Eocene-Miocene Longitudinal Depression and Quaternary volcanism in the Southern Andes, Chile (33-42.5°S): a geochemical comparison

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ABSTRACT

The Southern Andes Eocene-Miocene volcanism comprises a series of paleo-volcanic belts striking N-S to N10°E. Along the longitudinal depression of central-south Chile, remnants of this volcanism are distributed between about 33° and 42.5°S. Basalts and basaltic andesites predominate north of 37°S, while andesites and dacites do it south. This general trend is opposite to that of the Southern Volcanic Zone (SVZ) Quaternary volcanism (33-46°S), where andesites and dacites predominate north of 37°S and basalts and basaltic andesites do it south of this latitude. Except for those Eocene-Miocene basalts and basaltic andesites found at 35.7°S, basaltic rocks from the Longitudinal Depression Volcanic Belt are similar in major and trace elements, and in Sr-, Nd-, and Pb-isotopes to the so-called type-1 (incompatible element depleted) Quaternary minor eruptive centers basaltic rocks from the central province (37-41.5°S) of the SVZ. The 35.7°S basaltic rocks from the longitudinal depression have REE patterns that mimic those of some ocean floor basalts. The Sr- and Nd-isotope compositions of the type-1 Quaternary minor eruptive centers and basaltic rocks from the 33-33.5°S area of the Longitudinal Depression Volcanic Belt are similar to those of OIB from the Juan Fernández archipelago and E-MORB rocks from the Chile Ridge. On the contrary, basaltic andesites and dacites from the 41.5-42.5°S area of the belt are significantly enriched in radiogenic Sr. Andesites and dacites from the 37.5-39°S area are geochemically and isotopically similar to Quaternary andesites and dacites from the Nevados de Chillán Volcanic Group (36.8°S), which are one of the isotopically most primitive andesites and dacites from the SVZ of the Andes.

Key words: Volcanism, Geochemistry, Eocene-Miocene, Quaternary, Southern Andes, Central-south Chile.

RESUMEN

Volcanismos eoceno-mioceno de la Depresión Longitudinal y Cuaternario en los Andes del Sur, Chile (33-42,5°): una comparación geoquímica. El volcanismo eoceno-mioceno de los Andes del Sur, comprende una serie de paleo-cinturones volcánicos, de orientación N-S a N10°E. A lo largo de la depresión longitudinal, restos de este volcanismo están distribuidos, aproximadamente, entre las latitudes 33° y 42,5°S. En este cinturón volcánico, basaltos y andesitas basálticas predominan al norte de los 37°S, mientras que andesitas y dacitas lo hacen al sur de esta latitud. Esta tendencia general es opuesta a la presentada por el cinturón volcánico cuaternario, donde andesitas y dacitas predominan al norte de los 37°S, mientras que los basaltos y andesitas basálticas lo hacen al sur de esta latitud. Exceptuando los basaltos y andesitas basálticas, eocenos-miocenos, ubicados en la latitud 35,7°S de la depresión longitudinal, las rocas basálticas de este cinturón volcánico son semejantes, en elementos mayores y trazas y en razones isotópicas de Sr, Nd y Pb, a las rocas basálticas del llamado tipo-1 (empobrecidas en elementos incompatibles) de los centros eruptivos menores cuaternarios de la provincia central (37-41,5°S) de la Zona Volcánica Sur (ZVS) de los Andes. Las rocas basálticas, ubicadas en la latitud 35,7°S presentan patrones de tierras raras semejantes al de algunas rocas basálticas de fondo oceánico. Las razones isotópicas de Sr y Nd, de los centros eruptivos menores cuaternarios del tipo-1 y rocas basálticas del sector 33-33,5°S de la depresión longitudinal, son semejantes a las de los basaltos del archipiélago de Juan Fernández y a rocas basálticas, tipo E-MORB, de la Dorsal de Chile. Sin embargo, las andesitas basálticas y dacitas del sector 41,5-42,5°S de este cinturón volcánico están enriquecidas, significativamente, en Sr radiogénico. Las andesitas y dacitas del sector 37,5-39°S de la depresión longitudinal son, geoquímica e isotópicamente, semejantes a las andesitas y dacitas cuaternarias del grupo volcánico de los Nevados de Chillán (36,8°S), las cuales constituyen las andesitas y dacitas más primitivas, isotópicamente, de la ZVS de los Andes.

Palabras claves: Volcanismo, Geoquímica, Eoceno-Mioceno, Cuaternario, Andes del Sur, Chile central-sur.

INTRODUCTION

The Southern Andes Cenozoic volcanic activity developed as a series of N-S to N10°E -trending belts. One of these belts, that probably was formed by several magmatic episodes, is the Eocene-Miocene Longitudinal Depression Volcanic Belt (LDVB) (Fig. 1). Another one is the Eocene-Miocene High Andes Volcanic Belt and probably the best known one is the Quaternary Southern Volcanic Zone (SVZ).

Remnants of the LDVB (mainly stocks and volcanic necks, but also lavas) are distributed approximately between latitudes 33° and 42.5°S, showing a gap between about 39° and 40°S (Fig. 1). On the other hand, the Eocene-Miocene High Andes Volcanic Belt crops out in the Andean cordillera, between 33° and 39°S, either west from the SVZ or under it (Fig. 1). The High Andes Tertiary volcanism was probably the source of Oligocene-Miocene volcanic rocks that are now found in intermontane valleys, such as those of the Abanico and Coya-Machalí formations (33-34.5°S), defined respectively by Aguirre (1960) and Klohn (1960). Between about 39° and 40°S, remnants of the LDVB have been found only at the Peninsula Illaguapi of the Ranco lake (Muñoz and Moreno, personal communication, 1997). Between 40 and 42.5°S, outcrops of this volcanic belt are found along the coast and on the western part of the longitudinal depression. For this reason, it has received different names, such as Coastal Cordillera Volcanic Belt (Vergara and Munizaga, 1974), Eocene-Miocene Longitudinal Depression Volcanic Belt (López-Escobar *et al.*, 1976), and Central Valley Upper Oligocene-Miocene Volcanic Belt (Stern and Vergara, 1992). Rocks from the LDVB have K-Ar ages ranging from 40 to 15 Ma (Vergara and Munizaga, 1974; Vergara and Drake, 1978; Karzulovic *et al.* 1979; Vergara and López-Escobar, 1980; García *et al.*, 1988; Stern and Vergara, 1992; Rubio, 1993; Cisternas and Frutos, 1994; Kelm *et al.*, 1994; Muñoz *et al.* 1997).

Significant north-south petrographic and geochemical variations are observed in the SVZ (33-46°S; Moreno, 1976; López-Escobar, 1984; Hickey *et al.*, 1986; Hildreth and Moorbath, 1988; Tormey *et al.*, 1991). These variations seem to correlate with changes in the thickness of the continental crust and the value of the subduction angle. Latitude 37°S marks a major geophysical, tectonic and stratigraphic discontinuity (Charrier and Vicente, 1970; Swift and Carr, 1974), which coincides with the prolongation of the Mocha fracture zone into the continent (Onuma and López-Escobar, 1987). The subduction angle changes from about 30° north of this latitude to about 20° south of it (Swift and Carr, 1974). The thickness of the continental crust increases northward from about 30 km at 37°S to 55-60 km at 33-34°S, being about 30 km south of 37°S (Hildreth and Moorbath, 1988, and references therein). In addition, latitude 37°S also marks a major petrographic discontinuity: Quaternary volcanic rocks change from a predominance of andesites and dacites north of 37°S to a predominance of basalts and basaltic andesites south of this latitude (Moreno, 1976). This petrographic change is accompanied by geochemical changes. The $^{87}Sr/^{86}Sr$ isotopic ratio, for example, exhibits its minimum values at 37°S (Déruelle *et al.*, 1983; López-Escobar, 1984; Notsu *et al.*, 1987; Hildreth and Moorbath, 1988), increasing north and south from this latitude.

