Petrography and geochemistry of Quaternary rocks from the Southern Volcanic Zone of the Andes between 41°30' and 46°00'S, Chile

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ABSTRACT

Rocks from thirteen stratovolcanoes, belonging to the Quaternary front of the Southern Volcanic Zone (SVZ) of the Andes (41°30'S-46°00'S) are mainly low- to medium-K basalts and basaltic andesites. Andesites and dacites are less abundant, and rhyolites are found only at Chaitén volcano. Pleistocene volcanic rocks range in composition from basalt to dacite, but Holocene volcanic rocks are predominantly basalts and basaltic andesites. In general, stratovolcano-basalts from the 41°30'-46°00'S region of the SVZ are geochemically similar to stratovolcano-basalts from the 37°00'-41°30'S region, but exhibit a wider range of Pb-isotope ratios which is close to that of volcanic rocks from the 33-37°S region. In detail, two types of basalts, depleted (type-1) and enriched (type-2) in incompatible elements, are distinguished in this region of the SVZ. Compared to type-1 basalts, type-2 basalts have a lower degree of olivine zoning and higher $FeO^{(T)}/MgO$, La/Yb, and $^{87}Sr/^{86}Sr$ ratios. In type-2 basalts, olivine rarely coexists with augite. Plagioclase phenocrysts in both type of basalts exhibit strong normal zoning, from An_{93} (cores) to An_{58} (rims). In spite of being located in an area of presumably thin continental crust, the Chaitén rhyolites are geochemically similar to rhyolites from further north (33-37°S) where the continental crust is thick, but are notably enriched in radiogenic Pb, particularly in ^{206}Pb. Compared to the nearby Michinmahuida basalts, the Chaitén rhyolites have higher Sr-, Pb-, and O- isotope ratios, but lower Nd- isotope ratios, are notably depleted in Ca, Sr, Eu, Ti, Zr, Hf, Y and middle and heavy rare-earth elements, and have lower K/Rb ratios. On the basis of their chemical and isotopic differences, type-1 basaltic magmas are not parental magmas of type-2 basalts. These differences seem to reflect different degrees of partial melting of the asthenosphere followed by contamination of these melts with lower to intermediate crustal material. At upper crustal levels, basaltic magmas evolve to produce intermediate magmas, either by fractional crystallization combined with different degrees of crustal contamination or by mixing with rhyolitic liquids generated by partial melting of crustal material.

Key words: Petrology, Geochemistry, Quaternary volcanism, Southern Andes, Southern Chile.

Revista Geológica de Chile, Vol. 20, No. 1, p.33-55, 16 Figs., 3 tables, July 1993.

RESUMEN

Petrografía y geoquímica de rocas cuaternarias de la Zona Volcánica Sur de los Andes entre los 41°30' y 46°00'S, Chile. Los centros volcánicos del frente cuaternario de la Zona Volcánica Sur (ZVS) de los Andes, ubicados entre las latitudes 41°30'S y 46°00'S, son predominantemente basálticos y andesítico-basálticos, de contenidos bajos a medios de K. Andesitas y dacitas son menos abundantes que las rocas basálticas y se encuentran riolitas sólo en el volcán Chaitén. Las rocas volcánicas pleistocenas varían en composición de basalto a dacita, pero las holocenas son fundamentalmente basaltos y andesitas basálticas.En general, los basaltos de los estratovolcanes de la región comprendida entre 41°30'-46°00'S de la ZVS son geoquímicamente semejantes a los basaltos de los estratovolcanes de la región 37°00'-41°30'S, pero sus razones isotópicas de Pb presentan un intervalo más amplio de variación, siendo éste cercano al presentado por las rocas volcánicas de la región 33-37°S. En detalle, dos tipos de basaltos pueden distinguirse en esta región de la ZVS de los Andes: basaltos empobrecidos (tipo-1) y enriquecidos (tipo-2) en elementos incompatibles. En comparación con los basaltos del tipo-1, los del tipo-2 presentan un grado más bajo de zonación del olivino y sus razones $FeO^{(T)}/MgO$, La/Yb, y $^{87}Sr/^{86}Sr$ son más elevadas. En los basaltos del tipo-2, el olivino raramente coexiste con augita. Los fenocristales de plagioclasa de ambos tipos de basaltos exhiben una fuerte zonación normal, que varía de An_{93} (centro) a An_{58} (bordes). A pesar de estar ubicadas en un área de corteza continental presumiblemente delgada, las riolitas del Chaitén son geoquímicamente semejantes a las riolitas de los 33-37°S (donde la corteza continental es gruesa), pero son más ricas en Pb radiogénico, en especial en ^{206}Pb. En comparación con basaltos vecinos del Michinmahuida, estas riolitas tienen razones isotópicas de Sr, Pb y O más elevadas y de Nd más bajas, están notablemente empobrecidas en Ca, Sr, Eu, Ti, Zr, Hf, Y y en tierras raras medianas y pesadas, y presentan razones K/Rb más bajas. Sobre la base de sus diferencias de composición, los basaltos del tipo-1 no son magmas parentales del tipo-2. Sus diferencias parecen reflejar diferentes grados de fusión parcial de la astenósfera seguido de diferentes grados de contaminación a nivel de la corteza inferior o media. En niveles corticales superiores, los magmas basálticos evolucionan a intermedios ya sea por cristalización fraccionada, acompañada de contaminación cortical o por mezcla con magmas riolíticos generados por fusión de material cortical.

Palabras claves: Petrología, Geoquímica, Volcanismo cuaternario, Andes del Sur, Sur de Chile.

INTRODUCTION

The Quaternary volcanic front of the Southern Volcanic Zone (SVZ) of the Andes extends between latitudes 33° and 46°S, and is a product of the subduction of the oceanic Nazca plate beneath the continental South American plate. Its northern end is associated with the intersection of the Juan Fernández Ridge with the Chile-Perú Trench and its southern end is the triple junction Nazca-Antarctic-South American plates (Fig.1).

While numerous geochemical and petrological studies have been carried out in the Quaternary volcanic front of the SVZ of the Andes between latitudes 33°00' and 41°30'S (see Hildreth and Moorbath, 1988, and references therein; Tormey *et al.*, 1991, and references therein; Ferguson *et al.*, 1992, and references therein), similar studies are comparatively scarce between 41°30' and 46°00'S (see Stern *et al.*, 1976, and references therein, Onuma and López-Escobar, 1987, and references therein; Futa and Stern, 1988, and references therein), mainly because of serious logistic problems (lack of roads, bad climatic conditions, dense vegetation, massive glaciers).

In the 41°30'-46°00'S region of the SVZ, the underthrusting of the Nazca plate beneath the South American plate has produced thirteen major volcanic centers (Fig.1; Table 1). Most of them are basaltic in composition and Pleistocene to Recent in age (Kilian and López-Escobar, 1989, 1991). Rhyolites occur only at Chaitén volcano. Many of these centers are related, not only to the subduction of the oceanic Nazca Plate beneath the continental South American plate, but also to the Liquiñe-Ofqui fault zone, that extends for *ca.* 1,000 km, between latitudes 38° and 47°S.

The aim of this study is to present and to discuss petrographical and geochemical data (major and trace elements, and isotopic compositions) obtained from samples recovered at the thirteen major volcanoes located in the 41°30'-46°00'S region of the Quaternary volcanic front of the SVZ of the Andes.

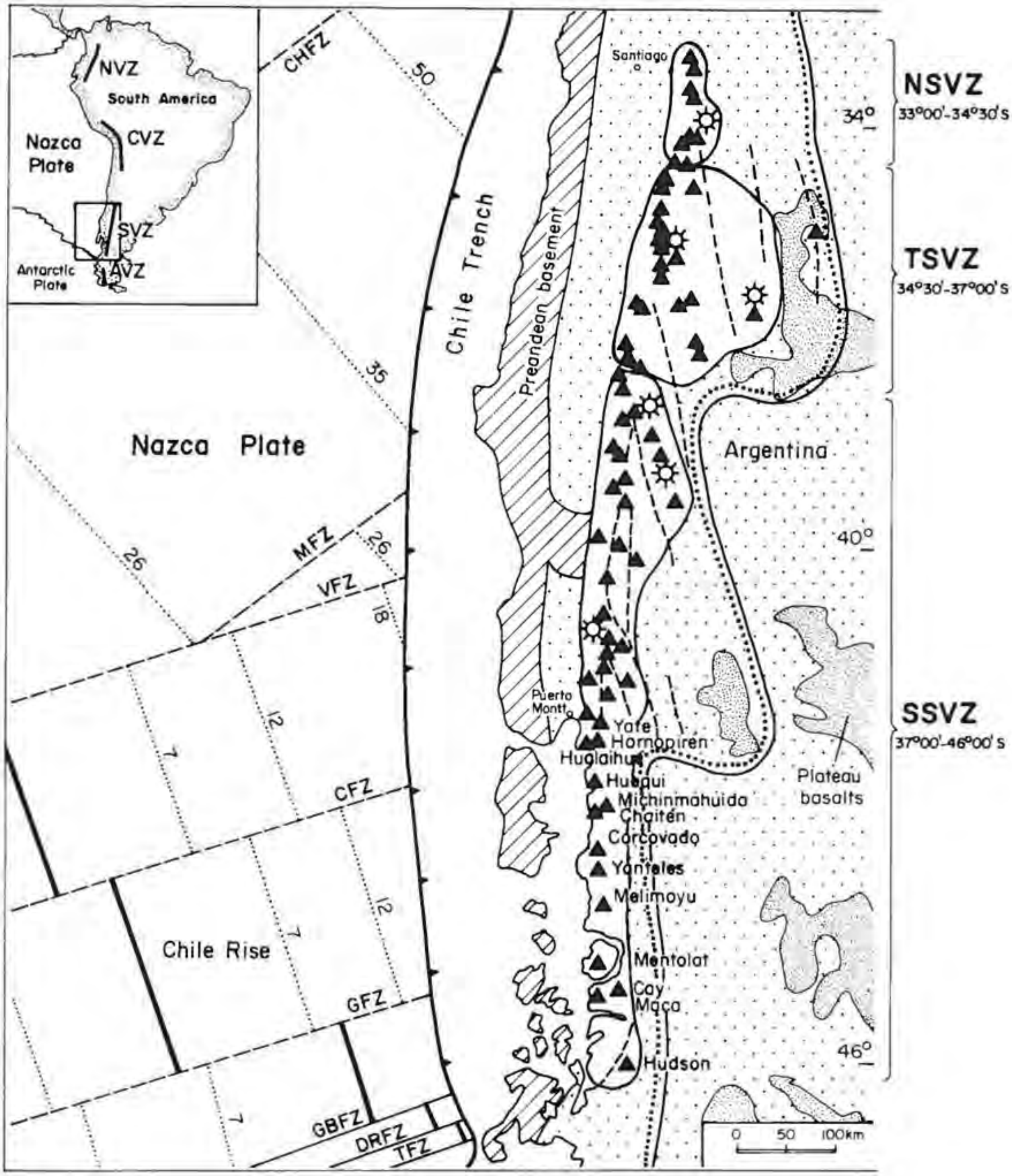


FIG.1. The Southern Volcanic Zone (SVZ) of the Andes and its three main regions: northern (NSVZ 33°00'-34°30'S), transition (TSVZ; 34°30'-37°00'S) and southern (SSVZ; 37-46°S). The location of the SVZ Quaternary volcanic front, Chile trench, Chile Rise and the ages of the oceanic Nazca plate (Herron *et al.*, 1981) are also shown.

TABLE 1. MINERAL COMPOSITION OF ROCKS FROM THE SSVZ OF THE ANDES BETWEEN 41°30' AND 46°00'S.

