A contribution to the petrogenesis of Osorno and Calbuco volcanoes, Southern Andes (41°00'-41°30'S): comparative study

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ABSTRACT

Osorno and Calbuco volcanoes, located respectively at 41°05'S and 41°20'S in the southern region of the Southern Volcanic Zone of the Andes (SSVZ; 37°-46°S), are Late Pleistocene-Holocene composite stratovolcanoes of contrasting chemical composition. While Osorno, like most volcanic centers of the SSVZ, is mainly basaltic, Calbuco is andesitic. Unlike Osorno, Calbuco is not located along any major regional lineament and its basement exhibits deeper levels of erosion. In contrast to Osorno lavas, Calbuco lavas have higher Sr- and lower Nd-isotope ratios, comparatively higher Al_2O_3 and lower K_2O contents, and heterogeneous incompatible element ratios. However, the Osorno basalts and Calbuco andesites have similar rare earth element patterns. Integrated field, petrographic and geochemical observations suggest that the particular composition of the Calbuco lavas is the result of a significant crustal contamination of subcrustal basaltic magmas. The contaminant of these magmas could be a liquid generated by melting of crustal amphibolite and/or pelitic schist. At lower pressures, the Calbuco hybrid magmas evolved mainly by fractionation of olivine and clinopyroxene. Although plagioclase is the most abundant phenocryst phase in the lavas of both centers, Calbuco lavas do not show any clear geochemical evidence of plagioclase fractionation.

Key words: Geochemistry, Petrogenesis, Quaternary volcanism, Southern Andes, Central-south Chile.

RESUMEN

Contribución a la petrogénesis de los volcanes Osorno y Calbuco, Andes del Sur (41°00'-41°30'S): estudio comparativo. Los volcanes Osorno y Calbuco, ubicados respectivamente en las latitudes 41°05'S y 41°20'S de la región sur de la Zona Volcánica Sur de los Andes (ZVSS; 37°-46°S), son estratovolcanes mixtos, de edad pleistocena tardía a reciente y de composición diferente. El volcán Osorno, al igual que la mayoría de los volcanes de la ZVSS, es predominantemente basáltico, en cambio el Calbuco es andesítico. A diferencia del Osorno, el volcán Calbuco aparentemente no está ubicado en un lineamiento regional y su basamento exhibe niveles más profundos de erosión. Al contrario de las lavas del Osorno, las del Calbuco tienen razones isotópicas de Sr más elevadas, de Nd más bajas, contenidos de $Al2O_3$ más elevados y de K_2O más bajos y presentan razones entre elementos incompatibles heterogéneas. Sin embargo, los basaltos del Osorno son semejante a las andesitas del Calbuco en la abundancia de tierras raras. Observaciones de terreno, petrográficas y geoquímicas sugieren que la composición andesítica del volcán Calbuco es el resultado de una contaminación de magmas basálticos subcorticales con magmas generados a nivel cortical. El contaminante cortical de los magmas del Calbuco sería un líquido generado por fusión de anfibolita o de esquisto pelítico. A presiones más bajas, los magmas híbridos del Calbuco evolucionaron por fraccionamiento de olivino y clinopiroxeno. A pesar de que la plagioclasa es el fenocristal más abundante en ambos centros volcánicos, las lavas del Calbuco no presentan evidencias geoquímicas claras de fraccionamiento de plagioclasa.

Palabras claves: Geoquímica, Petrogénesis, Volcanismo cuaternario, Andes del Sur, Chile central-sur.

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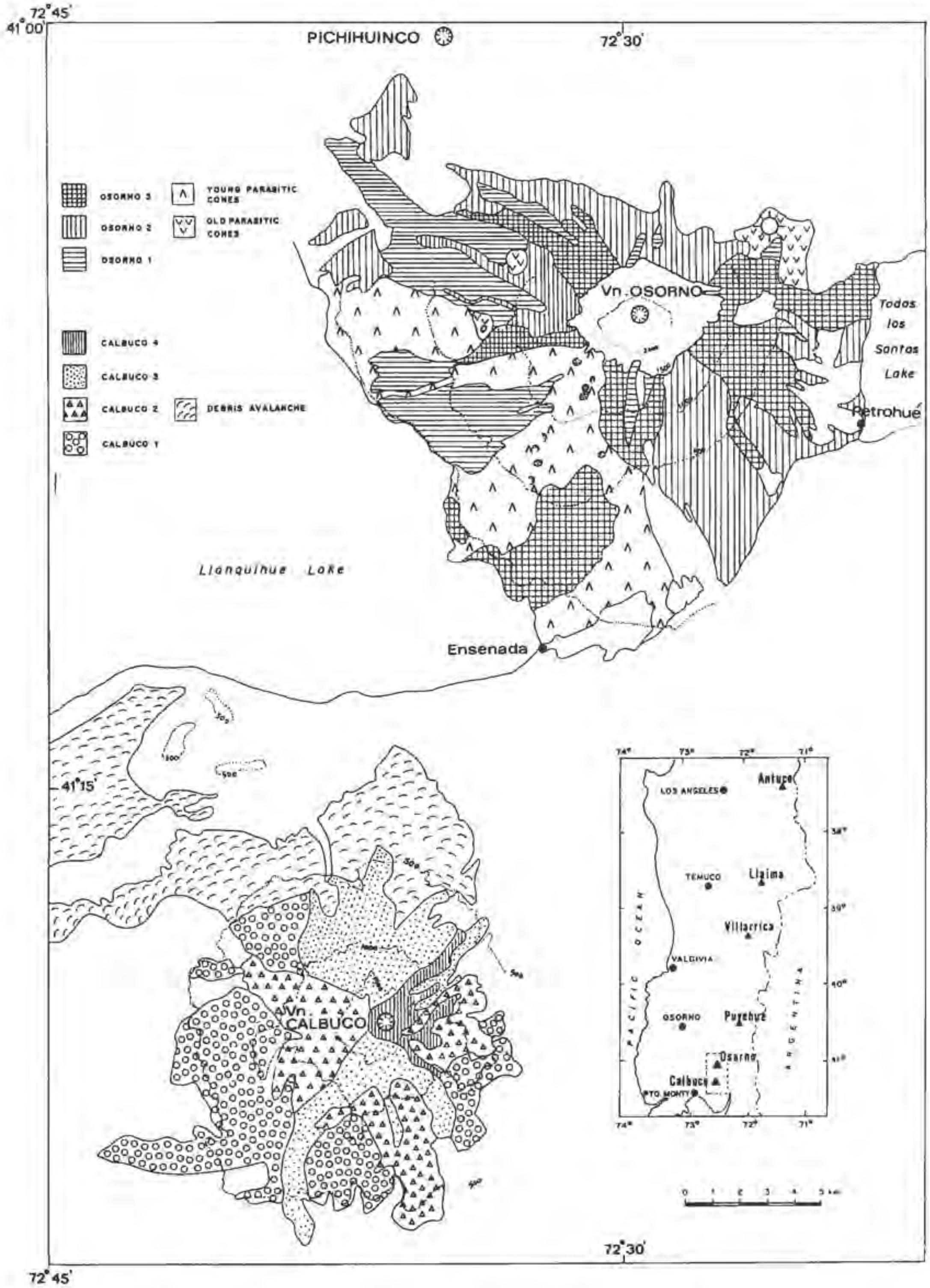


FIG. 1. Simplified geological sketch map of Osorno and Calbuco volcanoes, after Moreno *et al.* (1979); H. Moreno, J. Varela, L. López-Escobar, F. Munizaga and A. Lahsen[1]; A. Lahsen, H. Moreno, J. Varela, F. Munizaga and L. López-Escobar[2].

[1] 1985. Geología y riesgo volcánico del volcán Osorno y centros eruptivos menores. Proyecto Canutillar, ENDESA-Departamento de Geología, Universidad de Chile, Informe Técnico (Unpublished report), 212 p.

[2] 1985. Geología y riesgo volcánico del volcán Calbuco y centros eruptivos menores. Proyecto Canutillar, ENDESA-Departamento de Geología, Universidad de Chile, Informe Técnico (Unpublished report), 215 p.

