Miocene to present magmatic evolution at the northern end of the Andean Southern Volcanic Zone, Central Chile

Charles R. Stern
M. Alexandra Skewes

Department of Geological Sciences, University of Colorado
Boulder, Colorado 80309-0250, U.S.A.

ABSTRACT

At the northern end of the Andean Southern Volcanic Zone (NSVZ; 33-34°S), subduction angle decreased and the magmatic arc migrated eastward to its present location along the Andean drainage divide during the Pliocene. Prior to arc migration, the isotopic compositions of the magmas emplaced along the locus of the Miocene volcanic front changed significantly. Miocene igneous rocks have relatively low initial $^{87}Sr/^{86}Sr$ = 0.7038 to 0.7040 and high ϵ_{Nd} = +1.9 to +3.3, while Pliocene rocks emplaced along the same belt have higher $^{87}Sr/^{86}Sr$ = 0.7043 to 0.7049 and lower ϵ_{Nd} = -1.1 to +0.8. These isotopic changes imply a temporal increase in the role of crustal components in magma-genesis. This may have resulted, in part, from increased assimilation of lower crust. However, the crust below the Pliocene arc never reached the same thickness as that below the active NSVZ, although the Pliocene igneous rocks are isotopically similar to NSVZ lavas. Alternatively, these changes may be explained by an increase in the proportion of crustal components added to the sub-Andean mantle source region during the Pliocene. This resulted from an increase in the rate of subduction erosion and source region contamination below Central Chile due to a combination of both decreasing subduction angle and the subduction of the Juan Fernández Ridge. Similar isotopic changes imply an increase in crustal components in Andean magmas beginning before 14 Ma at 30°S, by 9 Ma at 32°S, by 7 Ma at 33°S, and after 5 Ma at 34°S. This suggests a close relation with the southwards migration of the locus of subduction of the Juan Fernández Ridge. Differences in the rates of subduction erosion and mantle source region contamination also explain some of the chemical differences between the Andean Central (CVZ) and Southern (SVZ) Volcanic Zones. The authors conclude that lower plate parameters (subduction geometry, rates of subduction erosion and sediment subduction) may be as important as upper plate parameters (crustal age and thickness) for producing not only the spatial, but also the chemical segmentation of the active Andean arc.

Key words: Andes, Volcanism, Isotopic composition, Miocene, Pliocene, Subduction.

RESUMEN

Evolución magmática desde el Mioceno al presente en el extremo norte de la Zona Volcánica de los Andes del Sur, Chile central. En el extremo norte de la Zona Volcánica de los Andes del Sur (NZVS; 33-34°S), el ángulo de subducción disminuyó durante el Plioceno y el arco magmático migró hacia el este, a su posición actual a lo largo de la línea divisoria de aguas en la cumbre de los Andes. La composición isotópica de los magmas emplazados en el frente volcánico miocénico cambió significativamente antes de la migración del arco. Las rocas ígneas del Mioceno tienen razones iniciales de $^{87}Sr/^{86}Sr$ relativamente bajas, entre 0,7038 y 0,7040 y valores de ϵ_{Nd} altos entre +1,9 y +3,3, mientras que las rocas del Plioceno, emplazadas en ese mismo cinturón, tienen razones iniciales de $^{87}Sr/^{86}Sr$ más altas, entre 0,7043 y 0,7049, y valores de ϵ_{Nd} más bajos entre -1,1 y +0,8. Estos cambios isotópicos indican un aumento en el tiempo del rol de los componentes corticales en la génesis de los magmas, lo que podría ser el resultado, en parte, de una mayor asimilación en la corteza inferior. Sin embargo, la corteza que infrayace al arco pliocénico nunca alcanzó el espesor de la corteza que existe en la actualidad bajo el extremo norte de la Zona Volcánica de los Andes del Sur, aun

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cuando las rocas ígneas del Plioceno son isotópicamente similares a las lavas de la NZVS. En forma alternativa, estos cambios podrían ser explicados por un aumento en la proporción de los componentes corticales en la fuente del manto subandino durante el Plioceno. Esto fue producto del mayor grado de erosión tectónica y de la contaminación cortical de la fuente bajo Chile central, consecuencia de la disminución del ángulo de subducción y de la subducción de la Dorsal Juan Fernández. Cambios isotópicos similares indican un aumento de los componentes corticales en los magmas andinos que comenzó antes de los 14 Ma en 30°S, a los 9 Ma en 32°S, a los 7 Ma en 33°S y después de 5 Ma en 34°S. Esto sugiere una estrecha relación con la migración hacia el sur del lugar de subducción de la Dorsal Juan Fernández. Las diferencias en la velocidad de la erosión tectónica y en la contaminación de las regiones fuente de magmas también explican algunas de las diferencias químicas entre la Zona Volcánica de los Andes Centrales (ZVC) y la Zona Volcánica de los Andes del Sur (ZVS). Esto sugiere que los factores relacionados con la placa inferior (geometría de subducción, velocidad de erosión tectónica y subducción de sedimentos) pueden ser tan importantes como los factores de la placa superior (espesor y edad de la corteza) para producir no sólo la segmentación espacial, sino también la segmentación química del arco andino activo.

Palabras claves: Andes, Volcanismo, Composición isotópica, Mioceno, Plioceno, Subducción.

INTRODUCTION

The most notable aspect of the north-to-south along-arc segmentation in the Andes is the occurrence of active volcanism in four different zones separated by volcanic gaps (Thorpe, 1984; Stern *et al.*, 1984a). The presence or absence of volcanism has been correlated with the angle of oceanic plate subduction below the Andes (Barazangi and Isacks, 1976). This correlation is consistent with a direct genetic link between the process of the subduction of Pacific oceanic lithosphere and Andean magmatism; a link confirmed by geochemical studies that imply the incorporation of small proportions of subducted oceanic crust in Andean magmas (Hickey *et al.*, 1986; Stern *et al.*, 1990).

