Quaternary volcanic activity of Hudson and Lautaro volcanoes, Chilean Patagonia: New constraints from K-Ar ages

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ABSTRACT

Twenty-nine K-Ar ages for lavas and juvenile ejecta obtained from Hudson volcano in the southern end of the Southern Volcanic Zone and Lautaro volcano in the northern end of the Austral Volcanic Zone, which are separated by a 350 km-long volcanic gap near the Chile ridge subduction zone, were determined using unspiked method that has significant sensitivity for dating young rocks (<0.1 Ma). It is newly revealed that Hudson is a significantly long-lived volcano; its activity started at *ca.* 1.0 Ma and continues to the Recent. The Hudson volcano has a well-preserved summit caldera complex of approximately 10 km in diameter, previously thought to be formed by a single event during the Holocene, perhaps at 6700 years BP. Our results for the K-Ar dating, however, indicate that the northeastern and southeastern flanks of the volcano formed at different times; formation of NE flank preceded that of SE flank. Aero-photographic observations indicate the presence of two or even three caldera rims. These data suggest that the Hudson volcano had a complex evolution, superimposing or partially nesting calderas rather than a simple caldera. The activity of the Lautaro volcano, began at *ca.* 0.17 Ma and has continued to the Recent, as it is indicated by our K-Ar first results. Though Lautaro volcano is a relatively large stratovolcano for Chilean Patagonia, the chemical and radiometric results indicate a narrow range in its variability when compared with those of the Hudson volcano. These narrow compositional and geochronological ranges suggest that the Lautaro volcano developed from a homogeneous magma chamber produced by slab melting during the late Quaternary, assuming that the sampled part of this heavily ice-mantled volcano, spans its full lifetime.

Key words: Quaternary volcanic activity, K-Ar dating, Chilean Patagonia, Ridge subduction, Southern Volcanic Zone, Austral Volcanic Zone, Hudson volcano, Lautaro volcano, Caldera, Unspiked method.

Revista Geológica de Chile, Vol. 31, No. 2, p. 207-224, 7 Figs., 3 tables, December 2004

RESUMEN

Actividad volcánica cuaternaria de los volcanes Hudson y Lautaro, Patagonia chilena: nuevas edades K-Ar. Mediante el uso del método K-Ar 'unspiked', el cual tiene notable sensibilidad para datar rocas jóvenes (<0,1 Ma), se obtuvieron 29 edades radiométricas de lavas y piroclastos juveniles de los volcanes Hudson y Lautaro. Separados por un 'gap' volcánico de 350 km, cercano a la zona de subducción de la dorsal de Chile, estos volcanes se ubican en los extremos sur de los Andes del Sur y norte de los Andes Australes, respectivamente. Estos datos indican que el volcán Hudson ha tenido un tiempo de desarrollo notablemente largo desde hace 1 Ma hasta el presente. Está formado por una caldera bien conservada de aproximadamente 10 km de diámetro, la cual, se pensaba había sido formada por sólo un evento eruptivo, probablemente a los 6700 años AP. Sin embargo, nuestros resultados revelan que los flancos nororiental y suroriental del volcán se originaron durante épocas diferentes, siendo más antigua la formación de la estructura norte. Observaciones fotogeológicas indican la presencia de dos o, eventualmente, tres bordes de caldera. Estos antecedentes indican que el volcán Hudson tuvo una evolución más bien compleja consistente en la sobreimposición o anidamiento parcial de estructuras, más que la formación de una caldera simple. De acuerdo con los primeros resultados de los presentes autores, en el caso del volcán Lautaro, la actividad que comenzó hace aproximadamente 0,17 Ma continúa hasta el presente. Aunque es un volcán relativamente grande comparado con otros de la Patagonia chilena, muestra un intervalo de edad y composición notablemente menores que el volcán Hudson. Asumiendo que el muestreo es representativo del espectro evolutivo completo del Lautaro, el cual está casi totalmente cubierto por hielo, estas características sugieren que este volcán se ha desarrollado durante un período corto en el Cuaternario tardío, a partir de una cámara magmática homogénea alimentada por la fusión de la placa.

Palabras claves: Actividad volcánica cuaternaria, Dataciones K-Ar, Patagonia chilena, Subducción dorsal oceánica, Zona Volcánica Sur, Zona Volcánica Austral, Volcán Hudson, Volcán Lautaro, Caldera, Método 'unspiked'.

INTRODUCTION

At latitude 46°16' where Antarctica, Nazca and South American plates meet, subduction of a segment of the active Chile ridge system along the Chile-Perú trench forms a ridge-trench-trench-type triple junction, namely the Chile Triple Junction (CTJ) (*e.g.,* Herron *et al.,* 1981). Near the CTJ, there is a significant gap (about 350 km long) in recent subduction-related volcanic activity. This volcanic gap separates two distinct volcanic zones along the axis of the southern Andean Cordillera (Fig.1); the Southern Volcanic Zone (SVZ; 33°-46°S) and the Austral Volcanic Zone (AVZ; 49°-55°S) (*e.g.,* Stern *et al.,* 1984; Notsu *et al.,* 1987; Futa and Stern, 1988; Ramos and Kay, 1992; Stern, 2004). Geochemical characteristics of the Quaternary volcanic products drastically change across this volcanic gap; AVZ is composed of calc-alkaline andesite to dacite of adakitic or high-Mg andesitic affinities, while SVZ consists mainly of low- to medium-K calc-alkaline basalt and arc-tholeiite with minor andesite and dacite (Harmon *et al.,* 1984; Stern *et al.,* 1984; Futa and Stern, 1988; López-Escobar *et al.,* 1995; Stern and Kilian, 1996). The distinction has been mainly attributed to the incorporation of contributions related to slab melting south of the CTJ, caused by subduction of the Chile ridge (Ramos and Kay, 1992; Stern and Kilian, 1996).

Recently, it has been shown that dacite and basaltic andesite of late Pliocene to Quaternary ages (younger than 2 Ma) dredged from the continental slope offshore of Taitao peninsula, adjacent to the active CTJ, also have subduction-related geochemical characteristics (Guivel *et al.,* 2003). This suggests the possibility that volcanic activity along the volcanic front of the Andean Cordillera had ceased and jumped to a forearc setting near the CTJ during late Pliocene to Quaternary. If so, information about spatiotemporal distribution of volcanic activity of this period provides an important key to understanding the variety of thermal structures in the mantle wedge influenced by the Chile ridge subduction. Precise age-controls of the Pliocene-Quaternary activity of volcanoes of the SVZ and AVZ near CTJ allow the necessary database for better understanding the processes involved in ridge subduction.

Hudson and Lautaro volcanoes, in the southernmost SVZ and northernmost AVZ, respectively, are the two closest active centers to the recent CTJ (Fig. 1). Previous studies reported the eruptive record

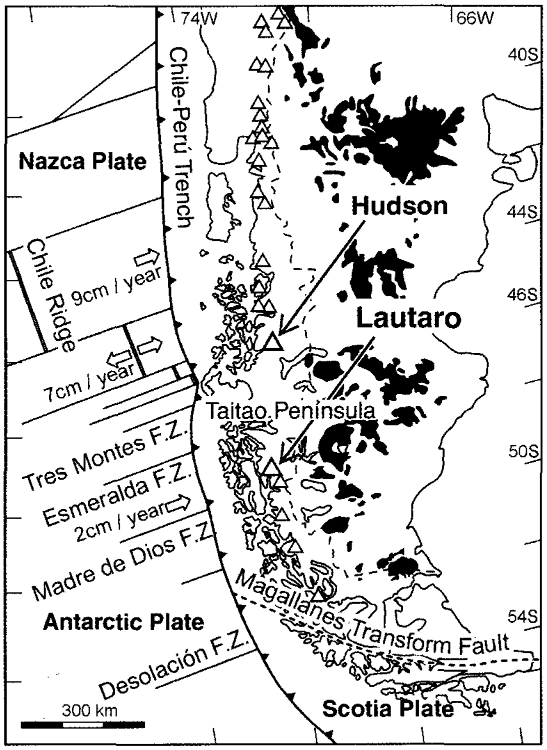


FIG. 1. Simplified tectonic map of southern Patagonia with location of the volcanic centers in the southern SVZ and AVZ (triangles) and distribution of the Cenozoic Patagonian plateau Basalts (in black). Modified from Stern *et al.* (1990) and Stern and Kilian (1996). F.Z. means fracture zone.

of both for the past 100 years (*e.g.*, Shipton, 1960; Naranjo, 1991; Naranjo *et al.*, 1993; Scasso *et al.*, 1994; González-Ferrán, 1995); and ^{14}C dating of Holocene tephra fallout deposits from Hudson volcano were reported by Naranjo and Stern (1998). However, few geochronological data for pre-historic volcanic units have previously been determined. During two recent field seasons, we conducted helicopter-aided field operations and took samples of dissected volcanic rocks adjacent to glaciers flowing down from the summit area of Hudson and Lautaro volcanoes, only few of them taken *in situ*. In this paper, we report twenty-nine K-Ar ages for Quaternary volcanic rocks of Hudson and Lautaro volcanoes based on the unspiked K-Ar technique, which has been shown to provide high-precision ages for volcanic rocks less than 0.1 Ma old (*e.g.*, Gillot *et al.*, 1982; Nagao *et al.*, 1991).