INTRODUCTION

The Scuthern Volcanic Zone of the Andes (SVZ) is the result of the subduction of the oceanic Nazca plate under the continental South American plate. This volcanic arc extends from latitude 33-46°S, being bounded by the intersection of the Juan Fernández ridge with the continental margin at *ca.* 32°S and the Chile Rise triple junction at *ca.* 47°S. At present. the SVZ of the Andes is the subject of numerous geochemical and petrological studies aimed at characterizing its products and determining their petrogenesis.

On the basis of petrographic, geochemical and tectonic considerations (López-Escobar, 1984, Hildreth and Moorbath, 1988; López-Escobar *et al.*, 1991; Tormey *et al.*, 1991) the Quaternary front of the SVZ of the Andes is currently divided into three main regions: the northern (NSVZ; 33°-34°30'S), transitional (TSVZ; 34°30'-37°S) and southern (SSVZ; 37°-46°S). In the NSVZ, where the thickness of the continental crust is 55-60 km, the predominant products are andesites and dacites. In the TSVZ, where the continental crust decreases in thickness from 55 km at 34°30'S to about 35 km at 37°S, andesites and dacites continue predominating, but basaltic rocks become increasingly important (Tormey *et al.*, 1991; Fergusson *et al.*, 1992). In the SSVZ, where the continental crust has a thickness of ≤ 30 km, the volcanic products are predominantly basalts and basaltic andesites. This general correlation between the crustal thickness and the composition of the Southern Andean Quaternary volcanic front is broken by Calbuco volcano, which is andesitic, despite being located (41°20'S) in a zone where the continental crust is relatively thin and most volcanic centers, including its neighbour Osorno, are dominantly basaltics.

The main objective of this paper is to compare the geochemistry of Osorno and Calbuco lavas, their geological setting and petrography with the ultimate goal of getting a better understanding of the causes of their contrasting chemical composition.

On the basis of previous experience (Moreno, 1974; Moreno *et al.*, 1979; López-Escobar *et al.*, 1988), two groups of Osorno lavas have been presently selected to carry out the above comparison: those belonging to the so called unit Osorno-3 and those of the youngest parasitic cones, located on the western flank of the volcano. The reasons for selecting Osorno-3 are: **a-** the unit has the largest area of exposure; **b-** is the best sampled; **c-** has the largest compositional range. Osorno-3 has a bimodal distribution of compositions (López-Escobar *et al.*, 1988). As the other units of Osorno stratovolcano, and most lavas of the SSVZ centers, Osorno-3 is mainly basaltic, but a small volume of dacitic lavas is also present. Osorno young parasitic cones lavas are also basaltic, but, as it will be discussed later, these lavas are different, in many respects, from the stratovolcano lavas, represented by the Osorno-3 lavas. No andesites have been yet found at Osorno.

GEOLOGICAL SETTING

OSORNO VOLCANO

Osorno volcano is a Late Pleistocene to Recent composite stratovolcano. It has an almost perfect cone shape and consists mainly of aa type lava flows interbedded with pyroclastic material. Its summit is located just 27 km NNE from the summit of Calbuco volcano (Fig.1). Osorno comprises three units, named Osorno-1, -2, and 3, which represent the volcanic activity developed since the Late Pleistocene up to the Recent (Moreno, 1974; Moreno *et al.*, 1979; Moreno *et al.*[1]; López-Escobar *et al.*, 1988). On the western and eastern flanks of this center there exist several parasitic cones (Fig.1). All Osorno units, including the parasitic cones, are mainly basaltic in composition.

According to Moreno *et al.* (1979) and López-Escobar *et al.* (1988), Osorno-1 is the remnant of the most primitive Osorno volcano, which grew during the interglacial period Riss-Würm and generated abundant laharic material and columnar basalts. This unit is almost completely covered by youngest lavas. Small outcrops are observed on the western flank of the actual edifice. Osorno-2 comprises those products erupted at the beginning of the post-Würm glaciation period. They consist mainly of basaltic lavas and scarce pyroclastic material of basaltic composition. Osorno-2 forms the base of the actual cone and is affected by glaciation. Osorno-3 includes those products erupted after the Würm glaciation period. Although this unit is also mainly basaltic, it also includes dacitic material, represented by two small domes located on its NW and SSE flanks. The products of this unit cover most of the Osorno-2 unit. Between the second and third stage of Osorno the old parasitic cones were formed (Fig.1). During prehistoric and historic times, the activity of Osorno volcano has been concentrated on the main cone and on the youngest parasitic cones located on the western and eastern flank of the edifice (Fig. 1),with exclusively basaltic products. The last eruption of this center ocurred in 1835 through one of the western parasitic cones.

Osorno volcano is located along a major N40°E trending lineament , which has also controlled the location of neighboring basaltic centers such as La Picada, Puntiagudo and Cordón Cenizos (Moreno, 1974; Moreno *et al.*, 1979). Its basement includes Tertiary volcanic and sedimentary rocks intruded by Miocene plutons (Moreno *et al.*, 1979; H. Moreno *et al.*[1]; R. Thiele, E. Godoy, F. Hervé, M.A. Parada and J. Varela[3]; López-Escobar *et al.*, 1988; Munizaga *et al.*, 1988). Early Pleistocene volcanic rocks, belonging to La Picada volcano, are also observed at the basement of Osorno.

CALBUCO VOLCANO

Calbuco volcano is also a young composite stratovolcano. It has a rough truncated-cone shape and consists mainly of blocky and aa type lava flows interbedded with pyroclastic rocks. The volcano comprises four units, named Calbuco-1, -2, -3 and -4 (Fig.1), which represent the volcanic activity developed since the Late Pleistocene up to the Recent (Moreno, 1974; Moreno, 1976; A. Lahsen *et al.*[2]). All these units have andesitic composition.

According to A. Lahsen *et al.*[2], Calbuco-1 is the remnant of the ancient volcano that pre-dates the last glaciation (Würm) and consists mainly of porphyritic andesites. Calbuco-2 forms the main cone of Calbuco and its andesitic flows fill glacial valleys cut into Calbuco-1. Calbuco-2 suffered a violent eruption that triggered a debris-avalanche that flowed down to the NNW (Fig.1). Calbuco-3 andesites post-date the debris-avalanche and are interbedded with breccias and tuffs. A small dome, located on the northern flank of the volcano has also been assigned to this unit. Calbuco-4 consists of a young historic «dome-cone» and associated lava flows. The 1893-1894 plinian eruption probably finished with a dome extrusion, which grew and evolved to a dome-cone through the 1917, 1929 and 1961 eruptions (Moreno, 1974).

Calbuco volcano mainly overlies Upper Paleozoic (?) metasedimentary rocks (Parada *et al.*, 1987), Upper Tertiary (16 to 10 Ma) plutonic rocks (Parada *et al.*, 1987; Munizaga *et al.*, 1988), and Early Pleistocene volcanic and volcanoclastic sequences (A. Lahsen *et al.*[2]). The plutonic rocks underlying Calbuco are part of an extensive Miocene plutonic belt of the Northern Patagonian Batholith, that extends to the north to latitude 39°S. In the Calbuco volcano area, the different lithologies of plutonic rocks (gabbros to granodiorites; Parada *et al.*, 1987) have been grouped into the Ralún superunit (Carrasco *et al.*, 1991). These plutonic rocks wholly crystallized at approximately 3 kbar (R.L. Hickey-Vargas, M.J. Abdollahi, M. A. Parada, L. López-Escobar and F.A. Frey)[4]. The Early Pleistocene volcanic sequence is represented by the Hueñuhueñu strata, which are the remnant of an old stratovolcano (1.4 Ma; A. Lahsen *et al.*[2]) that was located few kilometers to the east of Calbuco volcano. These strata consist of volcanoclastic material and porphyritic basalts.