Another significant aspect of the along-strike segmentation of the active Andean arc is that the chemistry of magmas erupted in each of the different volcanic zones is distinct (Harmon *et al.*, 1984). These differences involve variations in the Sr, Nd, Pb and O isotopic composition of Andean magmas, implying differences to the extent at which the magmas incorporated continental crust. However, unlike the presence or absence of volcanic activity, the chemical differences between the different segments of the Andean arc have generally been correlated with, and attributed to, variations within the overriding South American continental plate; specifically to variations in Andean crustal thickness and/or age (Harmon *et al.*, 1984; Hildreth and Moorbath, 1988; Davidson *et al.*, 1991; Wörner *et al.*, 1992), rather than to variations in the processes of oceanic plate subduction. Alternatively, it was suggested that some portion of the along-arc variation in Andean magma chemistry may result from differences in the extent to which subduction erosion tectonically removes continental crust from the western margin of the South American plate and subducts this crust into the sub-arc mantle source region below different Andean segments (Stern *et al.*, 1984b; Stern, 1988, 1989, 1990, 1991a, 1991b, 1991c; Futa and Stern, 1988).

The extent to which continental components are added to Andean magmas by intra-crustal assimilation as opposed to source region contamination, and more generally the extent to which along-arc differences in Andean magma chemistry are influenced by the upper over riding continental plate as opposed to the lower subducted oceanic plate, remain fundamental problems for understanding the evolution of the Andean lithosphere and the causes of segmentation of the Andean arc. As a contribution to this debate, the authors studied the temporal evolution, between the Miocene and the present, of Andean magma chemistry in Central Chile, at the northern end of the Southern Volcanic Zone (NSVZ; 33-34°S; Figs. 1 and 2).

The current segmentation of the Andean arc in Central Chile was established in the latest Miocene or Early Pliocene (Vergara *et al.*, 1988; Kay *et al.*, 1987, 1988, 1991; Stern, 1989; Rivano *et al.*, 1990). Beginning in the Middle Miocene, decreasing subduction angle below the developing flat-slab segment north of 33°S, perhaps in response to ridge subduction (Pilger, 1981, 1984), resulted initially in broad-

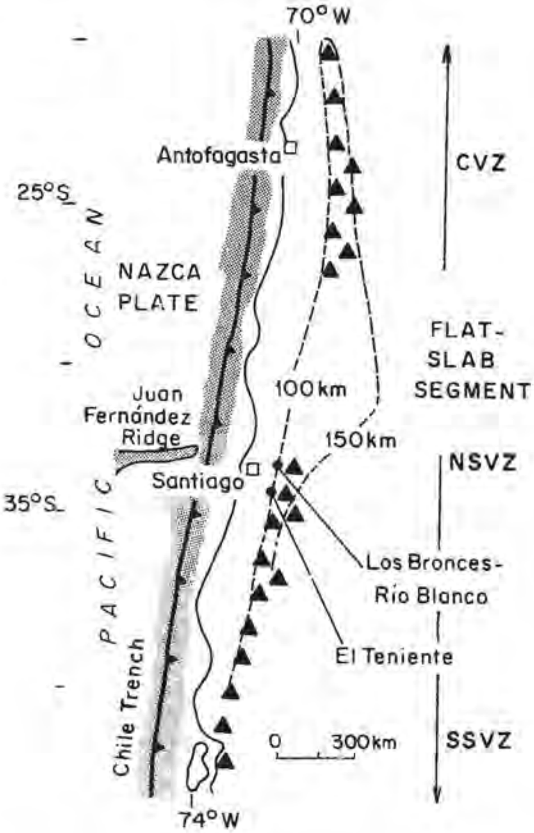

FIG. 1. Location of the flat-slab segment separating the Central (CVZ) from the northern (NSVZ) and southern (SSVZ) Southern Volcanic Zones of active volcanos (triangles), and the Los Bronces-Río Blanco and El Teniente copper deposits, west of the NSVZ, from the vicinity of which come the Miocene and Pliocene igneous rock samples discussed in this paper. Also shown are the Chile Trench, Juan Fernández Ridge and the depth to the Benioff zone of seismic activity (dashed lines; Bevis and Isacks, 1984).

ening of the Miocene magmatic arc, subsequently eastward migration of the volcanic front in the latest Miocene, and ultimately the termination of all magmatic activity during the Pliocene (Kay *et al.*, 1987, 1988, 1991). South of 33°S, later and less significant flattening of subduction angle caused the eastward migration of the volcanic front to its current location in the Pliocene (Figs. 2 and 3; Stern, 1989). As subduction angle decreased below the Andes of Central Chile, the crust was deformed, thickened and uplifted (Jordan *et al.*, 1983; Allmendinger *et al.*, 1990; Skewes and Holmgren, 1993; Skewes and Stern, 1994).

It is well documented that the active volcanos in the NSVZ have erupted magmas with higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than those erupted farther south in the SVZ (Stern *et al.*, 1984b; Stern, 1988, 1989, 1991a; Futa and Stern, 1988; Hildreth and Moorbath, 1988). Here the authors document temporal changes in magma chemistry between the Miocene and the present at the latitude of the NSVZ. These data constrain the relations between the timing of changes in magma chemistry and those in subduction geometry and crustal thickness, which together have led to and/or, occurred in conjunction with the eastward migration during the Pliocene, of the locus of volcanism at the northern end of the SVZ.

