Geochemical features of Lower Cretaceous back-arc lavas in the Andean Cordillera, Central Chile (31-34°S)

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ABSTRACT

A back-arc setting for the Lower Cretaceous volcanic rocks in the Andean Cordillera of Central Chile (31-34°S), previously proposed on paleogeographic grounds, is consistent with their geochemical features. The rocks are basic to intermediate lavas, predominantly basaltic andesites, of low initial $^{87}Sr/^{86}Sr$ ratio (0.7031-0.7039). They are characterized by relatively high contents of Ta, Nb, Zr and Hf compared with Y and Yb, consistent with an enriched mantle source, or a low degree of partial melting, or both. High contents of alkalis and Th relative to HFS elements are interpreted as a crustal contribution. The Ba/La, Ba/Nb and V/Ti ratios are lower than in coeval island arc lavas in the Coastal Cordillera. The Ce/Yb, Ce/Sm, Th/Yb and initial $^{87}Sr/^{86}Sr$ ratios show a northward decrease within the studied sector consistent with a thinner crust in the north during the Early Cretaceous, contrary to the present situation.

Key words: Geochemistry, Early Cretaceous, Back-arc, Andes, Chile.

RESUMEN

Características geoquímicas de las lavas de trasarco del Cretácico Inferior en la Cordillera de los Andes, Chile central (31-34°S). Las rocas volcánicas del Cretácico Inferior de la Cordillera de los Andes de Chile central (31-34°S), consideradas como de un trasarco en base a criterios paleogeográficos, tienen características geoquímicas consistentes con este marco tectónico. Las rocas son lavas básicas a intermedias, predominantemente andesitas basálticas, de baja razón inicial de $^{87}Sr/^{86}Sr$ (0.7031-0.7039). Ellas se caracterizan por contenidos relativamente altos en Ta, Nb, Zr y Hf en relación a Y e Yb, consistentes con una fuente magmática enriquecida, un bajo grado de fusión parcial, o ambos. Los altos contenidos en álcalis y Th en relación a los elementos HFS podrían deberse a contaminación cortical. Las razones Ba/La, Ba/Nb y V/Ti son menores que las de las lavas de arco de islas contemporáneas de la Cordillera de la Costa. Las razones de Ce/Yb, Ce/Sm, Th/Yb y las razones iniciales de $^{87}Sr/^{86}Sr$ disminuyen hacia el norte lo cual es consistente con una disminución del espesor cortical en esa dirección durante el Cretácico Inferior, al contrario de la situación actual.

Palabras claves: Geoquímica, Cretácico Inferior, Trasarco, Andes, Chile.

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INTRODUCTION

The Early Cretaceous evolution of Central Chile was characterized by vigorous volcanism. The largest volumes of volcanic rocks are found in the Coastal Cordillera (Coast Range) where they form about 6-15 km thick piles. They have been described and discussed by several authors (Åberg *et al.*, 1984; Aguirre *et al.*, 1989; Vergara *et al.*, 1995). However, the less voluminous coeval volcanic rocks in the Andean Cordillera (High Andes) are often overlooked and their geochemistry is less known. The purpose of this paper is to outline the geochemical features of the Lower Cretaceous lavas there, based on samples from different latitudes within the 31-34°S sector of the Andean Cordillera of Central Chile (Fig. 1), and indicate their tectonic setting. A detailed geochemical-isotopical comparison of the Mesozoic volcanic rocks in the Andean and Coastal Cordilleras will be presented separately.

