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Geomorphologic Environment and Age of Supergene Enrichment of the Cuajone, Quellaveco, and Toquepala Porphyry Copper Deposits, Southeastern Peru

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Abstract

Copper ore grades of the Cuajone, Quellaveco, and Toquepala porphyry Cu(-Mo) deposits, situated at 3,000 to 4,000 m a.s.l. on the Pacific slope of the Cordillera Occidental of southernmost Peru (lats 17°02′–17°15′ S), have been markedly increased by supergene sulfide enrichment. Following the emplacement of the hypogene mineralization in the early Eocene (52–57 Ma) as the terminal stage in the development of the Toquepala Group continental volcano-plutonic terrane, this Andean transect was gradually reduced by erosion in a semiarid climate to a low altitude topography; unroofing of the deposits had taken place by the mid-Oligocene. The initiation of cordilleran uplift at ca. 25 to 26 Ma, accompanied by the episodic eruption of felsic ash-flow tuffs at the oceanward front of the volcanic arc, led to more rapid erosion and the conversion of the mid-Tertiary landscape into the subplanar Altos de Camilaca surface. This regionally extensive pediplain constitutes the major landform component of the present precordillera surrounding the porphyry centers; its final configuration was attained at ca. 18 to 19 Ma. Ash-flow tuff eruption was widespread and frequent at this time.

Supergene enrichment began in the late Oligocene during the progressive lowering of topography and continued through the more abrupt water-table depression resulting from the latest Oligocene to early Miocene uplift. However, the distribution of chalcocite, sensu lato, in the three porphyry deposits and the local postmineralization landforms and volcanic histories differed significantly during the latter interval. At Toquepala and, to a lesser extent, Quellaveco, the landform regimes were dominated by open valleys and ignimbrite blanketing was short-lived, whereas the exposed Cuajone deposit was both the site of aggressive early Miocene valley incision and the deposition of an unusually thick, in part welded, ash-flow tuff at 22.8 ± 0.7 Ma. As a result, the enrichment blanket at Cuajone remained relatively thin and was even partially eroded in the early Miocene, whereas the blankets at Quellaveco and Toquepala were thickened.

Continued strong uplift in the mid-Miocene (ca. 8–15 Ma) generated the array of apron and terrace pediments of the Multiple Pediment stage which dominates the lower cordilleran slopes and, in the mineralized areas, led to the deepening of existing valleys and the development of new fluvial channels. Ignimbrite eruption persisted throughout the Miocene. Again, local regimes of erosion and volcanism proved inimical to supergene activity at Cuajone, but enrichment continued at Quellaveco and, particularly, Toquepala, where there is no record of later Miocene ash-flow accumulation. Uplift in this period was apparently also most extensive in the vicinity of the Toquepala deposit, which experienced the formation of a deep chalcocite blanket, while the extant enrichment zone at Quellaveco was thickened.

The development of enriched assemblages containing "massive" chalcocite had clearly terminated by 13.1 ± 0.4 Ma at Cuajone and by 9.5 ± 0.5 Ma at Quellaveco; the timing of later enrichment at Toquepala is less constrained, but a mid-Miocene age is probable. Supergene

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upgrading of the three Peruvian deposits was contemporaneous with that of copper mineralization in northernmost and northern Chile, as at Chuquicamata and La Escondida, and in the Copiapó mining district, in all of which areas a late Oligocene to mid-Miocene age has been inferred for supergene alteration. This major and regionally developed metallogenic episode took place during and between two major periods of cordilleran uplift, under semiarid climatic conditions. The termination of intense enrichment along this 2,000-km stretch of the Cordillera Occidental in the late Miocene was a direct result of marked climatic desiccation, which not only reduced the overall supergene activity but focused fluvial erosion, leading to the incision of steep-walled canyons less favorable for supergene alteration than the earlier subplanar landforms.

Introduction

SUPERGENE oxidation and attendant sulfide enrichment in the later Tertiary have contributed to the development of high copper grades in many of the Cretaceous and Paleogene porphyry copper deposits in the central Andes of Peru and Chile, as in other comparable mineralized regions. However, the weathering of these major deposits has received little concerted study from the perspective of regional and local geomorphology, despite the widely accepted importance of landforms in the development of supergene profiles. This paper addresses the physiographic environment and age of supergene alteration in the Eocene porphyry Cu(-Mo) subprovince of southernmost Peru (Fig. 1), with particular reference to the Cuajone (17°02′ S–70°42′ W) and Toquepala (17°15′ S–70°37′ W) mines of the Southern Peru Copper Corporation (SPCC) and the nearby Quellaveco prospect (17°06′ S–70°37′ W) of Mineroperú. Each deposit is situated at elevations between 3,000 and 4,000 m a.s.l. on the Pacific slopes of the Cordillera Occidental. The mineralized area now experiences an arid climate (Meigs, 1953; Instituto Nacional de Planificación, 1965) and is bordered to the southwest by the hyperarid Peruvian Coastal Desert, the northern extension of the Chilean Atacama Desert (di Castri and Hajek, 1976). However, it has been widely inferred on geomorphologic and other grounds (e.g., Mortimer, 1969, 1973) that semiarid conditions prevailed in this region until the onset of drastic climate desiccation in the late Miocene (e.g., Alpers and Brimhall, 1988).

The time scale of Berggren et al. (1985) is used here, although the term mid-Miocene rather than middle Miocene is employed informally for intervals significantly transgressing the boundaries of the latter time-stratigraphic unit, and mid-Oligocene is used to refer broadly to the middle part of that epoch.

Previous research on supergene enrichment in the Andean deposits

Detailed investigations (Clark et al., 1967a, b; Sillitoe et al., 1968; Mortimer, 1969, 1973; Sillitoe, 1969) of Mesozoic to Paleogene vein systems in the broader Copiapó mining district of north-central Chile (ca. lat 26°–29° S; Fig. 1), building on the pioneering work of Segerstrom (1963), defined empirical correlations between episodes of supergene enrichment of copper and silver and a sequence of regionally extensive subplanar erosional landforms, the ages of which were delimited by K-Ar geochronology of overlying ignimbrite flows. Following Hollingworth (1964), the erosion surfaces in this desertic area, close to the southern limit of the Atacama Desert, were interpreted as pediments or, where regionally extensive, pediplains, which were inferred to have formed rapidly in response to episodes of abrupt epeirogenic uplift of the oceanward flank of the present Cordillera Principal. Two distinct periods of metal enrichment were recognized, each ascribed to a specific episode of landform development. It was assumed that supergene sulfide formation was most active during the pe-

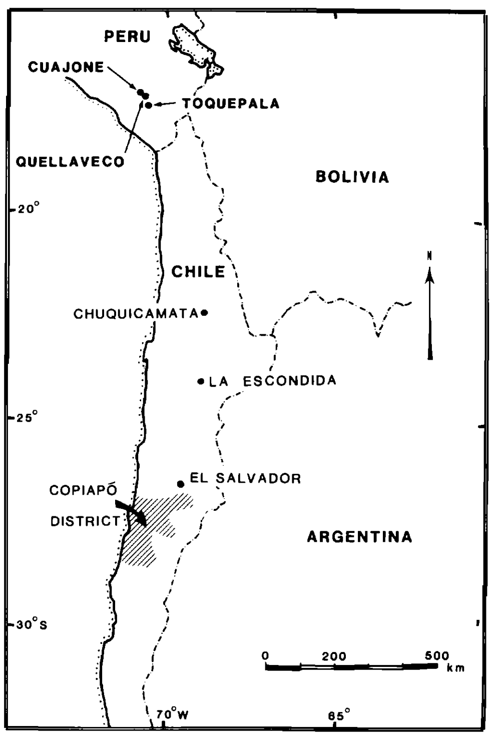

FIG. 1. Map showing the Cuajone, Quellaveco, and Toquepala porphyry copper deposits in southern Peru, and other mineralized areas cited in the text.

riods of relative tectonic quiescence and reduced erosional rate intervening between the incisions of the associated erosion surfaces. The earlier episode of enrichment was found to be as old as early Eocene, whereas the later enrichment period was less precisely assigned to the late Oligocene and early (or middle) Miocene interval. The prevalence of an arid or semiarid climate in this region throughout the Paleogene is implied both by the nature of the dominant landforms and by the widespread occurrence of evaporites in the continental supracrustal cover. All significant sulfide enrichment occurred prior to the middle and late Miocene (>12.9–9.8 Ma; ages recalculated with the decay constants of Steiger and Jäger, 1977) development of the very extensive Atacama pediplain, which widely truncated preexisting supergene profiles. Renewed tectonic uplift, and inferred climatic desiccation during the latest Miocene to Pliocene interval (ca. 9–2 Ma), was accompanied by the termination of pedimentation and the restriction of major erosion to the channels of the main exorheic rivers (Mortimer, 1973). Only limited oxidation and superficial sulfide enrichment of the vein systems occurred at this time (Segerstrom, 1963; Sillitoe et al., 1968). Supergene processes are all but inactive under the hyperarid climatic conditions now prevailing in the Chilean norte chico below ca. 3,000 m a.s.l. (di Castri and Hajek, 1976; UNESCO, 1980).

In the El Salvador porphyry copper deposit (Fig. 1), the intense supergene enrichment of the upper Eocene stockwork mineralization may not have been contemporaneous with that which affected the vein systems of the nearby Copiapó district. On the basis of K-Ar dating of supergene alunite, Gustafson and Hunt (1975) concluded that supergene upgrading at El Salvador began at ca. 37 Ma, within 5 Ma of the emplacement of the hypogene ores. Mortimer et al. (1977), however, have shown that oxidation and enrichment of the ca. 29-Ma Chuquicamata porphyry deposit, located 450 km to the north (lat 22°19′–20′ S; Fig. 1), and the concomitant formation of the contiguous Exótica (Mina Súr) chrysocolla mineralization, occurred in the late Oligocene to early Miocene and was thus essentially coeval with the later enrichment in the Copiapó district. Alpers et al. (1984) and Alpers and Brimhall (1988) more recently presented middle Miocene K-Ar dates for supergene alunite associated with the intense sulfide enrichment at the La Escondida porphyry prospect at 24°16′ S (Fig. 1). It was concluded that supergene sulfide enrichment at La Escondida occurred in the mid-Tertiary, and prior to the late Miocene, as in the Copiapó and Chuquicamata districts.

Methodology of the present study

Our aims in the present research were to establish the geologic-geomorphologic evolution of the areas immediately surrounding the Cuajone, Quellaveco, and Toquepala deposits subsequent to hypogene mineralization and to correlate those histories with the distribution of supergene ore minerals at each site. K-Ar dating of felsic ash-flow tuff units permits the delimitation of the ages of landforms which underlie or truncate them in the mine areas. The occurrence and nature of supergene minerals have received only reconnaissance study (Horlick et al., 1981; Satchwell, 1983; Clark, in prep.). Both "massive" and "sooty" supergene sulfide assemblages occur in the three deposits. As Sillitoe and Clark (1969) have shown, the initial stages, or lower limits, of enrichment zones are characterized by the development of powdery aggregates of copper sulfides, whereas more extensive replacement of hypogene minerals results in coarser grained, sectile masses of the supergene sulfides. Sooty assemblages are, however, also developed in the early stages of oxidative conversion of chalcocite and djurleite to more sulfur rich copper sulfides (e.g., anilite; Clark and Sillitoe, 1971). At Cuajone and Quellaveco, the single enrichment blankets, or chalcocite zones, are defined largely on the basis of megascopic mineralogical relationships and copper ore grades. At Toquepala, at least two spatially separated enrichment zones have long been recognized (Richard and Courtright, 1958), but the irregular distribution of supergene chalcocite (sensu lato) has not been investigated in detail. Regardless of these deficiencies, we consider that the enriched zones in each deposit are sufficiently delimited to permit their broad correlation with stages in local landform evolution.

It should be emphasized that our methodology differs radically from that employed by Gustafson and Hunt (1975) and Alpers et al. (1984) and Alpers and Brimhall (1988) in their analyses of the age and formational conditions of supergene enrichment zones at El Salvador and La Escondida, Chile, respectively. This is in part because careful search has so far failed to reveal the occurrence of supergene alunite suitable for K-Ar dating. More critically, the undoubtedly complex geomorphologic evolution of the mineralized areas during the Neogene would introduce unacceptable uncertainties to the mass balance calculations central to the model developed by Alpers and Brimhall at La Escondida, where a much simpler sequence of landform events attended the supergene processes. The physiographic development of the precordillera of southernmost Peru has played a key role in promoting and restricting the enrichment of the porphyry copper deposits and is thus critical to our analysis.

Our interpretations of the interrelations of supergene mineral zones and geomorphology are based on the standard supergene profile first defined in detail by Emmons (1917): a land surface genetically associated with alteration is underlain successively by a leached (lixiviated) zone, an oxidized zone, a zone of supergene sulfide enrichment, and the protore. The transition from oxide to sulfide assemblages is assumed to correspond approximately to the water table extant at the time of alteration. Because pyrite-poor hypogene mineral assemblages are not developed in the upper parts of the three deposits under discussion, the broad configurations of the upper and lower boundaries of the sulfide enrichment zones are inferred essentially to reflect those of the superjacent landforms (cf. Ambrus, 1977; Guilbert and Park, 1986, p. 800–802).

Geology and Geomorphology of Southernmost Peru

Selected features of the present-day topographic relationships, the post-Eocene geologic units, and the major Neogene landform domains of the area of study are outlined in Figure 2a–c. The region incorporates a transect of the Peruvian Coastal Desert, itself part of the Atacama Desert, and conforms physiographically to the basin and range or mountain and piedmont deserts of, e.g., Cooke and Warren (1973). The landscape is dominated by an assemblage of steep mountain slopes, rock-cut alluviated pediments or pediplains, and alluvial plains, traversed by widely spaced exorheic river systems, the Ríos Moquegua and Locumba and their major tributaries, fed by snow melt in the high cordillera.

A simplified chronology of mid- to late Tertiary geologic and geomorphologic events in southernmost Peru is provided in Table 1, based largely on Tosdal et al. (1981, 1984). In outline, four major physiographic terrains constitute the present-day topography (Fig. 2a): (1) the Cordillera de la Costa, a discontinuous belt of mountains attaining elevations of ca. 1,000 to 1,800 m a.s.l.; (2) the Llanuras Costaneras, a sloping faceted terrain rising northeastward from ca. 350 m a.s.l. at the inner foot of the coastal mountains to ca. 3,000 m a.s.l.; (3) the precordillera (informal term), a subplanar ca. 4,000-m bench with a steep southwestern interface with the Llanuras; and (4) the main Cordillera Occidental, which at this latitude is dominated by stratovolcanoes, in part glaciated, and reaching a maximum elevation of 5,815 m a.s.l. at Volcán Tutupaca (Fig. 2a).