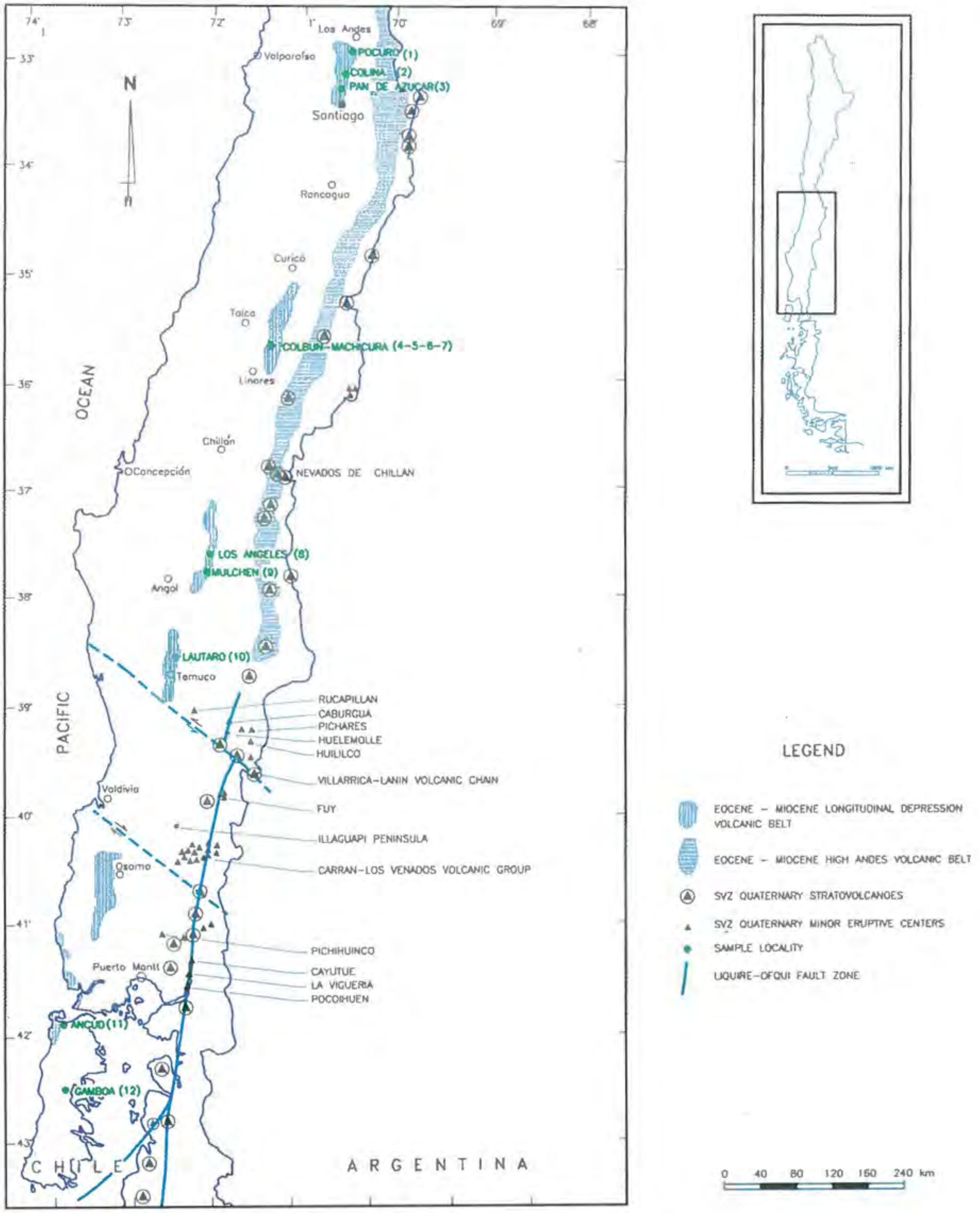


FIG. 1. Sketch map showing sample localities and the distribution of the Southern Andes Eocene-Miocene Longitudinal Depression Volcanic Belt (LDVB), Eocene-Miocene High Andes volcanic belt and SVZ Quaternary stratovolcanoes and minor eruptive centers (MEC).

North-south petrographic and geochemical variations have been also suggested to occur in the Eocene-Miocene LDVB (López-Escobar, 1984; Kelm *et al.*, 1994). In this paper the authors report the chemistry of 12 samples and the isotopic composition of 8 samples from different sectors of this belt (Fig. 1). The aim is: **a-** to evaluate possible north-south geochemical variations along it, and **b-** to get a better understanding of the geochemical evolution of the Southern Andes volcanism with time from Eocene-Miocene to Recent.

SAMPLE LOCATIONS

The location of 12 samples of rocks from the Eocene-Miocene Longitudinal Depression Volcanic Belt (LDVB) is given in the following paragraphs.

Three porphyritic basaltic samples of volcanic necks represent the northernmost part of the volcanic belt (32.9-33.5°S; Los Andes-Santiago sector; Fig. 1). Sample 1 was collected at Pocuro Hill (32.9°S), sample 2 at a hill located north of Colina (33.2°S) and sample 3 comes from a quarry of the Pan de Azúcar Hill (33.3°S). The K-Ar ages of samples 1 and 2 are respectively 20.6 and 21.2 Ma (Vergara and López-Escobar, 1980).

In the Precordilleran region located between 35° and 37°S a volcanoclastic continental sequence crops out, represented by lava flows, dykes and stocks of basic to intermediate composition. At Colbún-Machicura (35.7°S), samples 4 (basaltic dyke), 5 (basaltic neck), 6 (basaltic stock) and 7 (andesitic volcanic neck) were collected. Their K-Ar ages are respectively 23.8 ; 23.6 ; 22.2 and 25.6 Ma (Karzulovic *et al.*, 1979). The latter authors reported an age of 36.3 Ma for a dyke that intrudes the basal rocks of Colbún-Machicura and a K-Ar age of 35.3 Ma for rhyolitic domes also associated with these basal rocks, was obtained by the authors. According to the time scale of Bergren *et al.* (1995), the last two ages of Colbún-Machicura are Eocene.

Sample 8 is a dacitic rock from a hill located 9 km south of Los Angeles (37.5°S). Sample 9 is an andesitic rock collected near Mulchén (37.8°S), and Sample 10 is also an andesitic rock collected near Lautaro (38.6°S). The K-Ar ages of samples 8 and 10 are respectively 20.6 and 22.0 Ma (Vergara and Munizaga, 1974). Ages ranging between 18.8 and 28.8 Ma, for rocks of the LDVB between 37° and 39°S (Los Angeles-Temuco sector), have been reported (Rubio, 1990, 1993; Cisternas and Frutos, 1994; Kelm *et al.*, 1994).

Samples 11 and 12 belong to the southernmost part (41.5-42.5°S) of the volcanic belt. Both were collected at Chiloé Island. Sample 11 is a basaltic rock collected at the beach north of Ancud (41.7°S). In this place, a Miocene sequence of volcanic and sedimentary rocks crops out. Volcanic rocks are represented by lavas, ignimbrites and volcanic necks, ranging in composition from basaltic andesite to dacite. Stern and Vergara (1992) reported a K-Ar age of 25.6±0.7 Ma for a dacite of this sequence. Sample 12 belongs to a dacitic volcanic neck or sill near Gamboa (42.5°S), north of Castro. Vergara and Munizaga (1974) reported an age of 40.4 Ma for a sample collected in the northwestern coast of Chiloé Island (Cocotué beach). However, García *et al.* (1988) dated a sample from the same locality in 21.8 Ma. and Muñoz *et al.* (1997) have reported ages in the 26-32 Ma range. This raises an uncertainty about the real age of the volcanic rocks from the Cocotué beach.

Quaternary basaltic rocks, used as a comparison, belong to minor eruptive centers (MEC) from the Villarrica-Lanín volcanic chain area (39-39.5°S; Rucapillán, Caburgua, Huelemolle, Redondo, Huililco, Pichares; Fig. 1; Hickey-Vargas *et al.*, 1989; Moreno and López-Escobar, 1994; López-Escobar *et al.*, 1995a); Fuy (40°S); Carrán-Los Venados Volcanic Group (40.3°S; the largest group of MEC in the SVZ of the Andes, comprising about 70 centers; Moreno, 1977; López-Escobar *et al.*, 1995a; Rodríguez *et al.*, 1997); Pichihuinco (41°S; Moreno *et al.*, 1979), Cayutué, La Viguería and Pocoihuén (41.3-41.5°S; López-Escobar *et al.*, 1995b) and Puyuguapi Volcanic Group (44.3°S; Lahsen *et al.*, 1994; López-Escobar *et al.*, 1995a; González-Ferrán *et al.*, 1996). According to their abundance in incompatible elements, the products of these centers have been grouped into two categories: type-I (relatively depleted in those elements) and type-II (comparatively enriched in incompatible elements). While the first group is located in the western part of the SVZ (*e.g.*, Rucapillán, Caburgua, Pichihuinco), type-II group is located in its eastern part (*e.g.*, Huililco, Pichares, Puyuguapi). These MEC are emplaced in relatively thin crust (about 30 km) and some of them are associated with the Liquiñe-Ofqui Fault Zone (Fig. 1). Quaternary andesites and dacites used for comparison are those from the Nevados de Chillán volcanic complex (36.8°S; Fig. 1), which are one of the isotopically most primitive andesites and dacites from the Southern Andes (Déruelle *et al.*, 1983; López-Escobar, 1984; Notsu *et al.*, 1987; Hildreth and Moorbath, 1988; López-Escobar *et al.* 1997).