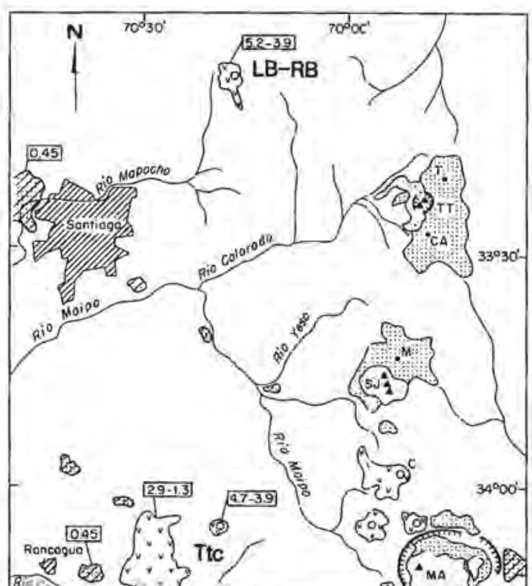

FIG. 2. Map of Quaternary igneous rocks at the latitude of the NSVZ (Stern, 1989). Samples discussed in this paper come from along the Miocene and Pliocene volcanic front in the vicintiy of the Los Bronces-Río Blanco (LB-RB; Warnaars *et al.*, 1985; Serrano *et al.*, in press) and El Teniente (Ttc; Charrier and Munizaga, 1979; Cuadra, 1986) copper deposits, all well west of the active volcanos of the NSVZ.NSVZ volcanos include: T- Tupungato; TT- Tupungatito; CA- Cerro Alto; M-Marmolejo; SJ- San José; MA- Maipo. Pliocene magmatic centers east of the Pliocene volcanic front include: C- Cerro Castillo ; PB- Picos de Barroso; L- Listado.

REGIONAL GEOLOGY AND TECTONICS

Early to Middle Miocene lavas of the Farellones Formation, and plutons that intrude these lavas, outcrop in a continuous belt across the current Andean segment boundary at 33°S (Vergara *et al.*, 1988; Rivano *et al.*, 1990). Beginning in the Middle Miocene, decreasing subduction angle below what is now the current flat-slab segment (Fig. 1) caused the volcanic belt to widen, the volcanic front to migrate eastward (after 6 Ma), and ultimately the termination of all magmatic activity in the Pliocene (Kay *et al.*, 1987, 1988, 1991). During the Early and Middle Miocene the crust in Central Chile was relatively thin (<40 km), similar to that presently below Southern Chile (Allmendinger *et al.*, 1990). Beginning in the Middle Miocene, as subduction angle decreased, the crust was deformed, thickened and uplifted (Jordan *et al.*, 1983). In the region of the flat-slab segment, the crust below the locus of the Miocene volcanic front is presently >55 km thick (Kay *et al.*, 1991).

South of 33°S, at the latitude of the NSVZ (Fig. 1), subduction angle also decreased, although not as greatly, in conjunction with the development of the flat-slab segment (Stern, 1989). Magmatic activity continued along the Miocene volcanic front until the Pliocene, at which time the arc broadened. Subsequently, the volcanic front migrated over 40 km east to its current location along the Andean drainage divide (Figs. 2 and 3).

In detail, the age of the termination of magmatic activity along the Miocene volcanic front decreased southwards (Fig. 2); it persisted until 6 Ma north of 33°S (Kay *et al.*, 1991), until 3.9 Ma at 33°S and until 1.8 Ma at 34°S (Stern, 1989).

The crust at the latitude of the NSVZ also thickened and was uplifted beginning in the Middle to Late Miocene (Skewes and Holmgren, 1993). However, the greatest thickening and uplift occurred below the current Andean drainage divide, not below, but east of the Miocene and Pliocene volcanic front. The active volcanos at the northern end of the SVZ overly thicker crust than the Miocene and Pliocene arc at the same latitude because, firstly, the crust at this latitude has continued to thicken through time. Secondly and more significantly, eastward arc migration placed the arc above the thickest section of crust (>50 km thick; Hildreth and Moorbath, 1988) along the Andean drainage divide where the base elevations of active NSVZ volcanos are >3,000 m (Fig. 3). In contrast, the youngest Pliocene lavas erupted along the locus of the Miocene volcanic front at 34°S (Fig. 2) are derived from a center over 40 km west of this drainage divide, at an altitude of only 900 m, and this area may have undergone 1500 m of uplift since their eruption (Charrier and Munizaga, 1979). Thus, the crust below the Miocene and Pliocene volcanic front at the latitude of the NSVZ never thickened as much as that north of 33°S, nor reached thickness equal to that below the active NSVZ.

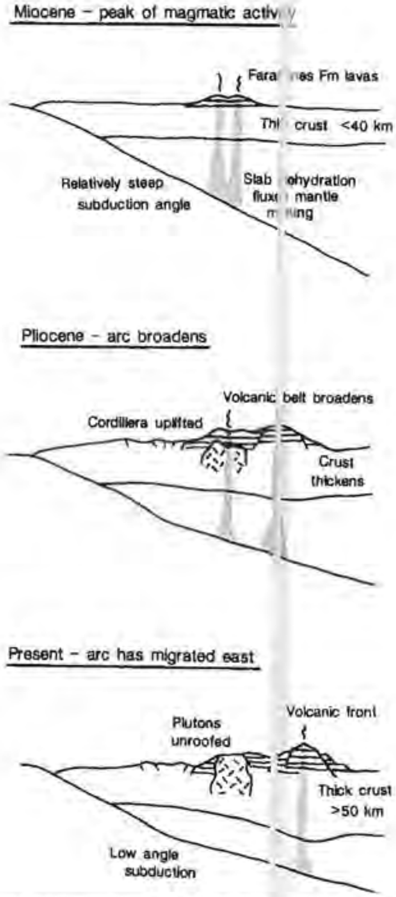

FIG. 3 Cross-sections illustrating general features of the magmatic and tectonic evolution, between the Miocene and Present, of the Andes of Central Chile at the latitude of the NSVZ (Skewes and Stern, 1994). Note that although the crust began to thicken below this region in the Middle to Late Miocene, crustal thickness below the Miocene and Pliocene volcanic front never reached those which occur below the active NSVZ volcanos.