Lava types	Phenocrysts									Groundmass							
	Pl	(An)	Bt	Am	Opx	Cpx	Ol	(Fo)	Or	Q	Pl	(An)	Opx	Cpx	Ol	Ap	Or	Gl
Yate-Basaltic Andesite	+++	(81-65)	-	-	++	+	+	(79-72)	+	-	++	(57-49)	+	-	-	-	+	+-
Hornopirén-Basalt	++	(87-73)	-	-	+	++	+	(81-70)	-	-	++	(70-61)	-	+	-	+	+	-
Hualaihué-Basalt	++	(84-69	-	-	+	++	+	(82-74)	+-	-	++	(59-48	+	+	-	+	+	+-
Huequi-Andesite	++	(72-48)	-	+	++	+-	+	(76-75)	+-	+	++	(67-49)	+	-	-	+	+	+-
Michinmahuida-Basalt	+++	(92-58)	-	-	+	+	+	(72-69)	+-	-	+	(64-61)	+-	+	-	+	+	+-
Chaitén-Rhyolite	+	(43-36)	+	+-	+	-	-		-	+	+	(37-36)	+	-	-	+	-	+++
Corcovado-Basalt	++	(92-56)	-	-	+	+	+	(80-71)	+-	-	++	(57-52)	-	+	-	-	+	-
Yanteles-Basalt	++	(90-69)	-	-	+-	+	+	(82-66)	+-	-	+	(67-46)	+-	+	-	-	+	-
Melimoyu-Andesite	++	(89-72)	-	-	+-	+	+-		-	-	++	(53-40)	+-	+	-	-	+	-
Mentolat-Andesite	+++	(92-47)	+-		+-	+	+-	(76)	+-	+	++	(63-47)	+-	+	-	+	+	+-
Cay-Basalt	+	(93-61)	-	-	-	++	++	(85-69)	-	-	+	(64-53)	+-	+	+	-	+	-
Maca-Basalt	+	(89-48)	-	-	-	++	++	(87-73)	-	-	+	(72-63)	+-	+	+	-	+	-
Hudson-Basalt	++	(86-70)	-	-	+-	++	+	(75)	-	-	+	(58-49)	+-	++	+	-	+	-

Am=Amphibole; An=Anorthite; Ap-Apatite; Bt=Biotite; Cpx=Clinopiroxene; Fo=Forsterite; Gl=Glass; Ol=Olivine; Or=Ore; Opx=Orthopyroxene; Pl=Plagioclase; Q=Quartz

Quantity: +++ main constituent; ++ frequent; + accessory, +- occasionally; - not detected

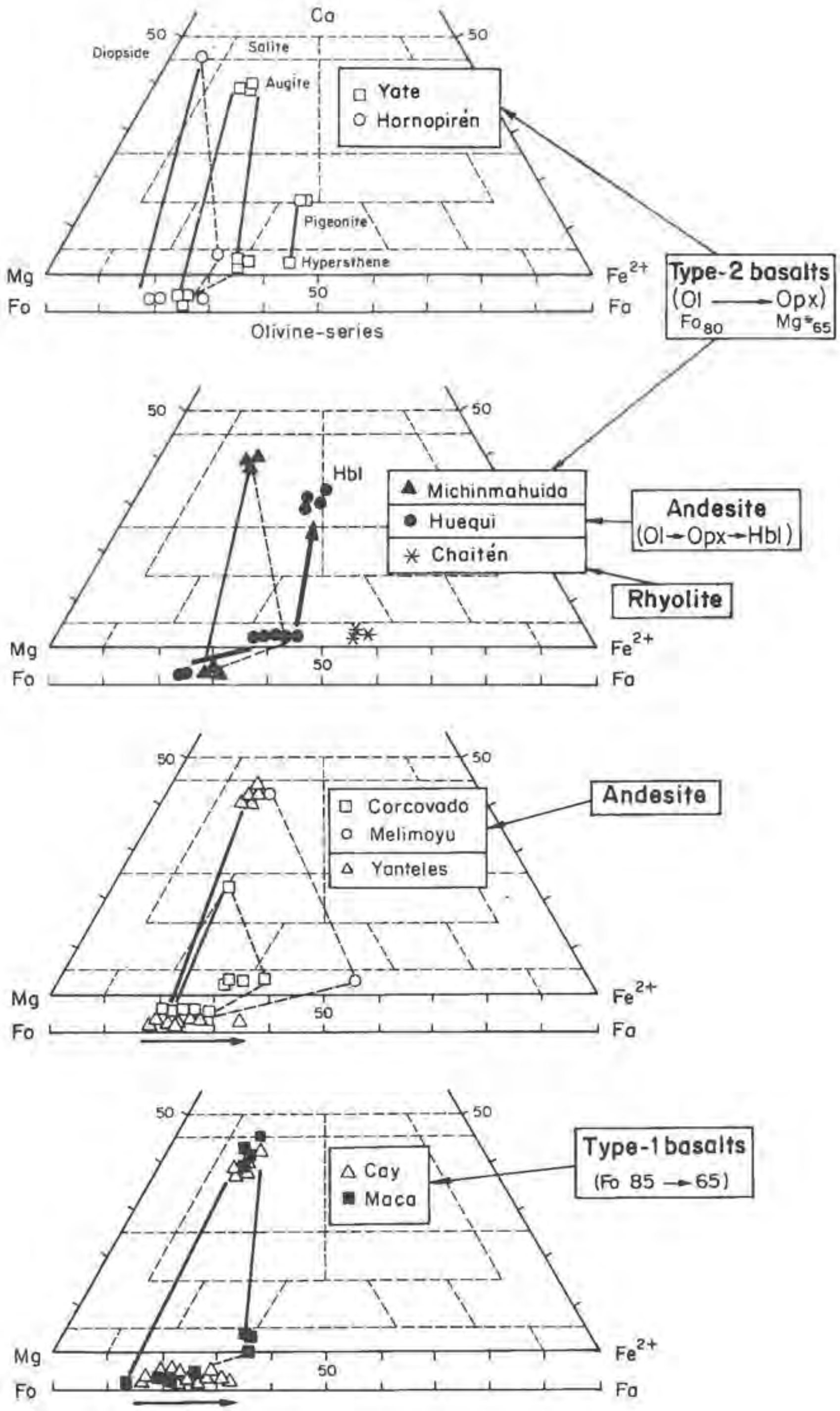


FIG. 2. Ca-Fe$^{(T)}$-Mg compositions of the orthopyroxene, clinopyroxene, olivine and amphibole in different rock types of the SSVZ between 41°30' and 46°00'S, ordered from north to south.

GEOLOGIC OUTLINE

One of the main structural features of the Andean region under study is the Liquiñe-Ofqui fault zone (Hervé *et al.*, 1978; Hervé *et al.*, 1979; Hervé, 1984; Thiele *et al.*, 1986), which is a dextral transcurrent dislocation (Hervé, 1984; Pankhurst *et al.*, in press; Cembrano, 1992), represented by a N-S trending belt of cataclastic and mylonitic rocks. South of 38°S, this fault zone controls a large number of SVZ centers (Hervé *et al.*, 1978; Thiele *et al.*, 1986; Fig. 1).

Many centers belonging to the 41°30'-46°00'S region of the Quaternary volcanic front of the SVZ of the Andes have Paleozoic to Mesozoic basement, but Yate, Michinmahuida and Mentolat overlie Miocene to Pliocene volcanic formations (Kilian and López-Escobar, 1989; 1991). Yate, Hualaihué, Michinmahuida and Hudson show evidence of having developed Pleistocene calderas. Relicts of the pre-caldera units are intensely eroded and partially covered by material erupted by Holocene volcanic cones. These cones are either developed within the Pleistocene calderas or as satellite cones.

Yate, Michinmahuida, Corcovado, Yanteles, Melimoyu, Mentolat, Cay, Maca, and Hudson are large composite stratovolcanoes, whose geology is now under a detailed study. Hualaihué is a small cinder cone, emplaced in the center of a volcanic caldera structure. Hornopirén is also a relatively small cinder and lava flow center, with almost a perfect conical shape, located 15 km north-east of the Hualaihué volcano. Chaitén volcano is a relatively small center, that apparently suffered a caldera collapse; it has a resurgent dome and is located 20 km south-west of the Michinmahuida volcano.

PETROGRAPHY

The petrography of the studied samples was determined by optical microscope and the chemical compositions of the constituent minerals and glass were obtained by electron microprobe (ARL-Applied Research Laboratories) at the Mineralogical Institute of the Tübingen University. A total of 6 electron-microprobe analyses were made of amphibole, 3 of biotite, 289 of plagioclase, 48 of olivine, 15 of opaques, 62 of pyroxene, and 12 of glass present in the groundmass, as well as glass occurring as inclusions in phenocrysts. Cross sections of the plagioclase, olivine and pyroxene phenocrysts were made with different intervals down to 4 mµ. The results are summarized in table 1 and figure 2.

The first petrographic investigations of the 41°30'-46°00'S volcanic rocks (López-Escobar *et al.*, 1985b) indicated that while a clinopyroxene+orthopyroxene +opaques assemblage was common in the northern part of this region, an olivine+clinopyroxene assemblage was common in the southern part. The current investigation modifies this general view.

Basaltic rocks from Yate, Hornopirén, Michinmahuida, Cay, Maca, and Hudson contain subhedral olivine+clinopyroxene+plagioclase phenocrysts. Basaltic andesites from Huequi, Melimoyu and Mentolat commonly contain plagioclase+clinopyroxene+orthopyroxene±olivine phenocrysts. Andesites contain subhedral plagioclase+clinopyroxene+ orthopyroxene phenocrysts. Acid andesites and dacites from Yate and Mentolat have plagioclase+ orthopyroxene±amphibole phenocrysts. The Huequi andesites and dacites and some Mentolat andesites have a plagioclase+olivine+orthopyroxene+ amphibole assemblage that reflects disequilibrium, confirming the observation and interpretation of Fuenzalida (1979). In addition, crystal clots of clinopyroxene+olivine are common in most basalts, and crystal clots of plagioclase+clinopyroxene+ orthopyroxene+ opaques are common in most andesites.

Plagioclase is the most abundant phase, both as phenocryst and in the groundmass. It is an early phenocryst in the Pleistocene andesites of Yate, Hornopirén, Michinmahuida, Yanteles and Mentolat, but was formed after olivine and clinopyroxene in the basalts of Mentolat, Cay, Maca and Hudson. Plagioclase phenocrysts in the basalts exhibit strong normal zoning (Fig. 3), from An_{93} (cores) to An_{58} (rims). The plagioclase phenocrysts of the Cay, Maca, and Hudson basalts have the highest An contents of all the investigated samples, with An_{92} to An_{88} in their

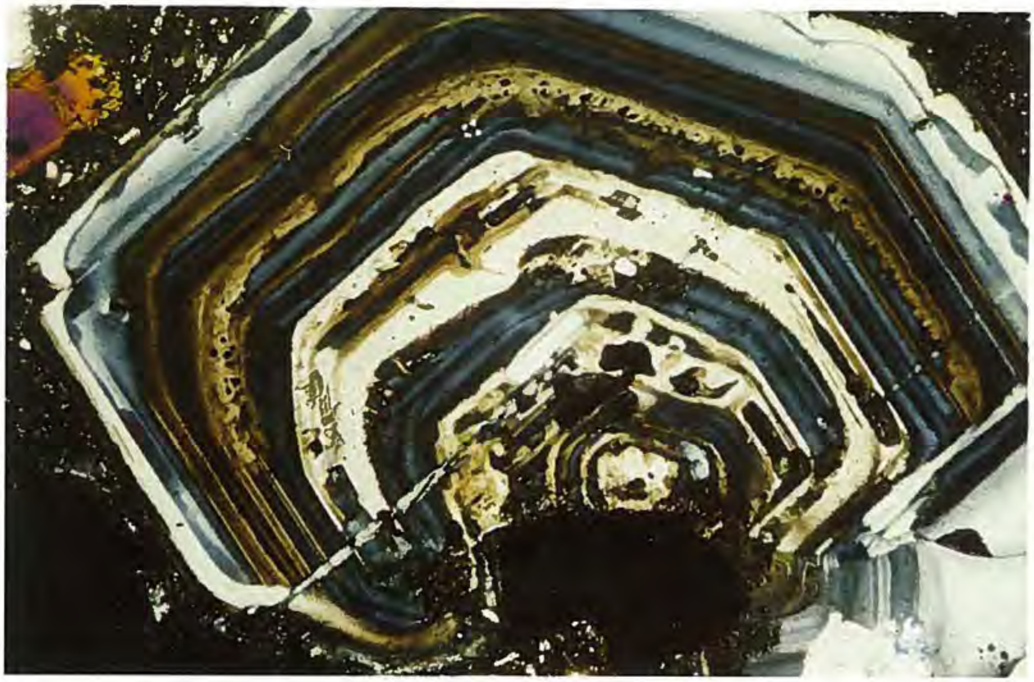


FIG. 3. Strong normal zoned plagioclase phenocryst of a Michinmahuida basalt (type-2 basalt).

cores and An_{62} to An_{50} in their rims. Normal zoning of plagioclase is even more marked (An_{93} to An_{45}) in the groundmass. Similar zoning is observed in the plagioclase of Corcovado and Melimoyu andesites. Oscillatory and reverse zoning are observed in the plagioclase crystals of Huequi andesites and dacites, and in some Mentolat andesites. Alkali feldspars formed in the groundmass of some basalts, and in Yate and Hudson andesites, as a very late-stage product of crystallization.

Ortho- and clinopyroxene coexist in most 41°30'-46°00'S volcanic rocks. Figure 2 shows their compositions in the Ca-Mg-Fe^{2}+pyroxene quadrilateral. The orthopyroxene is generally hypersthene, being Fe-hypersthene in the Chaitén rhyolites. The clinopyroxene is normally augite, being diopside in a basaltic sample from Hornopirén and salite in a sample from Mentolat. Orthopyroxene commonly occurs as a phenocryst phase (1-3 mm), but is also present in the groundmass of Yate, Hornopirén, Huequi, and Mentolat andesites. In most other rocks studied, orthopyroxene appears as small xenocrysts. Euhedral clinopyroxene phenocrysts occur in basalts and andesites from Yate, Hualaihué, Hornopirén, Huequi, Mentolat, Cay and Maca volcanoes (Fig. 4). Coexisting ortho- and clinopyroxenes have similar Fe/Mg ratios in lavas from Yate, Hornopirén, Corcovado, Melimoyu, Mentolat and Maca (Fig. 5). The lowest Fe/Mg ratios occur in orthopyroxenes from Mentolat lavas. Zonations were not clearly observed (Fig. 2).