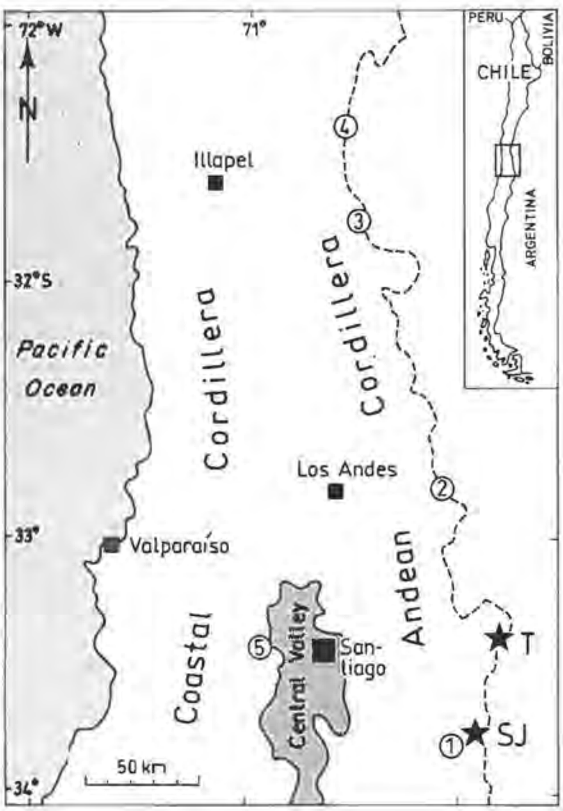

FIG. 1. The studied sector of the Andean Cordillera in Central Chile with sampled areas of Lower Cretaceous volcanic rocks (**1**= Lo Valdés; **2**= Portillo, and **3-4**= Pelambres Pass; see text). The Bustamante Hill area **(5)** in the Coastal Cordillera is mentioned in the paper for comparative purposes. The stars represent Quaternary volcanic complexes belonging to the northernmost part of the Southern Volcanic Zone; **SJ**= the San José-Marmolejo complex and **T**= the Tupungato complex.

GEOLOGIC SETTING AND METHODS

Lower Cretaceous stratigraphic sequences in the Andean Cordillera of Central Chile (Aguirre, 1985; Vergara *et al.*, 1995) are about 2-4 km thick and the proportion of volcanic rocks (15-50%) is commonly smaller than that of sedimentary rocks, including those of volcaniclastic character. The volcanic rocks consist of basic to intermediate lavas which erupted in marine as well as continental environments. Ignimbrites and acid lavas are scarce or absent and no associated granitoids have been observed. The Lower Cretaceous sequences rest conformably on continental Jurassic formations and are unconformably overlain by continental Upper Cretaceous sequences.

The samples included in this study were collected from non-amygdaloidal parts of lava flows at four different latitudes of the Andean Cordillera immediately west of the Chilean-Argentinean border (Fig. 1). A southern area, here called Lo Valdés, consists of the northern part of the Río Volcán valley from a point opposite Lo Valdés village to about 2 km upstream. A central area, Portillo, extends between the ski resort of this name and the western entrance of the tunnel at the border with Argentina. Two northern areas, a locality *ca.* 5 km south of Pelambres Pass and another situated 32 km north of the pass, were sampled. They are treated together and referred to as the Pelambres Pass area in this study, because the sampled volcanic rocks come from the same formation that outcrops as a continuous unit (Rivano and Sepúlveda, 1991; Vergara *et al.*, 1993). The sequences in the Pelambres Pass area are complicated by Cenozoic thrust faulting (Rivano and Sepúlveda, 1991), whereas Lo Valdés and Portillo are situated west of the zone with thrust faults that characterize the High Andes in westernmost Argentina (the Aconcagua fold-thrust belt; Mpodozis and Ramos, 1990).

At Lo Valdés, the lavas sampled are intercalated in the central part of the shallow water marine Lo Valdés Formation of Tithonian-Hauterivian age and in the lowermost part of the conformably overlying, predominantly continental Colimapu Formation of Barremian to Albian age that is characterized by red tidal flat deposits (Thiele, 1980; Hallam *et al.*, 1986; Charrier and Muñoz, 1994). At Portillo, the analyzed lavas occur in a continental redbed unit thought to correspond to the northern continuation of the Colimapu Formation. The lavas are situated just above the Cristo Redentor Formation as defined by Aguirre (1960), but incorporated within this unit by Aguirre *et al.* (1993); they are probably of Albian age. According to the map of Rivano *et al.* (1993) the sampled volcanic rocks belong to the Lower Cretaceous Los Pelambres Formation. The Pelambres Pass samples represent lavas that dominate the lower part of the Los Pelambres Formation in its type locality (Olivares, 1985; Rivano and Sepúlveda, 1991); the lavas alternate with continental volcaniclastic rocks and shallow water marine limestones. According to Rivano and Sepúlveda (1991), the age of the formation at Pelambres Pass is probably Berriasian-Hauterivian.

The lavas contain phenocrysts of calcic to intermediate plagioclase of high structural state, clinopyroxene (generally augite), and titanomagnetite. The plagioclase phenocrysts in many flows are coarse, up to 2 cm long. Inspection of thin sections and X-ray diffraction analysis showed that 16 out of the 27 samples collected for this study, contain well-preserved phenocrysts and a groundmass with only small to moderate amounts of secondary minerals, and therefore could be considered sufficiently unaltered to be used for geochemical work. The data given in the diagrams represent the 13 least altered samples unless specified otherwise in the caption. The rocks from the Pelambres Pass area are, as a rule, more altered than those from Lo Valdés and Portillo.

