High magma oxidation state and bulk crustal shortening: key factors in the genesis of Andean porphyry copper deposits, central Chile (31-34°S)

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ABSTRACT

The Andean segment between 31 and 34°S documents a unique Cenozoic tectono-magmatic evolution that involves the generation of three world-class Late Miocene porphyry copper deposits: Los Pelambres, Río Blanco-Los Bronces and El Teniente. The genesis of these giant ore-deposits occurred during a major copper mineralization cycle that took place progressively from north to south, in close association with the emplacement of a series of calc-alkaline, highly oxidized granitoids (Fe_2O_3/FeO = ratio between 1 and 3). These granitoids were emplaced coevally with bulk shortening and appear to have fractionated along active steep, margin-oblique fault zones that may have played a key role in the exsolution process of mineralized hydrothermal fluids. An increasing contamination of the mantle source by components from altered oceanic crust beneath the arc could account for a rise in the oxidation state of the magmas without producing a significant increase in the $^{87}Sr/^{86}Sr$ initial ratio, as suggested by new and previously published geochemical data. The authors propose that this increasing supply of oceanic crust components to the Miocene magmas could be linked to the progressive subduction of the Juan Fernández Ridge from north to south.

Key words: Porphyry copper, Bulk shortening, Magmatic oxidation state.

RESUMEN

Alto estado de oxidación magmático y acortamiento regional: factores claves en la generación de los pórfidos cupríferos de Chile central (31-34°S). El segmento andino comprendido entre los 31 y 34ºS documenta una evolución tectono-magmática cenozoica que involucra la generación de tres pórfidos cupríferos de clase mundial: Los Pelambres, Río Blanco-Los Bronces y El Teniente. La génesis de estos tres depósitos gigantes habría ocurrido como la culminación de un ciclo de mineralización que actuó progresivamente de norte a sur, en estrecha asociación con el emplazamiento de granitoides calcoalcalinos, fuertemente oxidados (razón Fe_2O_3/FeO = entre 1 y 3).

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Estos granitoides fueron emplazados en un ambiente de acortamiento regional y se fraccionaron a lo largo de zonas de falla sub-verticales activas, oblicuas al margen continental. Se propone que la actividad de estas zonas de cizalle habria jugado un rol clave en la exsolución de los fluidos mineralizadores. El elevado estado de oxidación de los magmas, junto con la ausencia de un aumento significativo en las razones iniciales ^{87}Sr/^{86}Sr, respaldados por nuevos datos geoquímicos y por datos previamente publicados, podría ser el resultado de un aumento de componentes de corteza oceánica alterada en la fuente mantífera de los magmas, bajo el arco. Se propone que este incremento de componentes de corteza oceánica en los magmas del Mioceno Superior estaria ralacionado con la progresiva subducción, de norte a sur, de la dorsal de Juan Fernández.

Palabras claves: Cobre porfirítico, Acortamiento regional, Estado de oxidación magmático.

INTRODUCTION

Deformation style and magmatic affinity at subduction zones are not only controlled by simple tectonic plate interaction. They also result from other first order factors such as oceanic plate segmentation, plate margin shape and ridge collision (Barazangi and Isacks, 1976; Cahill and Isacks, 1992; Jordan *et al.*, 1983; Jarrard, 1986). Whatever the driving mechanisms of orogen development, it has become clear that both active and ancient convergent plate margins show remarkable along- and across-strike variation in tectonic style, magmatism and ore deposit character (Sillitoe, 1988; Mpodozis and Ramos, 1990; Lavenu and Cembrano, 1999).

The Andean segment between 31 and 34°S is characterized by a Cenozoic magmatic and tectonic evolution that culminates during the Late Miocene with the genesis of three world class porphyry copper deposits: Los Pelambres, Río Blanco-Los Bronces and El Teniente (Fig. 1). When compared with present-day Andean segmentation, this segment lies in the southern portion of the flat-slab region, which in part overlaps the northernmost region of the Southern Volcanic Zone (Stern and Skewes, 1995).

The mega-porphyry copper deposits present in the segment between 31 and 34ºS are emplaced within a Miocene magmatic arc of calc-alkaline affinity. The deposits are characterized by large volumes of hydrothermal breccias, high hypogene grade (>0.8% Cu), Cu-Mo mineralization and absence of by-product gold.

Skewes and Stern (1994, 1995) and Kay *et al.* (1999) proposed that the genesis of the Late Miocene giant copper deposits occurred during a period of significant change in the tectono-magmatic framework. These changes occurred as a direct result of progressive shallowing of the Nazca Plate, in close association with subduction of the ancient Juan Fernández Ridge (Yáñez *et al.*, 2001, 2002).

This work presents independent evidence that is consistent with the tectono-magmatic framework proposed by Skewes and Stern (1995). However, the authors propose an alternative model for the key factors controlling the generation of the porphyry copper deposits based on two variables:

- A remarkably high magmatic oxidation state (Fe_2O_3/FeO between 1 and 3) of the ore-bearing granitoids.
- A strong shortening event that reached its peak during the formation of the deposits (Sillitoe, 1998). Margin-oblique shear zones, where the porphyry copper deposits are emplaced, are kinematically compatible with this shortening event. The shear zones are thought to enhance crystal-magma fractionation under disequilibrium that, in turn, triggers multi-episodic exsolution of large amounts of copper- and molybdenum-rich fluids.

