Holocene tephrochronology of the southernmost part (42°30'-45°S) of the Andean Southern Volcanic Zone

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ABSTRACT

Tephra deposits exposed in road-cuts in both Chile and Argentina between approximately 42°30' to 45°S preserve evidence of four small (VEI <3 and volume <0.15 km³) and seven medium size (VEI = 3-5 and volume between 0.15 to 1 km³), or possibly larger, explosive Holocene eruptions of seven of the eight stratovolcanoes in this southernmost segment of the Andean Southern Volcanic Zone (SVZ). These eruptions include one from the Chaitén volcano at approximately 9,370 BP, two from the Michinmahuida volcano occurring at ≤6,350 BP and ≤3,820 BP, three from the Corcovado volcano with the oldest one occurring sometime between ≤9,190 and ≥7,980 BP and the two younger ones at ≤7,980 BP and ≤6,870 BP, one from the Yanteles volcano at ≤9,190, two from the Melimoyu volcano occurring at ≤2,740 BP and ≤1,750 BP, one from the Mentolat volcano at ≤6,960, and one from the Macá volcano at approximately ≤1,540 BP. The principal orientation, to the east, of the tephra plumes produced by these Holocene explosive eruptions in this arc segment, indicates a possible impact for future explosive eruptions on aeronavigation routes in Argentinean Patagonia. The total of eleven small and medium size explosive eruptions over a period of about 8,000 years implies a frequency of one eruption approximately every 725 years in this segment of the Andean SVZ, with each of the eight volcanoes having produced on the average 1.4 eruptions during the Holocene. This is about as frequent as for similar size eruptions from individual volcanic centers further north in the SVZ. In contrast, the Hudson volcano, the southernmost volcano in the SVZ, located just north of the Chile Rise-Trench triple junction at 46°S, has had three very large and nine other documented small explosive Holocene eruptions, and thus both larger and more numerous explosive Holocene eruptions than all the other centers in the southernmost SVZ combined. Hudson volcano may be significantly more active than the other centers in the southernmost SVZ because of its location close to the triple junction.

Key words: Tephra, Tephrochronology, Explosive volcanism, Holocene, Andes, Argentina, Chile.

RESUMEN

Tefrocronología holocena de la parte más austral (42°30'-45°S) de la Zona Volcánica Andina del Sur. Los depósitos de tefra expuestos en los cortes de caminos entre aproximadamente 42°30' y los 45°S, tanto en Chile como en Argentina, muestran evidencias de cuatro niveles de erupciones explosivas holocenas de magnitud pequeña (IEV <3 y volumen <0,15 km³) y siete de tamaño mediano o mayor (IEV = 3-5 y volumen entre 0,15 y 1 km³). Dichos niveles se generaron en siete de los ocho estratovolcanes en este segmento austral de la Zona Volcánica de los Andes del Sur (ZVS). Estos niveles incluyen uno del volcán Chaitén de aproximadamente 9.370 AP, dos del volcán Michinmahuida originado a ≤6.350 AP y ≤3.820 AP, tres del volcán Corcovado, de las cuales, la más antigua ocurrió entre ≤9.190 y

≥7.980 AP y las dos más jóvenes ≤7.980 AP y ≤6.870 AP, una del volcán Yanteles de ≤9.190 AP, dos del volcán Melimoyu ocurrida entre ≤2.740 AP y ≤1.750 AP, una del volcán Mentolat aproximadamente ≤6.960 AP y una del volcán Macá ocurrida ≤1.540 AP. La orientación principalmente al este de la dispersión de las plumas de erupciones explosivas en el segmento estudiado, indica que futuras erupciones tendrían un impacto directo en las rutas de aeronavegación en la Patagonia Argentina. Un total de once erupciones explosivas de magnitud menor a media en un período de 8.000 años implica una frecuencia de aproximadamente una erupción cada 725 años en este segmento de los Andes del sur (ZVS), con un promedio de 1,4 eventos explosivos para cada uno de los ocho volcanes durante el Holoceno. Esta frecuencia para erupciones de similar tamaño es semejante a la obtenida en cada volcán hacia el norte dentro de la ZVS. Contrasta con esta cifra, sin embargo, la frecuencia de erupciones explosivas ocurridas en el Hudson, el volcán más austral en la ZVS, ubicado inmediatamente al nortedel Dorsal de Chile-Fosa de la conjunción triple a los 46°S, el cual ha tenido tres erupciones explosivas muy grandes y nueve eventos explosivos menores documentados durante el Holoceno. Esta característica lo convierte en el volcán que ha tenido las erupciones explosivas más grandes y numerosas del segmento austral de la ZVS. Debido a su ubicación cerca de la conjunción triple, el volcán Hudson podría ser significativamente más activo que otros centros en la parte sur de la ZVS.

Palabras claves: Tefra, Tefrocronología, Volcanismo explosivo, Holoceno, Andes, Argentina, Chile.

INTRODUCTION

This paper describes Holocene tephra deposits produced by explosive eruptions of volcanoes in the southernmost part, between 42°30' and 45°S, of the Andean Southern Volcanic Zone (SVZ; Figs. 1 and 2; see Stern, 2004). In the only previously published study of Holocene deposits containing tephra in this region, Heusser *et al.* (1992) reported a thick tephra layer dated at ≤10,880 BP from a road-cut 4 km north of Chaitén and eight different tephra layers younger than 12,310 BP within a bog profile at Cuesta Moraga approximately 60 km southeast of Chaitén. Naranjo and Stern (1998) described tephra deposits produced by explosive eruptions of the Hudson volcano, the southernmost in the SVZ at 46°S, just south of this region.

The results presented in this paper are a contribution to the understanding of the history of volcanic activity and the evaluation of volcanic hazards in the southern Andes. Eight large stratovolcanoes, as well as numerous small cones associated with the Liquiñe-Ofqui Fault System (LOFS; Cembrano *et al.*, 1996), occur in the segment of the active Andean volcanic arc between 42°30' to 45°S (Figs. 1 and 2). The eight larger volcanic centers include, from north-to-south, Chaitén, Michinmahuida, Corcovado, Yanteles, Melimoyu, Mentolat, Cay and Macá. All these volcanoes are remote from existing roads and logistically difficult to access, and only preliminary volcanic stratigraphy and geochemical data are available for any of these centers (Stern *et al.*, 1976; Futa and Stern, 1988; López-Escobar *et al.*, 1993; D'Orazio *et al.*, 2003). Only one of these volcanoes - Michinmahuida - has a confirmed record of historic activity, which occurred in the years 1834-1835 (Darwin, 1838; Martin, 1917; von Wolff, 1929; Casertano, 1963a and b).