Olivine is present in most basalts, basaltic andesites and andesites from this region of the SVZ. On the basis of its degree of zonation and association with augite, the basalts have been subdivided into two types(1 and 2). In type-1 basalts (Hualaihué, Corcovado, Cay and Maca); large euhedral olivine phenocrysts (1-4 mm), showing a comparatively strong normal zoning (Fo_{85}-Fo_{65}), coexist with large phenocrysts of augite (2-4 mm; Figs. 2, 4). By contrast, in type-2 basalts (Yate, Michinmahuida, Melimoyu and Hudson), olivine phenocrysts have a weaker normal zonation (Fo_{75}-Fo_{65}) and rarely coexist with augite (Fig. 5). In both types, hypersthene coexists in disequilibrium with olivine and augite (dashed lines in figure 2), but in some type-2 basalts (Yate and

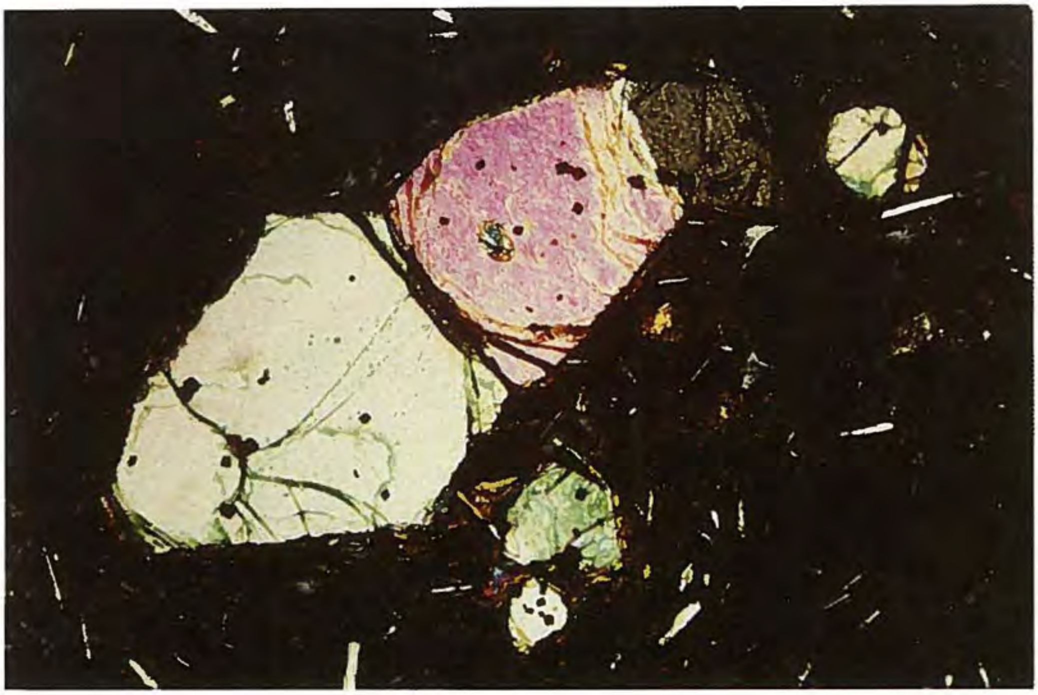


FIG. 4. Large olivine and augite phenocrysts, in a matrix of plagioclase microlites, in a basalt from Maca volcano (type-1 basalt).

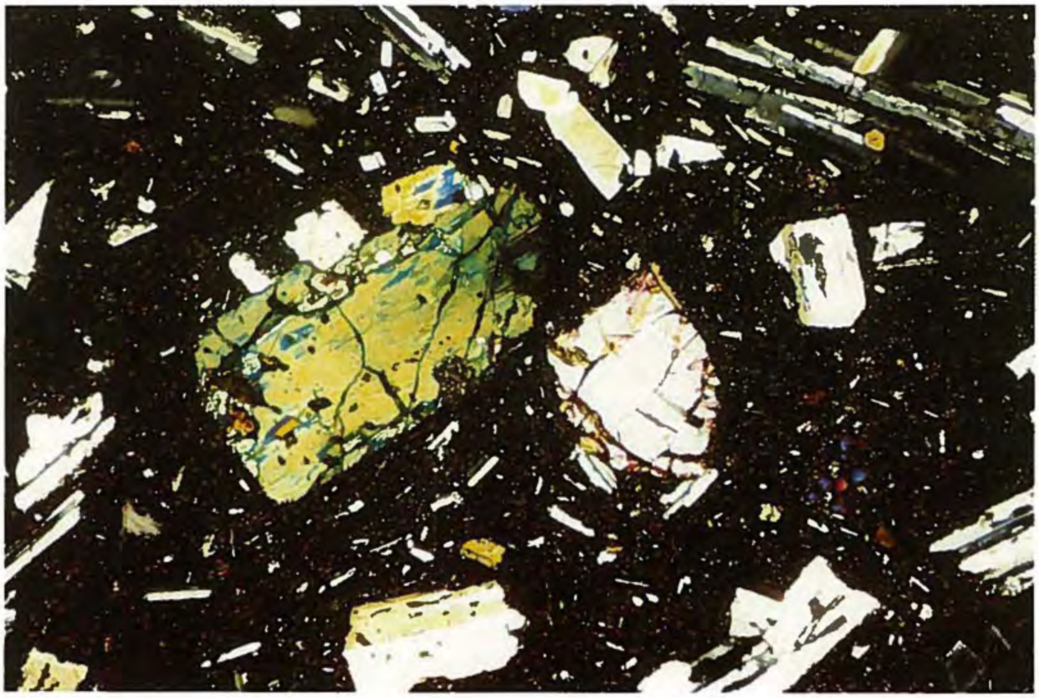


FIG. 5. Normal zoned plagioclase phenocrysts, hypidiomorphic augite and hypersthene in a basalt from Michinmahuida volcano (type-2 basalt).

TABLE 2. MAJOR AND TRACE ELEMENTS ABUNIANCES, AND ISOTOPIC AND INCOMPATIBLE ELEMENT RATIOS OF SELECTED SAMPLES FROM THE SSVZ OF THE ANDES BETWEEN 41°30' AND 46°00'S.

	YATE	HUALAIHUE	HORNOPIREN	HUEQUI	HUEQUI	MICHINMAHUIDA		CHAITEN	CORCOVADO	CORCOVADO	CORCOVADO
Latitude	41°48'S	41°53'S	41°53'S	42°23'S	42°23'S	42°48'S	42°48'S	42°50'S	43°11'S	43°11'S	43°11'S
Sample N°	120284-11	120284-09	120284-10	120284-08	120284-07	120284-05	120284-06	120284-04	120284-03	120284-02	120284-01
	(Yat-1)	(Hua-1)	(Hor-1)	(Hue-2)	(Hue-1)	(Mic-1)	(Mic-2)	(Che-1)	(Cor-3)	(Cor-2)	(Cor-1)
SiO_2	60.81	51.42	53.05	56.53	58.66	51.88	60.58	74.44	51.68	52.74	56.38
TiO_2	0.87	0.84	1.06	0.75	0.63	1.56	1.21	0.29	0.99	1.01	1.02
Al_2O_3	17.97	17.95	18.70	19.38	19.34	17.56	16.05	14.94	20.48	20.25	19.51
Fe_2O_3	2.29	6.22	2.56	3.20	5.16	2.84	3.26	0.47	2.85	2.30	2.33
FeO	4.08	2.84	6.12	4.28	1.60	7.64	4.64	0.94	5.04	5.38	5.13
MnO	0.12	0.14	0.15	0.14	0.13	0.16	0.16	0.05	0.14	0.14	0.14
MgO	1.78	7.14	4.70	3.40	2.72	3.94	1.75	0.27	5.25	3.96	3.45
CaO	5.08	9.44	8.64	7.34	6.72	8.75	4.40	1.43	9.63	9.03	6.82
Na_2O	4.14	2.70	3.00	3.63	3.94	3.42	4.81	4.11	3.04	3.51	3.80
K_2O	1.67	0.57	0.91	0.79	0.73	1.09	2.27	2.89	0.58	0.74	1.11
P_2O_5	0.26	0.18	0.29	0.23	0.25	0.39	0.46	0.08	0.19	0.20	0.29
LOI	0.80	0.67	0.53	0.43	0.07	0.79	0.50	0.35	0.44	0.64	0.63
TOTAL	99.87	100.11	99.71	100.10	99.95	100.02	100.09	100.26	100.31	99.90	100.61
Rb	55.7	10.7	20.3	-	20.5	29.5	-	117.0	11.4	-	-
Cs	2.46	0.40	0.82	-	1.41	1.43	-	7.79	0.63	-	-
Sr	375	519	425	403	403	395	318	147	414	429	350
Ba	491	155	321	245	266	315	554	680	210	237	336
Sc	17	31	28	14	12	31	22	2.2	29	26	23
V	89	182	182	96	81	225	62	11	190	176	155
Cr	3.0	191.0	76.0	-	3.9	43.2	-	2	87.2	-	-
Co	11.0	33.2	28.7	-	14.3	25.9	-	1.2	29.7	-	-
Zn	76	81	92	-	76	99	-	36	118	-	-
Y	36	20	28	18	19	41	59	14	22	24	29
Zr	184	85	145	-	155	188	-	129	104	-	-
Hf	4.55	1.90	3.40	-	3.06	4.67	-	3.22	2.17	-	-
Ta	0.44	0.16	0.37	-	0.39	0.56	-	0.95	0.29	-	-
Th	6.26	1.20	2.17	-	2.22	3.68	-	12.70	2.22	-	-
U	1.37	0.31	0.40	-	0.24	0.86	-	2.94	0.70	-	-
La	20.3	9.2	18.7	-	13.5	21.1	-	26.2	10.9	-	-
Ce	42.7	19.3	40.7	-	29.0	45.6	-	47.5	24.6	-	-
Nd	26.3	12.8	24.3	-	16.5	30.0	-	17.5	21.0	-	-
Sm	6.16	3.35	5.18	-	3.60	7.13	-	2.81	3.33	-	-
Eu	1.49	1.02	1.39	-	1.07	1.71	-	0.52	1.07	-	-
Gd	-	-	-	-	-	-	-	-	-		-
Tb	0.91	0.50	0.77	-	0.46	1.06	-	0.33	0.49	-	-
Yb	3.28	1.65	2.38	-	1.86	3.66	-	1.29	1.94	-	-
Lu	0.518	0.281	0.395	-	0.275	0.602	-	0.210	0.344	-	-
$^{87/86}Sr$	-	0.70356±3	-	-	-	0.70431±3	-	0.70560±3	0.70421±3	-	-
$^{143/144}Nd$	-	0.51283±2	-	-	-	0.51277±1	-	0.51259±1	0.51276±3	-	-
$^{206/204}Pb$	-	-	-	18.6243±148	-	18.6371±5	-	18.6286±7	18.6150±20	-	-
$^{207/204}Pb$	-	-	-	15.5923±124	-	15.6188±5	-	15.6344±6	15.6480±17	-	-
$^{208/204}Pb$	-	-	-	38.5245±303	-	38.5326±17	-	38.7643±14	38.6525±40	-	-
δ^{18}-O (o/oo)	-	-	-	-	-	+6.4	-	+9.4	-	+6.4	-
$^{87/86}Sr^{(d)}$	0.70437	0.70395	0.70434	0.70475	0.70482	0.70440	0.70438	0.70570	0.70440	0.70430	0.70456
K/Rb	250	444	374	-	297	308	-	206	424	-	-
Rb/Cs	22.6	26.8	24.8	-	14.5	20.6	-	15.0	18.1	-	-
Ba/La	24.2	16.8	17.2	-	19.7	14.9	-	26.0	19.3	-	-
La/Yb	6.2	5.6	7.9	-	7.3	5.8	-	20.3	5.6	-	-
Eu/Eu*	0.74	0.92	0.91	-	0.93	0.73	-	0.59	0.98	-	-
Zr/Hf	40.4	44.7	42.6	-	50.7	40.3	-	40.1	47.9	-	-
Th/U	4.57	3.87	5.43	-	9.25	4.28	-	4.32	3.17	-	-
Al_2O_3/CaO	3.5	1.9	2.2	2.6	2.9	2.0	3.6	10.4	2.1	2.2	2.9
$FeO^{(T)}$/MgO	3.5	1.2	1.8	2.1	2.3	2.6	4.3	5.0	1.4	1.9	2.1