The presence of Tertiary volcanic and sedimentary rocks at the Osorno basement but not at the Calbuco basement, together with the preservation at Osorno area of larger volumes of Early Pleistocene volcanic rocks than at Calbuco volcano area, has suggested that the degree of uplifting and unroofing at Calbuco has been larger than at Osorno (R.L. Hickey-Vargas *et al.*)[4]. Although no data on uplift have been obtained at the Osorno area, the calculated uplift rates of the Calbuco area is high and suggests an accelerating uplift during the last 12 Ma. In fact, on the basis of the hornblende crystallization pressure of the Miocene plutons underlying Calbuco (3 kbar) and their biotite K-Ar ages (12 Ma; Munizaga *et al.*, 1988), R.L. Hickey-Vargas *et al.*[4] have estimated an average uplift rate of 0.9 mm/y during the past 12 Ma. Thiele *et al.* (1986)

[3] 1985. Estudio geológico-estructural, regional y tectónico del área Petrohué-Canutillar. Proyecto Canutillar, ENDESA-Universidad de Chile, Informe Técnico, 157 p.

[4] 1992. Petrology and geochemistry of crustal xenoliths from Calbuco volcano, Andean Southern Volcanic Zone. Geology Department, Florida International University (Unpublished report) , 47 p.

found, in the Reloncaví fiord (few kilometers southeast of Calbuco volcano), post-glacial shell deposits situated 30 m above sea level, suggesting an average uplift rate of about 3 mm/y during the past 10,000 years. Moreover, Barrientos *et al.* (1992) have concluded that the uplift rate at the Calbuco volcano latitude has been of 25 mm/y during the past 30 years. The significance of this tectonic activity in the origin of Calbuco andesites is discussed below.

PETROGRAPHIC OUTLINE

OSORNO VOLCANO

The products of these volcanic center are mainly aphyric (<10% phenocrysts) and porphyritic (>10% phenocrysts) basalts and basaltic andesites (Moreno *et al.*, 1979; H. Moreno *et al.*[1]; López Escobar *et al.*, 1988). Plagioclase (An_{46-60}) is the most abundant phenocryst phase followed by olivine and clinopyroxene. The groundmass has generally an intersertal texture, and consists of plagioclase, clinopyroxene, opaques and glass. Crystal clots of plagioclase and olivine plus anhedral crystals of clinopyroxene, that could be xenocrysts, have been observed in lavas from the Osorno-3 and -4 units. The products of the parasitic cones are olivine basalts and basaltic andesites. The SSE dome is an hypersthene-bearing dacite with a hyalopilitic groundmass, showing some crystal clots of clinopyroxene, orthopyroxene and plagioclase.

CALBUCO VOLCANO

Calbuco lavas are porphyritic, with phenocrysts of plagioclase, clinopyroxene and orthopyroxene, plagioclase being the most abundant phenocryst phase (Parada, 1990). Plagioclase phenocrysts are generally euhedral, with inclusions of magnetite, and less common olivine (Fo_{80}). Their compositions range from An_{60} to An_{90}, exhibiting subtle normal zonation patterns. Clinopyroxene and orthopyroxene phenocrysts have similar compositions and Mg-numbers in the 0.50-0.59 range (Parada, 1990). However, the Mg-numbers of the orthopyroxene phenocrysts are slightly lower than those of the clinopyroxene phenocrysts. Small amounts of edenitic hornblende phenocrysts were found in samples from Calbuco-3 unit (Parada, 1990), and tschermakitic and Mg-hornblende xenocrysts were observed in samples from Calbuco-1 (R.L. Hickey-Vargas *et al.*)[4]. It is interesting to notice that unlike edenite, tschermakitic hornblende appears to be stable under high pressure conditions in andesitic and basaltic liquids (Allen and Boettcher, 1978).

Tschermakitic and Mg-hornblendes are euhedral and may exhibit either single or double reactions rims (R.L. Hickey-Vargas *et al.*)[4]. Single rims consist of a crystal association of plagioclase, clinopyroxene and magnetite. In the case of double rims, the external one consists of just clinopyroxene, and the mineralogy of the internal rim is similar to that of the single rims. A complete transition from tschermakitic hornblendes, surrounded by either single or double rims, to crystal clots of plagioclase + clinopyroxene + magnetite, preserving the original shape of the amphibole, suggests that crystal clots are breakdown products of tschermakitic and Mg-hornblendes (Parada, 1990).

Gabbroic and pyroxenitic microinclusions are common in lavas from Calbuco-3, and gabbroics and granulitic xenoliths, the latter with oceanic affinities, are included in the 1961 lava flow (Calbuco-4; R.L. Hickey-Vargas *et al.*[4]).

GEOCHEMISTRY

Major and trace element compositions of representative samples from Osorno-3, Osorno young parasitic cones and Calbuco volcano units 1-4 are shown in Table 1. This table also includes data of Klerkx (1965) and Deruelle (1982). Plots in figures 2, 3 and 4 also include data from Calbuco taken from L. López-Escobar, M.A. Parada, F. Frey, R.L. Hickey-Vargas and H. Moreno[5].

[4] 1992. Contrasting origin of andesitic and basaltic volcanism in the Southern Andes: case of Calbuco volcano and nearby minor eruptive centers associated with the Liquiñe-Ofqui fault zone, 41°-42°S. Universidad de Chile, Departamento de Geología (Unpublished report), 33 p.

TABLE 1. SELECTED CHEMICAL AND ISOTOPIC COMPOSITIONS OF OSORNO AND CALBUCO VOLCANIC ROCKS

	Osorno-3						Osorno young parasitic cones							
	250281-03 161282-13	230483-01	250281-01 161282-09	161282-08	230483-03	080385-04 DOME	040976-04	020976-02	161282-07	151282-06	151282-08	161282-04	250281-02 161282-03	161282-02
SiO_2	51.43	51.91	54.17	54.65	63.09	68.48	50.04	51.50	51.91	52.06	52.36	52.36	52.81	53.17
TiO_2	0.99	0.92	1.40	1.42	0.79	0.56	0.46	0.60	0.80	0.80	0.89	0.89	0.96	0.98
Al_2O_3	16.96	17.48	16.00	16.07	16.31	14.45	21.30	20.48	20.28	20.58	19.82	20.45	18.91	19.12
Fe_2O_3 (T)	10.29	9.55	11.72	11.38	6.59	4.69	9.99	9.73	8.32	8.09	8.57	8.15	9.68	9.04
MnO	0.17	0.17	0.17	0.19	0.12	0.08	0.13	0.13	0.14	0.15	0.15	0.14	0.16	0.14
MgO	6.48	6.27	3.79	3.75	1.72	1.10	3.11	3.68	4.51	4.08	4.04	4.09	3.91	4.09
CaO	9.99	10.00	7.86	7.89	5.10	3.51	11.96	10.62	10.93	10.81	10.41	10.63	9.71	9.69
Na_2O	2.77	3.03	3.67	3.87	4.53	4.36	3.12	2.78	2.87	3.03	3.11	3.24	3.28	3.37
K_2O	0.50	0.51	0.82	0.85	1.45	2.12	0.40	0.41	0.43	0.42	0.48	0.48	0.59	0.55
P_2O_5	0.15	0.17	0.26	0.21	0.25	0.16	0.15	0.14	0.11	0.14	0.15	0.17	0.18	0.16
LOI	0.08	0.20	0.27	0.29	0.33		0.54	0.77	0.16	0.16	0.19	0.14	0.19	0.55
SUM	**99.81**	**100.21**	**100.13**	**100.57**	**100.28**	**99.51**	**101.20**	**100.84**	**100.46**	**100.32**	**100.17**	**100.74**	**100.38**	**100.86**
Rb	13.4	13.9	22.5	23.5	45.6	69.1	12.4	9.6	12.0	10.5	11.9	12.6	14.9	14.4
Sr	327	339	337	336	294	190	409	412	404	402	395	400	378	380
Ba	144	149	238	257	396	550			150	132	152	148	161	176
Cr	177	150	25	21	4		54	46	51	67	51	70	54	51
Ni	62	57	11	19	10	11	12	9	25	25	28	30	21	24
Th	0.8		1.9	1.8	4.3	8.6	1.0	0.6				0.7	1.1	
La	5.89	5.92	10.60	10.30	17.00	26.00	5.37	5.06		4.49		5.36	6.50	
Ce	15.3	15.5	27.4	29.1	43.4	61.9	12.6		12.1	12.2	7.1	16.0	17.2	14.6
Nd	10.1	9.9	16.3	16.6	21.9	29.2	7.8			7.3		8.8	10.7	
Sm	2.81	2.85	4.33	4.32	5.73	6.65	2.2	2.22		2.25		2.48	2.91	
Eu	0.93	0.88	1.30	1.37	1.26	1.14	0.95	0.89		0.83		0.86	0.99	
Tb	0.52	0.48	0.84	0.53	1.07	1.12	0.40			0.31		0.41	0.50	
Y	18.7	18.2	27.9	28.2	33.2	42.2			16.1	14.9	16.8	16.5	17.8	18.8
Yb	1.98	1.71	2.98	2.89	3.41	4.33	1.76	1.88		1.45		1.70	1.99	
Lu	0.30	0.28	0.42	0.42	0.53	0.67	0.27	0.22		0.22		0.27	0.30	
$^{87}Sr/^{86}Sr$	0.70431±3		0.70429±3										0.70429±3	
$^{143}Nd/^{144}Nd$	0.512840±18		0.512790±18										0.512828±19	