The stratigraphy, distribution and chronology of tephra deposits generated by post-glacial explosive eruptions of the stratovolcanoes between 42°30' to 45°S were examined in numerous soil profiles along road-cuts associated with all the principal and secondary roads on both the Chilean and Argentinean sides of the Andes, in particular the Chilean Carretera Austral. Within 44 of these profiles (Fig. 2), tephra thickness was measured, internal textural variations of tephra deposits were described, the organic soils in which the tephra deposits occur were collected for ^{14}C age determinations (Table 1), and tephra were sampled for chemical analysis for comparison with published data for samples from the volcanic centers in the region (Fig. 3; Table 2). Correlations based on these data (Fig. 4) were used for tracing the regional distribution (approximate 10 cm isopach) of each tephra (Fig. 2), identifying their source volcano, and determining their age and the approximate magnitude of the explosive eruptions that generated each tephra.

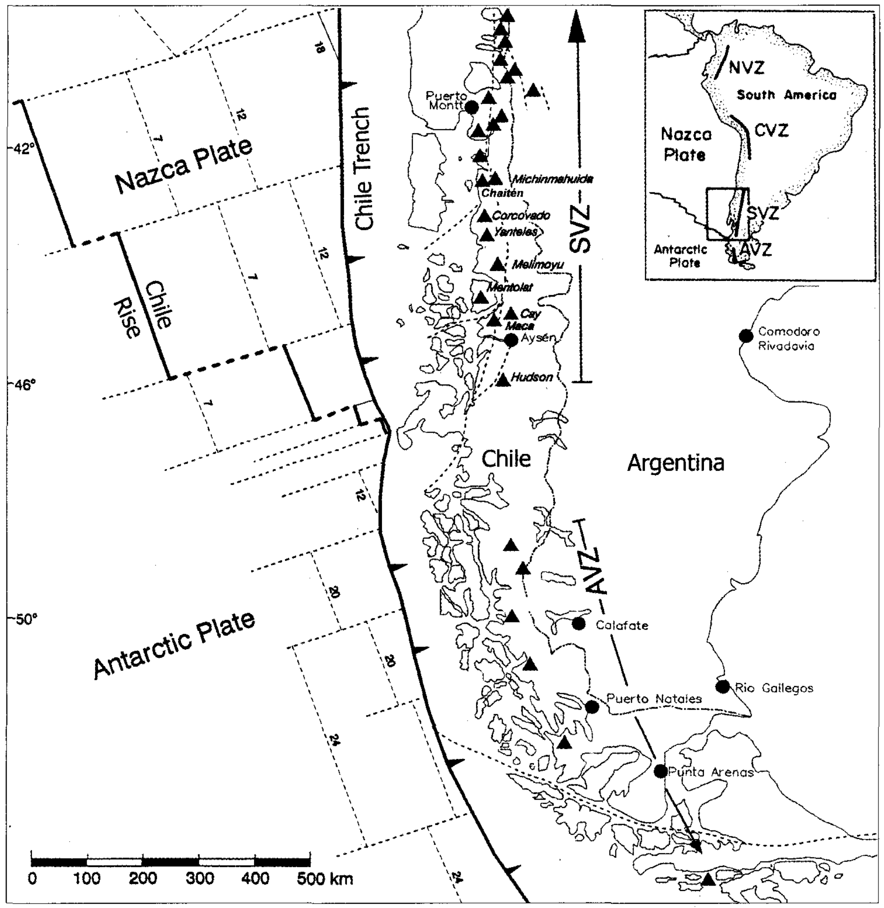

FIG. 1. Map showing the location of the volcanoes in the study area between 42°30' and 45°S, as well as the major plates and plate boundaries in the region. The numbers along ridge parallel dashed lines are in Ma. NVZ, CVZ, SVZ and AVZ are Northern, Central, Southern and Austral Volcanic Zones of the Andes, respectively (modified from López-Escobar *et al.* ,1993; see Stern, 2004).

SAMPLING AND ANALYTICAL TECHNIQUES

Samples of different organic materials contained in layers immediately below fallout layers were carefully collected, avoiding contamination with other datable organic material, and packed in aluminium foil. Conventional ^{14}C analysis were carried out at Beta Analytic Inc. Laboratories (Miami, U.S.A.) as radiometric standard analyses and standard AMS for one sample. The dates were reported as radiocarbon years before present ('present' = 1950 A.D.), using the Libby ^{14}C half life (5,568 years). All reported ages (Table 1) have quoted errors that represent the 68.3 % confident limit.

Major and trace element chemical analysis for samples from site 170299 (Table 2) were carried out at the Servicio Nacional de Geología y Minería laboratories (Sernageomin-Chile). Samples were crushed to less than 200 sieve size and then analysed by atomic absorption spectrometry (AAS) for major oxides, and by inductively coupled plasma-atomic emission spectrometry (ICP-AES) for trace elements. Samples preceded by the letter T (Table 2) were analysed for major and trace-elements at the University of Colorado, Boulder, by AAS and Xray fluorescence (XRF) techniques. The results in both laboratories are constantly calibrated with international standards. Errors in the methods used in both these laboratories are usually less than 0.5 % and 3 %, for major oxides and trace elements, respectively.

RESULTS

Based on the correlations made between tephra deposits in the different profiles examined, eleven different Holocene explosive eruptions of seven of the stratovolcanoes were identified. The distribution, lithologic and chemical characteristics, and age of each of the tephra deposits produced by these different volcanoes are described below.

TABLE 1. UNCALIBRATED C^{14} AGES OF ORGANIC MATERIALS UNDERNEATH TEPHRA FALL DEPOSITS IN THE REGION BETWEEN 42°30' AND 45°S.

