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Genesis of the Giant Late Miocene to Pliocene Copper Deposits of Central Chile in the Context of Andean Magmatic and Tectonic Evolution

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Abstract

Multiple large mineralized breccia pipes (Cu grades up to >10%; individual pipes with >10 × 10^6 metric tons of Cu) are prominent, if not dominant, features in the three giant Andean Cu deposits of Los Pelambres, Los Bronces–Río Blanco, and El Teniente of central Chile. At Los Bronces–Río Blanco, over 90% of the >50 × 10^6 metric tons of hypogene Cu occurs within the matrix of breccias and/or clasts and wall rock altered in association with the formation of these breccias, while at the other two deposits a lesser but still significant amount of Cu ore also is directly related to breccias. At both Los Pelambres and Los Bronces–Río Blanco, high-grade (>0.5%) Cu occurs in zones of potassic alteration characterized by stockwork biotite veining and intense biotitization associated spatially, temporally, and genetically with biotite breccias. At Los Bronces–Río Blanco, high-grade ore also occurs in younger tourmaline breccia pipes, emplaced both within and around the older central biotite breccia complex and potassic alteration zone after a period of uplift and erosion. Potassic alteration, sericitization, silicification, and mineralization of clasts in these tourmaline breccias occurred during their formation. At El Teniente, a significant amount of high-grade Cu ore also occurs in different tourmaline-rich breccias, including the marginal portion of the Braden breccia pipe and a related zone of quartz-sericite alteration that surrounds this pipe. Small, shallow, weakly mineralized or barren silicic porphyry intrusions occur in each of these three deposits, but their main role has been to redistribute rather than emplace mineralization.

The mineralized breccia pipes in each deposit were emplaced into early and middle Miocene volcanic and plutonic rocks during the late Miocene and Pliocene by the expansion of boiling aqueous fluids. Fluid-inclusion and stable-isotope data indicate that the high-temperature, saline, metal-rich fluids that produced the brecciation, precipitated the Cu ore in the matrix of the breccias, and generated the associated alteration and mineralization in clasts and wall rock were magmatic in origin. These magmatic fluids were not derived from the early and middle Miocene host plutons, which already were solidified at the time of breccia emplacement. Sr- and Nd-isotopic compositions of breccia-matrix minerals indicate that breccia-forming fluids were exsolved from magmas that were isotopically transitional between older volcanic and plutonic host rocks and younger silicic porphyry stocks, dikes, and extrusives. The fact that the roots of the breccias have not yet been encountered implies that these magmas cooled at depths >3 km to form plutons not yet exposed at the surface.

The generation of the multiple mineralized breccias at each deposit occurred over a relatively short (but still significant) time period of 1 to 3 million years, during the final stages of existence of the long-lived (>15 m.y.) Miocene magmatic belt in central Chile. The decline of magmatic activity in this belt was tectonically triggered, as subduction angle decreased in association with the subduction of the Juan Fernández Ridge. This caused a decrease in the sub-arc magma supply and subsequently eastward migration of the magmatic arc, as well as crustal thickening, uplift, and erosion, which led to the superposition of younger and shallower alteration and mineralization events on older and deeper events in each deposit.

The giant Cu deposits of central Chile cannot be explained by a static model in which their size is a function of the mass of a single pluton or the longevity of a single hydrothermal convection system. These deposits are giant because they were produced by multistage processes involving the formation, over a period of 1 to 3 million years, of multiple superimposed mineralized breccias and associated alteration zones resulting from the exsolution of metal-rich magmatic fluids from independent magma batches cooling at depths >3 km. Neither an unusually large magma supply nor Andean magmas of unusually high Cu content is required to produce the sequence of multiple mineralization events that together generated each deposit.

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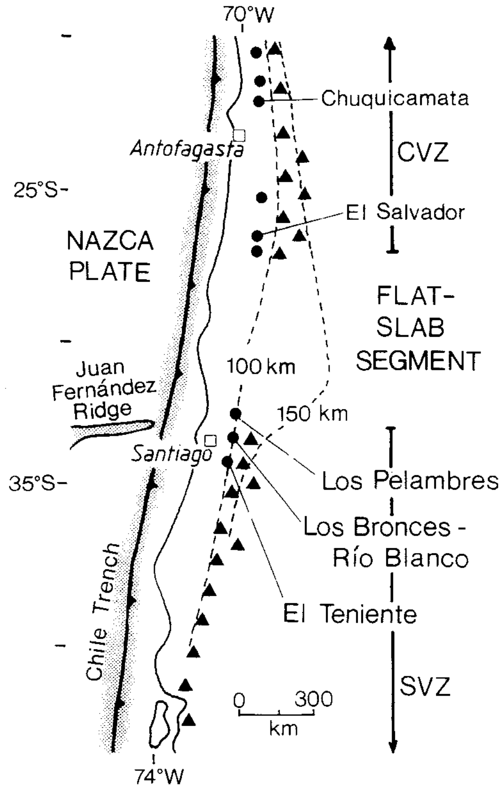

FIG. 1. Location of the late Miocene to Pliocene Cu deposits Los Pelambres, Los Bronces-Río Blanco, and El Teniente in central Chile, near the boundary of the Andean flat-slab segment and Southern Volcanic Zone (SVZ) of active volcanos (triangles). Also shown are the belt of mid-Tertiary Cu deposits in northern Chile (circles) west of the Central Volcanic Zone (CVZ) and tectonic features such as the Juan Fernández Ridge, Chile Trench, and depths to the subducted Nazca plate (dashed lines) (Bevis and Isacks, 1984).

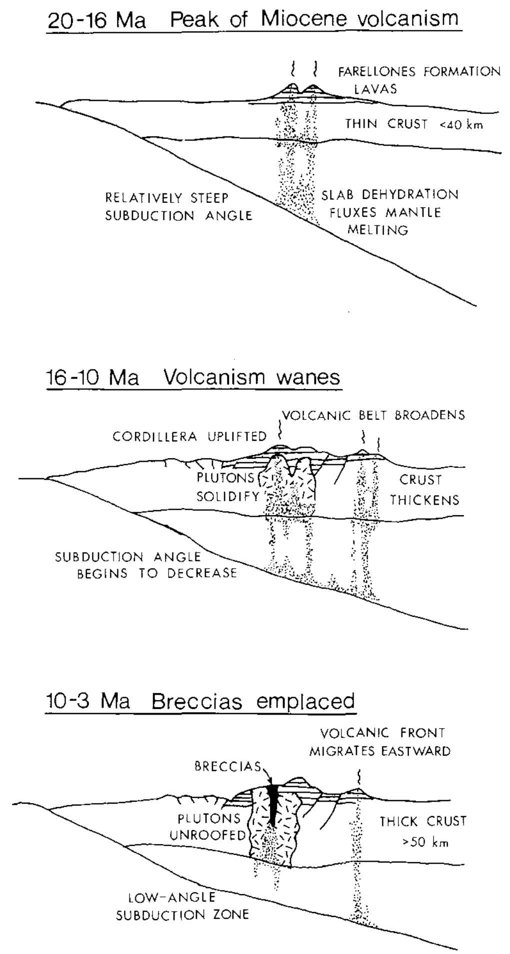

FIG. 2. Schematic tectonic framework along the western margin of central Chile since the early Miocene (Skewes and Stern, 1994; Stern and Skewes, 1995).