NEOGENE EVOLUTION OF THE MAGMATIC OXIDATION STATE (Fe_2O_3/FeO RATIO) WITHIN THE ANDEAN SEGMENT BETWEEN 31 AND 34°S

The Neogene magmatism within the segment between 31 and 34°S shows a very peculiar evolution when considering two key geochemical parameters: initial ^{87}Sr/^{86}Sr ratios and oxidation state (Fig. 2, Table 1). The initial isotopic ^{87}Sr/^{86}Sr ratios for plutonic and volcanic rocks from this segment show

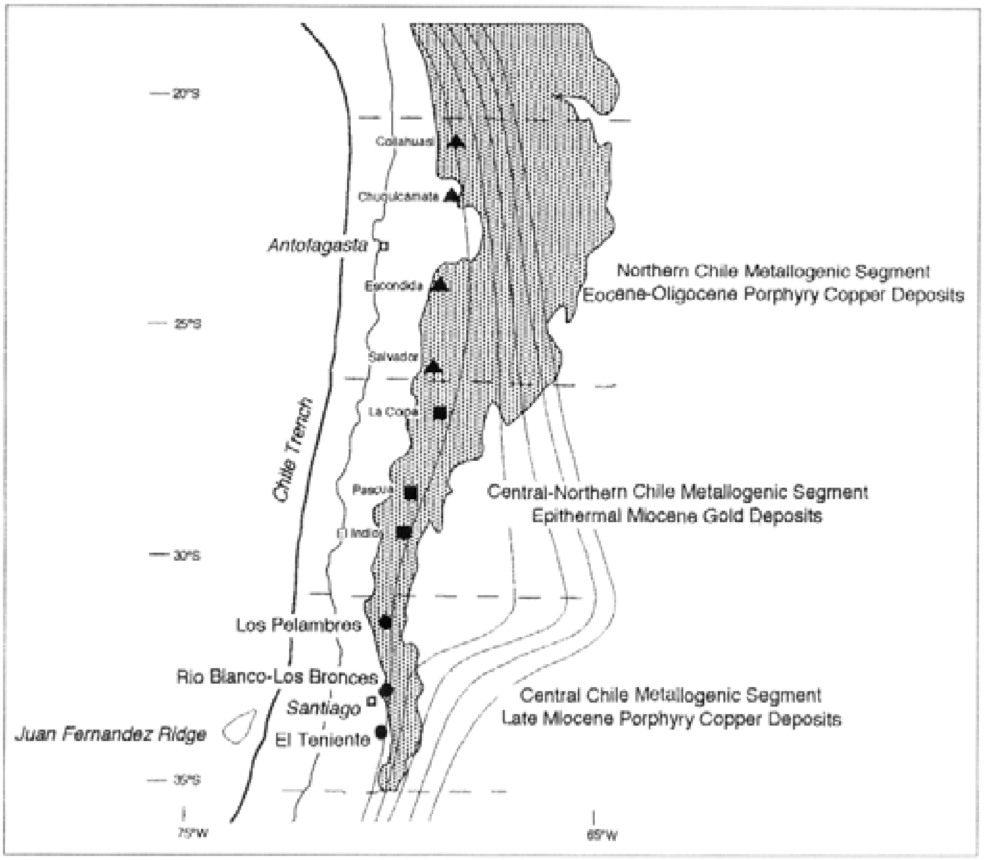

FIG. 1. Location of the Late Miocene porphyry copper deposits (solid circles), Miocene gold deposit (solid squares) and Eocene-Oligocene porphyry copper deposits (solid triangles) in the regional framework of the Tertiary metallogenic segmentation of central and northern Chile. The Peru-Chile trench, the Juan Fernández Ridge and depth contours of the subducting Nazca Plate are shown. The hatched zone represents cordilleran areas located at an altitude higher than 3,000 m.

a progressive change since 5 Ma, shifting from low initial ratios (0.70395) during the Miocene to progressively higher ratios (0.70445-0.70595) for recent magmas (Stern and Skewes, 1995). This change in the isotopic signature is preceded in time by an outstanding variation in the oxidation state of the magmas documented by the Fe_2O_3/FeO ratio. As seen in figure 2, the oxidation state changes since 10 Ma, from values lower than 1 during early to mid Miocene times, to progressively higher ratios, between 1 and 2, in the intrusive rocks associated with Los Pelambres (12-8 Ma, K-Ar; and $^{87}Sr/^{86}Sr$ ratios of 0.7040; Sillitoe, 1973; Faunes and Mora, 1994), 2 to 2.5 in the granitoids associated with Río Blanco-Los Bronces (7.4-4.9 Ma, K-Ar; $^{87}Sr/^{86}Sr$ =0.7039; Warnaars *et al.* 1985) and values close to 3 for plutonic rocks associated with El Teniente (7.1-4.0, K-Ar; and $^{87}Sr/^{86}Sr$ =0.7039; Cuadra, 1986). However, the authors' data suggest that from 4.7 Ma onward, and coinciding with the increase in the $^{87}Sr/^{86}Sr$ ratio, there is a marked decrease in the oxidation state. This parameter returns to values close to 1 or even lower, *ca.* 0.5, during the Pliocene (Fig. 2).

According to these data, the granitoids that are temporally and spatially related to Late Miocene giant porphyry copper deposits could be classified as strongly oxidized-magnetite series (Ishihara, 1981; Wilt, 1995).