PETROGRAPHY

On the basis of 205 petrographic analyses, volcanic rocks from the northern sector of the LDVB (33-37°S) are predominantly basalts and basaltic andesites (Vergara and López-Escobar, 1980; Padilla, 1981) and those from the southern sector (37-42.5°S) are mainly andesites and dacites (López-Escobar *et al.*, 1976; Vergara, 1982; Rubio, 1990, 1993; Troncoso *et al.*, 1994; Kelm *et al.*, 1994). Table 1 summarizes the mineralogy of the LDVB samples discussed in this paper.

In general, basalts and basaltic andesites from the northern sector are porphyritic, with olivine, augite, ±hypersthene and plagioclase (An_{65-90}) phenocrysts. The most Ca-rich plagioclase phenocrysts are those from Colbún-Machicura. The groundmass of the northern sector basaltic rocks is holocrystalline and contains microphenocrysts of plagioclase and microcrysts of pyroxene and magnetite. Secondary minerals (1-2%) consist mainly of chlorite, zeolite and smectite. The andesites contain phenocrysts of plagioclase (An_{40-50}), clinopyroxene, ±orthopyroxene and amphibole; their groundmass is similar to that of basalts and basaltic andesites. Vergara and López-Escobar (1980) have also reported the presence of dacitic porphyries between 33° and 33.5°S.

Andesites from the southern sector contain plagioclase (An_{30-45}), hypersthene, ±augite, ±amphibole phenocrysts. Their groundmass consists of plagioclase microlites, microcrysts of magnetite +pyroxenes, and glass. Secondary minerals (1-2% in volume) commonly consist of chlorite and smectite. Dacites also exhibit phenocrysts of plagioclase (An_{20-35}), ±orthopyroxene, ±amphibole. Their groundmass is vitrophyric and contains plagioclase microlites, microcrysts of magnetite, ±pyroxenes, ±amphibole. Hornblende phenocrysts are commonly altered to chlorite.

GEOCHEMISTRY

Table 2 includes new major and trace element and isotopic analyses of samples from the Eocene-Miocene LDVB. The major and trace element compositions of these samples are shown, as a function of their SiO_2 content, in figure 2. As a comparison, this figure also includes the elemental composition of **a-** Miocene volcanic rocks studied by López-Escobar *et al.* (1976) and **b-** Quaternary MEC basaltic rocks from the Villarrica-Lanín area and Carrán-Los Venados Volcanic Group. The comparison was made on water-free basis. According to table 2 and figure 2: **1-** analyzed rocks from the LDVB range in composition from basalts (47% SiO_2) to dacites (67% SiO_2); **2-** basaltic rocks from the northernmost and southernmost sectors of this belt are similar in major and trace elements to type-I Quaternary MEC basaltic rocks from the central province (37-41.5°S) of the SVZ; **3-** Independent of their age, basalts and basaltic andesites are quite heterogeneous in most elements, and most of them have low MgO (<6%), Cr, Co and Ni contents; **4-** TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Sc, V, Co and Sr tend to decrease as SiO_2 increases. However, K_2O, Ba and La tend to increase with SiO_2. These trends are common in Southern Andes calcalkaline rocks; **5-** samples from Colbún-Machicura, with SiO_2<50%, are low in TiO_2, MgO, Na_2O, K_2O, Sc, Cr, Ba and La, but high in CaO; **6-** Samples from the LDVB between 37° and 39°S range in composition from andesites to dacites; no basalts have been yet reported for this area.

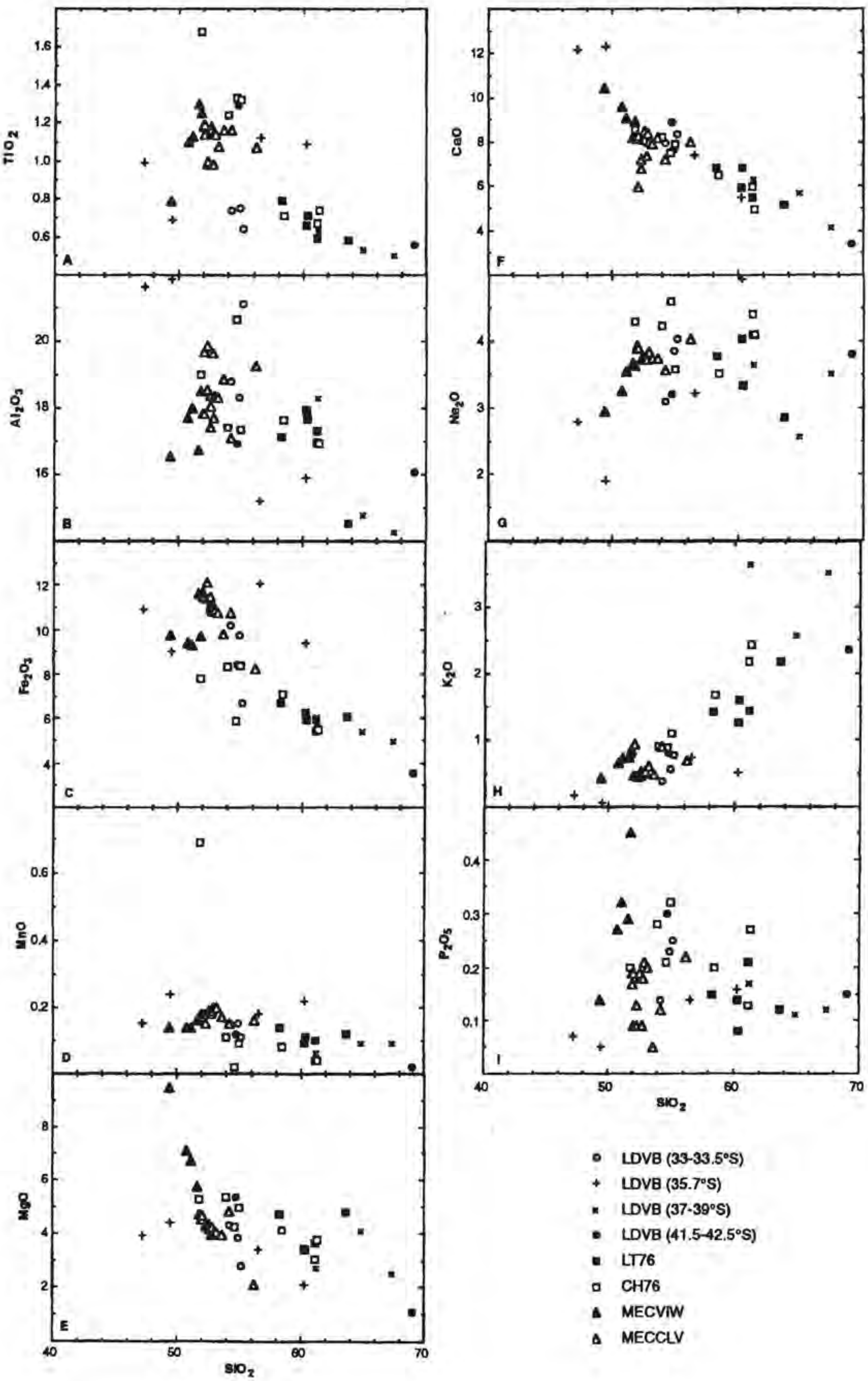
TABLE 1. MINERALOGY OF THE ANALYZED SAMPLES FROM THE EOCENE-MIOCENE LONGITUDINAL DEPRESSION VOLCANIC BELT.