	Calbuco-1		Calbuco-2		Calbuco-3					Calbuco-4		Calbuco literature			
	060385-03*	060385-06*	060385-01*	070385-05*	130185-01*	111284-01*	030282-05*	070385-01*	030284-04*	030282-02*	070385-07*	Déruelle, 82 19J	Déruelle,82 19K	Klerkx, 65 Ca 46	Klerkx, 65 Ca 37
SiO_2	57.03	59.15	57.22	59.78	55.48	55.80	56.01	56.69	57.68	55.66	56.02	50.9	56.35	51.3	56
TiO_2	0.78	0.73	0.97	0.65	0.87	0.90	0.85	0.82	0.81	0.89	0.82	1	0.89	0.7	0.9
Al_2O_3	18.46	18.15	17.83	19.02	18.29	18.68	18.50	18.34	18.48	18.59	19.32	20.1	17.74	20.4	19.1
Fe_2O_3 (T)	7.11	7.76	8.72	5.88	8.97	8.42	8.94	8.62	7.82	8.59	8.05	8.39	8.05	8.5	8.8
MnO	0.14	0.18	0.17	0.12	0.17	0.15	0.16	0.17	0.14	0.14	0.14	0.13	0.15	0.1	0.1
MgO	3.55	2.32	3.15	1.84	4.21	3.75	3.92	4.16	3.42	4.20	3.75	4.31	3.07	4.2	4.7
CaO	8.65	6.14	7.29	7.36	8.04	8.49	8.18	7.67	7.52	8.08	7.95	10.22	7.14	7.5	7.9
Na_2O	3.52	4.37	3.56	4.11	3.26	3.25	3.02	3.30	3.36	3.37	3.57	2.94	3.66	5.2	4.2
K_2O	0.77	0.65	0.69	0.76	0.53	0.59	0.52	0.53	0.70	0.61	0.64	0.43	0.73	1.2	0.6
P_2O_5	0.24	0.23	0.18	0.19	0.16	0.15	0.18	0.16	0.16	0.16	0.16	0.09	0.15	0.2	0.2
LOI	0.52	0.82	0.42	0.40	0.27	0.43		0.63			0.30	1.88	0	0.6	0.3
SUM	**100.77**	**100.50**	**100.20**	**100.11**	**100.25**	**100.61**	**100.28**	**101.09**	**100.09**	**100.29**	**100.72**	**100.39**	**97.93**	**99.9**	**102.8**
Rb	9.1	12.1	18.8				11.5		17.7	16.3		10	15		14
Sr	881	381	339				347		340	342		310	333		372
Ba	190	214	215				156		184	156		109	175		
Cr	14	4	3				3		5	9		66	49		
Ni	19	6	8				9		10	15		8	7		
Th	3.3	1.5	1.9				0.9		1.3	1.2		0.63	1.23		
La	11.30	8.34	8.48				6.79		7.80	6.47		4.1	6.7		
Ce	28.1	21.2	21.6				19.0		20.2	18.2		11.7	17		
Nd	15.6	13.9	12.7				12.0		12.5	11.6					
Sm	3.46	3.65	3.47				3.33		3.44	3.13					
Eu	1.10	1.22	1.09				1.06		1.04	1.03		0.86	1.07		
Tb	0.44	0.47	0.53				0.63		0.55	0.52		0.42	0.51		
Y															
Yb	1.39	2.38	2.39				2.13		2.09	2.05					
Lu	0.18	0.38	0.36				0.37		0.31	0.30					
$^{87}Sr/^{86}Sr$							0.70455±3		0.70464±3	0.70437±3					0.7043
$^{143}Nd/^{144}Nd$							0.512744±19		0.512727±19	0.512774±19					

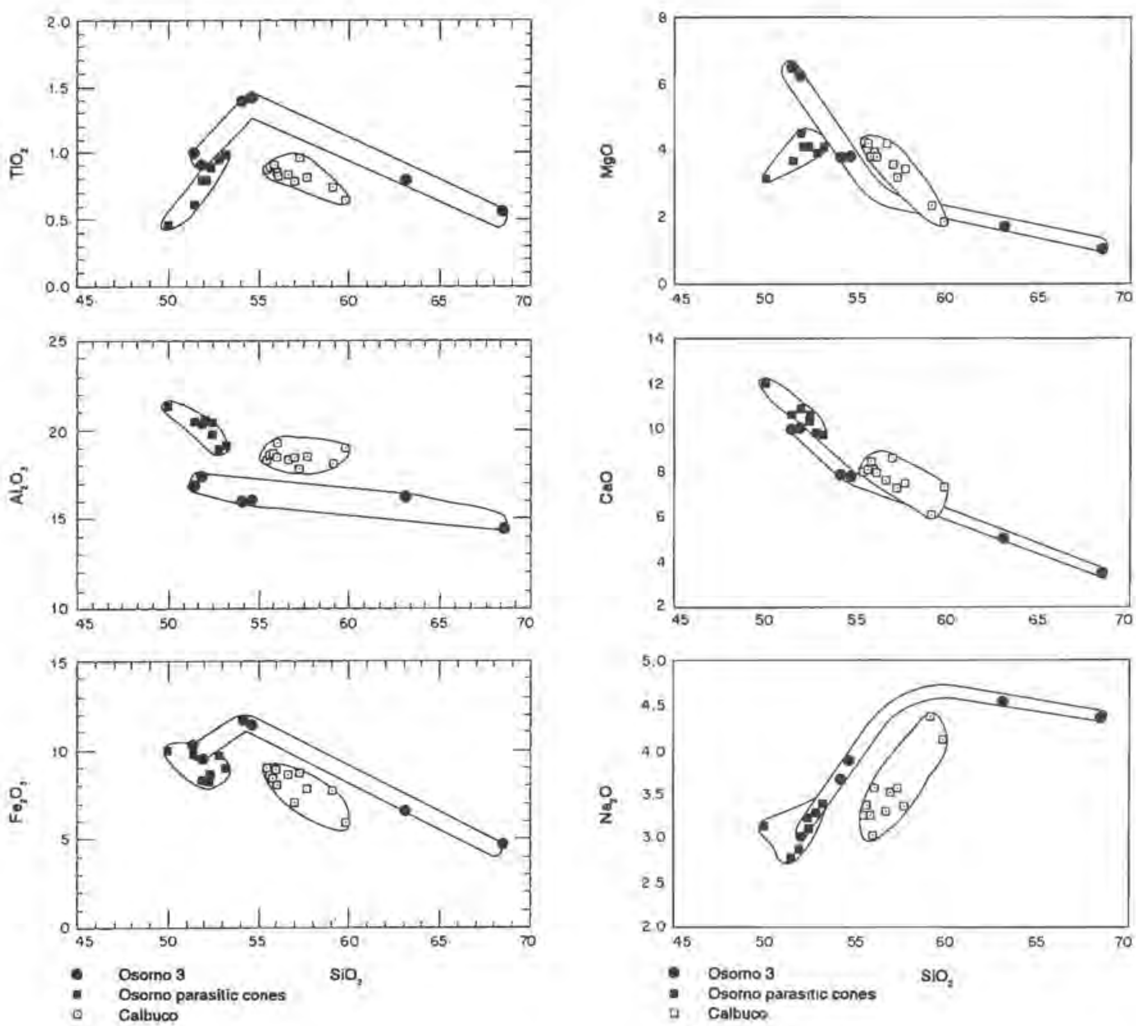
NOTE: Major elements were obtained by wet chemistry at the Department of Geology of the Universidad de Chile. All of them are expressed in weight percent. Trace elements of Osorno lavas were determined by XRF (Rb, Sr and Ni) and INAA (Ba, Cr, Th and REE) at the University of Massachusetts and Massachusetts Institute of Technology, respectively. All of them are expressed in ppm. Trace element abundances of Calbuco lavas are from L. López-Escobar *et al.*[5]. Isotopic compositions of Osorno and Calbuco lavas are from R.L. Hickey-Vargas *et al.*[4]