A limitation of the Fe_2O_3/FeO ratio as an indicator of magma oxidation state is its high sensitivity to rock alteration, which in turn results in highly scattered data hampering the interpretation of the data. To avoid this problem, the authors here used

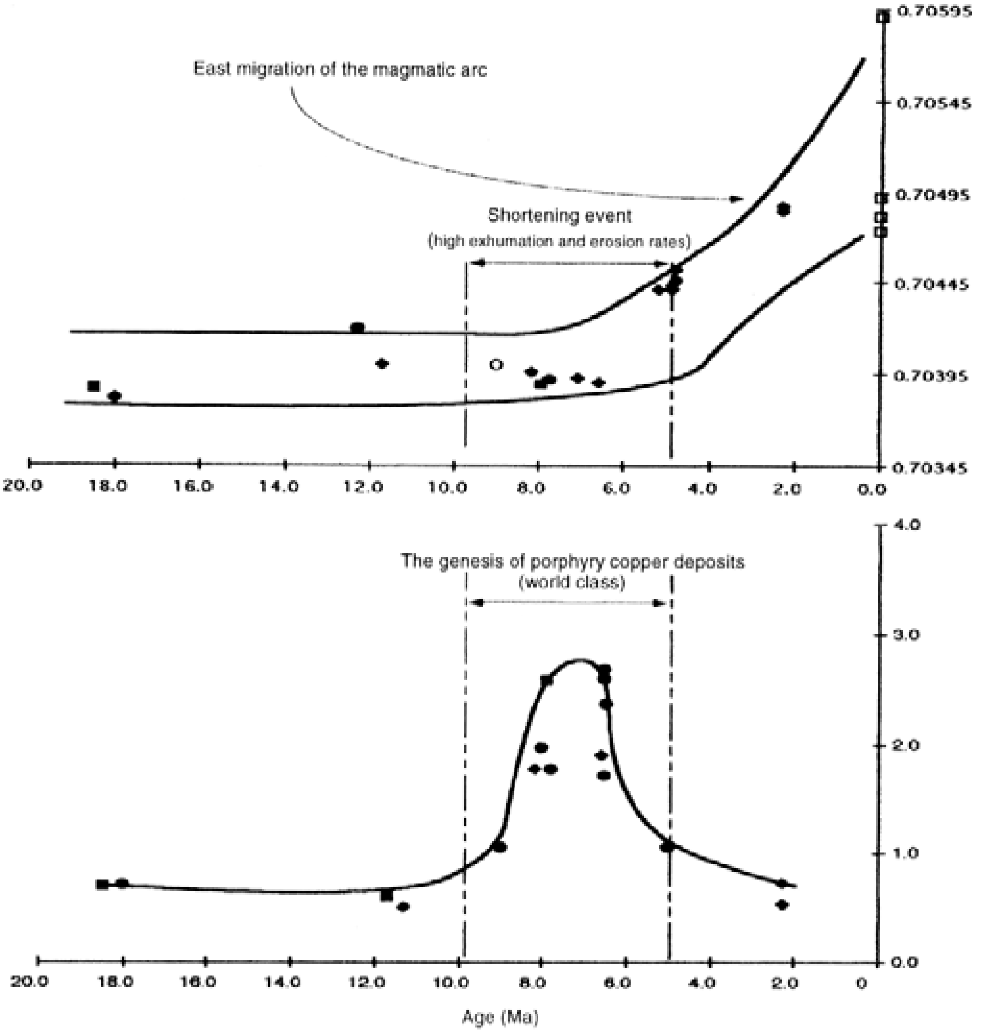

FIG. 2. Diagram showing Neogene and Quaternary evolution for the $^{87}Sr/^{86}Sr$ initial ratios and oxidation state of igneous rocks from the Andean segment between 31 and 34°S. Samples were taken from Warnaars *et al.* (1985; solid squares), Futa and Stern (1988; open squares), Stern and Skewes (1995; diamonds); Sillitoe (1973; open circles) and this work (filled circles).

the geochemical screening criteria of Wilt (1995) that allow the discrimination of rocks with hydrothermal alteration in porphyry copper systems. The criteria applied involve a series of parameters and diagrams (Fig. 3) including the following:

- Tests of sodic and potassic alteration through diagnostic indexes as proposed by Wilt (1995).
- Tests of phyllosilicate alteration using Shand's A/CNK index and the Ishikawa alteration index (*in* Wilt, 1995).
- Loss of ignition (any sample containing >2.5wt% is considered as altered and hence, is discarded).

Therefore, the data plotted in figure 2 correspond to those values, passing the screening criteria described above (Fig. 3), and thus could be considered as representative of the original magmatic oxidation state. In addition, the variety of scientific sources where the data come from (Table 1) and the systematic evidence of exceptionally high oxidation ratios between 10 and 5 Ma, strongly suggests that a highly oxidized magmatism took place within the segment between 31 and 34° at that geologic time.

TABLE 1. GEOCHEMICAL DATA FOR CENTRAL CHILE MIOCENE PLUTONS.