The porphyry copper deposits under consideration were emplaced in the early Eocene (52–57 Ma, Estrada, 1975; McBride, 1977; Zweng, 1984; Beckinsale et al., 1985; Clark et al., 1990) as the terminal stage in the development of an Upper Cretaceous to Paleogene subaerial volcano-plutonic arc comprising the Toquepala Group and a segment of the Peruvian Coastal batholith (Bellido, 1979; Beckinsale et al., 1985). The geology of the Toquepala deposit has been

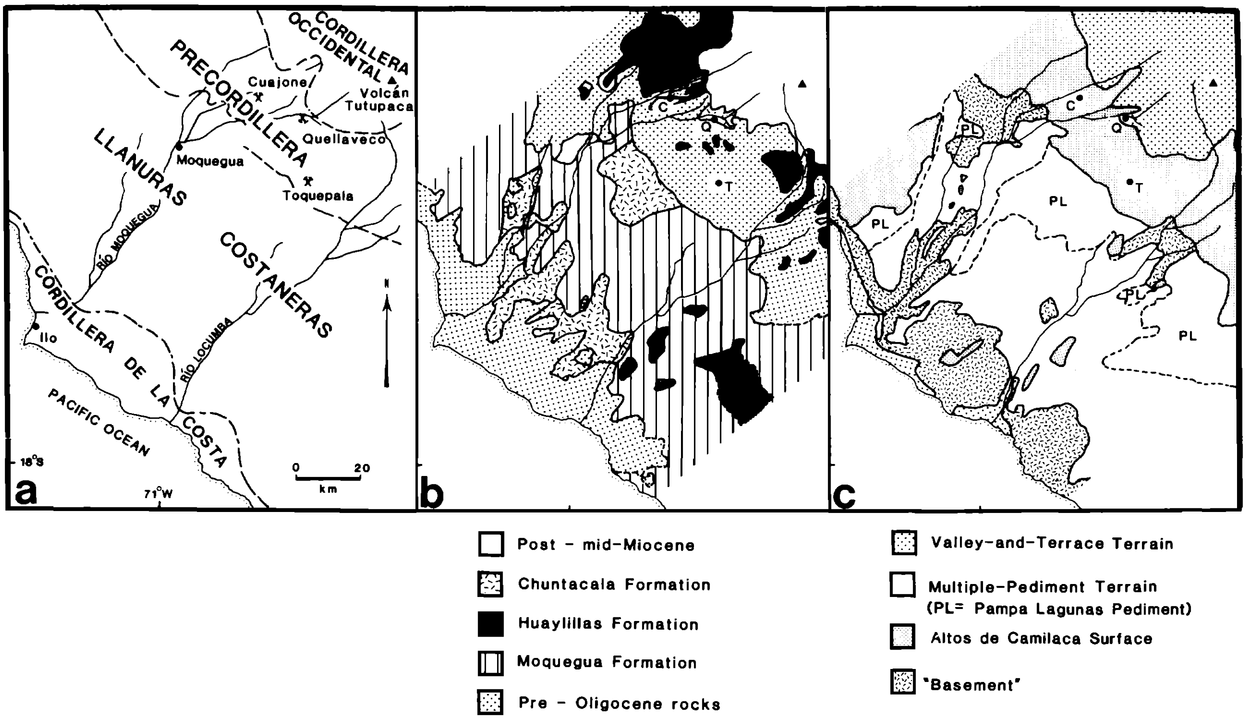

FIG. 2. The study area on the Pacific slope of the Cordillera Occidental, southern Peru. a. The major physiographic units and locations of the Cuajone and Toquepala mines and the Quellaveco prospect. b. Simplified geologic map of area (after Bellido and Landa, 1965; modified by Tosdal et al., 1981). c. Geomorphologic map, showing distribution of Tertiary landform domains (simplified after Tosdal et al., 1984). Abbreviations: C = Cuajone, Q = Quellaveco, T = Toquepala.

TABLE 1. Cenozoic Geologic and Physiographic Evolution of the Pacific Slope of the Cordillera Occidental of Southernmost Peru (after Bellido, 1979; Tosdal et al., 1981, 1984; Clark et al., 1990).

	Geologic events	Major geomorphologic events
Pliocene	Development of large andesitic-dacitic stratovolcanoes of Barroso Group (≤5.3 Ma) Capillune Formation sedimentation and minor volcanism	Valley and Terrace stage: continued episodic uplift, with incision of steep-walled valleys in precordillera and upper Llanuras Costaneras (ca. 8.5 Ma to present)
Miocene	"Sencca Formation" ignimbrite eruption (ca. 6.5 ± 0.3 Ma) "Maure Formation" sedimentation in basins of high cordillera Chuntacala Formation felsic volcanism and associated clastic sedimentation (14.2 ± 0.4-8.9 ± 0.6 Ma) Eruption of youngest ignimbrite assigned to Huaylillas Formation (18.6 ± 0.3-18.3 ± 0.3 Ma) Emplacement of major early ignimbrites of Huaylillas Formation (≤22.8 ± 0.7 Ma)	Multiple Pediment stage: renewed, episodic uplift, causing development of apron and terrace pediments in Llanuras Costaneras (9–15 Ma) and of broad, open valleys in evolving precordillera Final configuration of Altos de Camilaca surface (ca. 18–19 Ma)
Oligocene	Eruption of ignimbrite flows (≤29 ± 0.2 Ma) and deposition of conglomeratic horizons in uppermost Moquegua Formation Accumulation of Moquegua Formation fine clastics and evaporites (? ≤45–50 Ma)	Initiation of strong uplift and rapid erosion, tilting and modifying mid-Tertiary landscape Development of subdued, low-altitude landscape through slow erosion of Paleocene-Eocene arc
Eocene	Hypogene mineralization: Toquepala, ca. 57 Ma; Quellaveco, ca. 56 Ma; Cuajone, ca. 52 Ma	
Paleocene	Final stages of subaerial Toquepala Group volcanism (to ca. 59 Ma) Intrusion of granitoid plutons (ca. 58.7–65.5 Ma)	

described by Richard and Courtright (1958), Zweng (1984), and Zweng and Clark (1984, and in prep.), the Cuajone deposit by Lacy (1958), Manrique and Plazolles (1975), and Satchwell (1983), and the Quellaveco deposit by Estrada (1975), Kihien (1975), Guerrero and Candiotti (1979), Torpoco (1979), and Zimmerman and Kihien (1983).

Following hypogene hydrothermal activity, a prolonged mid-Tertiary period of erosion ensued, with the gradual reduction of the arc terrain to a topography of subdued relief which, in the vicinity of the deposits, may not have exceeded 500 to 1,000 m a.s.l. (Table 1). The predominantly continental clastic strata of the Oligocene to earliest Miocene Moquegua Formation (Barúa, 1961; Bellido and Landa, 1965; Bellido, 1979; and Marocco and Noblet, 1990) constitute the aggradational facies of this erosional system (Fig. 2b). Beginning in the late Oligocene and continuing into the early Miocene, a succession of more abrupt uplift episodes resulted in the development of a regionally extensive, generally subplanar, largely degradational landscape, now preserved in the precordillera (Fig. 3a) and at the summits of the Cordillera de la Costa (Fig. 2a and c). Relationships in the area upstream from the town of Moquegua illustrate that significant rapid degradation of the precordillera had taken place prior to 25 Ma, generating conglomerate horizons in the uppermost Moquegua Formation to the southwest. The erosional surface attained its final form immediately prior to 18 Ma and is referred to as the Altos de Camilaca surface (Tosdal et al., 1984; Table 1). A clear backscarp is preserved only locally for this landform in the immediate study area (e.g., Fig. 3d), but an extensive topographic step defines much of the upper limit of the surface in the Desierto de Clemesí north of the Río Moquegua (Fig. 2); in the area of the ore deposits, the Altos de Camilaca surface has, in part, the form of a pediment dome (Mabbutt, 1955; Cooke and Warren, 1973, p. 196).

During the middle and earliest late Miocene (ca. 15–8 Ma), the Altos de Camilaca surface was itself uplifted, variably tilted and eroded, with the formation of a succession of apron and terrace pediments (nomenclature of Cooke and Warren, 1973), assigned to the Multiple Pediment stage (Figs. 2c, 3b and c; Table 1). Broad open valleys developed at this time across the precordillera to the northeast. The later Miocene uplift of the southern Peruvian transect of the Cordillera Occidental was probably greater than that which occurred at this time in other transects of the continental margin (Tosdal et al., 1984) and presumably represents the topographic response to unusually abrupt crustal thickening. Pedimentation in the Cordillera Occidental, at this as at other latitudes, ceased in the late Miocene, contemporaneous with inferred climatic desiccation at lower topographic levels. Since that time, steep-walled valleys and canyons have been incised into the Pacific slope of the mountains as a result of continued episodic uplift

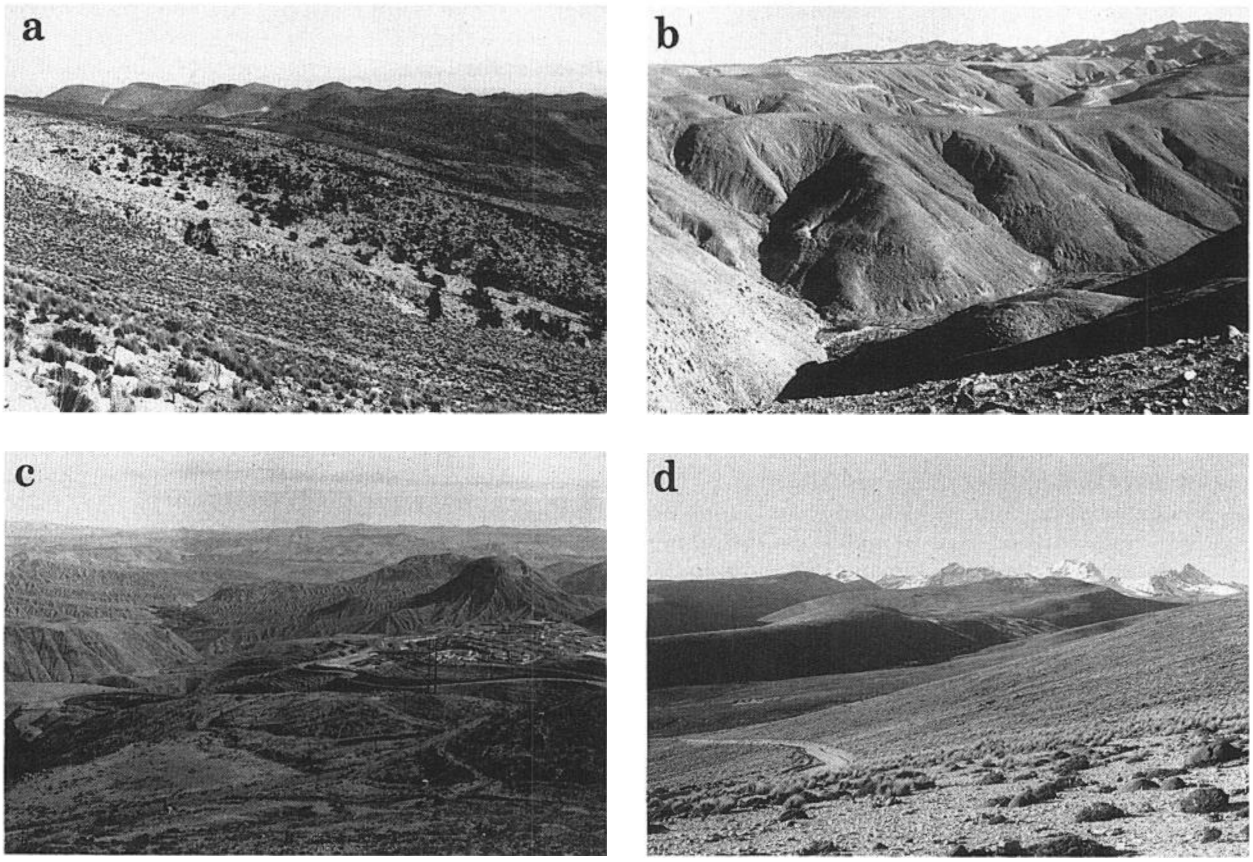

FIG. 3. Landforms of the Cuajone-Quellaveco-Toquepala district. a. Characteristic landscape of the precordillera: dissected area of the lower Miocene Altos de Camilaca surface, near Larampahuane (10 km north-northeast of Toquepala). View looking east-southeast. Accordant summits (ca. 4,100–4,200 m a.s.l.) represent remnants of the pediplain, whereas the southwest-dipping slopes are defined by the surfaces of flow units of the Upper Cretaceous or Paleocene Serie Alta Volcanics. b. Thinly alluviated Pampa Lagunas apron pediment (11–14 Ma), the dominant local landform of the middle to late Miocene Multiple Pediment stage in the upper Llanuras Costaneras; Pampa is some 20 km west-southwest of Toquepala. Steep slopes in background represent the back scarp of the pediment and the lower slopes of the precordillera. The valleys (Quebrada Cucule in foreground) dissecting the pediment formed mainly in the Pliocene Valley and Terrace stage. c. View to the southwest from Cerro Botiflaca, at the southwest margin of the precordillera, across the Llanuras Costaneras and toward the Cordillera de la Costa. Cerro Baúl, the mesa at right, is underlain by sediments of the Upper Moquegua Formation and capped by a 25.3 ± 0.8-Ma tuff. The course of the Río Tumilaca (left) is flanked by upper Miocene terrace pediments of the later Multiple Pediment stage. Another tuff, correlative with that overlying the Cuajone deposit (Tosdal et al., 1981), is interbedded with the Moquequa Formation and underlies the apron pediment on the distant (left) skyline. d. View to the northeast across the upper valley of Río Asana, northeast of Quellaveco, in the inner precordillera. Major moraines are draped across the dissected Altos de Camilaca surface. Cerro Condoriquiña (5,085 m), on the skyline, is probably underlain by the Upper Cretaceous Toquepala Group Volcanics, and thus constitutes the local back scarp, albeit subsequently glaciated, of the pediplain.

during the still active Valley and Terrace stage of landform development (Table 1), causing considerable degradation of the earlier planate or gently incised landforms (Figs. 2c and 3).

In the early Neogene, the mineralized area was situated, as it is today, at the oceanward front of the volcanic arc in the precordillera. The eruption of rhyodacitic ash-flow tuffs apparently began locally at ca. 29 Ma. (R. J. Langridge, pers. commun., 1989), but became more intense at 25 to 26 Ma during the initial late Oligocene phases of rapid uplift. Several tuffs are intercalated in the coarse clastic sediments of the uppermost Moquegua Formation (Fig. 3c; Bellido, 1979; Tosdal et al., 1981). Subsequently, felsic pyroclastic eruptions accompanied the development of both the Altos de Camilaca surface and the landforms of the Multiple Pediment stage, resulting in the mantling of wide areas of the precordilleran slope of the Cordillera Occidental (Tosdal et al., 1981, 1984). The widespread tuffs contemporary with incision of the Altos de Camilaca surface are assigned to the Huaylillas Formation. In contrast, tuffs that are predominantly restricted to valleys were erupted during the Multiple Pediment stage and are grouped as the Chuntacala Formation (Tosdal et al., 1981, 1984). This distinction, first recognized at Cuajone by Manrique and Plazolles (1975), is critical to the interpretation of the landform evolution of the area. Because the accumulation of even thin ignimbrites has been shown elsewhere to disrupt ground-water systems and terminate supergene activity beneath subjacent surfaces (e.g., Sillitoe et al., 1968), definition of the time-space relationships of the pyroclastic units and the associated landforms is clearly of potential importance in the prediction of the extent of local enrichment horizons. In the study area, the basal tuff overlying the eroded Cuajone deposit is unusually thick ($\leq$180 m) and includes a major welded zone containing essentially undevitrified shards. Similarly the upper Miocene tuff overlying the Quellaveco deposit in the Río Asana Valley exhibits relics of flattened shards, suggestive of original welding. In general, most tuffs of the Huaylillas Formation show only weak devitrification and hydrothermal alteration. Those of the Chuntacala Formation are extensively devitrified but are otherwise unaltered. We conclude, therefore, that the ash-flow tuffs emplaced in the vicinity of the ore deposits possessed low permeabilities and were thus likely to act as aquicludes.

During the Pliocene, a local transition from ignimbrite eruption to predominantly andesitic-dacitic volcanism culminated in the development of the stratovolcanoes of the Barroso Group (Table 1). Radical cooling of the climate in the Pleistocene led to the formation of alpine glaciers and to the development of extensive moraines, which are well preserved northeast of Cuajone and Quellaveco (Fig. 3d) but not in the immediate vicinity of the deposits.

Around the three deposits under discussion, the precordilleran landscape (Figs. 2a and 3a) is dominated by a high, southwest-sloping plain, representing both the degradational portion of the Altos de Camilaca surface and, over wide areas, the gently dipping surfaces of ignimbrite flows broadly coeval with that landform. The plain has been variably dissected by west- to southwest-trending valley systems. Some valleys originally possessed broad shallow cross sections and represented the uppermost extensions of the middle and upper Miocene pediments, which constitute much of the Llanuras Costaneras at lower altitudes. They were subsequently extensively modified during the Valley and Terrace stage, whereas other valleys were initiated during the latter stage, and display simple V-shaped profiles. Prior to mining, the porphyry copper deposits were exposed in composite polystage valleys.

The Altos de Camilaca surface of the immediate area is characterized by a significant degree of primary relief, with numerous inselbergs standing up to 30 to 60 m above the plain, and interspersed with gravel-filled depressions, the remnants of paleodrainage channels. The altitude of this old surface in the vicinity of the mines ranges from 3,500 to 4,000 m a.s.l. To the northeast, it constitutes the foundation for the young stratovolcanoes, the flanks of which extend to within 10 km of the deposits. To the southwest, a short distance from the mines, an abrupt decrease in altitude marks the erosional backscarp and the upper extensions of the Pampa Lagunas apron pediment, the oldest of the middle Miocene erosion surfaces (Figs. 2c and 3b). Thus, the porphyry copper deposits are intersected by erosional landforms of different origins which extend back in time to the Paleogene-Neogene boundary (ca. 23–24 Ma). Moreover, it is evident that the Cuajone and Quellaveco deposits, and probably also the Toquepala area, were blanketed for some time by Miocene ignimbrite sheets.

