molybdenite from B veins under the Turquoise Gulch orebody. Because this transitional stage of mineralization formed as the L porphyry cooled enough to sustain the first continuous fracturing, probably within 100,000 yr of emplacement (Norton and Cathles, 1979), 42.2 ± 0.2 Ma is also as good a date as any for the intrusion of L porphyry.

Latite dikes were intruded throughout the district at the end of primary mineralization, during the final stage of hydrothermal activity. Thus, the end of magmatic activity and primary mineralization is defined by the 41.16 ± 0.24 Ma isochron age of Latite biotite phenoocrysts in sample ES12152. This age is slightly younger than the former K-Ar date on Latite biotite (sample ES4269; Table 3, Fig. 8) but not significantly different at a 2σ error.

Slightly younger ages of secondary biotite and of sericite in D vein halos in Sector Granito (samples ES12471 and ES12470) raise the possibility that this center evolved later than the others. However, these ages are not considered to be definitive because (1) they are younger than another sericite age (sample ES12065) also in Sector Granito X porphyry; (2) there is no indication of younger sericitic alteration in Latite dikes on the northeast edge of the Sector Granito; and (3) these samples are from an area affected by supergene alteration and chalcocite enrichment, even though the samples themselves are free of supergene minerals. They may have undergone minor loss of radiogenic Ar. If this is a valid conclusion, there is no indication of any discernible difference in age or systematic migration of the centers of mineralization associated with granodioritic porphyries. Considering all the ages, it appears that the best age for the intrusion of Latite and the end of hydrothermal activity in the district is 40.9 Ma. Taking the molybdite ages to indicate the earliest events and the Latite age as the youngest event, this period of mineralization can be interpreted to have lasted 1.4 my., from 42.3 to 40.9 Ma, as indicated by shading in Figure 8. This brackets events in the Turquoise Gulch center and apparently also throughout the district.

The age of earliest granodiorite porphyry intrusion within the mineralized centers is poorly defined. Zircon U-Pb and biotite K-Ar ages on the oldest X porphyries, and even the relatively young L porphyry, have large uncertainties and may be

41 to 42 Ma events: Although our sampling was unsuccessful in confirming the correlation of the quartz porphyry and associated mineralization in M Gulch in the 44 Ma period, our results indicate that at least the last major thermal event in the area occurred in the 42 to 41 Ma period. K-Ar ages by SERNAGEOMIN of two L-type feldspar porphyries and one A porphyry in Copper Hill (Table 3, Fig. 8) are compatible with the geologic correlation of these units with similar rocks in Turquoise Gulch and their age of about 41 to 42 Ma. The only unaltered biotite found in O Nose (sample D489-91m) was from a drill hole in the contact area between the QG and L porphyries. It was interpreted to be from the older porphyry, but rock textures are not diagnostic and correlations in this area are not well established. Both phenocyst and alteration biotite contributed to the dated sample, so the 41.54 ± 0.45 Ma probably dates alteration of L porphyry rather than intrusion or alteration of the main-mineralizing QG porphyry.
as old as 43.0 Ma (Table 3, Fig. 8). While the equigranular porphyries are clearly the first intruded into the mineralized centers, and at least in the Turquoise Gulch center, some mineralization was associated with X porphyry; their ages relative to the 43 to 42 Ma Granite Gulch porphyry have not been established. In that equigranular intrusions are the earliest seen in many porphyry copper districts, it seems most likely that the intrusion age of X porphyry is close to 43 Ma. The hydrothermal biotite age of sample ES12471 (Table 2, Fig. 8) is younger than even relatively later sericite (sample ES12065) and has clearly been disturbed.

Sample ES3853 is from the unaltered and unmineralized feldspar porphyry in Granite Gulch, some 400 m south of the Sector Granito mineralized zone (Fig. 1). The biotite and hornblende $^{40}$Ar/$^{39}$Ar ages are somewhat unusual, in that the hornblende gives a younger date than the biotite, but the intrusion cooled between 42.1 and 43.0 Ma (Fig. 8, Table 2). The old K-Ar dates on this same sample (Table 3, Fig. 8) agree with this age within $\pm 1\sigma$ uncertainty. The dating indicates that this granodioritic intrusion was emplaced no later than 0.5 m.y. after the end of rhyolitic volcanism and associated mineralization at about 43.5 Ma, before the intrusion of any of the mineralized stocks. As such, it is analogous with the early barren stocks at Cerro Silica and Cerro Bochinche in the Potrerrillos district (Marsh et al., 1995).

