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RESEARCH ARTICLE

Holocene tephrochronology record of large explosive eruptions in the southernmost Patagonian Andes

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Abstract For regionally widespread Holocene tephra layers in southernmost Patagonia, correlations based on both chemical and chronological data indicate their derivation from five large-volume (>1 km^3) explosive eruptions of four different volcanoes in the southernmost Andes. Bulk-tephra and tephra-glass major and trace-element chemistry and Sr isotopic ratios unambiguously distinguish different source volcanoes, and imply that two of the regionally widespread tephra (MB_1 and MB_2) were derived from Mt. Burney (52°S), one (R_1) from Reclus (51°S), one (A_1) from Aguilera (50°S) and one (H_1) from Hudson volcano (46°S). The H_1 tephra derived from the Hudson volcano, which is located at the southern end of the Andean Southern Volcanic Zone (SVZ; 33–46°S), contains distinctive greenish andesitic glass with FeO>4.5 wt.% and TiO_2>1.2 wt.%. In contrast, rhyolitic glass in tephra derived from the eruptions of Mt. Burney, Reclus and Aguilera volcanoes, which are located in the Andean Austral Volcanic Zone (AVZ; 49–55°S), is clear and transparent and has significantly lower FeO and TiO_2. Tephra derived from these three AVZ volcanoes all contain plagioclase, orthopyroxene, minor clinopyroxene and amphibole. Biotite occurs only in the Aguilera A_1 tephra, which also has the highest bulk-tephra and tephra-glass K_2O and Rb contents. Averages of new and published ^{14}C ages determined on organic material in soil and sediment samples above and below these tephra constrain the uncalibrated ^{14}C age of the R_1 eruption of Reclus volcano to 12,685±260 years BP, the MB_1 and MB_2 eruptions of Mt. Burney to 8,425±500 and 3,830±390 years BP, the Hudson H_1 eruption to 6,850±160 years BP, and the A_1 eruption of Aguilera volcano to 3,000±100 years BP. The volume of the largest of these eruptions, H_1 of the Hudson volcano, is estimated as >18 km^3. The volume of the Reclus R_1 eruption is estimated at >10 km^3, the Aguilera A_1 eruption at between 4 and 9 km^3, and the younger Mt. Burney MB_2 eruption at ≥2.8 km^3. The volume of the older MB_1 Mt. Burney eruption is the least well constrained, but must have been larger than the younger MB_2 eruption. The data indicate that the frequency of explosive activity of volcanic centers in the AVZ is lower than in the southern SVZ.

Keywords Tephra · Tephrochronology · Patagonia · Explosive volcanism · Holocene · South America · Southern Andes

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Introduction

Six volcanic centers form the Andean Austal Volcanic Zone, the southernmost volcanically active segment in the Andes (Fig. 1; Stern and Kilian 1996; Stern 2004; Stern et al. 2007). These volcanoes, which are remote from major population centers, result from the relatively slow (<2 cm/year) subduction of the young (<24 Ma) Antarctic plate. The eruption of Lautaro volcano in 1959–1960 (Martinic 1988; Orihashi et al. 2004) is the only documented historic explosive eruption of any Andean AVZ volcano. However, regionally widespread Holocene tephra layers observed in southernmost Patagonia suggest that large explosive eruptions of AVZ volcanoes have occurred.

Auer (1974 and references therein) initially observed three regionally widespread Holocene tephra layers in Tierra del Fuego, which he termed, from oldest to youngest, Tephras I,

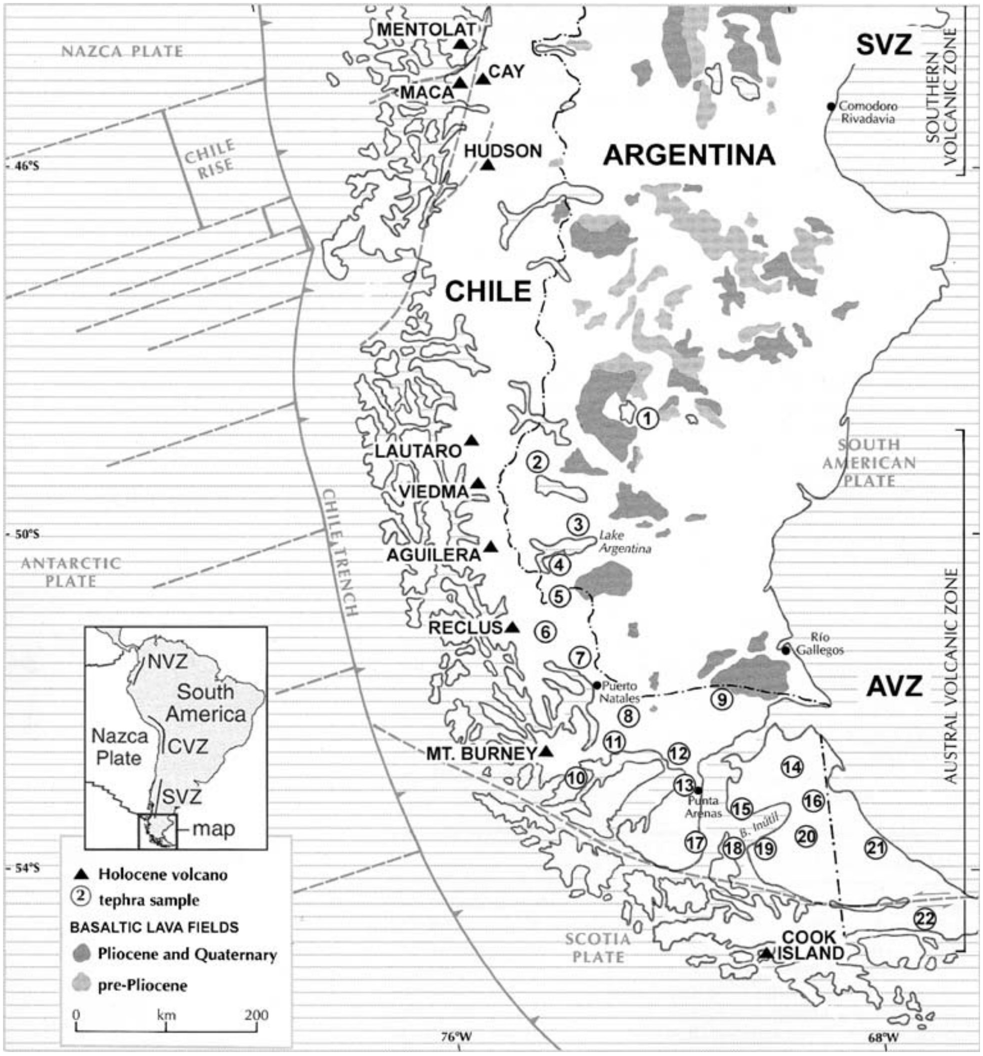

Fig. 1 Map of southernmost Patagonia showing the locations of the six volcanic centers in the Andean AVZ and the Hudson volcano in the southern SVZ (Stern and Kilian 1996; Stern 2004), plates and plate boundaries, and 22 numbered geographic areas where tephra layers were observed and collected (Tables 1, 4, 7 and 10). These areas include *1* Lago Cardiel (Markgraf et al. 2003); *2* North shore of Lago Viedma; *3* Northeast shore of Lago Argentino between Sosiego and Charles Fuhr ranches; *4* South shore of Lago Argentino between Calafate and Lago Roca; *5* Cordillera Baguales; *6* Torres del Paine park; *7* Ultima Esperanza fjord; *8* Rubens river; *9* Thomas Gold (Massone 1989) and Potrok Aike (Haberzettl et al. 2007) lakes; *10* Peninsula Muñoz Gamero (Kilian et al. 2003, 2006); *11* North shore of Skyring fjord; *12* East shore of Otway fjord and Lago Blanco; *13* Punta Arenas; *14* North-central Tierra del Fuego (Stern 1991); *15* Porvenir, Cape Boqueron and Altos de Boqueron (Stern 1990); *16* Tres Arroyos archaeological site (Massone 1987); *17* Puerto del Hambre (Heusser et al. 2000) *18* Northern Dawson Island (McCulloch and Bentley 1998; McCulloch and Davies 2001); *19* Cape Cameron and Rusphen river; *20* Chico river; *21* La Mission north of Rio Grande (Markgraf 1980); *22* Tunel archaeological site along the Beagle Canal (Orquera and Piana 1987)

II, and III (Fig. 2). He described Tephra I and Tephra III as white and considered the Andean stratovolcano Mt. Burney (Fig. 1) to be their source, and Tephra II as green and suggested that its source was some unidentified volcano perhaps among the Patagonian plateau lavas. Later he observed another white plagioclase-rich tephra he called Tehpra A, which he also attributed to an eruption of Mt. Burney. Auer's preliminary ^{14}C age dating of organic material in soils above and below each tephra yielded the Holocene ages illustrated in Fig. 2. On the basis of his two erroneous beliefs that (1) Holocene post-glacial climate, and consequently vegetation changes as indicated by pollen records, were synchronous throughout Patagonia, and (2) that volcanic activity was synchronous worldwide, Auer correlated these tephra with others he observed further north in Patagonia, and proposed that the simple tephrochronology illustrated in Fig. 2 applied to the entire region of Patagonia, not just Tierra del Fuego.

Based on chemical data for tephra from Tierra del Fuego (Fig. 3), Stern (1990, 1991, 1992) identified the Reclus stratovolcano in the AVZ (Fig. 1) as the source for Auer's white Tehpra I, Mt. Burney as the source for white Tephras

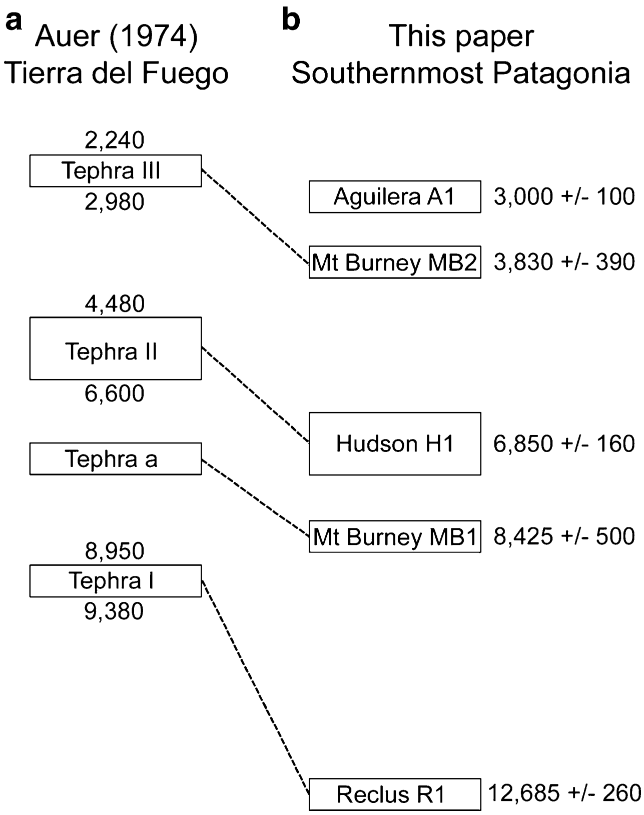

Fig. 2 Schematic tephrochronology for Tierra del Fuego and southernmost Patagonia as suggested by **a** Auer (1974), and **b** as revised in this paper. Ages are uncalibrated ^{14}C years BP. Auer erroneously suggested that his tephrochronology extended to all of Patagonia, but Naranjo and Stern (2004) have demonstrated that Andean SVZ volcanoes in northern and central Patagonia have produced tephra with different ages. Auer's ages are in error because, apart from sample contamination problems, it appears that for his Tephra III he dated tephra A_1 instead of MB_2 and for his Tephra I he dated tephra MB_1 instead of R_1

