Tephrochronology of the upper Río Cisnes valley (44°S), southern Chile

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ABSTRACT. Based on their petrography and chemistry, 18 tephra analyzed from two lake and bog cores and one outcrop in the upper Río Cisnes valley are believed to have been derived from nine different eruptions of the Mentolat volcano, four of the Melimoyu volcano, and one from the Hudson volcano. Some of these tephra correlate chronologically and petrochemically with previously documented large eruptions of these volcanoes, including the Late-Glacial Ho eruption of Hudson (17,340 cal yrs BP), the mid-Holocene MEN1 eruption of Mentolat (7,710 cal yrs BP), and the Late-Holocene MEL2 eruption of Melimoyu (1,680 cal yrs BP). A Melimoyu-derived tephra from the outcrop occurs in glacial-lacustrine sediments and is considered to pre-date the Last Glacial Maximum (>19,670 cal yrs BP). The data suggest that none of the tephra were produced by explosive eruptions of the Maca, Cay and Yanteles volcanoes.

Keywords: Tephra, Tephrochronology, Tephrostratigraphy, Volcanism, Andes, Chile.

RESUMEN. Tefrocronología en curso superior del valle del río Cisne (44°S), Chile Austral. Dieciocho tefras provenientes de testigos de un lago y un mallín, junto a un perfil expuesto en el alto valle del río Cisnes fueron caracterizadas sobre la base de su petrografía y química y correspondían a nueve diferentes erupciones del volcán Mentolat, cuatro del volcán Melimoyu y una del volcán Hudson. Algunas de estas tefras se correlacionan cronológicamente y petroquimicamente con grandes erupciones de estos volcanes previamente documentadas, incluyendo la erupción Ho del volcán Hudson (Tardiglacial, 17,340 años cal. AP), la erupción MEN1 del volcán Mentolat (Holoceno medio, 7,710 años cal. AP) y la erupción MEL2 del volcán Melimoyu (Holoceno tardío, 1,680 años cal. AP). Una tefra perteneciente a la erupción del volcán Melimoyu, hallada en un perfil expuesto en un contexto de depósitos glaciolacustres, tiene una edad (>19,670 años cal. AP) que precede al término del Último Máximo Glacial en Patagonia Central. Los datos sugieren que ninguna de las tefras fueron producidas por erupciones explosivas de los volcanes Maca, Cay y Yanteles.

Palabras clave: Tefra, Tefrocronología, Tefrostratigrafía, Volcanismo, Andes, Chile.
1. Introduction

Tephra layers in sediment cores from lakes and bogs provide information on the history of explosive volcanic eruptions from nearby volcanoes, and thus a basis for evaluating the possibilities for and potential effects of future eruptions. The identification, petrochemical description and correlation of synchronous volcanic tephra layers over large geographic areas and in different environmental settings also provides a stratigraphic correlation tool for a broad range of disciplines (Lowe, 2011; Fontijn et al., 2014), including archaeology (Prieto et al., 2013), palaeoclimatology and palaeogeomorphology (García et al., 2015, this volume).

Here we characterize both petrochemically and chronologically multiple Late-Glacial and Holocene tephra layers in two sediment cores from the area of the upper Río Cisnes valley (Figs. 1 and 2); one core from Lago Shaman (Fig. 3; de Porras et al., 2012), and one core from Mallín El Embudo (Fig. 4; de Porras et al., 2014). With this information we attempt to correlate tephra layers between the cores and to other previously described tephra in the region, and identify for each layer their possible source volcano, which potentially include the Yanteles, Melimoyu, Mentolat, Maca, Cay and Hudson stratovolcanoes, as well as numerous small monogenetic cones located between Puyuhuapi and Palena (Fig. 1). We also describe one sample of tephra that outcrops in glacial-lacustrine sediments, and pre-dates the Last Glacial Maximum.

2. Background

Bedrock geology in the upper Río Cisnes valley consists of plutons of the Patagonia batholith and Lower...
Cretaceous sediments overlain by Quaternary deposits, which include the materials examined in this study. de Porras et al. (2012, 2014) describe in some detail the environmental setting of the two cores. Lago Shaman is located in the semi-arid forest-steppe ecotone just west of the Chile-Argentina border, which at this latitude corresponds to a moraine complex formed during the last Late-Glacial Maximum (LGM; Fig. 2). This area became ice free at or soon after 19,000 BP, and the deepest organic layer dated, from 599 cm depth in the 613 cm long Lago Shaman core (LS0604A; Fig. 3), yields an age of 18,950 cal yrs BP (Table 1). In contrast, the Mallín El Embudo core is located in a wetter forested area ~35 km to the southwest of Lago Shaman (Fig. 2), west of a small frontal moraine interpreted to have formed by a Late-Glacial glacial advance before approximately 13,000 BP (de Porras et al., 2014). The oldest age obtained, from 809 cm deep in this 844 cm long composite core (EE0110A and B; Fig 4) was 12,997 cal yrs BP.

