MID-HOLOCENE TEPHRA ON TIERRA DEL FUEGO (54°S) DERIVED FROM THE HUDSON VOLCANO (46°S): EVIDENCE FOR A LARGE EXPLOSIVE ERUPTION

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ABSTRACT

The Hudson volcano (46°S) is identified, on the basis of chemical data, as the source of a characteristically green-brown tephra within Holocene deposits on Tierra del Fuego. The 10-15 cm thickness of these ash layers, found over 900 km from their source volcano, suggest an explosive eruption of significant magnitude. This eruption has been dated as between 6,625 and 6,930 years B.P. Younger Hudson-derived tephra in Aisén, Chile, and Santa Cruz, Argentina, indicate another explosive eruption of this volcano occurred shortly after 4,830 years B.P.

Key words: Tephra, Volcanism, Tierra del Fuego, Hudson volcano, Chile.

RESUMEN

El volcán Hudson (46°S) se identificó, sobre la base de información química, como la fuente de una tefra, de típico color verde-pardusco, intercalada en los depósitos del Holoceno en Tierra del Fuego. Estos niveles de ceniza, con espesores de 10-15 cm, situados a distancias mayores que 900 km de su fuente volcánica, sugieren una erupción explosiva de gran magnitud, datada entre 6.625 y 6.930 años A.P. Tefras más jóvenes en Aisén, Chile, y Santa Cruz, Argentina, indican otra erupción explosiva del volcán Hudson poco después de 4.830 años A.P.

Pelabres claves: Tefra, Volcanismo, Tierra del Fuego, Volcán Hudson, Chile.

INTRODUCTION

Auer (1974 and references therein) described 5-40 cm thick layers of distinctively green-brown tephra from Holocene bog deposits on Tierra del Fuego (Figs. 1, 2). Based on their stratigraphic position above an earlier white tephra layer (Fig. 2), he termed this green-brown ash Tephra II.

Salmi (1941) determined a high-K_2O andesite composition ($SiO_2 = 59.4$ and $K_2O = 2.5$ wt %; Table 1) for this green-brown tephra; both more mafic and K_2O-rich than white tephra from Tierra del Fuego. Based on Salmi's chemical analysis, I previously concluded that the green-brown tephra of Tierra del Fuego could not be derived from any of the volcanos that comprise the Andean Austral Volcanic Zone (AVZ; Fig. 1) because of its relatively low SiO_2 and high K_2O, as well as high FeO and TiO_2 (Stern, 1990). The relatively high FeO and TiO_2, compared to the white tephra of Tierra del Fuego (Table 1), is presumably what imparts the characteristic darker green-brown color to this volcanic ash.

Auer was more interested in Patagonian tephra as Holocene stratigraphic marker horizons than he was in their source volcanos, and he did not determine isopach maps for tephra. He attributed the green-brown Tephra II of Tierra del Fuego to the eruption of "some young, unknown volcano" between 4,500 and 5,000 years B.P. (Auer, p. 7-11, 1974). Based only on new chemical analysis of this tephra (Tables 1, 2),