Location/Unit	Sample No.	SiO_2 %	Al_2O_3 %	CaO %	K_2O %	Na_2O %	Fe_2O_3 %	FeO %	MgO %	MnO %	P_2O_5 %	TiO_2 %	L.O.I %	Age (Ma)	Age Type*	Oxid. State (Fe_2O_3/FeO)	$^{87}Sr/^{86}Sr$ Initial ratio	References
El Teniente	PVF2	55,40	17,60	7,10	1,80	3,65	3,10	4,30	4,50	0,12	0,28	1.12	0,10	2.30	A	0,72	0,704870	Stern and Skewes, 1995
El Teniente	PVF1	56,50	16,90	7,20	2,10	3,63	2,70	5,10	4,80	0,12	0,33	1.10	0,68	2.30	A	0,53	0,704850	Stern and Skewes, 1995
El Teniente	Ttc9	61,00	16,80	5,60	2,50	4,38	3,90	2,20	2,80	0,10	0,20	0.75	0,94	8,20	A	1,77	0,703960	Stern and Skewes, 1995
[1] El Teniente	Ttc10	61,50	16,90	5,70	2,50	4,54	3,60	1,90	2,60	0,08	0,22	0.77	0,69	6,60	A	1,89	0,703900	Stern and Skewes, 1995
[1] El Teniente	Ttc5	63,70	17,10	3,90	2,20	4,93	1,90	2,40	1,50	0,08	0,21	0.39	1,80	7,10	A	0,79	0,703930	Stern and Skewes, 1995
Rio Blanco-Los Bronces	GDRB	65,60	16,20	3,30	3,20	4,48	1,60	2,60	2,60			0.45	0,10	11,70	A	0,62	0,704000	Stern and Skewes, 1995
Rio Blanco-Los Bronces	CHDac	70,90	15,20	0,33	5,20	3,63	2,20	0,59	0,36			0.13	1,50	4,80	A	3,73	0,704460	Stern and Skewes, 1995
Rio Blanco-Los Bronces	PDL	68,70	15,70	0,73	4,80	4,70	1,10	0,59	0,48			0.14	2,00	4,90	A	1,86	0,704410	Stern and Skewes, 1995
Rio Blanco-Los Bronces	PQM	66,10	15,60	2,10	3,95	5,40	1,57	2,63	1,59			0.13	0,90	5,20	A	0,60	0,704410	Stern and Skewes, 1995
Rio Blanco-Los Bronces	An1	62,10	16,10	0,32	6,60	2,10	5,40	2,50	1,80			0.28	2,50	18,00	A	2,16	0,703810	Stern and Skewes, 1995
Rio Blanco-Los Bronces	An2	56,20	16,90	5,30	2,90	3,10	4,70	4,60	4,70			0.78	0,90	18,00	A	1,02	0,703820	Stern and Skewes, 1995
Rio Blanco-Los Bronces	LB-3	60,50	16,80	5,42	2,22	4,60	2,08	3,00	3,05	0,09	0,20	0.65		18,50	A	0,69	0,703870	Warnaars *et al.*, 1985
[2] Río Blanco-Los Bronces	LB-2	65,30	15,80	3,04	3,55	4,68	1,20	2,41	1,53	0,08	0,15	0.46		11,30	A	0,50		Warnaars *et al.*, 1985
Río Blanco-Los Bronces	LB-7	63,06	15,40	1,74	2,95	4,24	3,65	1,41	3,43	0,08	0,24		0,27	7,90	A	2,59	0,703910	Warnaars *et al.*, 1985
[5] Río Blanco-Los Bronces	LB-10	67,80	15,70	2,52	2,57	4,38	0,83	0,83	0,33	0,11	0,23		1,67	4,90	A	1,00	0,704440	Warnaars et a.l, 1985
[6] Río Blanco-Los Bronces	LB-11	69,50	15,50	1,75	2,43	4,76	0,63	0,91	0,41	0,02	0,28		0,85	4,80	A	0,69	0,704520	Warnaars et al. 1985
[7] Los Pelambres	A11219	68,00	16,50	2,59	2,93	5,18	1,48	1,40	1,21	0,01	0,14	0.51	1,30	9,00	A	1,06	0,704000	This work
Peuco-Volcán	A05571	62,58	15,97	4,49	3,08	4,05	2,06	2,96	2,41	0,09	0,14	0.72	0,38	18,00	R	0,70		This work
Peuco-Volcán	A05572	65,27	14,39	2,26	4,27	4,48	4,15	2,12	0,89	0,13	0,25	0.95	0,50	8,00	R	1,96		This work
[8] El Teniente	KET-146	63,31	16,50	4,64	2,61	3,55	2,78	1,57	1,96	0,08	0,14	0.56		7,80	A	1,77	0,703920	This work
[9] El Teniente	KET-144	63,38	16,29	4,67	2,68	3,55	2,74	1,61	2,01	0,08	0,14	0.56		6,50	R	1,70		This work
[10] El Teniente	KET-25	63,70	17,54	3,71	2,86	4,34	4,06	0,49	1,38	0,10	0,19	0.57		12,30	A	8,29	0,704191	This work
El Teniente	K-1	65,33	17,11	2,81	2,47	5,18	3,54	1,50	1,45	0,06	0,14	0.40		6,50	R	2,36		This work
El Teniente	K-2	66,07	15,79	2,27	3,17	5,68	3,51	1,34	0,96	0,10	0,22	0.88		6,50	R	2,62		This work
El Teniente	E-1359	67,46	16,17	2,95	3,06	4,65	2,94	1,10	1,12	0,06	0,12	0.36		6,50	R	2,67		This work
Río Blanco-Los Bronces	7,9E+07	65,91	15,65	3,48	3,10	4,47	1,87	1,76	1,70	0,06	0,15	0.53		5,00	R	1,06		
[*] South Volcanic Zone	MP-11	75,80	13,33	0,45	3,86	4,29		0,69*	0,19			0,15		0,01	R		0,705910	Futa and Stern, 1988
[*] South Volcanic Zone	MP-8	53,99	18,24	8,36	1,31	3,70		7,71*	4,51			1,32		0,01	A		0,704920	Futa and Stern, 1988
[*] South Volcanic Zone	MA-1	57,05	17,72	7,10	2,11	3,55		6,58*	4,34			1,01		0,01	R		0,704810	Futa and Stern, 1988
[*] South Volcanic Zone	T-1	62,15	17,38	5,20	2,58	3,90		4,63*	2,58			0,79		0,01	R		0,704740	Futa and Stern, 1988

*Age Type: **A** = Absolute age (radiometric age); **R** = Relative age (field geological relationships); **Unpublished report from Proyecto Geodinámico, División El Teniente, CODELCO-Chile. Other notes. [1] Radiometric Age *in* Cuadra (1986); [2] Isotopic data in Stern and Skewes (1995); [3] Isotopic data in Sillitoe (1973); [4] *In* Kay and Kurtz (1995)**; * Total iron as FeO.