Local Geomorphologic Settings and Enrichment Zones

Cuajone deposit

The Cuajone deposit occurs on the south (left) flank of the 500-m-deep canyon of the Río Torata (Fig. 4) and more extensively in its tributary, the Quebrada Chuntacala, the westerly course of which transected the central part of the mineralized zone (Manrique and Plazolles, 1975). Lacy (1958) first drew attention to the inversion of fluvial relief which took place during the recent geologic history of the area; thus, the present interfluve between the steep-walled Torata and Chuntacala Valleys is essentially coaxial with a paleovalley with gently dipping margins, partially preserved through infilling by volcanic flows.

The subplanar (Fig. 5a) northern and southern interfluves of the Torata-Chuntacala valley system, lying at ca. 3,800 to 4,200 m a.s.l. and dipping at ca. 4° to the west-southwest, are largely defined by the upper surfaces of ash-flow tuffs of the Huaylillas Formation, which locally comprises up to 280 m of predominantly rhyodacitic ash-flow tuffs with minor conglomerates and agglomerates (Manrique and Plazolles, 1975).

In the immediate Cuajone mine area, the basal member of the Huaylillas Formation is a thick welded tuff (Fig. 5b; the "trachyte" of Manrique and Plazolles, 1975, p.), 22.8 ± 0.7 Ma in age (Tosdal et al., 1981). The tuff overlies an irregular, southwesterly inclined topography with local relief up to 120 m (ca. 3,580–3,700 m a.s.l.). This flow is also coeval with an unwelded tuff intercalated in the uppermost Moquegua Formation (Fig. 3c) 30 km to the southwest (Tosdal et al., 1981). Ash-flow tuffs, therefore, probably covered much or all of the Cuajone area at this time. We consider the undulating erosional topography beneath the Huaylillas Formation to represent an early stage in the development of the Altos de Camilaca surface.

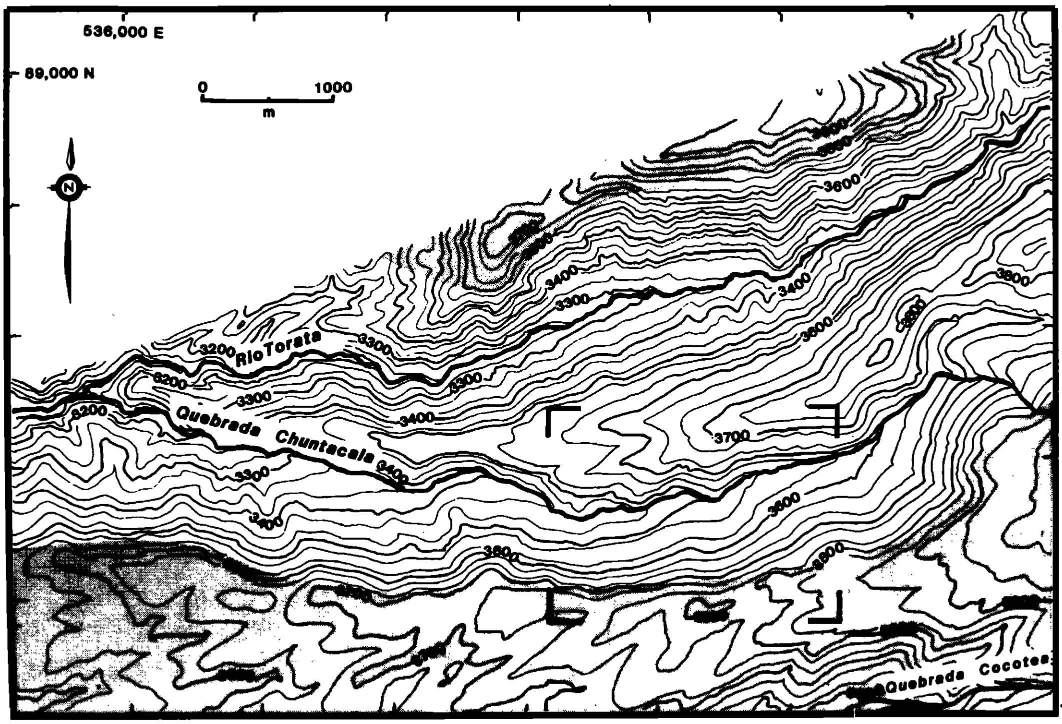

FIG. 4. Simplified premining physiographic map of the Cuajone mine area. Contour interval is 33.3 m. Shaded area, covering much of the interfluves between the Cocotea (south of map area), Chuntacala, and Torata valleys, indicates approximate extent of subplanar Oligocene and Miocene landscape, a conflation of Huaylillas Formation ash-flow tops and the erosional Altos de Camilaca surface. Area of Figure 6, centered over the Cuajone mine, is outlined.

In Quebrada Cocotea, the active drainage system immediately to the south of Quebrada Chuntacala (Fig. 4), the basal tuff attains a maximum thickness of 180 m, displays a complete welded tuff profile (Tosdal, 1978), and is underlain by a ca. 100-m-thick conglomerate (Manrique and Plazolles, 1975). These features strongly suggest that a significant valley existed in that area early in the evolution of the Altos de Camilaca surface. Consolidation of this major ash-flow tuff would probably have displaced the main local drainage to the south and north, in the latter case to the present position of Quebrada Chuntacala.

Detailed mapping of the Cuajone open pit in recent years (Satchwell, 1983; F. B. Stevenson, writ. commun., 1983) has outlined several postore stratigraphic units (Figs. 5c and 6) not clearly identified on the premine surface. These include a rhyolite clast conglomerate, exposed at the eastern extremity of the mineralized zone, and a younger "gray agglomerate" (a local informal term), exposed in the western and eastern sectors of the pit. Manrique and Plazolles (1975, fig. 2) mapped the western area of the latter unit as part of the Chuntacala Formation. Satchwell (1983) originally interpreted both units to be older than the basal ignimbrite of the Huaylillas Formation and assigned them a late Oligocene age. Subsequently, L. J. France (pers. commun., 1984) and P. C. Satchwell (pers. commun., 1986) concluded that these units are part of the Huaylillas Formation, with the rhyolitic conglomerate probably representing its local basal member and the agglomerate postdating the basal tuff. The agglomerate is in part underlain by thin mudflows that contain clasts identical to parts of the tuff.

The conglomerate, the lower contact of which has been intersected at elevations of ca. 3,565 to 3,670 m (Fig. 6), probably accumulated in a valley of moderate depth in the pre-Huaylillas Formation topography, perhaps continuous with the paleovalley underlying the present Quebrada Cocotea. The gray agglomerate filled in a relatively deep and probably more steep-walled channel, the floor of which lay at elevations of ca. 3,475 and 3,430 m in the east and west quadrants, respectively, of the present open pit (Fig. 6). Thus, significant valley development, approximately parallel to the more recent Quebrada Chuntacala, is inferred to have occurred in the immediate vicinity of the Cuajone orebody prior to and also at some later stage during the local deposition of the Huaylillas Formation. Because the youngest local ash-flow member of the formation is 18.6 ± 0.3 Ma (recalculated from date reported by Tosdal et al., 1981), the later of these erosional episodes probably took place at ca. 19 to 21 Ma. The gray agglomerate is overlain unconformably by conglomerate, thereby

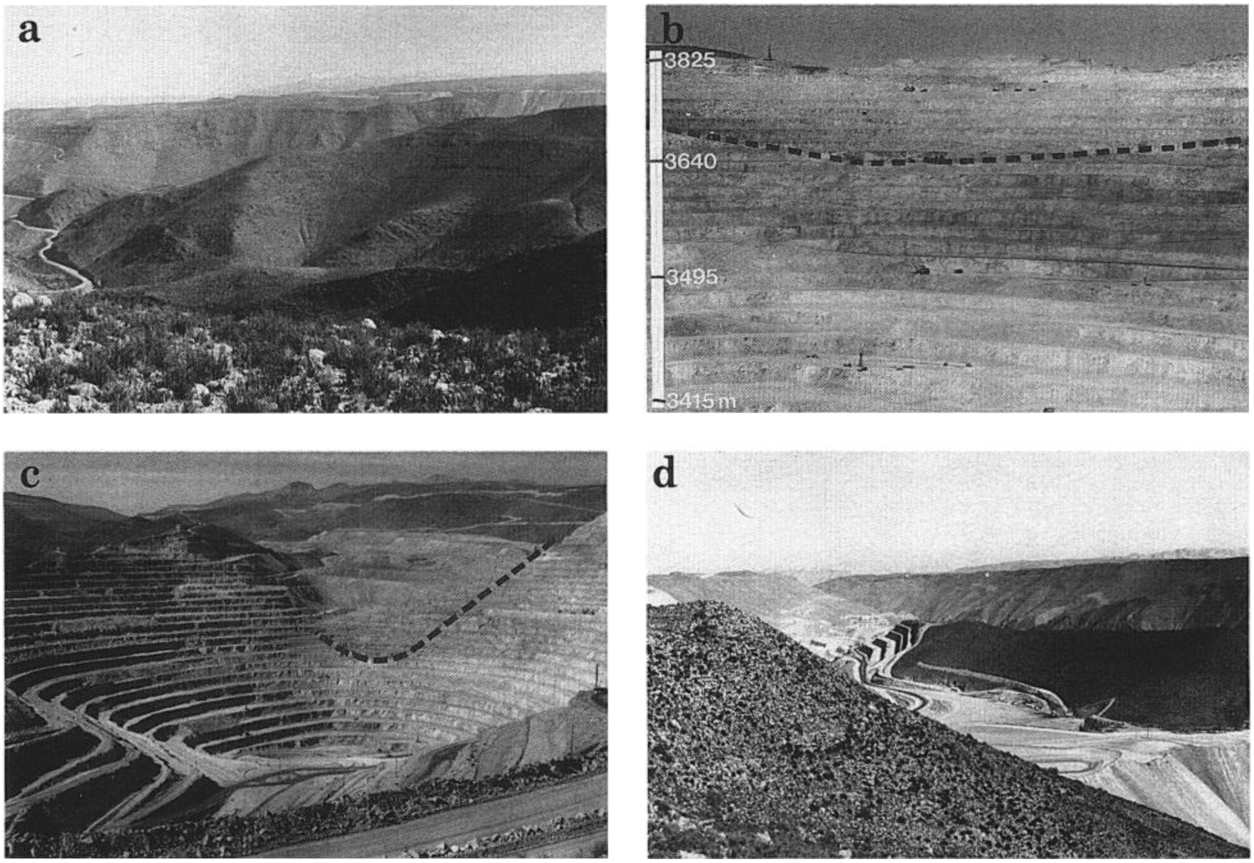

FIG. 5. Landforms and Neogene units in Cuajone mine area. a. View to the northwest from vicinity of Cerro Viña Blanca toward the Cuajone mine area (see dumps). The west-southwest-sloping subplanar ridges are largely defined by the tuffs of the lower Miocene Huaylillas Formation, but are locally degradational and represent the Altos de Camilaca surface. The thickest development of early Huaylillas Formation tuffs is exposed on the far (north) slopes of Quebrada Cocotea, the major valley in the middle distance. b. South wall of the Cuajone open pit, June 1980 (note selected bench elevations). Basal, 22.8 ± 0.7-Ma, ash flow of the Huaylillas Formation overlies an irregular unconformity (dashed line) incised into the Quellaveco quartz porphyry of the Toquepala Group. The leached capping extends from ca. 3,800 to ca. 3,495 m, overlying the tapered southern limit of the enrichment blanket. Lower part of the pit is in primary or "transitional," i.e., weakly enriched, ore (see text). c. Eastern quadrant of the Cuajone open pit, looking east-northeast, June 1983. Premine course of Quebrada Chuntacala is clearly shown. Ridge on the right is underlain by Huaylillas Formation ash flow (22.8 ± 0.7 Ma) and that on the left by ash flows and agglomerates of the middle and late Miocene Chuntacala Formation (≤13.1 ± 0.4 Ma). Trough-shaped body of gray agglomerate, herein assigned to the mid-Huaylillas Formation, fills in the steep-walled alluvial channel (dashed), incised into enriched ores. The exposed base of the agglomerate is at ca. 3,475 m. d. View to the west-southwest down Quebrada Chuntacala to upper levels of the Cuajone mine. Skyline is dominated by sloping ignimbrites of the Huaylillas Formation. The ridge separating the Chuntacala and Torata (right) valleys is underlain by the Chuntacala Formation and corresponds to the course of an open mid-Miocene valley. Axes of earlier lower Miocene valleys lay along, or to the south of, the area of the open pit.

suggesting that east-west valleys were incised here more than once in the later Huaylillas Formation interval.

With the transition to the Multiple Pediment stage after about 18 Ma, uplift and renewed erosion led to the development of a broad open valley, the axis of which lay 600 to 800 m to the north of the earlier channel or channels. Beginning at 13.1 ± 0.4 Ma (Tosdal et al., 1981), this valley was filled in by a thick (max 485 m) succession of ash-flow tuffs, agglomerates, and lahars of the Chuntacala Formation. The tuffs now underlie the interfluve between the Torata and Chuntacala Valleys (Figs. 5d and 6). This paleovalley was probably coeval with the regionally extensive middle Miocene (11.5–14.1 Ma) Pampa Lagunas apron pediment (Tosdal et al., 1984), which

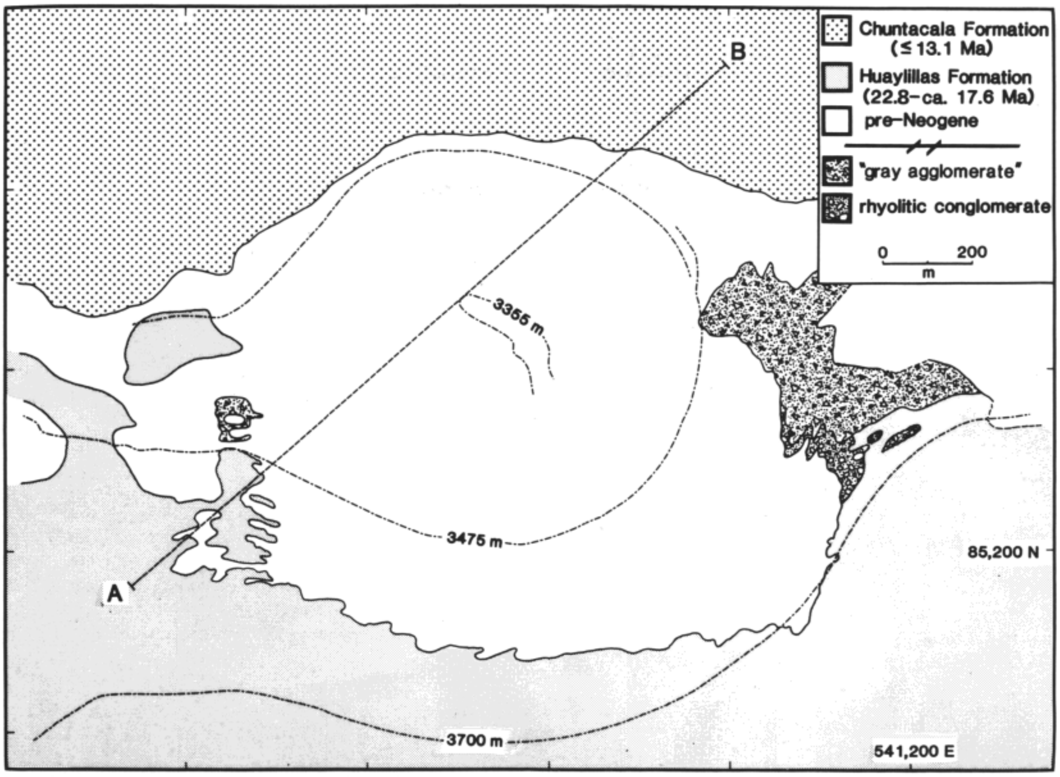

FIG. 6. Simplified map delineating the major postmineralization geologic units in the Cuajone mine area, including the Huaylillas Formation (≤22.8 ± 0.7 Ma) and Chuntacala Formation (≤13.1 ± 0.4 Ma) volcanics on the south and north margins of the open pit, respectively. The approximate locations of the rhyolitic conglomerate and gray agglomerate are shown (after Satchwell, 1983). Line A-B corresponds to the section in Figure 7.

defines much of the upper parts of the Llanuras Costaneras to the southwest of the Cuajone mine (Fig. 2c).