MAJOR ELEMENT COMPOSITION

Independently of their relative ages, Calbuco rocks have SiO_2 contents in the narrow range 55-60% (Fig.2). However, the oldest rocks, belonging to units Calbuco-1 and -2, tend to be richer in SiO_2 than the youngest ones. Calbuco lavas have relatively low K_2O contents, with K_2O/SiO_2 ratios in the 0.009-0.014 range. For comparison, this ratio varies between 0.029 and 0.045 in San José volcano andesites, located in the NSVZ at 33°45'S (López-Escobar *et al.* 1985). According to the classification criteria of Pecerillo and Taylor (1976) and the AFM diagram (Fig.3), Calbuco lavas are low-K calcalkaline basaltic andesites and andesites.

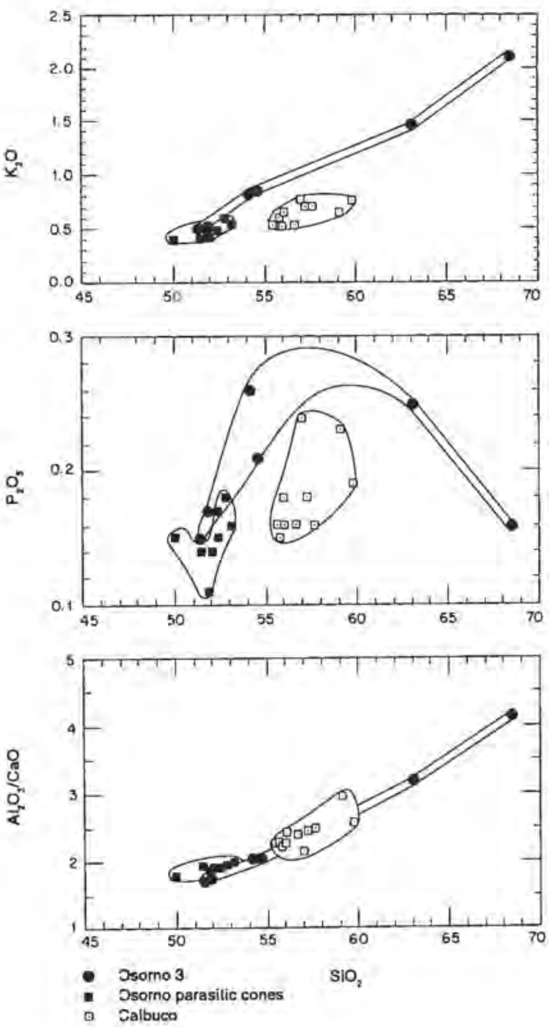
Calbuco lavas are very homogeneous in major element composition. With increasing SiO_2 content, Calbuco lavas show a general trend of decreasing TiO_2, Fe_2O_3, MgO and CaO contents, and increasing Na_2O, K_2O and P_2O_5 abundances (Fig.2). The MnO contents in Calbuco lavas are variable and, since the Al_2O_3 contents are relatively constant and high (17.8-19%), the Al_2O_3/CaO ratio also increases significantly with increasing SiO_2 content (Fig.2), reflecting the decreasing in CaO contents.

In comparison with the general trend of Osorno-3 lavas (interpolated linearly between the basaltic and dacitic compositions; Fig.2), Calbuco lavas are enriched in Al_2O_3, have similar MnO, MgO and CaO contents, but are depleted in TiO_2, Fe_2O_3, Na_2O, K_2O and P_2O_5.



Although the Osorno parasitic cones lavas are more mafic than Calbuco lavas, some of them overlap with Calbuco lavas in TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, Na_2O, K_2O and P_2O_5 (Fig.2). However, with increasing SiO_2 content, the behaviour exhibited by some of these major oxides in the Osorno parasitic lavas is opposite to that of the Calbuco lavas. For example, while TiO_2 and MgO increase, with increasing SiO_2 in the parasitic cone lavas, they decrease in the Calbuco lavas (Fig.2). P_2O_5 increases with SiO_2 both in Calbuco and Osorno young parasitic cone lavas, but the P_2O_5-SiO_2 trend n the Calbuco lavas is parallel to that of the

FIG. 2. Major element versus SiO_2 and Al_2O_3/CaO *versus* SiO_2 variations diagrams of Osorno-3, Osorno young parasitic cone and Calbuco lavas.



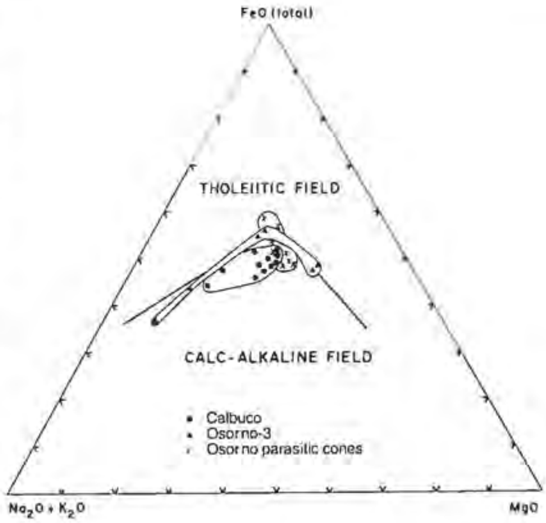


FIG. 3. AFM compositional diagram of Osorno-3, Osorno young parasitic cone and Calbuco lavas. The boundary between calc-alkaline and tholeiitic fields was taken from Irvine and Baragar (1971).