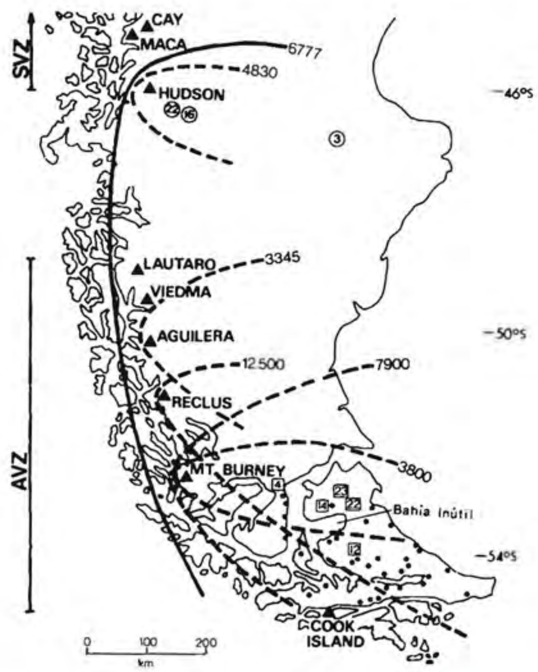

FIG. 1. Map showing the volcanic centers of the Austral Volcanic Zone (AVZ) and southernmost Southern Volcanic Zone (SVZ) of the southern Andes, including the recently documented Viedma Volcano in the AVZ (R. Kilian, personal commun., 1990), as well as the inferred distribution of tephra for some of the major eruptions of these volcanos (dashed lines, approximate ages indicated in years B.P.; Stern, 1990 and unpublished data). The inferred distribution of tephra from the 6,625 to 6,930 years B.P. (6,777) eruption of the Hudson volcano is indicated by the solid line. Locations of green-brown tephra described in this manuscript are indicated by numbers enclosed in squares (04, 12, 14, 22, 23 for samples listed in Table 2). Locations of tephra from Aisén, Chile, and Santa Cruz, Argentina, are indicated by numbers enclosed in circles (16 for RI-16, 22 for RI-22, and 3 for Cueva 3 de los Toldos, Table 2). Locations of green-brown Tephra II as described by Auer (1974 and references therein) are indicated by small black dots.

FIG. 2. Photograph of green-brown tephra layer within a Holocene deposit cut by a stream south of Punta Delgada (site 23, Fig. 1), Tierra del Fuego. The 15 cm thick green-brown tephra (arrow) overlies a 4 cm thick white tephra layer derived from an eruption of Mount Burney (Stern, unpublished data), and underlies a white caliche-rich soil layer.

TABLE 1. MAJOR ELEMENT COMPOSITIONS (VOLATILE-FREE AND NORMALIZED TO 100%) OF GREEN-BROWN TEPHRA FROM SOUTHERNMOST PATAGONIA AND TIERRA DEL FUEGO, COMPARED TO WHITE TEPHRA DERIVED FROM HOLOCENE ERUPTIONS OF THE AGUILERA, RECLUS, AND MT BURNEY VOLCANOS OF THE AUSTRAL ANDES (STERN, 1990)

Tephra	Green-brown			White		
Sample	1	2	3	4	5	6
SiO_2	59.36	63.04	62.58	66.37	70.27	73.00
TiO_2	1.79	1.23	1.24	0.37	0.40	0.42
Al_2O_3	20.97	16.71	16.79	17.20	17.05	15.04
FeO^*	5.12	4.66	4.55	3.14	3.04	1.75
MnO	0.11	-	-	0.05	-	0.04
MgO	1.59	1.64	1.76	2.07	1.19	0.45
CaO	3.93	3.98	4.38	4.64	2.53	3.10
Na_2O	4.34	5.89	5.78	3.91	2.94	4.15
K_2O	2.51	2.59	2.56	2.22	2.17	1.36
P_2O_5	0.28	0.29	0.36	-	0.37	0.66

No. 1: Green-brown Tephra II from southernmost Patagonia (No. 15; Salmi, 1941); No. 2: Sample 90-12 from Rio Rusphen 30 km south of Cameron, Chile (Location 12; Fig. 1); No. 3: Sample 90-23G from roadside river cut between Bahla Inútil and Punta Delgada (Location 23; Fig. 1); No. 4: Tephra II from shores of Lago Argentino (No.13; Salmi, 1941) correlated with a late Holocene eruption of the Aguilera volcano (Stern, 1990); No. 5: Tephra I from Tierra del Fuego (No. 19; Salmi, 1941) correlated with a late glacial eruption of the Reclus volcano (Stern, 1990); No. 6: Tephra III from Tierra del Fuego (No.17; Salmi, 1941) correlated with a late Holocene eruption of the Mt Burney volcano (Stern, 1990).
FeO^*: total Fe as FeO.

and without pretending to even begin the process of producing an isopach map of its distribution, I suggest that the green-brown tephra of Tierra del Fuego was derived, some time between 6,625 and 6,930 years B.P., from a large explosive eruption of the Hudson volcano, the southernmost volcanic center in the Andean Southern Volcanic Zone, more than 900 km to the north (Fig. 1).

SAMPLE DESCRIPTION

Samples from 10-15 cm thick layers of green-brown tephra were collected in four stream cuts into Holocene bogs both north and south of Bahía Inútil on Tierra del Fuego, and from a layer observed in a trench dug as a watering hole for animals just west of Laguna Blanco, north of Punta Arenas (Figs. 1, 2).