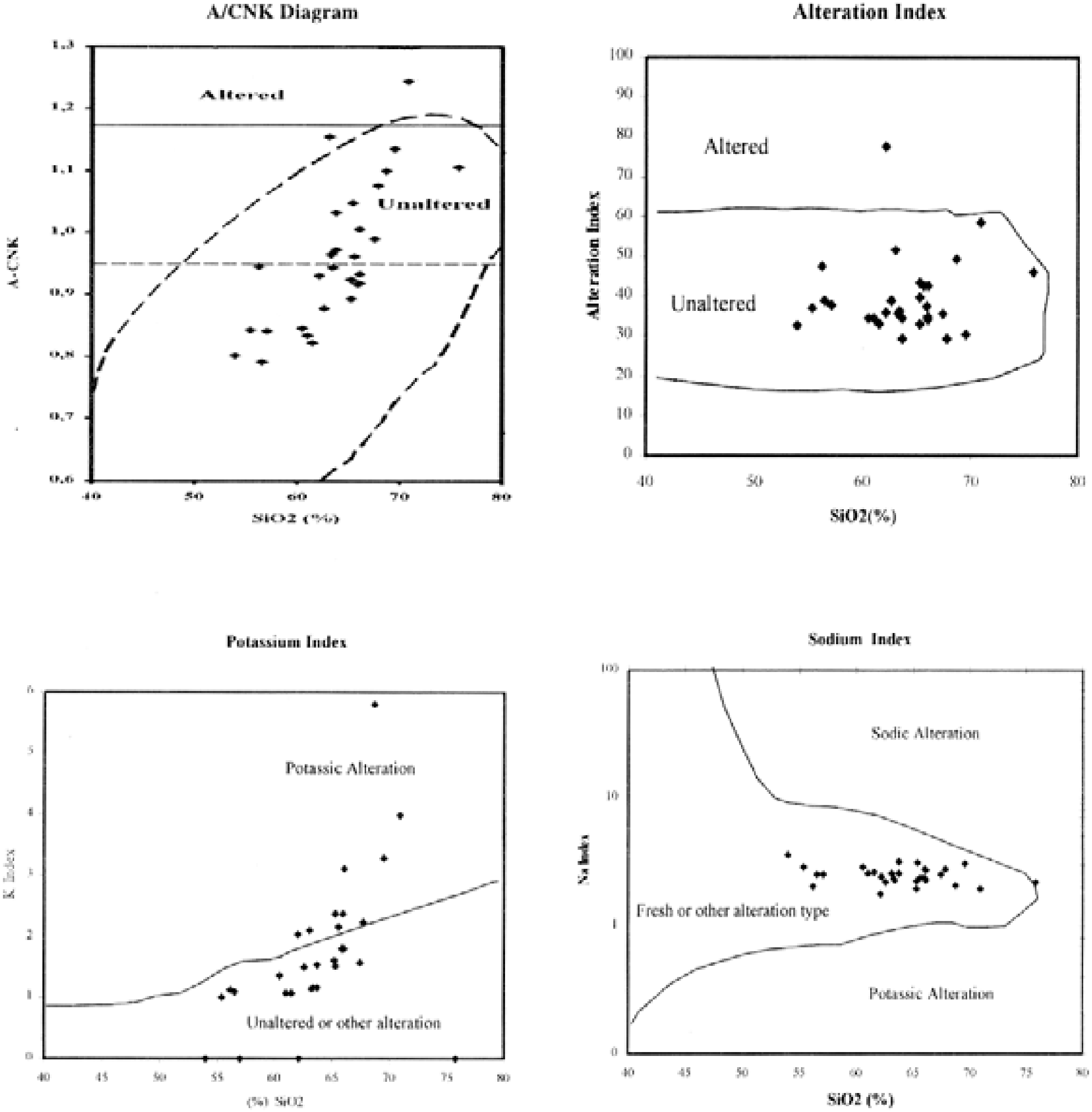

FIG. 3. Available data of Neogene igneous rocks from the Central Chile Metallogenic Segment plotted on the alteration filter diagrams proposed by Wilt (1995). A/CNK= molecular ratio $Al_2O_3/(CaO+Na_2O+K_2O)$; Alteration Index = $(MgO+K_2O) / (Na_2O+K_2O+CaO+MgO) * 100$; "Na" Index = (Na_2O/K_2O) + A/CNK; 'K' Index = $(Na_2O+K_2O+MgO)/ (CaO+FeO_T)$.

REGIONAL STRUCTURAL SETTING AT EL TENIENTE DISTRICT

El Teniente is located on the western portion of Central Chile's main Cordillera. The most important tectonic feature at the district scale is the ENE-striking, subvertical, Teniente Fault Zone (TFZ). The TFZ is a *ca.* 10 km long belt marked by densely faulted, altered and mineralized rock (Garrido *et al.*, 1994). Immediately east of El Teniente District, the regional-scale structure is dominated by north-south striking thrusts organized into the Aconcagua fold-and-thrust-belt of Miocene age (Ramos *et al.*, 1996).

