Geochronology of Miocene plutons and exhumation history of the El Teniente region, Central Chile (34-35°S)

Andrew C. Kurtz

Suzanne M. Kay

Institute for the Study of the Continents, Department of Geological Sciences, Snee Hall, Cornell University, Ithaca, NY 14853, U.S.A.

Reynaldo Charrier

Departamento de Geología, Universidad de Chile, Casilla 13518, Correo 21, Santiago, Chile

Edward Farrar

Department of Geological Sciences, Queen's University, Kingston, Ontario K7L 3N6, Canada

ABSTRACT

$^{40}Ar/^{39}Ar$ mineral dating and whole rock chemical analyses of Miocene to Pliocene Andean granitoids near the El Teniente copper deposit (34°S) provide new evidence for rapid Neogene exhumation. This exhumation is attributed to crustal thickening that culminated in the Late Miocene-Early Pliocene coincident with the emplacement of the ore deposit. Three groups of Neogene plutons in the forearc of the active Southern Volcanic Zone (SVZ) are considered. The oldest and westernmost is represented by the La Obra pluton (19.6 ± 0.5 Ma, biotite) which has chemical affinities with the host Late Oligocene-Early Miocene Coya-Machalí Formation volcanic rocks. Slow cooling of this pluton is required by a 3.4 my difference between biotite and K-feldspar $^{40}Ar/^{39}Ar$ ages. Modeling shows that this cooling is consistent with an exhumation rate of ~0.55 mm/yr between 19.6 Ma and 16.2 Ma. The second group, termed the El Teniente Plutonic Complex, consists of plutons with biotite ages clustering at ~11 to 12 Ma and ~8 to 9 Ma. These plutons have chemical affinities with the Middle to Late Miocene Teniente Complex (Farellones Formation) volcanic rocks whose chemical characteristics suggest that they erupted through a thicker crust than the Coya-Machalí units. A 0.7 my difference between biotite (8.4±0.3 Ma) and K-feldspar ages in the Nacimiento Río Cortaderal pluton requires an exhumation rate of ~3 mm/yr between 8.4 and 7.7 Ma. Although modeled exhumation rates depend on estimates of mineral closure temperatures, paleo-geothermal gradients, and errors in age determinations, a higher exhumation rate for the Nacimiento Río Cortaderal pluton than the La Obra pluton is a robust result of modeling. A third group of plutons (Young Plutonic Complex) farther west, is characterized by biotite ages of 6.6 to 5.6 Ma. Their steeper rare earth element patterns and more enriched isotopic signatures, are consistent with emplacement in a crust even more thickened by Late Miocene compressional deformation. An elevated paleo-geothermal gradient, consistent with the Miocene magmatic-arc environment, best explains the cooling histories of these plutons. Their mineral ages are interpreted as being controlled by exhumation associated with crustal thickening due to compressional deformation related to crustal shortening. The data are consistent with a moderate regional deformation associated with eastward shift of the magmatic front between 20 to 16 Ma, and a stronger regional deformation associated with frontal arc migration between 8 and 5 Ma.

Key words: Pluton, Exhumation, Miocene, Copper, El Teniente, $^{40}Ar/^{39}Ar$, Chile.

FE DE ERRATAS

En el Abstract, línea 15 dice... farther west ...y debe decir...farther east. En el Resumen, línea 7, dice... 1,6 Ma y debe decir 19, 6 Ma, y en línea 20 dice...ubicado al oeste del...debe decir ...ubicado al este del...

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RESUMEN

Geocronología de los plutones miocenos e historia del alzamiento andino en la región de El Teniente, Chile central (34-35°S). Dataciones $^{40}Ar/^{39}Ar$ en minerales y roca total de granitoides del Mioceno al Pleistoceno en las cercanías del yacimiento El Teniente, ubicado en el antearco del extremo norte de la zona volcánica activa de los Andes del Sur, proporcionan nuevas evidencias para la edad del alzamiento regional en esa zona de los Andes. Este fenómeno culminó en el Mioceno tardío-Plioceno temprano, durante el emplazamiento del pórfido cuprífero. Tres grupos de plutones del Neógeno se han identificado en esta zona. El más antiguo, y más occidental, está representado por el Plutón La Obra (1,6±0,5 Ma: biotita). Este tiene afinidades químicas con las rocas volcánicas huéspedes de la Formación Coya-Machalí que hicieron erupción a través de una corteza continental delgada. La diferencia de 3,4 Ma existente entre las edades $^{40}Ar/^{39}Ar$ de biotita y feldespato potásico indica un enfriamiento lento del plutón, que es consistente con un alzamiento regional a tasas bajas, del orden de 0,3-0,55 mm/año. El segundo conjunto (Complejo Plutónico El Teniente), ubicado más al este, está formado por una familia de plutones con edades $^{40}Ar/^{39}Ar$ en biotitas agrupadas entre los 11-12 Ma y 8-9 Ma. Estos plutones tienen afinidades químicas con las rocas del complejo volcánico Mioceno de El Teniente (Formación Farellones), cuyas características indican erupción a través de una corteza más gruesa. La diferencia de 0,7 Ma entre las edades en biotita (8,3±0,3 Ma) y feldespato potásico detectadas en el Plutón Nacimiento del Río Cortaderal señala un proceso de enfriamiento más rápido que para el plutón La Obra el cual es, a su vez, consistente con una tasa de alzamiento regional (1,5-2,0 mm/año) mayor que la determinada a partir del plutón La Obra. Un flujo calórico elevado, propio del ambiente de arco magmático dominante durante el Mioceno, se ajusta a la historia de enfriamiento de los plutones. En esas condiciones, la biotita se puede mantener por sobre su temperatura de cierre (300°C) hasta ser alzada a más de 3,5 km de profundidad. Un tercer grupo de plutones (Complejo Plutónico Joven), ubicado hacia el oeste del anterior, se caracteriza por edades $^{40}Ar/^{39}Ar$ en biotita de 6,6 a 5,6 Ma. Sus patrones empinados de Tierras Raras y una firma isotópica más enriquecida, son consistentes con su emplazamiento en una corteza engrosada tectónicamente por la deformación del Mioceno tardío. Estas observaciones, junto a otras, obtenidas tanto al sur como al norte de El Teniente, parecen indicar que este segmento de la cordillera sufrió un alzamiento regional a tasas bajas entre los 26 a 16 Ma y un alzamiento a tasas extremadamente elevadas, asociadas a deformación regional y migración del arco entre los 8 y 5 Ma.

Palabras claves: Plutón, Alzamiento, Pórfidos de Cobre, $^{40}Ar/^{39}Ar$, Mioceno, El Teniente, Chile Central.

INTRODUCTION

The central Chilean Andes are host to several 'Gigantic' Mio-Pliocene porphyry copper deposits, which occur at the southern end of a chain of exposed porphyry copper deposits on the western margin of the Americas. Among these, is the El Teniente deposit at 34°S latitude, located ~100 km southeast of Santiago (Fig. 1) in the forearc of the northern end of the active Andean Southern Volcanic Zone (SVZ, 33-46°S). North of the SVZ is the modern non-volcanic region (28-33°S) known as the Flatslab region, for the broad flat segment that has developed in the subducting Nazca plate at a depth of ~100 km beneath the South American continent (Fig. 1). Genesis of Mio-Pliocene Andean 'Gigantic' copper deposits, such as El Teniente, seems to be related to crustal thickening and uplift associated with Miocene to Recent southward flattening of the subducting Nazca plate (Kay *et al.*, 1987, 1991; 1995; Skewes and Stern, 1994, 1995; Stern and Skewes, 1995). Skewes and Holmgren (1993) and Skewes and Stern (1994) proposed that rapid uplift and exhumation of deep-seated plutonic systems in this environment resulted in exsolution of copper-bearing magmatic fluids that caused brecciation and mineralization of porphyry copper deposits.