A and III, and the Hudson volcano, located in the southern portion of the Andean Southern Volcanic Zone (SVZ in Fig. 1), as the source for green Tephra II. Stern (1990) also identified a petrochemically different late Holocene white tephra in the area of northwest Magallanes, Chile, and along the shores of Lago Argentino, Argentina, and suggested that this tephra is most probably derived from the Aguilera volcano in the northern part of the AVZ (Fig. 1). Stern (1991, 1992) obtained new ^{14}C ages from soils containing these tephra, and based on these new ages revised Auer's tephrochronology for southernmost Patagonia. This revised tephrochronology of southernmost Patagonia has been widely applied by Quaternary geologists to the chronological analysis of tephra-bearing bog and lake sediment cores and outcrops which constrain the late-glacial and Holocene paleoclimatic and paleogeographic evolution of southernmost Patagonia (Heusser 1995; Clapperton et al. 1995; Marden and Clapperton 1995; Marden 1997; McCulloch and Bentley 1998; Heusser et al. 2000; McCulloch and Davies 2001; Markgraf et al. 2003; Kilian et al. 2003, 2006, 2007a, b; McCulloch et al. 2005a, b; Haberzettl et al. 2007; Martínez and Moreno 2007), as well as for the chronological analysis of archaeological excavations (Massone 1987, 1989; Favier Dubois and Borrero 1997).

New chemical analysis of both rocks from the different volcanic centers of the AVZ (Stern and Kilian 1996), and analysis of numerous other exposures of tephra from southernmost Patagonia, have substantiated and refined this tephrochronology, which constrains only the five largest (>1 km^3 in volume) Holocene explosive eruptions generating

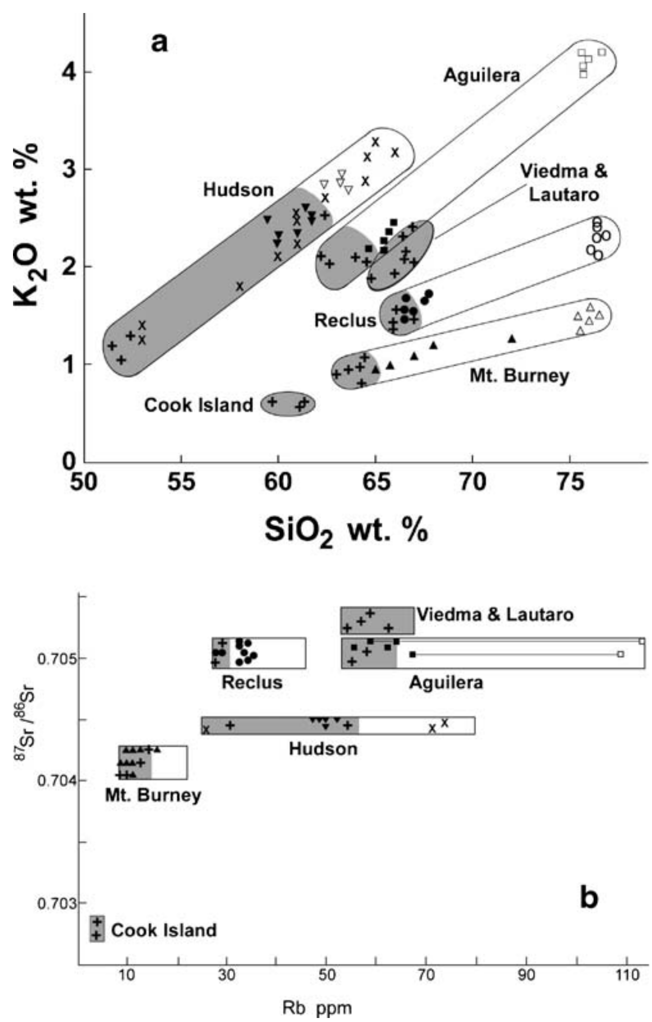

Fig. 3 Two different diagrams of chemical data (SiO_2 versus K_2O (**a**) and Rb versus $^{87}Sr/^{86}Sr$ (**b**)), each of which unambiguously distinguish the source volcanoes for different tephra layers in southernmost Patagonia. Data for whole-rock samples of lavas (pluses and shaded fields) are from Stern and Kilian (1996) and Naranjo and Stern (1998) and data for pumice and bulk-tephra (*solid symbols*) and tephra-glass (*open symbols*) are from Tables 2, 5, 8 and 11. The fields for the Hudson volcano also include tephra from eruptions other than H_1 (*crosses*). The range indicated for Rb contents reflects all samples analyzed, including some for which Sr isotopic composition has not been determined

regionally widespread distal tephra layers in this area. New ^{14}C ages have also allowed the ages of these five most important explosive eruptions to be better defined (Fig. 2). This paper summarizes these new and previously published data and provides estimates of the aerial distribution and volume of the tephra produced by these five large explosive Holocene eruptions in the southernmost Andes, as well as preliminary data constraining some smaller eruptions of AVZ volcanoes.

Sample sites

Tephra samples and enclosing peat, soil and/or sediment were collected at over 50 sites (Tables 1, 4, 7 and 10) where tephra layers outcrop due to river erosion, road cuts, drainage trenches and archaeological excavations. Other tephra samples were obtained from drill-core provided by geologists sampling bogs and lake sediments in Patagonia. The general areas where these samples were collected are located in Fig. 1. Figures 4, 7, 9 and 11 illustrate tephra distribution isopachs for eruptions from specific source volcanoes, determined by both chemical and chronological correlations as discussed below. Selected sites are pictured in Figs. 5, 8, 10 and 12.

Depositional environments at different sites differ and are variable through time, as indicated by the type of material within which the tephra layers are contained. These include eolian silt (loess), glaciolacustrine clays, sands and gravels, peat, soils, and lake sediments. Most sites contain only one or two tephra layers, but some sites have up to four, and a core from one site, Laguna Escondida (52°29′46.6″S; 71°55′46.5″W) on the northern shore of Seno Skyring (area #11 in Fig. 1), contains tephra from all five of the largest explosive eruptions that produced the regionally widespread tephra layers in southernmost Patagonia.

Petrochemical data

Tables 2, 5, 8 and 11 present pumice, bulk-tephra and tephra-glass major and trace-element chemical compositions, and $^{87}Sr/^{86}Sr$ isotopic ratios, of selected samples. The data are organized by source volcano as determined by comparison with whole-rock chemical analysis of lavas and pumice from these centers (Fig. 3). Bulk-tephra major-element compositions were determined by Actlabs (Tucson, AZ). Bulk-tephra and glass trace-element compositions were determined by energy dispersive XRF analysis at the University of Colorado (Boulder, CO) and the US Geological Survey (Denver, CO). Tephra-glass major-element compositions were determined with a JOEL electron microprobe at the University of Colorado and these glass compositions are reported LOI-free, normalized to 100%.

The six volcanoes of the Andean AVZ (Fig. 1) have each erupted exclusively adakitic andesites and dacites (Stern et al.

Table 1 Sample sites for the late-glacial R1 tephra derived from the Reclus volcano

Site #	Sample	Location	Lat. °S; long. °W	Outcrop lithology	Thickness (cm)	Reference
6	R6	Lago Grey (TDP)	51°06′S; 73°01′W	Pumice in outwash		Stern 1990
7	PAT14	Cerro Castillo (UE)	51°12′S; 72°15′W	Bog peat	15	Stern 1990
7	2HR	Alero Dos Herraduras (UE)	51°35′S; 72°45′W	Cave excavation	>40	Favier Dubois and Borrero 1997
7	907 cm	Vega Benitez (UE)	51°33′S; 72°40′W	Bog core PM-0302A	>40	Martinez and Moreno 2007
8	636 cm	Rio Rubens	52°02′S; 71°57′W	Barking Fox bog core	15	Markgraf (personal communication)
13	ALL	Pampa Alegre (Rio Seco)	53°04′S; 70°51′W	Fluvial–glacial sed	6	Uribe 1982
13	90-05/06	Pampa Alegre (Rio Seco)	53°04′S; 70°51′W	Fluvial–glacial sed	6	Stern 1992
13	671 cm	Punta Arenas	53°09′S; 70°57′W	Bog core	4	Heusser 1995
15	560 cm	Represa Porvenir (TDF)	53°18′S; 70°20′W	Bog core	4	Markgraf (personal communication)
15	93–29	Represa Porvenir (TDF)	53°18′S; 70°20′W	Bog peat	5	This paper
15	011198-3	Represa Porvenir (TDF)	53°18′S; 70°20′W	Fluvial sediment	5	This paper
15	90-08	Altos de Boqueron (TDF)	53°17′S; 70°10′W	Eolian silt	5	Stern 1992
15	CS-102	Cabo Boqueron (TDF)	53°28′S; 70°20′W	Eolian silt	5	Stern 1990 (Fig. 2)
15	CS-103	Chorillo Rosario (TDF)	53°27′S; 70°06′W	Fluvial–glacial sed	3	Heusser et al. 1989
16	3AR	Tres Arroyos cave (TDF)	53°23′S; 68°47′W	Cave excavation	4	Massone 1987
17	90-02	Rio Tres Brazos (PB)	53°16′S; 71°02′W	Fluvial–glacial sed	3	Stern 1992
17	230 cm	Puerto del Hambre (PB)	53°36′S; 70°55′W	Bog core	3	Heusser et al. 2000
18	CV-1	Cabo Valentin (DI)	53°34′S; 70°30′W	Glaciolacustrine clay	3	McCulloch and Bentley 1998
18	205 cm	Estancia Esmeralda II (DI)	53°35′S; 70°29′W	Bog core	3	McCulloch and Davies 2001
19	93–27	Cabo Cameron (TDF)	53°41′S; 69°51′W	Bog peat	3	This paper

TDP Torres del Paine; *UE* Ultima Esperanza; *TDF* Tierra del Fuego; *PB* Peninsula Brunswick; *DI* Dawson Island

Table 2 Major and trace-element (in ppm) compositions of bulk-tephra and tephra-glass derived from the late-glacial R1 eruption of the Reclus volcano