T. Cladouhos[1] studied the geometry and kinematics of minor faults in and around the TFZ. He determined that right-lateral strike-slip movement produced local northwest-trending shortening along the fault zone whereas roughly east-west shortening, predominates outside it. Geometry and kinematics of faulting at El Teniente mine is consistent with field observations in the surroundings, however, main activity of the TFZ appears to have ended before emplacement of the intrusions and mineralization (7-4.6 Ma). The last tectonic event of the region is documented by faults that cut a 2.9 Ma dyke (Cuadra, 1986) and yield a NNE-SSW shortening direction. Lavenu and Cembrano (1999), on the basis of kinematic analysis of fault populations in the forearc region of Central Chile, also determined that a regional east-west shortening direction predominated during the Pliocene and that a NNE-oriented shortening prevailed during the Quaternary.

T. Cladouhos[1] proposed that the Teniente fault zone is a transfer fault between separate domains or thrust plates implying that the shear zone was active during the regional east-west contractional event. Rivera and Cembrano (2000) also argued the conspicuous structures that cut the Andes at a high angle at these latitudes act as transfer fault zones that take up the differential shortening between major tectonic segments of the Andes.

NEOGENE TECTONIC EVOLUTION OF THE ANDEAN SEGMENT BETWEEN 31 AND 34°S

The geotectonic evolution responsible for the origin of the porphyry copper deposits started with a progressive decrease of the Nazca Plate subduction angle. This process may have been triggered by the arrival of the Juan Fernández ridge at these latitudes at *ca.* 12-10 Ma (Kay *et al.*, 1991, 1995; Stern and Skewes, 1995; Yáñez *et al.*, 2001, 2002). This first-order event activated other processes, as in a chain reaction, in such a way that crustal thickening and subsequent volcanic arc abandonment followed the bulk east-west shortening associated with subduction shallowing.

Available and new geometric and kinematic evidence supporting the initiation of a regional-scale east-west shortening event at around 10 Ma is shown in figures 4 and 5. Evidence can be summarized as follows:

- Precordillera uplift, which occurred during mid to Late Miocene times in the back arc zone (Jordan *et al.*, 1993). This geological process is represented by the Aconcagua fold-and-thrust belt (FTB, Fig. 4), which consists of a series of east-verging, low-angle reverse-slip fault zones that may have accommodated as much as 50 km of east-west total shortening (Ramos *et al.*, 1996).
- The development of 'El Fierro' regional thrust (Fig. 4), which affected 8 Ma volcanic rocks (Godoy, 1998).
- Syntectonic emplacement of the 7.1 Ma 'Sewell' granodiorite in the northeast trending, dextral strike-slip TFZ (TFZ, Garrido *et al.*, 1994; Fig. 4). The TFZ localized the magmatic and hydrothermal processes leading to Cu-Mo mineralization, between 7.1 and 4.9 Ma, at El Teniente (Garrido *et al.*, 1994). The authors have observed a similar deformation style at Los Pelambres and Río Blanco-Los Bronces districts.
- Inversion of kinematic fault-slip data from the 9.8 Ma 'La Gloria' Pluton and from El Teniente porphyry copper district, indicating an east-west oriented maximum shortening axis (Lavenu and Cembrano, 1999; this work; Fig. 5).

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[1] 1994. Fault Kinematics near the el Teniente mine. Report to Proyecto Geodinámico-El Teniente (Inédito), *Corporación del Cobre*, 29 p.

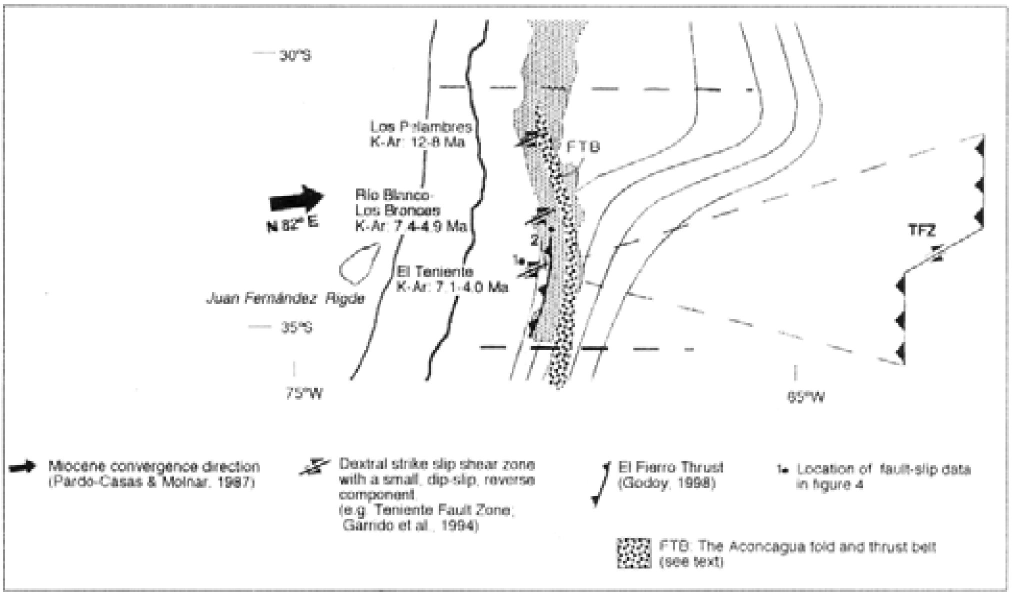

FIG. 4. Structural evidence that document an east-west directed shortening event (10-2.8 Ma) for the Andean segment between 31 and 34°S.