Tephra samples were cleaned initially by repeated immersion in water, ultrasonic vibration, and decanting to remove as much clay and organic material as possible. This was followed by twenty minute baths in first 2N HCl, to dissolve clay and carbonates, and then a 5.25% solution of NaOCl (household bleach) to dissolve remaining organic material (Steen-McIntyre, 1977). These steps also removed the finer fraction of the tephra and may have dissolved certain mineral components such as apatite grains. The so cleaned tephra were sieved to separate the 60 to 120 mesh fraction which was effective in removing large extraneous lithic fragments.

Two samples of bulk tephra (glass + minerals) were analyzed for major elements (Table 1). The results are similar to Salmi's (1941) analysis of green-brown tephra in their high K_2O and TiO_2 at relatively low SiO_2 compared to samples of both lava and tephra derived from volcanic centers of the Austral Volcanic Zone (Figs. 3, 4; Table 1; Stern, 1990). The major element composition of the green-brown tephra from southernmost Patagonia are, however, similar to intermediate rocks erupted from the Hudson volcano (Figs. 3, 4, Table 3), the southernmost in the Andean SVZ (Fig. 1).

Five samples of bulk tephra were analyzed for

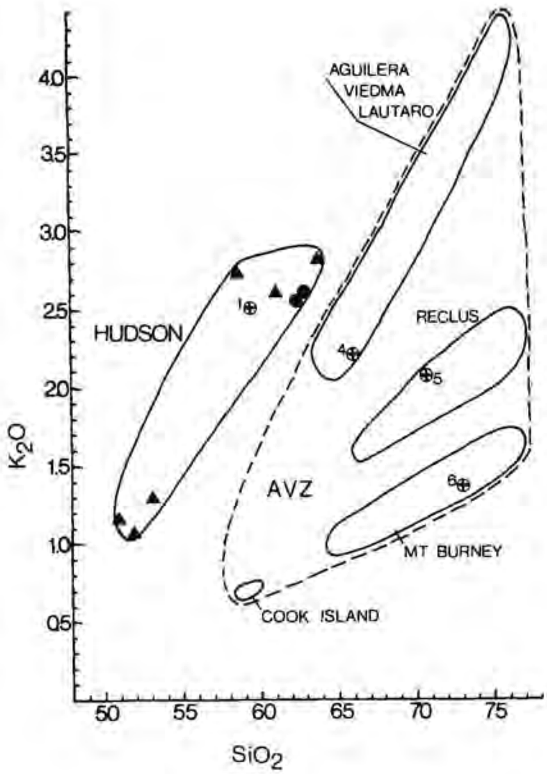

FIG. 3. K_2O *versus* SiO_2 diagram, illustrating fields for whole-rock, tephra, and glass separates for the volcanos of the AVZ (Cook Island, Mount Burney, Aguilera and Lautaro from Futa and Stern, 1988; Stern, 1990: Reclus from Harambour, 1989; Stern, 1990; Viedma from R. Kilian, personal commun.,1990), compared to whole-rock samples from the Hudson volcano (solid triangles; Table 3). Green-brown tephra from Tierra del Fuego (solid circles representing analyses No. 2 and No. 3 from Table 1, and crossed circle 1 representing analysis No. 1 from Table 1 determined by Salmi, 1941) plot in the field of the Hudson volcano of the SVZ. White tephra from southernmost Patagonia (circled crosses 4-6, analysis Nos.4-6, Table 1, Salmi, 1941) plot in the field of AVZ volcanos.