ROCK CHEMISTRY

Samples of Miocene and Pliocene volcanic and plutonic rocks were collected from the vicinity of the Los Bronces-Río Blanco and El Teniente copper deposits (Fig. 2), where previously published K-Ar chronological studies provide good age control (Charrier and Munizaga, 1979; Warnaars *et al.*, 1985; Cuadra, 1986; Serrano *et al.*, in press). Samples range in age from ≥18 to 1.8 Ma, and include the Miocene Farellones Formation and Cerro Montura lavas, plutons which intrude these lavas, and Pliocene stocks, dikes, and extrusives from the vicinity of both deposits. Detailed geologic maps, sample locations, and descriptions for those samples from Los Bronces-Río Blanco (Table 1) were published by Warnaars *et al.* (1985) and Serrano *et al.* (in press), and for those samples from El Teniente (Table 2) by Charrier and Munizaga (1979) and Cuadra (1986).

Based on silica content, samples range in composition from basaltic andesites to rhyodacites (Tables 1 and 2). At Los Bronces-Río Blanco, the Pliocene samples are all more silica-rich than the Miocene samples, but in the vicinity of El Teniente there is no systematic temporal trend in silica content. All the samples are medium to high-K calc-alkaline rocks. All have Ba/La >20 and La/Nb >1.6, similar to other Andean igneous rocks and to arc magmas in general (Hickey *et al.*, 1986; Stern *et al.*, 1990). High Ba/La and La/Nb ratios in Andean and other arc igneous rocks have been interpreted to have resulted from the addition of components that contain high Ba/La and La/Nb, possibly hydrous fluids from subducted oceanic lithosphere, into the sub-arc magma source region.

All the samples are enriched in light relative to heavy rare-earth elements and have La/Yb = 8 to 40, also similar to other Andean magmas (Fig. 4). Younger Pliocene rocks at Los Bronces-Río Blanco have lower Yb and consequently, higher La/Yb than older Miocene samples. Here, higher La/Yb correlates with higher SiO_2, which together may result from more extensive late-stage crystal-liquid fractionation involving amphibole (López-Escobar, 1982). In the vicinity of El Teniente, where no temporal change occurs in SiO_2, there is no systematic temporal trend in La/Yb.

The initial $^{87}Sr/^{86}Sr$ ratios for the samples range from 0.70378 to 0.70487, and initial ϵ_{Nd} values range from +3.3 to -1.1 (Fig. 5). Miocene rocks, which have lower $^{87}Sr/^{86}Sr$ ratios and higher ϵ_{Nd} values, are similar to magmas erupted from active volcanos in the southern SSVZ, a region of relatively thin (<40 km) crust. López-Escobar *et al.* (1991) and Nyström *et al.* (1993) also reported relatively primitive initial isotopic compositions for Miocene Farellores Formation lavas from Central Chile. In contrast, Pliocene samples have higher $^{87}Sr/^{86}Sr$ ratios and lower ϵ_{Nd} values, approaching those of magmas erupted from the active volcanos of the NSVZ to the east.

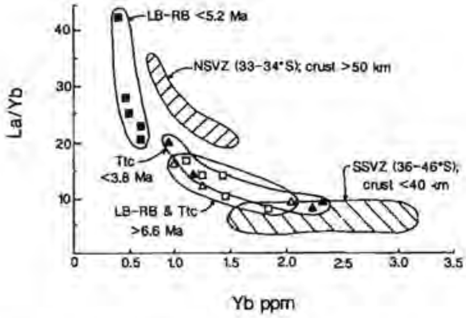

FIG. 4. La/Yb *versus* Yb content, in ppm, showing the fields for Middle and Late Miocene rocks at Los Bronces-Río Blanco (LB-RB; open squares) and El Teniente (Ttc; open triangles) compared to latest Miocene and Pliocene rocks from these same deposits (solid symbols; shaded fields). Also shown are fields for samples from active volcanos in the NSVZ (Stern, 1988; Hildreth and Moorbath, 1988), below which the crust is >50 km thick, and the SSVZ (Hickey *et al.*, 1986; Futa and Stern, 1988), below which the crust is <40 km thick.

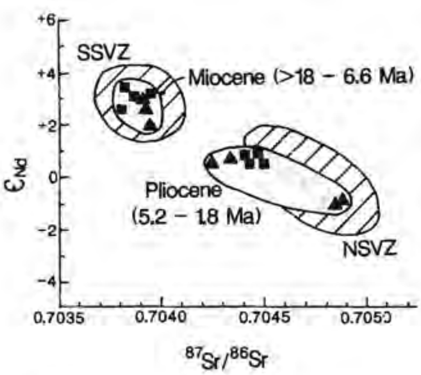

FIG. 5. $^{87}Sr/^{86}Sr$ ratios *versus* ϵ_{Nd} values for igneous rocks emplaced along the Miocene and Pliocene volcanic front west of the active NSVZ (squares from Los Bronces-Río Blanco, Table 1; triangles from El Teniente, Table 2) compared to samples from the active NSVZ and SSVZ (Hickey *et al.*, 1986; Futa and Stern, 1988; Stern, 1988; Hildreth and Moorbath, 1988).