Sample IP45, collected and dated by SERNAGEOMIN (Comejo et al., 1997b; Table 3), is a porphyry from the M Gulch pit. In thin section the sample has the typical and very distinctive texture of biotized A porphyry, which is common in both M Gulch and Turquoise Gulch. Geologic relationships of this sample are not reported, but all other geologic evidence recorded to date indicates that A porphyry is younger than all but the youngest phases of L porphyry, both in M Gulch and Turquoise Gulch. The 43.8 $\pm$ 1.2 Ma date is thus a problem. This could be an intrusion contemporaneous with the Granite Gulch porphyry, but it is puzzling that we have found no mappable evidence of older A porphyry in this area.

**Supergene events:** As an adjunct to the broader $^{40}$Ar/$^{39}$Ar dating study, a small group of samples was selected with jarosite and both fine- (supergene) and coarse-grained (primary) alunite. Plagued by analytical problems and inconclusive results, and because a much more thorough study of supergene features at El Salvador was begun by Mote and Brimhall (Mote et al., 2001a), this dating subproject was never completed. However, one aspect of our sulfate mineral dating deserves reporting.

Gustafson and Hunt (1975) suggested that supergene leaching and enrichment at El Salvador “followed within 5 m.y., and may have overlapped the final stages of hot spring activity.” They thought that the jarositic leached capping, which is clearly older than a later stage of oxidation and enrichment that formed an underlying hematitic capping, might have formed at a very last stage of the hot spring environment that formed advanced argillic alteration high on Cerro Indio Muerto. This interpretation was based on geologic arguments and on two K-Ar dates of about 36 Ma on fine-grained supergene alunite and thought to be probably a minimum age. The jarosite has the light sulfur isotope signature of supergene sulfate (Field and Gustafson, 1976), but it seemed plausible that a lack of isotopic equilibrium might be due to low but still warm temperatures at the dying end of the hydrothermal event, not necessarily a much later weathering period. This might explain why the jarositic capping was formed from such a wide range of sulfide assemblages, including very Cu rich bornite-pyrite with less than 1 to 2 vol percent pyrite. The idea received further confirmation by the discovery by Gustafson and Enrique Tidy of what appeared to be minute two-phase fluid inclusions in coarse-grained jarosite in a thin section of sample ES1639. Recent reexamination of this thin section, using a 100X oil immersion objective, has confirmed these as fluid inclusions. They are minute (1–2 $\mu$) and sparse but contain small (1–5 vol %) bubbles, occasionally seen in Brownian movement.

Jarosite sample ES5827 was taken from the same sample of quartz-alunite-altered rhyolite high on Cerro Indio Muerto that had previously yielded $^{34}$S sulfur isotope compositions of $+17.0$ for alunite and $-1.58$ for jarosite (Field and Gustafson, 1976). A coarse fraction +75 mesh and a finer fraction +150 and $-75$ mesh were dated. These yielded ages of 35.9 $\pm$ 1.6 and 43.9 $\pm$ 1.3 Ma, respectively (weighted mean plateau ages, Table 2). This result is not incompatible with the idea of oxidation and copper leaching at the end of the hypogene 41 to 42 Ma event, particularly if the younger age is partially disturbed by subsequent supergene processes, as suggested by anomalously young ages on some of our primary alunite samples (Gustafson and McWilliams, unpub. report to CODELCO, 1998). Most of the leached capping at El Salvador above an approximate 2,800- to 2,900-m elevation is jarositic (Gustafson and Hunt, 1975, fig. 21), so the age or ages of jarosite formation mark the time of oxidation and leaching of most of the copper above the top of sulfide. This age is much older than the 22 to 10 Ma age of the bulk of supergene minerals at lower elevations, convincingly determined by Mote et al. (2001a), but they have measured at least one 35 Ma age. J. W. Hedenquist (pers. commun., 1999) suggests that these fluid inclusions might reflect trapping of normal supergene water raised to perhaps 40° to 50°C by the exothermic oxidation of sulfides.