Intraformation unconformities within the Chuntacala Formation (Manrique and Plazolles, 1975) indicate that the mine area experienced episodic middle and late Miocene uplift, presumably during the successive developments, to the southwest, of the Cerro de las Chulpas, Pampa Sitana, and Cerro Sagollo terrace pediments (Tosdal et al., 1984), each of which records a discrete stage in the middle and late Miocene uplift of the Cordillera Occidental. However, erosion at that time apparently did not unroof the orebody. Thereafter (probably post-6.5 Ma), renewed uplift during the Valley and Terrace stage initiated the development of the extant valley of the Quebrada Chuntacala and the deeper canyon of the Río Torata (Fig. 4). This involved the erosion of much of the local Huaylillas and Chuntacala Formations volcanic cover and, eventually, renewed incision into the orebody along the axis of the Chuntacala Valley.

A cross section (Fig. 7) illustrates the premine topography in the immediate Cuajone mine area, the broad distribution of postore geologic units, and the approximate boundaries of the supergene zones. Cuajone was originally a 470-million-metric-ton deposit, with an average grade of 1 percent Cu, and containing ca. 75 million metric tons of enriched sulfide ores (avg grade ≥ 1.5% Cu). The sulfide enrichment, dominated by chalcocite sensu stricto, was apparently confined to a single blanketlike horizon, some 20 m in average thickness, which dipped gently to the west, and in the north-south cross section, showed a gentle troughing in its central portions (Fig. 7). To the south, the enrichment zone thinned markedly toward the limit of the mineralized zone (Fig. 5b). Partially oxidized ores with remnant supergene chalcocite were locally intersected by the (premine) floor of Quebrada Chuntacala, and beneath the northern interfluve, were clearly exposed on the floor of the paleovalley at the base of the Chuntacala Formation; oxidized remnants of chalcocite persist to within a few meters of this erosion surface. Moreover, it is evident that in the eastern area of the pit ores containing both coherent (massive) and powdery (sooty) chalcocite occurred within a few meters of the unconformity (paleovalley sides and bottom) underlying the gray agglomerate. It is not known if chal-

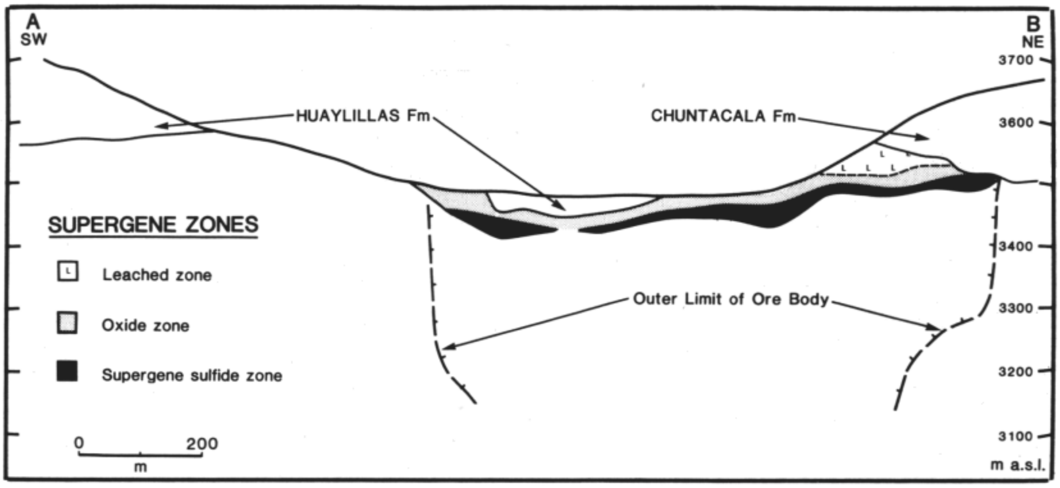

FIG. 7. Schematic southwest-northeast cross section through the Cuajone deposit showing premine topography, the approximate limit of ore-grade Cu mineralization, the major supergene zones, and the disposition of Neogene volcanic-sedimentary units. The small outlier of volcanic rocks close to the pit axis is mapped by Manrique and Plazolles (1975) as the Chuntacala Formation, but we concur with Satchwell (1983) in assigning it to the Huaylillas Formation (gray agglomerate). Note that there are other minor discrepancies between the two descriptions of the postore geology. Simplified and modified from Manrique and Plazolles (1975).

cocite occurred immediately beneath the rhyolitic conglomerate. On the southern benches of the open pit, the tapered extremity of the enrichment zone lay approximately 150 m below an irregular unconformity, representing an early stage in the evolution of the Altos de Camilaca surface (at ca. 3,500–3,640 m a.s.l.), and here it is overlain by the major ash-flow tuff of the lower Huaylillas Formation (Fig. 5b). By the early 1980s, much of the main enrichment zone had been mined out, and the lower part of the open pit lay in "transitional" ore (Satchwell, 1983), characterized by largely superficial coatings of sooty chalcocite on hypogene sulfides. The supergene assemblage comprises (Clark, in prep.) varying proportions of djurleite, roxbyite ($(Cu, Fe)_{1.83}$ S, Clark, 1972; $(Cu, Fe)_{1.74\text{-}1.82}$ S, Mumme et al., 1988), and anilite. The grade of the underlying primary ore averages 0.8 percent Cu (Satchwell, 1983).

The sulfide-enriched zone passes upward into the oxide zone (Fig. 7), which has an average thickness of 15 m and an average grade of 1.3 percent Cu. The oxide zone is considerably thicker (to 40 m) in the northern part of the deposit, i.e., in the area which lies beneath the gently inclined southern side of the valley which forms the depositional surface for the Chuntacala Formation. The oxide ores are dominated by malachite and chrysocolla, but remnants of supergene sulfides are widespread. The oxide zone itself is overlain by a hematite-bearing leached zone (0.1–0.2% Cu), with a maximum (preserved) thickness of 120 m. The mineralogic and textural relationships (Stevenson, 1972; Horlick et al., 1981; Satchwell, 1983) suggest that the entire oxide zone and at least the lower part of the leached zone formed through oxidation of sulfide-enriched (chalcocitic) ores, once continuous with the extant enrichment zone. It is, therefore, inferred that sulfide enrichment may have originally occurred as high as the 3,550-m level, i.e., within 20 to 100 m of the latest Oligocene or earliest Miocene erosional topography, and that subsequent lowering of the water table caused a significant downward penetration of oxidation and leaching. The transitional ore (see above) shows features characteristic of interfaces between supergene sulfide and primary ore zones (see Alpers and Brimhall, 1989) but probably represents a moderate redistribution of copper in response to the fall in the water table.

The observed relationships at Cuajone are in permissive agreement with a model in which sulfide enrichment took place beneath a subplanar topography ancestral to the Altos de Camilaca surface. If the leached capping developed through degradation of previously enriched sulfide ores, then the upper zones of the deposit may bear a record of a relatively prolonged period of supergene alteration beneath a subdued landscape undergoing gradual dissection; hence, supergene activity may have begun significantly before the end of the Oligocene. In any case, enrichment probably ceased at 22.8 ± 0.7 Ma when eruption of the basal (or near-basal) tuff of the Huaylillas Formation mantled the deposit. The thick leached zone underlying that unit, and exposed on the south wall of the open pit (Fig. 5b), probably developed largely prior to that volcanic episode.

Subsequently, but before 18.6 ± 0.3 Ma (see above), further oxidation and leaching of the super-

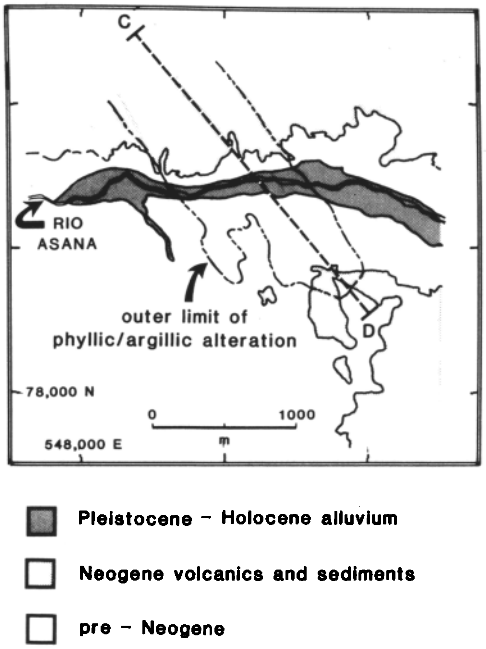

FIG. 8. Geologic sketch map of the Quellaveco prospect area (simplified and modified after Estrada, 1975) showing distribution of postmineralization Neogene volcanic and sedimentary units of the Huaylillas, Chuntacala, and "Sencca" Formations. The outline of the phyllic-argillic alteration approximately corresponds to the limit of ore-grade mineralization. The northwest-southeast line (C-D) indicates location of the cross section in Figure 12 and the southeast part of the cross section in Figure 11.

gene chalcocite ores may have resulted from their exposure during the erosion of the deep valley system occupied by the gray agglomerate, which directly overlies the orebody, and is now in contact with ores originally moderately rich in chalcocite. Satchwell (1983) ascribes the "troughing" of the leached zone and the local development of extensive supergene kaolinite to weathering beneath this valley. However, the steep configuration of the valley, and the probability that it was rapidly filled in by the agglomerate, suggests that supergene processes would not have been very effective at this stage and, moreover, would have again been terminated on the onset of eruption of the Chuntacala Formation at 13.1 ± 0.4 Ma. It remains possible that the troughing of the enrichment blanket (Fig. 7), and/or the development of the transitional enriched ores, may reflect valley incision in mid-Huaylillas Formation times, but it is more probable that they were controlled by the undulating nature of the earliest Miocene landforms ancestral to the Altos de Camilaca surface.

Supergene oxidation was probably renewed following the erosion of the Chutacala Formation strata during the Valley and Terrace stage, but it is considered unlikely that significant enrichment has occurred since the middle Miocene.

Quellaveco deposit

Copper ore reserves at the Quellaveco prospect (Fig. 1) are variously reported as 200 million metric tons at 0.95 percent Cu (Hollister, 1974) or 405 million metric tons at 0.8 percent Cu (Estrada, 1975). The Quellaveco orebody is exposed on both flanks of the deep westerly trending valley of the Río Asana and is elongated in a northwesterly direction (Fig. 8).

The broad physiographic relationships (Fig. 9) are similar to those at Cuajone. The Asana Valley is in-

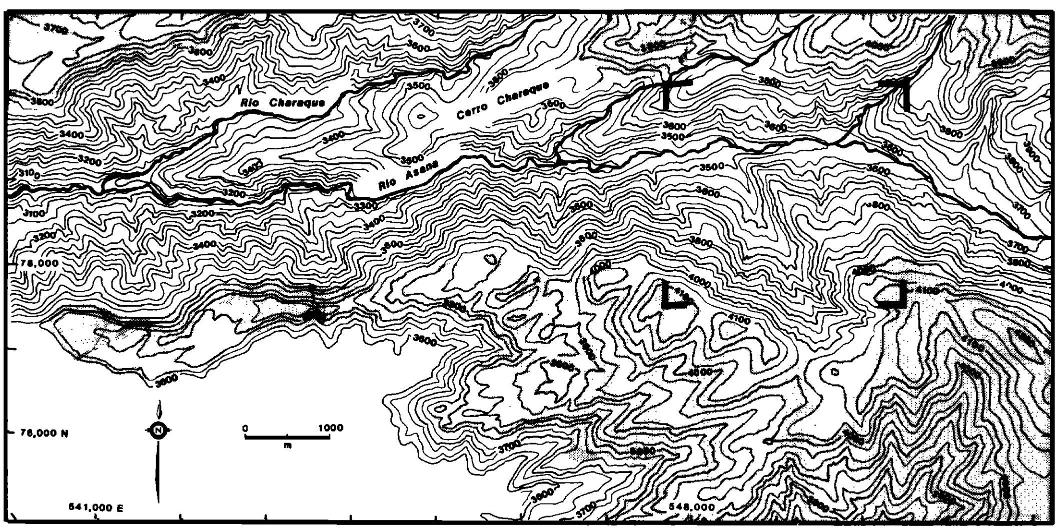

FIG. 9. Simplified physiographic map of the Quellaveco prospect area (cf. Fig. 4). Note the courses of the Ríos Asana and Charaque Valleys and the intervening unnamed quebrada. The shaded area indicates the approximate extent of the subplanar Oligo-Miocene landscape, but the smooth lower (southwesterly) part of the interfluve between the Asana and unnamed valleys is defined by gently dipping flows of the "Sencca Formation" (see Fig. 10b). The area of Figure 8 is outlined.

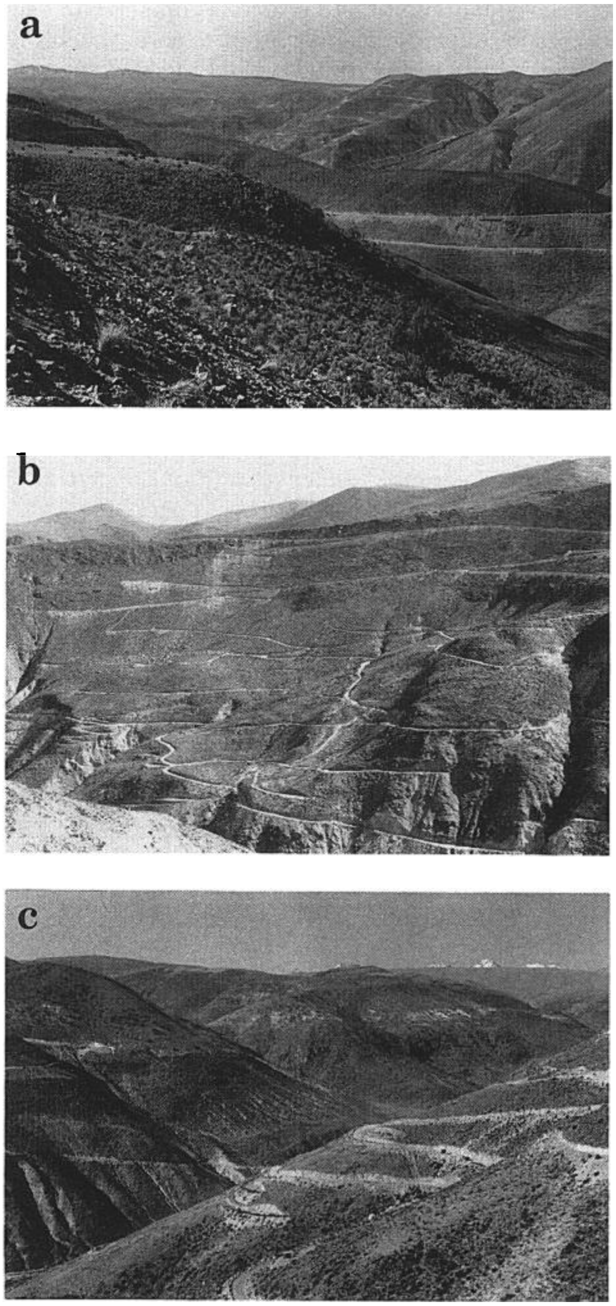

FIG. 10. Landforms and Neogene units in the Quellaveco prospect area. a. View to east-southeast from the slopes of Cerro Charaque toward the area of the Quellaveco prospect (note drill access roads on S slope of the Asana Valley). Unnamed quebrada visible in middle distance. The skyline is modified Altos de Camilaca surface capped locally by flows of the Huaylillas and Chuntacala Formations. b. View to the northwest across the Río Asana Valley and Quellaveco mineralized area. West-southwest-dipping interfluve is capped by a tuff tentatively assigned to the upper Miocene-Pliocene Sencca Formation, underlain by flows of the middle Miocene Chuntacala Formation. c. View northeast up the Río Asana Valley from the southern exposures of Quellaveco deposit. White tuff (9.5 ± 0.5 Ma) of the uppermost Chuntacala Formation is evident along the north bank of the valley, where it lies on a rock cut terrace incised into the Chuntacala Formation and underlying Toquepala Group. Smooth surfaces in distance are moraines overlying the Altos de Camilaca surface.

cised into a modified Altos de Camilaca surface, represented here (Fig. 10a) by a gently rolling high plain ca. 3,800 to 4,100 m a.s.l.; the valley floor at the Quellaveco camp is 3,500 to 3,600 m. Discontinuous remnants of Huaylillas and Chuntacala Formation ignimbrites occur on higher interfluves. One such ash-flow tuff, exposed ca. 7 km to the southwest of the deposit, has yielded a K-Ar age of 18.4 ± 0.6 Ma (Tosdal et al., 1981), similar to that of the younger of the dated Huaylillas Formation flows at Cuajone. On the southeast edge of the Asana Valley, a small erosional remnant of a 13.1 ± 0.7-Ma ignimbrite assigned to the Chuntacala Formation (Tosdal et al., 1981) is preserved in a swale on the Altos de Camilaca surface. To the northwest of the deposit, a similar middle Miocene age of 12.5 ± 0.6 Ma is reported for a thick sequence of alternating ash-flow tuffs and lahars which is exposed in the valley of the Río Charaque, a right bank tributary of the Río Asana (Fig. 8). The tuff sequence is lithologically similar to the Chuntacala Formation-type section at Cuajone. However, the uppermost preserved tuff in the Charaque Valley has an age of 6.5 ± 0.6 Ma and displays violet quartz phenocrysts considered characteristic of the Pliocene ash flows of the Sencca Formation in the region (Tosdal, 1978; Tosdal et al., 1981). This assignment is, however, probably incorrect (R. J. Langridge, pers. commun., 1989).