This paper presents new $^{40}Ar/^{39}Ar$, chemical data, and modeling for El Teniente region plutons that support and refine a model of regional rapid exhumation and crustal thickening associated with crustal shortening near the time of emplacement of the El Teniente copper deposit. A period of Early Miocene exhumation is also indicated. The data are consistent with a moderate regional deformation associated with eastward shift of the magmatic front between 20 to 16 Ma, and a stronger regional deformation associated with frontal arc migration

[1] 1993. Geología del área entre los ríos Claro del Maipo y Cachapoal. Informe final (Inédito), *Corporación Nacional del Cobre (Chile)-Servicio Nacional de Geología y Minería (Chile)*, 2 Vols.

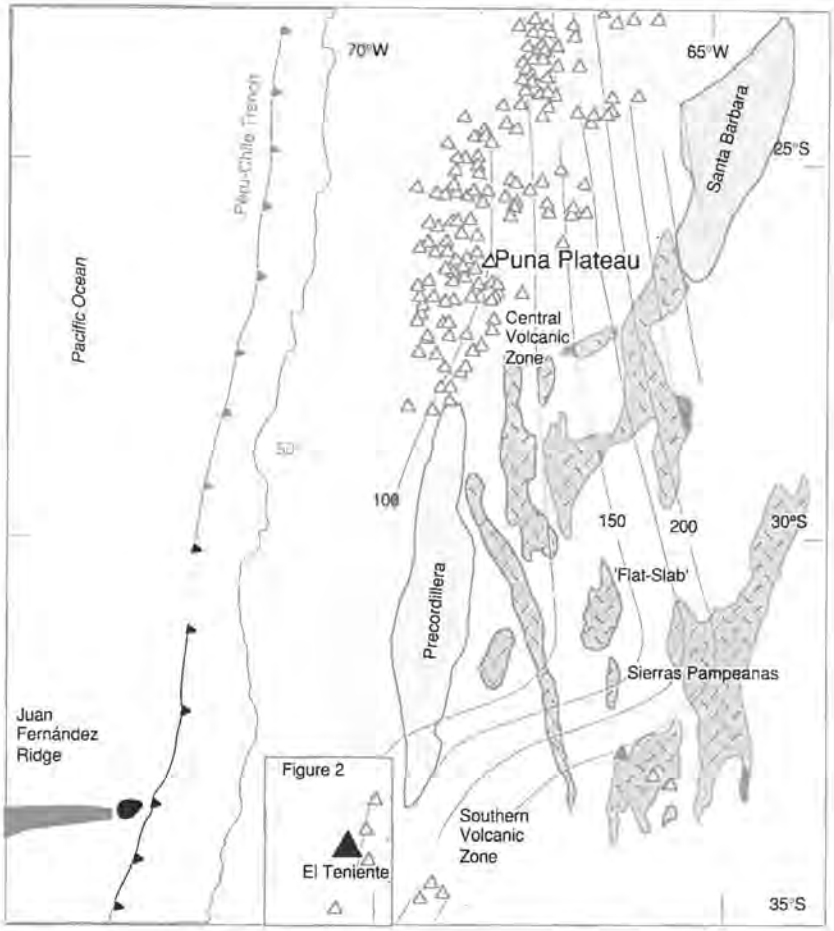

FIG. 1. Map showing location of El Teniente region (boxed area) and copper deposit (solid triangle) relative to the principal tectonic features of the central Argentine and Chilean Andes. Benioff zone contours are from Cahill and Isacks (1992). Light gray shaded area shows regions with elevations over 3,300 meters. Stippled regions are block-faulted ranges of the Sierras Pampeanas. Precordillera and Santa Barbara ranges are fold-thrust belts. Late Miocene to Recent volcanoes shown as small open triangles, define the Central (CVZ) and Southern (SVZ) Volcanic Zones which bound the modern volcanically inactive Flatslab. Note that the El Teniente region is in the forearc of the SVZ just south of the Flatslab.

between 8 and 5 Ma. Results presented here are part of a larger study on the Neogene magmatic and tectonic setting of the El Teniente region (E. Godoy[1]; Godoy and Lara, 1994; Godoy *et al.*, 1996; Kay *et al.*, 1995; Kay, 1996; S.M. Kay and A.C. Kurtz[2]).

EL TENIENTE REGION PLUTONS

Seventeen plutonic bodies were sampled from a region bounded by the Río Maipo to the north, the Río Tinguiririca to the south, the modern Southern Volcanic Zone arc to the east, and the Central Valley to the west (Fig. 2). Regional geologic and petrographic observations indicate that they are subvolcanic to shallow plutonic intrusions. Many are intruded into local Oligocene to Miocene volcanic formations, whose composite thickness is no more than 5 km (Villarroel and Vergara, 1988; Rivano *et*

[1] 1995. Magmatic and tectonic characterization of the El Teniente region. Final Report (Inédito), *Corporación Nacional del Cobre (Chile)*, 180 p.

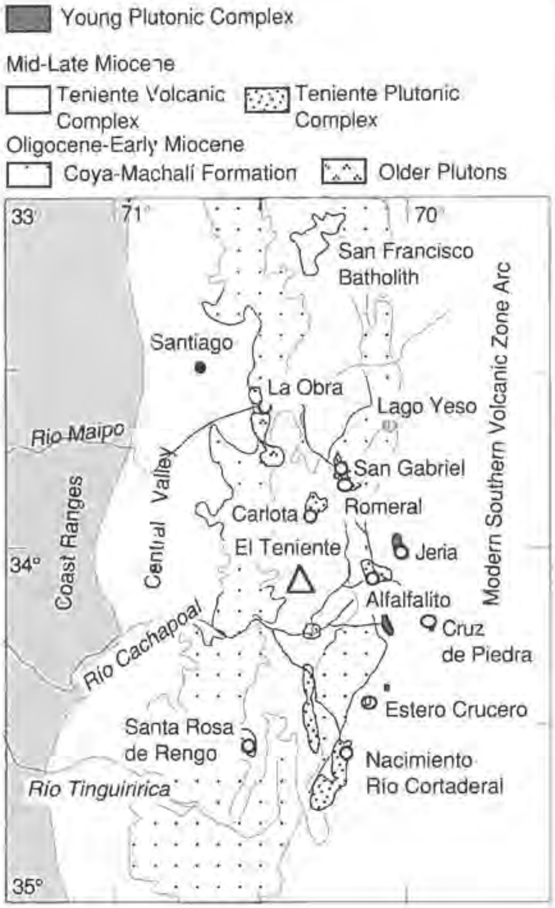

FIG. 2. Map of boxed area in figure 1, showing locations of the three Neogene pluton groups discussed in the text relative to the Late Miocene-Pliocene El Teniente copper deposit and Tertiary magmatic belts. Plutons dated in this study are identified by name. Also shown is the Miocene San Francisco plutonic complex in the Los Bronces district (Warnaars *et al.*, 1985). The El Teniente deposit (triangle) is in the Middle-Late Miocene Teniente Volcanic Complex belt (Farellones Formation), which is bounded by the western and eastern belts of the Oligocene to Early Miocene Coya-Machalí Formation. The western Coya Machalí and Teniente Volcanic Complex belts, respectively, mark the Oligocene to Early Miocene and the Middle to Late Miocene frontal magmatic arcs (E. Godoy, 1993[1]; Kay *et al.*, 1995; Charrier *et al.*, 1996). The Pliocene to Recent Southern Volcanic Zone (SVZ) frontal arc is to the east (Fig. 1). Map modified from R. Charrier[3] and Charrier *et al.* (1996).