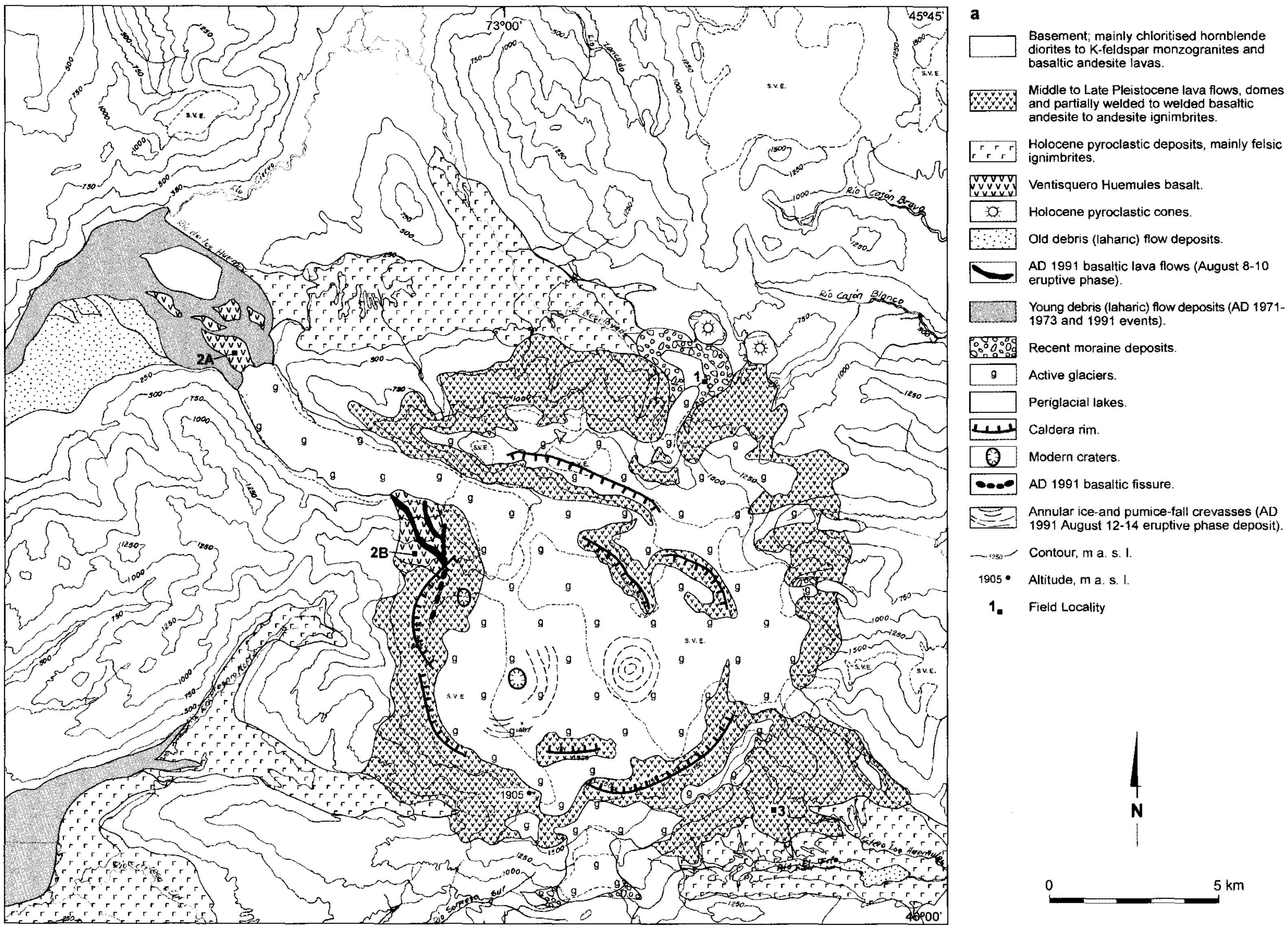
REGIONAL GEOLOGY AND FIELD OBSERVATIONS

Hudson and Lautaro volcanoes are located at the southern end of the SVZ (45°54'S, 72°58'W) and northern end of the AVZ (49°01'S, 73°33'W), respectively, in the middle of glacier fields. The field observations and sampling were performed with help of helicopter on 13th February, 2001 and 2nd March, 2002 in the Hudson volcano, and 28th February, 2002 in the Lautaro volcano. No detailed geological maps for Hudson and Lautaro volcanoes were published before, except for sketches by González-Ferrán (1995). Geological maps shown in figure 2 are our original maps based on field observations and aero-photographs.

HUDSON VOLCANO

In the southern SVZ (ranging roughly from 44°S to 46°S), five large stratovolcanoes, Melimoyu, Mentolat, Cay, Macá and Hudson, representing arc volcanism, are aligned along the Liquiñe-Ofqui fault system (LOFS; Nelson *et al.*, 1994) and its branches. Among them, Hudson volcano, topped by a nearly circular caldera complex approximately 10 km in diameter, produced Plinian eruptions in 1971 and 1991 (Tobar, 1972; Naranjo, 1991; Naranjo *et al.*, 1993; Scasso *et al.*, 1994).

Hudson volcano covers an area of approximately 300 km^2 over the top of the pre-Cenozoic basement rocks of mainly hornblende diorite to monzogranites (Fig. 2a). The southern and western rims of the caldera wall are well defined and the southern rim has a maximum elevation of 1905 m (Fig. 3a). New aero-photographic observation indicates presence of, at least, two caldera rims (Fig. 2a). Scarps eroded in the northern flank of the volcano show that it consists mainly of lava flows interbedded with ignimbrite layers of basaltic to andesitic composition along with a few dacitic intrusions and lava flows. Blocks of these rocks are observed in a terminal moraine of an outlet glacier on NNE flank of edifice (Fig. 3b). On the southern slope, 20 to 30 m thick ignimbrites are predominant in the lower part of the exposed section (Fig. 4). The caldera is partially filled by a glaciar of at least 2.5 km^3, which drains