These two cores were collected with the purpose of providing a pollen record and its implications for the changing climate in this region since the end of the last glaciation (de Porras et al., 2012, 2014), as well as a charcoal record and its implication for the history of fires caused possibly by climate change, volcanic activity and/or the human occupation of the valley, which dates back to 11,500 BP (Méndez and Reyes, 2008; Méndez et al., 2009; Reyes et al., 2009). Both cores contain clastic layers which are in most cases tephra (Figs. 3 and 4). The Lago Shaman core contains more numerous tephra, which may possibly reflect the fact that Lago Shaman occurs in an open arid area with no vegetation to interfere with tephra fall and wind redistribution of tephra, while Mallín El Embudo occurs in a wetter environment with forest cover. One other tephra sample (Cisnes 263A; Fig. 5) was also collected from an outcrop of glacial-lacustrine sediment at Las Barrancas (Fig. 2). It occurs ~3 meters below the contact, dated as
19,670 cal yrs BP, between these and overlying fluvial sediments (Fig. 5).

Previous tephrochronologic studies in this area of the southern Southern Volcanic Zone (SSVZ) of the Andes include those of Naranjo and Stern (1998, 2004), Mella et al. (2012) and Weller et al. (2014). These studies indicate that all the potential source volcanoes for the tephra in the upper Rio Cisnes valley (Yanteles, Melimoyu, Maca, Cay and Husdon) have had Holocene explosive eruptions producing locally or regionally distributed tephra falls (Naranjo and Stern, 1998, 2004; Mella et al., 2012; Weller et al., 2014).

FIG. 3. X-ray image of Lago Shaman core (de Porras et al., 2012). Bright white layers are either sand or tephra and darker areas are organic rich sediments.
2014). Melimoyu, Mentolat and Hudson have summit
-craters/calderas possibly formed in association with
these events. Melimoyu and Hudson are two of the
largest volcanic edifices in the SSVZ (Völker et al.,
2012). Also the many small monogenetic cones in
the region have produced basaltic scoria deposits
as well as lava flows (López-Escobar et al., 1995a;
Gutiérrez et al., 2005; Watt et al., 2013; Vargas et al.,
2013), but the potential regional extent of distribution
of tephra from these generally small volume mafic
eruptions is uncertain.

The previously published interpretations of the
source volcanoes of tephra in the SSVZ were made in
part on the basis of tephra major element chemistry
compared with published whole rock chemistry of
samples of lavas from the volcanoes of the SSVZ
(Naranjo and Stern, 2004; Weller et al., 2014). In
a similar fashion, the possible sources of seven of
the tephra in the Lago Shaman core were made on
the basis of bulk tephra trace-element chemistry
compared to published whole-rock trace-element
analysis of lava samples from the SSVZ volcanoes
to the west of the core site (de Porras et al., 2012).
These trace-element data suggest Melimoyu, Mentolat
and Hudson volcanoes as the sources for these seven
tephra (de Porras et al., 2012; Weller et al., 2014).

Since spatial coverage is still too restricted to
allow for the construction of tephra isopach maps,
which is the most conclusive way to identify source
volcanoes for tephra, this paper also employs the
geochemical approach of comparing tephra chemistry
with the published data concerning the volcanic
rocks associated with the different SSVZ centers
(Fig. 6) to identify possible tephra source volcanoes
of the tephra. Information concerning the chemistry
of the magmas erupted from the volcanic centers in
the SSVZ has been published by Stern et al. (1976),
Futa and Stern (1988), López-Escobar et al. (1993,
1995a), D’Orazio et al. (2003), Gutiérrez et al. (2005),
Kratzmann et al. (2009, 2010), Watt et al. (2013) and
Weller et al. (2014). Samples from SVZ volcanoes
in south-central Chile, and specifically the SSVZ