Site location	Sample	Tephra	Material	Pretreatment	Relation	Conventional C^{14} age $\pm 1\sigma$ error (BP)
T-13	**(42°43.3'S; 72°35.8'W)**					
	T-13D	CHA1	Charcoal	Acid/alkali/acid	$\leq$	9,370±60
	T-13E	CHA1	Partially burned wood	Acid/alkali/acid	<	9,810±90
170299-1	**(42°54.71'S; 71°20.90'W)**					
	170299-1L	MIC2	Organic soil	Acid washes	>	1,840±70
	170299-1J	MIC2	Peat	Acid washes	$\leq$	3,820±70
	170299-1i	MIC1	Peat	Acid washes	>	5,120±80
	170299-1G	MIC1	Peat	Acid washes	$\leq$	6,350±60
170299-7	**(42°51.06'S; 71°36.27'W)**					
	170299-7	MIC2	Charcoal (AMS)	Acid/alkali/acid	<	4510±40
T-20	**(43°06.6'S; 72°27'W)**					
	T-20B	COR3	Peat	Acid washes	$\leq$	6,870±90
	T-20D	COR2	Peat	Acid washes	$\leq$	7,980±100
T-23	**(43°21.2'S; 72°24'W)**					
	T-23	YAN1	Wood	Acid/alkali/acid	$\leq$	9,560±60
T-25	**(43°12'S; 71°54.5'W)**					
	T-25B	YAN1	Charcoal	Acid/alkali/acid	$\leq$	9,190±130
T-04	**(44°09.1'S; 72°28'W)**					
	T-04B	MEL2	Organic soil	Acid washes	$\leq$	1,750±80
	T-04F	MEL1	Charcoal	Acid/alkali/acid	$\leq$	2,790±70
T-07	**(44°03.6'S; 72°25.8'W)**					
	T-07	MEL1	Charred material	Acid/alkali/acid	$\leq$	2,740±70
T-36/58	**(45°23.7'S; 72°29'W)**					
	T-58B	MAC1	Organic soil	Acid washes	$\leq$	1,540±60
	T-58A	MEN1	Organic soil	Acid washes	$\leq$	6,690±60

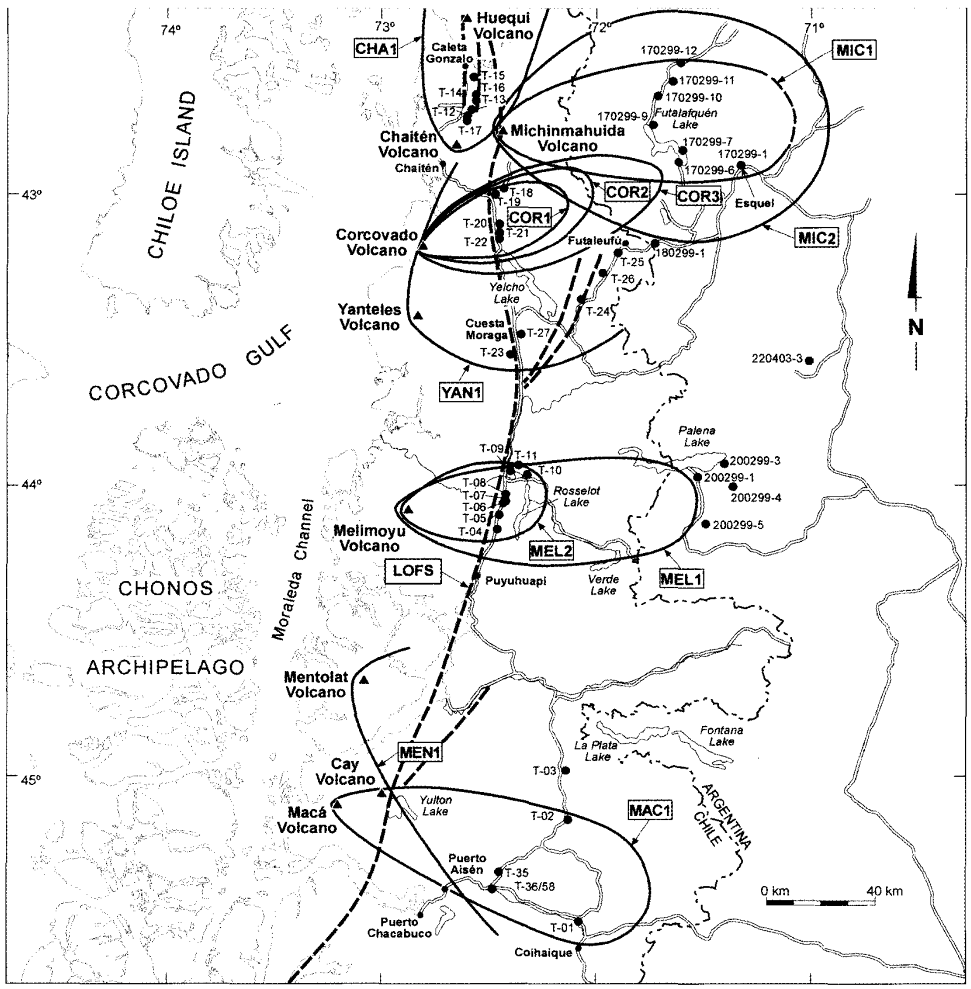

FIG. 2. Map showing the location of volcanoes and road-cut sites studied between 42°30' and 45°S, as described in the text, and the approximately 10 cm isopachs of the eleven Holocene eruptions identified in this area. LOFS = Liquiñe-Ofqui Fault System.

CHAITÉN VOLCANO

Chaitén volcano (42.85°S/72.52°W; 962 m), located on the western flank of the larger Michinmahuida volcano, is a small 3 km in diameter post-glacial caldera, or explosion crater, within which a rhyolite obsidian lava dome occurs (Figs. 2 and 5; López-Escobar *et al.*, 1993). Cobbles of this translucent grey rhyolite obsidian, which contains a very small volume (<2 volume percent) of plagioclase phenocrysts, are found in the Blanco River. This river originates within the summit crater of the Chaitén volcano and flows west into the Gulf of Corcovado (Fig. 2). These river cobbles are the source of obsidian fashioned into prehistoric artefacts found along the Pacific coast, as far away as 400 km to both the north and the south, in maritime canoe culture occupational sites that, in some cases, have

TABLE 2. CHEMICAL COMPOSITIONS OF BULK PUMICE SAMPLES SEPARATED FROM TEPHRA FALL DEPOSITS IN THE REGION BETWEEN 42°30'