	YANTELES	YANTELES	MELIMOYU	MELIMOYU	MELIMOYU	MENTOLAT	MENTOLAT	MENTOLAT	MENTOLAT	MENTOLAT	CAY
Latitude	43°28'S	43°28'S	44°04'S	44°04'S	44°04'S	44°42'S	44°42'S	44°42'S	44°42'S	44°42'S	45°04'S
Sample N°	100284-10	100284-09	100284-07	100284-08	100284-06	100284-03	100284-01	100284-02	100284-05	100284-04	070284-08
	(Yan-2)	(Yan-1)	(Mel-2)	(Mel-3)	(Mel-1)	(Men-3)	(Men-1)	(Men-2)	(Men-5)	(Men-4)	(Cay-4)
SiO_2	54.57	57.46	53.29	53.44	56.84	53.29	59.16	59.78	60.55	63.02	48.96
TiO_2	1.00	0.99	1.45	1.49	1.43	0.99	0.89	0.82	0.83	0.80	1.00
Al_2O_3	18.14	19.07	19.84	19.66	17.29	20.37	19.07	19.30	19.30	18.40	18.69
Fe_2O_3	2.81	3.02	3.64	4.37	3.04	5.02	2.40	2.74	2.95	1.96	3.55
FeO	6.03	4.16	5.24	4.66	5.62	3.57	4.13	3.59	3.22	3.02	5.20
MnO	0.14	0.14	0.16	0.16	0.17	0.16	0.15	0.15	0.14	0.15	0.14
MgO	4.02	2.76	2.80	2.72	2.85	3.29	2.20	2.06	2.04	1.48	5.89
CaO	8.33	6.94	7.26	7.02	5.95	8.18	5.59	6.06	5.73	4.25	9.75
Na_2O	3.53	3.97	4.20	4.18	4.64	3.66	4.82	4.87	4.87	5.95	2.96
K_2O	0.76	1.05	1.28	1.37	1.62	0.48	0.91	0.87	0.65	0.99	0.67
P_2O_5	0.17	0.23	0.38	0.38	0.44	0.20	0.26	0.22	0.21	0.27	0.18
LOI	0.79	0.45	0.98	0.96	0.38	1.39	0.94	0.21	0.17	0.39	2.85
TOTAL	100.29	100.24	100.52	100.41	100.27	100.60	100.52	100.67	100.86	100.68	99.84
Rb	18.9	-	-	56.0	-	-	-	-	21.6	29.4	-
Cs	1.07	-	-	1.17	-	-	-	-	0.31	2.13	-
Sr	409	383	501	497	420	436	376	403	404	378	610
Ba	229	341	406	482	465	183	295	288	301	325	198
Sc	29	23	27	24	23	23	19	15	15	11	28
V	219	141	237	234	196	163	116	94	95	56	198
Cr	34.1	-	-	6.6	-	-	-	-	4.0	1.9	-
Co	25.0	-	-	18.7	-	-	-	-	11.5	6.3	-
Zn	86	-	-	98	-	-	-	-	77	79	-
Y	25	31	36	36	42	30	34	34	33	35	19
Zr	90	-	-	213	-	-	-	-	165	165	-
Hf	2.40	-	-	5.39	-	-	-	-	4.23	4.49	-
Ta	0.27	-	-	1.03	-	-	-	-	0.40	0.44	-
Th	2.15	-	-	6.38	-	-	-	-	1.86	2.14	-
U	0.59	-	-	1.37	-	-	-	-	0.56	0.59	-
La	10.1	-	-	31.1	-	-	-	-	12.3	13.6	-
Ce	22.7	-	-	62.6	-	-	-	-	28.8	32.1	-
Nd	15.6	-	-	33.8	-	-	-	-	15.0	22.3	-
Sm	3.52	-	-	7.45	-	-	-	-	4.92	5.31	-
Eu	1.10	-	-	1.85	-	-	-	-	1.45	1.49	-
Gd	-	-	-	-	-	-	-	-	-	-	-
Tb	0.57	-	-	1.07	-	-	-	-	0.86	0.89	-
Yb	2.24	-	-	3.70	-	-	-	-	3.30	3.50	-
Lu	0.340	-	-	0.570	-	-	-	-	0.537	0.550	-
$^{87/86}Sr$	-	-	0.704075±10	-	-	0.70400±3	0.704142±10	0.704201±10	0.70409±4	-	-
$^{143/144}Nd$	-	-	0.51281±3	-	-	0.51287±3	0.512851±5	0.512845±14	0.51276±3	0.51290±2	-
$^{206/204}Pb$	-	-	18.5793±6	-	-	18.6131±11	18.5848±7	18.5327±12	18.5798±6	18.6230±4	18.4877±14
$^{207/204}Pb$	-	-	15.6021±5	-	-	15.6164±11	15.6040±6	15.6053±10	15.6007±5	15.6218±3	15.5880±12
$^{208/204}Pb$	-	-	38.5255±13	-	-	38.5834±25	38.5114±15	38.4713±25	38.4953±12	38.5648±8	38.4075±29
δ^{18}-O (o/oo)	-	+6.4			+7.1	-	+7.7	+7.6	-	-	+7.7
$^{87/86}Sr^{(d)}$	0.70422	0.70455	0.70417	0.70424	0.70420	0.70419	0.70431	0.70434	0.70400	0.70431	0.70394
K/Rb	335	-	-	204	-	-	-	-	328	281	-
Rb/Cs	17.7	-	-	47.9	-	-	-	-	69.7	13.8	-
Ba/La	22.7	-	-	15.5	-	-	-	-	24.5	23.9	-
La/Yb	4.5	-	-	8.4	-	-	-	-	3.7	3.9	-
Eu/Eu*	0.93	-	-	0.76	-	-	-	-	0.86	0.83	-
Zr/Hf	37.5	-	-	39.5	-	-	-	-	39.0	36.7	-
Th/U	3.64	-	-	4.66	-	-	-	-	3.32	3.63	-
Al_2O_3/CaO	2.2	2.7	2.7	2.8	2.9	2.5	3.4	3.2	3.4	4.3	1.9
$FeO^{(T)}$/MgO	2.1	2.5	3.0	3.2	2.9	2.5	2.9	2.9	2.9	3.2	1.4

	CAY	CAY	CAY	CAY	MACA	MACA	MACA	MACA	HUDSON	HUDSON	HUDSON
Latitude	45°04'S	45°04'S	45°04'S	45°04'S	45°06'S	45°06'S	45°06'S	45°06'S	46°00'S	46°00'S	46°00'S
Sample N°	070284-05	070284-06	070284-09	070284-07	070284-04	070284-02	070284-01	070284-03	010284-02	010284-03	010284-01
	(Cay-1)	(Cay-2)	(Cay-5)	(Cay-3)	(Mac-4)	(Mac-2)	(Mac-1)	(Mac-3)	(Hud-2)	(Hud-3)	(Hud-1)
SiO_2	49.71	50.47	50.77	51.23	50.36	53.50	54.72	55.32	49.56	50.82	51.90
TiO_2	1.13	1.13	1.03	1.07	0.95	1.30	1.01	1.20	1.55	2.33	1.57
Al_2O_3	19.42	18.35	20.30	18.18	19.34	18.24	17.82	18.09	18.27	16.62	16.87
Fe_2O_3	2.88	2.48	2.15	2.68	2.48	2.49	2.42	5.19	3.61	3.48	2.45
FeO	6.15	6.75	5.73	6.37	5.95	6.67	4.98	4.08	6.45	7.83	7.41
MnO	0.14	0.15	0.13	0.14	0.14	0.15	0.14	0.15	0.16	0.19	0.17
MgO	5.65	5.98	4.92	6.35	6.56	3.05	5.33	3.04	4.97	3.78	4.32
CaO	9.79	9.83	10.12	9.75	9.35	7.98	7.38	6.81	7.18	8.17	8.87
Na_2O	3.29	3.31	3.11	3.12	3.04	3.96	3.86	4.22	3.92	4.53	3.96
K_2O	0.76	0.84	0.62	0.85	0.57	1.28	1.21	1.29	1.58	1.14	1.03
P_2O_5	0.19	0.21	0.19	0.20	0.20	0.27	0.28	0.27	0.37	0.80	0.52
LOI	1.04	0.46	1.38	0.46	1.65	0.82	0.76	0.67	2.40	0.57	0.72
TOTAL	100.15	99.96	100.45	100.40	100.59	99.71	99.91	100.33	100.02	100.26	99.79
Rb	16.0	-	-	-	12.8	-	-	31.4	-	28.6	31.4
Cs	0.41	-	-	-	0.60	-	-	0.88	-	0.44	0.66
Sr	623	632	573	616	-	-	-	-	643	512	559
Ba	247	265	196	251	173	304	298	368	318	380	318
Sc	32	30	26	30	26	28	20	28	28	28	33
V	214	226	190	219	173	220	142	206	215	248	230
Cr	84.3	-	-	-	147.0	-	-	18.3	-	8.8	51.3
Co	32.4	-	-	-	34.7	-	-	21.8	-	25.4	27.7
Zn	92	-	-	-	81	-	-	105	-	108	112
Y	21	23	20	22	19	33	23	32	30	41	31
Zr	190	-	-	-	102	-	-	124	-	198	243
Hf	2.28	-	-	-	2.05	-	-	3.76	-	4.65	3.98
Ta	0.20	-	-	-	0.17	-	-	0.33	-	0.69	0.74
Th	1.67	-	-	-	-	-	-	-	-	3.55	2.75
U	0.49	-	-	-	0.44	-	-	0.77	-	0.82	0.67
La	10.2	-	-	-	7.9	14.6	12.9	16.0	-	30.0	22.9
Ce	21.8	-	-	-	18.0	34.0	28.5	35.1	-	64.9	50.3
Nd	14.0	-	-	-	13.1	-		27.6	-	38.0	30.0
Sm	3.82	-	-	-	3.13	-	4.02	5.35	-	8.63	6.57
Eu	1.20	-	-	-	1.05	1.57	1.14	1.43	-	2.43	1.89
Gd	-	-	-	-	-	5.0	4.4	-	-	-	-
Tb	0.55	-	-	-	0.49	-	-	0.80	-	1.23	0.84
Yb	1.82	-	-	-	1.81	2.66	1.62	3.07	-	3.61	2.86
Lu	0.340	-	-	-	0.288	0.438	0.296	0.498	-	0.582	0.430
$^{87/86}Sr$	-	0.703929±10	0.703981±7	-	-	-	0.704120±10	0.704183±10	0.704503±6	0.70413±2	-
$^{143/144}Nd$	0.51271±3	0.512797±5	0.512802±7	-	-	-	0.512789±5	0.512791±4	0.512818±4	0.512750±3	-
$^{206/204}Pb$	18.4814±10	18.5065±11	18.5252±33	18.5142±10	-	18.5716±8	18.5452±7	18.5718±9	18.5936±4	18.4733±11	-
$^{207/204}Pb$	15.5735±8	15.5835±9	15.5940±29	15.5943±9	-	15.6018±6	15.6005±6	15.6085±7	15.6063±4	15.5473±10	-
$^{208/204}Pb$	38.3795±25	38.4098±23	38.4481±71	38.4387±21	-	38.5122±16	38.4782±15	38.5197±19	38.5421±8	38.3281±24	-
δ^{18}-O (o/oo)	-	+6.3	+6.6	+7.6	+7.5	+7.7	+8.4	+7.4		+6.1	+5.8
$^{87/86}Sr^{(d)}$	0.70403	0.70402	0.70416	0.70395	0.70417	0.70422	0.70408	0.70431		0.70418	0.70424
K/Rb	396	-	-	-	371	-	-	342	-	332	273
Rb/Cs	39.0	-	-	-	21.3			35.7	-	65.0	47.6
Ba/La	24.2	-	-	-	21.9	20.8	23.1	23.0	-	12.7	13.9
La/Yb	5.6	-	-	-	4.4	5.5	8.0	5.2	-	8.3	8.0
Eu/Eu*	0.96	-	-	-	1.01	0.95	0.91	0.81	-	0.86	0.90
Zr/Hf	83.3	-	-	-	49.8	-	-	33.0	-	42.6	61.1
Th/U	3.41	-	-	-	-	-	-	-	-	4.33	4.10
Al_2O_3/CaO	2.0	1.9	2.0	1.9	2.1	2.3	2.4	2.7	2.5	2.0	1.9
$FeO^{(T)}$/MgO	1.5	1.5	1.6	1.4	1.2	2.9	1.3	2.9	2.0	2.9	2.2

Notes:

a- Major elements were determined by wet chemical analyses at the Department of Geology, Universidad de Chile. Trace elements were determined by atomic absorption, X-ray fluorescence, neutron activation analysis and ICP at the Universidad de Chile, Ibaraki University and USGS;

b-Sr, Nd and Pb were extracted on the same dissolution using 100-200 mg of powder. After dissolution using approximately 1ml of HNO_3 combined with 3 o 5 mls of HF, residues were converted to nitrate and finally chloride; 1ml of 1M HBr was then added to the residue. Pb was separated by passing the sample through columns prepared from PVP disposable pipette tips fitted with 2 mm diameter polyethylene frit and containing Dowex 1x8 200-400 mesh resin; completely new columns were prepared for each sample to minimize the Pb blank. The Sr and Nd fractions were collected in 2 mls of 1M HBr and Pb collected in 1ml of 6M HCl. Sr and Nd were purified using standard one and two-column cation exchange techniques, respectively. Sr and Pb were run as the metal especies on single Ta and single Re filaments, respectively, and Nd was run as the metal species on double/triple Re-Ta filament assemblies, using a Finnegan MAT 261 multicollector mass spectrometer at the Open University, Milton Keynes, UK. Blanks for Sr, Nd and Pb were less than 3, 0.5, and 1 ng, respectively. Reference standards throughout the course of analysis averaged values of $^{87}Sr/^{86}Sr$=0.71019 ±1 for the NBS 987 standard, $^{143}Nd/^{144}Nd$=0.511843±15 for the La Jolla Nd standard. $^{87}Sr/^{86}Sr$ was normalized to $^{86}Sr/^{88}Sr$=0.1194; $^{143}Nd/^{144}Nd$ was normalized to a value of $^{146}Nd/^{144}Nd$=0.7219. Pb isotopic ratios were corrected relative to the average standard Pb isotopic compositions of Catanzaro *et al.* (1968). Based on repeated runs of NBS 981 common Pb standard, the reproducibility is better than ±0.14% per amu. Errors quoted for samples are one standard deviation from measured or calculated values;

c- O-isotopic composition was determined on whole rock samples by W. Hildreth (USGS) and R. Harmon (NERC Isotope Geoscience Laboratory, England);

d- The original values of Notsu and collaborators were normalized to NBS 897=0.71024, the NBS 697 value of Notsu *et al.* (1987) was 0.71030.