Sample #	R6[a]	BF636	CS-103	PAT-14	3AR	R6[a]	BF636	CS-103	PAT-14	3AR	Kilian[b]	2HR	90-02	90-05	90-06	ALL	CS-102	90-08	POR560	93-27	011198-3	93-29
Material	Pumice	Tephra				Glass						Tephra										
SiO_2	66.29	66.24	67.61	66.71	67.44	76.72	76.11	76.26	76.17	76.05	76.76											
TiO_2	0.41	0.34	0.29	0.37	0.31	0.19	0.13	0.12	0.16	0.14	0.22											
Al_2O_3	16.28	15.58	15.45	15.96	15.31	14.01	13.96	14.26	14.06	14.25	13.12											
FeO[c]	3.61	3.31	3.15	3.52	3.09	1.47	1.35	1.48	1.45	1.43	1.61											
MnO	0.08	0.07	0.06	0.09	0.06	0.04	0.08	0.05	0.04	0.06	0.05											
MgO	1.53	1.23	1.13	1.45	1.19	0.21	0.25	0.25	0.25	0.26	0.26											
CaO	4.45	4.09	3.98	4.22	3.82	1.51	1.62	1.85	1.77	1.85	2.23											
Na_2O	4.29	4.02	4.19	4.04	4.21	3.68	3.86	3.44	3.73	3.68	3.44											
K_2O	1.59	1.65	1.66	1.51	1.69	2.14	2.51	2.29	2.47	2.18	2.32											
P_2O_5	0.18	0.15	0.14	0.17	0.13																	
LOI	1.39	2.71	2.46	2.15	2.82																	
Total	100.09	99.39	100.12	100.19	100.07	100[d]	100[d]	100[d]	100[d]	100[d]	100[d]											
Rb	32	34	36	27	35	46	42	46	43	41		28	29	37	33	32	32	29	32	33	30	34
Sr	497	406	428	515	398	276	252	212	219	198		486	411	414	505	456	450	475	381	412	423	442
Y	10	9	11	12	11	9	11	10	11	8		10	10	11	10	11	10	9	12	10	9	10
Zr	158	128	135	139	105	90	88	85	90	71		144	122	125	146	134	131	135	125	133	131	129
$^{87}Sr/^{86}Sr$	0.70511	0.70498		0.70505	0.70499								0.70507			0.70499	0.70513	0.70507		0.70503		0.70509

ppm Parts-per-million
[a] From Stern and Kilian (1996)
[b] From Kilian et al. (2003)
[c] Total Fe as FeO
[d] Microprobe determinations normalized LOI-free to 100%

Table 3 Uncalibrated ^{14}C age determinations for tephra derived from the Reclus volcano

Site #	Location	Sample #	Lab #	Date ^{14}C years BP	Reference
Reclus tephra derived from a minor eruption					
6	Lago Nordenskjold	117/13		>8,270±90	Stern 1990
6	Lago Nordenskjold	119/8		>9,180±120	Stern 1990
7	Vega Benitez	PM-0302 365–366 cm	AMS age	<9,145±40	Martinez and Moreno 2007
6	Vega Nandu	PM-0304 300–308 cm	AMS age	<9,310±40	Martinez and Moreno 2007
7	Pantana Eberhardt	PM-0301 382–383 cm	AMS age	<9,435±40	Moreno (personal communication)
Late-glacial tephra R1					
13	Pampa Alegre	90-06A	GX-16546	>11,795±365	Stern 1992
20	Tres Arroyos Cave	3AR	BETA-20219	>11,880±250	Massone 1987
13	Punta Arenas	Recluse	QL-1622	>11,960±170	Heusser et al. 2000
15	Chorillo Rosario	CS-103	QL-4293	>12,010±80	Heusser et al. 1989
13	Pampa Alegre	ALL	SRR-5240	>12,070±50	Clapperton et al. 1995
7	Vega Benitez core	<907 cm	98917	>12,325±40	Moreno (personal communication)
8	Rio Rubens	BF 579–582 cm	GX-19794	>12,415±250	Markgraf (personal communication)
7	Lago Dorotea core		107054[a]	>12,460±90	Moreno (personal communication)
7	Vega Benitez core	<907 cm	98916[a]	>12,490±40	Moreno (personal communication)
17	Puerto del Hambre	685 cm	AA30643[a]	>12,530±80	Heusser et al. 2000
13	Pampa Alegre	90-05A	GX-16543	>12,870±200	Stern 1992
17	Rio Tres Brazos	90-02A	GX-16535	>12,900±205	Stern 1992
13	Pampa Alegre	ALL	DIC-2322	~11,940±110	Uribe 1982
7	Alero dos Herraduras	2HR	AA12574[a]	~12,825±110	Favier Dubois and Borrero 1997
15	Chorillo Rosario	CS-103	QL-4294	<12,060±80	Heusser et al. 1989
15	Represa Porvenir	93-27B	GX-19432	<12,240±185	This paper
13	Pampa Alegre	ALL	A6813[a]	<12,310±240	Clapperton et al. 1995
8	Rio Rubens	BF 650–653 cm	GX-19426	<12,670±575	Markgraf (personal communication)
13	Punta Arenas	>671 cm	QL-1620	<12,740±260	Heusser 1995
15	Chorillo Rosario	Recluse	A7569[a]	<12,740±120	Clapperton et al. 1995
17	Puerto del Hambre	Recluse	AA20570[a]	<12,840±100	McCulloch and Bentley 1998
17	Rio Tres Brazos	90-02B	GX-16534	<12,950±100	Stern 1992
17	Puerto del Hambre	711 cm	AA30644[a]	<12,975±83	Heusser et al. 2000
7	Lago Dorotea core		107055[a]	<13,000±60	Moreno (personal communication)
8	Rio Rubens	BF 662–664 cm	A7618[a]	<13,029±340	Markgraf (personal communication)
8	Rio Rubens	BF 685–687 cm	A8378[a]	<13,160±270	Markgraf (personal communication)
13	Pampa Alegre	90-06B	GX-16546	<13,255±205	Stern 1992
13	Pampa Alegre	90-05B	GX-16544	<13,580±215	Stern 1992

[a] AMS ages

1984; Stern and Kilian 1996), in contrast to the common presence of basalts and basaltic andesites in the volcanic centers of the southern SVZ (Futa and Stern 1988; Lopez-Escobar et al. 1993; Stern 2004). The adakitic character of AVZ andesites and dacites is attributed to the melting of the young, relatively hot Antarctic Ocean lithosphere being subducted below the AVZ.

In the southernmost Andes the identification of source volcano for tephra can be made unambiguously because of the unique chemical characteristics of the individual volcanoes (Stern 1990, 1991; Stern and Kilian 1996). Although each AVZ volcano has erupted adakites of relatively uniform composition, each different volcanoes has distinctly different major, minor and trace-element contents and Sr isotopic ratios. K_2O and Rb contents and $^{87}Sr/^{86}Sr$ ratios increase, and Na_2O and Sr contents decrease, in a northward direction, going from Cook Island volcano in the south to the northernmost AVZ volcanoes Aguilera, Viedma and Lautaro (Fig. 3). These differences have been attributed to the extent to which melts derived from the subducted

Table 4 Samples sites for the two Holocene MB1 and MB2 tephra derived from Mt. Burney volcano

Site #	Sample #	Location	Lat. °S; long. °W	Outcrop lithology	Thickness (cm)	Reference
Mt. Burney late-Holocene tephra MB2						
10		Pen. Munoz Gamero	52°47′S; 72°56′W	soil profiles	13–15	Kilian et al. 2003
10	408 cm	Lago Chandler (PMG)	52°49′S; 72°54′W	Lake core CH-1	6	Kilian et al. 2003
10	187 cm	Canal Gajardo (PMG)	52°48′S; 72°55′W	Bog core GC-1	8	Kilian et al. 2003
10	58 cm	Canal Gajardo (PMG)	52°48′S; 72°55′W	Bog core GC-2	4	Kilian et al. 2003
11	335 cm	Seno Skyring	52°42′S; 72°18′W	Lake core ES-1	10	Kilian et al. 2003
11	172 cm	Seno Skyring	52°37′S; 71°42′W	Bog core Sky-1	8	Kilian et al. 2003
12	132 cm	Estancia Otway	52°47′S; 71°08′W	Bog core 110/3	6	Mercer 1970
13	288 cm	Punta Arenas	53°09′S; 70°57′W	Bog core	5	Heusser 1995
15	131 cm	Represa Porvenir (TDF)	53°18′S; 70°20′W	Bog core POR	2	Markgraf (personal communication)
15	93-28W	Represa Porvenir (TDF)	53°18′S; 70°20′W	Bog peat	2	This paper
15	90-16	Altos de Boqueron (TDF)	53°17′S; 70°10′W	Bog peat	2	Stern 1992
16	93-17	San Martin river (TDF)	53°23′S; 68°46′W	Bog peat	1	This paper
17	213 cm	Puerto Hambre (PB)	53°36′S; 70°55′W	Bog core	4	Kilian et al. 2003
17	93-07	Lago Parillar (PB)	53°26′S; 71°05′W	River sediment	4	This paper
17	PH-107/3	Puerto del Hambre (PB)	53°36′S; 70°55′W	Bog core	3	Stern 1990
17	245 cm	Puerto del Hambre (PB)	53°36′S; 70°55′W	Bog core	3	Heusser et al. 2000
18		Cabo Valentin (DI)	53°34′S; 70°30′W	Bog peat	3	McCulloch and Bentley 1998
18	95 cm	Estancia Esmeralda II (DI)	53°35′S; 70°29′W	Bog core	3	McCulloch and Davies 2001
19	90-13	Rusphen river (TDF)	53°45′S; 69°15′W	Bog peat	3	Stern 1992
19	93-24	Cabo Cameron (TDF)	53°41′S; 69°51′W	Bog peat	3	This paper
Mt. Burney mid-Holocene tephra MB1						
8	370 cm	Rio Rubens	52°02′S; 71°57′W	Barking Fox bog core	10	Markgraf (personal communication)
9	TG-1	Laguna Tom Gold	52°09′S; 69°56′W	Site excavation	5–10	Massone 1989
10	524 cm	Lago Chandler (PMG)	52°49′S; 72°54′W	Lake core CH-1	1	Kilian et al. 2003
11	275 cm	Seno Skyring	52°37′S; 71°42′W	Bog core Sky-1	2	Kilian et al. 2003
11	526 cm	Laguna Escondida	52°30′S; 71°56′W	Lake core PS0504D	12	Moreno (personal communication)
12	350 cm	Estancia Otway	52°47′S; 71°08′W	Bog core 110/4	6	Mercer 1970
14	90-21	Route 257 (TDF)	52°58′S; 69°25′W	Bog peat	4	Stern 1992
14	90-23W	Route 257 (TDF)	52°58′S; 69°25′W	Bog peat	4	Stern 1992
15	90-14W	Altos de Boqueron (TDF)	53°17′S; 70°10′W	Organic-rich soil	2	Stern 1992
17	368 cm	Puerto del Hambre	53°36′S; 70°55′W	Bog core	2	Kilian et al. 2003
19	93-26	Cabo Cameron (TDF)	53°41′S; 69°51′W	Bog peat	1	this paper
20	93-21W	Chico river (TDF)	53°33′S; 68°42′W	Bog peat	1	this paper

PMG Peninsula Munoz Gamero; *PB* Peninsula Brunswick; *TDF* Tierra del Fuego; *DI* Dawson Island

Antarctic oceanic crust interact with the overlying mantle wedge and crust as plate convergence becomes less oblique and more orthogonal in the northern part of the AVZ (Stern et al. 1984; Stern and Kilian 1996).