al., 1990); R. Charrier[3]; Charrier *et al.*, 1996). Although post-magmatic alteration is widespread, plutons are typically much less altered than associated volcanic rocks. Some plutons contain granophyric intergrowths of quartz and K-feldspar, which are commonly interpreted as indicating shallow emplacement (*e.g.*, Zen, 1989). The Al-in-hornblende geobarometer (Schmidt, 1992) yields crystallization depth estimates of 3.1 to 4 km for the Early Miocene La Obra pluton and up to 5 km for the Late Miocene Nacimiento Río Cortaderal pluton (Kurtz, 1995). Lack of precision is due to chemical inhomogeneities in hornblende grains, and because their low tetrahedral Al concentrations (0.78±0.22 and 0.88±0.04 cations per formula unit) are outside the geobarometer's experimental calibration. Taken together, the data are consistent with the plutons crystallizing within 5 km of the surface.

The El Teniente region Tertiary magmatic rocks have chemical trends similar to Flatslab magmatic rocks to the north studied by Kay *et al.* (1987, 1991) and Kay and Abbruzzi (1996). Among general younging trends in both regions are increasingly fractionated rare earth element (REE) patterns with steeper heavy REE patterns, higher Sr concentrations, and more radiogenic $^{87}Sr/^{86}Sr$ and less radiogenic $^{143}Nd/^{144}Nd$ ratios (*e.g.*, Kay *et al.*, 1987, 1991, 1995; Stern and Skewes, 1995; Kay and Abbruzzi, 1996; Table 1). Such trends in the El Teniente region, by analogy with the 'Flatslab' (Kay *et al.*, 1987, 1991; Kay and Abbruzzi, 1996), can be interpreted as evidence for an increasingly higher pressure lower crustal residual mineralogy as the crust thickened in response to compressional shortening (Kay *et al.*, 1996). The isotopic trends are consistent with increasing contamination of mantle-derived arc magmas by crustal material in the thickening crust (Kay *et al.*, 1991, 1995) and by subduction-related contamination of the source region (Stern and Skewes, 1995).

PLUTONIC GROUPS

The El Teniente region plutons can be put into three broad groups, based on chemical characteristics (Table 1), age (Table 2) and location (Fig. 2). The first group occurs in the westernmost part of the region and includes the Early Miocene La Obra pluton (19.6±0.5 Ma, biotite). This leucogranodiorite has chemical characteristics (*e.g.*, low $^{87}Sr/^{86}Sr$ ratios, flat REE patterns; Table 1; López-Escobar *et al.*, 1979) like those of the western belt Coya-Machalí Formation volcanic rocks (Fig. 2) that it intrudes (Kay *et al.*, 1995). An Oligocene to Early Miocene age for the Coya-Machalí Formation has recently been confirmed (Wyss *et al.*, 1994; Flynn *et al.*,

[3] 1983. Hoja El Teniente. Carta Geológica de Chile, escala 1:250.000 (Inédito). *Servicio Nacional de Geología y Minería* (Chile), 154 p.

TABLE 1. GEOCHEMICAL DATA FOR SELECTED EL TENIENTE REGION PLUTONS.

	Older Plutons		Teniente Plutonic Complex			Young Plutonic Complex	
Name	**La Obra**	**Santa Rosa de Rengo**	**Alfalfalito**	**Carlota**	**Nacimiento Río Cortaderal**	**Jeria**	**Cruz de Piedra**
Sample No.	**ETP-1**	**ETP-17**	**ETP-10A**	**ETP-9**	**ETP-7**	**ETP-11**	**ETP-14**
SiO_2	70.86	65.04	61.75	62.87	66.21	62.83	64.4
TiO_2	0.35	0.62	0.89	0.81	0.57	0.69	0.55
Al_2O_3	14.43	16.43	16.74	16.32	16.06	17.07	16.59
FeO^*(total)	2.95	4.11	5.85	5.04	3.71	4.13	3.84
MnO	0.11	0.10	0.07	0.04	0.04	0.11	0.04
MgO	1.17	1.87	2.11	2.41	1.85	2.9	2.65
CaO	3.08	4.02	4.27	4.92	4.03	5.97	4.71
Na_2O	3.55	4.35	4.33	3.78	3.85	4.6	4.26
K_2O	3.25	3.27	3.78	3.62	3.44	1.45	2.8
P_2O_5	0.23	0.18	0.21	0.2	0.24	0.25	0.16
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**
La	10.0	22.8	38.4	19.0	27.4	17.8	25.2
Ce	23.2	43.0	77.7	42.9	62.3	37.9	51
Nd	12.9	17.9	33.4	20.3	26.3	18.1	22.5
Sm	3.21	3.95	7.19	4.95	5.46	3.54	3.88
Eu	0.562	0.788	1.19	0.794	0.86	0.861	0.829
Tb	0.615	0.527	0.936	0.693	0.74	0.404	0.444
Yb	2.35	1.50	2.58	1.9	1.88	1.08	1.39
Lu	0.32	0.205	0.333	0.244	0.22	0.156	0.184
Sr	199	393	513	367	453	682	583
Ba	603	624	809	438	695	601	667
Cs	8.3	3.0	1.8	5.3	4.1	0.6	2.8
U	2.6	2.1	4.5	4.3	7.7	0.9	2.4
Th	11.2	8.7	13.7	13.5	23.3	3.8	9.8
Hf	4.4	5.1	9.6	7.4	5.4	3.9	4.8
Sc	8	9	14	12	9	10	10
Ta	0.32	0.38	0.86	0.49	0.72	0.4	0.86
Cr	8	18	21	27	19	38	72
Ni	3	10	18	108	12	17	26
Co	7	11	11	15	11	11	13
$^{87}Sr/^{86}Sr$	0.704005		0.704293	0.704022	0.704059	0.704435	0.704273
$^{87}Sr/^{86}Sr_i$	0.70361		0.70416	0.70392	0.70398	0.70442	0.70424
Epsilon Nd	+4.6		+2.5	+2.8	+1.6	+0.7	-0.1
$^{206}Pb/^{204}Pb$	18.453			18.558	18.576	18.588	
$^{207}Pb/^{204}Pb$	15.554			15.582	15.566	15.577	
$^{208}Pb/^{204}Pb$	38.210			38.362	38.329	38.378	

1995; Charrier *et al.*, 1996). The Santa Rosa de Rengo granodiorite pluton, which yields a hornblende $^{40}Ar/^{39}Ar$ age of 16.2±1.2 Ma, is compositionally transitional between the La Obra pluton and the younger plutonic groups. The second plutonic group, referred to as the Teniente Plutonic Complex, includes most of the plutons in the study region. In detail, these largely granodioritic plutons can be subdivided into two groups based on biotite plateau ages: one group between 13 and 11 Ma (*e.g.*, Alfalfalito pluton) and the other between 9 and 7 Ma (*e.g.*, Carlota and Nacimiento Río Cortaderal plutons). They share chemical characteristics including isotopic ratios and REE patterns with the contemporaneous El Teniente Volcanic Complex (Farellones Formation), supporting a common source region for both plutonic and volcanic rocks (Kay *et al.*, 1995). The third group, referred to as the Young Plutonic Complex (YPC), includes the Jeria and Cruz de Piedra plutons to the east which have biotite plateau

TABLE 2. NEW $^{40}Ar/^{39}Ar$ PLATEAU AGES FOR EL TENIENTE REGION PLUTONS.