Hudson), hypersthene coexists in equilibrium with pigeonite. The latter mineral is common in those type-2 basalts having holocrystalline groundmass. The Yate, Hornopirén and Michinmahuida andesites usually contain small olivine xenocrysts with Fo content in the range Fo_{76}-Fo_{66}. The highest Fe/Mg ratio is observed in an andesite sample from Melimoyu, whose olivine composition is Fo_{80} and that of the hypersthene is Mg_{45} (Fig. 2).

Opaques are generally titanomagnetite and sometimes hematite. Early titanomagnetite phenocrysts have higher Ti/Fe ratios (*ca.* 0.1) than titanomagnetite crystals present in the groundmass (*ca.* 0.05).

Chaitén rhyolites are highly vitrophyric, containing only 5% volume of plagioclase microphenocrysts together with ferrohypersthene and biotite. The An content (An_{42}-An_{37}) as well as the degree of zoning of the plagioclase are low. Apatite and zircon are present as accessory minerals.

CHEMISTRY

MAJOR AND TRACE ELEMENTS

The geochemical data of 32 volcanic rocks of the 41°30'-46°00'S of the SSVZ are presented in table 2. This data constitute the basis of the following discussion. In addition, other 35 whole rock analyses (major and trace elements) of volcanic rock were obtained and are shown in figures 6-13.

Based on the distribution of data on a K_2O-SiO_2 classification diagram (Fig. 6) and on an AFM diagram (Fig. 7), the analyzed samples are low- to medium-K calcalkaline volcanic rocks, with tholeiitic affinities. Although they range in composition from basalt to rhyolite (Table 2), there is a predominance of basalts and basaltic andesites, particularly in the Holocene cones. The basalts show variable Al_2O_3 concentrations in the range 16 to 21 wt % (Fig. 8). According to their high Al_2O_3 and intermediate alkali contents, basalts of Corcovado, Maca, Cay, Mentolat and Melimoyu stratovolcanoes can be classified as high-alumina basalts. Andesites and dacites are found in the Pleistocene units of Yate, Hualaihué, Michinmahuida, and Hudson. Rhyolites (70-75% SiO_2) are present only at Chaitén volcano.

The type-1 basalts (Hualaihué, Corcovado, Cay and Maca) tend to be depleted in some large ion lithophile elements (LILE = Na_2O, K_2O, Rb, Cs, Ba, REE, Y, Th and U) and high field strength elements (HFSE = TiO_2, Zr, Hf and Ta) in comparison with type-2 basalts (Michinmahuida and Hudson), but tend to be enriched in Al_2O_3 (Fig. 8), MgO, CaO, Cr and Co (Table 3). In addition, type-1 basalts tend to have higher K/Rb (Fig. 9) and Ba/La (Fig. 10) ratios than type-2 basalts, but lower $FeO^{(T)}/MgO$ (Fig. 11) and La/Yb (Table 3; Fig. 12) ratios. However, both types of basalts have similar Zr/Hf, Th/U and Al_2O_3/CaO ratios (Table 3).

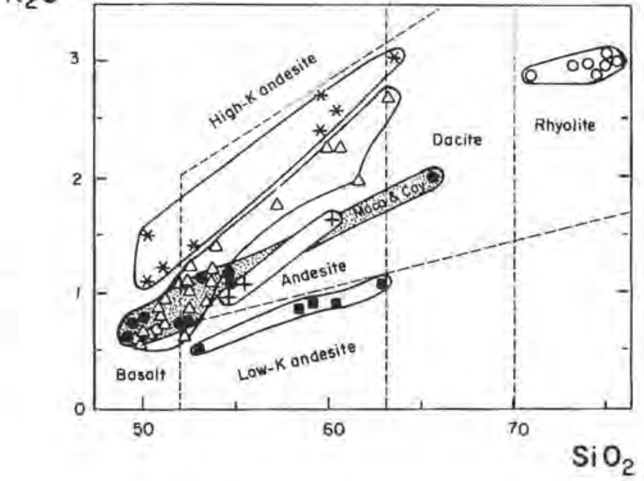


FIG. 6. K_2O *versus* SiO_2 diagram for rocks from different volcanic centers of the SSVZ between 41°30' and 46°00'S. Within each center, there exists a good K_2O-SiO_2 correlation, but the relationship between both oxides varies from one center to the other.

TABLE 3. COMPOSITIONAL RANGES OF TYPES 1 AND 2 BASALTS FROM THE SSVZ OF THE ANDES BETWEEN 41°30' AND 46°00'S COMPARED WITH THE COMPOSITIONAL RANGE OF THE SSVZ STRATOVOLCANO-BASALTS BETWEEN 37° AND 41°S.

	TYPE-1 BASALTS RANGE[1]		TYPE-2 BASALTS RANGE[2]		37°00-41°30'S BASALTS RANGE[3]	
SiO_2	48.96	51.68	49.56	51.90	48.39	52.08
TiO_2	0.84	1.13	1.55	2.33	0.43	1.22
Al_2O_3	17.95	20.48	16.62	18.27	14.64	22.37
$Fe_2O_3^{(T)}$	8.45	9.98	10.68	12.18	7.69	10.96
MnO	0.13	0.15	0.16	0.19	0.12	0.19
MgO	4.92	7.14	3.78	4.97	3.11	14.32
CaO	9.35	10.12	7.18	8.87	8.55	11.96
Na_2O	2.70	3.31	3.42	4.53	2.19	4.19
K_2O	0.57	0.85	1.03	1.58	0.29	0.88
P_2O_5	0.18	0.21	0.37	0.80	0.08	0.31
K	4731	7055	8549	13114	2407	7304
Rb	10.7	16.0	28.6	31.4	6.0	18.7
Cs	0.40	0.63	0.44	1.43	0.30	1.60
Sr	414	632	395	643	247	541
Ba	155	265	315	380	96	232
Ga	-	-	-	-	14.6	19.8
Pb	-	-	-	-	2.0	10.6
Sc	26.0	32.5	28.0	32.6	26.4	35.7
V	173	226	215	248	163	248
Cr	84	191	8	52	46	640
Co	29.7	34.7	25.4	27.7	23.0	64.5
Ni	-	-	-	-	9	302
Zn	81	118	98	112	68	96
Y	19	23	30	41	12	22
Zr	85	190	188	243	41	92
Nb	-	-	-	-	0.9	3.8
Hf	1.90	2.28	3.98	4.67	1.12	2.80
Ta	0.16	0.29	0.56	0.74	0.06	0.59
Th	1.20	2.22	2.75	3.68	0.01	2.50
U	0.31	0.70	0.67	0.86		
La	7.8	10.9	21.1	30.0	3.3	9.8
Ce	18.0	24.6	45.6	64.9	8.6	24.6
Nd	12	21	30	38	6.3	13.9
Sm	3.13	3.82	6.57	8.63	1.92	3.40
Eu	1.02	1.2	1.71	2.43	0.71	1.17
Tb	0.49	0.55	0.84	1.23	0.27	0.68
Yb	1.65	1.94	2.86	3.66	1.21	2.35
Lu	0.28	0.34	0.43	0.60	0.17	0.36
$^{87/86}Sr$	0.70356	0.70421	0.70413	0.70451	0.70381	0.70433
$^{143/144}Nd$	0.512710	0.512826	0.512771	0.512818	0.512808	0.512891
$^{206/204}Pb$	18.481	18.615	18.473	18.637	18.551	18.581
$^{207/204}Pb$	15.574	15.648	15.547	15.619	15.578	15.609
$^{208/204}Pb$	38.380	38.653	38.328	38.542	38.363	38.496
K/Rb	371	444	273	332	249	543
Rb/Cs	18	39	21	65	9	24
Ba/La	17	24	13	15	21	33
La/Yb	4.4	5.6	5.8	8.3	2.2	5.4
Zr/Hf	44.7	83.3	40.3	61.1	27.9	43.7
Th/U	3.17	3.87	4.10	4.33	-	-
Al_2O_3/CaO	1.9	2.1	1.9	2.0	1.5	2.1
$FeO^{(T)}/MgO$	1.2	1.5	2.2	2.9	0.7	2.9

[1] Hualaihué, Corcovado, Cay, Maca

[2] Michinmahuida, Hudson

[3] Antuco, Llaima, Villarrica, Puyehue, Casablanca, Osorno

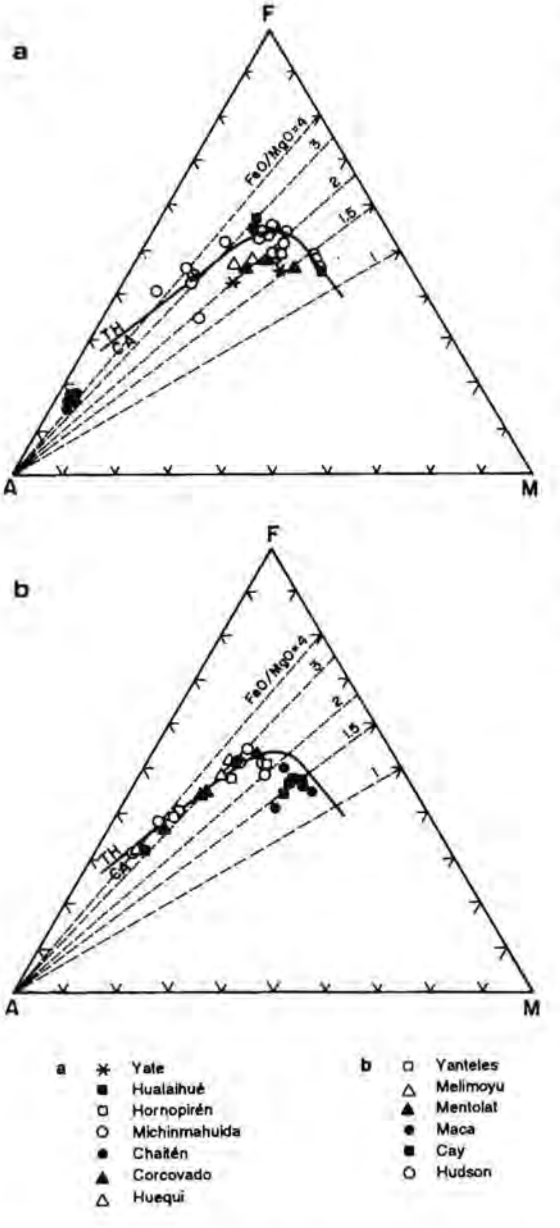


FIG. 7. AFM diagram for rocks from different volcanic centers of the SSVZ between 41°30' and 46°00'S showing boundary between tholeiitic and calcalkaline series lavas (after Irvine and Baragar, 1971). According to this diagram, many centers of the SSVZ region between 41°30' and 46°00'S have tholeiitic affinities.

Despite the differences between the two types of basalts of the studied region the overall compositional range is geochemically similar to that of stratovolcano-basalts from the 37°00'-41°30'S region (Hickey *et al.*, 1986). Both the 37°00'-41°30'S and the 41°30'-46°00'S stratovolcano-basalts have K/Rb ratios (Table 3) comparable to those of oceanic island basalts (OIB) but with Rb/Cs ratios that are almost three times lower, as they are strongly enriched in Cs.