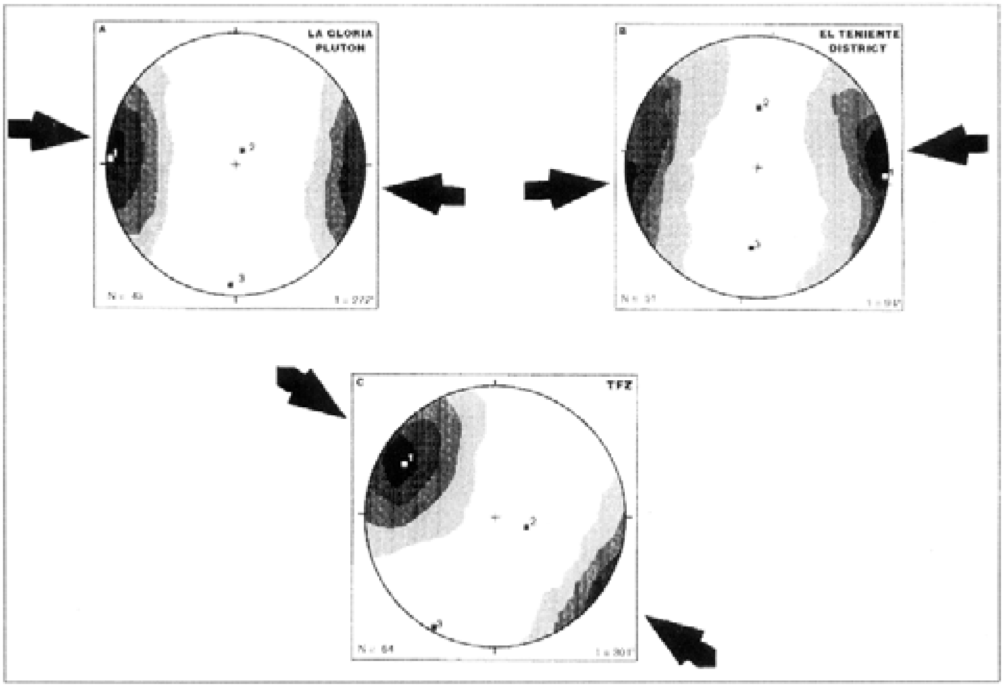

FIG. 5. Contoured diagrams (equal area projections) of shortening axes obtained from inversion of fault-slip data at **(a)** La Gloria Pluton (location 2 in figure 4); **(b)** El Teniente District and **(c)** Teniente Fault zone (TFZ; location 1 in figure 4). Fault-slip data within the TFZ yield a maximum shortening axis trending N301; however, outside the shear zone both the faults and fold axes document N094-trending maximum shortening axis shown with arrows. These local differences can be attributed to a rotation of the prevailing, regional east-west shortening, because of sharp contrasts in strength outside and inside the TFZ (see McKinnon and Garrido, 1998).

Intensification of east-west shortening at *ca.* 9.8 Ma may account for subsequent high exhumation rates of plutons from this Andean segment, for the period between 8.4 and 5 Ma (3 mm/year; Kurtz *et al.*, 1997). Likewise, high erosion rates were reported from the Río Blanco-Los Bronces area between 11.3 and 4.9 Ma (Skewes and Holmgren, 1993).

Thus, the period in which the porphyry copper deposits formed (9-4 Ma) was contemporaneous with the reinforcement of the east-west-directed shortening and with a significant increase in exhumation and erosion rates. The cycle culminates with the eastward migration of the magmatic arc (Kay *et al.*, 1991; Stern and Skewes, 1995) presently represented by the northernmost edge of the Southern Volcanic Zone.

A POSSIBLE ORIGIN FOR THE ANDEAN LATE MIOCENE GIANT PORPHYRY COPPER DEPOSITS

The genesis of the Late Miocene porphyry copper deposits can be envisioned as a mineralization cycle that took place progressively from north to south: Los Pelambres (32°S) at 9 Ma, Río Blanco-Los Bronces (33°S) at 5 Ma and El Teniente (34°S) at 4 Ma. According to geochemical and structural data, this copper-producing event is spatially associated with emplacement of a series of highly oxidized granitoids, which intruded and differentiated during regional shortening as shown by shear zones active at time of emplacement (Faunes and Mora, 1994; Garrido *et al.*, 1994).

Bulk shortening appears to have favored crystal-magma fractionation processes within the shear zones. The high O_2 fugacity of the magmas inhibited the separation and extraction of a sulfur-rich phase (sulfide melt blebs), the main metal-capturing agent during magmatic fractionation (Stimac and Hickmott, 1995). This, in turn, favored an increasing concentration of S, Cu and Mo available and become incorporated into hydrothermal fluids associated with the more differentiated porphyries (Ishihara, 1981; Candela and Blevin, 1995). According to Matthews *et al.* (1995) fractional crystallization of a highly oxidized magma, without an early releasing of gases, would lead to the formation of a sulphur-rich mineralized hydrothermal fluid. This can explain the early precipitation of pyrite accompanying copper sulphides in the potassic alteration zones of the Late Miocene porphyry copper deposits (Warnaars *et al.*, 1985). In contrast, the abundance of hydrothermal magnetite as a component of the mineralized potassic alteration zone in most of the gold-rich porphyry copper deposits, could be indicative of a sulphur-poor mineralized fluid, probably derived from a comparative less oxidized magma (cf. Leveille *et al.*, 1988).