73°00'
45°45'
46°00'
2A
2B
1
3
1905
Río Cajón Blanco
Río Cajón Bravo
S.V.E.
a
Basement; mainly chloritised hornblende diorites to K-feldspar monzogranites and basaltic andesite lavas.
Middle to Late Pleistocene lava flows, domes and partially welded to welded basaltic andesite to andesite ignimbrites.
Holocene pyroclastic deposits, mainly felsic ignimbrites.
Ventisquero Huemules basalt.
Holocene pyroclastic cones.
Old debris (laharic) flow deposits.
AD 1991 basaltic lava flows (August 8-10 eruptive phase).
Young debris (laharic) flow deposits (AD 1971-1973 and 1991 events).
Recent moraine deposits.
Active glaciers.
Periglacial lakes.
Caldera rim.
Modern craters.
AD 1991 basaltic fissure.
Annular ice-and pumice-fall crevasses (AD 1991 August 12-14 eruptive phase deposit).
Contour, m a. s. l.
1905 • Altitude, m a. s. l.
1 Field Locality
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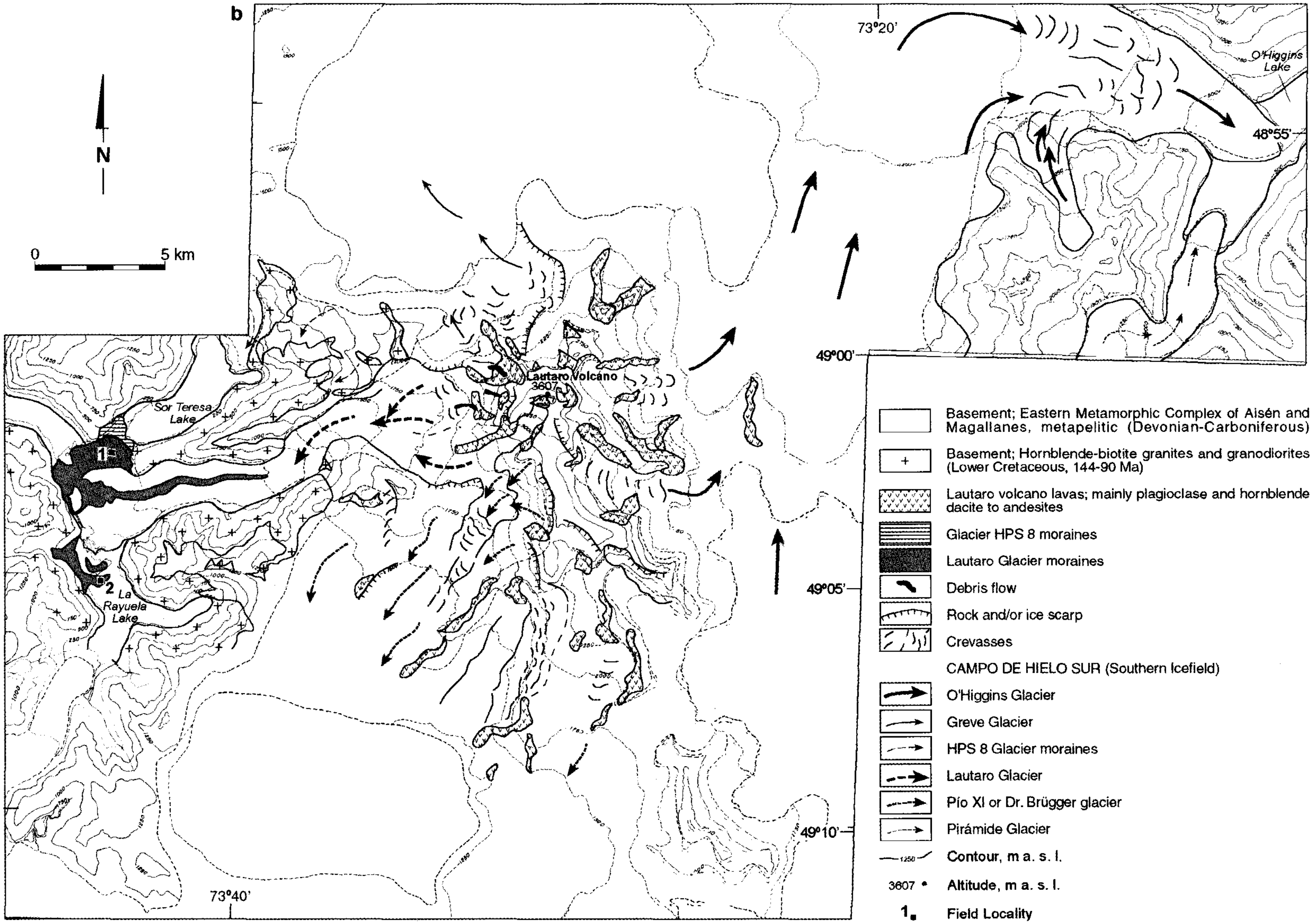

FIG. 2. Geological maps of **a.** Hudson volcano and **b.** Lautaro volcano.

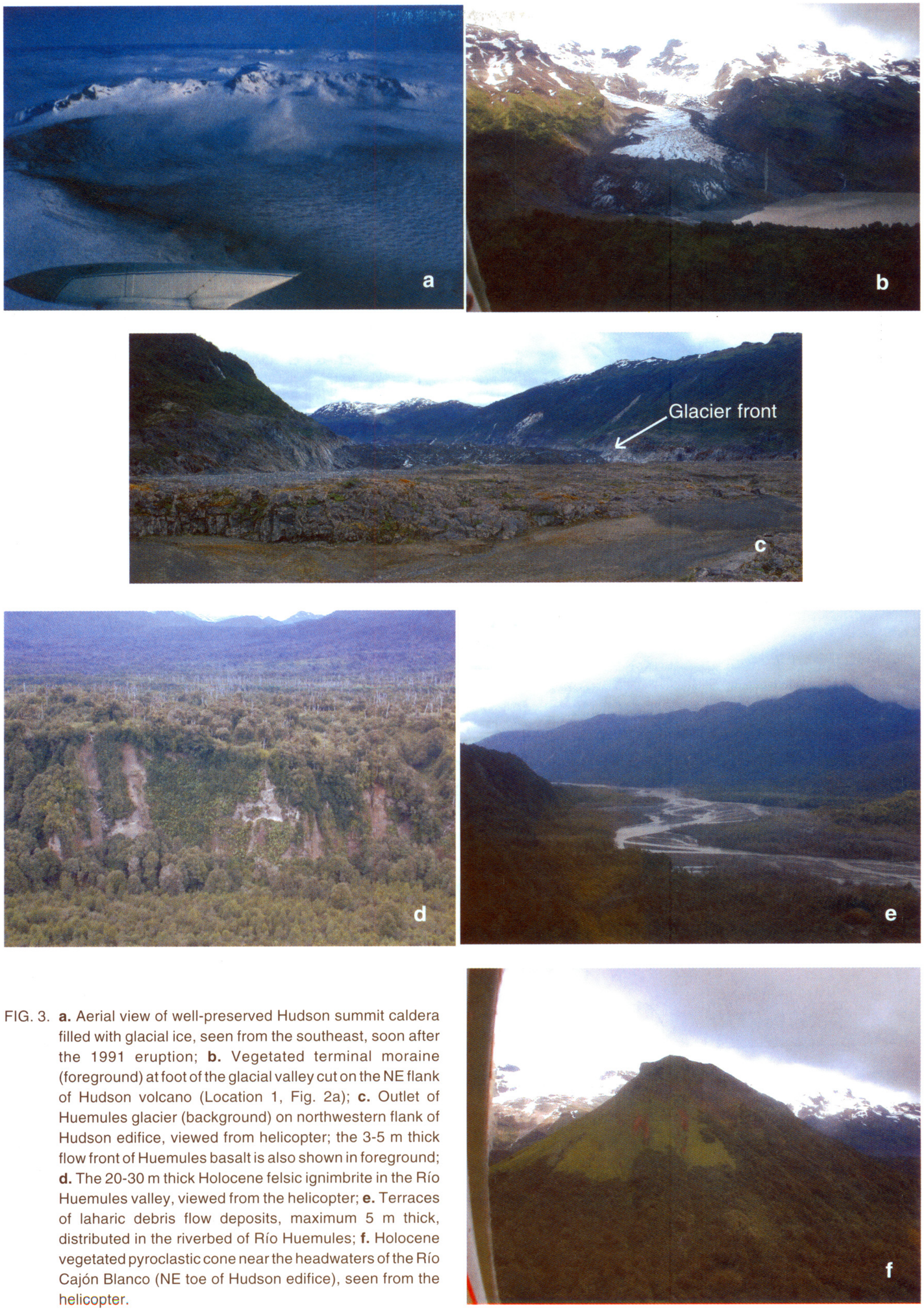

FIG. 3. **a.** Aerial view of well-preserved Hudson summit caldera filled with glacial ice, seen from the southeast, soon after the 1991 eruption; **b.** Vegetated terminal moraine (foreground) at foot of the glacial valley cut on the NE flank of Hudson volcano (Location 1, Fig. 2a); **c.** Outlet of Huemules glacier (background) on northwestern flank of Hudson edifice, viewed from helicopter; the 3-5 m thick flow front of Huemules basalt is also shown in foreground; **d.** The 20-30 m thick Holocene felsic ignimbrite in the Río Huemules valley, viewed from the helicopter; **e.** Terraces of laharic debris flow deposits, maximum 5 m thick, distributed in the riverbed of Río Huemules; **f.** Holocene vegetated pyroclastic cone near the headwaters of the Río Cajón Blanco (NE toe of Hudson edifice), seen from the helicopter.