The interfluves between the valleys of the Río Charaque and Río Asana have quasiplanar tops and dip gently to the west-southwest (Figs. 9 and 10b). The lower slopes in both valleys are underlain by volcanic rocks of the Upper Cretaceous-Paleocene Toquepala Group and intruded by broadly coeval plutons (Bellido, 1979). The smooth interfluve between the Asana and Charaque Valleys is the slightly eroded depositional surface of an ash-flow tuff that is tentatively correlated either with the Sencca Formation in the Charaque Valley, or with an underlying flow of the upper part of the Chuntacala Formation. Other tuffs assigned to the Chuntacala Formation are exposed on the northern slopes of the upper Asana Valley at an approximate elevation of 3,750 to 3,775 m a.s.l. Thus, the Quellaveco deposit was buried at different times by volcanic rocks of the middle and upper Miocene Chuntacala and uppermost Miocene and Pliocene Sencca Formations. Undoubtedly the deposit was also at one time covered by the Huaylillas Formation.

A conspicuous feature of the right bank of the Asana Valley for a considerable distance upstream from the Quellaveco deposit (Fig. 10c) is a thick, white-weathering, unwelded ash-flow tuff underlain by a discontinuous fluvial conglomerate, together constituting the Quellaveco breccias and conglomerates of Estrada (1975). The flow is 9.5 ± 0.5 Ma (Tosdal et al., 1981) and lacks the violet quartz eyes of the upper unit in the Charaque Valley. The tuff cannot be traced along the northern slopes of the Asana Valley to the west of the deposit. Upstream, a topographic bench incised into volcanic flows and intrusions of the Toquepala Group and the overlying Chuntacala Formation volcanics (above) locally takes the place of the white tuff, and we conclude that the latter was deposited in a valley incised into the older rocks to a level close to the Paleogene-Neogene unconformity. Similar stratigraphic and geomorphologic relationships probably occur on the south slope of the present Asana Valley, but the tuff and the underlying bench are less extensively preserved. Moreover, the erosional surface underlying the conglomerate and young tuff lies ca. 75 m higher on the south side of the valley, probably resulting from post-9.5-Ma faulting along the present Asana Valley (Estrada, 1974).

On the basis of the above relationships, the following sequence of Neogene events in the area is proposed: (1) final stages in the development of the Altos de Camilaca surface at ca. 19 to 25 Ma; (2) eruption of the younger Huaylillas Formation ignimbrites at about 18.4 Ma; (3) incision of a broad open valley, the axis of which probably coincided approximately with the present interfluve between the Asana and Charaque Valleys; (4) deposition of a thick succession of Chuntacala Formation ignimbrites and lahars, beginning at ca. 13.1 ± 0.7 Ma and filling in the paleovalley and locally spilling over its southern rim onto the Altos de Camilaca surface; (5) focusing of fluvial erosion in the area of the present Charaque Valley and in the approximate position of the present Río Asana, where these valleys are narrower and with steeper slopes than the earlier systems; (6) deposition of fluvial conglomerates and the 9.5 ± 0.5-Ma ignimbrite, which was assigned to the uppermost Chuntacala Formation (Tosdal et al., 1981); (7) eruption of the upper Miocene and Pliocene Sencca Formation ignimbrites, now preserved only above ca. 3,800 m a.s.l.; and (8) incision of the present deep canyon of the Río Asana, the valley of the Río Charaque, and the intervening quebradas. The age of the faulting episode along the axis of the Río Asana cannot be precisely defined, but it probably coincided with either stages (6) or (7) above. The approximate relationships of the above features are illustrated in the sketch cross section of Figure 11, along the northwesterly trending axis of the Quellaveco orebody (cf. Figs. 8, 9, and 12). Stage (3) is correlated with the development of the Pampa Lagunas pediment in the Llanuras Costaneras and stage (5) with the Cerro Sagollo pediment, respectively the earliest and latest episodes in the Multiple Pediment stage (Tosdal et al., 1984). The post-9.5-Ma deepening of the Asana and other valleys occurred during the subsequent Valley and Terrace stage.

Estrada (1974, 1975) has shown that a single supergene sulfide enrichment blanket is developed at

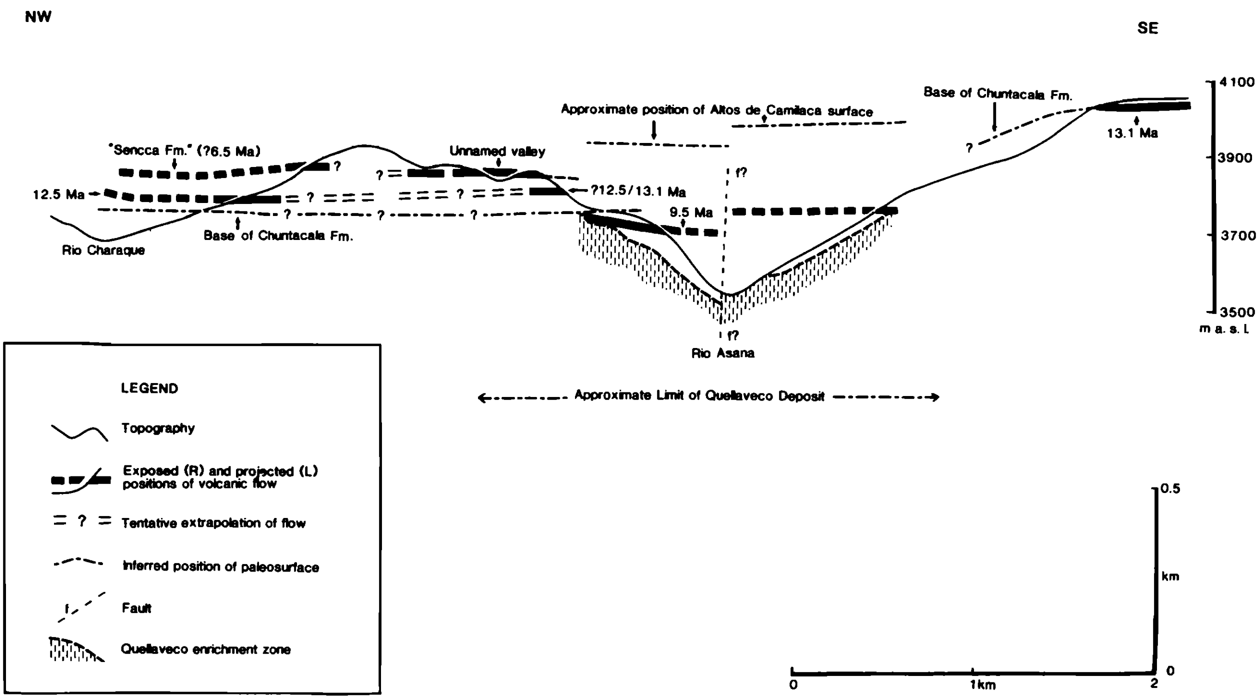

FIG. 11. Schematic northwest-southeast cross section along axis of the Quellaveco orebody, illustrating interrelationships of present topography, Neogene ignimbrite flows (some undated), inferred paleolandforms, and the Quellaveco enrichment zone. The section is approximately orthogonal to the extant river valleys. The last episode of faulting along the axis of the Asana valley is assumed to have occurred after eruption of the 9.5 ± 0.5-Ma ignimbrite. Vertical scale is exaggerated.

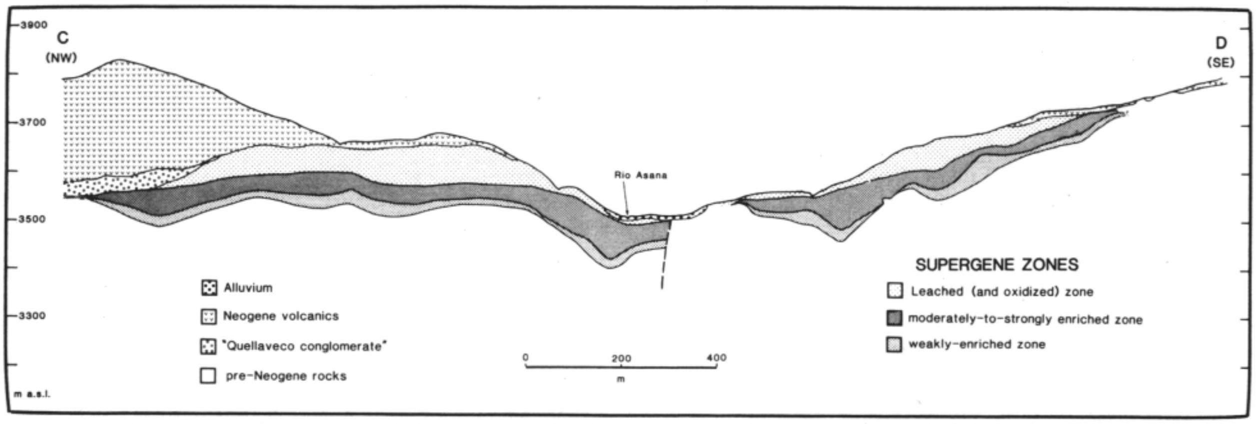

FIG. 12. Cross section (looking northeast) of the Quellaveco supergene zones, after Estrada (1974; sect. 13). Note the different distribution of postore sedimentary and volcanic units on the south and north flanks of the Asana Valley. The volcanics are undifferentiated, but in this section they probably comprise mainly the 9.5 ± 0.5-Ma white tuff (see Fig. 10c) of the upper Chuntacala Formation. Note the intersection of the enrichment zone by the erosion surface (valley bench) underlying the fluvial conglomerate and the displacement of the supergene profile by the easterly trending fault.

Quellaveco, as at Cuajone (Fig. 12). Two zones are distinguished: an upper zone of moderate to strong enrichment overlying a lower grade zone, presumably representing a downward transition to unaltered hypogene ores. The chalcocite-bearing zone is significantly thicker (50–60 m) and more irregular than at Cuajone. It attains depths of 250 to 300 m below the present surface and has a gentle troughlike form in vertical cross section, crudely reflecting the configuration of the Asana Valley slopes (Estrada, 1975). The enriched zone is generally overlain by a leached and/or oxidized zone, extending from surface to maximum depths of 80 m. An east-west-trending fault close to the present axis of the Asana Valley offsets the northern part of the enrichment blanket downward about 75 m (Fig. 12; Estrada, 1975). Restoration of this offset would enhance the subparallel relationship of the present valley and the trough in the enrichment blanket (Fig. 12).

The enriched zone at Quellaveco is truncated by the lower slopes of the present Asana Valley. On the north flank of the valley, the unconformity beneath the 9.5 ± 0.5-Ma ignimbrite and the underlying conglomerate intersects the sulfide enrichment zone as well as the overlying leached-oxidized zone (Figs. 12 and 13); oxidized remnants of chalcocite occur within 50 cm of this old valley floor. Similar relationships are apparent between the enrichment blanket and the vestigially preserved outliers of tuff on the southern slopes of the valley (Fig. 12; see Estrada, 1974, 1975).

The relationships between supergene enrichment and the older topographically higher landforms are less clear. The highest exposures of the enriched zone, at its southern extremity, lie at altitudes of ca. 3,750 m a.s.l. approximately 250 m below the horizontally extrapolated position (ca. 4,000 m a.s.l.) of the exhumed Altos de Camilaca surface (Fig. 11), which is at a significantly greater relative depth than at Cuajone (see above). A vertical separation of this extent

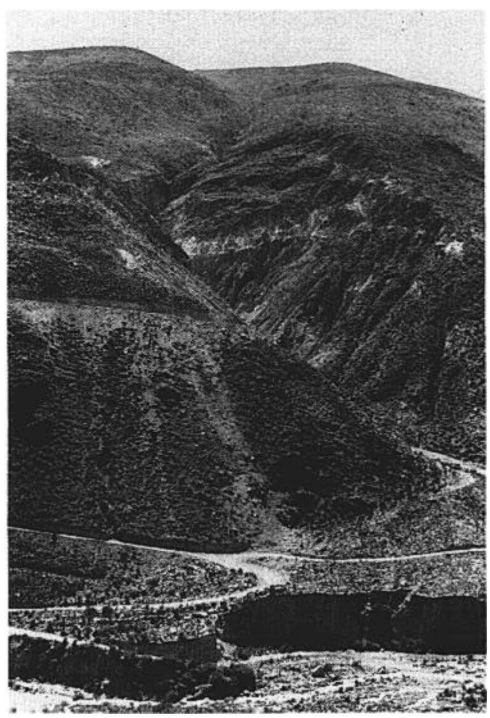

FIG. 13. View to the north-northeast across the Asana Valley incised into oxidized and enriched Quellaveco mineralization. White cliffs on the far slope of tributary quebrada are outcrops of 9.5 ± 0.5-Ma tuff, which immediately overlies a ca. 8-m-thick conglomerate. Lower slopes are in the ore zone, with remnants of supergene chalcocite persisting to within 50 cm of the unconformity.

between land surface and water table would not be unusual in a mountainous semiarid environment. For example, in physiographically similar settings in the Copiapó district of Chile (Fig. 1), enrichment assemblages are intensely developed at depths of ca. 200 to 300 m below the present surface in the Chañarcillo silver veins (Whitehead, 1919), and supergene chalcocite is abundant at depths in excess of 275 m in the Dulcinea de Llampos copper mine, at a level approximately coinciding with the premine water table (Sillitoe et al., 1968; Sillitoe, 1969). Similarly, the leached zone overlying the enrichment blanket at the La Escondida porphyry deposit (Fig. 1) locally attains depths of 400 m below surface (Brimhall et al., 1985; Ojeda, 1986; Alpers and Brimhall, 1989). It is therefore possible that enrichment at Quellaveco could have occurred beneath the lower Miocene surface prior to its mantling by the 18.4-Ma flow.

The open valley inferred to have subsequently developed at Quellaveco would (Figs. 11 and 12) have been incised to within 75 to 100 m of the preserved enrichment zone. If hydrologic conditions had been suitable for supergene alteration, it is highly probable that enrichment would have taken place at that time, perhaps involving upgrading and deepening of an earlier formed blanket. The troughlike form of the enriched zone may broadly reflect this valley. Enrichment would again have been interrupted and probably terminated by deposition of the thick Chuntacala Formation succession, beginning at ca. 13.1 Ma.

Our model, therefore, involves two or more superimposed enrichment phases resulting, not in the development of vertically separate blankets but in the thickening and upgrading of a single zone (see for example, Locke, 1926; Brimhall et al., 1985; Alpers and Brimhall, 1989). The apparently greater development (and/or preservation) of enriched sulfide ores at Quellaveco than at Cuajone may be in part the result of a less intense regime of local valley incision into the Altos de Camilaca surface during the early Miocene over the interval represented by the Huaylillas Formation. Although we infer that enrichment at Quellaveco was more protracted than at Cuajone—possibly extending from the later Oligocene to the middle Miocene—it had similarly terminated before the close of the Multiple Pediment stage prior to 9.5 Ma. Oxidation, but little sulfide enrichment, accompanied the more recent stages in the deepening of the Asana Valley. The major fault along the valley has not focused significant sulfide enrichment or oxidation of the ores.

Toquepala deposit

Of the three porphyry centers, the Toquepala deposit displays the most extensive record of sulfide enrichment (Richard and Courtright, 1958; Anderson, 1982), but paradoxically, this cannot be precisely constrained in time due to the absence of datable Neogene tuffs in the immediate mine area. However, an early Miocene K-Ar age of 18.3 Ma has been determined (Tosdal et al., 1981) for a tuff which caps a 40-m-thick succession of tuffs and conglomerates of the Upper Moquegua Formation some 20 km south-southeast of Toquepala. This tuff is lithologically and chronologically similar to the 18.4 ± 0.6-Ma ignimbrite in the Quellaveco area, some 15 km north of Toquepala (see above). Other tuffs of the Huaylillas Formation near Cuajone and also some 50 km to the south near the Peru-Chile border have similar K-Ar ages of 18.6 ± 0.6 and 18.4 ± 0.5 Ma, respectively (see above; Bellón and Lefèvre, 1976). The widespread occurrence of tuffs of similar age throughout the region renders it likely that the Toquepala deposit was covered by tuffs at that time in the early Miocene.