Introduction

THE THREE GIANT, supergiant, and/or behemothian (Clark, 1993) Andean Cu deposits of central Chile (Fig. 1)—Los Pelambres-El Pachón (>25 × 10^6 metric tons of Cu), Los Bronces-Río Blanco (>50 × 10^6 metric tons of Cu), and El Teniente (>70 × 10^6 metric tons of Cu)—formed during the late Miocene and early Pliocene in conjunction with an episode of significant regional tectonic changes involving crustal deformation, thickening, and uplift, and eastward migration of the Andean magmatic arc (Fig. 2) (Skewes and Stern, 1994). These tectonic changes have been attributed to decreasing subduction angle below the developing Andean flat-slab segment (Jordan et al., 1983; Stern, 1989; Kay et al., 1991), perhaps because of the subduction of the Juan Fernández Ridge (Pilger, 1981, 1984). Because of their young age and extensive exposure, the giant deposits of central Chile provide a unique opportunity for understanding the origin of such deposits in the context of Andean tectonic and magmatic evolution.

Prominent features in each of these deposits are multiple large, mineralized, biotite- and tourmaline-rich breccia pipes. Diameters of

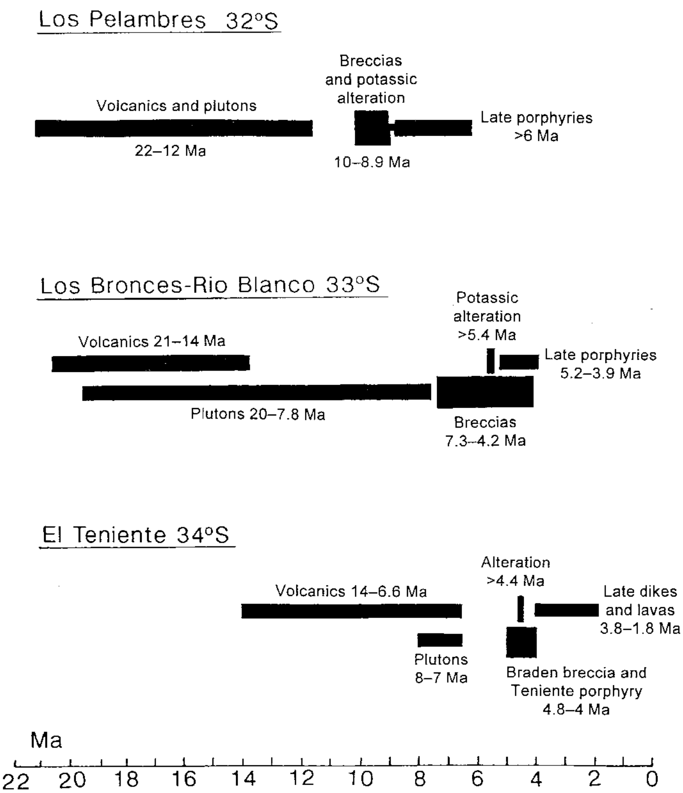

FIG. 3. Chronology of the Los Pelambres, Los Bronces-Río Blanco, and El Teniente Cu deposits as determined by K-Ar age dating. For Los Pelambres, ages of volcanic and plutonic host rocks are by correlation with regionally similar lithologies (Rivano et al., 1990); biotite breccias and potassic alteration are from Sillitoe (1988); the minimal age for late porphyries is from Kay et al. (1991). For Los Bronces-Río Blanco, ages are from Warnaars et al. (1985) and Serrano et al. (1996). A single Ar-Ar age of 14.8 Ma for a pluton previously dated by K-Ar as 11.3 Ma implies resetting, and suggests a greater time gap between emplacement of the youngest host plutons and breccias. Ages for El Teniente are from Cuadra (1986). Note the southward decrease in the age of both breccia emplacement and eastward arc migration.

these inverted funnel-shaped pipes at the current erosional surface range from 600 m at Los Pelambres (Fig. 4) (Skewes and Atkinson, 1985; Atkinson et al., 1996) to 1300 m at El Teniente (Fig. 6) (Camus, 1975; Cuadra, 1986). At Los Bronces-Río Blanco, a group of more than ten distinct breccias, emplaced during a 3-million-year period in the late Miocene to early Pliocene (Fig. 3), forms an elongated body over 4 km in length and 1 km wide (Fig. 5) (Stambuk et al., 1982; Warnaars et al., 1985; Serrano et al., 1996). The main breccia at El Teniente is known to be at least 1800 m in vertical extent, and the roots of this and the other mineralized breccia pipes in central Chile have yet to be encountered. Individual breccias, such as the Sur-Sur and Donoso tourmaline-rich breccias at Los Bronces-Río Blanco, locally contain Cu grades of up to >10% and total Cu of $>10 \times 10^6$ metric tons each, and thus are themselves giant deposits. At Los Bronces-Río Blanco, >90% of the $>50 \times 10^6$ metric tons of hypogene Cu occurs either in the matrix of such breccias or in clasts and wallrock altered in association with the emplacement of these breccias (Serrano et al., 1996).

Understanding the origin of these mineralized breccias is a key element in understanding the giant size of the Cu deposits in central Chile. Here we discuss the genesis of these breccias in the context of the middle Miocene to Recent tectonic and magmatic evolution of the Andes of central Chile.

Regional Geology and Tectonic Setting

Los Pelambres, Los-Bronces–Río Blanco and El Teniente occur near the boundary between two major Andean tectonic segments (Fig. 1)—the flat-slab segment, below which the angle of subduction has decreased significantly since the middle Miocene and where volcanism is now absent, and the Southern Volcanic Zone (SVZ), below which the subduction angle is steeper. Beginning in the middle Miocene, progressive flattening of the subduction angle below the flat-slab segment and the northern end of the SVZ, caused perhaps by the subduction of the eastern extension of the Juan Fernández Ridge (Pilger, 1981, 1984), resulted in eastward migration of volcanism as well as crustal deformation, uplift, and erosion (Fig. 2) (Jordan et al., 1983; Stern, 1989; Kay et al., 1991; Skewes and Holmgren, 1993).

The formation of Los Pelambres, Los Bronces–Río Blanco, and El Teniente is closely associated in time with these regional geotectonic changes (Skewes and Stern, 1994). In each deposit, multiple late Miocene and Pliocene mineralized breccias were generated within early and middle Miocene plutonic and volcanic rocks during the last stages of existence of the Miocene magmatic belt (Figs. 2 and 3). Each deposit also contains late Miocene and Pliocene porphyry stocks emplaced both contemporaneously with and after the mineralized breccias, just prior to the eastward migration of magmatic activity. Although none of these three deposits has been the focus of a detailed Ar-Ar chronological study, relative ages as indicated by geologic relations and supported by K-Ar dates (Fig. 3) provide reasonably good preliminary constraints on their temporal evolution. Here we summarize only the most significant features of each deposit.