Unit	Sample	Mineral	Plateau*	Age (Ma)	Error (2σ)
Older Plutons					
La Obra	ETP-1	Hornblende	4/100	21.6	4.9
La Obra	ETP-1	Biotite	7/100	19.6	0.5
La Obra	ETP-1	Plagioclase	4/99	17.1	0.4
La Obra	ETP-1	K-feldspar	4/92	16.2	0.3
Santa Rosa de Rengo	ETP-17	Hornblende	2/75	16.2	1.2
Teniente Plutonic Complex					
12 Ma Group					
Lago Yeso	ETP-5	Hornblende	3/100	12.4	2.5
Alfalfalito	ETP-10A	Biotite	4/99	12.3	0.2
San Gabriel	ETP-2A	Biotite	4/90	11.4	0.2
Romeral	ETP-4	Biotite	3/98	11.3	0.3
8 Ma Group					
Estero Crucero	ETP-8B	Biotite	2/88	8.8	0.1
Carlota	ETP-9	Biotite	4/99	8.7	0.3
Nacimiento Río Cortaderal	ETP-7	Biotite	6/87	8.4	0.3
Nacimiento Río Cortaderal	ETP-7	K-feldspar	3/93	7.7	0.1
Young Plutonic Complex					
Jeria	ETP-11	Biotite	4/97	6.6	0.1
Cruz de Piedra	ETP-14	Biotite	4/100	5.5	0.2

* Number of heating steps used in calculating plateau ages and % of ^{39}Ar released in these steps.

ages of 6.6 to 5.5 Ma. These granodioritic plutons are chemically distinguishable from the older plutons by their more radiogenic $^{87}Sr/^{86}Sr$ REE slopes (Table 1). Their chemical compositions approach those of young volcanic rocks in the northern part of the active Southern Volcanic Zone (*e.g.*, Hildreth and Moorbath, 1988; Kay, 1996).

GEOCHRONOLOGY

Prior to this study, and the K-Ar dating by E. Godoy[1] only limited geochronological data were available for Tertiary magmatic rocks in the El Teniente region. Age compilations for Chilean granitoids presented by Aguirre *et al.* (1974), and Drake *et al.* (1982) included some data for Tertiary granitoids between 30 and 35°S. Many of these ages were based on the lead-alpha technique and had precision inadequate for identifying temporal changes within the Miocene. Unpublished K-Ar ages obtained by SERNAGEOMIN, along with new age determinations by F. Munizaga, were compiled by R. Charrier[3]. Clark *et al.* (1983) reported and Cuadra (1986) discussed Pliocene K-Ar dates for dacite samples taken at depth from within the El Teniente mine. Recent work by Wyss *et al.* (1994) and Flynn *et al.* (1995) provided $^{40}Ar/^{39}Ar$ ages for several localities in the Coya-Machalí formation.

Samples dated in this study by $^{40}Ar/^{39}Ar$ methods were selected to clarify the spatial and temporal development of plutonism in the El Teniente region. Analytical techniques are described in Appendix 1. The mineral ages, summarized in table 2 (all spectra *in* Kurtz, 1996), range from 21.6 Ma (La Obra pluton, hornblende) to 5.5 Ma (Cruz de Piedra pluton, biotite). Among these, biotite fractions from nine plutons gave reliable $^{40}Ar/^{39}Ar$ plateau ages (representative spectra in figure 3). Hornblende fractions from the Lago Yeso and the Santa Rosa de Rengo plutons, which had insufficient biotite for analysis, gave less precise, but geologically reasonable plateau ages. The lower precision in hornblende age spectra resulted from analytical constraints associated with their low potassium concentration.

Two plutons, La Obra and Nacimiento Río Cortaderal (Fig. 2), were selected for cooling rate studies. These plutons were chosen on the basis of their petrographic freshness, and similarities in mineralogy, texture, and apparent physical size, to minimize the number of variables influencing cooling rate calculations. A K-Ar biotite age of 24 Ma for the La Obra pluton quoted by López-Escobar *et al.*

(1979) indicated that the La Obra pluton was significantly older than the other plutons. K-feldspar and biotite fractions from both plutons (Fig. 3), and the La Obra plagioclase fraction, produced excellent plateaus. The La Obra hornblende fraction produced a less precise, but geologically reasonable plateau age. In contrast, plagioclase and hornblende fractions from the Nacimiento Río Cortaderal pluton, which were analyzed twice, produced uninterpretable data. The plagioclase fraction had a 'saddle-shaped' release spectrum, a pattern commonly attributed to excess ^{40}Ar (*e.g.*, McDougall and Harrison, 1988).

Dalrymple and Lanphere (1969) pointed out that young minerals with low K contents like plagioclase and hornblende are readily contaminated by small quantities of excess ^{40}Ar. This can explain why Nacimiento Río Cortaderal plagioclase and hornblende fractions appear to have been affected by excess argon, whereas biotite and K-feldspar fractions, with their much higher K contents, appear unaffected. Most of the heating steps on Nacimiento Río Cortaderal plagioclase and hornblende fractions yielded ages >20 Ma, consistent with the incorporation of excess argon into this pluton. Apparent connections between excess argon and rocks involved in thrust tectonics have been discussed by Brewer (1969), Wanless *et al.* (1969), and McBride *et al.* (1987). Excess argon has been observed in metasediments and granitoids from both hangingwall and footwall rocks of thrust sheets by E. Farrar. Although the reasons for this association are not well understood, the diffusion of excess argon into rocks could be due to the presence of fluids related to thrusting. The Nacimiento Río Cortaderal pluton is located in the hangingwall of the El Fierro fault, which has been suggested to be a major structure in this region (E. Godoy[1]; Godoy and Lara, 1994; Godoy *et al.*, 1996).

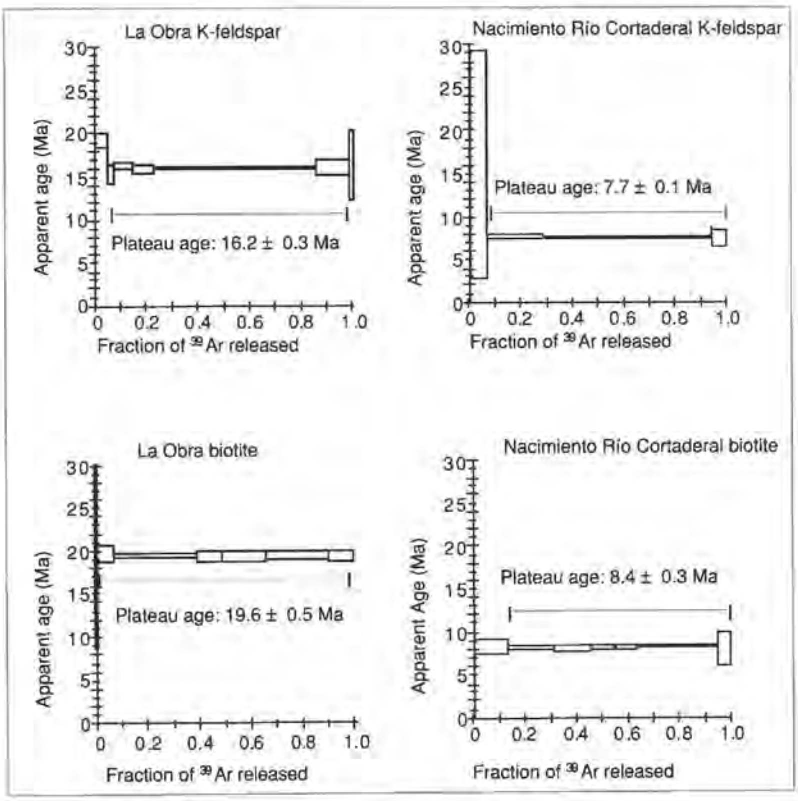

FIG. 3. Step-heating $^{40}Ar/^{39}Ar$ age spectra for biotite and K-feldspar in the La Obra and Nacimiento Río Cortaderal plutons which are critical to modeling in this paper. Bar defines portion of the spectra used in calculating plateau ages.