	Phenocrysts	Groundmass	Secondary Minerals	Lithology
Sample 1 090491-3A **Pocuro** 32.9°S	Plagioclase (An 70-75) Clinopyroxene Olivine	Plagioclase Clinopyroxene Ortopyroxene Magnetite	Chlorite Zeolite	Basaltic andesite
Sample 2 090491-02 **Colina** 33.1°S	Plagioclase (An 65-70) Clinopyroxene Olivine	Plagioclase Clinopyroxene Ortopyroxene Magnetite	Chlorite Zeolite	Basaltic andesite
Sample 3 090491-01 **Pan de Azúcar** 33.3°S	Plagioclase (An 65-70) Clinopyroxene Orthopyroxene	Plagioclase Clinopyroxene Ortopyroxene Magnetite	Zeolite	Basaltic andesite
Sample 4 CM-17 **Colbún-Machicura** 35.7°S	Plagioclase (An 85-90) Clinopyroxene Orthopyroxene	Plagioclase Clinopyroxene Magnetite Glass	Zeolite Smectite	Basall
Sample 5 CM-21B **Colbún-Machicura** 35.7°S	Plagioclase (An 85-90) Clinopyroxene Magnetite	Plagioclase Clinopyroxene Magnetite Glass	Zeolite Smectite	Basall
Sample 6 CM-12 **Colbún-Machicura** 35.7°S	Plagioclase (An 65-70) Clinopyroxene Orthopyroxene	Plagioclase Clinopyroxene Ortopyroxene Magnetite	Chlorite Zeolite	Basaltic andesite
Sample 7 CM-10 **Colbún-Machicura** 35.7°S	Plagioclase (An 40-50) Orthopyroxene Amphibole	Plagioclase Ortopyroxene Magnetite Glass	Zeolite Smectite	Andesite
Sample 8 300191-03 **Los Angeles** 37.5°S	Plagioclase (An 20-35) Orthopyroxene Amphibole	Plagioclase Ortopyroxene Magnetite Glass	Chlorite Smectite	Dacite
Sample 9 300191-02 **Mulchén** 37.8°S	Plagioclase (An 30-35) Orthopyroxene Amphibole	Plagioclase Ortopyroxene Magnetite Glass	Chlorite Smectite	Andesite
Sample 10 300191-01 **Lautaro** 38.7°S	Plagioclase (An 35-45) Clinopyroxene Orthopyroxene	Plagioclase Ortopyroxene Magnetite Glass	Chlorite Smectite	Andesite
Sample 11 140489-03 **Ancud** 41.9°S	Plagioclase (An 60-65) Clinopyroxene	Plagioclase Clinopyroxene Magnetite Glass	Chlorite Smectite	Basaltic andesite
Sample 12 130489-01 **Gamboa** 42.5°S	Plagioclase (An 20-25) Amphibole	Plagioclase Amphibole Magnetite Glass	Chlorite Smectite	Dacite

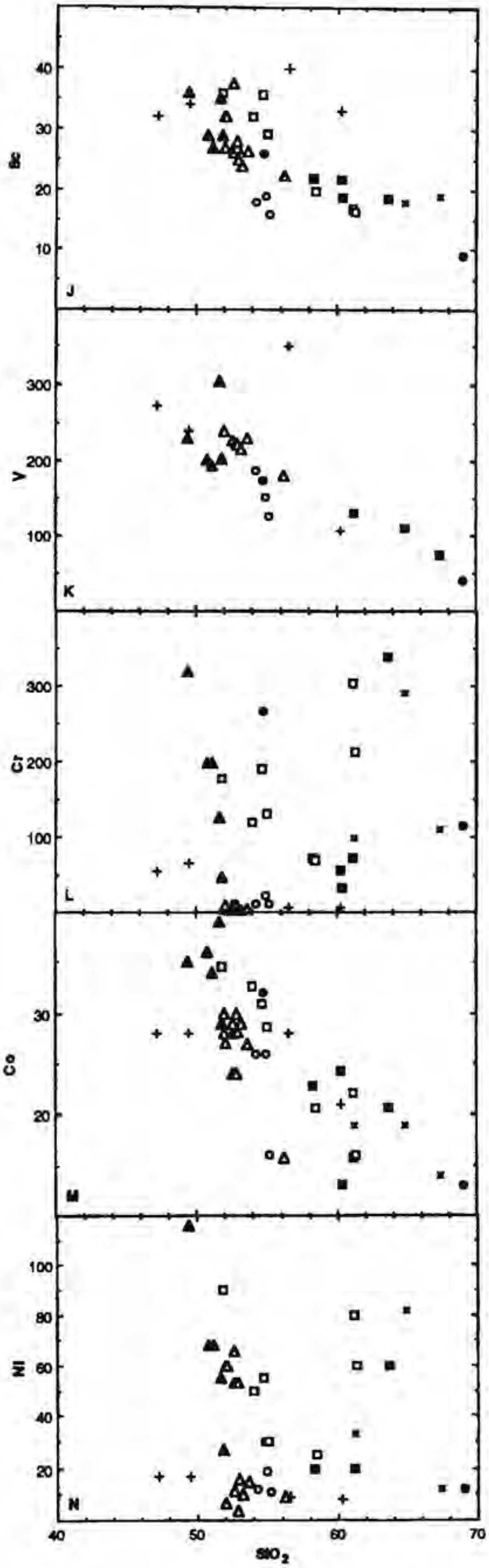
TABLE 2. MAJOR AND TRACE ELEMENT ABUNDANCES AND ISOTOPIC COMPOSITION OF ROCKS FROM THE EOCENE-MIOCENE LONGITUDINAL DEPRESSION VOLCANIC BELT.

	Sample 1 090491-3A POCURO 32.9°S	Sample 2 090491-02 COLINA 33.1°S	Sample 3 090491-01 PAN AZUCAR 33.3°S	Sample 4 CM-17 COLBUN-MAC 35.7°S	Sample 5 CM-21B COLBUN-MAC 35.7°S	Sample 6 CM-12 COLBUN-MAC 35.7°S	Sample 7 CM-10 COLBUN-MAC 35.7°S	Sample 8 300191-03 L.ANGELES 37.5°S	Sample 9 300191-02 MULCHEN 37.8°S	Sample 10 300191-01 LAUTARO 38.7°S	Sample 11 140489-03 ANCUD 41.9°S	Sample 12 130489-01 GAMBOA 42.5°S
SiO_2	53.54	52.92	52.80	45.83	47.07	54.90	58.55	65.39	62.67	58.94	53.36	66.98
TiO_2	0.62	0.72	0.72	0.96	0.66	1.09	1.06	0.49	0.51	0.61	1.26	0.54
Al_2O_3	20.51	18.35	17.60	20.99	20.83	14.75	15.45	13.83	14.28	17.59	16.50	15.58
Fe_2O_3*	6.51	9.92	9.36	10.59	8.60	11.69	9.11	4.79	5.20	5.41	8.23	3.43
MnO	0.11	0.15	0.14	0.15	0.23	0.17	0.21	0.09	0.09	0.06	0.12	0.02
MgO	2.70	4.20	3.67	3.80	4.20	3.27	2.02	2.43	3.92	2.62	5.24	1.07
CaO	8.10	7.74	7.37	11.78	11.74	7.18	5.31	4.00	5.50	6.06	8.63	3.28
Na_2O	3.92	3.02	3.71	2.71	1.82	3.13	4.79	3.41	2.48	3.50	3.13	3.70
K_2O	0.75	0.37	0.54	0.17	0.07	0.72	0.51	2.48	1.87	1.27	0.78	2.28
P_2O_5	0.24	0.14	0.22	0.07	0.05	0.14	0.16	0.12	0.11	0.16	0.29	0.15
LOI	3.34	2.84	4.32	3.47	5.41	3.13	2.87	2.86	3.87	3.30	2.67	2.27
	100.34	100.37	100.45	100.52	100.68	100.17	100.04	99.89	100.50	99.52	100.21	99.30
Rb	10.9	7.7	6.7					65.8	44.4		23.6	83.9
Sr	588	517	441	332	237	266	254	260	242	453	306	178
Ba	278	156	211	50	35	160	144	460	379	286	204	363
Sc	16	18	19	32	34	40	33	19	18	17	26	9
V	126	187	152	273	240	350	106	75	110	131	174	41
Cr	11	11	22	55	66	6	7	110	291	99	266	115
Co	16	26	26	28	28	28	21	14	19	19	32	13
Ni	11	12	19	17	17	9	8	12	82	33	30	12
Cu	59	91	61	75	75	78	16	39	42	31	25	12
Zn	66	64	86	82	62	98	105	62	51	58	81	48
Y	17	11	14	18	17	22	33	31	26	16	26	20
Zr	77	50	54	38	29	76	118	180	185	115	142	194
Nb	1.0	1.0	1.0	1.0	1.0	1.0	1.0	5.0	1.0	3.9	5.0	5.6
Hf	1.7	1.8	1.8	1.6	1.1	1.9	2.5	5.8	3.1	3.0	3.7	2.9
La	11	4	6	3	3	5	6	16	11	12	13	16
Ce	26	10	15	8	6	13	15	36	27	28	32	36
Nd	16	7	10	6	4	9	11	21	16	15	20	17
Sm	3.45	1.96	2.70	1.90	1.30	2.33	3.16	4.35	3.68	2.90	4.38	3.23
Eu	1.20	0.65	0.95	0.73	0.63	1.05	1.33	1.12	0.90	0.93	1.45	0.97
Gd	3.68	2.00	2.90	2.49	1.75	2.80	4.14	4.18	3.77	2.52	4.35	3.21
Dy	3.45	2.30	2.76	3.20	2.18	3.48	5.20	5.08	4.08	2.68	4.27	3.29
Ho	0.69	0.50	0.56	0.67	0.48	0.78	1.12	1.10	0.88	0.60	0.82	0.62
Er	1.73	1.44	1.63	1.93	1.40	2.45	3.31	3.21	2.54	1.52	2.35	1.64
Yb	1.70	1.45	1.65	1.93	1.33	2.40	3.27	3.10	2.50	1.57	2.42	1.55
Lu	0.25	0.23	0.26	0.28	0.22	0.37	0.48	0.50	0.38	0.24	0.36	0.23
$^{87/86}Sr$	0.703714	0.703744	0.703710					0.703924	0.703875	0.704374	0.704848	0.705019
$^{143/144}Nd$	0.512841	0.512937	0.512913					0.512862	0.512887	0.512731	0.512779	0.512779
$^{206/204}Pb$	18.444	18.460	18.448					18.445	18.435	18.547	18.605	18.632
$^{207/204}Pb$	15.589	15.581	15.593					15.597	15.598	15.575	15.608	15.588
$^{208/204}Pb$	38.318	38.337	38.363					38.400	38.377	38.418	38.543	38.494
Mg No.	0.45	0.46	0.44	0.42	0.49	0.36	0.31	0.50	0.60	0.49	0.56	0.38
K-Ar Ma	20.6	21.2		23.8	23.6	22.2	25.6	20.4		22.0	25.6	