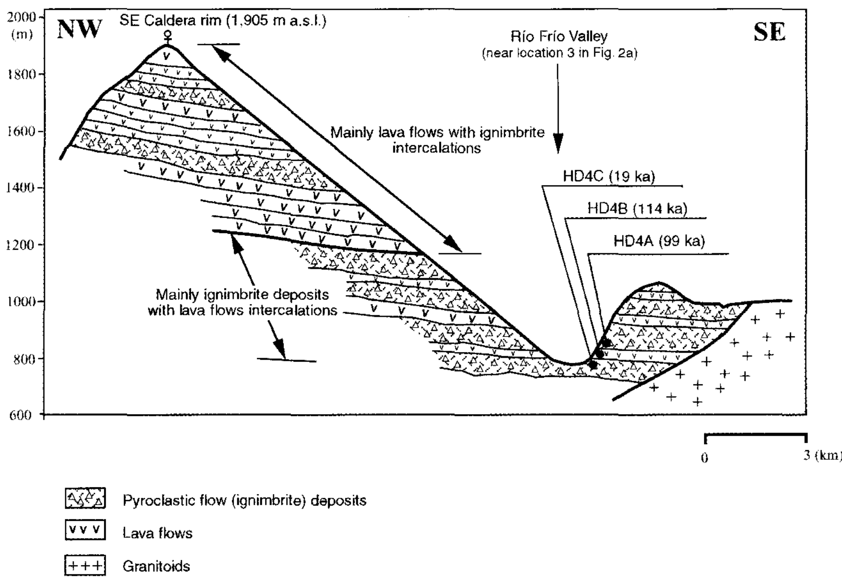

FIG. 4. Schematic cross-section of the SE caldera rim and adjacent valley on Hudson volcano, showing location sample point No. 3 (see figure 2a) of this study.

out of the caldera, principally northwestwards along the Huemules valley (Fig. 3c) (Naranjo and Stern, 1998), and overflows eastwards, as well. A Holocene basaltic lava flow, known as Huemules basalt, commonly 3 to 5 m thick, emerges beneath the Huemules glacier, as first reported by Godoy *et al.* (1981) (Fig. 3c). A felsic ignimbrite, roughly 20-30 m thick, probably related to Holocene caldera formation, was identified to the north, sporadically distributed along Río Desplayado, to the southwest along Río Sorpresa and to the southeast along Río El Frío (Fig. 3d), covering a total area of ~100 km^2 and having an estimated volume of *ca.* 3 km^3. It has been eroded by debris flows along the riverbeds, where old lahar exposures are currently 5-10 m thick (Fig. 3e). Two deeply weathered Holocene pyroclastic cones with significant vegetation cover exist to the north of the main edifice near the headwaters of the Río Cajón Blanco (Naranjo and Stern, 1998) (Fig. 3f).

LAUTARO VOLCANO

The AVZ is composed of six Holocene volcanic centers: Lautaro, Viedma, Aguilera, Reclus, Burney and Cook (roughly 49°S to 54°S). The Lautaro volcano, the northernmost of the AVZ, stands above a 2,400-m-high glacial plateau, known as the Southern Patagonian ice field (Fig. 5a). Since the volcano is mostly covered with a thick ice cap and strongly eroded by glacial action, its detailed volcanic structure is still unknown. Records of multiple eruptions (*e.g.*, Martinic, 1988; González-Ferrán, 1995) and existence of ash and pumice tephra fallout deposits on the ice surface of Viedma and O'Higgins glaciers (Kilian, 1990; Motoki *et al.*, 2003) indicate that Lautaro volcano is one of the most active stratovolcanoes in the AVZ (Fig. 5b).

The Lautaro volcano covers an area of *ca.* 150 km^2, and its summit is 3,607 m above sea level (Fig. 2b). A pre-Cenozoic granitoid is exposed along the sidewall of the Lautaro glacier on the western side of the volcano (Fig. 5c). Direct sampling from the scarce steep-cliff outcrops was impossible even with a helicopter due to high relief, high altitude, and weather conditions, including strong winds that made the approach unsafe. Therefore, we collected volcanic materials from the terminal moraine of the Lautaro glacier (Fig. 5c). The moraine is mostly composed of hornblende dacite with minor amounts of fresh glassy andesite clasts. Occurrence of prismatically jointed blocks of dacite was observed (Fig. 5d), suggesting that the Lautaro volcano might include one or more dacitic lava domes or coulées which may have collapsed into block-and-ash flows, although it is unknown when such events took place (Motoki *et al.*, 2003).

SAMPLES AND PETROGRAPHY

The sample locations and petrography of collected samples of both volcanoes are shown in Tables 1 and 2, and the details are summarized below.

TABLE 1 SAMPLE LOCATIONS AT HUDSON AND LAUTARO VOLCANOES.

Location No.	Sample No.	Latitude (S)	Longitude (W)	Outcrop
a) Hudson volcano				
Location 1	HD1A-H*	45°50.95'	72°55.12'	Terminal moraine of outlet glacier on NNE flank of edifice.
** Numbered as A, B1-3, C1-3, D, E1-2, F1-5, G1-4 and H*				
Location 2A	HD2B	45°50.58'	73°05.73'	Front of the glaciated lava flows at Ventisquero de Los Huemules (Huemules Basalt).
	HD2C			Boulder on the surface of Huemules Basalt.
Location 2B	HD3	45°53.12'	73°01.27'	Glaciated lava flows at Ventisquero de Los Huemules, covered thickly with a recent scoria.
Location 3	HD4A	45°57.85'	72°53.33'	Pyroclastic flow deposit forming a lower part of the SE caldera.
	HD4B	45°57.85'	72°53.37'	Dacitic lava flow forming a lower part of the SE caldera.
	HD4C	45°58.25'	72°53.10'	Pyroclastic flow deposit forming a lower part of the SE caldera.
b) Lautaro volcano				
Location 1	LT1A1-I2**	49°02.43'	73°43.43'	Terminal moraine of the Lautaro Glacier on western side of the volcano.
*** Numbered as A1-9, B1-3, D1, E1, F1-5, G1, H1-5, I1-2 and J1-2*				
Location 2	LT2A1-B3***	49°04,75'	73°44.26'	Relatively old terminal moraine with slight vegetal cover ~2 km S of present terminus of Lautaro Glacier.
**** Numbered as A1-3 and B1-3*				

HUDSON VOLCANO

In order to obtain rock samples from the northern flank of the volcano that we could not reach due to weather conditions, they were collected from the terminal moraine of the glacier flowing down from the northeastern flank, approximately 4 km away (Location 1 in Fig. 2a). Samples collected at this location (total 29 samples) are petrographically subdivided into eight types; A: hornblende diorite basement rock (one sample: No. HD1A), B: slightly-altered aphyric andesitic rocks (three samples: Nos. HD1B1-3), C: aphyric basaltic rocks (three samples: Nos. HD1C1-3), D: andesitic tuff breccia (one sample: No. HD1D), E: slightly-vesicular basaltic rocks (two samples: Nos. HD1E1-2), F: vesicular aphyric basaltic rocks (five samples: Nos. HD1F1-5), G: glassy dacite (four samples: Nos. HD1G1-4), H: scoria, probably erupted during 1971 or 1991 eruption (one sample: No. HD1H). At Location 2A, three samples were collected from the glaciated Huemules basaltic lava flow. Sample No. HD2B was obtained from the margin of the Huemules basalt and sample No. HD2C was collected from a block on the surface of the lava flow. Sample No. HD3 was collected from the Huemules basalt near the glacier outlet from the caldera where it was covered with >2m thick mantle of recent scoria (Location 2B). Outside the southeastern caldera wall, three samples (Nos. HD4A-C) were directly collected from an outcrop of interbedded lava flows and ignimbrite (Location 3, Fig. 2a). Sample No. HD4B is a dacite obtained from a 5 m thick massive lava flow, and the others (HD4A and HD4C) are highly vesiculated basaltic andesite juvenile bombs incorporated in an ignimbrite deposit (Fig. 4).

Under the microscope, the basalt, basaltic andesite and andesite of the Hudson volcano are similar. The rocks are aphyric to sparsely porphyritic with phenocryst assemblages of plag±cpx±ol. One sample (No. HD1B1) also contains orthopyroxene phenocrysts. Among four dacites, three samples are vitrophyric (No. HD1G1, G3 and HD2C) and one sample is sparsely porphyritic (No. HD4C) with a phenocryst assemblage of plag±cpx±opx±hb.

TABLE 2. DESCRIPTIONS FOR THE VOLCANIC ROCKS OF HUDSON AND LAUTARO VOLCANOES, CHILEAN PATAGONIA.