Tephra	CHA1	MIC2	MIC2	MIC1	COR3	COR2	COR1	YAN1	YAN1	MEL2	MEL1B
Sample	T-13A	170299-1K	170299-6	170299-1H	170299-1F	170299-1D	T-20E	170299-1B	T-20F	T-4A	T-4D
Site	T-13	170299-1	170299-6	170299-1	170299-1	170299-1	T-20	170299-1	T-20	T-04	T-04
SiO_2	72.18	71.11	69.89	57.25	56.67	66.47	53.21	63.49	65.92	60.16	50.1
TiO_2	0.13	0.15	0.07	1.24	0.85	0.26	1.89	0.44	0.37	1.23	1.66
Al_2O_3	14.76	13.31	14.92	17.85	18.67	14.11	16.27	16.22	16.07	17.03	16.2
Fe_2O_3		0.75	0.58	2.76	2.13	1.31		1.65			
FeO*	1.24	0.88	0.92	3.6	3.36	1.09	9.72	2.51	4.19	7.04	10.86
MnO	0.06	0.06	0.06	0.13	0.12	0.05	0.14	0.12	0.14	0.15	0.16
MgO	0.43	0.27	0.27	2.05	2.71	0.76	5.54	0.65	0.92	1.25	5.06
CaO	1.21	1.43	1.23	4.83	5.67	2.27	6.95	3.06	3.34	3.58	8.66
Na_2O	4.27	4.02	3.76	4.38	3.48	3.26	3.12	4.45	4.14	5.82	3.47
K_2O	2.89	2.98	2.92	1.68	0.91	2.02	0.83	1.45	1.32	2.1	0.88
P_2O_5	0.11	0.11	0.1	0.35	0.25	0.25	0.25	0.22	0.18	0.31	0.28
LOI	2.66	4.72	4.89	3.42	4.82	8.95	1.89	5.69	3.26	1.29	2.11
Total	99.94	99.72	99.6	99.54	99.64	99.81	99.81	99.96	99.85	99.96	99.44
SiO_2*	74.21	74.85	73.79	59.56	59.77	73.16	54.34	67.36	68.24	61.13	51.47
Trace elements parts-per-million (ppm)											
Rb	114	108	107	46	38	81	17	43	39	49	16
Sr	143	126	110	277	264	156	398	218	200	315	464
Ba	642	606	542	486	347	495	n.d.	436	n.d.	n.d.	n.d.
Nb	9	6	5	6	6	5	10	6	6	13	5
Y	15	14	12	42	21	11	16	35	31	34	26
Zr	86	76	67	224	174	176	147	184	177	263	135

SiO_2* = SiO_2 in rock with total oxides minus LOI normalized to 100%.
FeO* = total Fe as FeO when no analysis of Fe_2O_3 was available.
n.d. = not etermined.

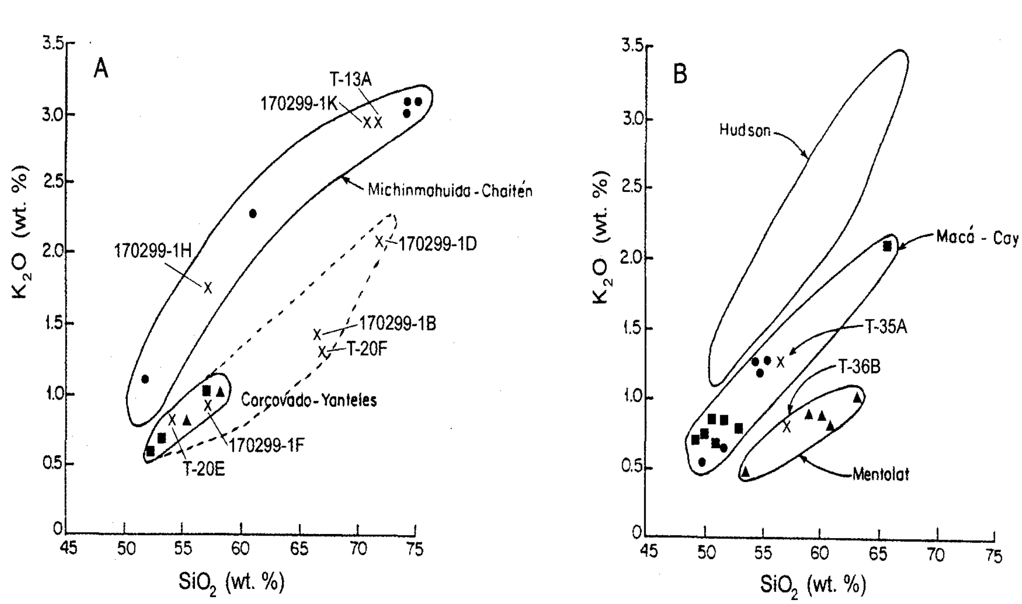

FIG. 3. SiO_2 *versus* K_2O of pumice collected from tephra fall deposits compared to the range of composition of samples from different volcanic centers in the region 42°30' to 45°S. Fields for Michinmahuida/Chaitén (circles) are from López-Escobar *et al.* (1993) and Stern *et al.* (2002), for Corcovado (squares) and Yanteles (triangles) from López-Escobar *et al.* (1993), for Macá (circles) and Cay (squares) from Futa and Stern (1988) and López-Escobar *et al.* (1993), and for Mentolat (triangles) from López-Escobar *et al.* (1993).

been dated as being as old as 5,610 BP (Stern *et al.*, 2002). This places a minimum age on the formation of this rhyolite dome and the older crater within which it occurs. There is no record of historic activity of this volcano.

A series of road-cut outcrops (T-12 through T-17; Fig. 2) expose a pyroclastic surge overlain by a tephra fall deposit (Fig. 6), beginning approximately 35 km north of the town of Chaitén along the Carretera Austral, where the road crosses over the topographic divide between Blanco and Negro lakes, and continuing another 15 km to Caleta Gonzalo at the southern tip of Reñihue fjord. The dark-grey pyroclastic surge deposit, which decreases from 3.5 to 1.5 m in thickness over this distance, contains abundant lithic fragments, including fragments of charcoal dated as 9,370 BP (sample T-13D; Table 1). This deposit overlies tree trunks, dated as 9,810 BP (T-13E; Table 1), and fluvial/glacial conglomerates. Above this surge layer is a tephra fall deposit, which decreases from 1.65 to 0.3 m in thickness over the same distance. This tephra fall deposit consists of white to yellow rhyolite pumice (sample T-13A; Table 2), inversely size-graded from fine lapilli to coarse pumice over 18 cm in diameter, capped by a thin layer of dark mafic scoria (Fig. 6). The proportion and size of lithic fragments also increases upwards in this deposit. The lack of any soil development between the pyroclastic flow and the tephra fall deposits suggests that they are closely related in time.