Los Pelambres

An estimated $>25 \times 10^6$ metric tons of Cu occur in Los Pelambres and El Pachón, the latter being a portion of the same deposit on the Argentine side of the Andean drainage divide (Clark, 1993). Alteration and mineralization at Los Pelambres occur within a quartz diorite stock and surrounding volcanic rock (Fig. 4) (Sillitoe, 1973; Atkinson and Souviron, 1984; Skewes and Atkinson, 1985; Atkinson et al., 1996). These rocks have not been dated directly, but are correlated with the 12 to 22 Ma Farellones Formation volcanics and intruding plutons that outcrop regionally (Fig. 3) (Rivano et al., 1990). The initial Sr- and Nd-isotopic composition of these rocks (Fig. 7) is similar to that of magmas erupted from volcanic centers in the southern Andes, an area of relatively thin (<40 km) crust, consistent with the formation of these early and middle Miocene igneous rocks prior to extensive late Miocene crustal thickening below central Chile (Skewes and Stern, 1994; Stern and Skewes, 1995).

At Los Pelambres, a zone of potassic alteration and high-grade (>0.5%) Cu mineralization developed in conjunction with the emplacement of multiple metal-rich biotite breccia pipes (Figs. 3 and 4) (Atkinson and Souviron, 1984; Skewes and Atkinson, 1985). The breccias, which range from a few meters to 600 meters in diameter, consist of angular fragments of both volcanic and plutonic rocks in a matrix rich in biotite, quartz, chalcopyrite, bornite, pyrite, K-feldspar, tourmaline, and anhydrite. Where the matrix is dominated by biotite, the grade of Cu mineralization in some cases is as high as >10%. The roots of these breccias have not been encountered. Contacts along the breccia margins are either sharp or gradational into crackle breccia with decreasing proportions of breccia-matrix minerals. Similar breccias have been described from El Pachón (Atkinson et al., 1996).

The mineralized biotite breccias at Los Pelambres are surrounded by a stockwork of brown and green biotite veins and quartz veins with biotite-rich halos (Skewes and Atkinson, 1985; Atkinson et al., 1996), as well as a zone of disseminated secondary biotite replacing primary igneous hornblende. Relatively high-grade Cu at Los Pelambres is restricted to this zone (Fig. 4). The density of biotite veins, other potassic alteration effects, and Cu grade all decrease radially away from the central biotite-rich breccias.

K-Ar age determinations on biotites from the matrix of the breccias, as well as from altered host rocks and secondary alteration pods and

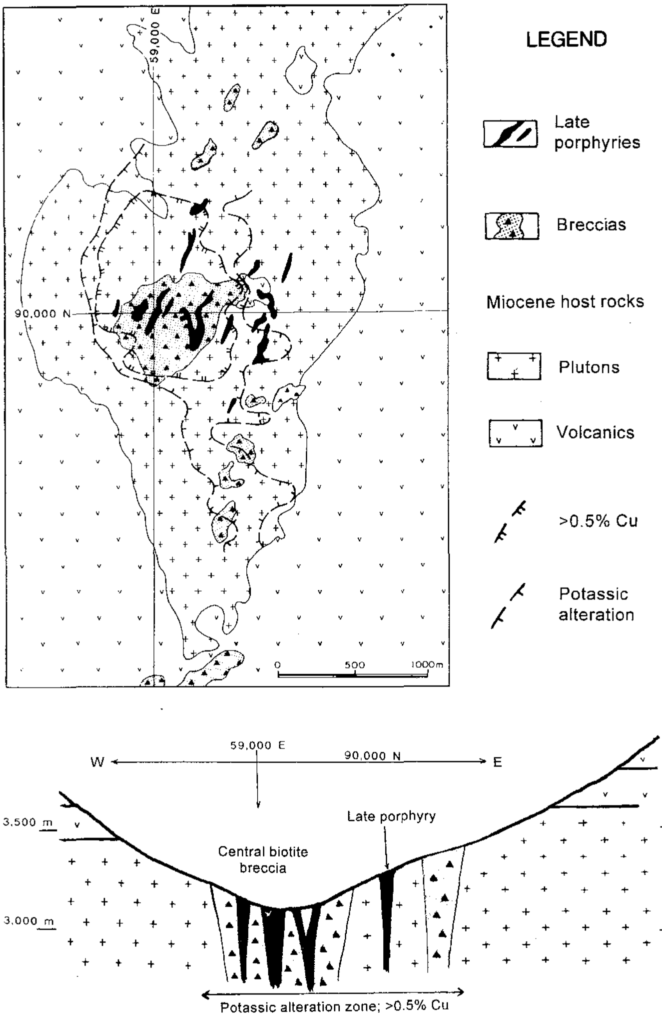

FIG. 4. Map and cross-section through Los Pelambres (Skewes and Atkinson, 1985; Atkinson et al., 1996). Note the greater extent of erosion above the central biotite breccia complex as compared to Los Bronces–Río Blanco (Fig. 5).

veins, range from 10 to 8.9 Ma (Sillitoe, 1988). The close spatial association, as well as the similarity in age and biotite chemistry (Skewes and Atkinson, 1985; Skewes, 1992), implies a genetic relation between biotite-breccia emplacement and potassic alteration. Fluid-inclusion data in quartz indicate that both breccia-matrix minerals and biotite-rich veins precipitated from boiling fluids at temperatures >300° C and with salinities >35% NaCl equivalent, and both are interpreted to have formed by the expansion of saline, metal-rich magmatic fluids. However, Sr- and Nd-isotopic composition of breccia-matrix minerals indicates that the fluids that formed the breccias were not in isotopic equilibrium with the host quartz diorite, and thus were not derived from this rock (Fig. 7) (Skewes and Stern, 1994, 1996). This is consistent with the angular nature of quartz diorite clasts in the biotite breccias, which implies that this host pluton already was crystallized at the time these breccias and the associated potassic alteration formed. We suggest that the fluids that formed the mineralized breccias at Los Pelambres were derived from cooling plutons not yet exposed at the surface, consistent with the deep, as yet undiscovered, roots of these breccias.

Small post-mineralization porphyry stocks, with notably low grades of mineralization (Atkinson and Souviron, 1984; Atkinson et al., 1996), intrude both the breccias and the central potassic alteration zone at Los Pelambres. They have not been dated, but the youngest age determined for any igneous rock in Chile at the latitude of Los Pelambres is 6 Ma (Kay et al., 1991). Magmatic activity at Los Pelambres may have persisted at least 2 (but probably no more than 3) m.y. after the deposit formed, prior to the eastward migration of the magmatic arc at this latitude (Fig. 3). The Sr- and Nd-isotopic composition of these late porphyry plutons implies that they incorporated more continental crust than the older host rocks of the deposit (Fig. 7), consistent with either increased crustal thickness or enhanced subduction erosion caused by the subduction of the Juan Fernández Ridge in the late Miocene (Skewes and Stern, 1994; Stern and Skewes, 1995).

Low-grade Cu mineralization at Los Pelambres has been disseminated over a large area in conjunction with late feldspar-destructive sericitic alteration related to quartz-molybdenite, quartz-sericite, quartz-pyrite, and pyrite-sericite veins. This stage of alteration clearly is later than breccia emplacement and redistributed Cu originally emplaced in the high-grade central breccia and potassic alteration zone of the deposit. However, the absolute age relation between the potassic and sericitic alteration zones is unknown.

Erosion associated with uplift, beginning in the middle to late Miocene, has removed a significant vertical section of the volcanics, quartz-diorite pluton, biotite breccias, and associated Cu ore at Los Pelambres. The largest central biotite breccia outcrops at the surface at 3100 m, more than 400 meters below the projected contact of the quartz-diorite pluton with andesite lavas (Fig. 4), which are estimated to have been at least 2500 m thick originally. The biotite breccias at El Pachón are eroded equally deeply. Thus the total amount of hypogene Cu originally emplaced at Los Pelambres–El Pachón probably was much greater than that remaining today.