	Rock Type	Crystallinity	Groundmass texture	Assemblage phenocryst								Groundmass mineral	Description
				Ol	Cpx	Opx	Hb	Bt	Plag	Qz	Opq		
a. Hudson volcano													
HD1B1	andesite	holocrystalline	intergranular			+			+++		+	Pl, Cpx, Opx, Opq	Opx phenocrysts are completely altered.
HD1B2	basaltic andesite	holocrystalline	pilotaxtic		tr				++++			Pl, Cpx, Opq	
HD1B3	andesite	holocrystalline	subophitic									Pl, Cpx, Opx, Opq	Opx in groundmass is partly altered.
HD1C1	basaltic andesite	hypocrystallne	intersertal	tr	tr							Pl, Cpx, Opq	Glass in groundmass is slightly altered.
HD1C3	basalt	hypocrystallne	hyalo-ophitic						tr			Pl, Cp, Opq	Slightly vesicular. Glass in groundmass is slightly altered.
HD1E1	basalt	hypocrystallne	hyalo-ophitic	tr	tr				tr			Pl, Cpx, Ol, Opq	
HD1E2	basalt	holocrystalline	fluidal	+	+				++			Pl, Cpx, Ol, Opq	
HD1F1	basalt	holocrystalline	intergranular	tr	tr				++			Pl, Cpx, Pl, Opq	Slightly vesicular.
HD1F2	basalt	hypocrystallne	intersertal		tr				tr			Pl, Ol, Cpx	Slightly vesicular.
HD1F3	basaltic andesite	holocrystalline	intergranular	+	tr				+++++			Pl, Cpx, Ol, Opx, Opq	Slightly vesicular.
HD1F4	basalt	holocrystalline	intergranular	tr	tr				tr			Pl, Ol, Cpx, Opq	Ol in groundmass is completely altered.
HD1F5	basalt	hypocrystallne	hyalo-ophitic		tr				++			Pl, Cpx, Ol	Slightly vesicular. Ol in groundmass is partly altered.
HD1G1	dacite	hypocrystallne	hyalopilitic		+	tr			++		+	Pl, Opq	Glassy.
HD1G3	dacite	hypocrystallne	hyalopilitic		tr	+			+++			Pl, Cpx, Opx, Opq	Glassy.
HD2B	basaltic andesite	holocrystalline	intergranular		tr				++			Pl, Cpx, Opx, Opq	
HD2C	dacite	hypocrystallne	hyalopilitic		++		tr		+++		tr	Pl	Glassy
HD3	basaltic andesite	holocrystalline	intergranular	tr	+				+++			Pl, Cpx, Opq	
HD4A	basalt	hypocrystallne	hyalopilitic		tr				tr			Pl, Cpx, Opq	Highly vesicular. Glassy.
HD4B	dacite	holocrystalline	pilotaxtic		++	tr			++++		tr	Pl, Cpx, Opq	
HD4C	basaltic andesite	hypocrystallne	hyalopilitic		+	tr			+			Pl, Cpx, Opq	Highly vesicucar. Glassy
b. Lautaro volcano													
LT1A2	dacite	hypocrystallne	fluidal			++	++	tr	+++++	tr		Pl, Opx, Opq	Hb phenocrysts are partly converted into opacite.
LT1A5	dacite	hypocrystallne	Seriate			++	+	tr	+++++	++		Pl, Opx, Hb, Opq	
LT1B3	dacite	hypocrystallne	Seriate			++	++	tr	+++++	tr		Pl, Opx, Hb, Opq	Most Hb phenocrysts are converted into opacite.
LT1D1	dacite	holocrystalline	pilotaxitic			+++	++		+++++	tr		Pl, Opx, Opq	Hb phenocrysts are completely converted into opacite.
LT1F2	dacite	hypocrystallne	Seriate		tr	+++	++		+++++	tr	tr	Pl, Opx, Cpx, Opq	Hb phenocrysts are partly converted into opacite.
LT1H1	dacite	hypocrystallne	Seriate			++	++		+++++	tr		Pl, Opx, Cpx, Opq	Hb phenocrysts are completely converted into opacite.
LT1H4	dacite	hypocrystallne	Seriate			++	tr		++++	tr		Pl, Opx, Cpx, Opq	Hb phenocrysts are completely converted into opacite.
LT2A1	dacite	hypocrystallne	fluidal		tr	+++	+	tr	+++++			Pl, Opx, Opq	Hb phenocrysts are partly converted into opacite.
LT2B1	dacite	hypocrystallne	Seriate		tr	+++	++		+++++	tr		Pl, Opx, Cpx, Opq	Most Hb phenocrysts are converted into opacite.

Mineral: Ol=olivine, Cpx=clinopyroxene, Opx=orthopyroxene, Hb=hornblende, Bt=biotite, Plag=plagioclase, Qz=quartz, Opq=opaque mineral
Percentage of phenocryst abundance: tr : trace, + : less than 1%, ++ : 1–3%, +++ : 3–5%, ++++ : 5–10%, +++++ : more than 10%.

LAUTARO VOLCANO

Samples were collected from the recent terminal moraine (Location 1, 17 km to the west the volcano, Fig. 2b) of Lautaro glacier flowing down from the western slope of the Lautaro volcano, which bifurcates and enters a fjord at sea level. Location 2 (Fig. 2b) is an older terminal moraine slightly covered by vegetation. Thirty samples collected at Location 1 are divided into nine categories on the basis of their petrography; A: plagioclase-hornblende-phyric dacite (nine samples: Nos. LT1A1-9), B: plagioclase-phyric dacite (three samples: Nos. LT1B1-3), D: sparsely porphyritic hornblende dacite (one sample: No. LT1D), E: partly brecciated hornblende dacite (one sample: No. LT1E), F: plagioclase-phyric glassy dacite (five samples: Nos. LT1F1-5), G: plagioclase-phyric glassy banded-dacite (one sample: No. LT1G), H: slightly altered plagioclase-phyric glassy dacite (five samples: Nos. LT1H1-5), I: hornblende-biotite basement granite (two samples: Nos. LT1I1-2), J: basement slate (two samples: Nos. LT1J1-2). The suite of clasts at Location 2 is similar to that of Location 1 in figure 2b. Three samples of type A and B (as above) were collected at Location 2.

Microscopic observation indicates that hornblende dacites in the two moraines are petrographically similar. These are mainly porphyritic to vitrophyric rocks, and their phenocryst assemblages are plag+opx+hb±cpx±bt±qz. Hornblende is commonly converted into opacite.

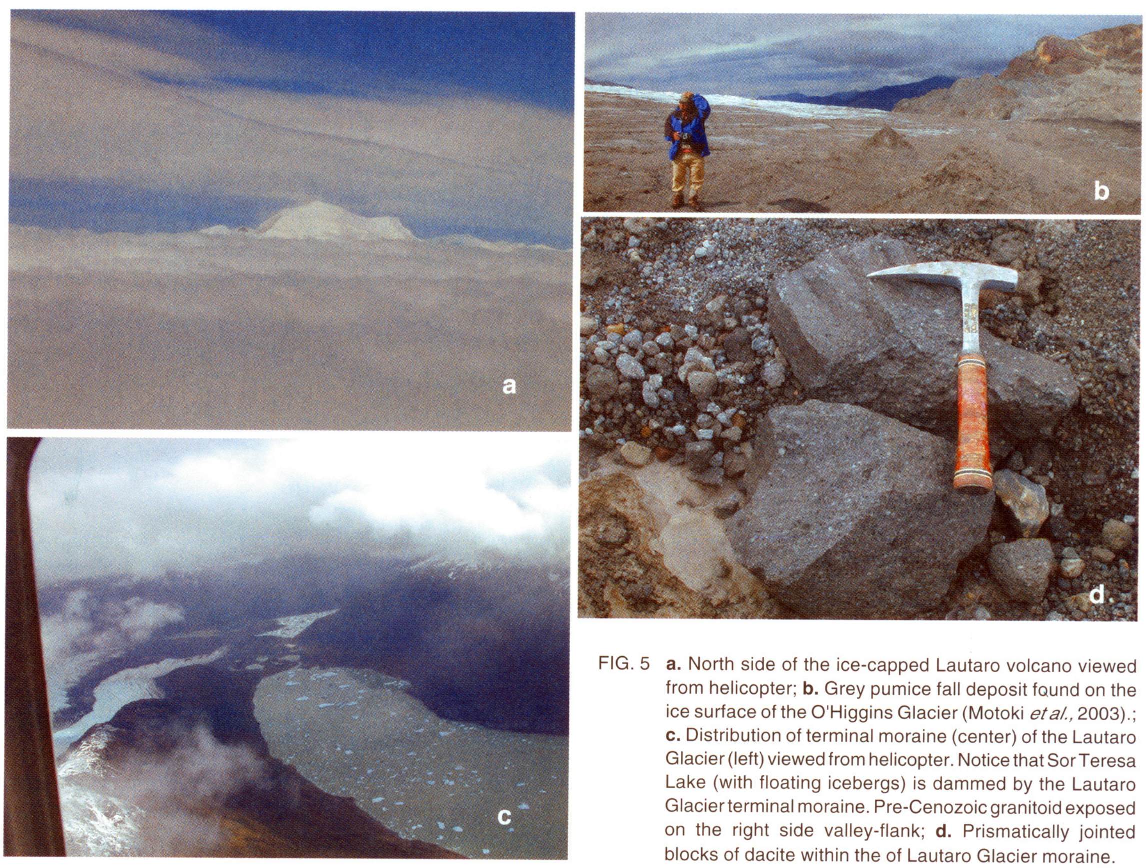

FIG. 5 **a.** North side of the ice-capped Lautaro volcano viewed from helicopter; **b.** Grey pumice fall deposit found on the ice surface of the O'Higgins Glacier (Motoki *et al.,* 2003).; **c.** Distribution of terminal moraine (center) of the Lautaro Glacier (left) viewed from helicopter. Notice that Sor Teresa Lake (with floating icebergs) is dammed by the Lautaro Glacier terminal moraine. Pre-Cenozoic granitoid exposed on the right side valley-flank; **d.** Prismatically jointed blocks of dacite within the of Lautaro Glacier moraine.