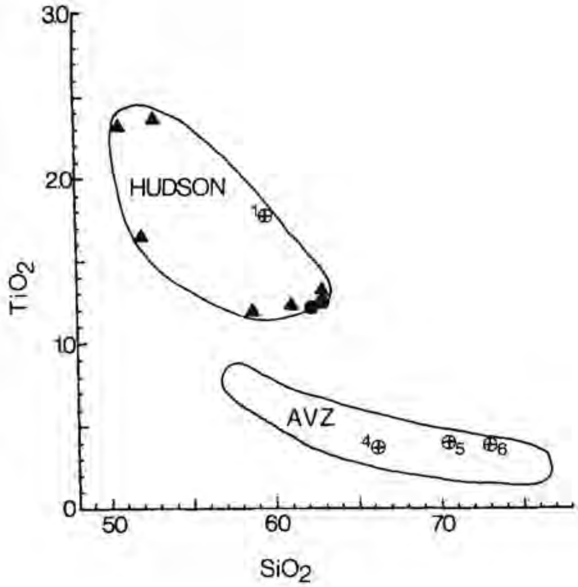

FIG. 4. TiO_2 *versus* SiO_2 diagram, illustrating fields for whole-rock, tephra, and glass separates from the volcanos of the AVZ (Futa and Stern, 1988; Harambour, 1990; R. Kilian, personal commun., 1990), compared to whole-rock samples from the Hudson volcano (solid triangles; Table 3). Green-brown tephra from Tierra del Fuego (solid circles for analyses No. 2 and No. 3, and circled cross for analysis No. 1, Table 1) plot in the field of the Hudson volcano. White tephra from southernmost Patagonia (circled crosses 4-6 for analysis Nos. 4-6, Table 1) plot in the field of the AVZ volcanos.

trace element (Rb, Sr, Zr, Nb, and Y) content by X-ray flourescence techniques. Although Rb contents of these tephra are within the range of lavas and tephra erupted from the northernmost volcanic centers in the AVZ, Zr (Fig. 5), Nb and Y (Stern, 1990) are significantly higher than for any AVZ center. As in the case of major elements, the concentration of these trace elements in the green-brown tephra are similar to intermediate rocks erupted from the Hudson volcano (Fig. 4, Table 3). Also, their Zr (Fig. 5), Nb, and Y contents are higher than has been reported for other volcanos of the southern SVZ such as Cay and Maca (Stern, 1990).

An $^{87}Sr/^{86}Sr$ ratio of 0.70451 was determined for one sample of green-brown tephra from Tierra del Fuego. This value, which is higher than $^{87}Sr/^{86}Sr$ of rocks erupted from the Cook Island and Mount Burney volcanos, but lower than the other volcanic centers of the AVZ (Fig. 6), is closely similar to published Sr-isotopic composition of rocks erupted from the Hudson volcano, which range from 0.70424 - 0.70449 (Table 3), and higher than published values for other volcanos of the southernmost SVZ south of 44°S, including the Maca, Cay, Mentolat and Melimoyu volcanos which range from 0.70400 to 0.70440 (Notsu *et al.*, 1987; Futa and Stern, 1988).

Organic material collected both above and below these tephra layers was dated by ^{14}C techniques by

TABLE 2. BRACKETING ^{14}C AGES, AND TRACE-ELEMENTS AND ISOTOPIC COMPOSITION OF GREEN-BROWN TEPHRA FROM TIERRA DEL FUEGO AND TEPHRA IN HOLOCENE DEPOSITS DIRECTLY TO THE EAST OF THE HUDSON VOLCANO IN AISÉN, CHILE[1], AND SANTA CRUZ, ARGENTINA[2]

Location	Tierra del Fuego				
Samples	**90-04**	**90-12**	**90-14**	**90-22**	**90-23G**
Age years B.P.[3]					
>	6,040± 205	6,625±110	6,575±110	-	-
<	6,930±120	7,435±120	7,550±120	7,015±215	7,535±250
Rb	50	50	50	54	52
Sr	368	361	392	351	374
Zr	393	386	380	390	356
Nb	20	21	21	21	19
Y	43	42	41	43	37
$^{87}Sr/^{86}Sr$	-	-	-	-	0.70451

Location	Aisén						Sta. Cruz
Samples[1, 2]	**RI-16**	**RI-16**	**RI-16**	**RI-22**	**RI-22**	**RI-22**	**Toldos**
	I	**II**	**II**	**11C/1**	**11D(N)/2**	**4A(N)/8**	
Age years B.P.[1,2]							
>	-	5,340±180	5,340+180	-	-	2,110±60	-
<	5,340±180	-	-	340±50	340±50	4,830±60	4,850±90
Rb	68	88	80	60	54	68	84
Sr	319	415	388	395	392	328	283
Zr	421	360	401	272	310	424	466
Nb	18	18	22	17	18	19	22
Y	41	41	45	34	41	46	47
$^{87}Sr/^{86}Sr$	0.70447	-	-	-	-	-	0.70445

1. Samples and chronological information from archaeological sites RI-16 and RI-22 (Mera, 1983, and personal commun.); 2. Samples and chronological information from the Toldos Cave 3 (Cardich, 1984-85); 3. ^{14}C age determinated on organic material above (tephra age >) and below (tephra age <) tephra layers by Geochron Laboratories of Krueger Enterprises.