The samples were analyzed at the Centre de Recherches Pétrographiques et Géochimiques, Nancy, France. Major elements were determined with ICP-AES, H_2O^+, CO_2 and FeO with wet chemical methods, and trace elements with ICP-MS. Strontium isotope compositions were determined at the Swedish Museum of Natural History, Stockholm.

GEOCHEMISTRY

Chemically, the sampled lavas range from basalt to andesite. Basaltic andesites predominate, whereas andesites are subordinate and most of them have low SiO_2 contents. The proportion of basalts is low except in the north (Pelambres Pass). Representative chemical analyses of basic lavas (basalt to basaltic andesite) from the different areas are given in table 1 and averaged ratios of some elements usually regarded as immobile are listed in table 2. Most of the ratios vary relatively little within each formation as seen in the low standard deviations, taking into account the considerable SiO_2 range.

The lavas have many geochemical features in common. The majority of them are high-to medium-K calc-alkaline. According to a preliminary geochemical study of volcanic rocks from the Pelambres Pass area by Vergara *et al.* (1993) some of the rocks have tholeiitic composition. However, XRD analysis reveals that these samples are quite altered.

The basic lavas have high Al_2O_3 contents (17-20 wt.%), low contents of MgO (2.4-4.1 %), Ni (8-21 ppm), Co (16-27 ppm) and Cr (9-40 ppm); TiO_2 varies between 1.0 and 1.9 %, FeO^{total} = 7.3-9.8%, Th = 4-14 ppm and U=0.6-3.6 ppm. A total alkali *versus* silica diagram (Fig. 2) shows that the lavas are of a transitional subalkaline to mildly alkaline character. MORB-normalized spiderdiagram patterns illustrate relatively high contents of Sr, K, Rb, Ba, Th and Ce, and marked troughs for Ta-Nb (Fig. 3). The MORB-normalized values for Ta-Nb and Zr-Hf are roughly similar and close to 1 (up to 6 times higher than that value at Portillo); the Y-Yb values are close to 1. The initial $^{87}Sr/^{86}Sr$ ratios are low (0.70308-0.70391) and show no correlation with SiO_2 (Tables 1 and 2; Fig. 4).

In the Lo Valdés area the lavas of the Colimapu Formation have lower Ce/Yb, Ce/Sm, Th/Yb and initial $^{87}Sr/^{86}Sr$ ratios and higher Nb/Y, Nb/Yb and Ta/Yb ratios than the older volcanic rocks in the Lo Valdés Formation (Table 2). The same chemical trends can be seen if the comparison is extended to the still younger volcanic rocks of similar SiO_2 content in the Cristo Redentor Formation at Portillo farther north. Here, the Th/Yb and Ce/Sm ratios are even lower and the Nb/Y, Nb/Yb and Ta/Yb ratios are generally higher. A comparison of coeval lavas at different latitudes shows that the northern ones (Los Pelambres Formation) have lower Ce/Yb, Ce/Sm, Th/Yb, Zr/Y, Zr/Yb and initial $^{87}Sr/^{86}Sr$ ratios than corresponding lavas in the south (Lo Valdés Formation); Nb/Y and Nb/Yb are similar in the two areas.