FIG. 4. X-ray image of Mallín El Embudo core (de Porras et al., 2014). Bright white layers are either sand or tephra and darker areas
are organic rich sediments.
TABLE 1. DEPTH IN CM OF TEPHRA AND $^{14}$C AGE DATES IN CAL YRS BP FROM THE LAGO SHAMAN (DE PORRAS ET AL., 2012) AND MALLÍN EL EMBUDO (DE PORRAS ET AL., 2014) CORES.

| Lago Shaman       | tephra | depth cm | ~age* | Source* | eruption* | age*     |
|-------------------|--------|----------|-------|---------|-----------|----------|
|                   | a      | 64-70    | 1,440 | Melimoyu| MEL2      | 1,680    |
|                   |        | 85       | 1,827±40 | -      | -         | -        |
|                   | b      | 94       | 2,140 | Mentolat| -         | -        |
|                   | c      | 104      | 2,490 | Mentolat| -         | -        |
|                   |        | 122      | 3,111±40 | -      | -         | -        |
|                   | d      | 160      | 3,720 | Mentolat| -         | -        |
|                   | e      | 170      | 3,880 | Mentolat| -         | -        |
|                   |        | 195      | 4,275±50 | -      | -         | -        |
|                   | f      | 207      | 4,610 | Melimoyu| -         | -        |
|                   | g      | 255      | 8,280 | Melimoyu| -         | -        |
|                   |        | 260      | 8,357±40 | -      | -         | -        |
|                   | h      | 261      | 8,400 | Mentolat| -         | -        |
|                   | i      | 270      | 8,800 | Mentolat| MEN1      | 7,710    |
|                   |        | 316      | 10,824±70 | -      | -         | -        |
|                   | m      | 326      | 11,140| Mentolat| -         | -        |
|                   |        | 392      | 13,241±40 | -      | -         | -        |
|                   | q      | 489      | 18,474±100 | -     | -         | -        |
|                   | v      | 533      | 18,665| Mentolat| -         | -        |
|                   | y      | 570      | 18,820| Hudson Ho| 17,340   |          |
|                   |        | 598      | 18,940| Mentolat| MENo      | >17,340  |
|                   |        | 599      | 18,951±50 | -      | -         | -        |

| Mallín El Embudo | tephra | depth cm | ~age* | source | eruption* | age*     |
|------------------|--------|----------|-------|--------|-----------|----------|
|                   | a      | 173-179  | 2,090 | Melimoyu| MEL2      | 1,680    |
|                   |        | 266      | 4,492±40 | -      | -         | -        |
|                   | b      | 255-278  | 4,810 | Melimoyu| -         | -        |
|                   | h      | 549      | 9,010 | Mentolat| MEN1      | 7,710    |
|                   |        | 585      | 9,567±30 | -      | -         | -        |
|                   |        | 699      | 11,179±30 | -     | -         | -        |
|                   |        | 740      | 11,302±69 | -     | -         | -        |
|                   | j      | 746      | 11,450| Mentolat| -         | -        |
|                   |        | 809      | 12,997±35 | -     | -         | -        |
|                   | CIS 263-A | -   | >19,670| Melimoyu| -         | -        |

*Measured $^{14}$C age dates in cal yrs BP; ~ages for tephra interpolated from measured ages; possible sources based on tephra chemistry (Table 3); ages of previously documented eruptions from Naranjo and Stern (2004) and Weller et al. (2014).
volcanoes, fall into different and distinguishable chemical groups (Fig. 6). Two of these groups have previously been termed Type-1, or Low Abundance, and Type-2, or High Abundance magmas (Hickey et al., 1986, 1989, 2003; López-Escobar et al., 1993, 1995a, 1995b). These two different magma types are distinguished by their different concentrations of the incompatible elements K2O (Fig. 6a), Rb, Ti, Ba, Zr, Sr, Y, Nb and La, as well as La/Yb and Ba/La ratios, over a large range of SiO2 contents from basalts to dacites. In the SSVZ, Maca, Cay and Yanteles stratovolcanoes (Fig. 6), and the Palena group of monogenetic cones are Type-1 or Low Abundance volcanoes (López-Escobar et al., 1993, 1995a; D’Orazio et al., 2003; Gutiérrez et al., 2005; Carel et al., 2011; Watt et al., 2013), while Hudson and Melimoyu volcanoes (Fig. 6) and the Puyuhuapi group of monogenetic cones are Type-2 or High