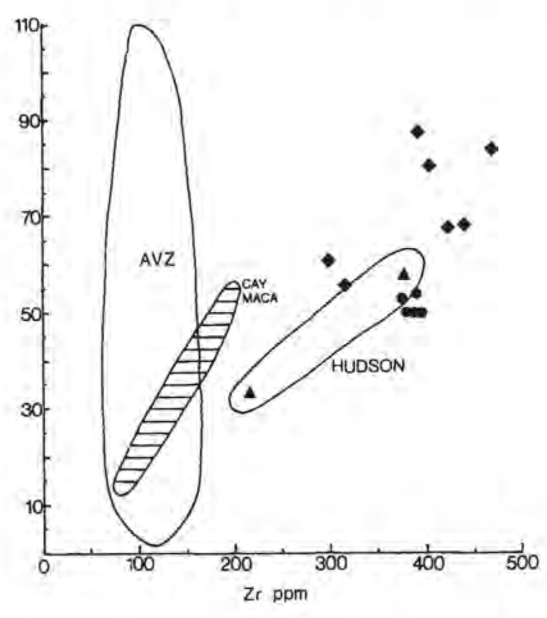

FIG. 5. Rb *versus* Zr diagram, illustrating fields for whole-rock, tephra, and glass separates for the volcanos of the AVZ (Futa and Stern, 1988; Stern, 1990), compared to whole-rock samples from the Hudson (solid triangles, Table 3) as well as the Maca and Cay volcanos (horizontally lined field, Futa and Stern, 1988; Stern, 1990) of the SVZ. Green-brown tephra from Tierra del Fuego (solid circles, Table 2) plot either within or close to the field of the Hudson volcano, while green-brown to yellow tephra from Aisén, Chile, and Santa Cruz, Argentina (solid diamonds, Table 2), generally plot at higher Rb and Zr. These latter samples, which are chemically more similar to samples from the Hudson compared to other volcanos of the southernmost Andes, may represent an eruption from the Hudson volcano of more differentiated magma, or may have undergone more concentration of the Rb-rich glassy phase during the physical processes associated with both airfall and redeposition of tephra on the ground.

TABLE 3. CHEMICAL COMPOSITION OF LAVAS AND PUMICE FROM THE HUDSON VOLCANO

Sample	1	2	3	4	5	6
SiO_2	50.82	51.90	52.79	58.68	60.92	62.20
TiO_2	2.33	1.57	2.38	1.23	1.25	1.29
Al_2O_3	16.62	16.78	16.20	16.28	16.41	16.72
FeO^*	10.97	9.61	10.61	6.32	6.03	5.42
MnO	0.19	0.17	0.19	0.18	0.17	0.21
MgO	3.78	4.32	3.74	1.64	1.45	1.61
CaO	8.17	8.87	6.69	3.15	3.54	3.62
Na_2O	4.53	3.96	4.82	6.02	5.68	6.11
K_2O	1.14	1.03	1.30	2.75	2.61	2.54
P_2O_5	0.80	0.52	0.53	0.47	0.43	0.37
Total	99.36	98.83	99.52	97.02	98.49	99.99
Rb	26	23	34	-	-	57
Sr	498	547	500	-	-	372
Zr	-	-	217	-	-	369
Nb	-	-	12	-	-	19
Y	41	31	34	-	-	45
$^{87}Sr/^{86}Sr$	0.70424	0.70430	0.70449	-	-	7.0449

No. 1. Sample HUD-003, Notsu *et al.* (1987); No. 2. Sample HUD-001, Notsu *et al.* (1987); No. 3. Sample H-1, Godoy *et al.* (1982) and Futa and Stern (1988); No. 4. Pumice, Fuenzalida (1976); No. 5. Cinder, Fuenzalida (1976); No. 6. Sample H-4, Stern (1990)
FeO^*: total Fe as FeO