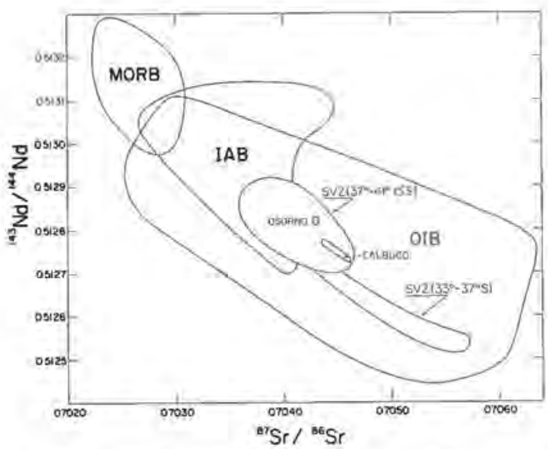
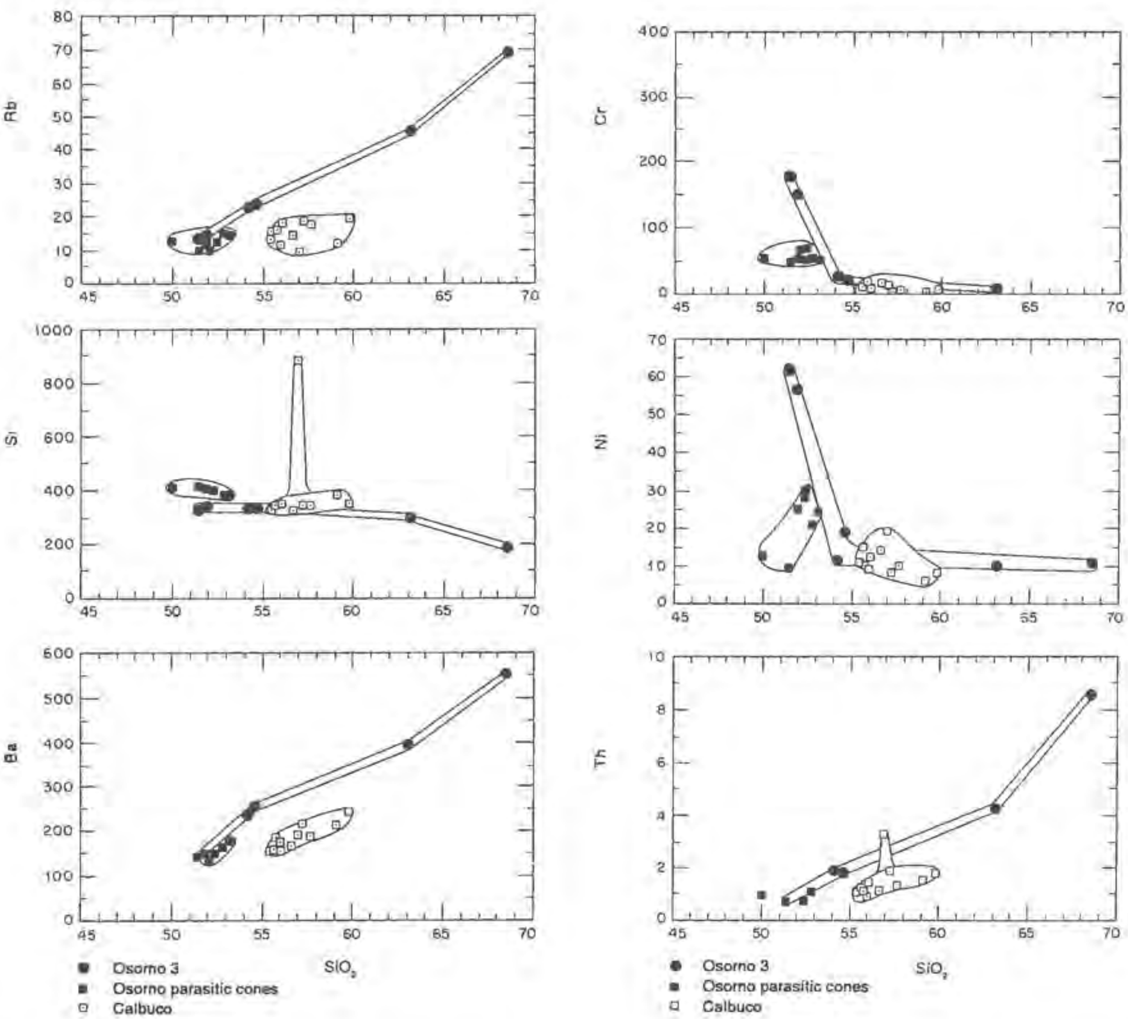


FIG. 4. $^{143}Nd/^{144}Nd$ - $^{87}Sr/^{86}Sr$ diagram showing the Sr and Nd isotopic composition of Osorno and Calbuco lavas in comparison with that of middle ocean ridge basalts (MORB), oceanic island basalts (OIB), intraoceanic island arc volcanic rocks (IAV), northern and transition SVZ of the Andes (NSVZ and TSVZ) rocks , southern SVZ of the Andes (SSVZ) rocks. Source of data: Hickey-Vargas *et al.* (1986) and references therein, Hildreth and Moorbath (1988) and references therein, and López-Escobar *et al.* (1991).



Osorno parasitic cone lavas. Figure 2 also shows that the major element trends of the Osorno young parasitic cone lavas are different from those of the Osorno stratocone lavas represented by the Osorno-3 lavas.

ISOTOPIC COMPOSITION

Two samples from Calbuco-3 and one from Calbuco-4, have Sr- and Nd- isotope ratios (L. López-Escobar *et al.*[5]; Fig.4). Calbuco volcano has higher Sr- and lower Nd-isotope ratios than MORB and intraoceanic island arc volcanics. Actually, the values of these ratios are intermediate between those of IAV and volcanic rocks from the NSVZ (López-Escobar, 1984; Stern *et al.*, 1984; López-Escobar *et al.*, 1985; Notsu *et al.*, 1987; Stern, 1988; Futa and Stern, 1988; Hildreth and Moorbath, 1988). The Sr- and Nd-isotope ratios of Calbuco lavas are respectively slightly higher and lower than those of lavas from Osorno-3 and Osorno young parasitic cones lavas (Fig.4; R.L. Hickey-Vargas *et al.*[4]).

TRACE ELEMENT COMPOSITION

The trace element composition of Calbuco, Osorno-3, and Osorno young parasitic cone lavas are shown in figure 5. Almost all Calbuco samples have similar rare earth element (REE) abundances (Fig.6), with La equal to 20-30 x chondrites and Yb equal to 9-12 x chondrites. Calbuco-1 and -2 lavas

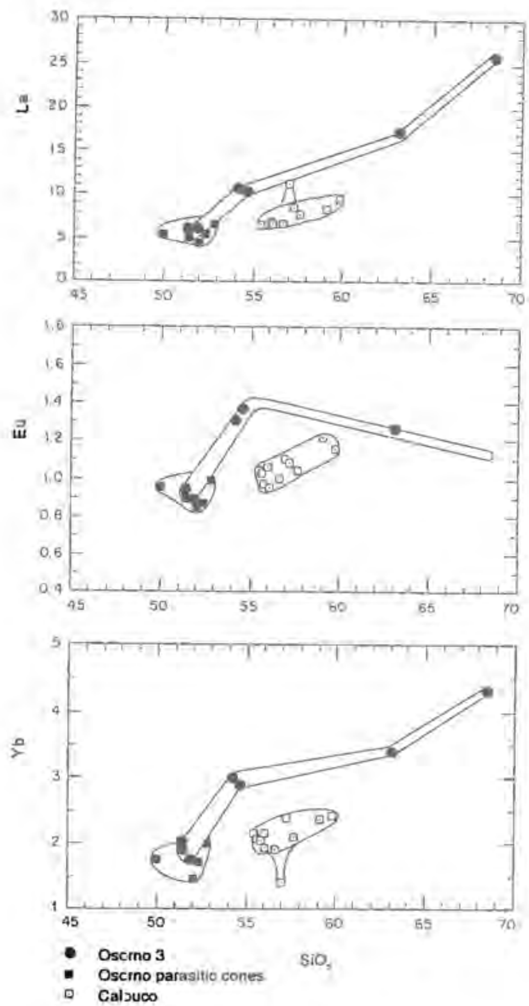


FIG. 5. Trace element-SiO_2 variations diagrams of Osorno and Calbuco rocks discussed in this paper.

are the richest in REE. Calbuco rocks do not exibit Eu anomalies. On the contrary, Eu as well as La, Yb, Sr, Ba and Th tend to increase with increasing SiO_2 contents (Fig.5). La/Yb ratios of Calbuco andesites range from 3.1-3.9 (Fig.7). These ratios are significantly lower than those of the NSVZ andesites. For example, La/Yb ratios of San José volcano andesites (33°45'S) vary between 11.6 and 22.5 (López-Escobar *et al.*, 1985). Only one sample from Calbuco-1 unit (060385-03) is notably depleted in heavy rare earth elements (HREE) in comparison with the other Calbuco samples (Figs. 5, 6), but is enriched in light rare earth elements (LREE), Sr, Ni and Th, having a La/Yb ratio equal to 8.1. Stratigraphically, this sample is the oldest one.

Osorno-3 and Osorno young parasitic cone basalts have REE patterns similar to Calbuco andesites (Fig.6). However, Osorno-3 basaltic andesites are richer in REE than Calbuco andesites. The latter andesites are also depleted in Rb, Ba and Th in comparison with the trends followed by Osorno-3 lavas (Fig.5).

Although most Calbuco lavas are relatively homogeneous in major and trace element composition, they are heterogeneous in their incompatible trace element ratios (Fig.7). This behaviour contrasts with that of Osorno-3 lavas, which show relatively constant incompatible trace element ratios. These ratios are also variable in the lavas of the Osorno young parasitic cones, but not to the extend shown by Calbuco lavas.