TABLE 1. MAJOR AND TRACE-ELEMENT AND ISOTOPIC COMPOSITION OF THE EARLY TO LATE MIOCENE (>8.6 MA) AND LATEST MIOCENE TO EARLY PLIOCENE (<5.2 MA) IGNEOUS ROCKS ASSOCIATED WITH THE RÍO BLANCO-LOS BRONCES COPPER DEPOSIT, 33°.

	EARLY TO LATE MIOCENE					LATEST MIOCENE AND EARLY PLIOCENE				
Rock type	Andesites		Granodiorites			Dacites and rhyolites				
Sample	AnI	An2	LB-3	GDRB	LB-7	PQM	PDL	CHDac	LB-1O	LB-11
Age Ma*	18	18	18.5	11.7	8.6	5.2	4.9	4.8	4.8	4.9
SiO_2	62.1	56.2	60.50	65.6	63.06	66.1	68.7	70.9	67.80	69.50
TiO_2	0.26	0.78	0.65	0.45	-	0.13	0.14	0.13	-	-
Al_2O_3	16.1	16.9	16.80	16.2	15.40	15.6	15.7	15.2	15.70	15.50
Fe_2O_3	5.40	4.70	2.08	1.60	3.65	1.57	1.10	2.20	0.83	0.63
FeO	2.50	4.60	3.00	2.60	1.41	2.63	0.59	0.59	0.83	0.91
MnO	-	-	0.09	-	0.08	-	-	-	0.11	0.02
MgO	1.80	4.70	3.05	2.60	3.43	1.59	0.48	0.36	0.33	0.41
CaO	0.32	5.30	5.42	3.30	1.74	2.10	0.73	0 33	2.52	1.75
Na_2O	2.10	3.10	4.60	4.48	4.24	5.4	4.70	3.63	4.38	4.76
P_2O	6.6	2.90	2.22	3.2	2.95	3.95	4.8	5.2	2.57	2.43
P_2O_5	-	-	0.20	-	0.24	-	-	-	0.23	0.28
LOI	2.5	0.9	0.25	0. 1	0.27	0.9	2.0	1.5	1.67	0.85
Total	**99.70**	**100.08**	**99.06**	**100.03**	**96.47**	**99.97**	**98.94**	**100.04**	**97.30**	**97.32**
Cs	5.1	4.1	2.7	3.6	5.0	2.7	1.4	3.6	11.6	14.1
Rb	151	158	41.5	90.2	37.7	42.4	112	192	66.7	29.8
Sr	136	392	677	450	730	650	358	173	703	903
Ba	480	422	535	512	545	560	864	967	708	745
La	17.9	21.1	14.2	17.1	15.0	12.0	16.4	11.8	12.3	13.3
Ce	34.4	38.1	28.6	31.1	27.9	20.6	27.9	23.5	26.1	28.6
Nd	14.9	18.2	18.7	16.4	20.8	7.7	14.6	10.4	13.4	13.0
Sm	2.82	3.56	3.53	2.52	4.06	1.18	1.98	1.45	2.25	2.20
Eu	0.78	0.94	0.92	0.67	1.05	0.42	0.52	0.50	0.48	0.58
Tb	0.30	0.38	0.31	0.28	0.37	0.12	0.13	0.13	0.24	0.25
Yb	1.25	1.45	1.85	1.08	1.43	0.48	0.39	0.56	0.45	0.59
Lu	0.20	0.22	0.29	0.14	0.11	0.05	0.05	0.06	0.05	0.09
Y	-	-	12	-	12	-	-	-	8	8
Zr	-	-	113	-	58	-	-	-	118	128
Nb	-	-	6	-	5	-	-	-	5	5
Hf	4.8	5.2	3.4	4.3	2.3	3.0	3.3	2.9	3.2	2.3
Th	9.6	8.5	5.0	12.0	3.3	4.3	4.1	4.2	2.6	2.8
U	3.6	4.2	5.6	3.5	5.0	1.2	1.8	2.2	1.6	2.2
Sc	9.6	10.8	13.3	6.3	12.8	2.1	2.3	2.0	1.9	2.3
$^{87}Sr/^{86}Sr$	0.70381	0.70382	0.70387	0.70400	0.70391	0.70441	0.70441	0.70446	0.70452	0.70444
$^{143}Nd/^{144}Nd$	0.51274	0.51279	0.51277	0.51278	0.51278	0.51267	0.51267	0.51268	0.51265	0.51264
ϵ_{Nd}	+2.5	+3.3	+3.0	+3.0	+2.9	+0.8	+0.7	+0.7	+0.3	+0.2

* Ages from Warnaars *et al.* (1985) and Serrano *et al.* (In press).

Major elements for samples LB-3, LB-7, LB-10, and LB-11 are from Warnaars *et al.* (1985). Major elements for the other samples were determined by Skyline Labs (Denver, Colorado).

Trace elements Zr, Nb and Y were determined by energy-dispersive XRF (University of Colorado, Boulder). Cs, Ba, Hf, Th, U, Sc, and REE were determined by INAA (Oregon State University, Corvallis).

Rb, Sr, Nd and Sm contents and Sr- and Nd-isotopic compositions were determined by solid-source mass-spectrometry (University of Colorado, Boulder). Isotopic values are initial values corrected for age. ϵ_{Nd} was calculated assuming CHUR=0.512638.

TABLE 2. MAJOR AND TRACE-ELEMENT AND ISOTOPIC COMPOSITIONS OF THE LATE MIOCENE (>6.6 MA) AND PLIOCENE (<3.8 MA) IGNEOUS ROCKS ASSOCIATED WITH THE EL TENIENTE COPPER DEPOSIT, 34°S.