Los Bronces–Río Blanco

At Los Bronces-Río Blanco, >50 × 10^6 metric tons of Cu was emplaced into andesitic volcanic rocks of the Abanico and/or Miocene Farellones Formation and quartz monzonite to granodiorite plutons of the San Francisco batholith that range in age, as determined by K-Ar dating, from 20 to 7.8 Ma (Figs. 3 and 5) (Stambuk et al., 1982; Warnaars et al., 1985; Serrano et al., 1996). However, a single Ar-Ar age of 14.8 Ma for a pluton dated by K-Ar as 11.3 Ma (Serrano et al., 1996) suggests that the younger ages, which are for samples from closer to the center of the deposit (Warnaars et al., 1985), have been reset. Thus the time period between cooling of the youngest host plutons and the subsequent generation of mineralized breccias may have been longer than that indicated in Figure 3. As at Los Pelambres, the Sr- and Nd- (Fig. 7), as well as the Pb- (Drake, 1981), O- ($\delta^{18}O$ = +6.5‰) (Holmgren at al., 1988), and S- ($\delta^{34}S$ = +6.1‰) (Sasaki et al., 1984), isotopic compositions of these early and middle Miocene igneous rocks are relatively primitive and imply incorporation of only small proportions of South American continental crust in magmas derived essentially from the sub-Andean mantle (Skewes and Stern, 1994; Stern and Skewes, 1995).

Alteration and mineralization at Los Bronces–Río Blanco developed in conjunction with the emplacement, during the late Miocene and early Pliocene, of multiple mineralized breccias. The >10 mineralized breccias at Los Bronces–Río Blanco form a large semi-continuous body >4 km long and 1 km wide (Fig. 5). Individual breccias have vertical extents of over 1,000 meters, but their roots have not yet been discovered.

Approximately 50% of the Cu ore at Los Bronces-Río Blanco—that portion currently being exploited in the Río Blanco underground mine—occurs as breccia-matrix, stockwork, and disseminated mineralization in a zone of potassic alteration formed at 1- to >3-km depth, in association with the emplacement of biotite-rich breccias of the Río Blanco breccia complex (Fig. 5). The roots of these breccias extend at least 800 m below the contact of the granodiorite host plutons with the overlying volcanics. Where these breccias have intruded the

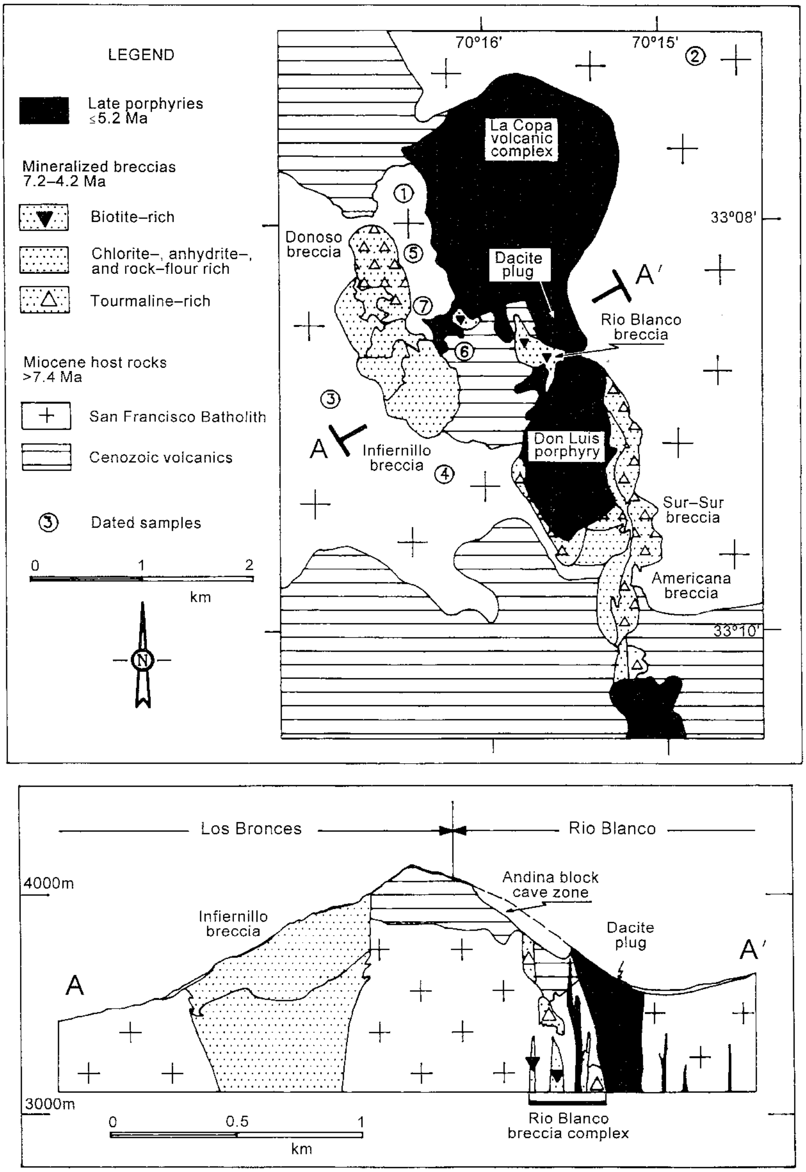

FIG. 5. Map and cross-section through Los Bronces–Río Blanco (Serrano et al., 1996).

volcanics, high-grade ore was removed from the Andina block-cave mine earlier this century. Late Miocene and early Pliocene ages have been determined for different breccias within the Río Blanco breccia complex, as well as for a sample of biotitized granodiorite from within the potassic alteration zone (Fig. 3) (Serrano et al., 1996). The biotite-rich breccias have a matrix of biotite, K-feldspar, anhydrite, magnetite, and sulfides (chalcopyrite, bornite, molybdenite, and minor pyrite). As at Los Pelambres, their intimate spatial association, temporal overlap, and the mineralogical similarity of breccia-matrix and potassic-alteration mineral assemblages suggest a genetic relation between the emplacement of the mineralized breccias and the development of potassic alteration and mineralization in the surrounding host rocks.

Subsequently, after a period of uplift and erosion (Skewes and Holmgren, 1993; Serrano et al., 1996), younger mineralized tourmaline breccia pipes, which contain the other 50% of the ore in the deposit, were emplaced both in and around the earlier zone of potassic alteration associated with the Río Blanco breccia complex. The most notable of these breccias, the Sur-Sur (Stambuk et al., 1985) and Donoso (Warnaars et al., 1985) breccias, have matrix cement dominated by tourmaline and sulfides (chalcopyrite, pyrite, and molybdenite, but with only minor or no bornite), with locally up to >10% Cu and >10 × 10^6 metric tons of Cu each within their matrix and the enclosed altered and mineralized clasts. Clasts, which generally constitute 70% to 90% of the volume of these breccias, are sericitized and silicified, and, in some cases, contain secondary K-feldspar. Where clast size is sufficiently large, it is clear by the concentric zonation in the intensity of this alteration that it occurred during the emplacement of the breccias and was produced by the same fluids that generated these breccias.