GEOCHEMICAL CHARACTERISTICS

Twenty samples from Hudson volcano, prepared for K-Ar dating, have a compositional range similar to the Holocene tephra fallout deposits reported by Naranjo and Stern (1998) from this volcano (50.5-66.6 wt% SiO_2, 0.63-2.83 wt% TiO_2, 0.66-4.94 wt% MgO and 0.78-3.13 wt% K_2O). As pointed out by previous authors (López-Escobar *et al.,* 1995; Naranjo and Stern, 1998; D'Orazio *et al.,* 2003), the rocks of Hudson volcano are relatively enriched in K_2O, Na_2O and TiO_2 compared with other volcanoes in the southern SVZ. The volcanic rocks studied plot in the medium-K to transitional high-K field (Middlemost, 1975) and close to the boundary between calc-alkaline and tholeiitic series in a FeO*/MgO vs SiO_2 diagram (Miyashiro, 1974) (Fig. 6).

Nine dacite samples from Lautaro volcano have a relatively narrow compositional range in most elements (60.5-67.5 wt% SiO_2, 0.53-0.90 wt% TiO_2, 14.8-16.4 wt% Al_2O_3 and 0.78-2.19 wt% K_2O), except for MgO that ranges from 1.88 to 4.07 wt%, of which trend is broadly similar on the other AVZ. Only significant difference in major element compositions between the northern AVZ and the southern AVZ, is in K_2O content; the former is more enriched than the latter (Fig. 6). The MgO contents and FeO*/MgO ratio for Lautaro volcano and the other AVZ are relatively higher than dacitic to rhyolitic rocks in Hudson volcano and other volcanoes in the southern SVZ. Stern and Kilian (1996) pointed out that the andesitic and dacitic rocks in the AVZ have adakitic characteristics: $SiO_2 > 56$ wt%, $Al_2O_3 > 15$ wt%, low HREE (Yb < 1.9 ppm) and Y (< 18 ppm), high Sr (> 400 ppm) and Sr/Y ratio (> 40), and positive Sr and Eu anomalies, as outlined by Defant and Drummond (1990; 1993). Furthermore, the volcanic rocks of Cook island (discovered in 1978, Suárez *et al.,* 1985; Puig *et al.,* 1984) are high-Mg andesites (59.6-61.5 wt% SiO_2, 3.3-4.5 wt% MgO), suggesting possible generation by small-degree partial melting of eclogitic MORB with limited mantle wedge interaction (<10%) (Stern and Kilian, 1996).

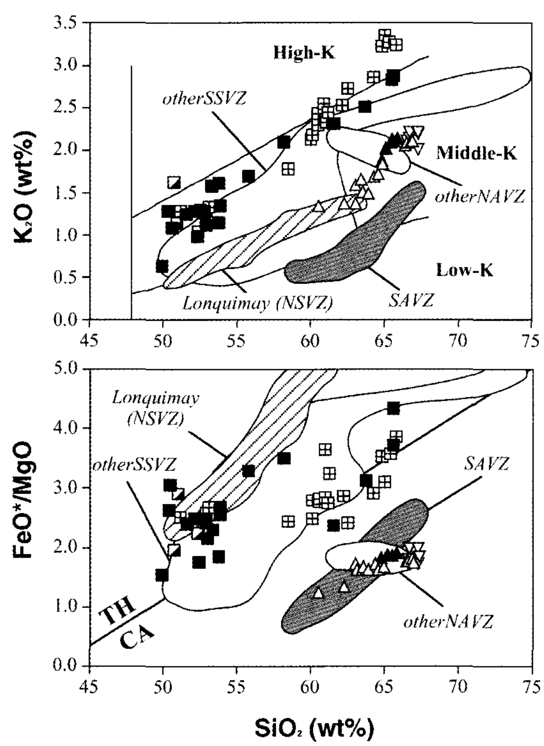

FIG. 6. Diagrams of K_2O *vs.* SiO_2 and Fe*O/MgO *versus* SiO_2 for Quaternary volcanic rocks of Hudson and Lautaro volcanoes. Data from López-Escobar *et al.* (1995), Naranjo and Stern (1998), Orihashi *et al.* (unpublished data) and Stern and Kilian (1996). Patterned areas outline data of all AVZ from Stern and Kilian (1996), southern SVZ from López-Escobar *et al.* (1995) and Lonquimay on northern SVZ from Orihashi and Hirata (unpublished data).

SAMPLE PREPARATION AND ANALYTICAL PROCEDURE

Twenty-nine samples from Hudson and Lautaro volcanoes were selected for K-Ar dating on the basis of mesoscopic and microscopic observations. The samples were crushed into roughly less than 5 mm fragments by a jaw crusher and sieved to 60 to 80 mesh size. The ferromagnetic minerals were separated using a hand magnet. The crushed samples were then washed with ion-exchanged water using an ultrasonic bath for 15 minutes, and dried at 110°C. The same material was used for both K and Ar analyses.

Ar analyses were performed using a noble gas mass spectrometer MS-III (modified-VG5400) in the Laboratory for Earthquake Chemistry, Graduate School of Science, University of Tokyo. The sieved samples (0.3-0.6 g) were wrapped in Al foil 10 mm thick and loaded in a sample holder made of Pyrex-glass, which was connected to a vacuum line at an extraction oven. In order to reduce atmospheric Ar adsorbed on the samples, the sample holder and the extraction and purification lines were baked out at 200 and 250°C, respectively, for more than one night. Molybdenum crucible in the extraction oven was also degassed by heating at about 1800°C repeatedly. The sample to be measured was fused at about 1700°C for 20 minutes. The extracted Ar was adsorbed on a charcoal trap in a purification line by cooling the trap at the temperature of liquid nitrogen. After isolation of the purification line from the extraction oven, Ar was released from the charcoal trap at *ca.* 250°C and then purified with two Ti-Zr getters maintained at about 800°C and two SORB-AC getters (NP-10, SAES getters Co. Ltd.). Ar isotope analyses were made on a relatively small amount of Ar gas (<$2x10^{-7}$ cm^3STP). If the amount of Ar gas extracted from the sample exceeded this limit, the amount of Ar gas was reduced using the purification line. Details of modification of the mass spectrometer are almost the same as that described in Nagao *et al.* (1996). A wide dynamic range (*ca.* 10^6) of an improved Daly-multiplier collector enable to measure precise isotopic ratios of $^{38}Ar/^{36}Ar$ and $^{40}Ar/^{36}Ar$ using the same detector. Sensitivity of the mass spectrometer is about $4x10^{-4}$ A/Torr corresponding to output voltage of $4x10^{-8}cm^3$STP/V. The mass discrimination factors for $^{38}Ar/^{36}Ar$ and $^{40}Ar/^{36}Ar$ ratios were determined with repeated measurement of atmospheric Ar standard ($1.5x10^{-7}$ cm^3STP) and the variation of the sensitivity and the mass discrimination factors were maintained within 5% and 0.2%, respectively. During this study, hot blank level for ^{40}Ar was $0.4\text{-}2.9x10^{-9}$ cm^3 STP and apparent Ar isotope ratios in the blank run were atmospheric within the range of analytical errors.

K concentration was determined by the X-ray fluorescence (XRF) method (Phillips PW 2400) at Earthquake Research Institute, the University of Tokyo. In this study, glass beads containing 0.4 g of sample and 4.0 g of flux (lithium tetraborate) were used. The analytical precision was checked by multiple analysis of the rock standard JB-1a, issued by Geological Survey of Japan, measured as unknowns during the analyses. The average of four runs was 1.409±0.006 wt% (SD), which agrees well with recommended value by Imai *et al.* (1995; 1.41 wt%, recalculated without H_2O^-). Taking the accuracy of the calibration line in K_2O of the XRF method and heterogeneity of the unknown samples into account, analytical uncertainty of K concentration is estimated at ±3%. The detail of procedure was described in Tani *et al.* (2002).