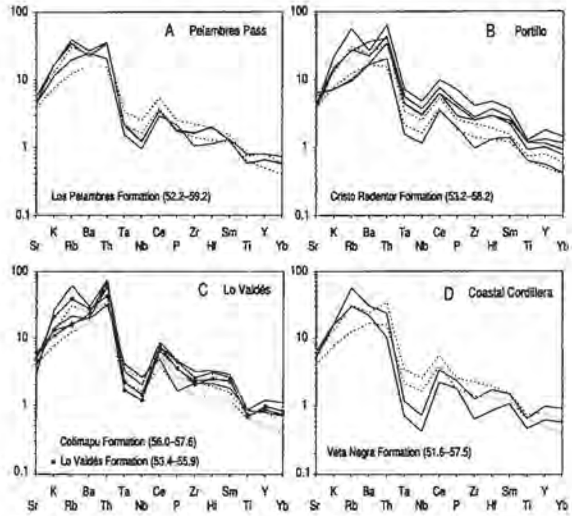

FIG. 3. MORB-normalized spiderdiagrams for basic to intermediate Lower Cretaceous lavas from the Andean Cordillera of Central Chile between 31° and 34°S (SiO_2 range of the plotted samples in parenthesis). The field between the dashed lines corresponds to six basaltic andesites from Quaternary volcanoes on and behind the volcanic front in Central Chile between 33°20' and 34°10'S (SiO_2= 54.0-68.9; data from Hickey *et al.*, 1986, and Hildreth and Moorbath, 1988). Diagram D shows the composite field for three representative Lower Cretaceous (Albian) lavas from the Veta Negra Formation in the Coastal Cordillera of Central Chile west of Santiago (Bustamante Hill; Vergara *et al.*, 1995). Normalization values after Pearce (1983).

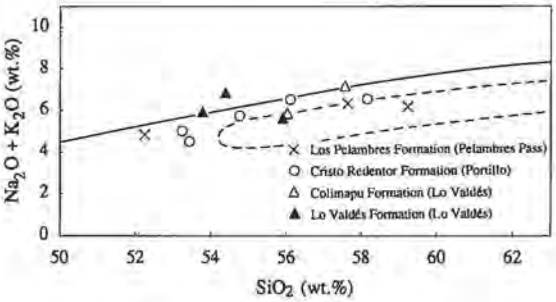

FIG. 2. Total alkali *versus* silica diagram for Lower Cretaceous lavas from the Andean Cordillera of Central Chile (Fig. 1). The boundary line separates the subalkaline (below) and alkaline series (above; after Irvine and Baragar, 1971). The field for Quaternary lavas from Central Chile between 33°20' and 34°10'S is included for comparison (dashed line; data from López-Escobar *et al.*, 1985, Hickey *et al.*, 1986, and Hildreth and Moorbath, 1988).

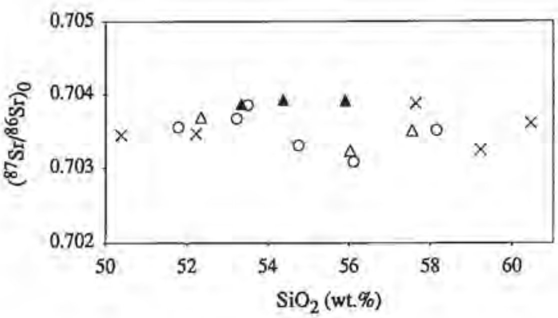

FIG. 4. Initial $^{87}Sr/^{86}Sr$ ratios *versus* SiO_2 content for Lower Cretaceous lavas from the Andean Cordillera of Central Chile (31-34°S), including three moderately altered samples, and an andesite not taken into account in table 2; symbols as in figure 2.

TABLE 1. REPRESENTATIVE CHEMICAL ANALYSES OF LOWER CRETACEOUS BASIC LAVAS FROM THE ANDEAN CORDILLERA OF CENTRAL CHILE.

Area	Lo Valdés			Portillo		Pelambres Pass
Formation	Lo Valdés		Colimapu	Cristo Redentor		Los Pelambres
Age*	Late Tithonian to Valanginian		Barremian	Albian		Berriasian to Hauterivian
Sample	VAL-45	VAL-43	VAL-68	ACO-99	ACO-9	R-379¤
(wt.%)§						
SiO_2	53.35	55.90	56.02	53.23	56.11	52.23
TiO_2	1.01	1.01	1.26	0.96	1.92	1.20
Al_2O_3	19.98	18.10	17.61	20.38	16.52	19.24
Fe_2O_3	3.00	1.86	4.81	4.12	5.17	4.67
FeO	4.84	5.93	3.46	3.55	3.89	4.49
MnO	0.10	0.15	0.19	0.14	0.29	0.29
MgO	3.51	3.16	3.14	3.38	2.69	4.14
CaO	8.54	7.73	7.45	8.99	6.05	8.53
Na_2O	3.91	4.00	3.72	3.93	3.24	3.10
K_2O	1.99	1.63	2.14	1.09	3.27	1.73
P_2O_5	0.42	0.53	0.19	0.23	0.86	0.26
(ppm)						
Rb	31	33	43	19	113	40
Sr	589	730	461	776	518	534
Ba	469	409	391	334	535	500
V	228	201	180	206	192	268
Ni	10	21	8	18	21	17
Co	16	18	20	21	17	27
Cr	9	29	28	20	51	26
La	36.8	33.3	22.4	15.1	42.7	12.5
Ce	75.2	75.7	48.6	34.8	99.5	29.4
Nd	40.6	38.3	27.3	19.6	54.9	18.0
Sm	7.69	8.49	5.92	4.59	12.25	4.40
Eu	1.97	1.71	1.57	1.30	2.37	1.41
Gd	6.57	6.42	4.55	3.41	10.16	3.81
Dy	5.15	4.77	4.21	2.76	9.31	4.16
Er	2.64	2.49	2.25	1.64	4.86	2.32
Yb	2.83	2.82	2.37	1.44	4.91	2.47
Lu	0.46	0.38	0.36	0.25	0.75	0.39
Y	28.7	29.4	23.9	16.9	54.2	23.9
Zr	205	230	193	88	374	95
Hf	5.92	7.37	5.06	3.22	11.60	2.71
Nb	5.09	5.01	9.13	4.01	17.00	3.33
Ta	0.40	0.39	0.74	0.28	1.30	0.28
Th	13.90	12.00	6.38	4.09	12.80	4.14
U	3.26	3.01	1.93	0.61	3.62	0.95
Sr(i)#	0.70386	0.70391	0.70323	0.70367	0.70308	0.70346