The spatial dispersion of these deposits and the chemistry of the rhyolite pumice in the tephra fall deposit (Fig. 3) together, imply that they were derived from a small to medium size explosive eruption of the Chaitén volcano (CHA1; Fig. 2). They were presumably generated by the same explosive event that created the summit crater of the volcano. Heusser *et al.* (1992) dated a 'thick tephra layer' exposed in a road-cut along the east side of the Carretera Austral 4 km north of the town of Chaitén, to the west of the volcano, as ≤10,880 BP. More recently, P. Moreno (personal communication, August 2003) redated this same deposit as <10,260

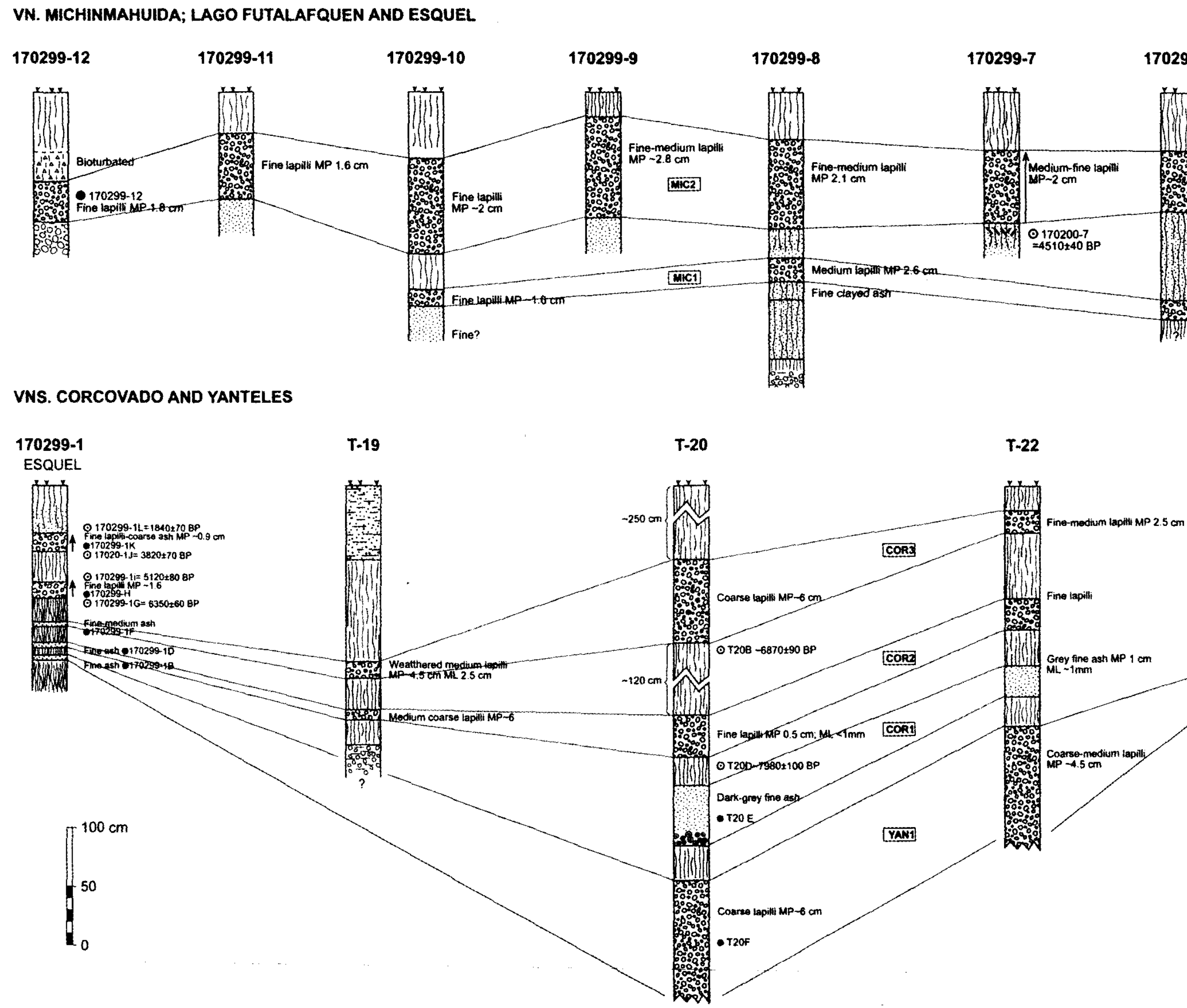

FIG. 4. Diagram showing the correlation of different tephra deposits occurring in the soil profiles located in figure 2. These correlations were based on the interna
their age (Table 1) and chemical composition (Table 2 and Fig. 3). Maximum pumice size (MP) and scoria size (MS) are indicated.

(Fig. 4 continued)