The Toquepala porphyry copper deposit originally cropped out in a southerly trending valley, Quebrada Toquepala, and its short tributary, Quebrada Huancanani, which were eroded to depths of ca. 300 m into an erosion surface with a local mean altitude of ca. 3,600 m a.s.l. and with a gentle south-southwesterly slope (Figs. 14 and 15a). As at Cuajone and Quellaveco, this landscape near Toquepala had significant primary relief but, from the widespread occurrence of accordant, in part planate summits (Fig. 15a), it may be assigned to the Altos de Camilaca surface (Tosdal et al., 1984). Immediately to the southwest of Toquepala, the surface slope steepens to ca. 7° (Fig. 15b) before falling abruptly to an altitude of ca. 2,600 m a.s.l. at the northeastern margin of the Pampa Lagunas pediment (Fig. 2). This landform configuration postdates all significant local movement on the major west-northwest-trending Incapuquio fault (Wilson and García, 1962), which traverses the lower precordilleran slope (Bellido and Landa, 1965; Tosdal, 1978). A comparably steep inclination to the Altos de Camilaca surface is observed elsewhere only at the margin of an apparent Miocene caldera some 30 km southeast of Toquepala. A similar volcanic event may have occurred north or northeast of the mine, although no circular structure is visible on Landsat images in that area, perhaps due to burial by younger volcanics.

Prior to mining, Quebrada Toquepala possessed a composite, goblet-shaped profile which, by analogy with other valley profiles in this region, suggests that the gently dipping upper slopes probably developed during the Multiple Pediment stage, and the more steeply incised lower slopes during the ensuing Valley and Terrace stage.

Supergene sulfide enrichment in the Toquepala deposit extends over a much greater vertical interval than at Cuajone or Quellaveco; secondary chalcocite after chalcopyrite and bornite occurred between 3,525 and at least ca. 3,100 m a.s.l. (Richard and Courtright, 1958; Southern Peru Copper Corp., unpub. repts.). Much of the enriched ore has been

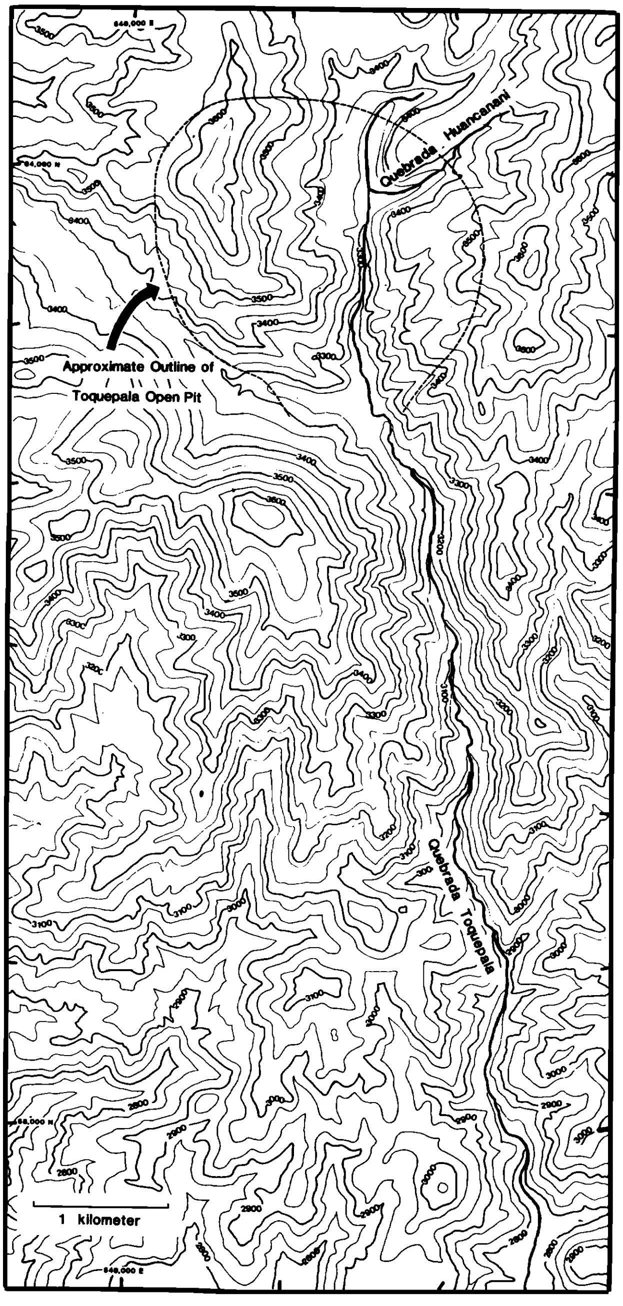

FIG. 14. Premine physiography of the Toquepala mine area. Quebrada Toquepala and its tributaries are incised into a south-southwest-dipping planate landform assigned to the Altos de Camilaca surface.

mined, but its original distribution may be defined approximately. Remnants of zones affected by enrichment are visible (Fig. 16a) in the open pit because of the associated supergene argillic alteration, which gives rise to a pale, bluish-gray coloration on broken rock surfaces and, in the upper levels, through the development of reddish-brown hematite, an oxidation product of chalcocite-pyrite associations (Anderson, 1982). The most extensive enrichment zone, and the only one systematically delimited on the basis of ore grade by mine personnel (Fig. 17), has a broadly planar, but locally irregular, upper surface which is subhorizontal in east-west projection but which falls from an altitude of ca. 3,350 m at the northern limit of the deposit to ca. 3,250 m at the southern limit (a horizontal distance of ca. 700 m). In contrast, the lower boundary of the enrichment zone is very indented, with deep roots resulting in enriched ore thicknesses in excess of 150 m. Although locally such downward extensions of chalcocite development lie beneath the valley axis, in general there is no correlation between enrichment blanket configuration and/or thickness and the premine valley form. A local

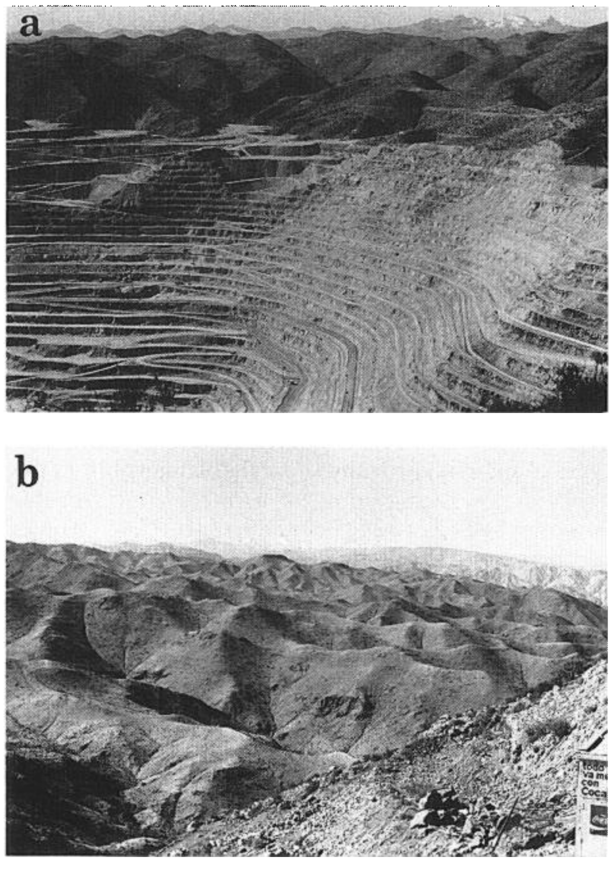

FIG. 15. Landforms in the Toquepala mine area. a. View to the northeast from Cerro Toquepala, across the eastern half of the Toquepala open pit (June 1982). In the distance, Cerro Condoriquiña stands above the southwest-sloping, planate, rock-cut, landform—the Altos de Camilaca surface. Upper courses of the Quebradas Toquepala (center) and Huacanani (right) incise the pediplain. b. View to the east-southeast from Barrio Azul (5 km southwest of the Toquepala open pit), along the southwestern margin of the precordillera. The southwest-dipping landform represents a tilted and strongly dissected remnant of the Altos de Camilaca surface, developed here in the Upper Cretaceous Toquepala Group volcanics and Paleocene granitoid intrusions. The flat-topped mesa rising above the surface in the middle ground is a remnant of the Huaylillas Formation (Bellido and Landa, 1969).

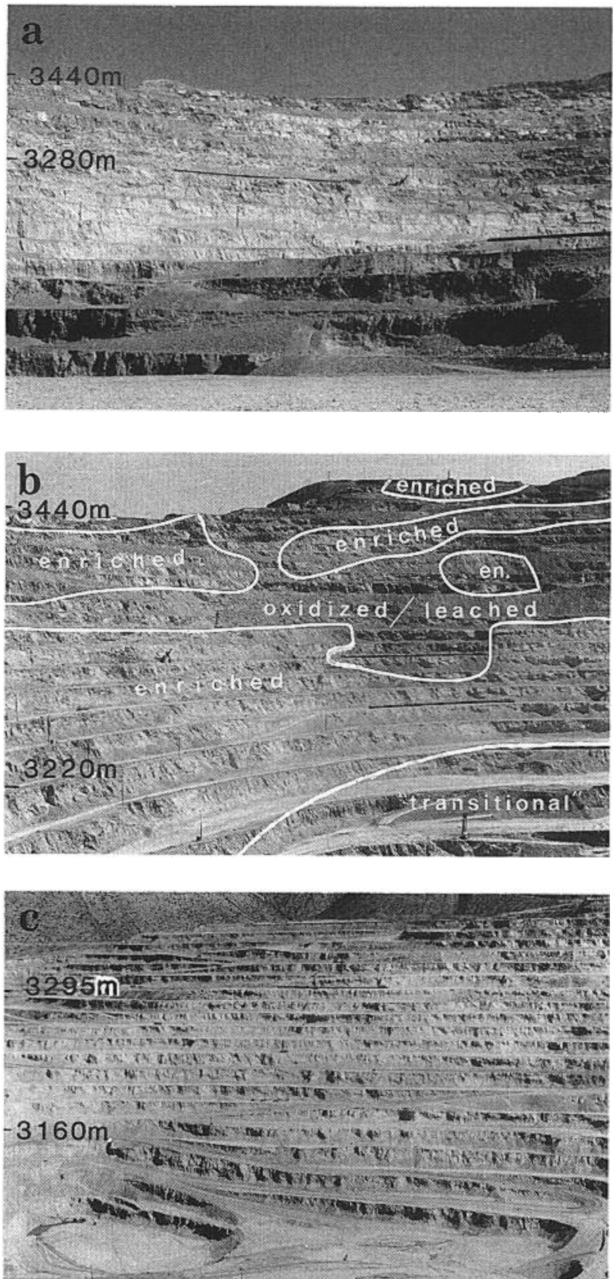

FIG. 16. Distribution of enriched zones on west and northwest walls of the Toquepala open pit. a. Strongly foreshortened view looking west from the 3,145-m level (June 1975). Dark (in part shadowed) benches in foreground are in transitional ore, with erratic distribution of powdery (sooty) chalcocite on hypogene assemblages. In higher levels, the sulfide-enriched zones are whitish, due to the development of supergene kaolinite, and the oxidized and leached zones are darker. The lower (main) enriched zone immediately overlies the transitional ore and is essentially continuous around the west wall of the pit. The overlying older enriched zones are less regular in form. Selected bench elevations are shown (m.a.s.l.). b. Northwest quadrant of the open pit (August 1975), showing (areas delimited by white lines) the main lower enriched zone and the irregular, discontinuous, distribution of the upper enriched zones (view is essentially contiguous with that in 17a). The highest development of chalcocite (at top-right), now strongly oxidized, extends to the margin of the pit and to within 50 m of the dissected Altos de Camilaca surface, here partially mantled by dumps. The lower three visible benches are mainly in transitional ore. Selected bench elevations are shown. c. Oblique view of the west wall of the open pit, looking southwest from the 3,280-m bench (June 1982). Compare with Figure 17a—enriched ores (pale) are now exposed quasicontinuously from the shallowest levels (top-right) to the upper boundary of the hypogene ore (lower 4–5 benches). The oxidized zone on the upper benches corresponds to dark areas. Bottom level at 3,085 m a.s.l.

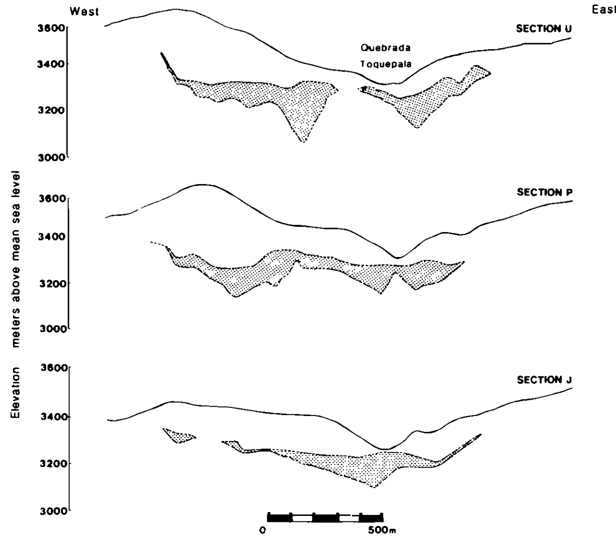

FIG. 17. Schematic west to east cross sections through the lower main enrichment blanket of the Toquepala mine, showing its relations to the premine configuration of Quebrada Toquepala. The sections traverse the southern (J), central (P), and northern (U) parts of the deposit. The central break in the enrichment in the northern part of the deposit delimits the postore and essentially barren dacite agglomerate breccia pipe. The enrichment blanket shown is as delimited by premine drilling on the basis of copper grades (+0.45%: after unpub. data, Southern Peru Copper Corp.).

control of the depth of enrichment by postore faults is apparent in some parts of the deposit. This does not, however, explain why the main enrichment zone was both thicker (Fig. 17) and of higher mean grade in the western quadrant of the deposit than in the eastern part in many east-west sections. In the absence of evidence for major north-striking faults through the deposit, this asymmetrical distribution of enrichment may be inferred to reflect primary-grade variations, or the preservation of thick impermeable rhyolites (Serie Alta) of the premineralization Toquepala Group over the eastern part of the orebody (Richard and Courtright, 1958), which could have inhibited copper leaching and enrichment.

At the northern and southern limits of the open pit, the main enrichment zone was locally separated from the lower slopes of Quebrada Toquepala by less than 20 m (Fig. 17), and its formation therefore certainly predated at least the later stages of valley incision. The overall southerly dip (ca. 8°–9°) of its upper surface, broadly paralleling that of the upper precordilleran slope in the southern part of the mine area (Fig. 15b), implies a control by a subplanar south-dipping topography. Whereas the upper and central parts of this enrichment zone were dominated by massive coherent chalcocite, its lower section and lateral peripheries display extensive development of sooty supergene sulfides, giving rise to transitional ore, as at Cuajone. The lowermost enriched ores are mineralogically similar to those at Cuajone, comprising black to midnight-blue powdery coatings of djurleite, roxbyite, and anilite (Clark, in prep.).

The original large-scale distribution of chalcocite-bearing ores in the shallower levels of the open pit is now difficult to reconstruct, largely because routine mineralogic observations have not been carried out during mining, while, to the authors' knowledge, no such studies were made in the initial drilling program. It is evident that such higher altitude and presumably older enrichment was also focused in the western (or northwestern) quadrant of the deposit. Anderson (1982, fig. 12.15) identified such a single zone dipping fairly steeply to the south. However, observation of the distribution of relict chalcocite and supergene kaolinite on the western and northwestern benches of the pit has revealed extremely irregular and varying patterns as the pit walls were displaced to the west from 1975 to 1982. Whereas in 1975 to 1978 (Fig. 16a, b), two, apparently separate, supergene sulfide zones were evident, centered at ca. 3,330- and 3,440-m elevations, in 1982 remnants of chalcocite were visible (Fig. 16c) on most benches between the 3,280- and 3,490-m benches and were locally apparently continuous with the lower main enrichment zone. However, as pointed out by Anderson (1982), ores immediately overlying the lower enrichment zone are characterized by extensive development of jarosite after hypogene chalcopyrite. The highest surviving enrichment observed during the period of study, at the 3,535-m level, lies only 40 to 75 m below the accordant summits assigned to the Altos de Camilaca surface adjacent to the northwest margin of the pit (Figs. 15a and 16b).