* Refers to the sampled part of the formation.

¤ The only unaltered sample of basic lava from this area.

§ Recalculated anhydrous.

\# Sr(i)= $(^{87}Sr/^{86}Sr)_0$; the following ages (Ma) were used for the age correction: 143 (Lo Valdés Formation), 130 (Colimapu Formation), 106 (Cristo Redentor Formation) and 137 (Los Pelambres Formation).

TABLE 2. SOME GEOCHEMICAL FEATURES OF LOWER CRETACEOUS LAVAS FROM THE ANDEAN CORDILLERA OF CENTRAL CHILE.

Area	Lo Valdés		Portillo	Pelambres Pass
Formation	Lo Valdés	Colimapu	Cristo Redentor	Los Pelambres
Age*	Late Tithonian to Valanginian	Barremian	Albian	Berriasian to Hauterivian
Number of samples	3	3	6	4
SiO_2¤	53.4-55.9	52.3-57.6	51.8-58.2	50.4-59.2
K_2O vs. Si_2§	High-K calc-alkaline to shoshonitic		High-K to medium-K calc-alkaline	High-K calc-alkaline
Ce/Sm	9.1 ± 0.6	8.3 ± 0.9	8.0 ± 0.4	7.7 ± 0.9
Nb/Y	0.17 ± 0.01	0.27 ± 0.09	0.31 ± 0.04	0.19 ± 0.04
Nb/Yb	1.7 ± 0.1	2.7 ± 1.0	3.4 ± 0.4	1.8 ± 0.4
Ta/Yb	0.13 ± 0.01	0.22 ± 0.08	0.26 ± 0.04	0.16 ± 0.04
Th/Yb	4.2 ± 0.8	3.0 ± 0.9	2.6 ± 0.3	2.6 ± 1.2
Zr/Y	7.3 ± 0.4	7.1 ± 1.6	6.5 ± 0.8	5.9 ± 1.9
Zr/Yb	75 ± 5	71 ± 16	72 ± 9	58 ± 19
Sr(i)	0.70390 ± 0.00003	0.70347 ± 0.00023	0.70349 ± 0.00027	0.70350 ± 0.00026

Note: The ratios are given as averages with standard deviation.

* See table 1 for comments on ages.

¤ Range; wt.% recalculated anhydrous.

§ Most frequent magma type for the relatively unaltered samples (2+3+5+3).

DISCUSSION

The Lower Cretaceous volcanic rocks in the Coastal Cordillera of Central Chile erupted from a volcanic arc that was separated from the continent by a marginal sea. Vergara *et al.* (1995) concluded that the arc was built on moderately thick crust belonging to the old continental margin that had become progressively more attenuated with time since the Jurassic, and that the basic volcanic rocks chemically resemble the lavas in some mature island arcs in the western Pacific. In the following discussion the authors will attempt to show that the geochemistry of the coeval Lower Cretaceous volcanic rocks in the Andean Cordillera is consistent with a back-arc setting. The geology suggests that the back-arc was situated in the continental edge east of the marginal sea; no oceanic crust was generated. The volcanic rocks are intercalated with marine limestones, conformably overlie predominantly volcaniclastic sequences, and were deposited in basins close to sea level. A back-arc setting for Lower Cretaceous volcanic rocks in various parts of the Andean Cordillera of Central Chile has been suggested by several authors based on paleogeographic data (Thiele and Nasi, 1982; Charrier, 1984; Charrier and Muñoz, 1994).