Major and trace elements, but Rb and Sr, were obtained by ICP at the Chemical Laboratory of the Department of Geology of the Universidad de Chile by Mr. Jaime Martínez. Rb and Sr and isotopic data were obtained at the NERC Isotope Geology Lab of the British Geological Survey by Dr. P. Kempton. Rb and Sr were obtained by Isotope Dilution plus XRF. Isotopic data were determined by Mass-spectroscopy. Accuracy and precision of data as in López-Escobar (1995b).



TiO2
Al2O3
Fe2O3
MnO
MgO
CaO
Na2O
K2O
P2O5
SiO2
A
B
C
D
E
F
G
H
I
LDVB (33-33.5°S)
LDVB (35.7°S)
LDVB (37-39°S)
LDVB (41.5-42.5°S)
LT76
CH76
MECVIW
MECCLV



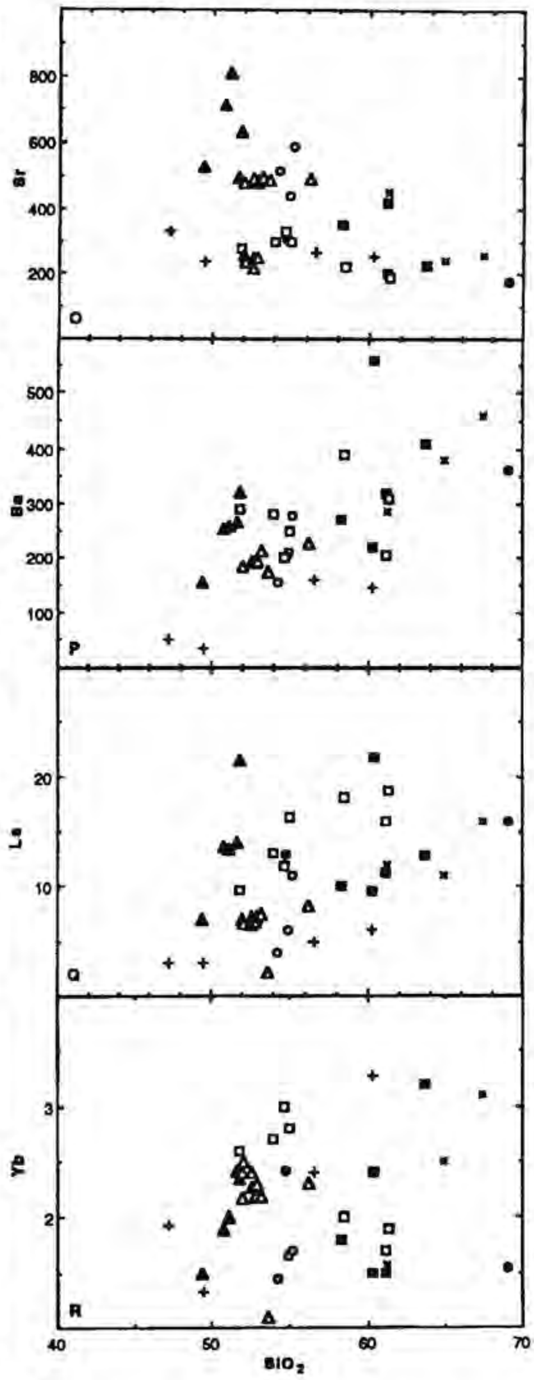


FIG. 2. Harker diagrams for major and trace elements of the LDVB. This figure also includes data, previously reported by López-Escobar *et al.* (1976), for the Los Angeles-Temuco (LT76) and Chiloé Island (CH76) sectors of this volcanic belt and data from Quaternary MEC of the western part of the Villarrica-Lanín volcanic chain (Rucapillán, Caburgua, Huelemolle; Hickey-Vargas *et al.*, 1989; Moreno and López-Escobar, 1994; López-Escobar *et al.*, 1995a) and Carrán-Los Venados Volcanic Group (Moreno, 1977; López-Escobar *et al.*, 1995a; Rodríguez *et al.*, 1997).

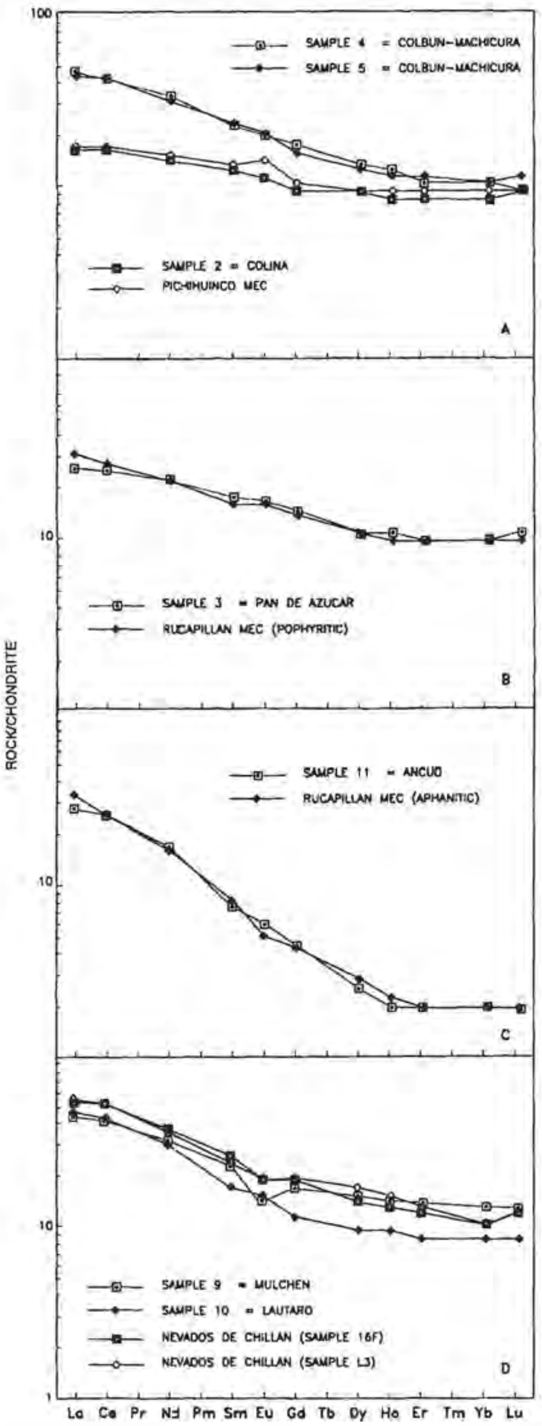


FIG. 3. Chondrite normalized REE patterns of the LDVB rocks discussed in this paper. Chondrite composition used for normalization is that of Sun and McDonough (1989).