THERMOCHRONOLOGY

Geochronological data like those in table 2 for the La Obra and Nacimiento Río Cortaderal plutons can be used for exhumation studies of plutonic rocks as age differences between coexisting mineral phases can track cooling histories controlled by exhumation. Exhumation is defined as the rate at which rock is displaced toward the surface, and is the sum of erosional and tectonic unroofing (Abbott *et al.*, 1997). Geochronology cannot address 'uplift' in the sense of broad regional change in elevation with respect to sea level. However, 'exhumation' is a key component in the Skewes and Holmgren (1993) and Skewes and Stern's (1994) model for the genesis of Central Andean porphyry copper deposits, and rapid exhumation can result from crustal thickening and uplift.

$^{40}Ar/^{39}Ar$ mineral ages are used below to model low-temperature (*i.e.*, 300 to 150°C) portions of cooling histories and to infer exhumation rates for the La Obra and Nacimiento Río Cortaderal plutons. Differences in apparent ages between coexisting biotite and K-feldspar from these plutons (Table 3) point to major differences in their cooling rates. In particular, biotite and K-feldspar show a 3.4±0.8 my age difference in the Early Miocene La Obra pluton, and a 0.7±0.4 million year age difference (my) in the Late Miocene Nacimiento Río Cortaderal pluton implying a more rapid cooling rate for the Nacimiento Río Cortaderal pluton than for the La Obra pluton. K-Ar mineral ages obtained by Warnaars *et al.* (1985), and reinterpreted by Skewes and Holmgren (1993) for the San Francisco batholith, ~100 km north of El Teniente (Fig. 2), suggest that cooling rate differences between Early and Late Miocene plutons extend beyond the El Teniente region. In particular, as shown in table 3, two San Francisco plutonic samples with Early Miocene K-Ar ages show large differences (4.2±2.6 my) between hornblende and biotite ages, whereas a third sample with a Late Miocene K-Ar age shows a smaller difference (0.7±1.3 my). This result as that for the La Obra and Nacimiento Río Cortaderal plutons indicates more rapid cooling in the Late Miocene than in the Early Miocene pluton.

TABLE 3. THERMOCHRONOLOGY OF LOS BRONCES AND EL TENIENTE REGIONS.

Los Bronces region (~33°S)			
	Hornblende	**Biotite**	**Age difference**
Closure temperature	(~500°C)	(~300°C)	(my)
San Francisco Batholith			
LB-1	20.1 ± 2.0 Ma	15.9 ± 0.6 Ma	4.2 ± 2.6
LB-7	8.6 ± 0.9 Ma	7.9 ± 0.4 Ma	0.7 ± 1.3
Data from Warnaars *et al.*, 1985			
El Teniente region (34°S)			
	Biotite	**K-feldspar**	**Age difference**
Closure temperature	(~300°C)	(~200°C)	(my)
La Obra Pluton			
ETP-1	19.6 ± 0.5 Ma	16.2 ± 0.3 Ma	3.4 ± 0.8
Nacimiento Río Cortaderal pluton			
ETP-7	8.4 ± 0.3 Ma	7.7 ± 0.1 Ma	0.7 ± 0.4

THERMAL MODELS AND CONDITIONS

Thermal modeling is used here to investigate reasons for differences in biotite and K-feldspar closure ages in the La Obra and Nacimiento Río Cortaderal plutons (Table 3). Simple end-member cooling models are used to constrain the role of exhumation of plutons in controlling cooling rates. A second objective is to understand if biotite $^{40}Ar/^{39}Ar$ ages in all of the plutons approximate the time of intrusion, or of later cooling.

Closure temperatures for minerals in the $^{40}Ar/^{39}Ar$ system required for thermal modeling are sensitive to mineral structures and compositions as well as cooling rate (Dodson, 1973). Although $^{40}Ar/^{39}Ar$ step-heating spectra can be used to directly determine Ar closure temperatures for individual minerals within a sample (Berger and York, 1981), closure temperatures of hydrous minerals (micas and amphiboles) are usually estimated. In some cases, feldspars are well suited for direct determination of closure temperature from $^{40}Ar/^{39}Ar$ step-heating spectra. However, studies show that Ar diffusion in K-feldspars can be complicated by mineral microstructure and the presence of 'multiple diffusion domains' (*e.g.*, Burgess *et al.*, 1992; Fitz

Gerald *et al.*, 1993; Lovera *et al.*, 1993), and that a large number of temperature steps is needed to resolve these domains, and to confidently estimate closure temperatures (*e.g.*, Knapp and Heizler, 1990). Arhhenius plots for K-feldspar from the La Obra and Nacimiento Río Cortaderal plutons were not interpretable in terms of diffusion parameters, probably due to the limited number of temperature steps in the Ar release spectra (Fig. 3).

Because of these problems, a closure temperature of 300°C is assumed for biotite based on the compilation of Hanes (1991), and a range of closure temperatures for K-feldspar are considered. Shibata *et al.* (1994) determined Ar closure temperatures for rapidly cooled K-feldspars based on step-heating $^{40}Ar/^{39}Ar$ dating of several Japanese arc granitoids. They found a rough negative correlation between calculated closure temperature and degree of perthite development, which they considered to be the decisive factor in controlling Ar diffusion in K-feldspar. For three samples with moderate perthite development (0.4-1.5 volume percent albite lamellae), they calculated closure temperatures ranging from 178 to 151°C. A perthite-free K-feldspar in another sample yielded a closure temperature of 331°C, whereas a K-feldspar with 17.3% albite lamellae in a different sample yielded a closure temperature of 115°C. Cooling rate is another variable, but an order of magnitude change in cooling rate changes the calculated closure temperature by only a few degrees (Dodson, 1973). In the case of the Teniente region plutons, K-feldspars from both the Nacimiento Río Cortaderal and La Obra plutons show moderate perthite development, with those in the La Obra pluton being somewhat less developed. Comparing the K-feldspars in these plutons with those of Shibata *et al.* (1994) suggests that the closure temperatures for K-feldspars in the La Obra and Nacimiento Río Cortaderal plutons should be in the range of 180°C to 150°C, with that for the La Obra K-feldspar being slightly higher than that for the Nacimiento Río Cortaderal K-feldspar. As uncertainties in biotite and K-feldspar age determinations introduce uncertainties in cooling models, the best way to evaluate a range of potential cooling rates is quantitative modeling.