	LATE MIOCENE			PLIOCENE			
Rock type	**Andesites**		**Diorite**	**Andesites**			
Sample	**Ttc9**	**Ttc10**	**Ttc5**	**Ttcl**	**Ttc8**	**PVFl**	**PVF2**
Age Ma*	**8.2**	**6.6**	**7.1**	**3.8**	**2.8**	**2.3**	**2.3**
SiO_2	61.0	61.5	63.7	56.3	61.1	56.5	55.4
TiO_2	0.75	0.77	0.39	0.85	0.67	1.10	1.12
Al_2O_3	16.8	16.9	17.1	16.9	17.2	16.9	17.6
Fe_2O_3	3.9	3.6	1.9	3.6	2.6	2.7	3.1
FeO	2.2	1.9	2.4	2.0	2.0	5.1	4.3
MnO	0.1	0.08	0.08	0.06	0.05	0.12	0.12
MgO	2.8	2.6	1.5	3.3	3.2	4.8	4.5
CaO	5.6	5.7	3.9	5.8	5.5	7.2	7.1
Na_2O	4.38	4.54	4.93	4.61	5.14	3.63	3.65
K_2O	2.5	2.5	2.2	1.6	2.0	2.1	1.8
P_2O_5	0.20	0.22	0.21	0.29	0.21	0.33	0.28
LOI	0.94	0.69	1.80	5.10	0.90	0.68	0.10
Total	**101.17**	**101.00**	**100.17**	**100.41**	**100.57**	**101.16**	**98.95**
Cs	2.8	3.8	6.1	0.6	1.9	2.7	3.1
Rb	82	74	96	28	35	60	60
Sr	543	700	699	910	856	566	561
Ba	539	504	528	445	644	471	401
La	19.1	16.7	14.4	16.8	16.5	22.3	21.8
Ce	44.9	38.8	34.7	40.4	35.1	50.0	52.2
Nd	25.0	21.9	19.2	22.9	21.2	31.9	29.8
Sm	5.13	4.26	3.39	4.19	4.00	6.52	6.26
Eu	1.18	1.00	0.88	1.08	1.06	1.36	1.37
Tb	0.60	0.41	0.29	0.39	0.41	0.66	0.73
Yb	2.03	1.27	0.92	0.84	1.17	2.32	2.25
Lu	0.26	0.16	0.09	0.14	0.26	0.30	0.29
Y	21	15	11	13	12	24	27
Zr	158	133	94	129	130	196	196
Nb	8	5	6	6	4	12	10
Hf	4.8	4.3	3.2	3.5	3.8	5.0	5.0
Th	9.0	7.9	4.3	2.4	3.5	6.9	7.0
U	2.5	2.4	1.6	1.9	1.8	1.6	1.7
Sc	14.6	12.1	6.0	11.4	8.9	17.8	18.5
$^{87}Sr/^{86}Sr$	0.70396	0.70390	0.70393	0.70425	0.70434	0.70485	0.70487
$^{143}Nd/^{144}Nd$	0.51273	0.51279	0.51277	0.51266	0.51267	0.51258	0.51259
ϵ_{Nd}	+1.9	+3.0	+2.7	+0.5	+0.7	-1.1	-0.9

* Ages are from Cuadra (1986) (Ttc9=E-1292; Ttc10=E-1233; Ttc5=DDH-1091A; Ttc1=T3-22; Ttc8=BS-588) and Charrier and Munizaga (1979) (PVFl=SPK3836; PVF2=SPK-3855).

Analytical techniques are described in table 1.

These temporal isotopic changes correlate with increasing SiO_2 at Los Bronces-Río Blanco, but are independent of SiO_2 at El Teniente. The changes at both deposits are independent of Sr content (Tables 1 and 2). Average Sr is actually higher in Pliocene compared to Miocene samples from both deposits, but significant variability in Sr content occurs in samples of all ages.

When plotted with age, along with the isotopic composition of minerals from magmatic breccias at each deposit (Skewes and Stern, 1994, in press), the data indicate that increasing $^{87}Sr/^{86}Sr$ ratios began to occur at Los Bronces-Río Blanco before 7 Ma, but at El Teniente only after 5 Ma (Fig. 6). At 32°S such changes occurred before 9 Ma (Skewes, 1992), and at 30°S before 14 Ma (Kay *et al.*, 1991). Still farther north (22°S) similar changes occurred before 23 Ma (Rogers and Hawkesworth, 1988).