Fluid-inclusion data indicate that the fluids that formed both the biotite and tourmaline breccias at Los Bronces–Río Blanco were high-temperature, highly saline, boiling fluids (Holmgren et al., 1988; Kusakabe et al., 1990; Skewes and Holmgren, 1993). Oxygen (total fluid $\delta^{18}O$ = +6 to +8‰), sulfur (total fluid $\delta^{34}S$ = +4 to +7.5‰), and hydrogen (fluid δD = −55 to −90‰) determined from the isotopic compositions for both breccia-matrix minerals and associated alteration assemblages preclude the participation of significant quantities of meteoric water and imply that the high-temperature saline fluids that produced both generations of breccias were magmatic in origin (Kusakabe et al., 1984, 1990; Holmgren et al., 1988).

As at Los Pelambres, the Sr- and Nd-isotopic composition of breccia-matrix minerals indicates that the breccias at Los Bronces–Río Blanco were generated by fluids isotopically distinct from, and thus not derived from, the older plutonic host rocks (Fig. 7) (Skewes and Stern, 1994, 1996). This is consistent with the angular nature of plutonic clasts in these breccias, which implies that the host plutons already were solidified at the time of breccia formation. The magmatic fluids that generated the mineralized breccias at Los Bronces–Río Blanco must have been derived from magmas that crystallized to form plutons not yet exposed at the surface, consistent with the roots of these breccias not yet being exposed.

The central Río Blanco breccia complex and the associated zone of potassic alteration, as well as some of the younger tourmaline breccias, are intruded by late Miocene to Pliocene dacite to rhyodacite porphyries (Figs. 3 and 5). Some porphyries in turn are cut by tourmaline breccias. It is clear from their porphyritic textures and modes of emplacement, which include subvolcanic chimneys, domes, diatremes, and extrusives that rest directly on top of granodiorite with potassic alteration, that these porphyries were emplaced at shallow depths (<1 km) after a significant amount of erosion had affected the deposit (Serrano et al., 1996). Although these shallow silicic porphyry stocks, dikes, and subvolcanic chimneys occur both within and around the zone of intense biotitization and high-grade mineralization in the area of the Río Blanco breccia complex, they themselves are not biotitized and are only weakly mineralized (<0.5% Cu) (Blondel, 1980) compared to the surrounding granodiorite. Instead, these porphyries are sericitized and silicified. They are cut by quartz-sericite and less frequently K-feldspar veins, but not biotite veins. Also, both primary and secondary biotites and feldspars in the surrounding altered and mineralized granodiorite are replaced by fine-grained biotite, sericite and corundum at the contacts with porphyry dikes and stocks, and chalcopyrite/pyrite ratios decrease significantly in these contact zones.

These chronological, geological, and petrological relations imply that the porphyries postdated and remobilized pre-exisiting mineralization associated with potassic alteration (Serrano et al., 1996). The late porphyries have Sr- and Nd-isotopic compositions that are distinct from both the older volcanic and plutonic host rocks of the deposit (Fig. 7) and minerals in the matrix of the breccias within the Río Blanco breccia complex (Skewes and Stern, 1994, 1996). Their isotopic compositions imply incorporation of greater proportions of continental crust than the older host rocks of the deposit (Stern and Skewes, 1995; Serrano et al., 1996).

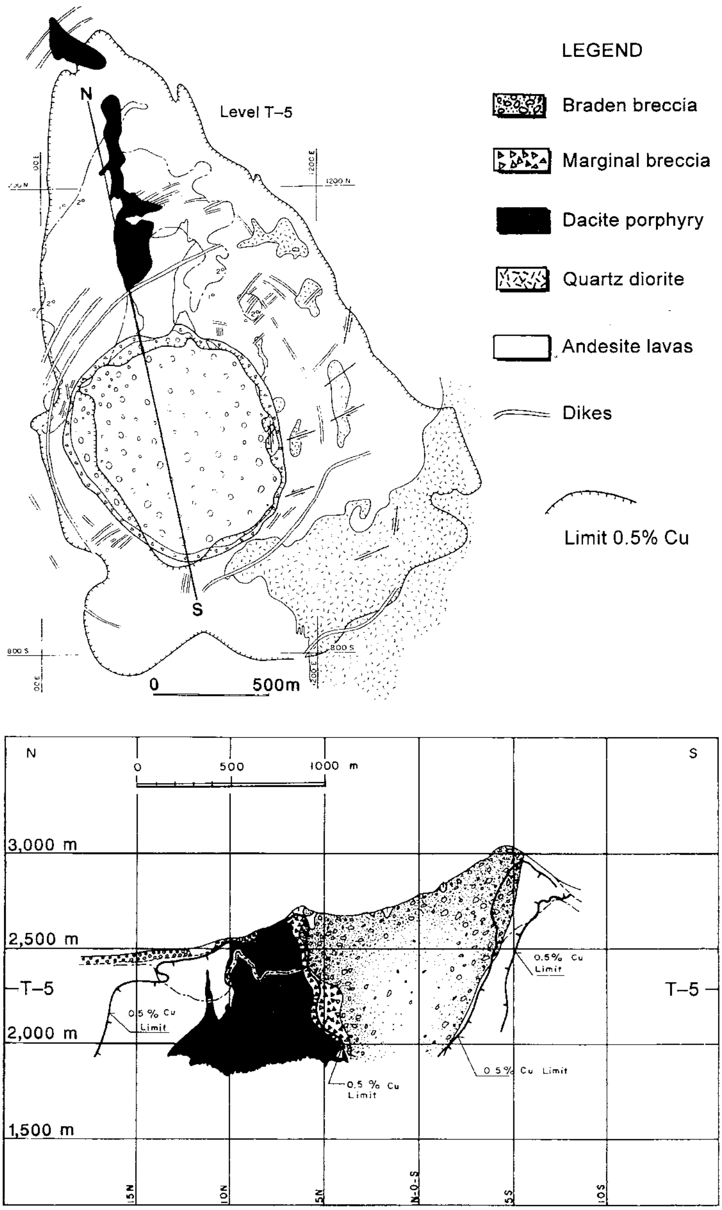

FIG. 6. Map of El Teniente level T-5 (Cuadra, 1986) and cross-section (Camus, 1975). Note the concentricity of the limit of Cu >0.5% around the Braden breccia.

El Teniente

El Teniente contains an estimated >70 × 10^6 metric tons of Cu. The Pliocene Braden breccia pipe (4.7 to 4.5 Ma) (Figs. 3 and 6) is a prominent central feature in this deposit (Camus, 1975; Cuadra, 1986). This pipe is emplaced within andesitic volcanic rocks of the Miocene Farellones Formation. Locally, these volcanics also are intruded by the Sewell diorite (7.1 Ma), as well as the Teniente dacite porphyry, which is subcontemporaneous with the Braden breccia pipe (published K-Ar ages between 4.8 and 4.0

Ma) (Cuadra, 1986). Camus (1975) attributes early stages (the late magmatic and principal hydrothermal stages) of potassic and sericitic alteration and mineralization at El Teniente to the emplacement of these shallow plutons. Younger, post-mineralization igneous rocks in the area of El Teniente include latite and andesite dikes, and andesitic lava flows in the valley of the Río Cachapoal to the southwest (3.8 to 1.8 Ma) (Fig. 3). As at Los Pelambres and Los Bronces–Río Blanco, temporal changes in the Sr- and Nd-isotopic composition of the igneous rocks related to the El Teniente deposit imply an increase in the proportion of continental crust incorporated in the younger magmas (Fig. 7) (Skewes and Stern, 1994; Stern and Skewes, 1995).