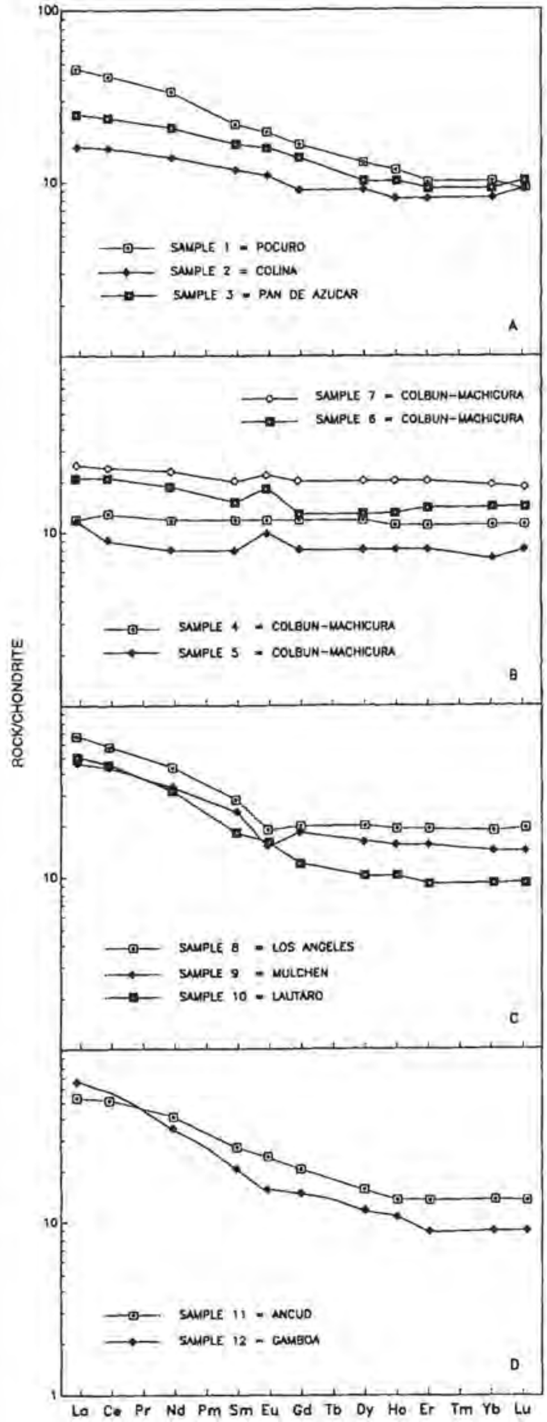


FIG. 4. Chondrite normalized REE patterns of LDVB rocks from the 33-33.5°S, 37-39°S and 41.5-42.5°S sectors in comparison with patterns of SVZ Quaternary volcanic rocks

Figure 3 shows the chondrite normalized REE patterns of the analyzed rocks: **1**- basaltic andesites from the northernmost sector of the Eocene-Miocene LDVB have La contents ranging from 16 to 46 times chondrites and Yb equal to 8-10 times chondrites. Their $(La/Yb)_N$ ratios range from 2.0 to 4.6. The most silicic of these basaltic andesites (Pocuro sample) exhibit the highest $(La/Yb)_N$ ratio. None of these rocks shows a clear negative Eu anomaly. **2**- basalts to andesites from Colbún-Machicura present a very flat REE pattern (La_N/Yb_N=1.0-1.7), with La ranging between 12 and 25 times chondrites and Yb between 7 and 19 times chondrites. Some of these samples exhibit positive Eu anomaly and their REE abundances increase with their SiO_2 contents. **3**- andesites and dacites from the 37-39°S sector have La abundances ranging between 46 and 67 times chondrites and their Yb contents vary from 9 to 18 times chondrites. Dacites from this sector exhibit negative Eu anomalies. **4**- compared to the Pocuro basaltic andesite (northernmost sector), the Ancud basaltic andesite (southernmost sector) has similar LREE, but lower $(La/Yb)_N$ (3.9 *versus* 4.6).

Except for the flat REE patterns of the Colbún-Machicura rocks, the REE patterns of volcanic rocks from the LDVB are similar to those of Quaternary volcanic rocks from the SVZ between 36.8-41.5°S. In fact, the REE patterns of the Pocuro, Colina and Pan de Azúcar basaltic andesites mimic those of Cayutué, Pichihuinco and porphyritic Rucapillán basalts respectively (Figs. 4A and 4B), which are among the most primitive MEC basalts from the SVZ of the Andes (López-Escobar *et al.*, 1995a). The REE pattern of the Ancud basaltic andesite matches that of the aphanitic Rucapillán basalts (Fig. 4C). The REE patterns of the andesites and dacites from the 37-39°S sector of the LDVB are similar to those of Quaternary andesites and dacites from the Nevados de Chillán (López-Escobar and Frey, 1976; López-Escobar *et al.*, 1997; Fig. 4D). The flat REE patterns of the Colbún-Machicura basalts are rather similar to patterns exhibited by some ocean floor basalts from Nazca plate.

Basaltic rocks have low Ba/La ratios (<40) and their La/Yb ratios vary from about 2 to 10 (Fig. 5). Basaltic andesites from both the northernmost and

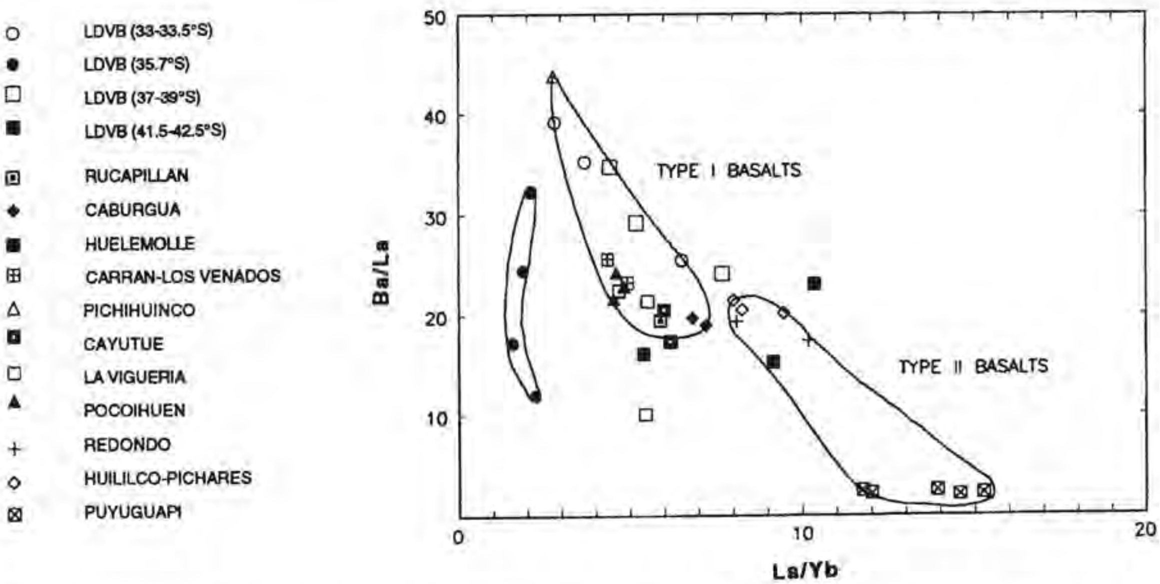


FIG. 5. Ba/La *versus* La/Yb diagram for LDVB rocks compared with Quaternary MEC rocks from the central province of the SVZ and Puyuguapi. Source of data: this paper, Hickey-Vargas *et al.* (1989); Moreno and López-Escobar (1994); López-Escobar *et al.* (1995a, b); Rodríguez *et al.* (1997); Moreno *et al.* (1979); Lahsen *et al.* (1994) and González-Ferrán *et al.* (1996). Note: Type-I and II basalts are respectively depleted and enriched in LILE. The former are located in the western part of the Quaternary volcanic belt (*e.g.*, Rucapillán, Caburgua, Pichihuinco), type-II are located in the eastern part (*e.g.*, Huililco, Pichares, Puyuguapi).

southernmost parts of the belt fall in the Ba/La-La/Yb field of type-1 Quaternary MEC basalts. The Colbún-Machicura basalts and basaltic andesites have similar Ba/La ratios to the previous ones, but exhibit significantly low La/Yb ratios.