Cooling histories for the La Obra and Nacimiento Río Cortaderal plutons were mathematically simulated using the two end-member cooling models of McDougall and Harrison (1988). Input parameters include the dimensions and depth of the pluton, thermal properties of the host and plutonic rocks, and initial temperatures for the magma and the country rock at the time of intrusion. A simplified geothermal gradient is calculated from an assumed value of geothermal heat flux (McDougall and Harrison, 1988). The first model treats cooling by purely conductive diffusion of heat into relatively cool country rock. Cooling is very rapid until the temperature within the intrusion asymptotically approaches that of the country rock. The second end-member model simulates exhumation-controlled cooling. The pluton maintains thermal equilibrium with the country rock, and cools only as it moves toward the earth's surface by removal of overlying rocks.

The dimensions of both the La Obra and Nacimiento Río Cortaderal plutons were assumed for modeling to be 12 km long and 3 km wide, with initial tops at 3 km depth and bases at 6 km depth. These dimensions approximate the outcrop area of the two plutons, but may not reflect their true size. They are appropriate for thermal modeling done here, which is insensitive to top and bottom depth, and in which, the distance from the sample to the pluton margin is the most critical. The conductive cooling curves shown in figure 4 were calculated for a depth of 3.5 km at the center of the pluton, where cooling is slowest. Overall cooling is initially rapid, and slows as the pluton approaches thermal equilibrium with country rock.

Attempts to explain the biotite - K-feldspar age differences of the La Obra and Río Cortaderal plutons by these purely conductive cooling were largely unsuccessful as most models predict much smaller apparent age differences than those observed from chronological data. Using a continental average heat flux value of 0.056 W/m² (Turcotte and Schubert, 1982), the conductive cooling model predicts a 100,000 year apparent age difference between biotite and K-feldspar, compared to the measured values of ~ 700,000 years for the Nacimiento Río Cortaderal and 3.4 million years for the La Obra pluton. The situation changes if shallow crustal rocks are initially at higher temperatures as shallow intrusions cool more slowly. A conductive cooling model with a geothermal heat flux double the continental average can roughly approximate the cooling history of the Nacimiento Río Cortaderal pluton. In this case, cooling from the biotite to K-feldspar closure

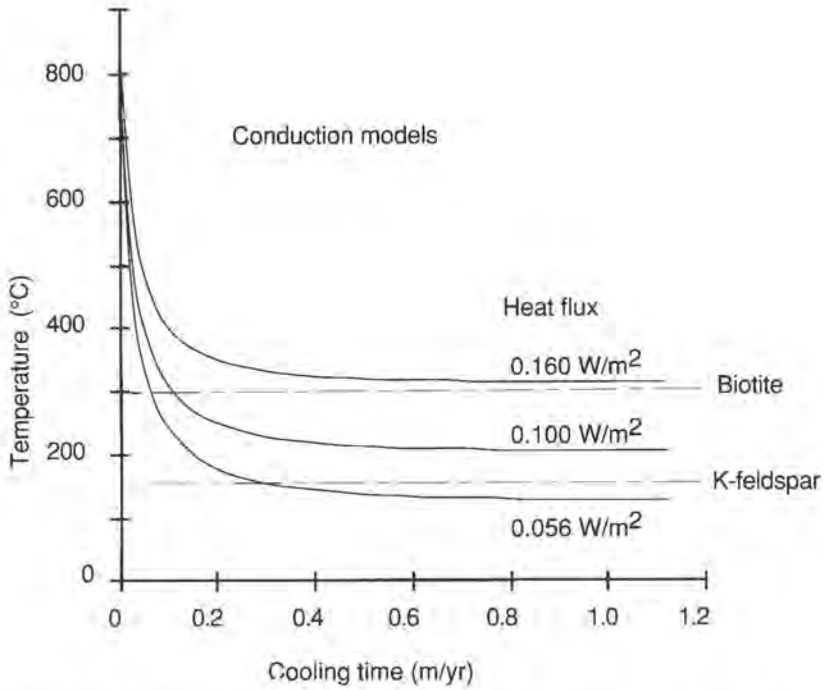

FIG. 4. Conductive cooling models for El Teniente region plutons that are 12 km long, 3 km in width and height, and have a top at 3 km depth. Curves are drawn for samples at the centers of the plutons (location corresponding to slowest cooling) at a depth of 3.5 km. Dashed lines show approximate closure temperatures for biotite (300°C) and K-feldspar (165°C). Geothermal heat fluxes of 0.056 W/m² and 0.100 W/m² result in cooling through the biotite to K-feldspar interval occurring too quickly to account for the slow cooling of the La Obra pluton. Allowing for uncertainties in closure temperatures, a geothermal heat flux of 0.056 W/m² could explain the more rapid cooling of the Nacimiento Río Cortaderal pluton, but is inconsistent with active magmatism and associated high heat flux. With a heat flux of 0.16 W/m², plutons reach ambient temperatures in ~ 0.3 Ma and remain above the biotite closure temperature until exhumed. Model is based on equations of McDougall and Harrison (1988).

temperature takes place in less than one million years (Fig. 4), consistent with the ~700,000 year interval inferred from geochronology. The measured 3.4 million year cooling interval for the La Obra pluton is still nearly impossible to explain by a purely conductive cooling model. If geothermal heat fluxes are made still higher, plutons will not cool below the biotite closure temperature until exhumed.

In contrast, exhumation-controlled cooling models incorporating high geothermal heat fluxes can produce reasonable matches for the cooling histories of both plutons. These models are insensitive to plutonic size, because the plutons maintain thermal equilibrium with the country rock. Exhumation models require that the upper crust in the El Teniente region was locally hot enough to keep these plutons above the ~ 300°C biotite closure temperature until exhumation began. A minimum geothermal gradient averaging 100°C/km through the upper few kilometers of the crust is needed to sustain this condition. This very high geothermal gradient requires a minimum geothermal heat flux of 0.16 W/m², roughly three times the continental average. Such a high upper crustal gradient need not be representative of conditions at deeper crustal levels. A pluton intruded under these conditions and remaining below 3 km would stay above the biotite closure temperature indefinitely (Fig. 4). Cooling below 300°C would begin only when the pluton was exhumed to within about 3 km of the earth's surface. In this case, biotite and feldspar ages are 'uplift ages', and do not necessarily reflect intrusion age. Exhumation rates can be modeled based on the duration of the biotite to K-feldspar cooling interval.

Previous studies in the El Teniente region provide a rationale for high Miocene upper crustal temperatures. In particular, R. Koeppen and E. Godoy[4] used shallow level Miocene plutons as indicators of centers of remnant calderas in this region. The geothermal heat flux in the immediate vicinity of

[4] 1994. Volcanic geology of the El Teniente study area, Chile. Informe Final (Inédito), *Corporación del Cobre-Servicio Nacional de Geología y Minería (Chile)-U.S. Geological Survey*, 111 p.

active calderas, and their associated plutons would be significantly higher than that for average continental crust. Further, 'geothermal type' metamorphic assemblages in late Cretaceous to late Tertiary volcanic rocks in this part of the Andes have been interpreted as evidence for high paleogeothermal gradients (Levi *et al.*, 1989; Thiele *et al.*, 1991; Vergara *et al.*, 1993). Thiele *et al.* (1991) suggested that Miocene geothermal gradients were 70°C to 150°C/km based on alteration assemblages in Farellones Formation volcanic rocks. Geothermal gradients in this range are consistent with those required by the uplift-dependent cooling models presented here. Such high upper crustal temperatures could be sustained by new inputs of magma from below.