**Summary and Interpretations**

**Multiple cupolas, sequence, and duration**

Neither geologic evidence nor radiometric dating define sequences of emplacement among either the early rhyolitic or later granodioritic centers of mineralization. The durations of the two multiple intrusion periods of mineralization are poorly constrained by the dating but probably were about 1 m.y. each and were separated by about 1.5 m.y. The intrusion of Granite Gulch porphyry, and possibly the equigranular X and O porphyries, occurred between the two periods but was not accompanied by hydrothermal mineralization.

The pattern of multiple centers of intrusion, each with multiple porphyries and zoned hydrothermal alteration, is best explained as multiple cupolas rising above a larger magma chamber or chambers. The best documented analogy is in the Yerington district, Nevada, where Tertiary faulting rotated various structural blocks, followed by erosion. This analogy and diamond drilling exposed the vertical dimension from less than a 1- to more than a 6-km paleodepth, allowing
detailed three-dimensional reconstruction (Proffett and Dilles, 1984; Dilles and Einaudi, 1992; Dilles and Proffett, 1995). Here four separate porphyry copper systems were developed at a 1- to 5-km paleodepth about dike swarms cutting four individual cupolas above a Jurassic composite batholith, roughly 15 km in diameter. The five centers of intrusion and mineralization in the Quebrada Blanca-Collahuasi district of northern Chile, overlaying a magnetic anomaly that is interpretable as an underlying batholith, is another example of the pattern (Beln and Canas, 2001). Intrusive activity, evolving from early rhyolitic to granodioritic and finally andesitic, continued over 3 m.y. at El Salvador. As discussed by Norton and Cathles (1979) and Marsh et al. (1997), magma bodies in the shallow crust should solidify in well under 1 m.y. if not sustained by injection of new magma. No new modeling has been done to determine how long a much deeper and possibly zoned magma reservoir might persist and provide first granitic and then more mafic magma to the shallower chamber at El Salvador. Modeling of the aeromagnetic data shows a high susceptibility body below County Indio Muerto, which extends well above a deeper east-west anomaly (G. H. Ware, pers. commun., 1999).

Three cupola-related sets of dikes apparently arose from a roughly 44 Ma granitic magma chamber at Cerro Pelado, Old Camp, and M Gulch-Copper Hill. Old Camp is the smallest, simplest in terms of intrusive history and best mineralized. Two separate injections of quartz porphyry are recognized, filling structures that appear to be radial and ring dikes about the Cerro Pelado volcanic neck, but there is no evidence that these ever vented to surface. On the other hand, textural and geometric evidence indicates that the much more massive rhyolitic porphyry and breccia complex of Cerro Pelado probably did vent. The quartz porphyry dikes in M Gulch-Copper Hill indicate a center similar in diameter to Cerro Pelado, and locally abundant broken phenocrysts suggest a possible feeder for pyroclastic extrusion (Howell Williams, pers. commun., 1963). Subsequent granodioritic intrusions and erosion have obliterated evidence needed for further interpretation. The quartz porphyry dikes which appear (Fig. 1) to be radial about the north edge of the O Nose intrusive complex could indicate a fourth center of rhyolitic intrusion, more than 3 km southwest of Cerro Pelado. These dikes are the apparent feeders for the massive sills around Turquoise Gulch (Gustafson and Hunt, 1975, figs. 3 and 5). The lifting of basal rhyolitic pyroclastics by quartz porphyry sills in O Nose and elsewhere indicates forceful injection and suggests a lack of ready access to the surface at the time of intrusion. It is not clear how much of the differences among these centers in apparent depth of emplacement may reflect buildup of a now-eroded volcanic pile derived from a relatively early source at Cerro Pelado. No evidence of such a volcanic pile remains, and alternatively the differences may be due to topographic relief around the earlier Indio Muerto rhyolitic dome complex. Roughly 4 km in diameter, this dome complex was probably about 1 km thick when emplaced.