We concur with Richard and Courtright (1958) and Anderson (1982) that the unusually thick enrichment in the Toquepala deposit resulted from periodic uplift and that the spatial isolation of the lower (main) zone probably records an episode of uplift of a sufficient magnitude to have depressed the local water table below the level previously affected by supergene sulfide formation. The irregular enrichment zones above ca. 3,330 m may reflect either two or more periods of alteration separated by significant uplift events or a single protracted period of enrichment accompanying a relatively slow depression of the water table.

As noted previously, no firm temporal constraints may be placed on the supergene sulfide enrichment at Toquepala. The proximity of the uppermost chalcocite zone to the Altos de Camilaca surface indicates that enrichment began prior to the final stages in the development of that landform, i.e., in the earliest Miocene or before. Although no tuffs crop out in the mine area, the widespread preservation of ca. 18-Ma ash-flow tuffs throughout the region renders it probable that the deposit was then buried, resulting in interruption of the supergene process. Moreover, an earlier episode of covering by tuff may be recorded by the occurrence of a 23.3 ± 0.8-Ma tuff (Tosdal et al., 1981) in the Moquegua Formation some 25 km to the west of, and broadly downslope from, Toquepala. It cannot be confirmed whether any tuffs of the Chuntacala Formation were subsequently emplaced in the area.

The higher altitude early enrichment, at least in part, clearly predated the initial incision of Quebrada Toquepala. Indeed, the subplanar upper surface of the lower (main) supergene sulfide zone, and its close approach to the premine valley bottom, implies that it was similarly generated, largely or entirely, prior to local valley development. However, the available data do not permit us reliably to assign an age to the important uplift episode which we infer immediately preceded the main enrichment period. Three possible models may explain the interrelations of enrichment and landform development at Toquepala. In the first model, all enrichment would be ascribed to weathering beneath the evolving Altos de Camilaca surface in the late Oligocene and early Miocene, the supergene activity being eventually terminated by eruption of the 18.3- to 18.4-Ma Huaylillas Formation ignimbrite. According to this model, the major uplift which preceded the main enrichment would be assigned to the latest stages in the generation of the surface. In the second model, the early upper chalcocite zones are inferred to have formed during the final stages in the development of the Altos de Camilaca surface, whereas the deep zone may have developed in response to rapid uplift, tilting, and water table descent caused by local caldera formation, presumably in the early Miocene (at 18.3 Ma ?). This model must remain hypothetical in the absence of evidence for a caldera to the north of Toquepala. However, because ash-flow eruption would normally be intimately associated with crustal flexure in a caldera setting (Smith and Bailey, 1968), the period immediately following such an event would probably be unpropitious for supergene activity. The third model would correlate the early enrichment with the Altos de Camilaca surface and the later with the earlier part of the Multiple Pediment stage and probably specifically with the intermediate stages in the development of the Pampa Lagunas apron pediment, for which the tilted surface south of the mine constitutes the original backscarp. The lower main enrichment would thus have developed following erosion of the 18.3 ± 0.6-Ma ignimbrite and probably at ca. 13 Ma (see Tosdal et al., 1984, fig. 5). In this model, the considerable extent of the lower chalcocite zone would reflect (1) the strong uplift and resulting downward displacement of the water table which characterized the Multiple Pediment stage (Tosdal et al., 1984); (2) the absence, or rapid removal by erosion, of the Chuntacala Formation in the immediate area; and (3) the lack of deep incision of Quebrada Toquepala until the later Miocene.

Whereas we consider it clear that enrichment of the Toquepala deposit had begun prior to the Multiple Pediment stage, very probably in the latest Oligocene to earliest Miocene, we cannot decide between the above models for the age of the later, more intense enrichment stage. Nevertheless, we prefer the third model in which chalcocite development persisted into the middle Miocene (ca. 11–18 Ma; see above).

Synthesis

The above discussion of the Tertiary geomorphologic context of supergene processes in the area surrounding the Cuajone, Quellaveco, and Toquepala mines demonstrates both the potential of this approach in the elucidation of the controls on the economically critical enrichment and the uncertainties inherent in the unraveling of complex cordilleran landform development.

The ore deposits were emplaced in the early Eocene (Clark et al., 1990) at shallow depths (equivalent to confining pressures of ca. 100–150 bars; Zweng, 1984) but, given the considerable thickness of subaerial volcanic strata constituting the Toquepala Group, at a significant elevation (≥2,000 m a.s.l.). Following their unroofing in the Eocene and Oligocene during a prolonged period of comparative tectonic quiescence, all three porphyry centers experienced a history of episodic uplift and mantling by tuffs during the initial stages in the development of the present-day Cordillerra Occidental at this latitude. It is evident that supergene activity was most intense during conversion of a regionally extensive erosional surface of low altitude and relief into the faceted, polyphase, and mountainous landscape of the present precordillera.

Despite the lacunae in our knowledge of local Neogene geologic events, a comparison of the enrichment histories of these three deposits provides a basis for an understanding of the factors which influence supergene processes. In particular, the progressive increase in the extent of chalcocite mineralization, from the modest blanket at Cuajone through the thicker enriched zone at Quellaveco to the multiple blankets at Toquepala, can be linked with differences in erosional history and the extent of burial beneath Neogene pyroclastic rocks. It is apparent that the critical parameters affecting the formation and/or preservation of enrichment zones in these deposits were (1) the location and rate of valley incision during the early Miocene; and (2) the local frequency of emplacement and persistence of Miocene tuffs. Both parameters were themselves strongly influenced by the local regime of fluvial channel development.

In passing from Cuajone to Toquepala, there was evidently a progressive diminution in the intensity (i.e., extent and frequency and/or rapidity) of valley development across the evolving subplanar precordilleran landscape during the earliest Miocene and a concomitant decrease in blanketing by tuff flows. At Cuajone, we infer that the supergene sulfide enrichment blanket is largely relict from the late Oligocene and was formed in association with the evolution of the subdued landscape ancestral to the Altos de Camilaca surface. At that time, gradual erosion and depression of the water table permitted the progressive downward extension of chalcocite development and the encroachment of the leached zone over earlier enriched horizons. Since then, the local conditions have been largely unfavorable for supergene activity, due almost entirely to the presence of extensive tuffs on top of the deposit. Valley incision across the tuffs and subjacent orebody and potentially favorable water table lowering were of insufficient duration for any significant enrichment, because the valleys were quickly filled by successive tuffs and other pyroclastic rocks of the Huaylillas and Chuntacala Formations. It is clear in any case that all significant supergene activity predated consolidation of the basal (13.1-Ma) ash flow of the Chuntacala Formation. Thus, the major episodic uplift associated with the Multiple Pediment stage failed to generate important enrichment at Cuajone, although it is possible that some development of the sooty chalcocite of the transitional ores may have persisted into this period. Only minor oxidation may be assigned to the later Miocene and subsequent interval.

The 80-m-thick enrichment blanket in the Quellaveco deposit formed prior to the 9.5 ± 0.5-Ma tuff of the Chuntacala Formation which directly overlies oxidized chalcocite ores. The markedly troughlike form of the enriched zone suggests that it developed, at least in part, beneath an extensive open valley which we infer to have been in existence in the mid-Miocene, between 18.4 and 13.1 Ma. However, we strongly favor a model in which such enrichment during the Multiple Pediment stage was superimposed upon an earlier supergene profile which was generated beneath the Altos de Camilaca surface in the earliest Miocene or latest Oligocene, probably coeval with the enrichment at Cuajone. Thus, despite the complex succession of Miocene erosional and volcanic events represented in the Quellaveco district, the episodes of valley incision were, in aggregate, favorable for the deepening of the main chalcocite zone, and the blanketing by the Huaylillas and Chuntacala Formation tuffs was insufficiently protracted to impede seriously the supergene activity.

In our opinion, the considerable vertical extent and apparently polystage nature of the Toquepala enrichment is a direct reflection of the ephemeral nature of Miocene ignimbrite cover in the mine area and of unusually strong uplift and tilting, probably in the mid-Miocene. The disposition of the highest altitude residual chalcocite zones shows clearly that they formed beneath the Altos de Camilaca surface or its late Oligocene antecedents. A brief interruption of supergene activity at ca. 18.3 Ma probably occurred in response to burial beneath tuffs. The deepest main enrichment zone was generated following a significant episode of uplift and oceanward tilting of the precordillera in the Toquepala transect. This event cannot be dated, but we favor an origin during the earlier part of the Multiple Pediment stage, i.e., at ca. 13 Ma, rather than prior to the probable emplacement of the 18.3-Ma flow. Thus, development of massive chalcocite ores may have persisted somewhat later than at Quellaveco and it is implicit that no significant burial by the Chuntacala Formation ignimbrites took place.

It is evident that both physiographic and climatic conditions were broadly favorable for supergene activity in the late Oligocene to middle Miocene interval in southern Peru. Economically important enrichment certainly occurred in the early Miocene (ca. 23–18 Ma) but had ceased by the earliest late Miocene. The correspondence between the uppermost preserved zones of supergene chalcocite and the Altos de Camilaca surface strongly implies that enrichment began as early as approximately 25 to 30 Ma, probably shortly following exhumation of the deposits. Subsequently, whereas climatic conditions favorable for enrichment clearly persisted into, and perhaps throughout, the middle Miocene Multiple Pediment stage, the extent of new enrichment and preservation of extant supergene zones was entirely dependent upon the local configuration of valley development and the presence or absence of Miocene tuffs over the deposits. Thus, the aggressive development of cordilleran relief in the Miocene caused the upgrading of an earlier formed chalcocite blanket at Quellaveco and generated new enrichment zones at Toquepala, but led to oxidation and erosion of supergene profiles at Cuajone.

Regional Correlations

Supergene enrichment has upgraded numerous small copper vein systems exposed on the Pacific slope of the Cordillera Occidental elsewhere in southernmost Peru. The Norvill mine, 13 km southeast of Toquepala (Várgas, 1975), worked ores in which chalcocite, after chalcopyrite, had been oxidized to malachite and chrysocolla (Clark, unpub. data). The deposit crops out on the southwesterly tilted segment of the Altos de Camilaca surface (see Fig. 15b), and the supergene enrichment was presumably related to an early stage in the development of that landform.

In the small Lluta (Cercana) Cu(-Ag, Pb) district (Várgas, 1975), situated 120 km south of Toquepala, veins were exploited in which massive supergene chalcocite was extensively converted to malachite. The enriched veins crop out on a rock-cut bench of the Quebrada Lluta. This bench is interpreted as a restricted terrace pediment, and its elevation strongly suggests that it is equivalent in age to the Multiple Pediment stage of the Toquepala-Cuajone area. Thus, enrichment here is at least middle Miocene in age and may have begun development in the early Miocene.

Elsewhere in southern Peru, 110 km west-northwest of Cuajone, the large Cerro Verde-Santa Rosa porphyry copper center (16°32′ S), broadly coeval with the deposits under discussion (Estrada, 1975), displays an extensive supergene profile (Kihien, 1975; Mineroperú, unpub. data). Mining operations by Mineroperú in the Cerro Verde sector have been based on high-grade oxidized ores, dominated by brochantite, which overlie a zone of sulfide enrichment up to 300 m in thickness, attaining a depth of 465 m below the 2,903-m-a.s.l. summit of Cerro Verde. In the adjacent Santa Rosa sector, 1.5 km to the southeast, a much thinner (30–50 m), but laterally extensive, subhorizontal enrichment zone lies ca. 50 m beneath an interconnected series of small intermontane basins. The surrounding summits are accordant and, in many cases, are flat topped. They are tentatively interpreted as the remnants of the landform which controlled the enrichment process, the "Caldera surface" of Jenks (1948). Both the accordant summits and the intermontane basins are considered to represent pediments that are as yet undated. However, on the basis of long-distance correlations of landforms, we tentatively suggest that the older summit surface is equivalent in age to the Altos de Camilaca surface, whereas the basin floors, representing the upper extensions of the very extensive alluviated pediplain which constitutes the Pampas Costaneras (Pampa de La Joya) ca. 15 to 20 km southwest of the mine area, are probably coeval with the Multiple Pediment stage. If this model is correct, the enrichment of the Cerro Verde-Santa Rosa deposit would be inferred to be, at least in its earlier stages, of late Oligocene or earliest Miocene age. The great depths attained by the enrichment process beneath Cerro Verde itself may reflect the permeability of the breccia bodies which host the mineralization in this area and may record a protracted history of supergene activity extending into the Multiple Pediment stage.

The age and physiographic setting of supergene enrichment in northern Chile are remarkably similar to those established in southern Peru. Supergene enrichment of the Chuquicamata porphyry system in northern Chile (Fig. 1) occurred in the interval 16.5 to 26 Ma (Mortimer et al., 1977) beneath a regionally developed planate landscape broadly correlative with the Altos de Camilaca surface. To the south, the younger of the two enrichment episodes recognized in the Copiapó district (e.g., Sillitoe et al., 1968; Mortimer, 1973), though not precisely delimited, had terminated prior to the development of the Atacama pediplain, before 12.9 Ma (Clark et al., 1967a; Sillitoe et al., 1968). This episode followed a late Eocene (39- to 43-Ma) episode of copper mineralization (Farrar et al., 1970; Clark et al., 1976). A late Oligocene and early Miocene age for enrichment in that area of northern Chile may therefore be inferred. The attendant regional erosional landform, the Sierra Checo del Cobre surface (Mortimer, 1973), thus probably formed at the same time as the Altos de Camilaca surface in the study area. Finally, Alpers and Brimhall (1988) report early and middle Miocene K-Ar ages for supergene alunite within the unusually extensive and high-grade chalcocite blanket and associated leached capping of the La Escondida porphyry deposit (Fig. 1).

It is therefore apparent that the late Oligocene to early Miocene interval proved favorable for intense supergene upgrading of copper deposits along a ca. 2,000-km stretch of the Pacific slope of the evolving Cordillera Occidental (-Principal), from southern Peru to north-central Chile. The essential simultaneous enrichment defines a discrete metallogenic episode, or perhaps two closely spaced episodes, of great importance, directly correlated with major pulses of uplift of the cordillera in the latest Oligocene (ca. 18–25 Ma) and early middle Miocene (ca. 12–16 Ma). In this context, the ca. 37-Ma age of supergene alunite in the El Salvador deposit recorded by Gustafson and Hunt (1975) is anomalous. For this deposit the geomorphology only constrains enrichment to have predated the local formation of the Atacama pediplain, prior to 12.9 Ma. Lacking any evidence to the contrary, we can only conclude that climatic and landform conditions at El Salvador were suitable for major enrichment in the early Oligocene, although no regional erosional surface or enrichment episode of this age has been recognized in the region (Mortimer, 1973).

Conclusions

Supergene enrichment processes in the central Andes context achieved their maximum development in the late Oligocene and early to middle Miocene, stimulated by an optimal conjunction of episodic uplift of the Cordillera Occidental and a prevailing semiarid climate. The moderate precipitation (perhaps exceeding 10 cm/annum) inferred for this period not only permitted significant circulation of meteoric water through the upper parts of the exposed ore deposits but favored the formation of subplanar pediments and open valleys. That both supergene activity and pedimentation have essentially terminated in this region has long been ascribed to the onset in the later Miocene of an arid and even hyperarid climatic regime (e.g., Mortimer, 1969; Mortimer and Sarič, 1975; Mortimer et al., 1977), itself a product of the northward propagation of a cold littoral current. This aspect of the later history of the Andes has been analyzed in detail by Alpers and Brimhall (1988), who identify the essential causative factors to be the establishment of the circum-Antarctic current and the subsequent formation of the Antarctic ice cap at 13 to 15 Ma. They also emphasize the key importance of the climatic desiccation and resultant decrease in erosion rates in the preservation of earlier formed supergene zones in what is now the Atacama Desert. In this context, it should be emphasized that economically significant enrichment has also affected the very young Río Blanco-Disputada (≤7.4 Ma; Warnaars et al., 1985) and El Teniente (Howell and Molloy, 1960; ≤4.7 Ma; Clark et al., 1983) deposits of central Chile, which have experienced a pluvial cold-temperate, or even periglacial, climate throughout much of their brief exposure history.