FIG. 5. A. Photo of the ~6 cm thick Cisnes 263A tephra in glacial-lacustrine sediment formed during the last glaciation; B. This tephra occurs ~3 meters below the contact, dated as 19,670 cal yrs BP, between the glacial-lacustrine clay and overlying fluvial sediments.
FIG. 6. A. SiO$_2$ versus K$_2$O for samples of both lavas and tephra from Yanteles, Melimoyu, Maca, Cay and Hudson volcanoes (Futa and Stern, 1988; López-Escobar et al., 1993; Naranjo and Stern, 1998, 2004; D’Orazio et al., 2003; Gutiérrez et al., 2005; Kratzmann et al., 2009, 2010), illustrating the separation of these samples into what have previously been termed High, Low and Very Low Abundance magma types (Hickey et al., 1986, 1989, 2003; López-Escobar et al., 1993, 1995a, 1995b; Sellés et al., 2004; Watt et al., 2011). Line separating the fields of High-, Medium-, and Low-K convergent plate boundary magmas are from Peccerillo and Taylor (1976); B. Ti versus Rb for the SSVZ volcanoes and each individual tephra from the upper Río Cisnes valley (Table 3); C. Sr versus Ba for the SSVZ volcanoes and tephra from the upper Río Cisnes valley (Table 3).
Abundance centers (López-Escobar et al., 1993, 1995a; Naranjo and Stern, 1998, 2004; Kratzmann et al., 2009, 2010; Carel et al., 2011). The Palena and Puyuhuapi group basalts are not plotted in figure 6 because they both contain abundant olivine and lack orthopyroxene and amphibole, and are therefore petrologically distinct from the tephra in the upper Río Cisnes valley described below (Table 2).

Although samples from different Type-1 Low Abundance volcanoes are generally similar to each other, a specific exception in this southern part of the SSVZ is the Mentolat volcano, which at any given SiO₂ content has lower K₂O (Fig. 6a; López-Escobar et al., 1993; Naranjo and Stern, 2004; Watt et al., 2011), Rb, Ti (Fig. 6b), Sr, Ba (Fig. 6c) and La/Yb (Watt et al., 2011), similar to other unusually or Very Low Abundance samples from Nevado de Longaví (Sellés et al., 2004), Calbuco (López-Escobar et al., 1995b) and Huequi (Watt et al., 2011) volcanoes further to the north. Like Mentolat, all these other Very Low Abundance centers are characterized by the presence of amphibole in their eruptive products (López-Escobar et al., 1993, 1995b; Sellés et al., 2004; Watt et al., 2011).

### 3. Methods

X-ray images of the cores (Figs. 3 and 4) were taken to allow for better visual identification of the tephra deposits and to provide a means of stratigraphic correlation of the tephra layers between the cores. The white layers in these images, arbitrarily termed a though z in the Lago Shaman core (Fig. 3) and a, b, g, h and j in the Mallín El Embudo core (Fig. 4), are the denser lithologies, often tephra deposits, but in some cases sand, and the darker layers are less dense organic-rich lacustrine sediments. The chronology of the tephra in the trenches and cores is constrained by AMS radiocarbon dates of organic material in the overlying and underlying sediments.
4. Results

A summary of some of the most obvious petrographic features of each of 13 tephra samples from the Lago Shaman core, four from the Mallín El Embudo core, and one other outcrop sample (Cisnes 263A), are presented in Table 2 and tephra trace-element chemistry are presented in Table 3. The chemical and petrologic characteristics of each tephra, and the reasons for suggesting a possible source volcano, are discussed below in chronological order from the youngest to the oldest.