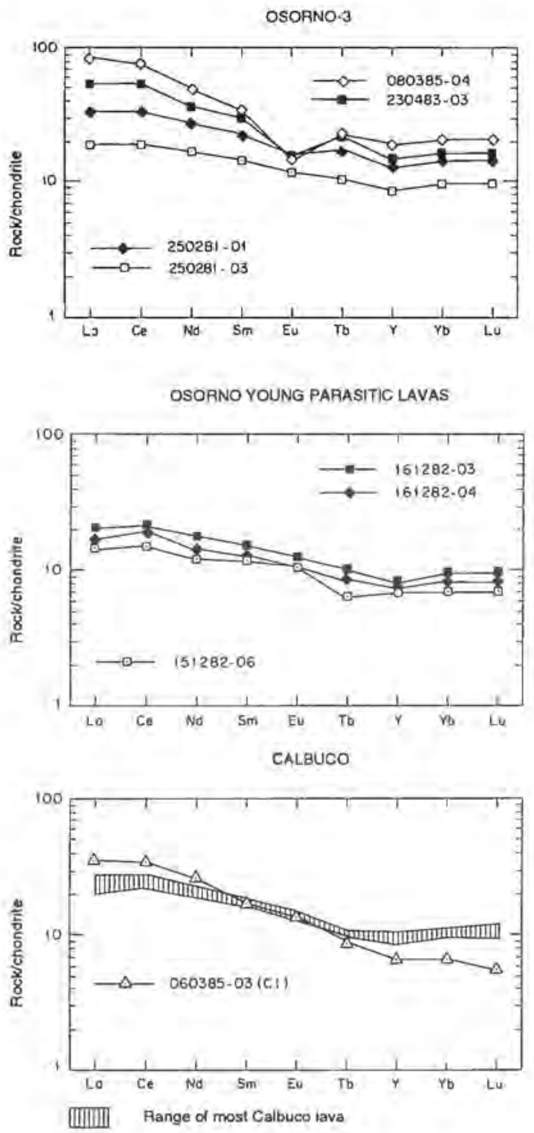
COMPARATIVE SUMMARY

OSORNO AND CALBUCO DIFFERENCES

The analysis of the geological, petrographic and chemical differences between Calbuco volcano and its inmediate neighbour, Osorno volcano can help to elucidate the possible origin of their magmas. The following are the most significant differences between both centers and the genetic implications of those differences:

- While the location of Osorno volcano is related to a major N40°E fracture (Moreno, 1974; Moreno *et al.*, 1979), no significant major structure seems to control the activity of Calbuco volcano. On this basis, it is reasonable to assume that the interaction of subcrustal magmas with crustal material is larger at Calbuco than at Osorno.
- Unlike the basement of Calbuco, the basement of Osorno volcano includes Tertiary volcanic rocks, intruded by the Miocene plutons, and extensive outcrops of Early Pleistocene volcanic rocks (Mo-

FIG. 6. Chondrite-normalized rare earth element patterns of Osorno and Calbuco volcanic rocks discussed in this paper. Note: the increase in REE contents and Eu depletion observed in Osorno-3 volcanic rocks parallels the increases in SiO_2 content of these rocks.



reno *et al.*, 1979; R. Thiele *et al.*[3]; López Escobar *et al.*, 1988). This fact implies that, despite their proximity, the Calbuco area has experienced a larger degree of uplifting and unroofing than the Osorno area. The accelerating uplift mentioned previuosly, favors crustal melting (Zeitler and Chaberlain, 1991) and the possibility of crustal contamination.

- Calbuco rocks are andesitic and contain a large number and wide variety of crustal xenoliths and microxenoliths (R.L. Hickey-Vargas *et al.*)[4]. In contrast, Osorno volcano is mainly basaltic and crustal xenoliths are almost absent (López-Escobar and Parada, 1991). The presence of crustal xenoliths and microxenoliths in Calbuco lavas is indicative of crustal contamination in the evolution of Calbuco magmas.

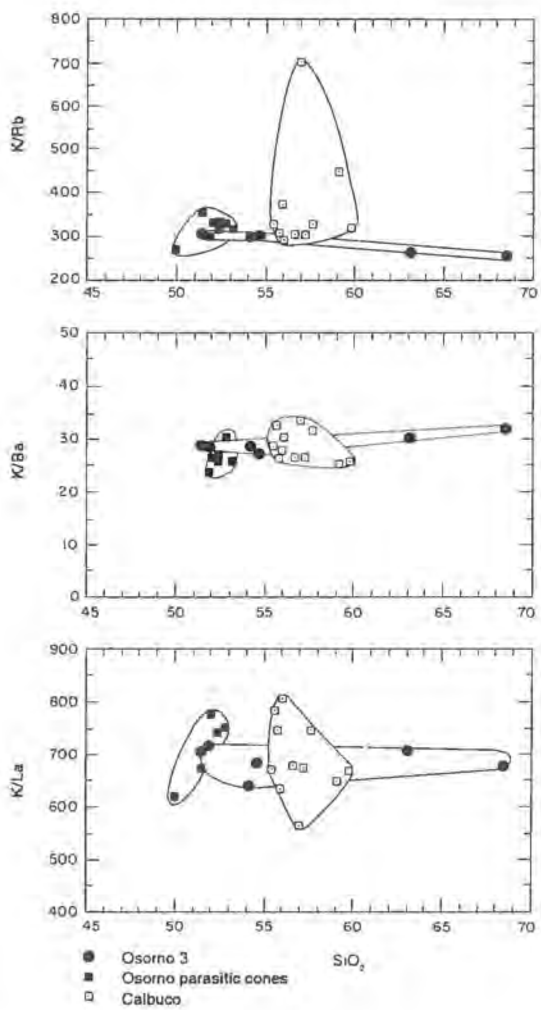
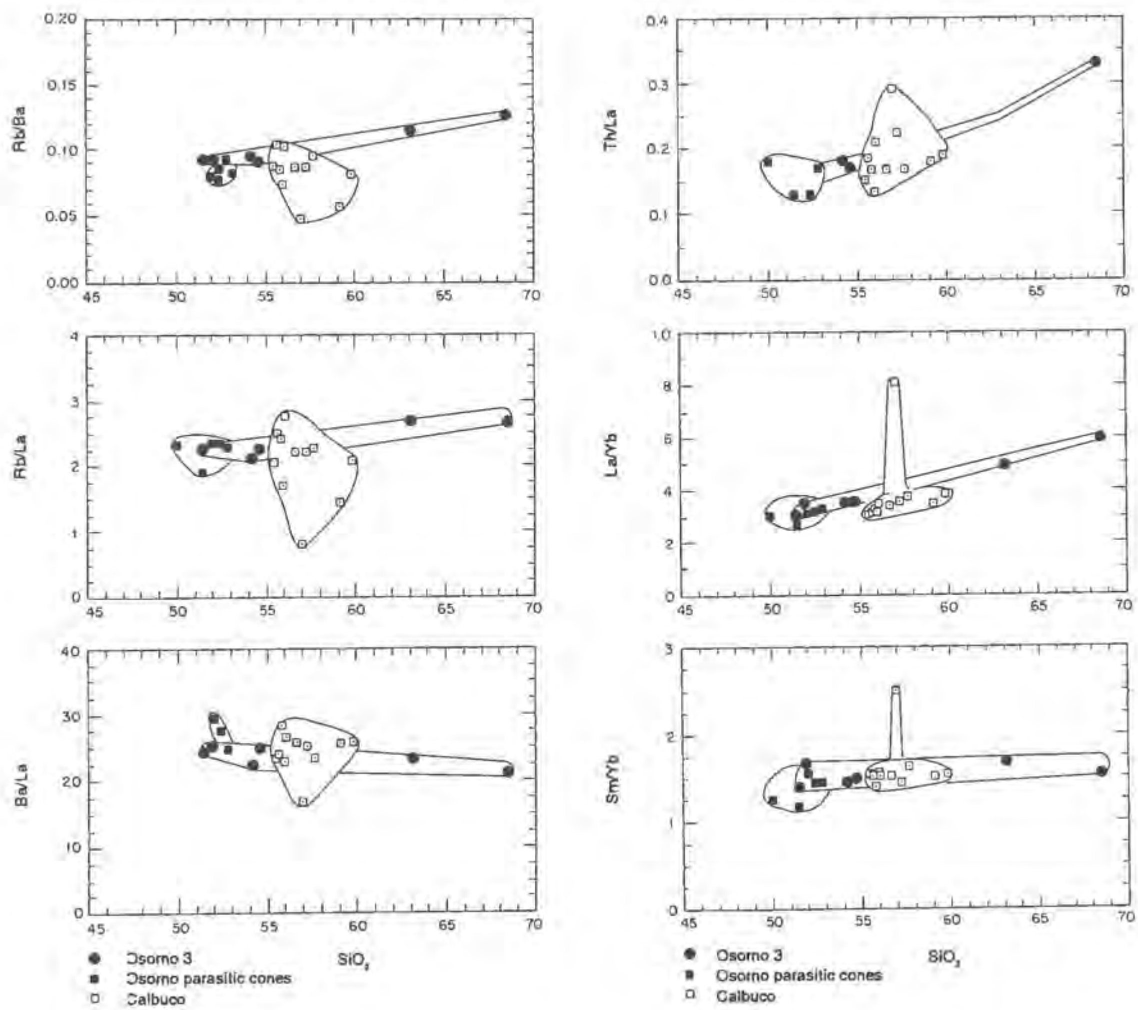