The low Mg, Ni, Co and Cr contents of the basic lavas suggest early fractional crystallization of olivine and perhaps also orthopyroxene and spinel. This is consistent with the Al-rich nature of the volcanic rocks and the lack of basalts with low SiO_2 values. The low proportion of basalts among the lavas and the minerals occurring as phenocrysts in all the samples indicate that fractional crystallization of plagioclase-augite-dominated assemblages took place. The spiderdiagram patterns in figure 3 can be used for genetic purposes since they are subparallel for basalts, basaltic andesites and andesites. In addition, most of the ratios in table 2 are rather constant regardless of the SiO_2 content of the samples. According to Pearce (1983) and Pearce and Peate (1995) the degree of fractional crystallization changes the level of the spiderdiagram patterns, but has little effect on their shape.

The geochemistry of the volcanic rocks in the Andean Cordillera is characterized by a clear within-plate component and a small subduction-related component, consistent with a back-arc setting. The within–plate component is given by relatively high contents of the highly incompatible HFS elements Ta, Nb, Zr and Hf compared to somewhat less incompatible HFS elements like Y and Yb (Fig. 3). It is also indicated by the high Nb/Y, Nb/Yb and Ta/Yb ratios (Table 2). These ratios are 2.3-6 times higher than corresponding values for N-MORB (Nb/Y= 0.083, Nb/Yb= 0.76 and Ta/Yb= 0.043; Pearce and Parkinson, 1993). The spiderdiagrams (Fig. 3) and some of the chemical ratios given in table 2 indicate that the mantle sources of the magmas were enriched, or that the magmas were formed by a low degree of partial melting, or both. A low degree of partial melting is in good agreement with the relatively small volumes of volcanic rocks here, compared with the much larger volumes of coeval volcanic rocks in the Coastal Cordillera. The geochemistry of the latter (Vergara *et al.*, 1995) suggests generation by a higher degree of partial melting that is typical of volcanic arcs in oceanic settings (Pearce and Parkinson, 1993).

The ratios of Nb/Y, Nb/Yb and Ta/Yb are highest for the lavas in the central part of the investigated sector, *i.e.*, the Portillo area (Table 2). This distinct within-plate component may be, at least partly, related to the younger age of the volcanic rocks at Portillo, because the older rocks in the two other areas (the coeval Lo Valdés and Los Pelambres formations) do not differ significantly from each other with respect to these ratios. A change in chemistry with time during the Early Cretaceous is supported by the ratios for the Colimapu Formation which are intermediate between those of the older rocks in the same area (Lo Valdés Formation) and the values for the younger rocks at Portillo (Table 2).

A back-arc setting for the volcanic rocks of the Andean Cordillera is supported by the Ba/La, Ba/Nb and V/Ti ratios for the basic lavas (12–22, 31-132 and 0.017-0.037, respectively). The ratios are lower than corresponding values for coeval basic lavas in the Coastal Cordillera (42-50, 238-327 and 0.055-0.062, respectively; Vergara *et al.*, 1995) which formed in an island arc. These differences are in accordance with lower ratios for back-arcs compared with associated arcs (Shervais, 1982; Woodhead *et al.*, 1993; Pearce and Peate, 1995), including arc and back-arc pairs at continental margins (Muñoz and Stern, 1989; Kay *et al.*, 1991). Note that samples from the Pelambres Pass area are not included in the comparisons because the region studied by Vergara *et al.* (1995) in the Coastal Cordillera only extends northward to 32°30'S, so a strict east-west comparison cannot be made.

High contents of alkalis, Sr, Ba, and to a lesser extent Th and LREE relative to HFS elements are generally attributed to a subduction-related component, but a similar effect can result from crustal contamination (Pearce, 1983). Crustal contamination is a more likely source of these elements in the lavas studied by the authors than addition from the slab or from the mantle by slab-derived fluids, because the Th and Rb contents are high (Fig. 3) and the Ba/La and Ba/Nb ratios are lower than in volcanic arcs where slab-derived fluids play a prominent role. Crustal contamination (in addition to early fractional crystallization) is probably responsible for the absence of basalts with low SiO_2 content among the relatively few basalts in the studied areas.