Four separate granodioritic cupolas are marked by multiple intrusions and zoned alteration and mineralization at M Gulch-Copper Hill, O Nose, Turquoise Gulch, and Sector Granito. All of these rocks have a similar set of porphyritic textures and were apparently emplaced between 42.3 and 40.9 Ma. This followed emplacement of equigranular X and O porphyries, which are more or less continuous for 3 km along the main N 20°E trend of the district. At the southwest end of this trend, Granite Gulch porphyry was emplaced between 42.1 and 43 Ma, with the timing relative to X porphyry still not determined. X porphyry was evidently accompanied by minor mineralization. By contrast, the first porphyritic intrusions with chilled aplitic groundmass into each of the separate centers were the best mineralized and were followed by relatively barren intramural porphyry. Whereas K feldspar is abundant in the matrix or groundmass of both the early equigranular and porphyritic intrusions, the later intramural (A porphyry) and postmineral porphyry (Latite) are more mafic and have little or no K feldspar. They are andesites and are evidence of evolution of the underling magma chamber to a quartz dioritic composition. In that this sequence is repeated in four separate centers over 3 km, it suggests either parallel evolution in separate segments of the granodioritic magma chamber or evolution of a single magma chamber at greater depth. In that this is the reverse of the normal differentiation trend from mafic to felsic, and the duration of magnetism is so long, the latter is more likely. This implies repeated injection of new, probably quartz dioritic magma over at least 2 m.y. As discussed below, it is probable this mafic injection began even 1 m.y. earlier.

This study has further demonstrated the difficulty, despite the precision of the Ar-Ar method, of dating individual events within a complex, evolving, and very hot porphyry copper district. Even with great care in sample selection and preparation, several of the sericites and biotites analyzed in this study appear to have been subjected after formation to temperatures hot enough to at least partially release radiogenic argon. The El Salvador centers are close together and partially superimposed, unlike Potrerillos (Marsh et al., 1997) where individual centers occur over a larger area, are more confined, and have had less influence on one another. The poorer quality of samples available for dating at El Salvador is evidenced by the larger errors in our data relative to the Potrerillos data. It would take not only a more precise analytical capability to define the individual pulses at El Salvador, but also even greater care and luck in finding samples which have not been affected by the thermal and chemical effects of the overlapping hydrothermal systems.

Variations on the theme

In trying to relate patterns seen and processes inferred at El Salvador to other porphyry copper deposits, Gustafson and Hunt (1975, p. 908) cited as critical factors “geometries and time factors of the intrusive process, and include differences in depth of emplacement, degree of availability of ground water, size and timing of successive magma advances, and abundance of metals and mineralizing elements in the fluids evolved from the melt.” An analysis of differences seen among the individual centers at El Salvador, all of which were formed at about the same depth of emplacement in the same country rock, structural regime, and climate, allows further insights into processes involved and invites quantitative follow up.

The most striking differences between centers occur at Old Camp and Cerro Pelado, formed 1 km apart and within 1 m.y.
of each other. Old Camp is relatively small and simple but has patterns and evolution of mineralization and alteration that are typical of a porphyry copper deposit. Cerro Pelado has many features more similar to a Climax-type porphyry Mo deposit, even though it is most likely related to the same magma chamber that produced Old Camp. Cornejo et al. (1975, p. 42–43) interpreted the difference between the sanidine-dominant quartz rhyolite and the plagioclase and biotite-dominant quartz porphyry as probably reflecting an increase in water content. This was “most likely in response to fractional crystallization of anhydrous phases, thereby stabilizing biotite over K feldspar as the crystallizing K-rich phase.” The only pertinent study of trace elements in intrusions at El Salvador (Gustafson, 1979) indicates that quartz porphyry, like the granodioritic porphyries, lacks the strong negative Eu anomaly of quartz rhyolite and early Indio Muerto rhyolite. This argues against fractional crystallization of feldspar as the dominant cause of the difference and further supports injection of new magma as more likely. The single sample of quartz rhyolite in this study was from Rhyolite Hill rather than Cerro Pelado, but the quartz porphyry sample was from Old Camp. A low water content in the magma underlying County Pelado might explain the much higher Mo/Cu in Cerro Pelado, because Candela and Piccoli (1995, figs. 1 and 4) showed that the efficiency of partitioning from the melt into exsolved fluid is much higher for Mo than for Cu for both low initial water content and low Cl/water. Quartz in both deposits contains high-salinity fluid inclusions. The possibility that copper was introduced into both centers but was simply lost to the atmosphere from the Cerro Pelado volcanic neck, while Mo was deposited closer to the magma, runs counter to the evidence that Mo is commonly more abundant than Cu in eruptive products (J. W. Hedenquist, pers. commun., 1999). The enrichment of the magma chamber in copper as well as water by the introduction of new magma seems the most likely explanation of the evidence at hand. Hildreth (1981) has argued that the dominant cause of lithospheric magmatism is mantle-derived basaltic magma, combined with crustal melting and differentiation in zoned magma chambers. Huppert and Sparks (1988) have further illuminated this process, which we think is pertinent to the formation of the Indio Muerto district magmatism. Keith et al. (1997) have argued that introduction of mafic alkaline magma to the magma chamber below Bingham Canyon, Utah, was responsible for enrichment of both copper and water. To whatever extent the late anodesitic porphyries represent the least modified late injections of magma, their lack of associated mineralization argues against the influence of a new introduction of volatiles having persisted until 41 Ma. On the other hand, a still unpublished isotopic study at El Salvador by the Geological Survey of Japan (J. W. Hedenquist, pers. commun., 1999) indicates that magmatic fluids have been an important contributor to post-A porphyry D veins and high-level advanced argillic alteration at the Turquoise Gulch center. Further geochemical study of these centers should be productive.