Figure 6 shows the relationship between the Sr and Nd isotope ratios for the samples under discussion. In this figure, the mantle array is defined on the basis of isotopic data from the East Pacific Ridge (N-MORB; White and Hofmann, 1982; Zindler *et al.*, 1984; Macdougall and Lugmair, 1985, 1986; Ito *et al.*, 1987; Bach *et al.*, 1994), Chile Ridge (N-MORB and E-MORB; Klein and Karsten, 1995), Easter Island (Nazca plate OIB; White and Hofmann, 1982; Macdougall and Lugmair, 1985, 1986) and Juan Fernández archipelago (also Nazca plate OIB; Gerlach *et al.*, 1986; Baker *et al.*, 1987; Farley *et al.*, 1993). Excepting those samples from Chiloé Island (one basaltic andesite from Ancud and one dacite from Gamboa), the Eocene-Miocene LDVB as well as the type-I Quaternary MEC volcanic rocks fall within the mantle array. All of them have higher Sr- and lower Nd-isotope ratios than N-MORB, but their isotopic composition is similar to that of Juan Fernández archipelago rocks (OIB) and E-MORB from the Chile Ridge. Compared with all these rocks, the Ancud basaltic andesite and Gamboa dacite are significantly enriched in radiogenic Sr. Unfortunately, no isotopic data are yet available for the Colbún-Machicura basalts and basaltic andesites.

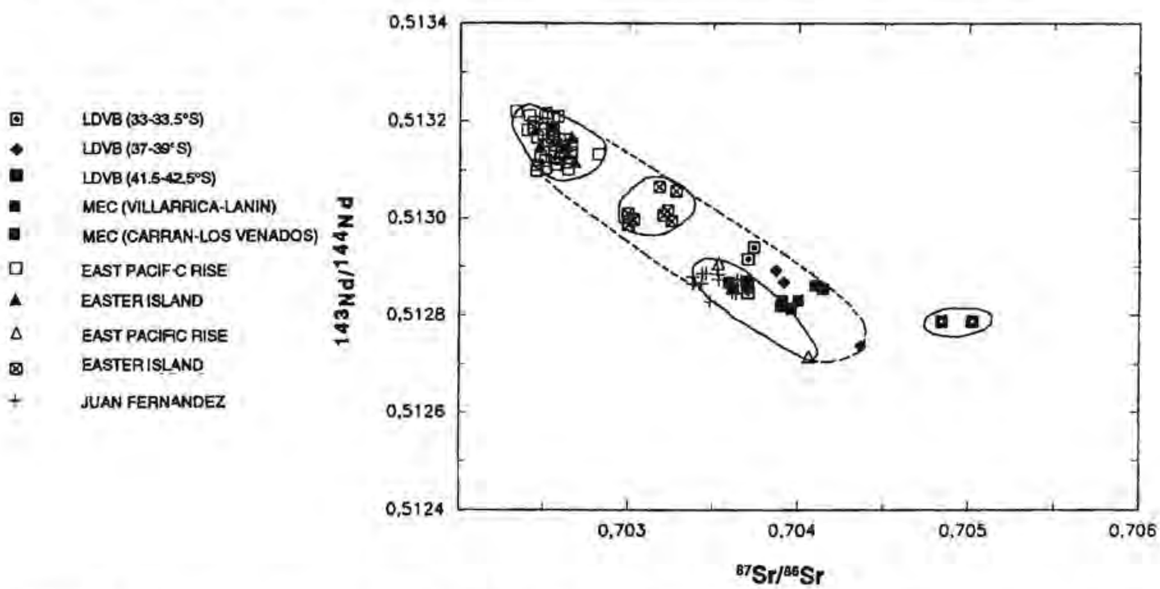
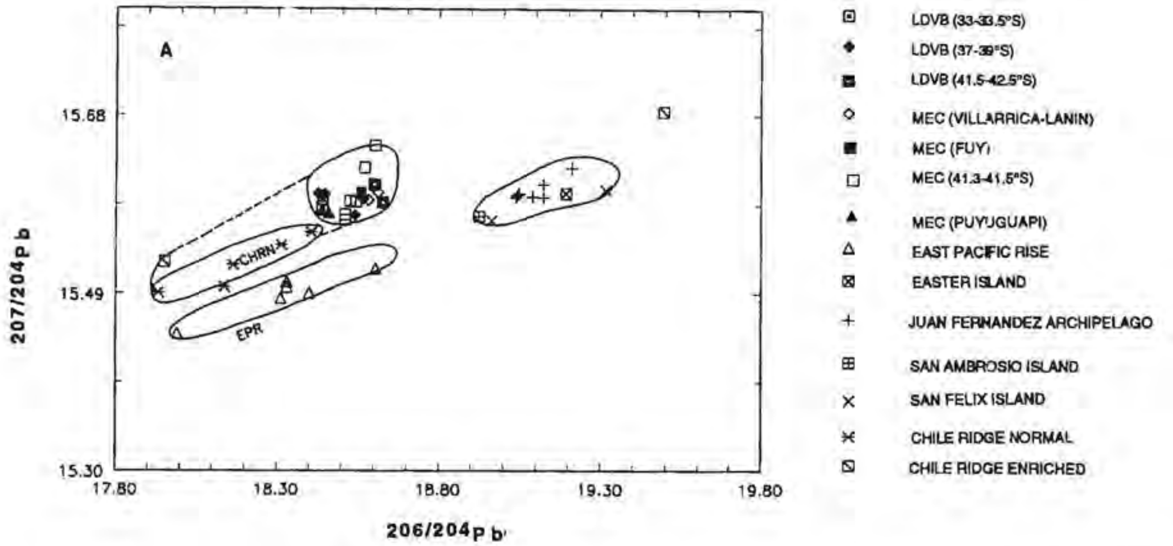
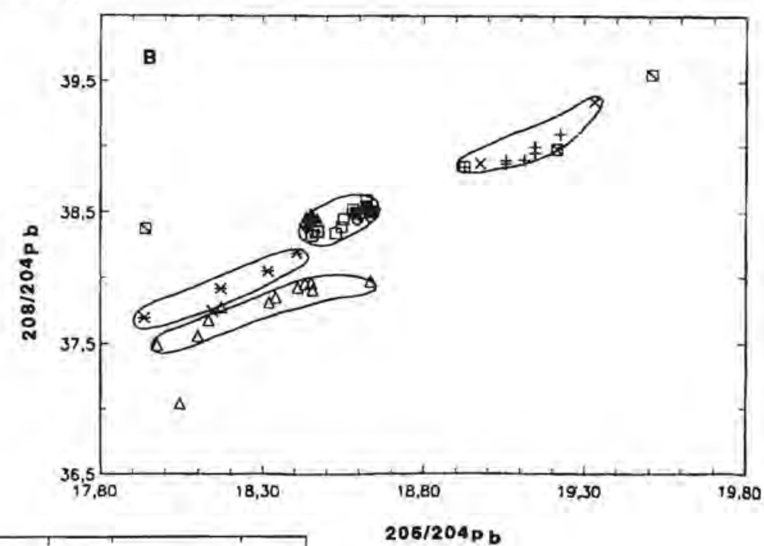


FIG. 6. $^{143}Nd/^{144}Nd$ *versus* $^{87}Sr/^{86}Sr$ diagram for LDVB and Quaternary MEC rocks compared with those of the East Pacific Ridge (MORB), Chile Ridge (MORB), Easter Island (Nazca plate OIB) and Juan Fernández archipelago (Nazca plate OIB).

Figure 7 shows the Pb isotopic composition of samples from the Eocene-Miocene LDVB in comparison with that of rocks from the SVZ Quaternary MEC, East Pacific Ridge, Chile Ridge and Nazca plate oceanic islands. This figure and table 2 indicate that rocks from the 33-33.5°S sector have the lowest $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios; the highest ones are found in the samples from the 41.5-42.5°S sector. However, all of them fall in the field of the Quaternary MEC rocks. In comparison with oceanic rocks, LDVB as well as Quaternary MEC volcanic rocks are enriched in ^{207}Pb and have higher $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios than normal basalts from the East Pacific and Chile ridges, but lower than basalts from the Nazca plate oceanic islands. Actually, the latter are notably enriched in ^{206}Pb and ^{208}Pb.





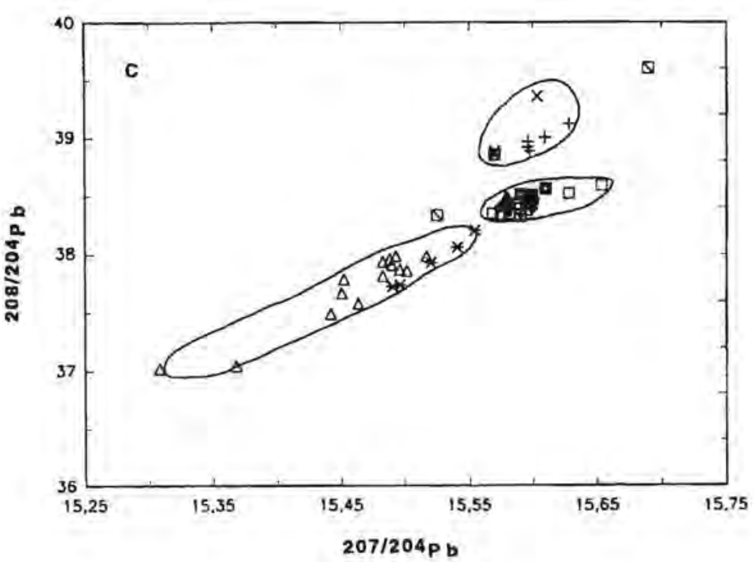


FIG. 7. $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$; $^{208}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ *versus* $^{207}Pb/^{204}Pb$ diagrams for LDVB and Quaternary MEC rocks compared with those of the East Pacific Ridge, Chile Ridge Normal and Chile Ridge Enriched (MORB), and Easter Island, Juan Fernández archipelago, San Ambrosio and San Felix (Nazca plate OIB).