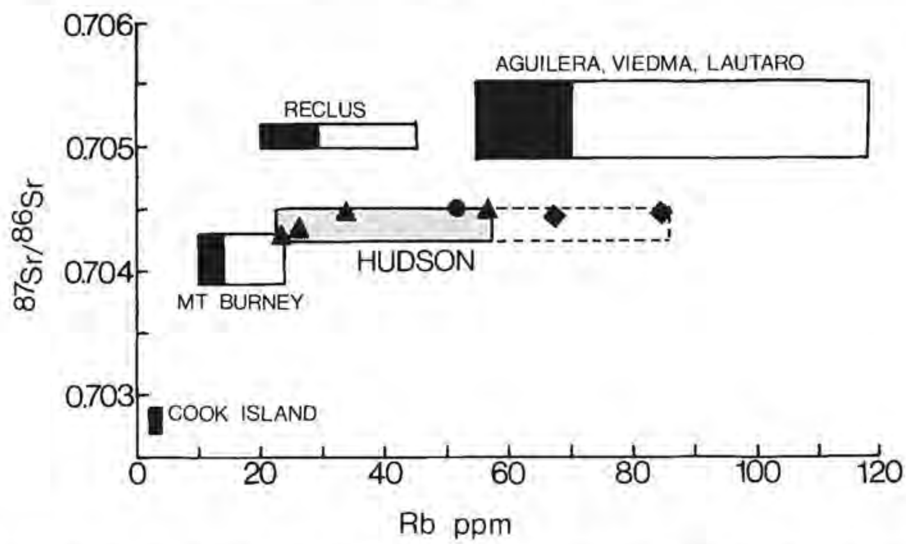

FIG. 6. Rb *versus* $^{87}Sr/^{86}Sr$ diagram, illustrating the fields for whole-rock (solid fields), as well as tephra and glass separates (open fields) for the volcanos of the AVZ (Futa and Stern, 1988; Stern, 1990), compared to whole-rock samples from the Hudson volcano (solid triangles, shaded field, Table 3). Green-brown tephra from Tierra del Fuego (solid circle, Table 2) falls in the field for the Hudson volcano. Tephra samples from Aisén, Chile, and Santa Cruz, Argentina (solid diamonds, Table 2), have higher Rb, but similar $^{87}Sr/^{86}Sr$, and fall in a field (enclosed in dashed line) expected for eruptions from the Hudson volcano of more differentiated magmas, or of Hudson-derived tephra in which the Rb-rich glassy phase has been concentrated by physical processes associated with airfall and redeposition of tephra on the ground.

Geochron Laboratories of Krueger Enterprises, Cambridge, Massachusutes, USA. The ages determined for material below these tephra layers range from 6,930 to 7,550 years B.P., while the ages determined for material above these tephra layers range from 6,040 to 6,625 years B.P. (Table 2).

DISCUSSION

On the basis of the similarity of the chemical composition of the green-brown tephra of Tierra del Fuego and samples of intermediate rocks erupted from the Hudson volcano of the southern SVZ, it was concluded that this tephra was derived from a large explosive eruption of this volcano sometime between 6,625 and 6,930 years B.P. The size of this eruption may be approximated by comparison of the thickness of the green-brown tephra layers on Tierra del Fuego, 900 km south of the Hudson volcano, with the thickness of ash laid down at different distances from eruptions of known size (Fig. 7). For example, the Mount St. Helens eruption of 1980 erupted a total volume of 1 km^3 of ash with a distal maximum of 4 cm of uncompacted ash deposited 250 km to the east (Sarna-Wojcicki *et al.*, 1981), while in 1932 Quizapu of the southern Andes erupted a volume of 18 km^3 of pumiceous material (Hildreth and Drake, 1988) which formed a 10-15 cm thick uncompacted ash layer as far as 600 km to the east (Larsson, 1936). Although post-airfall redeposition may have thickened the layers of green-brown tephra on Tierra del Fuego, these greater than 10 cm thick compacted layers up to more than 900 km south of the Hudson volcano suggest an eruption greater in size than that of Quizapu (Fig. 7). This eruption may have produced the 9 km caldera of the Hudson volcano described by Fuenzalida (1976).