Reworking of alteration and mineralization by late intramagmatic intrusions has been important in producing patterns at M Gulch-Copper Hill. The situation is similar to the intrusion of K porphyry by L porphyry in the southeast part of the Turquoise Gulch orebody, but here there is apparently a larger time gap between intrusions. In both centers, early mineralized rock has been intruded and presumably assimilated by a relatively poorly mineralized porphyry magma. Also at the east contact of the Copper Hill feldspar porphyry complex, much of the Cu emplaced as early chalcopryite-borneite in quartz porphyry has been removed and the rock converted to pyritic low-grade material by late hydrothermal activity. The phenomenon has been seen in halos of deep D veins at Turquoise Gulch (Gustafson and Hunt, 1975) and around similar deep veins at Butte, Montana (Brinshall, 1980). As in these other occurrences, some of this Cu was redeposited at a higher elevation in rich pyrite-borneite D veins that cut the feldspar porphyries. Strong vertical zonation to pyrite-borneite assemblages over very low grade pyritic mineralization, seen at O Nose and Red Hill near the margins of L porphyry, probably also reflects this same phenomenon. The low-intensity chalcopryite-borneite dissemination seen in L porphyry at Red Hill is similar to that along the southeast margin of L porphyry where it intrudes well-mineralized K porphyry (Fig. 2). Both probably result from assimilation of earlier mineralization in the intruded rock.

The patterns of sulfide and alteration in Figures 2 and 3 represent background assemblages, outside veins, and halos, and reflect these superimposed late vein assemblages only where they coalesce and become pervasive. These late effects extend beyond and tend to merge the individual centers. It is apparent from the dating (Fig. 8) that sericite in late-stage D veins at 41 to 42 Ma extended from Sector Granito to Old Camp and thermal effects are seen as far as Cerro Pelado. Supergene clay alteration also affected all rocks across the district, depending on their pyrite content, further tending to mask individual centers. Lateral migration of copper during the supergene process also blurred the edges of primary mineralization. At El Salvador there are examples of exotic chalcocite forming a thin enrichment zone at the top of sulfide in the otherwise barren M Gulch breccia (Carrasco and Rojas, unpub. report, 1992) and under the eastern half of the Damiana exotic oxide orebody. The exotic copper oxides and silicates at Damiana, as well as the minor chalcocite, have been interpreted to be derived from westward migrating solutions derived from oxidizing sulfides under Cerro Indio Muerto (Rojas and Mueller, 1994; Munchmeyer, 1996; Mote et al., 2001a). John Hunt (pers. commun., 1999) points out the additional possibility that significant amounts of copper at Damiana were derived more locally from the west-northwest– and east-northeast–trending pyrite veins under the orebody, which are barren where seen but could have been zoned upward to contain chalcopryite-borneite. Dating of supergene alunite interpreted to have been formed by the same acid solutions that formed the Damiana orebody, and copper wad from the orebody itself, indicate supergene activity from 35 to 10 Ma (Mote et al., 2001).