Due to the chemical difference observed between each AVZ volcano, the source volcano for each tephra found in Tierra del Fuego and southern Patagonia can be identified based solely on Rb content and Sr isotopic ratio (Fig. 3b) or SiO_2 versus K_2O content (Fig. 3a) measured in either bulk-tephra or tephra-glass. Green mid-Holocene Tephra II, although only slightly more mafic than other tephra in southernmost Patagonia, is chemically unlike rocks erupted from any AVZ volcano with respect to its high high K_2O (Fig. 3a), FeO, TiO_2, Zr, and Y contents (Stern 1991). The Hudson volcano in the southern SVZ (Fig. 1) can also be uniquely identified as the source of this tephra based on Rb content and Sr isotopic ratios (Fig. 3b; Stern 1991; Naranjo and Stern 1998).

Tephra produced by different eruptions of the same source volcano, for example the two large Holocene eruptions of Mt. Burney, appear to be chemically indistinguishable. Also, the three northernmost volcanoes in the AVZ (Aguilera, Viedma and Lautaro; Fig. 1) are chemically somewhat similar, but the regionally widespread Holocene tephra that chemistry implies was produced by one of these volcanoes is attributed to Aguilera based on the spatial distribution of this tephra, which is thickest in the area of Lago Argentino just east of this volcano (Fig. 11).

Table 5 Major and trace-element (in ppm) compositions of bulk-tephra and tephra-glass for Holocene tephra MB1 and MB2 derived from the Mt. Burney

Eruption			MB2							MB1	MB2						MB1			
Sample #	MB-21P[a]	MB-21P[a]	Salmi #16	110/3	PH-107/3	110/3	PH-107/3	Kilian[b]	Sahlstein	BF-370	93-07	POR-131	93-28W	90-16	90-13	93-24	TG-1	90-14W	90-21	90-23W
Material	Pumice	Glass	Tephra			Glass				Tephra										
SiO_2	65.06	76.11	72.85	66.84	67.97	76.11	75.74	76.26	75.29	65.69										
TiO_2	0.33	0.21	0.11	0.29	0.31	0.31	0.27	0.34	0.41	0.31										
Al_2O_3	17.55	14.37	15.18	17.05	16.84	14.61	14.69	13.64	14.72	17.74										
FeO[c]	3.45	1.55	2.38	2.95	2.66	1.43	1.67	1.45	1.57	3.37										
MnO	0.08	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.05										
MgO	2.02	0.31	0.86	1.77	1.41	0.31	0.37	0.29	0.42	1.89										
CaO	5.19	2.04	3.17	3.95	3.27	1.97	2.03	2.32	2.29	4.92										
Na_2O	4.51	3.78	4.12	4.15	4.32	3.76	3.67	4.17	3.97	4.39										
K_2O	0.89	1.59	1.29	1.12	1.19	1.41	1.52	1.51	1.29	0.96										
P_2O_5	0.21			0.17	0.16					0.19										
LOI	1.12			1.56	1.73					0.91										
Total	100.41	100[d]	100	99.73	99.91	100[d]	100[d]	100[d]	100[d]	100.23										
Rb	11	21		16	12	19				9	12	11	12	10	8	14	11	8	9	10
Sr	563	268		405	425	282				558	534	398	423	501	530	425	481	477	505	525
Zr	83	95		101	105	90				89	89	98	105	82	91	75	96	110	79	84
Y	6	10		8	11	9				7	7	8	10	9	9	9	8	10	8	8
$^{87}Sr/_{86}Sr$	0.70406			0.70425	0.70426					0.70419			0.70421	0.70422	0.70416		0.70417			0.70414

ppm Parts-per-million
[a] Pumice from Stern and Kilian (1996)
[b] From Kilian et al. (2003)
[c] Total Fe as FeO
[d] Microprobe determinations normalized LOI-free to 100%

Table 6 Uncalibrated ^{14}C ages for tephra derived from the Mt. Burney volcano

Site #	Location	Sample #	Lab #	Date ^{14}C years BP	Reference
Mt. Burney minor late-Holocen eruption					
10	Pen. Munoz Gamero	GC1 66 cm	AMS age	>1,529±28	Kilian et al. 2003
10	Pen. Munoz Gamero	GC1 82 cm	AMS age	<1,944±29	Kilian et al. 2003
Mt. Burney large late Holocene eruption MB2					
15	Porvenir reservior	93-28A	GX-19433	>3,115±110	This paper
10	Pen. Munoz Gamero	GC2 50 cm	AMS age	>3,382±44	Kilian et al. 2003
10	Pen. Munoz Gamero	CH1 380 cm	AMS age	>3,520±30	Kilian et al. 2003
15	Altos de Boqueron	90-16A	GX-16538	>3,575±90	Stern 1992
11	Seno Skyring	Sky1 168 cm	AMS age	>3,610±35	Kilian et al. 2003
19	Rio Rusphen	90-13A	GX-16787	>3,830±95	Stern 1992
15	Altos de Boqueron	90-16B	GX-16539	<3,700±90	Stern 1992
17	Puerto de Hambre	PH-107/3	QL-1467[a]	<3,960±70	Heusser et al. 2000
10	Pen. Munoz Gamero	CH1 422 cm	AMS age	<4,420±40	Kilian et al. 2003
19	Rio Rusphen	90-13B	GX-16788	<4,470±100	Stern 1992
11	Seno Skyring	Sky1 244 cm	AMS age	<5,191±xx	Kilian et al. 2003
16	San Martin River	93-17B	GX-19431	<5,430±250	This paper
Mt. Burney large mid-Holocene eruption MB1					
9	Laguna Tom Gould	TG	GAK-9195	>>4,280±50	Massone 1989
9	Laguna Tom Gould	TG	DIC-2320	>>4,560±130	Massone 1989
14	Ruta 257	90-21A	GX-16541	>7,015±215	Stern 1992
14	Ruta 257	90-23WA	GX-16540	>7,535±25	Stern 1992
10	Pen. Munoz Gamero	GC2 144 cm	AMS age	>7,635±40	Kilian et al. 2003
10	Pen. Munoz Gamero	CH1 520 cm	AMS age	>7,890±45	Kilian et al. 2003
8	Rio Rubens	BF 356 cm	NSRL-10169[a]	>8,870±65	Markgraf (personal communication)
14	Ruta 257	90-21B	GX-16542	<8,305±260	Stern 1992
10	Pen. Munoz Gamero	CH1 536 cm	AMS age	<8,520±70	Kilian et al. 2003
8	Rio Rubens	BF 380–385 cm	GX-19427	<8,875±360	Markgraf (personal communication)
8	Rio Rubens	BF412 cm	NSRL-10170[a]	<8,880±60	Markgraf (personal communication)
17	Puerto de Hambre	Pbr2 480 cm	AMS age	<9,537±46	Kilian et al. 2003
10	Pen. Munoz Gamero	GC2 195 cm	AMS age	<9,740±42	Kilian et al. 2003
Mt. Burney minor early Holocene tephra					
10	Pen. Munoz Gamero	CH1 536 cm	AMS age	>8,527±70	Kilian et al. 2003
10	Pen. Munoz Gamero	GC2 195 cm	AMS age	>9,740±42	Kilian et al. 2003
10	Pen. Munoz Gamero	CH1 605 cm	AMS age	<10,320±55	Kilian et al. 2003
10	Pen. Munoz Gamero	GC2 269 cm	AMS age	<12,017±203	Kilian et al. 2003

[a] AMS age

Hudson-derived green Tephra II consists of dominantly greenish-brown andesitic glass shards, with only minor amount of plagioclase, orthopyroxene and opaque mineral grains. Because of the high glass-shard content of this tephra, the bulk composition of the tephra is very similar to the composition of its tephra-glass (Table 8). In contrast, white tephra layers derived from AVZ volcanoes are formed of rhyolitic glass shards (Tables 2, 5 and 11), and generally contain significant proportions of plagioclase grains along with orthopyroxene, minor clinopyroxene and amphibole. Biotite also occurs in the tephra derived from the Aguilera volcano, but only in these tephra, which have the highest K_2O contents of any tehpra derived from an AVZ volcano (Fig. 3a). Similarly, biotite occurs in samples of lavas from Aguilera volcano, but not in those from either Mt. Burney or Reclus volcanoes (Stern and Kilian 1996).

Tephrochronology

Both new and previously published uncalibrated ^{14}C age dates of organic material collected above and below individual tephra layers constrain the ages of the five most important eruptions that produced regionally wide-spread tephra layers in southernmost Patagonia, as well as some minor eruptions of AVZ volcanoes (Tables 3, 6, 9 and 12).

Late-glacial Reclus R_1 eruption

The oldest known Holocene tephra observed in southern Patagonia, Auer's Tephra I, occurs within late-glacial deposits of eolian silt (Fig. 5a), glaciolacustrine clay, sand and gravels (Fig. 5b), and alluvial fan and bog deposits along the north

Table 7 Sample sites for the mid-Holocene H1 tephra derived from the Hudson volcano

Site #	Sample #	Location	Lat. °S; long. °W	Outcrop lithology	Thickness (cm)	Reference
1	463 cm	Lago Cardiel	48°48.5′S; 71°13′W	Lake core CAR99-2L	2	Markgraf et al. 2003
9	1074.5 cm	Laguna Potrok Aike	51°58′S; 70°23′W	Lake core	2	Haberzettl et al. 2007
10	480 cm	Lago Chandler (PMG)	52°49′S; 72°54′W	Lake core CH-1	1	Kilian et al. 2003
10	134 cm	Canal Gajardo (PMG)	52°48′S; 72°55′W	Bog core GC-2	1	Kilian et al. 2003
11	516 cm	Laguna Escondida	52°30′S; 71°56′W	Lake core PS0504D	4	Moreno (personal communication)
12	90-04	Laguna Blanca	52°30′S; 71°21′W	Bog peat	3	Stern 1991, 1992
13	420 cm	Punta Arenas	53°09′S; 70°57′W	Bog core	2	Heusser 1995
14	90-22	Route 257 (TDF)	52°58′S; 69°25′W	Bog peat	15	Stern 1991, 1992
14	90-23G	Route 257 (TDF)	52°58′S; 69°25′W	Bog peat	15	Stern 1991, 1992
15	93-28G	Represa Porvenir (TDF)	53°18′S; 70°20′W	Bog peat	6	This paper
15	90-14G	Altos de Boqueron (TDF)	53°17′S; 70°10′W	Organic soil	10	Stern 1991, 1992
16	93-16	San Martin river (TDF)	53°23′S; 68°46′W	Bog peat	15	This paper
17	308 cm	Puerto del Hambre (PB)	53°36′S; 70°55′W	Bog core	3	Kilian et al. 2003
18	121 cm	Estancia Esmeralda II (DI)	53°35′S; 70°29′W	Bog core	2	McCulloch and Davies 2001
19	90-12	Rusphen river (TDF)	53°45′S; 69°15′W	Bog peat	10	Stern 1991, 1992
19	93-25	Cabo Cameron (TDF)	53°41′S; 69°51′W	Bog peat	6	This paper
20	93-21G	Chico river (TDF)	53°33′S; 68°42′W	Bog peat	20	This paper
21		La Mission (TDF)	53°42′S; 67°45′W	Core	6	Markgraf 1980
22		Tunel 1 (TDF)	54°52′S; 67°59′W	Excavation	1	Orquera and Piana 1987