4.1. Tephra ‘a’ from both cores

The youngest tephra in both cores, tephra ‘a’ (Figs. 3 and 4; Tables 1-3), is approximately 6 cm thick in each core and in both consists dominantly of identical appearing brown glass with a few round and only rarely stretched vesicles and containing
occasional plagioclase microlites (Fig. 8A). Phenocrysts of plagioclase, which are the most abundant along with both clinopyroxene and orthopyroxene, are similar in size to the glass shards. The samples from both cores have nearly identical chemistry, which is similar to the High Abundance types of rocks erupted in the southern SVZ by the Hudson and Melimoyu volcanoes (Fig. 6) and Puyuhuapi cones (López-Escobar et al., 1993, 1995a). However, olivine is abundant in and orthopyroxene has not been reported from the Puyuhuapi group basalt samples (López-Escobar et al., 1995a), and Hudson tephra glasses are typically stretched-vesicle-rich and microlite-poor (Fig. 8C). Also Hudson, located over 200 km to the southwest of Lago Shaman (Fig. 1), had no known large eruption in the time period 1,440 to 2,090 BP when the tephras ‘a’ were deposited (Table 1). The proximity of the core to the Melimoyu volcano suggests that this is the most likely source for these two chemically High Abundance type tephra ‘a’ samples. Their ages have been estimated as ~1,440 BP (<1,827±40 cal yrs BP) in the Lago Shaman core and ~2,090 BP (>1,743±40 cal yrs BP) in the Mallín El Embudo core (Table 1), and they may possibly represent two separate events, but their near identical appearance, thickness and chemistry suggest they formed from the same eruption, despite the difference in their estimated ages. Naranjo and Stern (2004) documented a relatively large explosive eruption of the Melimoyu volcano (MEL2) at 1,680±100 cal yrs BP (Table 1; Fig. 7), essentially splitting the difference between the interpolated age
TABLE 3. TRACE-ELEMENT CONTENTS IN PARTS-PER-MILLION (PPM) OF BULK TEPHRA SAMPLES FROM THE LAGO SHAMAN AND MALLIN EL EMBUDO CORES AND AN OUTCROP OF GLACIAL-LACUSTRINE SEDIMENT.

| Core    | Shaman | Embudo | Cis-263A |
|---------|--------|--------|----------|
| Lab #   | CS5054 | CS5055 | CS5056   |
| tephra  | CS5058 | CS5059 | CS5060   |
| ~age    | 1,440  | 2,140  | 2,490    |
| source  | Mel    | Men    | Men      |
| Ti      | 8,813  | 5,632  | 5,281    |
| Mn      | 1,036  | 569    | 1,425    |
| Rb      | 34     | 16     | 12       |
| Sr      | 508    | 431    | 457      |
| Zr      | 224    | 98     | 51       |
| Nb      | 16     | 6      | 4        |
| Cs      | 1.6    | 0.5    | 0.5      |
| Ba      | 486    | 199    | 134      |
| Hf      | 6.6    | 2.3    | 1.7      |
| Pb      | 8.4    | 3.4    | 3.0      |
| Th      | 6.8    | 2.6    | 1.2      |
| U       | 1.0    | 0.4    | 0.3      |
| La      | 28.4   | 9.76   | 6.16     |
| Ce      | 64.7   | 21.3   | 15.5     |
| Pr      | 7.99   | 2.62   | 2.18     |
| Nd      | 31.9   | 11.7   | 10.4     |
| Sm      | 7.11   | 2.65   | 2.82     |
| Eu      | 2.02   | 0.93   | 1.19     |
| Gd      | 8.07   | 3.20   | 3.21     |
| Tb      | 0.97   | 0.43   | 0.48     |
| Dy      | 5.84   | 2.55   | 2.98     |
| Ho      | 1.09   | 0.45   | 0.58     |
| Er      | 3.52   | 1.54   | 1.82     |
| Tm      | 0.42   | 0.18   | 0.23     |
| Yb      | 3.03   | 1.24   | 1.72     |
| Lu      | 0.41   | 0.17   | 0.23     |
estimations for tephra ‘a’ in these two cores, and we tentatively attribute both these tephra layers to this same MEL2 eruption (de Porras et al., 2012). We suggest that the different ages are due either to near surface contamination of the samples dated or uncertainties in the interpolated estimates.

4.2. Tephras ‘b, c, d and e’ from Lago Shaman

These tephras are all only 1 cm thick or less. They all have chemistry similar to Very Low Abundance types of rocks erupted in the southern SVZ from the Mentolat volcano, and they all have very similar petrographic appearance, with clear glass shards containing rounded but not stretched vesicles (Fig. 8B), and a large proportion of phenocryst phases including plagioclase, two pyroxenes, brown amphiboles and minor olivine. Both their chemistry and petrography, which are essentially identical to Mentolat derived tephra MEN1 (Naranjo and Stern, 2004), which has also been observed in cores from near Coyhaique (Weller et al., 2014) and Cochrane (Stern et al., 2013), are consistent with their being derived from the Mentolat volcano. Mella et al. (2012) dated tephra related to an explosive eruption of Mentolat volcano between 2,615±90 and 4,340±60 cal yrs BP, and either tephra ‘d’ or ‘e’ in the Lago Shaman core could have been produced by this same eruption. These tephra do not appear in the Mallín El Embudo core.