K-AR DATING RESULTS

The first K-Ar ages for pre-historical products of Hudson and Lautaro volcanoes were determined using the unspiked technique in this study. The results are shown in Table 3. As mentioned above, the unspiked technique can precisely date younger rocks than 0.1 Ma (*e.g.,* Gillot *et al.,* 1982; Nagao *et al.,* 1991). The technique permits measurement of small amounts of radiogenic Ar and determines the isotopic composition of the initial Ar in the sample by measuring $^{38}Ar/^{36}Ar$ without assuming that the $^{40}Ar/^{36}Ar$ ratio in sample is equal to the modern atmospheric value of 296. Most $^{38}Ar/^{36}Ar$ ratios for these samples were in agreement with the modern atmospheric value of 0.1880 within the range of analytical error (2σ). Four samples have either lower $^{38}Ar/^{36}Ar$ ratios (0.18544-0.18670; LT1A5, B3 and LT2A1) than the atmospheric value beyond the range of analytical error (2σ) or a negative value (HD2B) in K-Ar age calculated by the conventional method. In these cases, the mass fractionation effect was corrected using the measured $^{38}Ar/^{36}Ar$ ratio of the samples, and then K-Ar ages were re-calculated. In such cases, the analytical error of K-Ar dating often became much larger than those for the other samples due to insufficient accuracy of the measured $^{38}Ar/^{36}Ar$ ratio for the correction of mass fractionation.

TABLE 3. RESULTS OF K-AR DATING FOR LAUTARO AND HUDSON VOLCANOES, PATAGONIAN CHILE.

Sample No.	K (wt%)	^{40}Ar rad (10^{-8} cm^3STP/g)	$^{38}Ar/^{36}Ar$	$(^{40}Ar/^{36}Ar)$initial *	Age (Ma)	Air Fraction (%)
a. Hudson volcano						
HD1B1	1,660 ± 0,050	6,65 ± 0,35	0,18805 ± 0,00051		1,032 ± 0,063	88,2
HD1B2	0,922 ± 0,028	0,600 ± 0,073	0,18813 ± 0,00072		0,168 ± 0,021	98,6
HD1B3	0,853 ± 0,026	1,87 ± 0,17	0,18816 ± 0,00075		0,565 ± 0,055	98,3
HD1C1	1,375 ± 0,041	2,43 ± 0,33	0,18796 ± 0,00083		0,456 ± 0,063	99,1
HD1C3	1,023 ± 0,031	1,116 ± 0,099	0,18877 ± 0,00062		0,282 ± 0,026	97,9
HD1E1	1,077 ± 0,032	0,878 ± 0,092	0,18849 ± 0,00071		0,210 ± 0,023	98,7
HD1E2	1,043 ± 0,031	0,764 ± 0,044	0,18849 ± 0,00034		0,189 ± 0,012	97,5
HD1F1	0,810 ± 0,024	0,87 ± 0,11	0,18824 ± 0,00049		0,275 ± 0,036	99,4
HD1F2	0,524 ± 0,016	0,152 ± 0,029	0,18850 ± 0,00062		0,075 ± 0,015	98,5
HD1F3	1,326 ± 0,040	0,213 ± 0,024	0,18836 ± 0,00074		0,0414 ± 0,0048	99,1
HD1F4	1,289 ± 0,039	0,88 ± 0,29	0,18839 ± 0,00080		0,176 ± 0,058	99,6
HD1F5	1,063 ± 0,032	2,08 ± 0,49	0,18881 ± 0,00070		0,50 ± 0,12	99,1
HD1G1	2,290 ± 0,069	0,443 ± 0,047	0,18814 ± 0,00041		0,0498 ± 0,0055	97,6
HD1G3	2,052 ± 0,062	0,300 ± 0,022	0,18839 ± 0,00074		0,0376 ± 0,0031	98,3
HD2B	1,133 ± 0,034	0,11 ± 0,14	0,18671 ± 0,00082	291,9 ± 2,6	0,024 ± 0,031	99,3
HD2C	2,348 ± 0,070	0,045 ± 0,027	0,18802 ± 0,00096		0,0049 ± 0,0030	99,5
HD3	0,965 ± 0,029	0,049 ± 0,020	0,18826 ± 0,00039		0,0130 ± 0,0053	99,7
HD4A	1,028 ± 0,031	0,395 ± 0,033	0,18842 ± 0,00056		0,0991 ± 0,0088	97,4
HD4B	1,930 ± 0,058	0,855 ± 0,049	0,18834 ± 0,00080		0,1141 ± 0,0073	90,7
HD4C	1,060 ± 0,032	0,491 ± 0,036	0,18812 ± 0,00071		0,1193 ± 0,0095	96,2
b. Lautaro volcano						
LT1A2	1,369 ± 0,041	0,516 ± 0,034	0,18867 ± 0,00081		0,0970 ± 0,0070	94,7
LT1A5	1,314 ± 0,039	0,44 ± 0,35	0,18670 ± 0,00047	291,9 ± 1,5	0,086 ± 0,068	99,3
LT1B3	1,234 ± 0,037	0,33 ± 0,46	0,18635 ± 0,00050	290,8 ± 1,6	0,068 ± 0,097	99,6
LT1D1	1,252 ± 0,038	0,552 ± 0,032	0,18817 ± 0,00108		0,1135 ± 0,0074	86,4
LT1F2	1,402 ± 0,042	0,912 ± 0,049	0,18815 ± 0,00085		0,168 ± 0,010	88,9
LT1H1	1,140 ± 0,034	0,712 ± 0,042	0,18774 ± 0,00069		0,161 ± 0,011	92,7
LT1H4	1,113 ± 0,033	0,443 ± 0,032	0,18857 ± 0,00054		0,1026 ± 0,0080	96,1
LT2A1	1,441 ± 0,043	0,17 ± 0,41	0,18544 ± 0,00053	287,9 ± 1,7	0,030 ± 0,073	99,8
LT2B1	1,136 ± 0,034	0,438 ± 0,026	0,18797 ± 0,00094		0,0993 ± 0,0065	91,1

$(^{40}Ar/^{36}Ar)$ initial=296.0 is assumed. Error : 1σ

* $(^{40}Ar/^{36}Ar)$initial was estimated from the measured $^{38}Ar/^{36}Ar$ ratio, which was fractionated from the atmospheric value of 0.1880.

HUDSON VOLCANO

Fourteen samples collected from the terminal moraine at Location 1 (Figs. 2b and 3b) yield K-Ar (whole-rock) ages ranging from 1.03±0.06 Ma to 38±3 ka. Among them, two basaltic andesite samples classified as aphyric andesite (B type) have the oldest ages of 1.032±0.063 Ma (sample HD1B1) and 0.565±0.055 Ma (sample HD1B3), whereas two dacite samples of G type (HD1G1 and G3) yield the youngest ages of 49.8±5.5 ka; 37.6±3.1 ka, respectively. Other rock types have scattered K-Ar ages, although the samples classified as aphyric basalt (C type) are older than the vesicular and vesicular-aphyric basalts (E and F types, respectively). By grouping samples on the basis of K-Ar ages coinciding within the range of analytical error (1s), they are possibly subdivided into six groups; 1.0 Ma (HD1B1), 0.57-0.46 Ma (HD1B3, C1, F5), 0.28 Ma (HD1C3, F1), 0.21-0.18 Ma (HD1B2, E1, E2, F4) and 75-38 ka (HD1F2, F3, G1, G3).

Three samples of basaltic andesite to dacitic ignimbrite and lava collected from the outcrop at the base of the southeastern caldera flank (Location 3, Fig. 2a) yield K-Ar ages ranging from 119.3±9.5 to 99.1±8.8 ka (HD4A, B and C). These results suggest that formation of the southeastern flank is much younger than that of the northeastern part of the volcano, although northeastern stratigraphy is still unknown.

The K-Ar ages for two basaltic samples collected from different localities of the Huemules basalt are 24±31 ka (HD2B) and 13.0±5.3 ka (HD3). Considering that the latter age is more precise than the former, which has a large analytical error, probably due to the mass fractionation effect of atmospheric Ar trapped in the sample, the Huemules basalt was possibly erupted from near the summit of the volcano around 13 ka. The K-Ar age for one dacite sample (HD2C) collected from the block on the surface of the Huemules basalt is 4.9±3.0 ka. Field observation suggests that the round boulders were left on the surface during regression of the Huemules glacier.

LAUTARO VOLCANO

Nine samples were selected for K-Ar (whole rock) dating among thirty dacite samples collected from two terminal moraines of the Lautaro glacier (Locations 1 and 2, Fig. 2b). Ages for these samples range from 161±11 ka to 30±73 ka. Three samples have large analytical errors of more than 100% due to mass fractionation effects. Excluding these three samples, K-Ar ages for other samples are possibly divisible into two groups, *i.e.,* 168-161 ka (LT1F2 and H1) and 114-97 ka (LT1A2, D1, H4 and 02B1), although these samples consist entirely of uniform hornblende dacite. This suggests that compositions of products on Lautaro volcano must have remained similar through time, in contrast to Hudson volcano.