VN. MELIMOYU, NORTH OF PUYUHUAPI

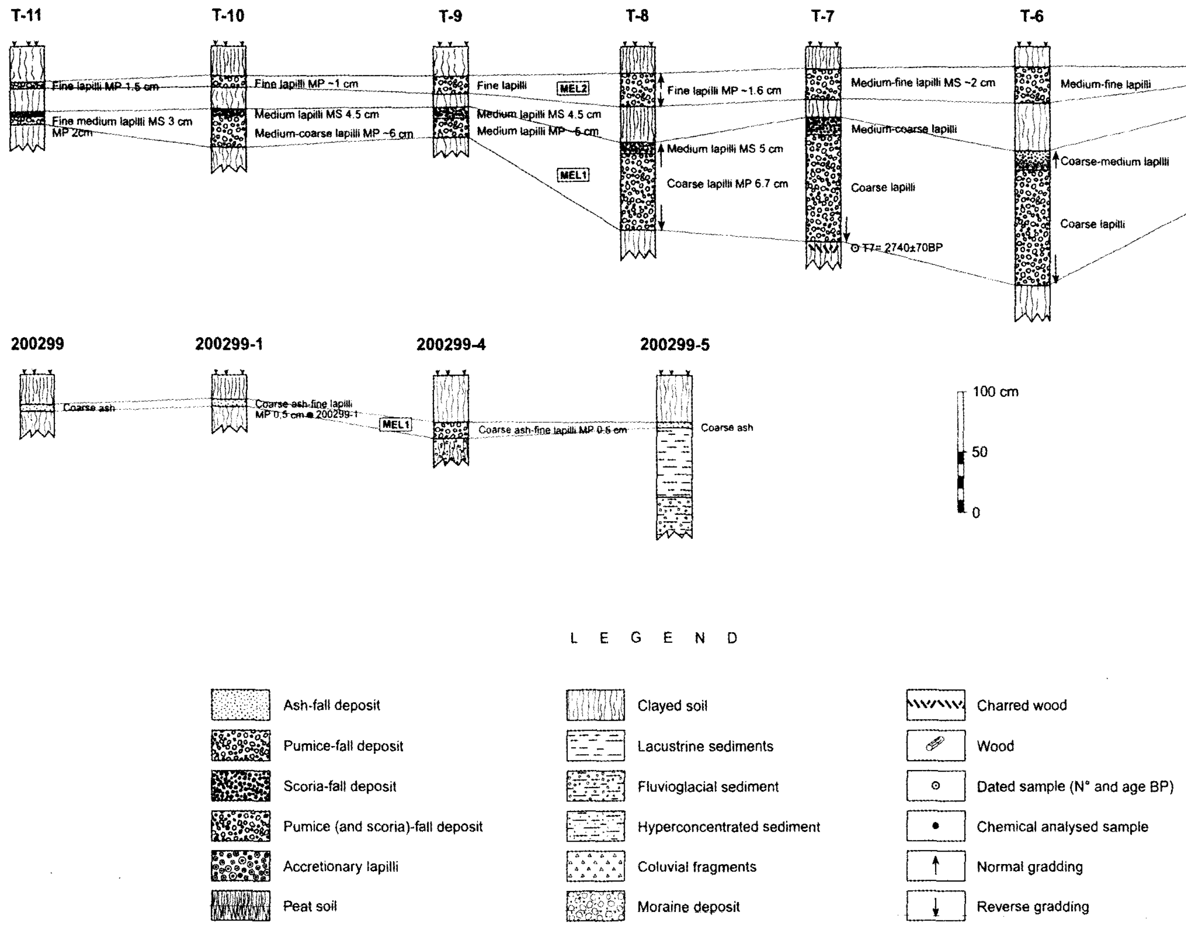

FIG. 5. Aerial photographs (SAF93-251865, taken in 1993) of the 3 km in diameter Chaitén crater and dome complex, located to the northeast of the village of Chaitén. North is upwards.

FIG. 6. Photograph (CS-8) taken at site T-13 (Fig. 2) of the dark, charcoal and lithic-rich pyroclastic surge deposit, with charcoal C^{14} dated at 9,370 BP (Table 1), and the upper white rhyolite tephra fall deposit, capped by a thin layer of dark mafic scoria, derived from the Chaitén volcano. The scale is 2 m long.

BP, and another outcrop closer to Caleta Santa Barbara, where the Blanco River enters the Gulf of Corcovado, as <9,580 BP. These deposits presumably were produced by the same eruption that produced the deposits to the north of the volcano. The scarcity of other exposures of these deposits to the west and south of the volcano probably results from extensive erosion over the last >9,000 years.

MICHINMAHUIDA VOLCANO

Michinmahuida volcano (42.78°S/72.43°W; 2,404 m) is a massive ice covered Pleistocene to Holocene stratovolcano/caldera complex developed along 14 km of a northeast-southwest oriented fissure (Fig. 7). There are dependable historic records of an explosive eruption in November of 1742, and another episode of explosive activity between November 26, 1834, and the middle of March, 1835, when a lava flow is reported to have been extruded from a crater on the flank of the volcano (Darwin, 1838; Martin, 1917; von Wolff, 1929; Casertano, 1963a and b).

Tephra deposits derived from two late Holocene explosive eruption of Michinmahuida are recognized as far to the east as the city of Esquel (Figs. 2 and 8) and the shores of Futalafquén lake in Argentina (MIC1 and MIC2; Fig. 2). The older deposits, 20 cm thick at a distance of 70 km east of their source (sample site 170299-8; Figs. 2 and 4), consist of fine lapilli and fine to medium ash size grey andesitic pumice (170299-1H; Table 2 and Fig. 3). These formed from a medium size explosive eruption dated as having occurred between 6,350 and 5,120 BP (samples 170299-1G and 1I; Table 1). The younger deposits, 85 cm thick at a distance of 60 km from the volcano (sample site 170299-9; Figs. 2 and 4), consist of white rhyolite pumice (sample 170299-1K; Table 2 and Fig. 3) and medium size lapilli. These formed from a medium to large size explosive eruption dated to have occurred between 3,820 and 1,840 BP (samples 170299-1J and 1L; Table 1).

CORCOVADO VOLCANO

Corcovado volcano (43.18°S/73.80°W; 2,300 m) is an intensely eroded conical stratovolcano (Fig. 9) with Holocene lava flows at the base. In contrast to the larger volcanic edifice, these lava flows are not eroded, but they are covered by dense vegetation and are certainly prehistoric. Although there are historical reports of a cycle of activity beginning in November, 1934, and ending with the eruption of a lava flow, presumably from one of the

FIG. 7. Photograph of the ice covered Michinmahuida volcano as seen from the west.

flanking cones, on November 11, 1935 (Darwin, 1838; Martin, 1917; Von Wolff, 1929; Casertano, 1963a and 1963b), the authors believe these reports are likely mistaken. They were probably based on observations made from boats sailing in the Gulf of Corcovado and they most likely pertain to the well documented activity during this same time period of the Michinmahuida volcano.

Three separate tephra layers derived from small to medium size explosive eruptions of this volcano have been documented (COR1-3; Figs. 2, 4 and 10). The oldest layer (COR1) consists of a distinctive fine grey to black basaltic andesite tephra with a concentration of accretionary lapilli at its base. This tephra is 50 cm thick 25 km northeast of the volcano (site T-20; Figs. 2, 4 and 10). The very small particle size and the abundance of accretionary lapilli suggest deposition from a vapor-rich eruption. This deposit has not been dated directly, but overlies a

FIG. 8. Photograph (JAN-598) taken at sample site 170299-1 in Esquel, Argentina (Fig. 2), of five tephra units, the upper two derived from eruptions of the Michinmahuida volcano, and the next lower two from eruptions of the Corcovado volcano, and the lowest one derived from an eruption of the Yanteles volcano. Bracketing ^{14}C ages 3,820 to 1,840 BP and 6,350 to 5,120 BP were obtained for the two Michimahuida eruptions near the top of the exposure.