PMG Penisula Munoz Gamero; *TDF* Tierra del Fuego; *DI* Dawson island

and south shore of the Strait of Magellan and in the area of Tierra del Fuego around Bahia Inutile (Fig. 4). Chemical data indicate that these tephra are derived from the Reclus volcano (Fig. 3), and ^{14}C ages (Table 3) confirm the late-glacial age of these and other Reclus-derived R_1 tephra that occur closer to this volcano in the area of Ultima Esperanza (area #7 in Fig. 1). The average of all 28 ^{14}C available ages from organic material in soils above and below this tephra bracket its age as 12,572±467 ^{14}C years BP. This age may be refined by ignoring the ten ages that fall outside this range, which

Table 8 Major and trace-element (in ppm) compositions of whole-tephra and tephra-glass from the large mid-Holocene H1 eruption of the Hudson volcano

Sample #	Salmi #15	94T-44[a]	94T-44[a]	90-12	90-23G	90-14	94T-44[a]	90-12	90-23G	90-14
Material	Tephra		Pumice	Tephra			Glass			
SiO_2	59.36	60.61	61.12	61.88	61.76	60.61	62.89	63.26	63.61	63.85
TiO_2	1.79	1.59	1.52	1.42	1.39	1.38	1.39	1.31	1.26	1.21
Al_2O_3	20.97	16.06	16.01	16.24	16.41	17.14	15.61	15.96	15.55	15.74
FeO[b]	5.12	5.45	5.54	5.67	5.15	4.98	5.16	4.97	5.04	4.74
MnO	0.11	0.17	0.18	0.15	0.15	0.18	0.16	0.14	0.13	0.14
MgO	1.59	1.97	1.89	1.79	1.76	1.57	1.81	1.66	1.61	1.48
CaO	3.93	4.02	3.78	3.84	4.01	3.56	3.54	3.39	3.21	3.14
Na_2O	4.34	5.57	5.61	5.76	5.48	5.13	5.79	5.85	5.92	5.74
K2O	2.51	2.27	2.37	2.51	2.56	2.26	2.81	2.91	2.88	2.79
P_2O_5	0.28	0.36	0.36	0.31	0.32	0.38	0.29	0.26	0.25	0.24
LOI		1.14	1.61	1.11	1.05	2.12				
Total	100	99.21	99.99	99.59	100.04	99.29	100[c]	100[c]	100[c]	100[c]
Rb		49	47	50	52	50				
Sr		388	382	361	374	392				
Y		39	38	42	37	41				
Zr		345	338	386	356	380				
$^{87}Sr/^{86}Sr$		0.7045	0.7045	0.70452	0.70451	0.70448				

ppm Parts-per-million
[a] From Naranjo and Stern (1998)
[b] Total Fe as FeO
[c] Microprobe determinations normalized LOI-free to 100%

Table 9 Uncalibrated ^{14}C ages for tephra H1 derived from the Hudson volcano

Site #	Location	Sample #	Lab #	Date ^{14}C years BP	Reference
12	Laguna Blanca	90-04A	GX-16591	>6,040±205	Stern 1991, 1992
22	Tunel I	T1		>6,300±190	Orquera and Piana 1987
Aisen	Juncal Alto	94T-49E		>6,330±90	Naranjo and Stern 1998
15	Altos de Boqueron	90-14A	GX-16596	>6,575±110	Stern 1991, 1992
19	Rio Rusphen	90-12A	GX-16594	>6,625±110	Stern 1991, 1992
10	Pen Munoz Gamero	GC2 116 cm		>6,915±40	Kilian et al. 2003
Aisen	Cerro Teodoro	94T-65A		<6,720±140	Naranjo and Stern 1998
Aisen	Juncal Alto	94T-49G		<6,840±90	Naranjo and Stern 1998
Aisen	Rio Ibanez	93-43B		<6,865±220	Naranjo and Stern 1998
12	Laguna Blanca	90-04B	GX-16592	<6,930±120	Stern 1991, 1992
22	Tunel I	T1		<6,980±110	Orquera and Piana 1987
Aisen	Lago Verde	94T-44D		<7010±40	Naranjo and Stern 1998
14	Ruta 257	90-22B	GX-16541	<7,015±215	Stern 1991, 1992
19	Rio Rusphen	90-12B	GX-16595	<7,435±120	Stern 1991, 1992
14	Ruta 257	90-23GB	GX-16540	<7,535±120	Stern 1991, 1992
15	Altos de Boqueron	90-14B	GX-16597	<7,550±120	Stern 1991, 1992
10	Pen Munoz Gamero	GC2 144 cm		<7,635±40	Kilian et al. 2003

were all obtained by traditional techniques, and averaging only the 18 ages within this range, which include all the more recently published AMS determinations. The average of these 18 best ages suggests an age of 12,685±260 ^{14}C years BP for the Reclus R_1 eruption, or 14,373–15,260 calibrated years BP based on the calibration curve CALIB 5.0.2 available at http://calib.qub.ac.uk/calib/ (Stuiver et al. 2006).

Auer originally suggested an age of 9,115±165 ^{14}C years BP for this tephra, >3,000 years younger than the above estimate (Fig. 2). Stern (1990) suggested an age of 10,330±110 ^{14}C years BP based on a single set of bracketing ages from in the Tres Arroyos site (area #16 in Fig. 1; Massone 1987), but revised this to 12,480±470 ^{14}C years BP considering a number of new ^{14}C determination (Stern 1992). McCulloch (1994) estimated the age of this eruption as 11,880±40 ^{14}C years BP, and Marden and Clapperton (1995) and McCulloch and Bentley (1998) revised this estimated age to 12,010±55 ^{14}C years BP based on a statistical analysis of the then available ages

Table 10 Sample sites for the late Holocene tephra A1 derived from the Aguilera volcano

Site #	Sample #	Location	Lat. °S; long. °W	Outcrop lithology	Thickness (cm)	Reference
1	LC-1	Lago Cardiel	48°48.5′S; 71°13′W	Lake sediment	1	Markgraf et al. 2003
2	CS-109	Lago Viedma	49°29′S; 72°46′W	Fluvial sediment	2	Stern 1990
3	SOS-1	Estancia El Sosiego (LA)	50°14′S; 72°30′W	Lake sediment	8	This paper
3	LL-1	Estancia La Laurita (LA)	50°12′S; 72°04W	Fluvial sediment	6	This paper
3	CF-1	Charles Fuhr (LA)	50°21′S; 71°58′W	Lake sediment	6	This paper
4	CS-108	Calafate (LA)	50°21′S 72°31′W	Lake sediment	10	Stern 1990
4	93-03	Lago Roca	50°22′S; 72°45′W	Bog peat	10	This paper
4	LR-1	Lago Roca	50°22′S; 72°45′W	Bog peat	10	This paper
5	CV-1	Cerro Verlika (CB)	50°30′S; 72°29′W	Bog peat	8	This paper
5	260 cm	Cerro Fraile (CB)	50°34′S; 72°52′W	Bog core CFR	6	Markgraf (personal communication)
5	PAT-6	Estancia Las Cumbres (CB)	50°45′S; 72°20′W	Fluvial sediment	6	Stern 1990, 1992
6	117/4	Lago Nordenskjold (TDP)	51°01′S; 72°51′W	Bog core	3	Heusser 1995
6	108 cm	Vega Nandu (TDP)	50°57′S; 72°40′W	Bog core PM-0304A	2	Martinez and Moreno 2007
6	1,508 cm	Laguna Guanacos (TDP)	50°57′S; 72°40′W	Bog core PM-0404A	2	Martinez and Moreno 2007
11	283 cm	Seno Skyring	52°42′S; 72°18′W	Lake core ES-1	2	Kilian et al. 2003
11	307 cm	Laguna Escondida	52°30′S; 71°56′W	Core PS-0504D	1	Moreno (personal communication)
17	90-01	Rio Tres Brazos (PB)	53°16′S; 71°02′W	Bog peat	1	Stern 1992

LA Lago Argentino; *CB* Cordillera Baguales; *TDP* Torres del Paine; *PB* Peninsula Brunswick

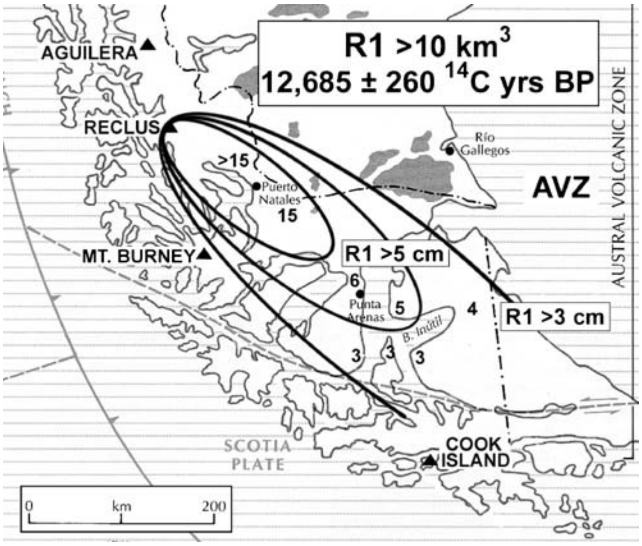

Fig. 4 Tephra thicknesses (in cm) at sample sites (Table 1) and the >10, >5 and >3 cm tephra isopachs for the late glacial R_1 tephra derived from the Reclus volcano

dates. More recently McCulloch and Davies (2001) and McCulloch et al. (2005a) suggested an age of 12,693±192 ^{14}C years BP. This is essentially the same as the new estimate presented above, and both are consistent with the 12,720±50 BP age indicated by the stratigraphic position of this tephra at 230 cm depth (Fig. 6) in a core from Puerto del Hambre (area #17 in Fig. 1) described and dated in detail by Heusser et al. (2000).