While the MgO contents of type-1 basalts are among the highest reported for basalts from the SVZ of the Andes, the MgO contents of type-2 basalts are among the lowest (Tables 2, 3). However, differences in MgO contents, almost as large as those existing between both types of basalts from the 41°30'-46°00'S region of the SVZ, have been reported in basalts from the Villarrica volcano (39°S; Hickey-Vargas *et al.*, 1989). Likewise, type-1 basalts have some of the lowest HFSE contents among basalts from the SVZ of the Andes (Table 3), and type-2 basalts are among the richest in these elements (see also: López-Escobar *et al.*, 1977; Hickey *et al.*, 1986; Hildreth and Moorbath, 1988).

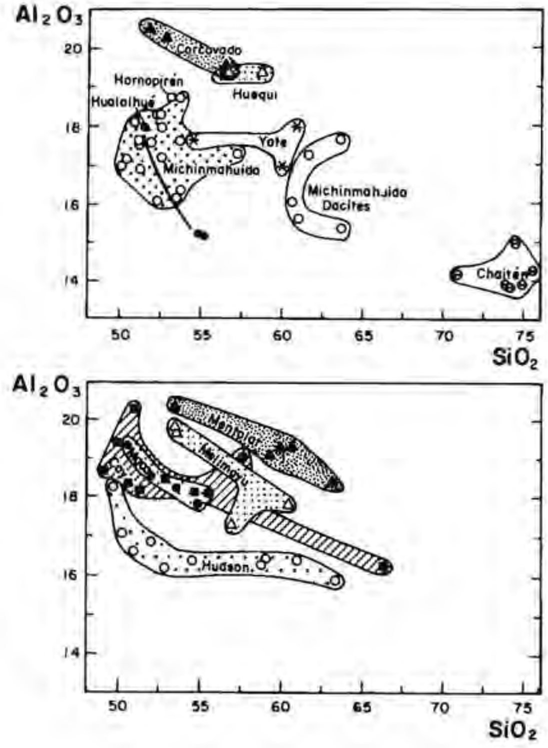
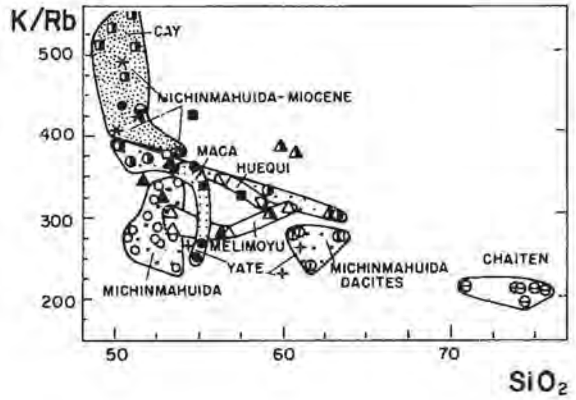


FIG. 8. Al$_2$O$_3$ *versus* SiO$_2$ diagram for SSVZ rocks between 41°30' and 46°00'S. Corcovado, Mentolat, Melimoyu, Cay and Maca basalts and basaltic andesites (type-1) have relatively high Al$_2$O$_3$ contents. However, Michinmahuida and Hudson basaltic rocks (type-2) have relatively low Al$_2$O$_3$ contents.



■	Yanteles	△	Melimoyu
▲	Mentolat	●	Maca
◨	Cay	◑	Hudson
+	Yate	◒	Hualaihué
□	Hornopirén	○	Michinmahuida
⦶	Michinmahuida dacite	⊖	Chaitén
▲	Corcovado	▽	Huequi
✱	Michinmahuida Miocene		

FIG. 9. K/Rb *versus* SiO_2 diagram for rocks from different volcanic centers of the SSVZ between 41°30' and 46°00'S. The K/Rb ratio is highly variable among basalts and basaltic andesites, but not in the most silicic rocks. This behaviour is common in SVZ Quaternary volcanic rocks (see, for example, Hildreth and Moorbath, 1988 and Davidson *et al.*, 1988). The general trend in passing from basalts to dacites mimics that of an AFC trend.

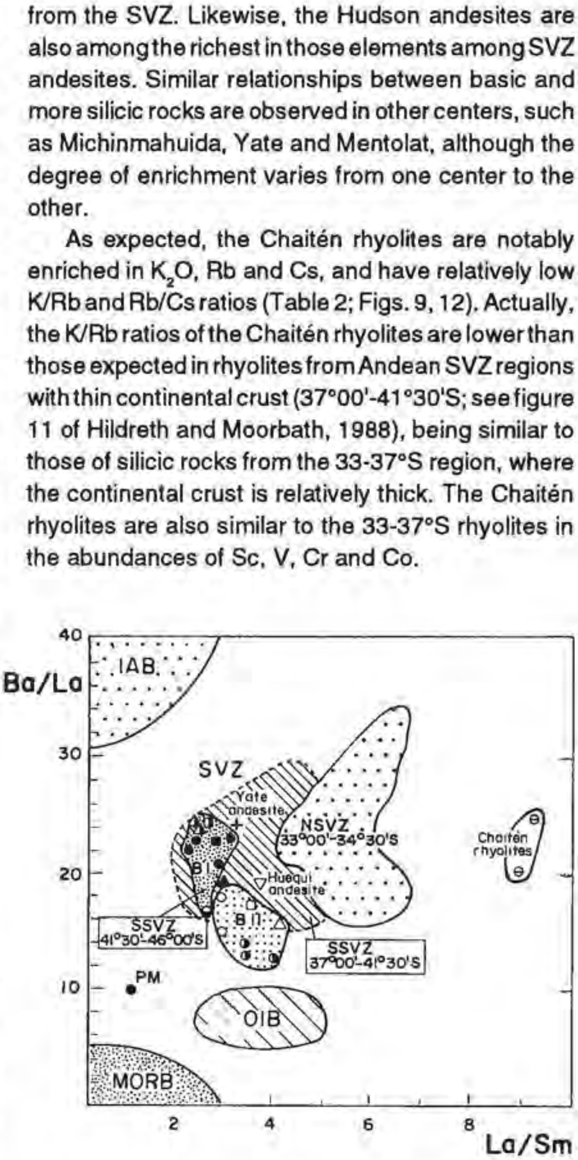
Like the 37°00'-41°30'S stratovolcano-basalts, the 41°30'-46°00'S stratovolcano-basalts have Ba/La ratios (Table 3) that are intermediate between those of intraoceanic island arcs (IAB: 30-50; Davidson *et al.*, 1988, and references therein), and those of OIB (8-13; Hildreth and Moorbath, 1988, and references therein) and MORB (Fig. 10). In general, both the 41°30'-46°00'S stratovolcano-basalts and the 37°00'-41°30'S stratovolcano-basalts have similar rare-earth elements (REE) abundances (Table 3; Fig. 13; López-Escobar and Frey, 1976; López-Escobar *et al.*, 1977; Hickey *et al.*, 1986; Futa and Stern, 1988). However, while the type-1 and 37°00'-41°30' basalts exhibit relatively low La/Yb ratios (3-6; Table 3) and normal Eu abundances, type-2 basalts have higher La/Yb ratios (5.8-8.3; Table 3) and display a slightly negative Eu anomaly (Fig.13).

The chemical characteristics of the petrographically identified 'normal' andesites parallel those of the basalts with which they are associated (Figs. 6, 8, 9, 11). For example, the Hudson basalts are among the richest in incompatible elements among basalts from the SVZ. Likewise, the Hudson andesites are also among the richest in those elements among SVZ andesites. Similar relationships between basic and more silicic rocks are observed in other centers, such as Michinmahuida, Yate and Mentolat, although the degree of enrichment varies from one center to the other.

As expected, the Chaitén rhyolites are notably enriched in K_2O, Rb and Cs, and have relatively low K/Rb and Rb/Cs ratios (Table 2; Figs. 9, 12). Actually, the K/Rb ratios of the Chaitén rhyolites are lower than those expected in rhyolites from Andean SVZ regions with thin continental crust (37°00'-41°30'S; see figure 11 of Hildreth and Moorbath, 1988), being similar to those of silicic rocks from the 33-37°S region, where the continental crust is relatively thick. The Chaitén rhyolites are also similar to the 33-37°S rhyolites in the abundances of Sc, V, Cr and Co.

■	Yanteles	△	Melimoyu
▲	Mentolat	●	Maca
◨	Cay	◑	Hudson
+	Yate	◒	Hualaihué
□	Hornopirén	○	Michinmahuida
⊖	Chaitén	▲	Corcovado
▽	Huequi		

FIG. 10. Ba/La *versus* La/Sm diagram for SSVZ rocks between 41°30' and 46°00'S compared with NSVZ (33°00'-34°30'S) rocks, SSVZ rocks between 37° and 41°S, IAB (island arc basalts), OIB (oceanic island basalts), and MORB (mid-ocean ridge basalts). Types 1 (BI) and 2 (BII) basalts from the SSVZ region between 41°30' and 46°00'S form different clusters. PM = average of primitive mantle after Hofmann (1988).



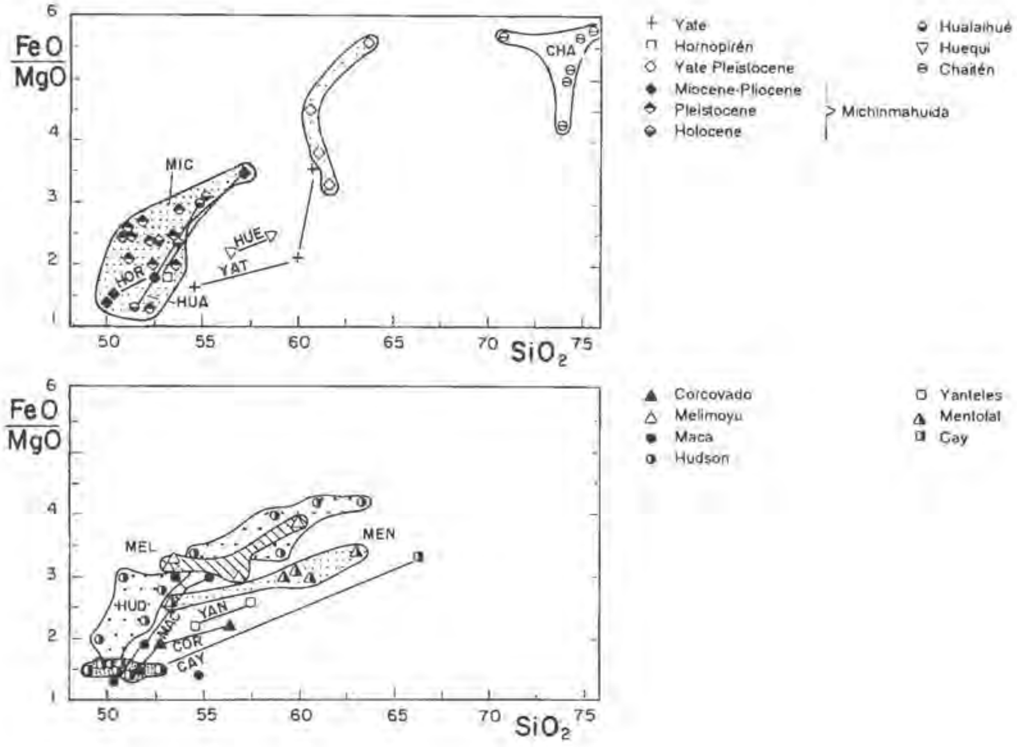


FIG. 11. FeO/MgO *versus* SiO_2 diagram for SSVZ rocks between 41°30' and 46°00'S. Michinmahuida (MIC), Hualaihué (HUA), Hudson (HUD), Hornopirén (HOR) and Maca (MAC) show a strong increase of FeO within the 50-55 wt % SiO_2 range, which could reflect the effect of olivine fractionation.

The REE patterns of the Chaitén rhyolites (Fig. 13) are notably different from those of the basaltic and andesitic rocks from the 41°30'-46°00'S region of the SVZ. They are depleted in MREE and HREE and exhibit larger negative Eu anomalies (Eu/Eu*=0.59). Their REE pattern resembles those of 33-37°S rhyolites rather than rhyolites from the 37°00'-41°30'S region (see López-Escobar and Munizaga, 1983; Frey *et al.*, 1984; Gerlach *et al.*, 1988; Hickey-Vargas *et al.*, 1989).

Compared to the nearby Michinmahuida basalts (type-2), the Chaitén rhyolites are enriched in Ta (1.7x), Th (3.5x) and U (3.4x), depleted in TiO_2 (4.2x), Zr (1.5x) and Hf (1.5x), but have similar Zr/Hf and Th/U ratios (Table 2; López-Escobar *et al.*, 1991). Analogous to the REE data, HFSE in the Chaitén rhyolites are also more similar to rhyolites from 33-37°S than to rhyolites from the 37°00'-41°30'S region.