Contamination of mantle-derived magmas by upper crustal rocks should increase the contents of Rb, Th and U in the final products, and might explain the high values of these elements in the volcanic rocks of the Andean Cordillera. It might also be partly responsible for the within-plate component by raising the level of Ta and Nb. A melt contribution from the lower crust cannot be excluded, but it should not be a major factor since the rocks are too rich in HREE and Y for melting at depths great enough for garnet to be an important residual phase. Moreover, higher contents of Sr (and Ba) than actually present in the samples might be expected if the lower crust were a major contaminant.

The low values and limited range of the initial $^{87}Sr/^{86}Sr$ ratios of the Lower Cretaceous basalts, basaltic andesites and andesites (0.7031-0.7039; Fig. 4) suggest that the isotopic contrast between magmas and contaminating crust cannot have been too large and that the inferred upper crustal contaminant was young. The Upper Jurassic continental unit below the Lower Cretaceous rocks is the Río Damas Formation and corresponding units to the north (Thiele, 1980; Rivano and Sepúlveda, 1991; Rivano *et al.*, 1993); three Río Damas lavas yielded initial $^{87}Sr/^{86}Sr$ ratios of 0.7037 (Nyström, unpublished data). Other possible contaminants are Upper Paleozoic plutonic rocks that outcrop along the international border north of the studied region (initial $^{87}Sr/^{86}Sr$ ratios of the order of 0.7048-0.7078; Hervé *et al.*, 1987; Mpodozis and Kay, 1992), and radiogenic basement rocks of Paleozoic to Triassic age which have a wide distribution in westernmost Argentina (Sr data for the southern part of the Frontal Cordillera in Hildreth and Moorbath, 1988). However, the positive correlation between initial $^{87}Sr/^{86}Sr$ and Sr for the Portillo samples in figure 6 argues against much contamination by rocks of high $^{87}Sr/^{86}Sr$ and low Sr contents. The samples are too few and their Sr range is too small to allow a conclusion for the other areas in the studied sector. The main contaminant(s) cannot be identified until more isotope data are available.

One of the ratios in table 2 that is higher in the south compared to the north, in coeval rocks (Lo Valdés and Los Pelambres formations, respectively), is Ce/Yb (Fig. 5). This ratio (or La/Yb and Ce/Sm) has been used in the literature as a measure to estimate crustal thickness. The values of this ratio suggest that the crust was thicker in the south than in the north during the Early Cretaceous, *i.e.*, a trend reverse to the present situation, as suggested by Levi *et al.* (1988). According to the Ce/Sm *versus* crustal thickness diagram of Hawkesworth *et al.* (1994) the crust was *ca.* 5-10 km thicker in the Lo Valdés area compared with Pelambres Pass. The northward decrease in Ce/Yb, Ce/Sm, Th/Yb, Zr/Y and Zr/Yb, and initial $^{87}Sr/^{86}Sr$ ratio (Fig. 4), is opposite in direction to the trends for these ratios in Hildreth and Moorbath (1988); Hickey *et al.* (1986) and Tormey *et al.* (1991) for the Quaternary lavas in the Southern Volcanic Zone that coincide with a southward decrease in crustal thickness.

The decrease with time in Ce/Yb, Ce/Sm, Th/Yb and initial $^{87}Sr/^{86}Sr$ at Lo Valdés (Table 2; Figs. 4-5) is consistent with a progressive crustal attenuation. In the 32°30'-34°30'S sector of the Andes the attenuation culminated at the end of the Oligocene (Nyström *et al.*, 1993; Vergara *et al.* 1995). An analogous trend of decreasing La/Yb in lavas of the Andean Cordillera at 33-34°S from the Early Cretaceous to the Oligocene, followed by a subsequent increase in this ratio up to the present, was noted by Levi *et al.* (1988, Fig. 7). Cristallini *et al.* (1994) arrived at a different conclusion in a study of Cretaceous-Tertiary volcanic rocks in westernmost Argentina at *ca.* 32°S which included rocks that were correlated with the Los Pelambres and Cristo Redentor formations. They reported considerably higher values for La/Yb (and Ce/Yb) than the authors obtained, and an increase in La/Yb with time that was attributed to crustal thickening. However, the results of the present study and that of Cristallini *et al.* (1994) cannot be compared because the rocks in Argentina correlated with the Los Pelambres and Cristo Redentor formations are rhyolitic tuffs. The opposite trends for the La/Yb ratio with time reported by Levi *et al.* (1988) and Cristallini *et al.* (1994) can be explained by west-east differences in tectonic evolution.