Other thinner and spatially less extensive Reclus tephra, which are younger than R_1, occur in the vicinity of both Torres del Paine and Ultima Esperanza (areas #6 and #7 in Fig. 1). One has been dated as 9,270±130 ^{14}C years BP in five cores from these sites (Table 3), and at least three other even younger Reclus tephra have also been observed in the cores from the vicinity of Torres del Paine (Stern 1990), which is the area closest to the volcano.

Mt. Burney MB_1 and MB_2 eruptions

Auer's white Tephra A (Fig. 8a and b) and Tephra III (Fig. 8a) from Tierra del Fuego are chemically similar to samples of ash, pumice and lava erupted from Mt. Burney (Fig. 3). Petrochemically similar mid and late Holocene white tephra are found north of the Strait of Magellan (Fig. 7). Eleven ^{14}C ages from five different sites for the older MB_1 tephra average 8,440±750 ^{14}C years BP. The average of only the seven dates in this range are 8,425±500 ^{14}C years BP, or 8,851–9,949 calibrated years BP (CALIB 5.0.2; Stuiver et al. 2006), within the range of 9,009–9,175 calibrated years BP estimated by Kilian et al. (2003) based on a single set of bracketing ages in a core from Peninsula Muñoz Gamero (site #10 in Fig. 1).

Twelve ^{14}C ages for the younger MB_2 eruption, determined at seven different sites, average 4,015±720 ^{14}C years BP, while the average for only those nine ages in this range is 3,830±390 ^{14}C years BP, or 3,818–4,711 calibrated years BP (CALIB 5.0.2; Stuiver et al. 2006). This age is approximately 1,000 years older than that determined for Tephra III by Auer (Fig. 2), but similar to 3,860±50 ^{14}C years BP (4,290±90 calibrated years BP) estimated by McCulloch and Bentley (1998) and McCulloch and Davies (2001), as well as the age of 4,254 calibrated years BP determined by Kilian et al. (2003) by refining bracketing ^{14}C ages dates with peat growth rates in a bog on Peninsula Muñoz Gamero just south of Mt. Burney (site #10 in Fig. 1).

At least two other thin tephra layer in cores from Peninsula Muñoz Gamero (site #10 in Fig. 1), southeast of the volcano, were produced by minor eruptions of Mt. Burney (Kilian et al. 2003). These have been dated as 10,015 ^{14}C years BP and 1,735 ^{14}C years BP (Table 6).

Fig. 5 White late-glacial tephra R_1 at two different sites on Tierra del Fuego (area #15 in Fig. 1): **a** Sample 90-08 (5 cm thick; Table 1) in eolian silt (loess) at Rio del Oro, Altos de Boqueron. **b** Sample 011198-3 (5 cm thick; Table 1) in fluvial sediments at Represa Porvenir

Table 11 Major and trace-element (in ppm) compositions of bulk-tephra and tephra-glass derived from the large late Holocene A1 eruption of the Aguilera volcano

Sample #	Salmi #13	A6[a]	CS-108	PAT-6	93-03	CS-108	PAT-6	93-03	117/4	Kilian[b]	LC-1	CS-109	CRF260	SOS-1	CF-1	LR-1	CV-1	0304A-108	0404A-1508	90-01
Material	Tephra	Pumice	Tephra			Glass					Tephra									
SiO_2	64.58	65.29	65.96	65.62	65.27	75.81	75.54	75.6	75.81	76.32										
TiO_2	0.36	0.52	0.48	0.55	0.59	0.21	0.19	0.14	0.17	0.26										
Al_2O_3	16.61	16.21	15.32	15.94	15.54	14.15	14.41	12.26	14.53	12.82										
FeO[c]	3.06	3.86	3.89	3.68	3.93	1.09	1.11	0.97	1.06	0.98										
MnO	0.05	0.09	0.07	0.07	0.08	0.03	0.03	0.03	0.04	0.01										
MgO	2	2.02	1.82	2.09	2.04	0.19	0.18	0.17	0.18	0.12										
CaO	4.48	4.18	3.66	3.86	4.06	1.23	1.19	1.05	1.16	1.22										
Na_2O	3.77	3.95	3.86	3.91	3.91	3.12	3.24	3.37	3.36	3.63										
K_2O	2.14	2.25	2.44	2.31	2.15	4.17	4.11	4.01	4.22	4.21										
P_2O_5		0.18	0.23	0.18	0.16															
LOI	2.52	1.56	2.35	2.06	2.14															
Total	100.07	100.11	100.08	100.27	99.87	100[d]	100[d]	100[d]	100[d]	100[d]										
Rb		62	67	64	59	109	114		92		68	67	52	56	61	66	69	56	54	55
Sr		486	439	465	492	126	150		162		307	450	393	414	382	360	426	455	412	301
Zr		142	150	130	126	82	100		110		147	144	142	138	155	135	144	138	133	121
Y		12	12	16	14	8	9		9		12	15	14	13	9	11	15	13	14	10
$^{87}Sr/^{86}Sr$		0.70509	0.70509	0.70512	0.70514	0.70507	0.70513													0.70511

ppm Parts-per-million

[a] From Stern and Kilian (1996)

[b] From Kilian et al. (2003)

[c] Total Fe as FeO

[d] Microprobe determinations normalized LOI-free to 100%

Table 12 ^{14}C age for tephra derived from the large A1 and other late Holocene eruptions of Aguilera volcano

Site #	Location	Sample #	Lab #	Date ^{14}C years BP	Reference
Large late-Holocene Aguilera eruption					
5	Estancia las Cumbres	93-15A	GX-19429	>2,975±225	This paper
1	Lago Cardiel	LC-1	NSRL-11243[a]	<3,010±45	Markgraf et al. 2003
5	Estancia las Cumbres	PAT6	GX-8678	<3,345±195	Stern 1992
10	Pen. Munoz Gamero	CH1 380 cm	AMS age	<3,520±30	Kilian et al. 2003
4	Lago Roca	93-03B	GX-19428	<3,705±155	This paper
17	Rio Tres Brazos	90-01B	GX-16533	<3,930±340	Stern 1992
5	Estancia las Cumbres	93-15B	GX-19430	<4,025±160	This paper
6	Lago Guanacos	1,508 cm	AMS age	<<4,560±60	Martinez and Moreno 2007
6	Vega Nandu	108–110 cm	AMS age	<<5,750±60	Martinez and Moreno 2007
Other Aguilera eruptions					
6	Lago Guanacos	1,562 cm	AMS age	<4,560±60	Martinez and Moreno 2007
6	Vega Nandu	144–150 cm	AMS age	<5,750±60	Martinez and Moreno 2007

[a] AMS ages

Hudson H_1 eruption

The age of the green tephra derived from a large explosive eruption (H_1; Figs. 8 and 10) of the Hudson volcano (Auer's Tephra II; Fig. 2) has been determined at eight different sites in southernmost Patagonia (Table 9), as well as at four sites further north in Aisen, Chile, closer to the volcano (Naranjo and Stern 1998). The average of all the 17 available ages is 6,900±460 ^{14}C years BP, and the average of the 10 best age determination that fall within this range is 6,850±160 ^{14}C years BP, or 7,571–7,849 calibrated years BP (CALIB 5.0.2; Stuiver et al. 2006).

Auer (1974) originally estimated the age of this tephra as 5,640±1,060 ^{14}C years BP (Fig. 2), but this estimate is clearly too young. Stern (1991) suggested an age of 6,775±150 ^{14}C years BP based on eight ^{14}C age dates from sites in Tierra del Fuego. Naranjo and Stern (1998) considered the age of the eruption to be 6,720±140 ^{14}C years BP, based on what they believed to be their most reliable determination in peat (sample 94T-65A; Table 9). McCulloch and Davies (2001) estimated a very similar age of 6,725±65 ^{14}C years BP for this tephra based on a statistical analysis of the available data. These three ages are all within the error range of the new estimate, as is a somewhat older age of 7,275±

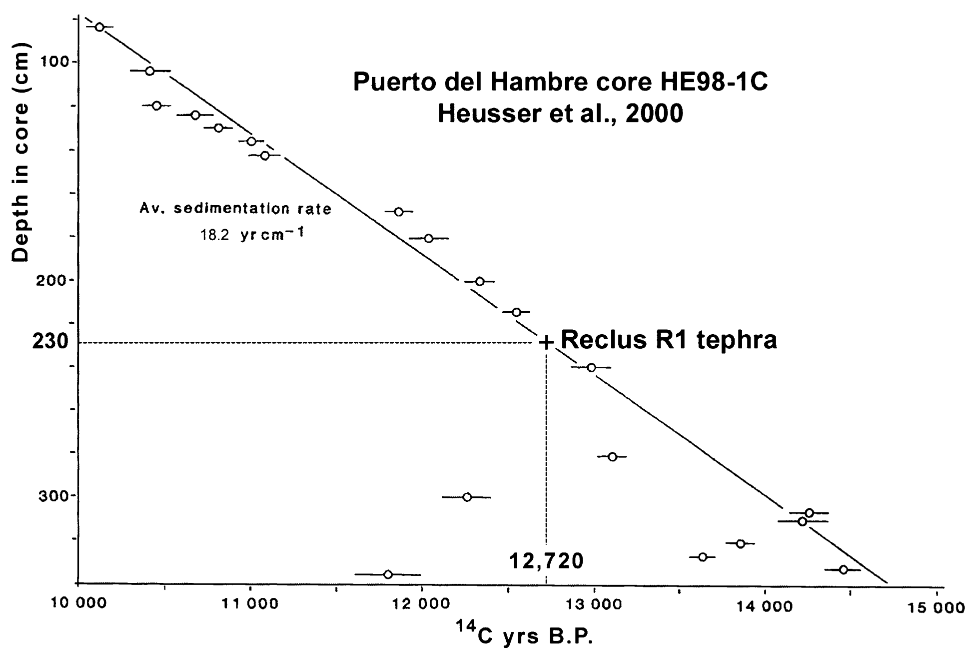

Fig. 6 Uncalibrated AMS ^{14}C ages versus depth in the core HE98-1C taken at Puerto del Hambre (area #17 in Fig. 1: Heusser et al. 2000). The Recluse-derived R_1 tephra occurs at 230 cm depth in this core, which implies an age of 12,720 uncalibrated ^{14}C years BP for this tephra, similar to the estimate of 12,685 BP ± 260 ^{14}C years BP (Fig. 2) based on the average for the 18 best ^{14}C ages for this tephra from this and other sites (Table 3)