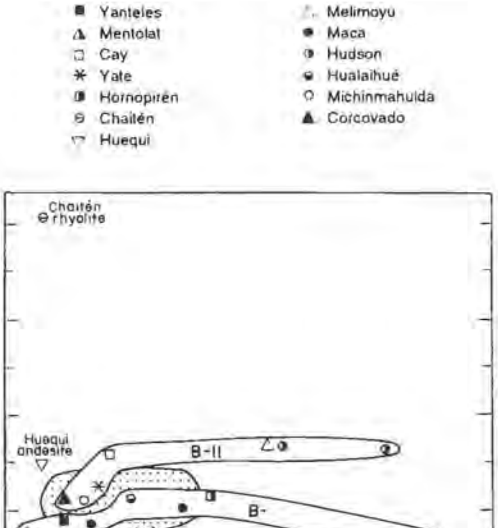


FIG. 12. La/Yb *versus* Rb/Cs diagram for SSVZ rocks between 41°30' and 46°00'S compared with SSVZ rocks between 37° and 41°S and MORB. Symbols are the same as in figure 10.

ISOTOPIC COMPOSITIONS

Sr-isotope analyses were made on 32 samples of the 41°30'-46°00'S region of the SVZ by Notsu *et al.* (1985, 1987; Table 2). According to these authors, their results indicate that the basalts to dacites have $^{87}Sr/^{86}Sr$ ratios of 0.70394-0.70482, with the majority ranging from 0.70404 to 0.70434; exceptions to this are the andesites from Huequi, Yanteles and Corcovado which have $^{87}Sr/^{86}Sr$ ratios of 0.70455 to 0.70482. The $^{87}Sr/^{86}Sr$ ratio of the Chaitén rhyolites (0.70570) is the highest among the analyzed rocks by Notsu *et al.* (1985; 1987). Fifteen of these samples were rechecked isotopically at the Open University (Table 2: NBS=071024), the $^{87}Sr/^{86}Sr$ relations being in general lower. The Sr isotope ratios of Hualaihué amount to 0.70356 (-0 00039), those of Chaitén rhyolite to 0,70560 (-0.00010). According to the new determinations, type-1 basalts have slightly lower $^{87}Sr/^{86}Sr$ ratios than type-2 basalts (Tables 2, 3, and Fig. 14), and the rhyolites of Chaitén have significantly higher Sr isotope ratios than the basalts and andesites of its neighbour Michinmahuida. A similar relationship is observed at the Maipo area (34°S), where the $^{87}Sr/^{86}Sr$ ratios of the rhyolites are significantly higher than those of the more basic volcanic rocks (Stern *et al.*, 1984). This situation contrasts with that observed in other centers of the SVZ, Villarrica for example, where rocks ranging in composition from basalt to rhyolite have similar $^{87}Sr/^{86}Sr$ ratios (Déruelle *et al.*, 1983; Hickey-Vargas *et al.*, 1989).

The $^{143}Nd/^{144}Nd$ ratios of basalts to dacites range from 0.51271-0.51290. The few data available, suggest that type-1 basalts have similar $^{143}Nd/^{144}Nd$ ratios to type-2 (Tables 2, 3). The lowest value is observed for the Chaitén rhyolite (0.51259; Table 2). This ratio is similar to those of rhyolites from the northernmost region of the SVZ (33°00'-34°30'S; Fig. 14), where the continental crust is comparatively thick (Futa and Stern, 1988; Hildreth and Moorbath, 1988).

In a plot of $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ (Fig.15), as well as in the $^{208}Pb/^{204}Pb$ *versus* $^{207}Pb/^{204}Pb$ diagram (Fig. 16), the 41°30'-46°00'S region basaltic to dacitic rocks (Table 2) fall within the fields of the 33-37°S Quaternary volcanic rocks determined by Hildreth and Moorbath (1988). This field also includes the volcanic rocks from 37°00'-41°30'S analyzed by Harmon *et al.* (1984) and Hickey *et al.* (1986). Thus, all the SVZ (33-46°S) rocks, regardless of latitude or

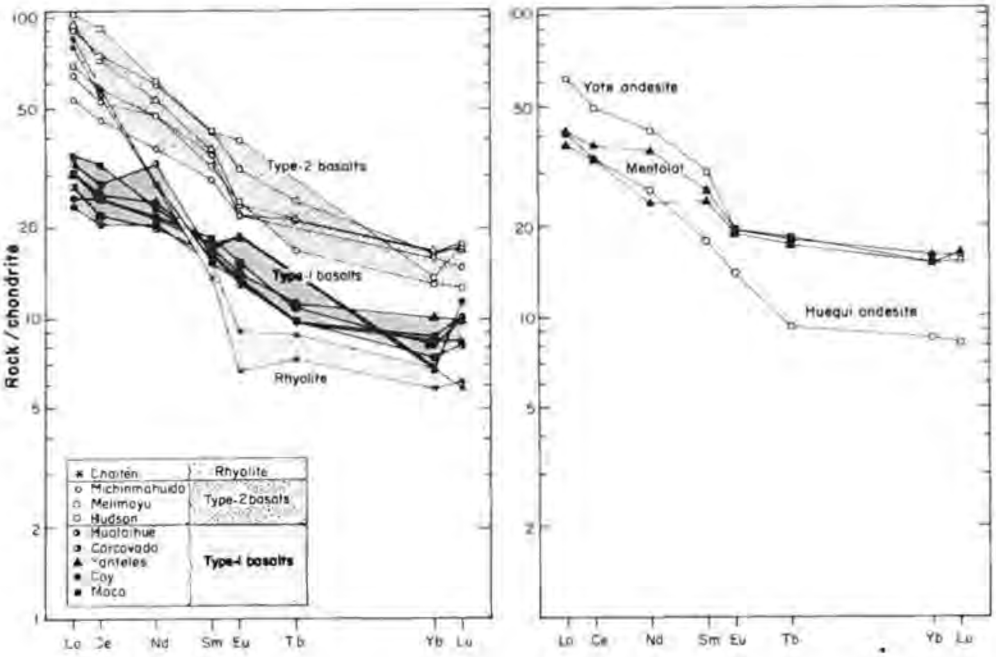


FIG. 13. Chondrite normalized REE patterns of types 1 and 2 basalts, Huequi, Yate, and Mentolat andesites, and Chaitén rhyolites.

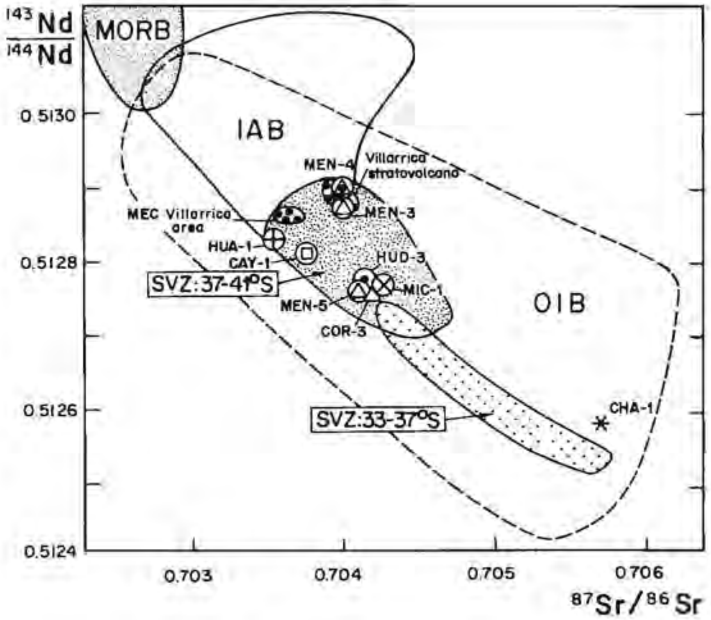


FIG. 14. $^{143}Nd/^{144}Nd$ *versus* $^{87}Sr/^{86}Sr$ for SSVZ rocks between 41°30' and 46°00'S compared with SVZ between 33° and 37°S, SSVZ between 37° and 41°S, MORB, IAB and OIB. Data sources: Hickey *et al.* (1986) and references therein; Futa and Stern (1988) and references therein; Hildreth and Moorbath (1988) and references therein. Villarrica stratovolcano and minor eruptive centers (MEC) of the Villarrica area rocks after Hickey-Vargas *et al.* (1989).

crustal thickness, have similar Pb isotope compositions. The only exception is the Chaitén rhyolite, which is notably enriched in radiogenic Pb, particularly in ^{208}Pb.

The $\delta^{18}O$ values of the 41°30'S-46°00'S SVZ basalts vary from +5.8 to +7.7‰(Table 2). However, only the Hudson basalts have values within the range of mantle derived rocks (5.8-6.2‰) reported by Kyser (1986), Ito *et al.* (1987) and Woodhead *et al.* (1987). The $\delta^{18}O$ values of the basaltic andesites and dacites fall in the range +6.4 to +8.4‰, which is significantly higher than that of mantle derived rocks. The O-isotope composition of the Chaitén rhyolite is +9.4‰, which is typical of upper crustal rocks. The O-isotope ratio of this rhyolite is similar to those exhibited by rhyolites from the northernmost region of the SVZ (Stern *et al.*, 1984; Hildreth and Moorbath, 1988).

DISCUSSION

Although the data presented in this paper are not sufficient to evaluate in detail any particular petrogenetic model, they, at least, improve our petrographic and chemical knowledge of SVZ Quaternary volcanism between latitudes 41°30' and 46°00'S, and place some constraints on the origin and evolution of volcanic rocks from this region.

Petrographically, the rocks of the 41°30'S-46°00'S SVZ Quaternary volcanic front can be grouped into five categories : **a**- type-1 basalts are characterized by the coexistence of highly zoned olivine (Fo_{85}-Fo_{65}) and augite; **b**- type-2 basalts are characterized by weakly zoned olivine (Fo_{75}-Fo_{70}), which commonly does not coexist with augite; **c**- 'normal' andesites and dacites are characterized by plagioclase phenocrysts exhibiting normal zoning; **d**- 'mixed' andesites are characterized by disequilibrium mineral assemblages (*e.g.* plagioclase+olivine+orthopyroxene+amphibole) that are compatible with mixing of basaltic and acidic magmas; **e**- rhyolites, represented by the Chaitén rhyolites, which, to the best of our knowledge, are the only rhyolites reported in this region of the SVZ.

Chemically, type-1 basalts have comparatively low LILE and HFSE, high MgO and CaO, and low $FeO^{(T)}/MgO$, La/Yb and $^{87}Sr/^{86}Sr$ ratios. Type-2 basalts, on the other hand, have comparatively high LILE and HFSE, low MgO and CaO, high $FeO^{(T)}/MgO$, La/Yb and $^{87}Sr/^{86}Sr$ ratios. The normal andesites follow the chemical trends observed in their coexisting basalts.

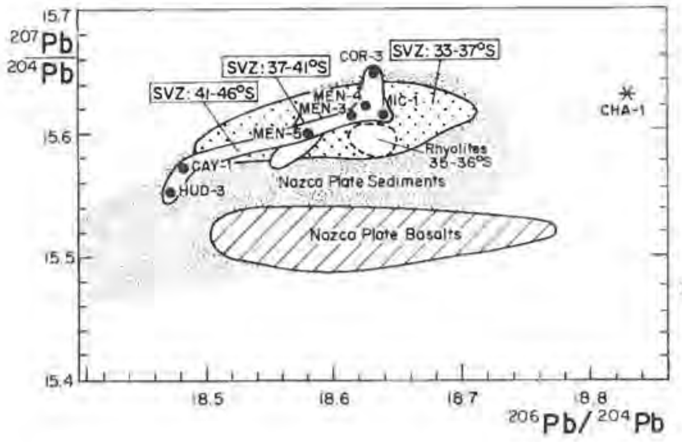


FIG. 15. $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ for SSVZ rocks between 41°30' and 46°00'S compared with SVZ between 33° and 37°S, SSVZ between 37° and 41°S, SVZ rhyolites between 35° and 36°S, Nazca plate basalts and Nazca plate sediments. Data sources: Hildreth and Moorbath (1988 and references therein) and Hickey-Vargas *et al.* (1989) and references therein.

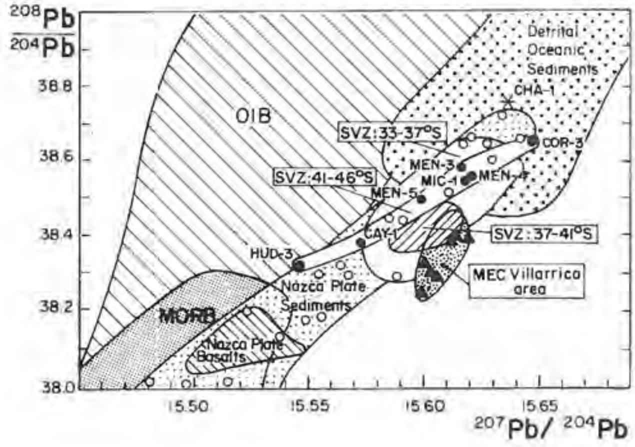


FIG. 16. $^{208}Pb/^{204}Pb$ *versus* $^{207}Pb/^{204}Pb$ for SSVZ rocks between 41°30' and 46°00'S compared with SVZ between 33° and 37°S, SSVZ between 37° and 41°S, MEC Villarrica area, Nazca plate basalts, Nazca plate sediments, detrital oceanic sediments, MORB and OIB. Data sources: Hildreth and Moorbath (1988, and references therein) and Hickey-Vargas *et al.* (1989, and references therein).