FIG. 7. This figure illustrates the behaviour of the incompatible element ratios of Osorno and Calbuco volcanic rocks as a function of their SiO_2 contents.

- Some Calbuco lavas include edenitic hornblende as a phenocryst phase and high pressure tschermakitic and Mg-hornblendes as xenocrysts. In contrast, no hornblende has been found in Osorno lavas, even in the most acidic ones. This fact indicates either that Calbuco magmas are richer in water than Osorno magmas or that they evolved by crystallization at higher pressure. A relatively higher water content of Calbuco magmas would explain the explosive nature of some Calbuco volcano eruptions, such as the eruption that triggered the debris-avalanche in Calbuco-2 unit and the 1893-94 Plinian eruption.
- Calbuco rocks have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios than Osorno lavas. This feature is consistent with a higher degree of contamination by ancient sialic continental crust in the case of Calbuco magmas.
- Although Osorno volcano does not have andesitic rocks, whose composition could be compared with that of Calbuco andesites; figures 2 and 5 show that the abundance fields of many major and trace elements of Calbuco rocks are either above or below the trends connecting the basaltic and dacitic compositions of Osorno-3 lavas.
- Although Calbuco lavas are very homogeneous in major and trace element abundances, they are relatively heterogeneous in their incompatible element ratios (Fig.7). In contrast, the incompatible element ratios of the Osorno-3 lavas have similar values for different SiO_2 contents. The heterogeneity of these ratios in Calbuco lavas



could be a consequence of contamination of Calbuco subcrustal magmas with magmas generated in the crust.

ROLE OF FRACTIONATION IN THE ORIGIN OF OSORNO AND CALBUCO MAGMAS

The isotopic and chemical differences between Osorno and Calbuco magmas suggest that they are not linked by a simple crystal fractionation process involving the mineral present as phenocrysts. Suporting this hypothesis is the fact that the REE abundances of andesitic Calbuco lavas are similar to those of Osorno basalts and lower than those of some Osorno basaltic andesites (Fig.6). In contrast, the evolution of Osorno-3 lavas does seem to be dominated by a crystal fractionation process. For example, the REE contents as well as the degree of Eu depletion of Osorno-3 lavas increase as SiO_2 increases (Fig.6) and their incompatible element ratios do not vary with increasing SiO_2 (Fig.7). This does not mean that Calbuco magmas themselves did not experience fractional crystallization. On the contrary, their relatively low abundances of MgO, Cr and Ni (Figs. 2, 5), plus the increasing of Al_2O_3/CaO ratio, as SiO_2 increases (Fig.2), reflect fractionation of olivine and clino-pyroxene during their evolution. However, although plagioclase is the most abundant phenocryst phase in these magmas, there is no clear evidence of plagioclase fractionation. In fact, Eu and Sr behave as incompatible elements in Calbuco magmas (Fig.5). Similarly, fractionation of edenitic amphibole is limited on the basis of the Sm/Yb ratios of Calbuco magmas (Fig.7), which are similar to those of Osorno-3 basaltic rocks. Therefore, the authors conclude that the fractionation of plagioclase and hornblende is not responsible for the generation of Calbuco andesitic magmas from more basaltic ones.

ROLE OF MAGMA CONTAMINATION

The isotopic and chemical differences between Calbuco and Osorno magmas in conjunction with: **a-** the presence of metabasaltic rocks with oceanic affinities in the basement of Calbuco volcano and of crustal xenoliths in Calbuco lavas (R.L. Hickey-Vargas *et al.*)[4]; **b-** the presence of high pressure tschermakitic hornblende, sometimes partially to totally broken-down to a plagioclase + clinopyroxene + magnetite association; **c-** the evidence of significant uplifting at Calbuco area; **d-** the lack of a major structural control; **e-** the lack of extreme members (basalts and rhyolites) at Calbuco suggests that the andesitic composition of Calbuco magmas probably resulted from contamination of subcrustal magmas. Partial melting of crustal rocks may have been promoted by accelerating uplift as suggested by Zeitler and Chamberlain (1991) for the Himalayas. Although the nature of the crustal source is unclear, the presence of xenoliths and tschermakitic and Mg-hornblende xenocrysts suggest an oceanic metabasite protolith (in amphibolite facies), similar to those belonging to the Paleozoic subduction complex, extensively developed to the west of the studied area (cf. Munizaga *et al.*, 1988). Marine metasediments typically found interbedded with these metabasites may also have been present.

According to Beard and Lofgren (1991), dehydration melting of basaltic amphibolites produces felsic liquids and granulite residues. The mineral assemblage of the latters (plagioclase + ortho-pyroxene + clinopyroxene + magnetite) is similar to that observed by R.L. Hickey-Vargas *et al.*[4] in granulite xenoliths of Calbuco lavas. The felsic liquids, on the other hand, are rich in Al_2O_3 and H_2O, and may be poor in K_2O depending upon the nature of the parental rock. Therefore, mixing of crustal liquids generated by partial melting of amphibolite with subcrustal magmas can reasonably explain the high Al_2O_3 and H_2O contents and low K_2O abundances of Calbuco magmas, and also can reasonable explain the trace element composition of the Calbuco andesites (L. López-Escobar *et al.*)[5].

In contrast, the isotopic composition of Calbuco lavas is not consistent with the contamination of basaltic magmas by the metabasaltic crustal rocks, because, like MORB, the metabasites have significantly higher $^{143}Nd/^{144}Nd$ than any SVZ basaltic magma. The higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ in Calbuco lavas compared with Osorno is more consistent with a metasedimentary contaminant, like those that are found intercalated with crustal amphibolites elsewhere in the SVZ. Probably a crustal section including both marine metabasalts and metasediments was involved in the contamination.

Assuming the assimilated assemblage included amphibolites and pelitic schists, the tschermakitic hornblende found in some Calbuco-1 lavas, could represent a mineral belonging to the contaminant source. This hornblende would be unstable in the Calbuco magmatic environment, and decompression during magma ascent would favor its breakdown to a plagioclase + clinopyroxene + magnetite association, which is common in tschermakitic hornblende rims and crystal clots.

Osorno magmas, on the other hand, particularly those represented by the most basic rocks of the young parasitic cones, differ from Calbuco magmas in that they do not show clear evidence of significant contamination by crustal material. Probably, the N40°E fracture played a major role in avoiding a significant magma-crust interaction. At Osorno-3, the most acidic magmas exhibit geochemical characteristics of being derived from more basic magmas by a crystal fractionation dominated process. Probably rheologic factors (Tormey *et al.*, 1991) prohibited the eruption of andesites at Osorno.

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