DISCUSSION AND CONCLUSION: EVOLUTION OF HUDSON AND LAUTARO VOLCANOES

HUDSON VOLCANO

Hudson volcano was first recognized as an active volcano because of its Plinian eruption in 1971, after a quiescence period of more than 100 years (Fuenzalida and Espinosa, 1974). Another Plinian eruption occurred in 1991 which was the second largest eruption in the Andean volcanic arc in the 20th century, producing more than 4 km^3 (bulk volume; <2 km^3 DRE) of tephra (Naranjo, 1991; Naranjo *et al.,* 1993; Scasso *et al.,* 1994). Previous studies were, therefore, focused on the Holocene explosive activity (*e.g.,* Stern, 1991, Stern and Naranjo, 1995; Naranjo and Stern, 1998), but also revealed that two prehistoric eruptions took place at about 6,700 years BP and 3,600 years BP on the basis of dated fallout deposits.

K-Ar ages for twenty volcanic rocks of Hudson volcano indicate that the volcanic activity started at least 1 Ma ago and continues to the present. This implies that Hudson is a long-lived volcano, at least, compared with Lautaro volcano. Among the available data, seven age groups can be recognized in this period, *i.e.,* 1.0 Ma, 0.57-0.46 Ma, 0.28 Ma, 0.21-0.18 Ma, 0.12-0.10 Ma, 75-38 ka and <30 ka (Fig. 7a). It is not clear whether these groups represent seven eruptive pulses or just a partial record of more continuous activity. There is hardly any stratigraphic reconstruction (or identification of unconformities) due to the fact that most of the edifices are concealed under ice. Comparing K-Ar ages for the rock layers from NE caldera and SE caldera, it has been recognized that formation of SE flank of Hudson began at *ca.* 0.12 Ma (Fig. 4), whereas the edifice of the NE flank was dominantly formed during 0.57-0.17 Ma period. Our aerophotographic interpretations agree with the presence of two or even three caldera rims (Fig. 2a). These results suggest that the early activity of Hudson volcano began in the area of the present NE caldera flank at *ca.* 1.0 Ma and/or 0.56 Ma, and then shifted to the SE at *ca.* 0.12 Ma, subsequently forming multiple calderas near the former summit. Felsic volcanism of Hudson volcano probably began in the SE caldera at 0.11 Ma continuing to the recent. The felsic volcanic products spread out to the whole area, suggesting that eruption style has been explosively maintained since 0.11 Ma and that the last caldera collapse possibly took place at that time. The Hudson volcano must have evolved complexly, superimposing or partially nesting calderas rather than being the result of a simple caldera structure.

Stern (1991) suggested that the summit caldera of Hudson volcano might have formed during the Holocene and that the primary caldera collapse might have taken place during the eruption at 6,700 BP, which was considered to be the first and largest eruption of Hudson volcano during the Holocene. Naranjo and Stern (1998) reported that tephra fallout deposits of the 6,700 BP eruption consist of a high proportion of very finely-grained ash with accretionary lapilli, suggesting that the potential source might have violently interacted with either the glacier cover and/or ground water within the pre-caldera summit cone or intra-caldera glacier. Although a huge and violent phreatomagmatic Plinian eruption was assumed, no pyroclastic flow deposit, expected to be accompanied by the eruption at 6,700 BP, was previously reported in this area. During our fieldwork, we found that a Holocene felsic ignimbrite is widely distributed in the valleys of Desplayado, Sorpresa and El Frío rivers, and it probably overlies the Huemules basalt of 13±5 ka. This is consistent with our conjecture that the felsic ignimbrite formed during the 6,700 BP eruption. The volume of this felsic ignimbrite is roughly estimated to be around 2-3 km^3. Assuming that the recent summit caldera of about 10 km in diameter was formed by the 6,700 BP eruption as suggested by Stern (1991), the volume of the pyroclastic products seems to be too small, even taking erosive losses into account. An estimated minimum volume of 40-50 km^3 is required to fill such a large-diameter caldera. Therefore, we suggest that a major part of the present-day caldera complex might have formed by multiple collapse events extending back into the late Pleistocene. As Naranjo and Stern (1998) pointed out, the caldera must have been filled with thick glacier ice when the 6,700 BP eruption took place. Our interpretation supports their observation.

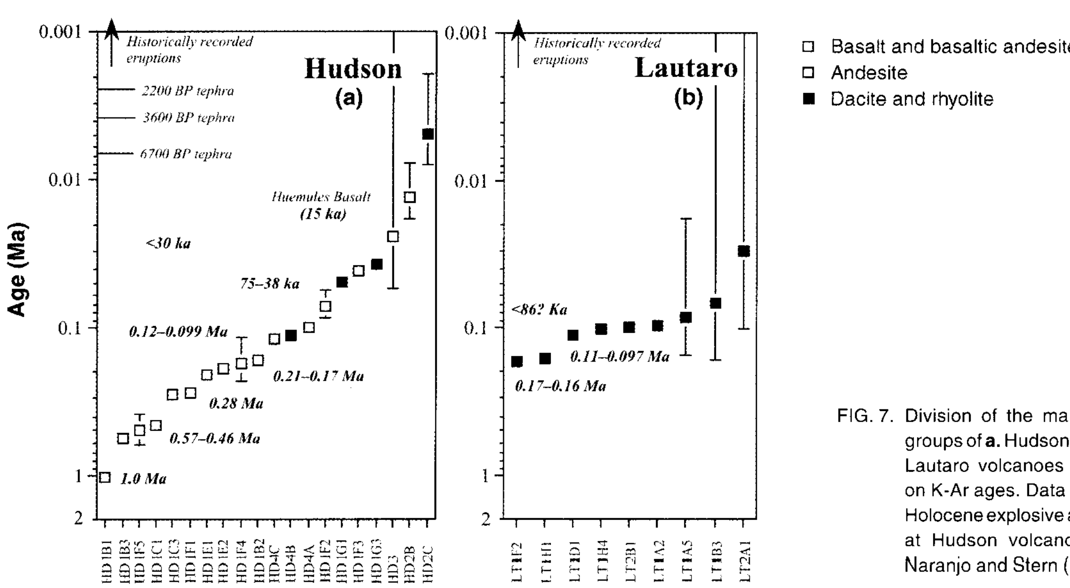

FIG. 7. Division of the main age groups of **a.** Hudson and **b.** Lautaro volcanoes based on K-Ar ages. Data for the Holocene explosive activity at Hudson volcano from Naranjo and Stern (1998).

LAUTARO VOLCANO

Due to inaccessible topography and unfavorable weather conditions on the icefield, Quaternary volcanic activity at Lautaro volcano is not known yet, except for the historical record of eruptions, at least one in 1959 (*e.g.,* Martinic, 1988; González-Ferrán, 1995). In addition, multi-stage fallout deposits on the ice surface of Viedma and O'Higgins glaciers (Kilian, 1990; Motoki *et al.,* 2003) have been sampled. In this study, K-Ar ages for nine dacite samples collected from the moraine at Lautaro glacier were determined, representing the first radiometric ages for this volcano. These results indicate that activity at Lautaro volcano began at *ca.* 0.17 Ma and has continued to the recent. Three main age groups also seem to be distinguishable at 0.17-0.16 Ma, 0.11-0.097 Ma, and <86 ka (Fig. 7b). However, these age groups are not clear due to non-stratigraphic reconstruction on the volcano and large analytical error of more than 100 % for three young samples with ages ranging from 86 ka to 30 ka. It is also not clear whether they represent three main pulses or the preserved record of a more continuous volcanic history.

Topographic information indicates that the deeply glaciated Lautaro volcano, about 1,000 m high above its base, is more likely a composite stratovolcano with dacitic dome or coulée complex rather than a compound volcano. Though the Lautaro is a relatively large stratovolcano for the Chilean Patagonia, ranges of K-Ar ages and chemical compositions from the analysed samples are significantly smaller than, at least, those of Hudson volcano. These modest ranges suggest that Lautaro volcano developed in a relatively short period of time in comparison with Hudson volcano. It is also suggested that it evolved from a relatively homogeneous magma chamber, perhaps, produced by slab melting during late Quaternary time, provided that the glaciated volcanic edifice sampled in this study represents the whole sequence of volcanic activity. Further sampling from deeply eroded parts of the edifice is necessary to reveal the whole eruptive history of Lautaro volcano, the highest peak of the Southern Patagonian Ice-field.

CONCLUDING REMARKS

In this paper, we present the results of twenty-nine K-Ar (whole rock) ages for lavas and ejecta obtained from Hudson volcano at the southern end of the SVZ and Lautaro volcano at the northern end of the AVZ which are separated by a 350 km-long volcanic gap near the Chile ridge triple junction. As a result, it is now possible to trace the eruptive history back to 1 Ma for Hudson volcano and to 0.17 Ma for Lautaro volcano. Combining these data with petrochemical data, the formation of the volcanic gap related to the Chile Triple Junction (CTJ) and the compositional contrast across it must have been achieved during the evolution of Lautaro volcano, at least 0.17 Ma ago.

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