GENESIS OF THE 41°30'-46°00'S STRATOVOLCANO-BASALTS

In terms of major and trace element abundances, type-1 basalts are among the most primitive basalts in the SVZ, and type-2 basalts among the most evolved. With the exception of the Hudson basalts, the 41°30'-46°00'S stratovolcano-basalts and those from the 37°00'-41°30'S region of the SVZ have similar K/Rb, Rb/Cs, Ba/La, La/Yb ratios and isotopic compositions. Compared to the latter basalts, the Hudson basalts have higher Rb/Cs and La/Yb, but lower Ba/La and $^{207}Pb/^{204}$ Pb ratios (Tables 2, 3). Actually, the La/Yb and Ba/La ratios of the Hudson basalts mimic those of basalts from some minor eruptive centers (MEC) situated along the LOFZ in the 37°00'-41°30'S region (*e.g.* MEC of the Villarrica and Calbuco areas; Hickey-Vargas *et al.*, 1989; L. López-Escobar, M.A. Parada, R.L. Hickey-Vargas, F.A. Frey, H. Moreno[1].

The compositional similarities between the 41°30'-46°00'S and the 37°00'-41°30'S stratovolcano-basalts suggest that the main source of the former is also the asthenospheric mantle wedge above the subduction zone as proposed by López-Escobar and Frey (1976);

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[1] 1993.Contrasting origin of adjacent andesitic and basaltic volcanism in the Southern Andes: case of Calbuco volcano and minor eruptive centers distributed along the Liquiñe-Ofqui Fault Zone, 41-42°S. *Universidad de Chile, Departamento de Geología* (Unpublished), 40 p.

López-Escobar *et al.* (1977) and Hickey *et al.* (1986) for the 37°00'-41°30'S rocks. The Ba/La ratios of these rocks, which are slightly higher than those of oceanic basalts, suggest that melting was triggered by fluids derived from the subducted oceanic slab (Hickey *et al.*, 1986; Tormey *et al.*, 1991)

A contribution from oceanic sediments to the composition of the slab derived fluids is suggested by the relatively high Cs/Rb and $^{207}Pb/^{204}Pb$ ratios of the Michinmahuida, Corcovado, Cay and Maca basalts, which are similar to the values exhibited by the 37°00'-41°30'S stratovolcano-basalts. The Cs/Rb and $^{207}Pb/^{204}Pb$ ratios of the latter basalts correlate with ^{10}Be (Morris *et al.*,1985; Hickey *et al.*, 1986), which is another indicator of subducted sediment involvement. U-Th disequilibrium studies (Tormey, 1989; Sigmarsson *et al.*, 1990; Tormey *et al.*, 1991) also confirm the participation of subducted sediment in the genesis of the 37°00'-41°30'S stratovolcano-basalts. However, the relatively low Cs/Rb and $^{207}Pb/^{204}Pb$ ratios of the Hudson basalts in conjunction with the similarity between their O-isotope signature and that of mantle-derived rocks suggest that sediments were not significantly involved in the genesis of their primary magmas. Considering that Michinmahuida, Corcovado, Cay and Maca are large stratovolcanoes, whose magmas probably underwent one or more stages of homogenization during their ascent to the surface, the relatively high and variable $\delta^{18}O$ values of their basalts could reflect variable degrees of upper crustal contamination.

The differences in LILE, HFSE, $FeO^{(T)}/MgO$, and La/Yb ratios between type-1 and -2 basalts could be explained by different degrees of partial melting of asthenospheric material. In fact, relatively high degrees of melting could generate magmas with similar trends to those observed in type-1 basalts, *i.e.*, with low abundances of LILE and HFSE, and low $FeO^{(T)}/MgO$, and La/Yb ratios. Low degrees of melting could produce magmas with the compositional trends of type-2 basalts. However, the Sr-isotopic differences existing between both types of basalts require isotopically distinct sources. If it is assumed that the mantle under the 41°30'-46°00'S region of the SVZ is isotopically heterogeneous, due to contamination via subducted sediments (Futa and Stern, 1988), both sources could be in the asthenosphere. However, if both the asthenospheric mantle under the 41°30'-46°00'S region and the primary magmas are homogeneous, another mechanism is required to explain the chemical differences between types-1 and -2 basalts. Possible mechanisms include: **a-** different degrees of partial melting of the asthenosphere followed by interaction of these melts with heterogeneous lithosphere and **b-** crustal contamination. In the latter case, the compositional differences cannot be generated in the upper crust, because differentiation of basaltic magmas in this region produces more silica rich magmas (Tormey *et al.*,1991), and since most of the mafic type-2 basalts are enriched in incompatible elements, the differences must be produced at lower or intermediate crustal levels.

According to Hildreth and Moorbath (1988), the Zr, Hf and Ta abundances in crustal uncontaminated SVZ basalts would be respectively 125 ppm, 3 ppm and 0,2 ppm. In this context, type-1 would appear to be practically uncontaminated by crustal material (Tables 2, 3). Therefore, their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios, respectively higher and lower than those of middle ocean ridge basalts (MORB), suggest that the mantle under the 41°30'-46°00'S region is, isotopically, an OIB-type mantle, as it was postulated, for the mantle under the 37°00'-41°30'S region of the SVZ, by Hickey *et al.* (1986).

The comparatively low Ca and Sr abundances of type-2 basalts, as well as their negative Eu-anomaly and high $FeO^{(T)}/MgO$ ratios, may be generated at lower or intermediate crustal levels by fractionation of plagioclase and olivine. This fractionation process could be accompanied by crustal assimilation that raised the $^{87}Sr/^{86}Sr$ in the ascending magmas. The similarity in SiO_2 contents between type-1 and type-2 basalts, in conjunction with their differences in isotopic composition, suggests that they represent different evolutionary lineages.

Since neither type-1 nor type-2 basalts show HREE depletion (López-Escobar, 1984; López-Escobar *et al.*, 1985a), the role of garnet as a residual phase either in the mantle or in the lower crust seems to be insignificant.

GENESIS OF THE 41°30'-46°00'S ANDESITES

As discussed by Tormey *et al.* (1991), the basalt-andesite-dacite differentiation in the SVZ would take place in the upper crust. As seen in figure 6 (K_2O *versus* SiO_2), most of the 41°30'-46°00'S region 'normal' andesites and dacites are derived from their respective parental basaltic magmas (either of type-1 or -2) by crystal fractionation of those phases present as phenocrysts (mainly olivine, pyroxenes and plagioclase). This process results in enrichment in elements that are incompatible with those phases (LILE and HFSE), and depletion in those that are compatible (Sc, Co, Cr, Eu). However, different degrees of upper crustal contamination are required to explain their modified and variable Sr, O and Pb isotope compositions.

Huequi andesites and dacites, and some andesites from Mentolat, can be distinguished from 'normal' andesites and dacites because they show petrographical evidence of originating by mixing of type-1 basaltic and rhyolitic magmas. The Sr-isotope composition of the Huequi samples supports this hypothesis, since their $^{87}Sr/^{86}Sr$ ratios are intermediate between those of Hualaihué basalts (type-1) and those of Chaitén rhyolite.

GENESIS OF THE CHAITEN RHYOLITES

The Chaitén rhyolite differs significantly from type-1 and -2 basalts in incompatible trace element abundances and ratios, and in isotopic ratios (Table 2, Figs. 9-16). The incompatible trace element pattern and Sr and Nd isotope ratios of the Chaitén rhyolite resemble those of rhyolites from the 33-37°S region of the SVZ (Stern *et al.*, 1984; Hildreth and Moorbath, 1988), which are situated in an area of relatively thick continental crust, rather than those from the 37°00'-41°30'S region (Deruelle *et al.*, 1983; Gerlach *et al.*, 1988; Hickey-Vargas *et al.*, 1989), which are situated in an area of relatively thin continental crust. However, in Pb-isotope compositions, the Chaitén rhyolite is unique in relation to rhyolites from the 33°00'-41°30'S region of this volcanic arc (Figs. 15, 16).

The differences, in incompatible trace element patterns and Sr Nd, Pb and O isotope compositions, between the Chaitén rhyolite and the 41°30'-46°00'S region basalts strongly indicate that their main sources are different. The isotopic differences suggest that the rhyolite has a crustal origin. Its low Al_2O_3, CaO, Sr, and Eu-depletion on one hand, and its low abundances of Cr, Co, MREE, Y and HREE, on the other, suggest that plagioclase and amphibole were residual phases in its source. On this basis, the Chaitén rhyolite primitive magma would have been generated by melting of an amphibolitic source. The low K/Rb ratio seems to confirm this hypothesis. In fact, as suggested by Hanson (1978) and Davidson *et al.* (1988), low K/Rb ratios are characteristic of liquids generated by low degrees of partial melting of an amphibolitic source within the crust. The high $\delta^{18}O$ value of the Chaitén rhyolite sample suggests, in addition, that this source probably originated by metamorphism of rocks that were once near the surface of the earth. The presence of accreted metabasalts west of the volcanic arc (Charrier *et al.*, 1991, and references therein) supports this hypothesis.

CONCLUSIONS

Five types of petrographically and chemically distinct Quaternary volcanic rocks are distinguished in the 41°30'-46°00'S region of the SVZ of the Andes: depleted basalts (type-1), enriched basalts (type-2), normal andesites and dacites, mixed andesites and dacites, and rhyolites.

With the exception of the Hudson basalts, the stratovolcano-basalts from this region are geochemically similar to stratovolcano-basalts from farther north (37°00'-41°30'S region of the SVZ). In some geochemical features (relatively high La/Yb and low Ba/La ratios), the Hudson basalts are similar to basalts from some minor eruptive centers (MEC) situated along the LOFZ in the 37°00'-41°30'S region.

Both types of basalts are consistent with generation by melting of OIB-type asthenospheric material. Melting would be triggered by fluids derived from the subducting oceanic lithosphere (as indicated by the relatively high Ba/La ratios in these basalts). Subducted sediments are commonly involved in this process (as suggested by the high Cs/Rb and $^{207}Pb/^{204}Pb$ ratios of most basalts).

Primary asthenospheric magmas could be modified, to various extents, within the mantle lithosphere or within the lower or intermediate crust. This contamination process could have created some of the compositional differences observed between type-1 and type-2 basalts. The modified magmas would represent the parental magmas of erupted basalts. The depletion in MgO, CaO and Sr, observed in type-2 basalts in relation to type-1, and their negative Eu-anomalies, could be also due to fractionation of plagioclase and olivine from their parental magmas. However, this process had to be accompanied by some kind of crustal assimilation in order to raise their $^{87}Sr/^{86}Sr$ ratios, keeping their $^{143}Nd/^{144}Nd$ ratios approximately constant relative to type-1 basalts.

At upper crustal levels, some basaltic magmas evolved by fractional crystallization, involving phases present as phenocrysts, accompanied by assimilation of upper crustal material, to create intermediate rocks; others, however, mixed with rhyolitic magmas to generate the so-called mixed andesites and dacites.

The Chaitén rhyolites have chemical and isotopic characteristics that suggest that their primitive magmas were generated by partial melting of crustal material of amphibolitic composition. This partial melting was probably induced by the intrusion of the relative hot (<1200°C) type-1 basaltic magma into the lower crust. A mixing of basaltic and rhyolitic magmas could have produced the Huequi andesites. This process would explain the occurrence of basalts, rhyolites and mixed andesites in the small local zone of the SVZ between 42° and 43°S.

ACKNOWLEDGEMENTS

LLE acknowledges the financial support of the following grants: FONDECYT 1051-89 and 1221-91, DTI- Universidad de Chile E-2834. The Fundación Andes-Chile is also acknowledged for the Sabbatical Period Program grant, and the hospitality of the NERC Isotope Geoscience Laboratory, Keyworth, Nottingham, United Kingdom is greatly appreciated. We also acknowledge the grants N° 58041009 and 59043009 of the Ministry of Education, Science and Culture of Japan, obtained by Dr. N. Onuma, former Professor of the Ibaraki University, deceased on January 15, 1985, that made possible the sampling by helicopter, of thirteen volcanoes belonging to the 41°30'-46°00'S region of the SVZ of the Andes. RK gratefully thanks the Deutsche Forschungsgemeinschaft for their support and funding. We thank Drs. K. Notsu, of the University of Tokyo (Laboratory for Earthquake Chemistry), Wes Hildreth of the U.S. Geological Survey, Jon Davidson of the University of California at Los Angeles, and Russell Harmon of the NERC Isotope Geosciences Laboratory, Keyworth (Nottingham), for their kind collaboration in obtaining isotopic and trace element data. We also thank the critical suggestions of Drs. Moyra Gardeweg, Robert Drake, Francisco Hervé and Robert Pankhurst that improved the manuscript. This work is a contribution to the IGCP Project N°345 'Lithospheric Evolution of the Andean Continental Margin'.

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Manuscript received: November 12, 1991; accepted: March 24, 1993.