**Economic significance**

Exploration geologists have long recognized the importance of the tendency for porphyry copper deposits to cluster in well-mineralized districts like Yerington in Nevada, Globe-Miami and the Sierrita Mountains in Arizona, and Quebrada Blanca-Collahuasi in Chile, but more closely spaced and partially overlapping centers of mineralization have not been as
widely recognized. This is because the careful mapping of alteration and sulfide mineralogy, with petrographic support, is frequently neglected at operating mines. Failure to recognize incomplete zonal patterns can mean that drilling is never done to find the missing part. Everyone recognizes when a portion of an orebody is truncated by an obvious fault, but loss of ore by intrusion of a late intraminal porphyry or distortion of symmetry by superimposed, structurally controlled sericite-pyrite is less easily recognized and can be equally significant. The project described here stimulated drilling that developed new ore within the M Gulch-Copper Hill area. Development of new ore within the mine complex is generally more valuable than a comparable discovery far away.

Acknowledgments

As well as the many authors of unpublished reports referred to in the text, the following contributed to this report and are gratefully acknowledged. The modeling project was initiated by Pedro Carrasco, Superintendent of Geology at El Salvador, and continued and aided by his successor Guillermo Mueller. The project was funded by CODELCO Central, under the guidance of Francisco Camus and later Pedro Carrasco. Enrique Tidy facilitated the project in many ways and offered useful comments on the manuscript. Tim Marsh provided critical assistance in sample preparation for the dating. Osvaldo Villar at El Salvador and later Graphic Harmony in Reno assisted with the computer graphics. Insightful reviews of the manuscript by John Hunt, Jeffrey Hedenquist, and John Dilles resulted in considerable improvement. Yasushi Watanabe and Holly Stein gave permission to publish their Re-Os results, and CODELCO-Chile gave permission to publish this paper. The cost of color illustrations was provided by CODELCO and the Economic Geology.

REFERENCES


Castro, M., 1993, Antecedentes de geologia y analysis de estabilidad de taludes del yacimiento arajo abierto Quebrada M, III region: Memoria de Titulo, Santiago, Departamento de Geologia, Universidad de Chile.


Godoy, S., 1983, Estudio geologico del yacimiento satelite Campamento Antiguo, El Salvador, III Region, Chile: Memoria de Titulo, Santiago, Departamento de Geologia, Universidad de Chile.


APPENDIX

Apparent Age Spectra for Incremental Heating (left) and Isochron Isotope Correlation Plots (right) for All Samples

The age spectra show apparent age (Ma ± 1σ) plotted against cumulative 39Ar released for individual heating steps (temperature shown). Steps defining plateau or used for calculating weighted mean ages are shaded; their ages are summarized in Table 2. The isochron diagrams plot 39Ar/40Ar against 36Ar/40Ar. Values of initial 40Ar/36Ar, mean square weighted deviates (MSWD), and the isochron age are shown.
ES 3853 Biotite
TFA 43.12 ± 0.12 Ma
WM PA 42.86 ± 0.09 Ma

MSWD 0.64 (2.41)

ES 5827 Jarosite -75/+150 mesh
TFA 43.4 ± 16.6 Ma
WM PA 43.9 ± 1.3 Ma

MSWD 1.34 (3.00)

ES 5827 Jarosite +75 mesh
TFA 35.51 ± 1.70 Ma
WM PA 35.87 ± 1.59 Ma

MSWD 0.35 (2.26)

ES 6010 Sericite
TFA 43.33 ± 0.13 Ma
WM PA 42.60 ± 0.34 Ma
40Ar/36Ar = 776

MSWD 0.51 (2.41)

ES 6010 Sericite
TFA 43.33 ± 0.13 Ma
WM PA 41.55 ± 0.19 Ma
40Ar/36Ar = 443

MSWD 1.83 (2.15)

ES 6010 Sericite
TFA 43.33 ± 0.13 Ma
WM PA 41.55 ± 0.19 Ma
40Ar/36Ar = 443

MSWD 1.83 (2.15)
ES 12165 Sericite
TFA 42.95 ± 0.21 Ma
WMA 44.13 ± 0.20 Ma

ES 12470 Sericite
TFA 41.10 ± 0.13 Ma
WMA 40.61 ± 0.14 Ma

ES 12471 Biotite
TFA 40.99 ± 0.10 Ma
WMPA 41.06 ± 0.10 Ma

ES 12604 Biotite
TFA 39.42 ± 0.42 Ma
WMPA 41.46 ± 0.42 Ma