The Braden breccia pipe has the shape of an inverted cone. It has a known vertical extent of >1800 m, with a diameter of approximately 1300 m at the present surface and >650 m at its deepest documented level (Fig. 6) (Camus, 1975). In its central sector, the Braden pipe is formed by rounded to subangular heterolithic volcanic and plutonic rock fragments in a matrix of rock flour cemented principally by sericite with minor amounts of tourmaline, calcite, and sulfides (pyrite). The central sector has gradational contacts with a marginal zone of Cu-rich tourmaline breccia, which consists of angular fragments of wall rock with varying degrees of quartz-sericite alteration, cemented mainly by tourmaline, anhydrite, quartz, sulfides (chalcopyrite, bornite, and pyrite), tennantite-tetrahedrite, and minor gypsum and calcite. This marginal breccia ring has an average width of 20 to 80 meters and sharp contacts with the surrounding host rocks. It apparently was emplaced prior to the central breccia, as indicated by the occurrence of clasts of the marginal breccia within the central portion of the pipe, as well as by injections of dikes of material from the central portion of the pipe into and through the marginal breccia ring.

At least one stage—the late hydrothermal stage (Cuadra, 1986)—of alteration and mineralization at El Teniente is associated directly with the emplacement of the marginal portion of the Braden breccia pipe (Camus, 1975; Cuadra, 1986). This alteration involves both sericitization and silicification of clasts, as well as quartz, anhydrite, and tourmaline veins with quartz + sericite + chlorite halos developed over a 100- to 150-m-wide zone around the Braden pipe. High-grade (>0.5%) Cu mineralization in both this breccia-related alteration zone and the marginal tourmaline-rich portion of the breccia pipe is associated with chalcopyrite, bornite, and tennantite-tetrahedrite. Oxygen- (total fluid $\delta^{18}O = +6‰$) and sulfur- (total fluid $\delta^{34}S = +4.5‰$) isotopic compositions of samples from both the marginal breccia and the alteration assemblages associated directly with its emplacement imply that magmatic fluids played a dominant role in the generation of this portion of the Braden breccia pipe (Kusakabe et al., 1984, 1990). Other volumetrically less significant mineralized breccia bodies occur at El Teniente, including a tourmaline breccia possibly associated with the emplacement of the Sewell diorite (Camus, 1975), as well as biotite + anhydrite breccias within this pluton.

Discussion

Either a large volume of magma, a magma with distinctive compositional characteristics such as high Cu or H_2O content, and/or a unique mechanism for concentrating metals is required to generate a giant orthomagmatic Cu deposit. Following Clark (1993), we discuss the giant size of the three late Miocene to Pliocene Cu deposits in central Chile with regard to both ore genesis (as reflected by their anatomy) and metallogenesis in the context of their geotectonic setting.

These three deposits without doubt are orthomagmatic. In the broader sense, they developed entirely within and therefore must have derived Cu and S entirely from Miocene and Pliocene igneous rocks. In a more specific sense, the high-grade Cu ore in each deposit occurs either in breccias or in stockwork vein and disseminated alteration zones generated by high-temperature, saline magmatic fluids, as implied by fluid-inclusion and stable-isotope data (Kusakabe et al., 1984, 1990; Skewes and Atkinson, 1985; Holmgren et al., 1988). Furthermore, the isotopic composition of the Andean magmas associated with these deposits suggests derivation from the sub-Andean mantle modified by the addition of a small proportion of subducted components (Skewes and Stern, 1994; Stern and Skewes, 1995). Assimilation of crustal components in these magmas was limited. As discussed in more detail below, the igneous rocks associated with these deposits have sufficient Cu, as well as S and H_2O, for their generation from reasonable volumes of magma.

Differences in the present size and anatomy among these three deposits reflect, in part, differences in their depth of erosion and exposure. Erosion and exposure are greatest at Los Pelambres, both because this deposit is older and because it occurs along the high Andean drainage divide, and is least at El Teniente, because that deposit is the youngest and occurs farthest west of the drainage divide. Estimated rates of erosion in central Chile are between 150 and 250 m/m.y. over the last 12 million years (Skewes and Holmgren, 1993). These rates are consistent with unroofing of all of the 2500 m of lavas estimated to have occurred originally above the Los Pelambres breccias (Fig. 4) (Rivano et al., 1990), of 1250 to 1750 m of these lavas above the Los Bronces–Río Blanco breccias (Fig. 5), but of only as much as 600 to 1000 m above the Braden pipe at El Teniente. With regard to anatomy, these differences mean that at Los Pelambres we see only the deeper portion of the original deposit, and at El Teniente we see only the upper portion of the deposit.

Differential erosion also may account for some of the size differences among these three deposits. Simplistically assuming that the rocks removed from above each deposit were mineralized to the same extent as those that remain, then El Teniente (where total Cu is estimated over a 1500-m section above which 750 m of rock may have been removed by erosion) might originally have contained approximately 50% more Cu, or 100 × 10^6 metric tons. Los Bronces–Río Blanco, where total Cu is estimated over a 1250-m section above which over 1250 m of rock has been removed by erosion, originally might have contained twice the Cu, or again 100 × 10^6 metric tons. Los Pelambres–El Pachón, where reserves are estimated over a 700-m section above which more than 2000 m of rock has been removed by erosion, originally might have contained four times the Cu, or once again approximately 100 × 10^6 metric tons. Thus, these three deposits almost certainly were larger originally than they are today, and more similar in size to one another.

The giant size of these deposits is not the result of either the emplacement of a single large pluton or the longevity of a single hydrothermal convection system generated by the cooling of such a pluton. Alteration and mineralization at each deposit formed by multistage processes involving emplacement of both multiple mineralized breccias and porphyry intrusions over at least a 1- to 3-million-year period (Fig. 3). Different breccias and porphyries at each deposit have variable Sr- and Nd-isotopic composition (Fig. 7) as well, implying that they were not derived from a single magma batch, but from distinct magmas in complex, dynamically evolving magmatic systems (Skewes and Stern, 1994, 1996). Whatever the quantity of magma involved in the generation of these deposits, the details of the anatomy of each deposit imply that this magma did not occur as a single mass at a single time, but instead must be considered as the sum of different independent magma bodies developed over a 1- to 3-million-year time period.

Prominent, if not dominant, anatomical features common to all three deposits are multiple large mineralized breccia pipes. An important amount of high-grade Cu in each deposit is associated directly with breccias. This is most obvious at Los Bronces–Río Blanco, where early potassic alteration and high-grade mineralization is associated with biotite breccias, whereas later high-grade mineralization is associated with younger and shallower tourmaline breccias that generated sericitic alteration. Here, both tourmaline breccias and late, shallow (<1 km) porphyries were emplaced in and around the older central potassic alteration zone after a period of uplift and erosion, and it is clear that these shallow porphyries did not generate this alteration. At Los Pelambres, early potassic alteration and high-grade mineralization is also associated with biotite breccias. At El Teniente, a late stage of sericitic alteration and high-grade mineralization is associated with the emplacement of the tourmaline-rich marginal phase of the Braden breccia pipe.