Samples of green-brown to yellow-brown ash from archaeological sites in Aisén, Chile, and Santa Cruz, Argentina (Fig. 1), have chemical characteristics similar to the green-brown ash of Tierra del Fuego (Table 2) as well as the intermediate rocks erupted from the Hudson volcano. On this basis I previously attributed the origin of ash layers in the archaeological site Cueva Las Guanacas (RI-16; Mena, 1983), just east of the Hudson volcano along the Ibáñez River, Aisén, to eruptions of this same volcano (Stern, 1990). The author would conclude that the ashes from other archaeological sites in Aisén (RI-22, Table 2; F. Mena, personal commun., 1991) and Santa Cruz, Argentina (Cueva 3 de los Toldos, Table 2; Cardich, 1984-85), are also derived from eruptions of the Hudson volcano.

However, it is clear on the basis of the available

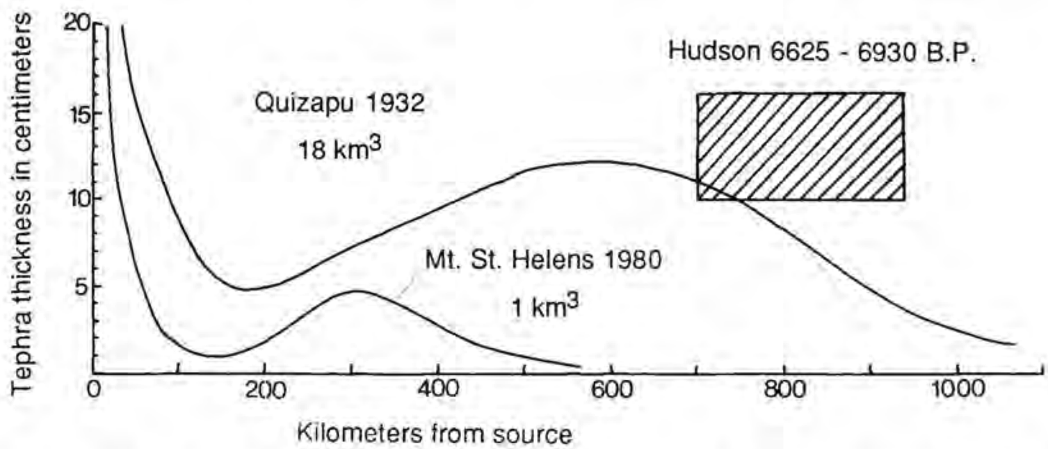

FIG. 7. Diagram illustrating the relation between thickness of uncompacted tephra deposits, in centimeters, relative to distance from the source volcano, in kilometers, of two recent eruptions of different volumes of magma: Quizapu, 1932, which erupted 18 km^3 of material (Hildreth and Drake, 1988) and Mount St. Helens, 1980, which erupted 1 km^3 of material (Sarne-Wojcicki *et al.*, 1981). The 10-15 cm thick layers of green-brown tephra on Tierra del Fuego, derived from the Hudson volcano located 700-950 km to the north, may have been thickened by redepositional processes on the ground, but also may have been thinned by compaction. Simple comparison with uncompacted tephra suggests an eruption of significant magnitude; probably larger than the Quizapu eruption of 1932.

chronological data (Table 2) that not all these ashes are derived from the same eruption that formed the green-brown tephra of Tierra del Fuego. Although two layers of Hudson-derived ash in the Cueva Las Guanacas, Aisén, are older than 5,340 years B.P. (RI-16II and RI-16III, Table 2), only one could have formed from the same eruption that generated the Tierra del Fuego ash. Also, a more recent, by approximately 2,000 years, eruption of the Hudson volcano must have occurred to form the ash layers just younger than 5,340 to 4,830 years B.P. found in this site (RI-16I) as well as both RI-22 (4A(N)/8, Table 2) and Cueva 3 de los Toldos (Table 2). This indicates that the characteristically green-brown mid-Holocene tephra that Auer (1974) termed Tephra II and identified over all of southern Patagonia, may in fact, represent at least two different eruptions of the Hudson volcano; one >6,625 years B.P. and one <4,830 years B.P. It is not possible, on the basis of the trace-element and isotopic data listed in Table 2, and even less so on simple characteristics such as color, to distinguish the ashes produced by these two different eruptions.

The youngest samples in site RI-22 (11C/1 and 11D(N)/2), shown to be different lenses of a single ash layer (F. Mena, personal commun., 1991), may or may not have formed in the eruption of the Hudson volcano which occurred in 1971 (Fuenzalida, 1976). In either case, the Hudson volcano clearly has a long history of explosive Holocene activity prior to its most recent eruption in August, 1991.

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