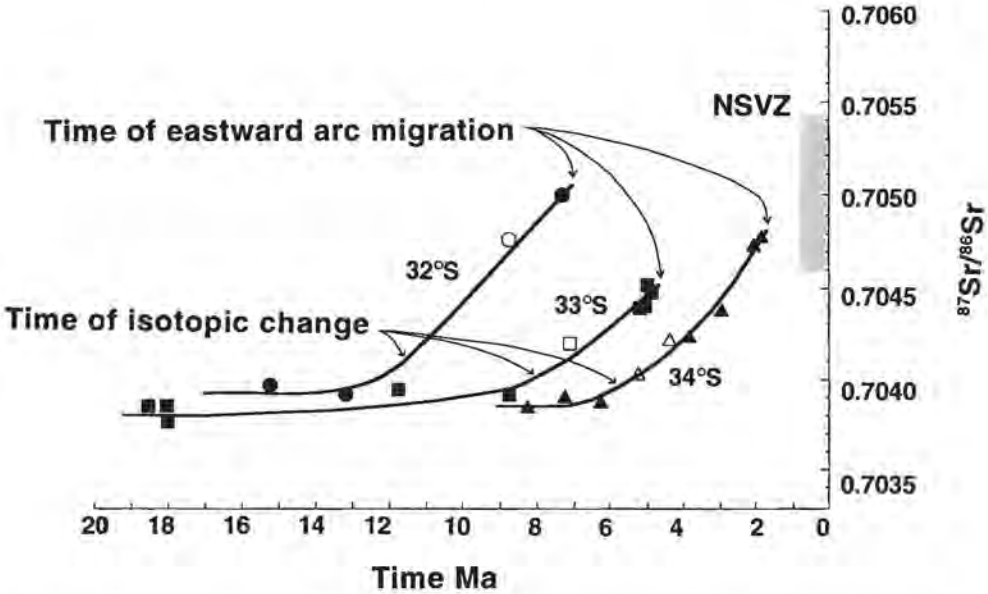

FIG. 6. $^{87}Sr/^{86}Sr$ ratios *versus* age for samples of igneous rocks from the Miocene and Pliocene volcanic front (solid symbols) at 32°S (circles; Skewes, 1992), at 33°S (squares, Table 1) and at 34°S (triangles, Table 2). Also shown are the compositions of minerals from the matrices of magmatic breccias (open symbols) at Los Pelambres (32°S), Los Bronces-Río Blanco (33°S) and El Teniente (34°S) (Skewes and Stern, 1994, in press), and samples from active NSVZ volcanos (Futa and Stern, 1988; Stern, 1988; Hildreth and Moorbath, 1988). The figure illustrates the diachronous, southwards progression for the timing of both eastward arc migration and increasing $^{87}Sr/^{86}Sr$ in Andean magmas of Central Chile.

DISCUSSION

The data indicate that the isotopic compositions of magmas emplaced along the Miocene to Pliocene volcanic front at the latitude of the northern end of the NSVZ, changed prior to the eastwards migration of the arc to its current location along the High Andean drainage divide. This observation is significant. It implies that the observed isotopic changes must be explained by the incorporation of a greater amount of continental crust in the younger Pliocene magmas, not the incorporation of older crust. Rogers and Hawkesworth (1988) attributed similar temporal isotopic changes, which occurred in conjunction with the mid-Tertiary eastwards migration of the Andean arc at 22°S, to incorporation of components from older continental lithosphere in the magmas formed below the younger, more easterly located arc. McKee *et al.* (1994) also suggested that between 26° and 28°S, at the southern end of the CVZ (Fig. 1), magmas erupted from Miocene centers more to the east had higher initial $^{87}Sr/^{86}Sr$ ratios, because they were contaminated by older, rather than greater, amounts of crust. However, at 33-34°S, the temporal changes in isotopic composition of Andean magmas between the Miocene and the Pliocene are not associated with any change in the location of the arc. Younger Pliocene magmas were erupted through the same crustal section as older Miocene magmas, unless thrusting related to Andean compressional deformation emplaced older rocks below the Miocene arc prior to the Pliocene. This seems unlikely, particularly in the vicinity of El Teniente (34°S; Fig. 2), which is located well west of any known Andean thrusts. Thus, the authors conclude that, here, the observed isotopic changes are due to changes in the amount, not in the age of continental crust incorporated in magmas of different ages.

Although the observed temporal isotopic variations result from the incorporation of more continental crust in the younger magmas, different mechanisms exist by which this crust could have been incorporated in these magmas. Alternatives include intra-crustal contamination of mantle-derived magmas (Harmon *et al.*, 1984; Hildreth and Moorbath, 1988), and source region contamination of the subarc mantle (James, 1981; Stern, 1988, 1991a). The implications of producing the isotopic compositions of the younger Pliocene magmas by intra-crustal contamination of mantle-derived basalts, *versus* by source region contamination, are important (Stern, 1991a, 1991b). The former involves recycling a large proportion of Andean crust (Hildreth and Moorbath, 1988), the latter a much smaller proportion (Stern, 1991a). Chemical data alone are not sufficient to distinguish which process is occurring (Stern, 1991a, 1991b, 1991c). However, the general lack of correlation of isotopic composition with either SiO_2 or Sr content implies that crustal components were not incorporated in the younger Pliocene magmas by increased intra-crustal assimilation combined with crystal fractionation in shallow level magma chambers. In a shallow crustal environment, crystallization of plagioclase would cause decreasing Sr content. Intra-crustal assimilation near the base of relatively thick (>40 km) crust, at which depth garnet may replace plagioclase, could produce magmas with higher $^{87}Sr/^{86}Sr$ without reducing Sr content (Hildreth and Moorbath, 1988).

The isotopic changes observed between the Miocene and Pliocene at the latitude of the NSVZ are similar in magnitude to the isotopic differences that occur between the SSVZ and NSVZ (Fig. 5). Hildreth and Moorbath (1988) attributed these spatial differences to a northward increase in intra-crustal assimilation, in a lower crustal MASH zone of magma mixing, assimilation, storage and homogenization, as the crust below the SVZ thickens northwards from <40 km below the SSVZ to greater than >50 km below the NSVZ. Here the authors focus on the relation of the timing of the observed isotopic changes at the latitude of the NSVZ with both the timing and extent of crustal thickening below this region, as well as processes that might affect source region contamination such as decreasing subduction angle and/or ridge subduction.