Three important observations obtain concerning the genesis of these breccias: (1) they formed by the expansion of boiling, high-temperature, saline, metal-rich magmatic fluids that also precipitated the breccia-matrix minerals, including the Cu ore; (2) these fluids

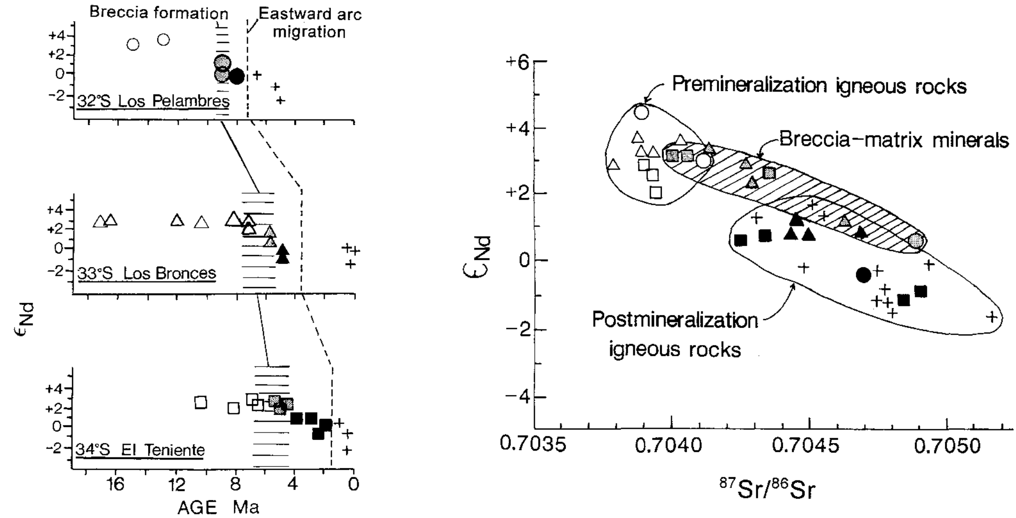

FIG. 7. Nd-isotopic composition versus both age (Skewes and Stern, 1994) and Sr-isotopic composition (Stern and Skewes, 1995) for host rocks (open symbols), minerals from the matrix of breccias (shaded symbols), and post-mineralization igneous rocks (solid symbols) from Los Pelambres (circles), Los Bronces–Río Blanco (triangles), and El Teniente (squares). Also shown is the isotopic composition of magmas erupted from younger volcanos east of the Miocene volcanic front after arc migration (pluses) (Stern, 1989; Kay et al., 1991).

were derived not from the older host plutons, but from magmas transitional in Sr- and Nd-isotopic composition between these older plutons and younger post-mineralization igneous rocks found at each deposit; and (3) the breccia-forming fluids exsolved from magmas cooling at depths >3 km. The magmatic character of the breccia-forming fluids is implied by fluid-inclusion and stable-isotope data summarized above. Such fluids might form by interaction of meteoric water with hot igneous rocks in a hydrothermal convection system, but these fluids would have to have been stored in some deep reservoir to be available for the essentially instantaneous event that formed each breccia. We consider this unlikely. Instead, the large volume of high-temperature, saline, metal-rich fluids that generated the breccias in central Chile must have exsolved directly from magmas. Sr- and Nd-isotopic data imply that these magmas were not the same as those that formed the host plutons of the deposits (Fig. 7) (Skewes and Stern, 1994, 1996). This is consistent with the fact that the host plutons were crystallized by the time of breccia emplacement, as indicated by the angular nature of clasts within the breccias.

Finally, the fact that these fluids exsolved from magmas cooling at depths >3 km is suggested by their deep roots, which at both Los Pelambres and Los Bronces–Río Blanco extend at least 800 m below the contact between host plutons and the overlying volcanics (Figs. 4 and 5), the original thickness of which has been estimated as over 2500 m (Rivano et al., 1990). This may be one factor contributing to the large size and high metal content of the deposits in central Chile, because pressure increases both the total amount of water dissolved in magmas and the solubility of Cl and Cu in exsolved fluids (Burnham, 1979; Clark, 1993).

Within these deposits, erosion has not yet been sufficiently deep to expose the intrusions from which the fluids that generated the mineralized breccias exsolved. Nevertheless, the approximate volume of these plutons can be estimated from the total amount of magmatic fluids required for the formation of the breccias. In the case of Los Bronces–Río Blanco, where almost all the Cu in the deposit is associated directly with breccia emplacement, we estimate the volume of unexposed plutons as follows: (1) the 10 or more breccias form nearly a continuous body 5 km long, 1 km wide, and a minimum of 1 km deep, for a total volume of 5 km^3; (2) on average, breccias contain 80% clasts and 20% matrix, implying 1 km^3 of breccia-matrix material; (3) fluid-inclusion data suggest that the breccia-forming fluids carried at least 35 wt% total dissolved solids (Skewes, 1992), implying that the total amount of fluid involved in breccia formation was at least three times the weight of the 1 km^3 of precipitated breccia-matrix material; (4) assuming that these fluids exsolved from magmas with 2 wt% dissolved water, these plutons therefore must have been at least 50 times more massive than the exsolved breccia-forming fluids, and thus a minimum of 150 times more massive than the total precipitated solids in the matrix of the breccias; and (5) assuming that breccia-matrix material has a similar density to that of crystallized plutons, the volume of plutons from which the breccia-forming fluids exsolved was thus at least 150 times that of the total breccia-matrix material deposited, or >150 km^3.

Could this volume of plutons produce the $>50 \times 10^6$ metric tons of Cu in the breccias at Los Bronces-Río Blanco? Cline and Bodnar (1991) calculated that between 50 and 60 km^3 of magma with 62 ppm Cu could produce the 6×10^6 metric tons of Cu at Yerington, Nevada. Farellones Formation andesites in central Chile, considered representative of the magmas generated in the Andean magmatic arc during the Miocene, average 200 ppm Cu (Camus, 1975), or 3.3 times that of the ore-related intrusion at Yerington. To produce a deposit 10 times as large as Yerington from such andesites would require 3 times the volume of magma required at Yerington, or 150 to 180 km^3, which is essentially the same as the volume we calculate would be required to form the multiple mineralized breccias that contain >90% of the Cu at Los Bronces-Río Blanco.

This volume of magma is large compared to that of the small silicic porphyry intrusions at Los Bronces-Río Blanco, and these weakly mineralized or barren late intrusions clearly are not responsible for the large quantitiy of Cu and S in this giant deposit. However, this volume of magma is small compared to the total volume of Miocene igneous rock associated with Los Bronces-Río Blanco, which outcrops in a 20-by-20-km region around the deposit (Warnaars et al., 1985). The vertical extent of these rocks includes 2.5 km of lavas and at least 2.5 km of plutons. It is likely that a vertical section of Miocene intrusives amounting to another 5 km or more is unexposed, implying that the total volume of Miocene igneous rocks associated with Los Bronces-Río Blanco is at least 2000 km^3 and may be as great as 4000 km^3. Even if, as discussed above, half the original Cu and half the total volume of breccias at Los Bronces-Río Blanco have been removed by erosion, so that the plutons from which the breccia-forming fluids exsolved were 300 to 360 km^3 in size, this still is a small volume compared to the total for igneous rocks associated with the deposit.