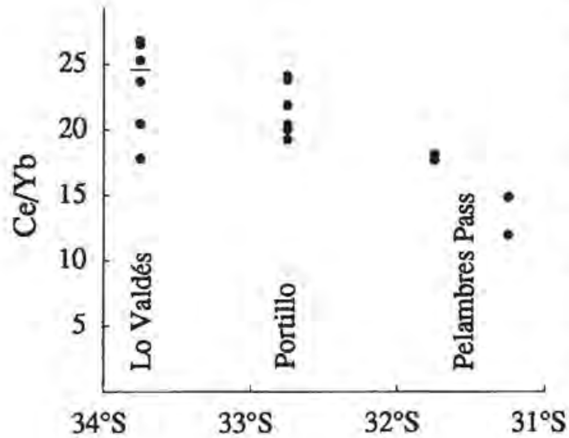

FIG. 5. Variation in Ce/Yb ratios with latitude for Lower Cretaceous lavas from the Andean Cordillera of Central Chile, including three moderately altered samples. The Lo Valdés samples above the short horizontal line are from the Lo Valdés Formation; the samples below the line represent the younger formation in the area (Colimapu). The Pelambres Pass area consists of two localities.

It could be argued that the chemical evidence presented here for a back-arc setting in the east reflect formation behind the volcanic front of a wide arc, where the weaker arc signature of the eastern volcanic rocks in the Andean Cordillera compared with the stronger signature of the western rocks in the Coastal Cordillera is due to a smaller contribution from the subducted slab. The distance between the coeval sequences in the two cordilleras may have increased since the Early Cretaceous due to extension during volcanism and emplacement of batholiths (Levi and Aguirre, 1981; Drake *et al.*, 1982). At the Pelambres Pass, the separation between them is smaller than farther south, which might, at least in part, be caused by thrusting. However, the geochemical contrast between the Lower Cretaceous volcanic rocks in the Coastal and Andean Cordilleras argues against splitting of a single arc.

A back-arc setting for the Lower Cretaceous volcanic rocks in the Andean Cordillera is consistent with the geochemical features discussed in previous sections. Additional support comes from: **a-** the paleogeographic situation, where an up to 15 km thick pile of volcanic rocks forming in the west was separated from an eastern volcanic sequence by a marginal sea (Thiele and Nasi, 1982; Charrier, 1984; Charrier and Muñoz, 1994); **b-** the higher gradients inferred from secondary mineral assemblages in the altered rocks of the eastern sequence compared with the gradients for the coeval western sequence during the regional alteration that took place closely after deposition of the sediments and volcanic rocks that compose the two sequences (Vergara *et al.*, 1994); **c-** the apparent lack of associated granitoids in the east, and **d-** the abundance of volcanic rocks of shoshonitic affinity in the west that implies a steep angle of subduction (Levi *et al.*, 1988; Vergara *et al.*, 1995), and therefore a smaller contribution from subduction-related fluids in the east.

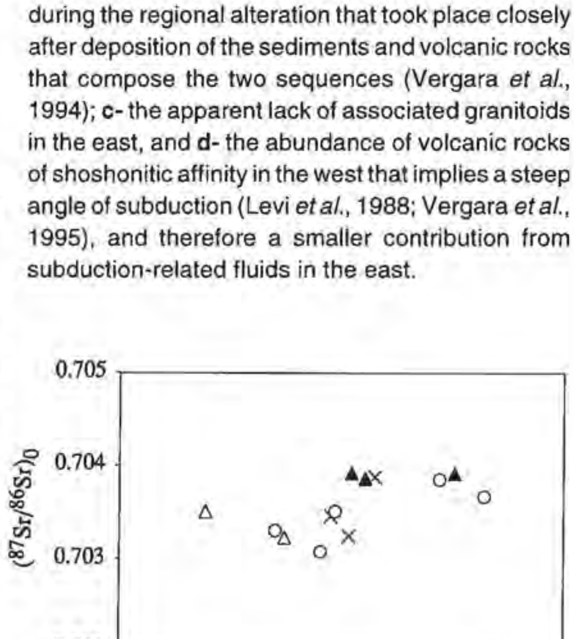

FIG. 6. Initial $^{87}Sr/^{86}Sr$ ratios *versus* Sr content for Lower Cretaceous lavas from the Andean Cordillera of Central Chile (31-34°S); symbols as in figure 2.

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