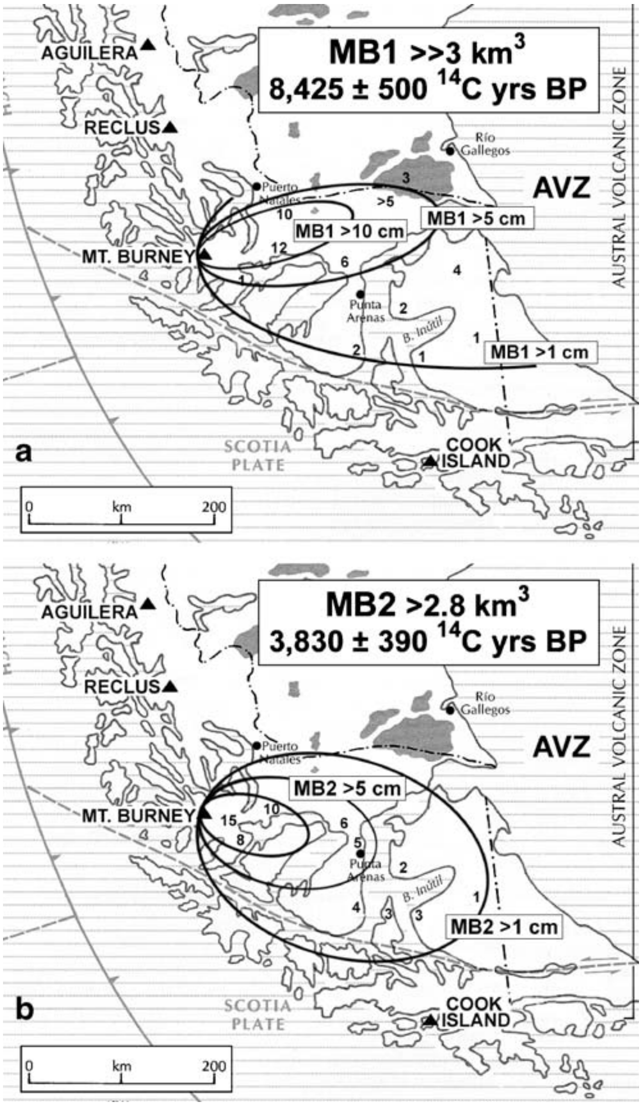

Fig. 7 Tephra thicknesses (in cm) at samples sites (Table 4) and the >10, >5 and >1 cm tephra isopachs for **a** the MB_1 and **b** the MB_2 tephra derived from eruptions of Mt. Burney

360 ^{14}C years BP (7,707–7,795 calibrated years BP) determined by Kilian et al. (2003) based on bracketing ages in a single core (core GC2 in Table 1 of Kilian et al. 2003).

The Hudson volcano has had at least 11 other small, medium and large Holocene explosive eruptions (Naranjo and Stern 1998), including a large >3.6 km^3 explosive eruption in August 1991 (Naranjo et al. 1993; Scasso et al. 1994), but none of these deposited tephra in southernmost Patagonia.

Aguilera A_1 eruption

Petrochemical data indicate that tephra exposed in sites around Lago Argentino (Fig. 12a) and in northern Magallanes, Chile (Fig. 12b), are derived from a large eruption (A_1) of the Aguilera volcano (Table 10; Fig. 11). Seven ages from five different sites (Table 12) average 3,500±420 ^{14}C years BP. However, in the core CH1 from Lago Chandler on Peninsula Muñoz Gamero (site #10 in Fig. 1; Kilian et al. 2003), the Aguilera tephra occurs at 310 cm, 70 cm below the 3,520 ^{14}C years BP age date for a sample taken at 380 cm (Table 12). Sedimentation rates in this lake have been estimated at 1.34 mm/year, which suggests that the Aguilera tephra is 522 years younger than the dated layer, or 3,000 ^{14}C years BP. Based on this, and the high precision AMS date of <3,010±45 ^{14}C years BP from Lago Cardiel (site #1 in Fig. 1; sample in LC-1 in Table 12), the age of the Aguilera tephra A_1 is estimated as approximately 3,000±100 ^{14}C years BP, or 3,067–3,339 calibrated years BP (CALIB 5.0.2; Stuiver et al. 2006). Stern (1992) had previously estimated the age of this tephra as <3,345±195 ^{14}C years BP based on

Fig. 8 White Mt. Burney tephra and greenish tephra H_1 at two different sites in Tierra del Fuego: **a** H_1 sample 90-14G (10 cm thick; Table 7), in organic-rich soil at Altos de Boqueron (area #15 in Fig. 1), above sample 90-14W of white tephra MB_1 (2 cm thick; Table 4) and below white tephra MB_2. Note that this site is directly along the main axis of dispersion of MB_2 (Fig. 7b), but well to the south of the main axis of dispersion of MB_1 (Fig. 7a), and that the greater thickness of the MB_1 tephra at this site is consistent with this being the larger of these two eruptiona. **b** H_1 sample 90-23G (15 cm thick; Table 7), in bog-peat and lake sediment overlying lacustrine clay along Route 257 (area #14 in Fig. 1), above sample 90-23W of white tephra MB_1 (4 cm thick; Table 4)

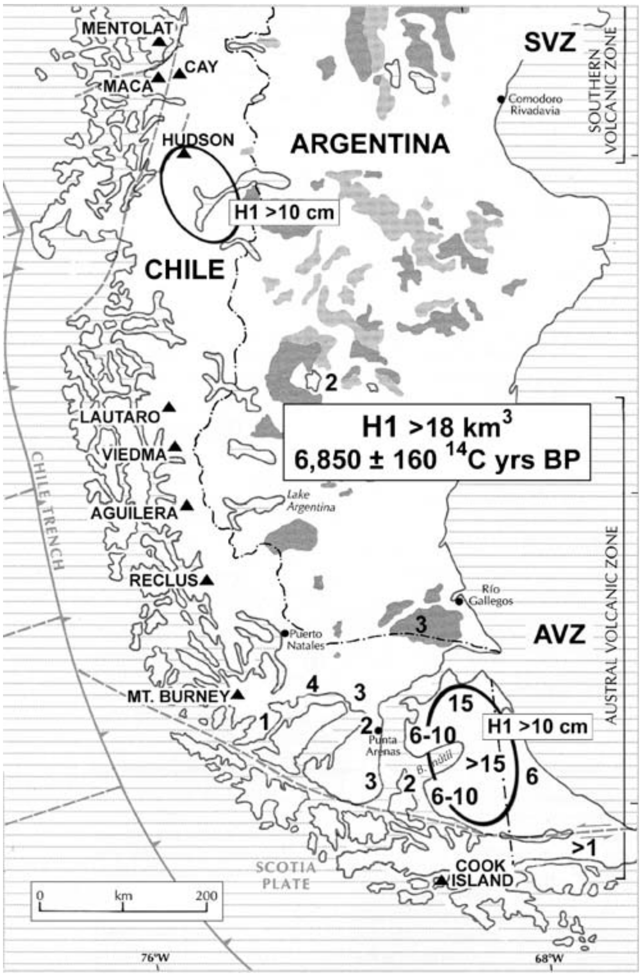

Fig. 9 Tephra thicknesses (in cm) at samples sites of southern Patagonia and Tierra del Fuego (Table 7), and the >10 cm proximal (Naranjo and Stern 1998) and distal maxima (Stern 1991) isopachs for green H_1 tephra derived from the Hudson volcano in the Andean SVZ. The >1 cm isopach for this eruption covers all of southern Patagonian from the Pacific to the Atlantic coast

the single set of bracketing ages from Estancia Las Cumbres (site #5 in Fig. 1; sample PAT-6 in Table 12; Fig. 12b).

Aguilera has also had several other smaller late-Holocene eruptions producing thinner more spatially restricted tephra layers observed in the vicinity of Lago Argentino and Torres del Paine, Chile. Strelin and Malagnino (2000) mention these as a “tephra sequence” in a <5,730±580 ^{14}C years BP stratigraphic section from the north shore of Lago Argentino (west of site #3 in Fig. 1). One layer older than the A_1 tephra has been dated as <4,560 ^{14}C years BP in two bog cores from the Torres del Paine area (site #6 in Fig. 1; Table 12). The other tephra younger than A_1 have not been dated.

Tephra distribution and eruption size

Tephra isopach maps for three of the five regionally widespread tephra layers in southernmost Patagonia are only moderately well constrained, especially to the east where the semi-arid climate conditions limit the occurrence of appropriate locations to preserve tephra, and where few bogs and/or lakes have been cored. Nevertheless, some qualitiative constraints on the volume of tephra that form these layers may be made (Fig. 13).

Reclus R_1 tephra

Reclus R_1 tephra is >40 cm thick 90 km southeast of the volcano at two sites in Ultima Esperanza (area #7 in Fig. 1), >10 cm thick 150 km southeast of the volcano at Rio Rubens (area #8 in Fig. 1), and >5 cm thick 350 km southeast of the volcano in the area of Cabo Boqueron, Tierra del Fuego (area #15 in Fig. 1; Figs. 4 and 5). The regional widths of these isopachs are uncertain, both to the west and east, but the 3 cm isopach extends from Peninsula Brunswick (area #17 in Fig. 1), located 100 km west of the main axis of R_1 tephra dispersion, to central Tierra del Fuego (area #16 in Fig. 1) 50 km east of the main axis of R_1 tephra dispersion. Based on these constraints the volume of the R_1 eruption is estimated as at least >10 km^3, somewhat larger in size than the 1932 eruption of the Andean volcano Quizapu (Fig. 13). The R_1 eruption is the largest Holocene eruption of any of the AVZ volcanic centers.

This tephra has not been observed in any exposures or bog core sample in the area of Torres del Paine, less than 35 km southeast of the volcano, possibly because of ice cover in this area at the time of the eruption. However, large >14 cm in diameter Recluse-derived (Table 2) pumice clasts are found interbedded with glacial and fluvial–glacial sediments in a number of localities near Torres del Paine.

Fig. 10 H_1 sample 93-21G (Table 7) in lake sediment above lacustrine clay along Rio Chico (area #20 in Fig. 1) in central Tierra del Fuego. This >20 cm thick H_1 tephra, over 900 km southeast of the Hudson volcano, has undergone soft sediment deformation and has also been faulted

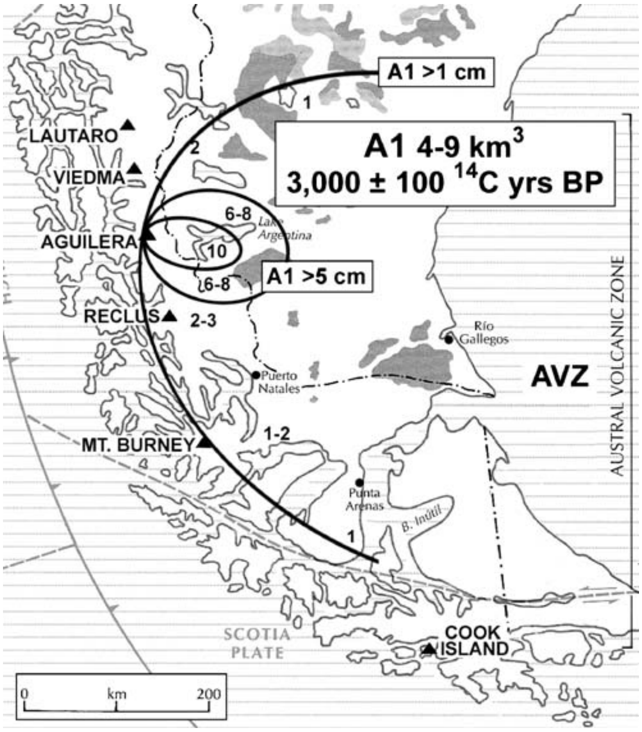

Fig. 11 Tephra thicknesses (in cm) at samples sites (Table 10) and the >10, >5 and >1 cm tephra isopachs for the A_1 tephra derived from Aguilera volcano

These are interpreted as reworked products of the late-glacial R_1 eruption transported superglacially and deposited in meltwater at the contemporaneous ice margin (Stern 1990; Marden and Clapperton 1995; Marden 1997).