The breccias at Los Bronces-Río Blanco were placed over a 3-million-year period (Fig. 3), thus requiring an average 100 to 120 km^3 of magma per million years for their generation, again assuming that these breccias originally were twice their current size. The 2000 to 4000 km^3 of associated Miocene igneous rocks formed over a 12-million-year period (Fig. 3), requiring the generation of 160 to 320 km^3 of magma per million years. Thus, no special increase in magma production rates during the late Miocene is required to produce the Los Bronces-Río Blanco deposit. In fact, magma production rates probably were declining when this deposit formed, as discussed below.

We conclude that, although more magma was required to produce the giant Los Bronces-Río Blanco than to produce the smaller Yerington deposit, this volume—which represents the sum of individual plutons formed over a 3-million-year period—is consistent with the long-term magma production rates calculated in the Miocene Andean magmatic belt of central Chile. Furthermore, magma production rates during the Miocene were not greatly different from those in the Andes today. The 160 to 320 $km^3/m.y.$ of magma calcuated above is for a 20-km N-S section of the Andean arc, implying 8 to 16 $km^3/m.y.$ for each kilometer of arc. These estimates are within the estimated magma production rates of 4.7 to 25 $km^3/m.y.$ per kilometer of arc length for different areas of the active volcanic arc in the southern Andes (Stern, 1989).

Although each of the three giant deposits in central Chile formed by multiple events over a 1- to 3-million-year period, this represents a relatively short interval in the >15-million-year existence of the Miocene and Pliocene magmatic belt (Fig. 3). These three deposits formed specifically at the time when igneous activity in the Miocene and Pliocene magmatic belt declined as a result of regional geotectonic changes caused by ridge subduction and decreasing subduction angle (Skewes and Stern, 1994). Their genetic relation with the southward migration of the locus of subduction of the Juan Fernández Ridge (Fig. 1) (Pilger, 1981, 1984) is suggested by the fact that the ages of breccia formation are older in the north and younger in the south.

For a >15-million-year period, melting of the sub-arc mantle fluxed by dehydration of the subducted oceanic crust (Fig. 2) kept the Miocene and Pliocene magmatic belt in central Chile active. During the early Miocene, mafic andesite magmas were erupted to form the Farellones Formation volcanic rocks in a belt that extended from north of Los Pelambres to south of El Teniente. With continued magma flux from the mantle, the crust was heated, magmas began to collect in chambers to form plutons rather than erupting directly to the surface, and volcanism decreased. The middle Miocene batholiths of central Chile were generated during this phase of progressive pluton growth.

Beginning in the middle to late Miocene, a decreasing subduction angle, due to subduction of the Juan Fernández Ridge, caused a decrease in the flux of magma and heat from the sub-Andean mantle into the magmatic belt. The progressive phase of pluton growth ended. Plutons that had intruded the overlying lavas stopped growing and started cooling and solidifying. This process was enhanced by crustal deformation, uplift, and erosion, which also were caused by decreasing subduction angle beginning in the middle Miocene (Jordan et al., 1983; Skewes and Holmgren, 1993).

By the late Miocene, as magma supply from the mantle continued to decrease, relatively small magma batches were cooling in chambers below an already completely solidified roof of >3 km of older intrusive and extrusive rocks. Saline, metal-rich magmatic fluids exsolved from these magmas. These fluids, as well as small volumes of differentiated magma, penetrated the solidified roof of early and middle Miocene volcanic and plutonic rocks to generate the mineralized breccias, shallow silicic porphyry intrusions, and other post-mineralization igneous rocks found in the vicinity of each of the three Cu deposits in central Chile. Active uplift and erosion during this period caused different generations of breccias, porphyries, and alteration and mineralization to be telescoped, with younger and shallower events superimposed on older and deeper ones. By the latest Miocene and/or Pliocene, the Andean volcanic front migrated to the east (Figs. 2 and 3). Continued uplift and erosion in central Chile has exposed the deposits at their current levels.

As magma production rates below the Miocene volcanic belt declined, the isotopic composition of these magmas also changed to reflect the incorporation of greater amounts of continental crust in younger magmas (Fig. 7) (Skewes and Stern, 1994; Stern and Skewes, 1995). These changes began to occur at the same time that the giant deposits in central Chile formed, as indicated by the fact that the mineralized breccias in these deposits were generated by fluids derived from magmas isotopically transitional between their older volcanic and plutonic host rocks and younger igneous rocks. These changes may have resulted in part from increasing crustal thickness and intra-crustal assimilation during the late Miocene. However, increased subduction erosion and mantle-source-region contamination in association with the subduction of the Juan Fernández Ridge also played an important role in producing these isotopic changes (Stern, 1991; Stern and Skewes, 1995). As with the ages of both breccia formation and eastward arc migration, isotopic changes occurred first in the north and later in the south (Fig. 7), indicating a close relationship with the southward migration of the locus of ridge subduction. Increased sediment subduction, subduction erosion, and source-region contamination of the sub-Andean mantle may have produced other temporal changes in the chemistry of Andean magmas that might have been significant in the genesis of the giant Cu deposits, such as increasing average H_2O, Cu, S, or B content, but at present we have no direct information to constrain this possibility. However, it is worth noting that some mineralized breccias are isotopically similar to older host rocks, some are similiar to younger post-breccia igneous rocks, and some are transitional between the two (Fig. 7), which suggests that magma composition alone was not responsible for the generation of these breccias (Skewes and Stern, 1994, 1996).

Conclusions

In summary, geotectonic changes related to ridge subduction, decreasing subduction angle, and eastward arc migration played an important role in controlling the timing of the genesis of the giant deposits in central Chile, which coincides with a decrease in sub-arc magma supply during the late Miocene. These late Miocene geotectonic changes also caused changes in Andean magma chemistry, but this does not appear to be a significant factor in generating the giant size of the deposits in central Chile. Instead, their giant size essentially appears to reflect the fact that during the time when conditions were conductive to breccia formation, which occurred after the main growth phase of the middle Miocene plutonic belt in central Chile, a diminished but nevertheless continued supply of sufficient volumes of new magma with appropriate Cu, S, and H_2O concentrations allowed the repeated emplacement of superimposed breccias and associated alteration and mineralization events. In aggregate, these multiple events, superimposed over an extended (1- to 3-million-year) time period, produced giant deposits. The availability of sufficient volumes of magma over this time period resulted ultimately from the continuous subduction of oceanic lithosphere below the Andean arc.

What focused the uprise and intrusion of magmas below the three giant deposits in central Chile for this extended time period is a different question. This focusing may have resulted from long-term rheological contrast between the areas below each deposit and the intervening areas as a result of diapiric uprise of magmas, either within the crust (Damon, 1986; Yañez and Maksaev, 1994) or as deep as just above the subducted slab (Marsh, 1979). Alternatively, the focusing may reflect important lithospheric structures in this region of the Andes. In this regard, it is noteworthy that Los Bronces–Río Blanco occurs directly on the major tectonic boundary between the Andean flat-slab segment and the Southern Volcanic Zone (Fig. 1), whereas Los Pelambres and El Teniente occur close to the northern and southern extremes, respectively, of that segment of the subducting Nazca plate that has ruptured to produce a very large earthquake in central Chile every 83 ± 9 years (1985, 1906, 1822, 1730, 1647, and 1575) (Comte et al., 1986).

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