From the metallogenic point of view, the occurrence of a bulk shortening regime during this copper mineralization event is of great importance. It is well known that seismic slip at certain structural sites can cause localized pressure drops, fluid migration and mineral precipitation. Both the suction pump and fluid-valve mechanisms, promoted by seismic slip, can contribute to separation and/or differentiation of hydrothermal fluids through repeated episodes of faulting (Sibson, 1987, 1990, 2000). As stated before, The Teniente Fault zone may have acted as a dextral strike-slip transfer fault within the westernmost part of the regional-scale Aconcagua thrust belt. The authors speculate that large volumes of fluid were pumped into now obliterated dilational jogs within the Teniente Fault Zone. This may have led to repeated episodes of pressure fluctuation, high volumes of fluid migration and subsequent mineral precipitation. Structural conditions favorable for such suction pump and fault-valve behavior have been described for El Teniente and Los Pelambres (Garrido *et al.*, 1994; Faunes and Mora, 1994).

Apparently similar structural settings have been documented in studies undertaken at the El Salvador and Chuquicamata porphyry copper deposits (Mpodozis *et al.*, 1994; Lindsay *et al.*, 1995; Tomlinson and Blanco, 1997; Maksaev and Zentilli, 1999), located in the Northern Chile Metallogenic Segment (Fig. 1). These authors have suggested that the Eocene-Oligocene porphyry copper deposits were emplaced along active transcurrent faults during regional transpression. However, in contrast to porphyry copper deposits of northern Chile, that are spatially associated with major margin-parallel intra-arc fault systems, El Teniente is spatially and temporally associated with a more local margin-oblique transfer fault linking regional-scale thrusts.

Following the above reasoning, the authors emphasize the active role of fault zones in the origin and evolution of hydrothermal activity. Fault zones where magmas are emplaced, can account for the depressurization and devolatilization processes commonly proposed to explain the separation of mineralized hydrothermal fluids from crystallizing magmas (Candela and Blevin, 1995).

Furthermore, it seems likely that the huge size of the porphyry copper deposits discussed here and their typical multi-episodic character, *i.e.*, progressively more differentiated porphyritic intrusives associated with successive stages of hydrothermal mineralizing activity, are precisely the result of repeating episodes of crystal-magma fractionation and subsequent porphyry emplacement under disequilibrium conditions (Stimac and Hickmott, 1995) triggered by reverse and/or strike-slip faulting occurring during regional shortening. The abundant hydrothermal breccia bodies occurring in the Late Miocene porphyry copper deposits also support fractionation and devolatilization under disequilibrium.

DISCUSSION AND CONCLUSIONS

The significant increase in the oxidation state of the magmas responsible for Late Miocene copper mineralization may have resulted from modifications of the mantle source. Ishihara *et al.* (1984) suggested that the predominance of oxidized granitoids (magnetite series) in the Chilean Mesozoic-Cenozoic batholiths resulted from a significant supply of oceanic crust to the volcanic arc magma source. Hydration of the mantle source and magmas by different mechanisms, including especially fluids coming from the shallowing and cooling subducting slab, was pointed out by Kay *et al.* (1999) as an important contribution to the mineralization processes in the Andean segment between 31 and 34°S.

The well-documented high oxidation state of the Late Miocene magmas may be related to an increased supply of components from oxidized oceanic crust, because of the progressive slab shallowing concomitant with subduction of the Juan Fernández Ridge beneath the continent (Yáñez *et al.*, 2001). Ocean floor volcanic activity is accompanied by seawater circulation and subsequent formation of hydrous metamorphic minerals with a concomitant rise in the oxidation state. In this context, an increased contamination of the mantle source by components from hydrated oceanic crust, transferred as a fluid or a silicate melt, may account for an increase in fO_2 of the magmas (high oxidation state), without significantly increasing the $^{87}Sr/^{86}Sr$ initial ratio. This is the observed geochemical signature of the Late Miocene porphyry copper deposits.

The Sr isotope geochemistry of the igneous rocks from the Andean segment between 31 and 34° shows a rise in the $^{87}Sr/^{86}Sr$ initial ratios after 4.7 Ma (Fig. 2), indicating greater continental crust input. This may result from crustal contamination during magma ascent or –as suggested by Stern (1991)- may be generated by slab-dip shallowing and tectonic erosion of the continental margin leading to incorporation of crustal material into the source region. Consistently, the oxidation state of the granitic rocks decreases significantly to a Fe_2O_3/FeO ratio of *ca.* 0.5 (Fig. 2), which, in turn, is compatible with a reduced continental crust, presumably of carbonaceous meta-sedimentary nature (Ishihara, 1981).

From the analysis of previously published and new data, the authors conclude that the Late Miocene porphyry copper deposits result from a complex combination of distinctive tectonic and magmatic processes. Both types of processes were the result of a common first-order geodynamic constraint corresponding to progressive slab shallowing in close association with ridge subduction. In this model, the strongly oxidized Late Miocene magmatism is a key factor in the high potential for copper deposits in central Chile. However, it is the interaction of such magmatism with active regional shortening, which turns this potential into the actual release of enormous amounts of mineralizing fluids leading to the formation of the huge porphyry copper deposits.

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