Although there is some evidence that major enrichment may have locally persisted to a slightly later period in southern Peru than in northern Chile, the available age constraints are insufficient to define a significant northerly change in the time of enrichment cessation. Instead, in comparing the two broad transects, we would emphasize the greater extent, both absolute and relative, of the late Oligocene to middle Miocene uplift events in southern Peru. Thus, whereas much of northern Chile had already achieved considerable altitudes by the Eocene (e.g., Mortimer, 1973), southern Peru lay close to sea level until the late Oligocene (Tosdal et al., 1984). Thereafter, uplift and crustal thickening were far more abrupt in this area than farther to the south. This would favor deep enrichment of the ore deposits. However, the region surrounding the Cuajone, Quellaveco, and Toquepala porphyry centers experienced more intense volcanic activity during the late Oligocene and early Miocene interval than did geomorphologically comparable areas in northern Chile. The closely spaced eruption of thick tuffs at this critical juncture in southern Peru must have played a key role in limiting the extent of enrichment in the deposits under study and particularly in the case of Cuajone. In contrast, there is no evidence for local volcanism in the area surrounding La Escondida, Chile, during the early and middle Miocene, thus permitting essentially uninterrupted development of an enrichment blanket both considerably thicker and of higher grade than those preserved in southern Peru. Volcanism of late Oligocene and early Miocene age (ca. 25–15 Ma) affected wide areas of northern Chile, extending from the Peruvian border to at least latitude 26° S (e.g., Zentilli, 1974; Coira et al., 1982). However, the scattered geochronologic data suggest that major mid-Tertiary tuffs were erupted less frequently south of ca. 21° S in northern and north-central Chile where the Paleocene to mid-Oligocene porphyry copper deposits occur, than in northernmost Chile and southernmost Peru (Mortimer et al., 1974; Tosdal et al., 1981; Lahsen, 1982). In particular, ignimbrites of this age are probably less extensively developed on the lower altitude slopes of the cordillera. The lack of significant enrichment in some porphyry deposits in northern Chile, e.g., at El Abra (lat 21°55′ S), thus must reflect the pyrite-poor nature of the outcropping ores (Amrus, 1977) rather than unfavorable physiography or burial beneath upper Oligocene and lower Miocene ash flows.

In conclusion, we propose that the approach followed in the present study, involving the clarification of the geomorphologic evolution of mineralized districts, holds considerable promise in the prediction of the extent of supergene enrichment in cordilleran environments, as was early envisaged by those pioneers of modern Andean landform study, Kenneth Segerstrom and Stanley Hollingworth.

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REFERENCES

Alpers, C. N., and Brimhall, G. H., 1988, Middle Miocene climatic change in the Atacama Desert, northern Chile: Evidence from supergene mineralization at La Escondida: Geol. Soc. America Bull., v. 100, p. 1640–1656.

—— 1989, Paleohydrologic evolution and geochemical dynamics of cumulative supergene metal enrichment at La Escondida, Atacama Desert, northern Chile: ECON. GEOL., v. 84, p. 229–254.

Alpers, C. N., Brimhall, G. H., Cunningham, A. B., and Burns, P. J., 1984, Mass balance and timing of supergene enrichment at La Escondida, Antofagasta province, Chile [abs.]: Geol. Soc. America Abstracts with Programs, v. 16, p. 428.

Ambrus, J., 1977, Geology of the El Abra porphyry copper deposit, Chile: ECON. GEOL., v. 72, p. 1062–1085.

Anderson, J. A., 1982, Characteristics of leached capping and techniques of appraisal, *in* Titley, S. R., ed., Advances in the geology of porphyry copper deposits, southwest North America: Tucson, Univ. Arizona Press, p. 245–287.

Barúa, V., 1961, Reconocimiento geológico—zona de Tacna y Moquegua: Cong. Nac. Geologia Soc. Geol. Perú, 2nd, Anales pt. 1, v. 36, p. 35–59.

Beckinsale, R. D., Sánchez-Fernandez, A. W., Brook, M., Cobbing, E. J., Taylor, W. P., and Moore, N. D., 1985, Rb-Sr whole-rock isochron and K-Ar age determinations for the Coastal batholith of Peru, *in* Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., eds., Magmatism at a plate edge: The Peruvian Andes: Glasgow, Blackie, p. 177–202.

Bellido, E., 1979, Geología del cuadrángulo de Moquegua (hoja: 35-u): Lima, Perú, Inst. Geol. Minero Metal., 78 p.

Bellido, E., and Landa, C., 1965, Mapa geológico del cuadrángulo de Moquegua (1:100,000): Lima, Perú, Comm. Carta Geol. Nac.

Bellón, M., and Lefèvre, C., 1976, Données géochronométriques sur le volcanisme andin dans le sud du Pérou: Acad. Sci. [Paris] Comptes Rendus, v. 283, p. 1–4.

Berggren, W. A., Kent, D. W., Flynn, N. J., and Van Couvering, J. A., 1985, Cenozoic geochronology: Geol. Soc. America Bull., v. 96, p. 1407–1418.

Brimhall, G. H, Alpers, C. N., and Cunningham, A. C., 1985, Analysis of supergene ore-forming processes and ground-water solute transport using mass balance principles: ECON. GEOL., v. 80, p. 1227.

Clark, A. H., 1972, A natural occurrence of hexagonal $Cu_{1.83}S$, El Teniente, Chile: Nature: Phys. Sci., v. 238, no. 86, p. 123–124.

Clark, A. H., and Sillitoe, R. H., 1971, Supergene anilite from mina Estrella (Salado), Atacama, Chile: Neues Jahrb. Mineralogie Monatsh., 1971, no. 11, p. 515–523.

Clark, A. H., Cooke, R. U., Mortimer, C., and Sillitoe, R. H., 1967a, Relationships between supergene mineral alteration and geomorphology, southern Atacama Desert, Chile—an interim report: Inst. Mining Metallurgy Trans., v. 76, sec. B, p. B89–B96.

Clark, A. H., Mayer, A. E. S., Mortimer, C., Sillitoe, R. H., Cooke, R. U., and Snelling, N. J., 1967b, Implications of the isotopic ages of ignimbrite flows, southern Atacama Desert, Chile: Nature, v. 215, p. 723–724.

Clark, A. H., Farrar, E., Caelles, J. C., Haynes, S. J., Lortie, R. B., McBride, S. L., Quirt, G. S., Robertson, R. C. R., and

Zentilli, M., 1976, Longitudinal variations in the metallogenetic evolution of the central Andes: A progress report: Geol. Assoc. Canada Spec. Paper 14, p. 23–56.
Clark, A. H., Farrar, E., Camus, F., and Quirt, G. S., 1983, K-Ar age data for the El Teniente porphyry copper deposit, central Chile: ECON. GEOL., v. 78, p. 1003–1006.
Clark, A. H., Farrar, E., Kontak, D. J., Langridge, R. J., Arenas, M. J., France, L. J., McBride, S. L., Woodman, P. L., Wasteneys, H. A., Sandeman, H. A., and Archibald, D. A., 1990, Geologic and geochronologic constraints on the metallogenetic evolution of the Andes of southeastern Peru: ECON. GEOL., v. 85, p. 1520–1583.
Coira, B., Davidson, J., Mpodozis, C., and Ramos, V., 1982, Tectonic and magmatic evolution of the Andes of northern Argentina and Chile: Earth-Sci. Rev., v. 18, p. 302–332.
Cooke, R. U., and Warren, A., 1973, Geomorphology in deserts: Berkeley, Univ. California Press, 393 p.
di Castri, E., and Hajek, E. R., 1976, Bioclimatogía de Chile: Santiago, Chile, Univ. Católica, 128 p.
Emmons, W. H., 1917, The enrichment of ore deposits: U. S. Geol. Survey Bull. 625, 530 p.
Estrada, F., 1974, Geological cross-sections (1:4000) through Quellaveco deposit: Lima, Perú, Minero-Perú, unpub. rept.
—— 1975, Geología de Quellaveco: Soc. Geol. Perú Bol., v. 46, p. 65–86.
Farrar, E., Clark, A. H., Haynes, S. J., Quirt, G. S., Conn, H., and Zentilli, M., 1970, K-Ar evidence for the post-Paleozoic migration of granite intrusion foci in the Andes of northern Chile: Earth Planet. Sci. Letters, v. 9, p. 17–28.
Guerrero, T., and Candiotti, H., 1979, Ocurrencía de monzonita porfirítica y zonamiento alteración-mineralización en el stock de granodiorita-Quellaveco—yacimiento de cobre Quellaveco: Soc. Geol. Perú Bol., v. 63, p. 69–79.
Guilbert, J. M., and Park, C. F., Jr., 1986, The geology of ore deposits: New York, W. H. Freeman and Co., 985 p.
Gustafson, L. B., and Hunt, J. P., 1975, The porphyry copper deposit at El Salvador, Chile: ECON. GEOL., v. 70, p. 857–912.
Hollingworth, S. E., 1964, Dating the uplift of the Andes of northern Chile: Nature, v. 201, p. 17–20.
Hollister, V. F., 1974, Regional characteristics of porphyry copper deposits of South America: Soc. Mining Engineers AIME Trans., v. 255, p. 45–53.
Horlick, J. M., Cooper, W. C., and Clark, A. H., 1981, Aspects of the mineralogy and hydrometallurgy of chrysocolla, with special reference to the Cuajone, Peru, ores: Internat. Jour. Mineral Processing, v. 8, p. 49–59.
Howell, F. M., and Molloy, J. S., 1960, Geology of the Braden orebody, Chile, South America: ECON. GEOL., v. 55, p. 863–905.
Instituto Nacional de Planificación, 1965, Projecto de Irigación en Moquegua: Lima, República Perú, Inst. Nac. Planificación, 110 p.
Jenks, W. F., 1948, Geología de la Hoja de Arequipa: Inst. Geologico Perú Bol., v. 9.
Kihien, A., 1975, Alteración y su relación con la mineralización en el pórfido de cobre de Cerro Verde: Soc. Geol. Perú Bol., v. 46, p. 103–126.
Lacy, W. C., 1958, Porphyry copper deposit, Cuajone, Peru: Am. Inst. Mining Metall. Petroleum Engineers Trans., v. 11, p. 104–107.
Lahsen, A., 1982, Upper Cenozoic volcanism and tectonism in the Andes of northern Chile: Earth-Sci. Rev., v. 18, p. 285–302.
Locke, A., 1926, Leached outcrops as a guide to copper ores: Baltimore, Williams Wilkins Co., 166 p.
Mabbutt, J. A., 1955, Pediment landforms in Little Namaqualand, South Africa: Geographical Jour., v. 121, p. 77–83.
Manrique, J., and Plazolles, A., 1975, Geología de Cuajone: Soc. Geol. Perú Bol., v. 46, p. 137–150.
Marocco, R., and Noblet, C., 1990, Sedimentation, tectonism and volcanism relationships in two Andran basins of southern Peru: Geol. Rundschau, v. 79, p. 111–120.
McBride, S. L., 1977, A K-Ar Study of the Cordillera Real, Bolivia, and its regional setting: Unpub. Ph.D. thesis, Kingston, Queen's Univ., 230 p.
Meigs, P., 1953, World distribution of arid and semi-arid homoclimates, *in* Reviews of research on arid zone hydrology: Paris, UNESCO, Arid Zone Programme, v. 1, p. 203–210.
Mortimer, C., 1969, The geomorphological evolution of the southern Atacama Desert, Chile: Unpub. Ph.D. thesis, Univ. London, 283 p.
—— 1973, The Cenozoic history of the southern Atacama Desert, Chile: Geol. Soc. Jour. London, v. 129, p. 505–526.
Mortimer, C., and Sarić, N., 1975, Cenozoic studies in northernmost Chile: Geol. Rundschau, v. 64, p. 395–420.
Mortimer, C., Farrar, E., and Saric, N., 1974, K-Ar ages from Tertiary lavas of the northernmost Chilean Andes: Geol. Rundschau, v. 63, p. 484–489.
Mortimer, C., Munchmeyer, F. C., and Urqueta, D. I., 1977, Emplacement of the Exótica orebody, Chile: Inst. Mining Metallurgy Trans., v. 86, sec. B, p. B121–B127.
Mumme, W. G., Sparrow, G. J., and Walker, G. S., 1988, Roxbyite, a new copper sulphide mineral from the Olympic Dam deposit, Roxby Downs, South Australia: Mineralog. Mag., v. 52, p. 323–336.
Ojeda, J. M., 1986, Escondida porphyry copper deposit, II Región, Chile: Exploration drilling and current geological interpretation: Mining Latin America/Minería Latinoamericana Conf., Santiago, Chile, Nov. 17–19, 1986, Proc., p. 299–318.
Richard, K., and Courtright, H. W., 1958, Geology of Toquepala, Peru: Mining Eng., v. 10, p. 262–266.
Satchwell, P. C., 1983, Geología de la mina Cuajone: Soc. Geol. Perú Bol., v. 72, p. 127–146.
Segerstrom, K., 1963, Matureland of northern Chile and its relationship to ore deposits: Geol. Soc. America Bull., v. 74, p. 513–518.
Sillitoe, R. H., 1969, Studies of the controls and mineralogy of the supergene alteration of copper deposits, northern Chile: Unpub. Ph.D. thesis, Univ. London, 498 p.
Sillitoe, R. H., and Clark, A. H., 1969, Copper- and copper-iron sulfides as the initial products of supergene oxidation, Copiapó mining district, northern Chile: Am. Mineralogist, v. 54, p. 1684–1710.
Sillitoe, R. H., Mortimer, C., and Clark, A. H., 1968, A chronology of landform evolution and supergene mineral alteration, southern Atacama Desert, Chile: Inst. Mining Metallurgy Trans., v. 77, sec. B, p. B166–B169.
Smith, R. L., and Bailey, R. A., 1968, Resurgent cauldrons: Geol. Soc. America Mem. 116, p. 613–662.
Steiger, R. H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth Planet. Sci. Letters, v. 36, p. 359–362.
Stevenson, F. B., 1972, Summary report: Geology and mineralization, Cuajone porphyry copper deposit, Moquegua, Peru: Cuajone, Peru, Southern Peru Copper Corp., unpub. int. rept., 56 p.
Torpoco, C., 1979, Petrografía, alteraciones y mineralización del yacimiento de Quellaveco—Moquegua: Soc. Geol. Perú Bol., v. 63, p. 117–134.
Tosdal, R. M., 1978, The timing of the geomorphic and tectonic evolution of the southernmost Peruvian Andes: Unpub. M.Sc. thesis, Kingston, Queen's Univ., 136 p.
Tosdal, R. M., Farrar, E., and Clark, A. H., 1981, K-Ar geochronology of the late Cenozoic volcanic rocks of the Cordillera Occidental, southernmost Peru: Jour. Volcanology Geotherm. Research, v. 10, p. 157–173.
Tosdal, R. M., Clark, A. H., and Farrar, E., 1984, Cenozoic polyphase landscape and tectonic evolution of the Cordillera Oc-

cidental, southernmost Peru: Geol. Soc. America Bull., v. 95, p. 1318–1332.

UNESCO, 1980, Desertification in the region of Coquimbo, Chile, *in* Mabbutt, J. A., and Floret, C., eds., Case studies on desertification: London, UNESCO Nat. Resources Ser. 18, p. 52–114.

Vargas, R., 1975, Geología minera del Departamento de Tacna: Soc. Geol. Perú Bol., v. 46, p. 187–204.

Warnaars, F. W., Holmgren, C., and Sergio Barassi, F., 1985, Porphyry copper and tourmaline breccias of Los Bronces—Río Blanco, Chile: ECON. GEOL., v. 80, p. 1544–1565.

Whitehead, W. L., 1919, The veins of Chañarcillo, Chile: ECON. GEOL., v. 14, p. 1–45.

Wilson, J. J., and García, W., 1962, Geología de los cuadrángulos de Pachía y Palca (hojas 36-v y 36-x): Lima, Peru, Com. Carta Geol. Nac., v. II, no. 4, 82 p.

Zentilli, M., 1974, Geological evolution and metallogenetic relationships in the Andes of northern Chile between 26° and 29° south: Unpub. Ph.D. thesis, Kingston, Ontario, Queen's Univ., 446 p.

Zimmerman, J.-L., and Kihien, A., 1983, Détermination par la méthode K/Ar de l'âge des intrusions et des minéralisations associées dans le porphyre cuprifère de Quellaveco (sud oeste du Pérou): Mineralium Deposita, v. 18, p. 207–213.

Zweng, P. L., 1984, Evolution of the Toquepala porphyry Cu (-Mo) deposit, Peru: Unpub. M.Sc. thesis, Kingston, Queen's Univ., 131 p.

Zweng, P. L., and Clark, A. H., 1984, Impact of major tourmaline breccia formation on the evolution of the Toquepala Cu-(Mo) porphyry, Peru [abs.]: Geol. Soc. America Abstracts with Programs, v. 16, p. 706.