EXHUMATION MODELS

The exhumation-dependent model of McDougall and Harrison (1988) allows simulation of cooling histories as a function of geothermal heat flux and exhumation rate. Using the heat flux of 0.16 W/m^2 estimated above, figure 5 shows model cooling curves for exhumation rates ranging from 0.1 to 10 mm/yr. The zero point on the x-axis is the point where each cooling curve crosses the biotite closure temperature at 300°C, the x-axis is the biotite to K-feldspar apparent age difference, and the y-axis is the estimated K-feldspar closure temperature. The labeled points are the best estimates for each pluton whereas the gray fields indicate the cumulative uncertainties in biotite-K-feldspar apparent age differences (Table 3), and the range of possible K-feldspar closure temperatures. The modeling is more sensitive to age uncertainties than to closure temperature estimates. The position of the points relative to the curves allow graphical estimates of exhumation rates that show that the Nacimiento Río Cortaderal pluton was exhumed faster than the La Obra pluton. Exhumation rates for biotite-K-feldspar median age differences assuming closure temperatures of 180° to 150°C for K-feldspar are 0.5 to 0.6 mm/yr for the La Obra pluton, and 2.7 to 4 mm/yr for the Nacimiento Río Cortaderal pluton. Even if closure temperatures for K-feldspar in the two plutons differed by 100°C, and the most extreme errors in mineral ages are considered, the model still requires a higher exhumation rate for the Nacimiento Río Cortaderal (**minimum** 1 mm/yr) than for the La Obra pluton.

Exhumation rates for the La Obra and for the Nacimiento Río Cortaderal plutons are compared in figure 6 to exhumation and erosion rates from elsewhere in the northern SVZ (Fig. 1). In the El Teniente region, Charrier and Munizaga (1979) determined a down-cutting rate of 0.1 mm/yr over the last 1.8 Ma in the Cachapoal Valley, whereas E. Godoy[1] determined a rate of 0.3 mm/yr over the last 2 Ma at a locality farther upstream. The difference could be related to more vigorous upland glacial erosion. Stern *et al.* (1984) determined a down-cutting rate of 0.3 mm/yr over the last 0.5 my at the junction of the Río Maipo and the Río Yeso. These down-cutting rates are determined by comparing the elevation of a dated paleo-surface cut by the river to the present river channel elevation. Like plutonic exhumation rates, they can reflect tectonic uplift, although their meaning can be complicated. Farther north in the Los Bronces region near 33°S, Skewes and Holmgren (1993) used fluid inclusions in quartz to determine pressures of crystallization and breccia formation near the Los Bronces deposit. Combining these data with age constraints, they calculated an exhumation rate of 0.26 mm/yr from 11.3 to 4.9 Ma, and a slower rate of 0.15 mm/yr for the last 4.9 Ma. To the south near 36°S, Davidson and Nelson (1994) used $^{40}Ar/^{39}Ar$ dating and Al-in-hornblende geobarometry from the Cerro Risco Bayo pluton to calculate an uplift rate of 0.6 to 0.8 mm/yr over the last 7 million years.

Exhumation rates modeled for the two El Teniente region plutons are high compared to most other estimated exhumation/erosion rates in the region and very high compared to average erosion rates for continental crust (Fig. 6). These high rates must have been short-lived as if they were not, the middle crust would be exposed. The rate of 0.55 mm/yr for the La Obra applies to the interval from 19.6 to 16.2 Ma and accounts for 1.9 km of exhumation. The higher rate of 3 mm/yr for the Nacimiento Río Cortaderal pluton applies to the interval from 8.4 to 7.7 Ma and accounts for 2.1 km of exhumation. These high

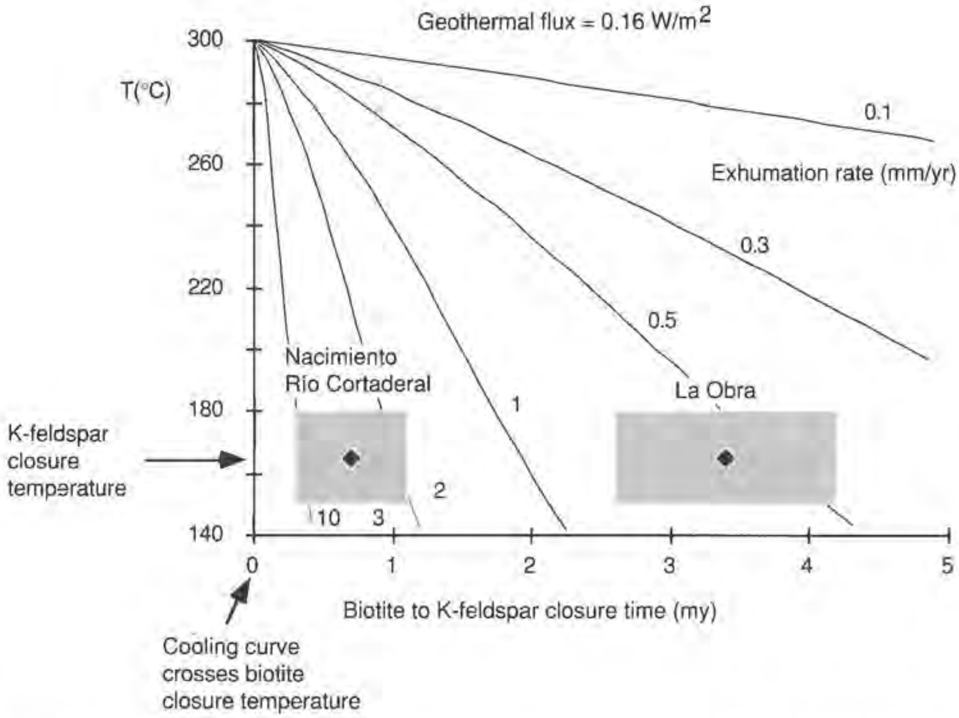

FIG. 5 Exhumation controlled cooling model, based on a geothermal heat flux of 0.16 W/m² for a range of uplift rates (in mm/yr). The x-axis represents time since cooling below the biotite closure temperature, which occurs a maximum of 0.5 my after exhumation begins. Points for the La Obra and Nacimiento Río Cortaderal plutons assume a K-feldspar closure temperature of 165°C. Gray fields show the sensitivity of the model to closure temperatures ranging from 150°C to 185°C, and to uncertainties in biotite and K-feldspar age determinations. Median exhumation rates (♦) are 3 mm/yr for Nacimiento Río Cortaderal and 0.55 mm/yr for La Obra. Model is based on equations of McDougall and Harrison (1988).

exhumation rates are suggested to be related to peaks of crustal thickening associated with compressional deformation in the El Teniente region. Similar, high 'tectonic surface uplift' rates of 0.8 to 2.1 mm/yr calculated for the Finisterre mountains of Papua New Guinea are likewise interpreted by Abbott *et al.* (1997) to reflect the isostatic response of the crust. In the New Guinea case, the crust is thought to have thickened from 37 to 52 km over the last 3.7 Ma (Abbott *et al.*, 1997).

Based on Late and Early Miocene periods of high exhumation rates for El Teniente region plutons along with changes in geochemical signatures of arc magmatic rocks erupted before and after these times (Table 2; also Kay *et al.*, 1995, unpublished data), two peak periods of crustal thickening associated with compressional deformation related to crustal shortening are proposed in the El Teniente region. Both events occurred near the time of eastward migration of the arc magmatic front (Kay, 1996; Fig. 2). The Late Miocene event at about 19 Ma caused the exhumation of the La Obra pluton and the Early Miocene plutons of the San Francisco batholith near 33°S. The second, and stronger event culminating at ~8 to 7 Ma is reflected by the rapid exhumation of the Nacimiento Río Cortaderal and other plutons of the El Teniente Plutonic Complex. The emplacement of the El Teniente deposit is associated with the second event (Kay *et al.*, 1995).