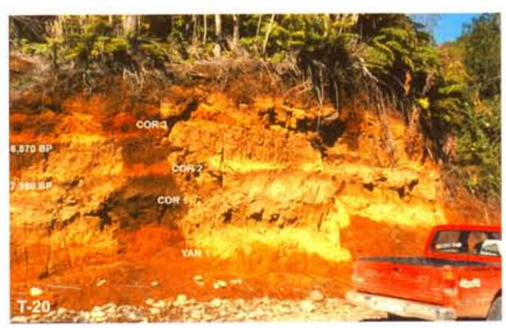

FIG. 10. Photograph (JAN-50) taken at sample site T-20 (Fig. 2) showing four tephra layer, the upper three derived from eruptions of the Corcovado volcano and the lowest layer derived from the Yanteles volcano. The base of the Yanteles tephra is not exposed. The oldest tephra derived from Corcovado volcano is a distinctive grey color and mafic composition (sample T-20E; Table 2), while the other tephra are all yellow-orange in color. Movement along a near vertical fault, visible just above the rear-end of the truck, has displaced upwards approximately 40 cm these tephra layers to the right of the fault.

FIG. 9. Photograph of the highly eroded Corcovado volcano looking south from the town of Chaitén.

tephra derived from the Yanteles volcano (YAN1; described below) which formed from an eruption dated at ≤9,190 BP and underlies a younger Corcovado tephra dated as having formed ≤7,980 BP (COR2, Figs. 4 and 10; sample T20D, Table 1). This younger tephra deposit (COR2) is 35 cm thick 25 km northeast of the volcano, and may also occur as a thin layer as far to the east as Esquel, Argentina (Figs. 4 and 8). This deposit consists of fine lapilli and pumice weathered to an orange color. The youngest tephra deposit derived from the Corcovado volcano consists of a layer of fine to medium lapilli mixed with coarse pumice weathered to a yellow color. This tephra is 70 cm thick 25 km northeast of the volcano layer, and may also occur as a thin layer (COR3, Figs. 2, 4 and 8) in the deposits at Esquel, Argentina, over 100 km northeast of the volcano. This deposit was formed by a small to possibly medium size eruption which occurred at ≤6,870 BP (sample T-20B; Table 1).

YANTELES VOLCANO

Yanteles volcano (43.42°S/72.83°W; 2,050 m), which is covered by glaciers, occurs at the northeast end of a 10 km structure probably formed by older volcanic deposits. A tephra deposit attributed to a medium to possibly large size explosive eruption of this volcano is >1 m thick 35 km northeast of the volcano (YAN1 in site 94T-20; Figs. 2, 4 and 10), and also occurs as a thin layer in Esquel, Argentina, over 120 km northeast of the volcano (Fig. 8). This deposit consists of yellow andesitic pumice (Table 2 and Fig. 3) and medium size lapilli. It has been dated as having formed at ≤9,190 BP (samples T-23 and T-25A; Table 1). This tephra may correspond to either of the two tephra layers observed by Heusser *et al.* (1992) in their core at Cuesta Moraga; the one at 7 m deep which they dated as 9,970 BP, or the one at 5,5 m depth which they dated as approximately 8,600 BP. All the other younger tephra described by Heusser *et al.* (1992) in their Cuesta Moraga core were also most probably produced by other smaller eruptions of the Yanteles volcano.

MELIMOYU VOLCANO

Melimoyu volcano (44.08°S/72.88°W; 2,400 m) is a large glacial covered stratovolcano, elongated 10 km in an east-west direction, with a small 1 km diameter summit crater (Fig. 11). There is no record of historic activity for this volcano.

Along the Carretera Austral between 22 to 41 km north of Puyuhuapi, which passes approximately 33 km east of Melimoyu at its closest point, tephra fall deposits preserve evidence of two late Holocene explosive eruptions of Melimoyu volcano (MEL1 and MEL2; Figs. 2, 4 and 12). The older, larger eruption produced a deposit which is 1.35 m thick directly east of the volcano and up to 12 cm thick east of Palena lake, over 115 km east of the volcano (localities 200299-1; Figs. 2 and 4). The proximal deposit is compositionally layered, grading from white dacitic pumice upwards to coarse dark basaltic scoria (Samples T-4E and T-4D; Table 2 and Fig. 3). The mafic scoria layer does not occur in the more distal deposits of this eruption. Two independent C^{14} dates place the age of the medium size eruption that produced this tephra deposit at ≤2,740 and ≤2,790 BP (samples T-4F and T-7; Table 1). A younger thinner deposit, 30 cm thick 33 km east of the volcano, which consists of white andesitic tephra (Sample T-4A; Table 2 and Fig. 3), was generated by a smaller eruption which occurred at ≤1,750 BP (samples T-4B; Table 1).

MENTOLAT VOLCANO

Mentolat volcano (44.70°S/73.10°W; 1,660 m) is a stratovolcano formed by Pleistocene to Holocene basaltic andesites and andesite lava flows (López-Escobar *et al.*, 1993). The volcano is capped by a large summit crater infilled with either a Holocene dome or simply ice (Fig. 13). No record of historic activity exists for the Mentolat volcano.

A tephra fall deposit attributed to the Mentolat volcano based on chemistry (sample T-36; Table 2 and Fig. 3) occurs in sediments overlying river gravels along the Simpson River west of Coihaique (Fig. 14). This deposit, which consists of fine grey basaltic andesite pumice, has been dated as ≤6,960 BP (sample T-58A; Table 1). An 18 cm thick deposit of grey pumice grading upwards into a layer of oxidized red mafic scoria, which underlies >1m of soil and directly overlies fluvial sands in an exposure along the valley of the Mañiguales river (site T-03; Fig. 2), may have resulted from this same eruption. The lack of other sites in the region containing deposits dating back to this age makes the determination of the size of this eruption uncertain.

FIG. 11. Photograph of the small ice-filled summit crater of the Melimoyu volcano looking east.

FIG. 12. Photograph (CS-1) at site T-4 (Fig. 2), a road cut along the Carretera Austral 22 km north of the town of Puyuhuapi, showing the two late Holocene tephra deposits derived from explosive eruptions of the Melimoyu volcano. The older deposit MEL1 is compositionally layered, grading upwards from white dacitic pumice into very dark mafic scoria, almost as dark as the organic-rich soils which contain the tephra layers.

FIG. 13. Photograph of the dome and/or ice filled summit caldera of the Mentolat volcano as seen from the west.

FIG. 14. Photograph (JAN-101) of two tephra layers exposed in a cut along the valley of the Simpson river west of Coihaique (site T-36, Fig. 2). Based on chemistry, it appears that the younger 12 to 15 cm layer is derived from the Macá volcano and the older one (15 cm) from the Mentolat volcano.