Mt. Burney MB_1 and MB_2 tephra

Tephra isopachs for the younger late Holocene Mt. Burney MB_2 eruption are very well determined in the area of tephra dispersion southeast of the volcano (Fig. 7b) because of the numerous outcrops of tephra in this area (Table 4). As a result, the volume of this eruption has been well constrained as ≥2.8 km^3 (Fig. 13; Kilian et al. 2003). In contrast, the older MB_1 eruption of Mt. Burney is the least well constrained of the five large eruptions in the southernmost Andes, in part because the tephra it produced was dispersed in a much more easterly direction (Fig. 7a). However, 10–12 cm thick layers of MB_1 tephra occur >100 km to the east of Mt. Burney in both the Barking Fox bog at Rio Rubens (area #8 in Fig. 1; Table 4) and Laguna Escondida on the north shore of Seno Skyring (area #11 in Fig. 1; Table 4). This is greater than the same distance of dispersion of the 10 cm isopach for the MB_2 tephra. Also, a 5–10 cm layer of MB_1 occurs >200 km east of the volcano at Laguna Tom Gold (area #9 in Fig. 1; Table 4; Massone 1989) and a 4 cm thick layer of MB_1 tephra occurs >300 km to the east on Tierra del Fuego (area #14 in Fig. 1; Fig. 8b; Table 4), while MB_2 tephra is not thicker than 3 cm anywhere on Tierra del Fuego (Fig. 7b; Table 4). Thus the MB_1 eruption must have been significantly larger than the MB_2 eruption, thus at least >3 km^3.

Hudson H_1 tephra

Green Hudson H_1 tephra forms a distal maximum deposit >10 cm thick covering over 40,000 km^2 in Tierra del Fuego, which is >900 km south of its source volcano (Figs. 8, 9, 10). This unusually thick distal tephra deposit implies a large volume explosive eruption, possibly >18 km^3 (Fig. 13; Stern 1991; Naranjo and Stern 1998). Proximal isopach maps of both tephra thickness and maximum pumice dimensions for the H_1 eruption in the vicinity of the Hudson volcano confirm this interpretation and suggest that this explosive eruption was among the largest of any volcano in the southern Andes during the Holocene (Naranjo and Stern 1998; Stern 2004; Stern et al. 2007).

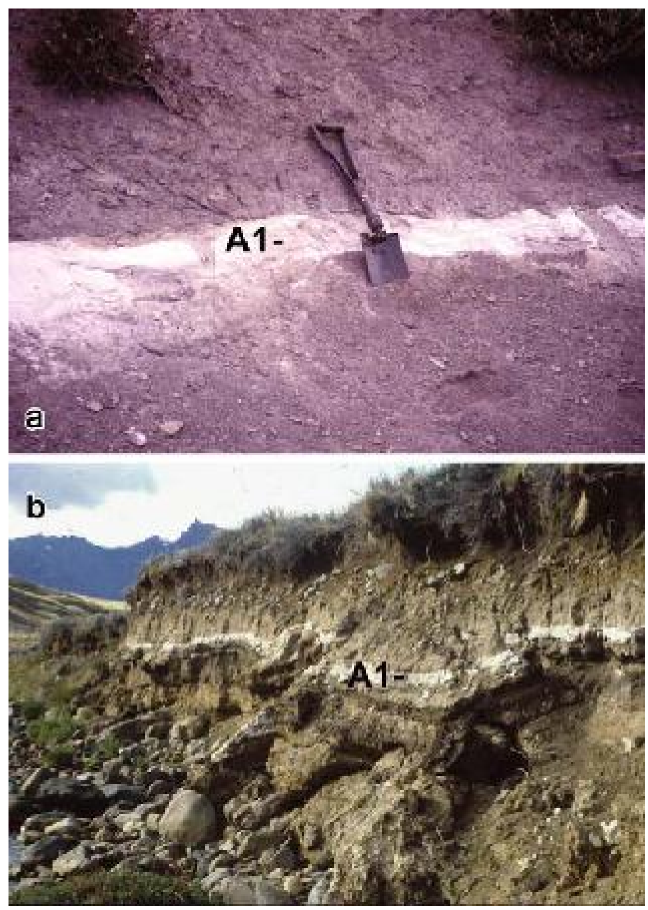

Fig. 12 White tephra A_1 at two different sites: **a**. Sample CS-108 (10 cm thick; Table 10), in lake sediment along south shore of Lago Argentino 22 km west of Calafate (area #4 in Fig. 1). **b**. Sample PAT-6 (6 cm thick; Table 10) in fluvial sediments at Estancia Las Cumbres, Cordillera Baguales (area #5 in Fig. 1)

Aguilera A_1 tephra

The Aguilera A_1 tephra has not been observed on Tierra del Fuego, but has a very wide distribution north of the Strait of Magellan (Fig. 11). The >10 cm thick tephra isopach extends at least 80 km east of the volcano and the >5 cm isopach at least 130 km east of the volcano, suggesting an eruption volume that is larger than either the late-Holocene MB_2 eruption of Mt. Burney (≥2.8 km^3; Fig. 13) or the 1991 eruption of the Hudson volcano (≥3.6 km^3; Fig. 13). Although the total area covered by the >1 cm isopach is uncertain, it reaches as far south as the Strait of Magellan and as far northeast as Lago Cardiel (area #1 in Fig. 1), and thus covers a known area >140,000 km^2 (Fig. 11). Based on this (Fig. 13), the volume of the A_1 eruption is estimated to be larger than the 1991 eruption of the Hudson volcano (≥3.6 km^3; Scasso et al. 1994), but not quite as large as the 1932 eruption of Quizapu (~9.5 km^3; Hildreth and Drake 1992).

Discussion

The data indicate that regionally widespread Holocene tephra layers in southernmost Patagonia were produced by five large explosive eruptions, large enough (Fig. 13) that if they occurred again they could cause significant impact to local population centers such as Calafate, Puerto Natales and Punta Arenas. The ≥3.6 km^3 (Scasso et al. 1994) eruption of the Hudson volcano in 1991 had a significant negative impact on the sheep-ranching industry in the semi-arid area of Patagonia southeast of this volcano that was affected by tephra-fall from this event, and it could be expected that an equally large eruption of one of AVZ volcanoes could similarly impact ranching in the semi-arid areas of southernmost Patagonian and Tierra del Fuego. Recent studies by Kilian et al. (2003, 2006) have suggested that tephra-fall from Mt. Burney MB_2 eruption also had negative impact on both wetter forest and aquatic ecosystems southeast of this volcano due to SO_2 released from altering pumice and tephra, which produced intense soil and lake acidification, nutrient leaching, and ultimately increased soil erosion.

The source volcano for one of the five regionally widespread tephra in southernmost Patagonia is the Hudson volcano, which is located well to the north in the Andean SVZ (Fig. 1). The source volcanoes for the other tephra are Mt. Burney, Reclus and Aguilera, which are located in the Andean AVZ. Each of these AVZ volcanoes also had smaller explosive eruptions not capable of producing tephra deposits large enough to be preserved in the distal record that is the basis for the tephrochronology scheme summarized in Fig. 2.

Based on the distal record summarized in Fig. 2, the six volcanoes in the AVZ have in total produced only four large explosive Holocene eruptions, compared with three equally large or larger explosive eruptions for the Hudson volcano itself (Naranjo and Stern 1998) in the southern SVZ. Ignoring Cook Island volcanic center, which consists of a group of small domes located well south of the other AVZ stratovolcanoes, and considering only the five AVZ stratovolcanoes between latitudes 49 and 52°S, still implies less than one large explosive eruption per volcano during the Holocene in this segment of the Andean arc, compared with at least 11 medium and large Holocene explosive eruptions derived from the 9 volcanic centers in a comparable sized part of the southern SVZ between latitudes 43 and 46°S (Naranjo and Stern 1998, 2004). This, and the closer spacing of the more numerous volcanic centers in this part of the Andean SVZ, suggests higher magma production rates in the southern SVZ, possibly associated with the higher convergence rates between the Nazca and South American plates (9 cm/year) north of the Chile Rise–Trench triple junction compared to the lower convergence rates of the Antarctic and South American plates (2 cm/year) south of this triple junction.

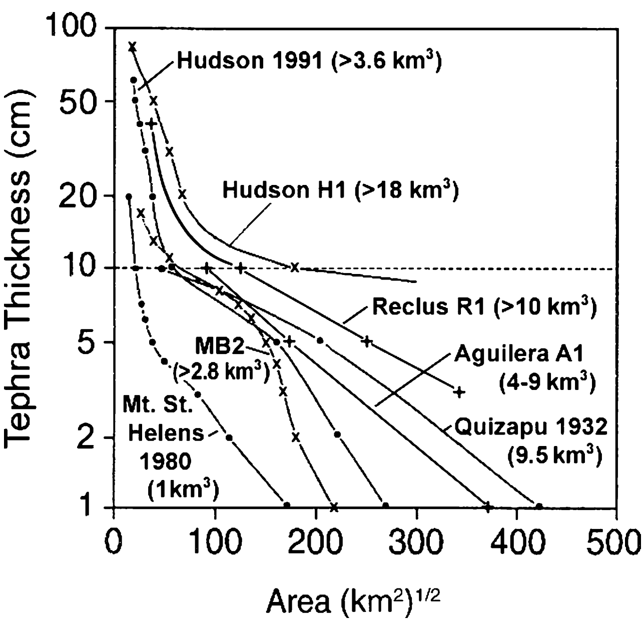

Fig. 13 Plots of the thickness of tephra isopachs (in cm) versus the square root of the area (km^2)$^{1/2}$ for the isopachs, which provide a basis for estimating the volume of these eruptions as described by Pyle (1989) and Fierstein and Nathenson (1992), for the Reclus R_1 and Aguilera A_1 tephra in southernmost Patagonia compared to the H_1 tephra produced by the Hudson volcano (Naranjo and Stern 1998) and the MB_2 tephra from the Mt. Burney volcano (Kilian et al. 2003), as well as the previously well document eruptions of Quizapu in 1932 (Hildreth and Drake 1992), Mt. St. Helens in 1980 (Sarna-Wojcicki et al. 1981), and Hudson in 1991 (Naranjo et al. 1993; Scasso et al. 1994)

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