An important implication of a high Miocene exhumation rate is that biotite ages from many El Teniente Complex plutons are exhumation ages reflecting timing of structurally controlled uplift. The grouping of biotite ages from Miocene Teniente Plutonic Complex plutons in two general groups - one near 12 Ma and one near 8 Ma - could reflect events related to Miocene crustal thickening associated with motion on major thrust faults (E. Godoy[1]; Godoy *et al.*, 1996). Chemical similarities between Miocene El Teniente region plutonic and volcanic rocks suggest that the intrusion ages of the plutons are not much older than their exhumation ages.

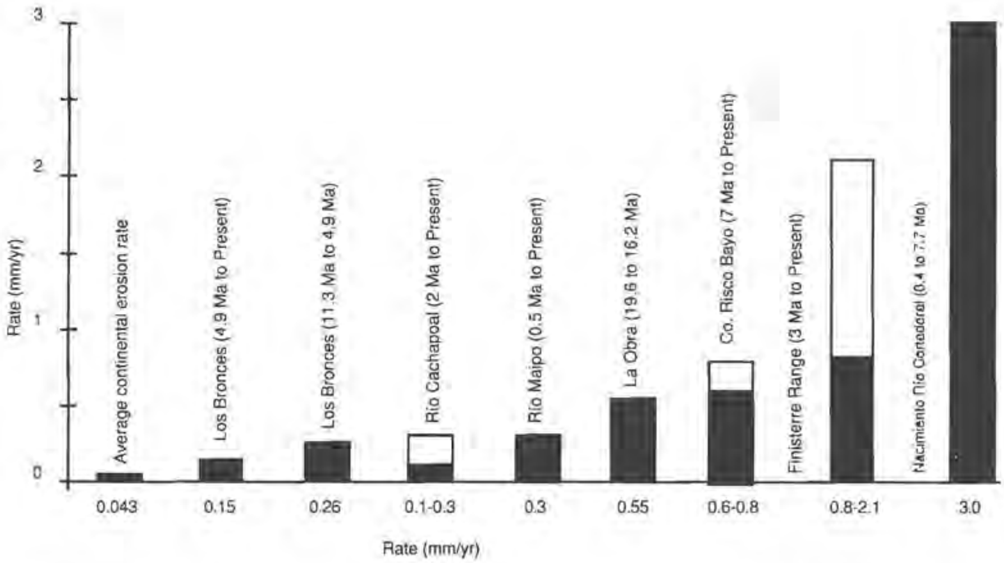

FIG. 6. Bar graph comparing exhumation rates for the La Obra and Nacimiento Río Cortaderal plutons to other estimates of erosion and exhumation rates in the northern SVZ, the average erosion rate for continental crust (Ritter, 1986), and the rate of 'tectonic surface uplift' calculated for the Finisterre mountains of Papua New Guinea (Abbott *et al.*, 1997). Other rates in the northern SVZ are based on down-cutting of rivers (Río Cachapoal-Charrier and Munizaga, 1979; Río Maipo- Stern *et al.*, 1984) in the El Teniente region, fluid inclusions from the Los Bronces district near 33°S (Skewes and Holmgren, 1993), and $^{40}Ar/^{39}Ar$ thermochronology from the Cerro Risco Bayo pluton near 36°S (Davidson and Nelson, 1994). The highest rate over a short period is the Late Miocene rate for the Nacimiento Río Cortaderal pluton. This high rate is comparable to that for the surface uplift rate of the Finisterre Mountains which Abbott *et al.* (1997) argued reflects the isostatic response of crust thickened from 37 to 52 km in the last 3.7 Ma. As this 'surface uplift rate' is averaged over a large area (>1000 km²), rates of local rock uplift or exhumation could be either higher or lower, depending on local conditions. Quaternary rates of rock uplift ranging from 2.0 to 7.6 mm/yr have been measured locally in the Markham Valley, a collisional suture zone associated with the Finisterre mountains (Crook, 1989). Minimum and maximum rates estimates for the Río Cachapoal and the Finisterre. Ranges are indicated by solid and open regions in bars.

CONCLUSIONS

The plutons of the El Teniente region can be put in Early Miocene (~19 Ma), Middle to Late Miocene (~12 to 8 Ma), and latest Miocene-Pliocene (~ 6 to 5 Ma) groups based on their $^{40}Ar/^{39}Ar$ mineral ages, chemical signatures, and field setting. $^{40}Ar/^{39}Ar$ ages for biotite from these plutons are interpreted to record the time of exhumation. Differences in $^{40}Ar/^{39}Ar$ biotite and K-feldspar ages from the Early Miocene La Obra pluton and the Late Miocene Nacimiento Río Cortaderal pluton are consistent with an exhumation rate of 0.55 mm/yr between 19.6 Ma and 16.2 Ma for the La Obra pluton, and a much faster exhumation rate of 3 mm/yr for the Nacimiento Rio Cortaderal pluton between 8.4 Ma and 7.7 Ma. Cooling models require the upper crust to be hot, consistent with the low grade metamorphic overprint seen in El Teniente region volcanic rocks. Periods of high exhumation rates along with temporal geochemical changes in plutonic and contemporaneous volcanic rocks are suggested to reflect peaks of crustal thickening associated with compressional deformation at times of arc migration. The first peak in the El Teniente region occurs near 19 Ma in association with the exhumation of the La Obra pluton. A second, more dramatic peak occurs near 8 to 7 Ma in association with the exhumation of the Nacimiento Río Cortaderal pluton. The emplacement of the El Teniente deposit is associated with this second event.

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APPENDIX

ANALYTICAL METHODS

Mineral separates for $^{40}Ar/^{39}Ar$ geochronology were obtained by standard magnetic and gravimetric separation techniques. Samples were crushed in a rotating-barrel sample crusher and sieved. Sample fractions between sieve sizes 35 and 100 were wet-sieved to remove powder, and dried at room temperature. Dried samples were separated in separatory funnels with Bromoform, TBE, and Methylene Iodide. Mineral separates were additionally purified with a Frantz magnetic separator. Samples were then hand-picked to ensure purity. The samples were finally cleaned several times with acetone and de-ionized water. Analyzed sample weights ranged from 500 mg for biotite to 1000 mg for plagioclase. Geochronological work was done in the laboratory of Dr. E. Farrar at Queen's University, in Kingston, Ontario. $^{40}Ar/^{39}Ar$ analysis followed the procedures outlined by Sandeman *et al.* (1995) except that irradiation time in the McMaster Nuclear Reactor was 14.5 h.

All geochemical analyses were done at Cornell University. Trace elements are by Instrumental Neutron Activation analyses (INAA) in Ward Laboratory. Whole rock major element analyses were determined on fused glasses by electron microprobe following methods described in Kay *et al.* (1987). Isotopic analyses were done by thermal ionization mass spectrometry (TIMS) in the Department of Geological Sciences. $^{87}Sr/^{86}Sr$ for NBS 987 standard = 0.710221±0.000044; $^{143}Nd/^{144}Nd$ for La Jolla standard = 0.511888 ± 0.000055. Pb isotopic ratios corrected for mass fractionation using values of $^{206}Pb/^{204}Pb$ = 16.931, $^{207}Pb/^{204}Pb$ = 15.485, and $^{208}Pb/^{204}Pb$ = 36.681 measured on Pb standard NBS SRM981.