FIG. 15. Photograph of the Macá volcano, taken from Moraleda channel looking to the east.

MACÁ VOLCANO

Macá volcano (45.10°S/73.20°W; 3,028 m) is a large partially eroded stratovolcano (Fig. 15) formed by basalts and basaltic andesites (Stern *et al.*, 1976; Futa and Stern, 1988; López-Escobar *et al.*, 1993; D'Orazio *et al.*, 2003). A small basaltic cinder cone occurs on the southeast flanks of this volcano. Outcrops of a tephra fall deposit consisting of light grey pumice overlying a darker grey ash layer that constitutes 10 to 20% of the deposit occur in both road and river cuts along the valleys of both the Simpson and Mañiguales rivers east of this volcano. These deposits, which are 10 to 15 cm thick at approximately 70 km east of the volcano (sites T-35 and T-36/58), have been dated as ≤1,540 BP (sample T-58B; Table 1). This basaltic-andesite tephra (T-35A; Table 2 and Fig. 3) is attributed to a small to medium size explosive eruption of the Macá volcano based on distribution and chemistry, as well as on the highly eroded morphology of the nearby Cay volcano, which precludes this latter volcano as being the source.

CAY VOLCANO

Cay volcano (45.05°S/72.98°W, 2,090 m) is a highly eroded stratovolcano, located approximately 30 km east of Macá volcano. Cay volcano is formed by basalts and dacites (Stern *et al.*, 1976; Futa and Stern, 1988; López-Escobar *et al.*, 1993; D'Orazio *et al.*, 2003). No record of historic activity exists for the Cay volcano and no evidence has been observed of any Holocene tephra deposits derived from this volcano.

DISCUSION AND CONCLUSIONS

Holocene deposits of volcanic tephra exposed in road-cuts along the Carretera Austral in Chile and other roads to the east in Argentina provide evidence of at least eleven explosive eruptions from seven of the eight stratovolcanoes in the southern Andean SVZ between 42°30' and 45°S (Fig. 2). The Cay volcano was apparently the only volcano is this region that did not have any explosive eruptions during the Holocene. Based on regional correlations of these deposits, approximate 10 cm isopachs indicate that four of these eruptions were small (VEI < 3 and volume <0.15 km^3) and seven were either medium size (VEI=3-5 and volume between 0.15 to 1 km^3) or, in some cases, possibly larger. However, the total number of explosive eruptions may be underestimated due to the remote location of these volcanoes and the scarcity of road-cuts, and thus the very limited amount of information provided by the few exposures examined in this study, particularly with respect to small eruptions which may produce only proximal deposits.

The total of eleven small and medium size explosive eruptions as defined above, over a period of about 8,000 years implies a frequency of one approximately every 725 years for this segment of the Andean SVZ. The 11 small and medium sized Holocene eruptions for these eight volcanic centers is about the same frequency, when calculated per volcano, as the 42 explosive eruptions documented from the 39 volcanic centers further north in the SVZ (Naranjo *et al.*, 2001).

In contrast, the Hudson volcano, the southernmost volcano in the SVZ, located just north of the Chile Rise-Trench triple junction at 46°S, has had three very large and nine other documented smaller explosive Holocene eruptions, and thus both larger and more numerous explosive Holocene eruptions than all the other centers in the southernmost SVZ combined. Even within the limitation of the results of this preliminary study for determining the frequency of explosive eruptions, particularly small eruptions, it is clear that the Hudson volcano is significantly more active than the other volcanoes in the southernmost SVZ. In fact, the Hudson has produced larger Holocene eruptions (three large and very large eruptions) than any other volcanic center in the SVZ and also the largest of them all (Naranjo and Stern, 1998), perhaps because of its location close to the triple junction.

One of the tephra deposits is a basaltic andesite (COR1), four are andesitic (MIC1, COR3, MEL2 and MAC1) and three are dacites and/or rhyolites (MIC2, COR2 and YAN1; Table 2). The other three of the tephra deposits observed (CHA1, MEL1, and MEN1) were compositionally zoned, grading upward from white dacitic and/or rhyolitic pumice to dark mafic scoria, indicating eruption from a compositionally zoned magma chamber, with more silicic magmas overlying more mafic magmas. The Hudson eruption of 1991 also produced compositionally distinct basaltic and andesitic pumice and tephra during different stages of the eruption (Naranjo *et al.*, 1993). In this case, however, the more mafic material was erupted during the initial phase of the cycle of explosive activity, from a parasitic lateral fissure on the caldera rim of the volcano. The input of basaltic magma into the base of an andesitic magma chamber was interpreted as the trigger for the subsequent large explosive eruption.

Of the eleven Holocene explosive eruptions documented in this study, all but one (CHA1) produced tephra deposits dispersed in a dominantly eastwards direction (Fig. 2). For volcanic centers further north in the SVZ (Naranjo *et al.*, 2001), and also for both the Hudson volcano (Stern, 1991; Naranjo *et al.*, 1993; Naranjo and Stern, 1998) and other volcanoes further to the south in the Andean Austral Volcanic zone (Stern, 1990, 1991, 1992, 2000), dispersion of tephra produced by explosive eruptions is dominantly to the southeast, reflecting high-altitude wind directions. In contrast to the volcanoes in these other regions of the southern Andes, the centers between 42.5°S and 45°S are located with <25 km of relatively open coast, with only low islands to the west. This allows east-directed, low-altitude coastal winds to have a more significant influence on the dispersion of tephra produced by these volcanoes. Thus, the plume dispersion produced by an explosive eruption of these volcanoes could affect the aeronavagation routes in Argentina.

The single exception to the general regional eastwards distribution of tephra is the ≤9,370 BP eruption of the Chaitén volcano (Fig. 2), which dispersed tephra to the northeast. The initial August 8-9, 1991 phase of the Hudson eruption also dispersed in this same direction. This reflects winds from the south, which occur in the southern Andes during high-pressure weather events, primarily during the winter months.

The results discussed above imply that volcanic hazard evaluation during an active eruption requires knowledge of not only prevailing high-altitude wind patterns, but also geography, seasonal weather and low-altitude wind patterns which may vary during the multiple days that an eruption persists. In the region 42.5°S to 45°S, both the proximity of the volcanoes to the coast and the low coastal topography allow seasonally dependent coastal winds to strongly influence the direction of dispersion of the products of explosive eruptions.

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