DISCUSSION AND CONCLUSIONS

Petrographic and major element data suggest that the Eocene-Miocene LDVB shows a discontinuity at 37°S. Volcanic rocks from the northern sector (33-37°S) exhibit a more primitive character than those from the southern sector (37-42.5°S). This segmentation is opposite to that exhibited by the SVZ of the Andes, where the most evolved volcanic rocks predominate north of 37°S and the most primitive ones do it south of this latitude. The subduction geometry and thickness of the continental crust probably changed between the Eocene-Miocene and the Quaternary. However, since the major compositional discontinuity takes place at the same latitude (37°S) in both belts, its existence would reflect the presence of a major structure (at present the extension of the Mocha fracture zone under the continent) that already existed during the Eocene-Miocene and has remained until the Recent.

In addition to their petrographic and major element differences, the northern and southern sectors of the LDVB would have had different paleogeographic evolutions. According to Cisternas and Frutos (1994) and Kelm *et al.* (1994), the formation of a hemigraben-type trough would have started, during the Upper Oligocene, between 37.5°S and 40.5°S. Continental material was deposited in this trough and a volcanic arc developed associated with an oblique subduction zone. This episode concluded, during the Middle-Upper Miocene, with west to east transgressive marine facies that penetrated deeply into the cordilleran environment. Middle to Upper Miocene marine deposits are not known in the northern sector of this volcanic belt.

Basaltic rocks from the northernmost and southernmost parts of the LDVB are similar in major and trace elements to type-I (incompatible elements depleted) Quaternary MEC basaltic rocks from the central province (37-41.5°) of the SVZ (CSVZ). This chemical similarity suggests that the tectonic environment and magma production related processes in those parts of the belt were similar to those currently found in the western part of the CSVZ.

Some geochemical features of the Colbún-Machicura basaltic rocks are unique among volcanic rocks from the Southern Andes. For example, none of either the Eocene-Miocene LDVB or Quaternary volcanic rocks from the SVZ mimic the flat REE patterns exhibited by basalts and basaltic andesites from Colbún-Machicura. These patterns are rather similar to those exhibited by some ocean floor basalts from the Nazca plate.

In addition to their similarities in REE contents, the dacites from the 37-39°S area of the Eocene-Miocene LDVB and the Quaternary dacites from the Nevados de Chillán exhibit negative Eu anomalies, suggesting an evolution under low pressure conditions, where plagioclase is a stable phase. Furthermore, andesites and dacites from both the 37-39°S area of the LDVB and Nevados de Chillán also have similar isotopic composition. As it was previously mentioned, the Nevados de Chillán andesites and dacites show one of the lowest Sr-isotopic ratios (about 0.70387) among Quaternary volcanic rocks from the SVZ (Déruelle *et al.*, 1983; López-Escobar *et al.*, 1997).

Ellam (1992), Hawkesworth *et al.* (1994), Kay *et al.* (1994) and Mpodozis *et al.* (1995) suggested that the La/Yb ratio is a good indicator of the degree of maturity and thickness of the continental lithosphere. For example, Kay *et al.* (1994) interpreted the trends of increasing La/Yb and Sr-isotope ratios with decreasing time, in Oligocene-Miocene volcanic rocks from the 27-33°S flat slab region of the Andes, as an evidence of an increase of the crustal thickness in passing from the Oligocene to the Miocene. The La/Yb - $^{87}Sr/^{86}Sr$ relationship observed in rocks from the LDVB is opposite to that reported for the volcanic rocks from the flat slab region. Thus, although the Pocuro (32.9°S) and Ancud (41.7°S) basaltic andesites have similar La abundances (Figs. 4A and 4C), the former has higher La/Yb ratio, but lower Sr-isotope ratio than the second one. This suggests that the geochemical characteristics of basaltic rocks from, at least, the northernmost part of the LDVB would have depended more on subduction-related processes than on crustal processes. This hypothesis is supported by the isotopic similarity existing between rocks from the northernmost part of this belt and rocks emplaced in oceanic environments. On the other hand, the fact that the three analyzed basaltic andesites from this part of the LDVB have similar and relatively low Yb contents, but different La abundances, is consistent with a generation of their primary magmas by different degrees of partial melting of a similar mantle source, where garnet was a refractory phase (López-Escobar *et al.*, 1977).

The similarity between the REE pattern of the Ancud basaltic andesite and that of the aphanitic basalt from the Rucapillán Quaternary MEC, which is one of the most primitive basalts from the central province of the SVZ, also suggests that the primary magma of the Ancud basaltic andesite has a mantle origin. The relatively high Yb content of this basaltic andesite is consistent with a generation of its primary magma at a depth where garnet was not a stable phase. On the other hand, the relatively high $^{87}Sr/^{86}Sr$ ratio of the Ancud basaltic andesite could reflect the isotopic characteristics of its mantle source, which may have become enriched in radiogenic Sr by a process of source region contamination, as proposed by Stern and Skewes (1995) to explain the differences between the Miocene and Quaternary rocks between latitudes 33° and 34°S. If this magma suffered intracrustal contamination, then this process would have affected its isotopic composition, but not its La/Yb ratio.

Between 33° and 34°S, volcanic rocks from the Eocene-Miocene LDVB have significant lower Sr- and higher Nd-isotope ratios than volcanic rocks from the SVZ (López-Escobar, 1984; Stern *et al.* 1984; López-Escobar *et al.* 1985; Notsu *et al.*, 1987; Stern, 1988; Hildreth and Moorbath, 1988; Futa and Stern, 1988; López-Escobar *et al.* 1991; Nyström *et al.*, 1993; Stern and Skewes, 1995). According to Introcaso *et al.* (1992) and Sempere *et al.* (1994), a major tectonic-sedimentary episode, related to an increase in the velocity of convergence between the oceanic Nazca plate and the South-American continental plate (Pilger, 1984; Pardo-Casas and Molnar, 1987), affected, 27-20 Ma ago, the present day high Andes between 30 and 37°S, causing an increase in the thickness of the continental crust. Although the isotopic changes between the Eocene-Miocene and the Quaternary seem to coincide with the eastward migration of the volcanic arc to its current location, where the continental crust has a thickness of 55-60 km, Stern and Skewes (1995) pointed out that the isotopic compositions changed during the Pliocene, prior to the eastward migration of the arc. Since the Eocene-Miocene LDVB and the Pliocene belt are emplaced in a relatively thin crust, they concluded that the isotopic changes are independent of crustal thickness, as postulated by Hildreth and Moorbath (1988). Stern (1988, 1991) and Stern and Skewes (1995) proposed that these changes 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.

It is worthwhile highlighting the large range of ages exhibited by rocks from the wide Southern Andes Eocene-Miocene LDVB (15-40 Ma). More detailed studies are needed in this belt, in order to determine the geological meaning of those ages and how many magmatic episodes they actually represent. At present, it is important to point out that the oldest age (40.4 Ma; Vergara and Munizaga, 1974) has been obtained in a sample collected in the coast of Chiloé Island at latitude 41.8°S. Probably, this sample is representative of an Eocene belt whose remnants would be found along the Chilean coast between 41 and 42°S. Oligocene to Lower Miocene volcanic rocks predominate in the LDVB and in the western part of the High Andes cordillera. Finally, along the main Andean range, the volcanic rocks cover mainly the whole Miocene epoch. Considering that most volcanic episodes commonly last less than 5 Ma, a span of time of about 25 Ma, in a wide volcanic arc, suggests the existence of several volcanic episodes, representing different magmatic events. Actually, there seems to exist a gradual migration, from west to east, of these potential volcanic belts since the Late Eocene. This apparent trend is opposite to that observed east of the High Andes in Argentine territory (Llambías and Malvicini, 1978; Llambías and Rapela, 1987, 1989). There also seems to exist some periods of overlapping of the volcanic activity from one belt to the other within the arc.

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