With regard to the temporal changes in isotopic composition between the Miocene and Pliocene, the authors make three points. First, the crust never thickened to >50 km below the Pliocene volcanic front, which is well west of the High Andean drainage divide, although magmas erupted along this front approach the isotopic composition of those currently erupted in the NSVZ (Figs. 5 and 6). Below the region of the youngest Pliocene lava flows at 34°S, which occur at an elevation similar to the base of active volcanos in the SSVZ (<1,000 m), the crust is probably <40 km thick, even today. Second, the eastward migration of the arc during the Pliocene placed the currently active arc over thicker crust, without any significant change in isotopic composition (Figs. 3 and 6). Thus, between the Pliocene and the Present there is no temporal correlation between the isotopic composition of Andean magmas and crustal thickness. Third, the timing of the temporal changes in magma isotopic composition does not correlate with the timing of the changes in crustal thickness below Central Chile. Although the timing of crustal deformation, thickening and uplift in Central Chile is poorly constrained, it is believed to have begun in the Middle Miocene (Allmendinger *et al.*, 1990; Kay *et al.*, 1991; Skewes and Holmgren, 1993). In detail, for the region between 33° and 34°S, Skewes and Holmgren determined, from fluid inclusion geothermometry, that an 11.3 Ma pluton at the Los Bronces-Río Blanco deposit had undergone >1,400 m of unroofing related to crustal deformation, thickening, uplift and erosion prior to 5 Ma. The implied rate of erosion (>200 m/my) is higher than that calculated between 5 Ma and the Present (150 m/my; Skewes and Holmgren, 1993), and would be higher still if crustal thickening, uplift and erosion did not begin until after 7 Ma, the time when isotopic changes are first identified in the vicinity of Los Bronces-Río Blanco. These data are, thus, consistent with crustal thickening in Central Chile beginning significantly before the observed isotopic changes in Andean magma chemistry.

Hildreth and Moorbath (1988) attributed increasing La/Yb northwards in the SVZ (Fig. 4) to increased garnet in the deep lower crustal MASH zone below the NSVZ. Kay *et al.* (1991) also interpreted temporal increases in La/Yb in Andean magmas erupted above the developing flat-slab segment during the Miocene to reflect increasing crustal thickness and a greater petrogenetic role for lower crustal garnet. Significantly, no systematic increase in La/Yb occurs between the Miocene and Pliocene in the magmas erupted in the vicinity of El Teniente (Fig. 4). Here, it is clear that the Andean crust never thickened to the extent required to stabilize lower crustal garnet (>40 km), and the youngest lavas, with the most crustal isotopic signature, have relatively low La/Yb ratios. This is consistent with the cause, here, of the temporal isotopic changes being independent of crustal thickness.

Stern (1988, 1989, 1991a, 1991b, 1991c) suggested that an alternative explanation for isotopic changes similar to those occurring through time at the latitude of the NSVZ (Fig. 5) is increased subduction erosion and source region contamination of the subarc mantle. Two factors are likely to have increased the significance of both source region contamination and subduction erosion below Central Chile between the Miocene and Pliocene. One is decreasing subduction angle, which acts to decrease the volume of the sub-arc mantle wedge and thus, increase the relative significance of subducted components (Stern *et al.*, 1984b; Stern, 1988, 1989, 1991a). The second is ridge subduction. Marine geologic and geophysical studies in the vicinity of the Nazca ridge in Peru (Von Huene, Suess *et al.*, 1988) and the Chile Rise in Southern Chile (Candie and Leslie, 1986) indicated that ridge subduction enhances the effects of subduction erosion during a period of time prior to the actual subduction of the ridge. Thus, as the locus of subduction of the Juan Fernández Ridge migrated southwards west of the developing flat-slab segment in the Miocene (Pilger, 1981, 1984), the effects of enhanced subduction erosion also presumably migrated southwards ahead of the locus of subduction of this ridge. The southwards migration of the timing of isotopic changes in Andean magmas (Fig. 6) is closely associated with the areas south of the locus of subduction of the Juan Fernández Ridge as calculated by Pilger. This supports a genetic relation between these two events.

The authors conclude that temporal isotopic changes observed in Andean magmas erupted between the Miocene and Present at the latitude of the active NSVZ in Central Chile are independent of crustal thickness. Instead, they may be due to increased subduction erosion and source region contamination of the subarc mantle caused by the subduction of the Juan Fernández Ridge and the associated decrease in subduction angle.

Stern (1988, 1989, 1991a, 1991b, 1991c) argued that the spatial differences in isotopic chemistry of magmas erupted in the NSVZ compared to the SSVZ are caused by increased subduction erosion and source region contamination below the NSVZ, due to the active subduction of the Juan Fernández Ridge. Furthermore, Stern (1991a) suggested that differences in isotope chemistry between CVZ and SVZ magmas reflect greater amounts of subduction erosion and source region contamination below the Central Andes, due, in this case, to lower sediment supply to the trench west of the CVZ. Although some along-arc spatial variations in Andean magma chemistry correlate with crustal thickness (Harmon et *al.*, 1984), an equally significant correlation exists between variations in the along-arc rate and extent of subduction erosion (Stern, 1991a). The authors' conclusion, that at the latitude of the northern end of the SVZ, temporal changes in magma chemistry correlate more directly with the timing of ridge subduction and increased subduction erosion than with the timing of increasing crustal thickness, supports the suggestion that lower plate processes (subduction angle, ridge subduction, rates of subduction erosion) may have an equal or greater importance than upper plate parameters (crustal age and thickness) in producing the well documented along-arc spatial variations in Andean magma chemistry. This is clearly so, for the spatial distribution of active volcanism and volcanic gaps (Barazangi and Isacks, 1976; Thorpe, 1984).

Intra-crustal assimilation may be a significant process in Andean magma genesis, but the role of subduction erosion and source region contamination must also be taken into consideration in evaluating the total amount of crustal recycling involved in the genesis of Andean magmas, as well as for explaining the causes of segmentation of the Andean arc.

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