4.3. Tephra ‘b’ in Mallín El Embudo and ‘f’ in Lago Shaman

Tephra ‘b’ in Mallín El Embudo and ‘f’ in Lago Shaman both occur as diffuse layers mixed with organic sediment over a zone of between 10-20 cm thickness (Figs. 3 and 4). Both have nearly identical chemistry similar to High Abundance type rocks erupted from Melimoyu and Hudson volcanoes (Fig. 6), and both consist of dark brown glass with only a few generally round vesicles and occasional plagioclase microlites similar to the two samples of tephra ‘a’. Plagioclase phenocrysts are abundant and both orthopyroxene and clinopyroxene crystals also occur, along with minor olivine. The presence of orthopyroxene and their high Rb, Ba, and La contents and relatively low Sr and Ti contents (Fig. 6) distinguishes them from Puyuhaupi basalts (López-Escobar et al., 1995a). Although they were previously attributed to the H2 eruption of the Hudson volcano based on their chemistry (de Porras et al., 2012, 2014), the lack of vesicles and the plagioclase microlites in the glass distinguishes them from typical Hudson H2 samples, and the constraints on their age (4,600 to 4,800 cal yrs BP) suggest they are older than the ~3,900 cal yrs BP age of the H2 eruption (Naranjo and Stern, 1998). Therefore we now attribute these tephra to a mid-Holocene eruption of the Melimoyu volcano not previously recognized in outcrop in this region.

4.4. Tephra ‘g’ from Lago Shaman

Tephra ‘g’ from Lago Shaman has petrography (brown glass; Table 2) and High Abundance chemistry (Fig. 6; Table 2) similar to tephra ‘a’ and ‘f’ from this core, and we suggest the Melimoyu volcano as its source.

4.5. Tephras ‘h’ from both cores and ‘i’ from Lago Shaman

These tephra have Very Low Abundances chemistry (Fig. 6) and petrography (clear glass, abundant phenocrysts including amphibole; Table 2) similar tephra ‘b, c, d and e’ from Lago Shaman, and MEN1 from cores near Coyhaique and Cochrane (Stern et al., 2013). They are attributed to explosive eruptions of the Mentolat volcano. Tephra ‘i’ from Lago Shaman and ‘h’ from Mallín El Embudo are both similar in age and coarser grained than tephra ‘h’ from Lago Shaman, and we consider them to be deposited from the same eruption. This eruption may correspond to the MEN1 eruption, although the ~7,710±120 cal yrs BP age of the MEN1 eruption (Naranjo and Stern, 2004; Stern et al., 2013) is somewhat younger than the approximate ages (8,800 and 9,010 cal yrs BP, respectively; Table 1) of these two tephra (Fig. 7).

4.6. Tephras ‘m’ from Shaman and ‘j’ from Mallín El Embudo

These two tephra have similar age and Very Low Abundance type chemistry to each other, and are also similar petrologically (clear glass, phenocryst-rich with amphiboles; Table 2) to other tephra in these cores and elsewhere derived from the Mentolat volcano.
4.7. Tephra ‘q’ from Lago Shaman

This Late-Glacial age tephra has similar Very Low Abundance chemistry (Fig. 6) and petrography (clear glass, abundant phenocrysts with amphibole; Table 2) to other tephra in these cores and elsewhere derived from the Mentolat volcano.

4.8. Tephra ‘v’ from Lago Shaman

Tephra ‘v’ from Lago Shaman occurs as a 2 cm thick layer of brown to tan glass with abundant stretched vesicle (Fig. 8C). The glass lacks micro-lites and the tephra contains only rare phenocrysts of plagioclase and orthopyroxene. The chemistry of this tephra layer is characteristic of a High Abundance type samples and identical to that of Hudson Ho tephra (Weller et al., 2014). The age determined in the Lago Shaman core is ~18,820 BP, while that determined for Ho in multiple cores from near Coyhaique is 17,340 ±90 cal yrs BP (Table 1; Weller et al., 2014). Tephra from the Ho eruption was distributed to the northwest of the volcano, and the 2 cm thickness of tephra ‘v’ in the Lago Shaman core is consistent with the isopachs of Ho tephra estimated by Weller et al. (2014).

4.9. Tephra ‘y’ from Lago Shaman

This Late-Glacial age tephra has similar petrography (clear glass, abundant phenocrysts with amphiboles; Table 2) and Very Low Abundance chemistry to other tephra in these cores and elsewhere derived from the Mentolat volcano. A Late-Glacial tephra MENo derived from Mentolat volcano has also been described from sediment cores taken from lakes near Coyhaique (Weller et al., 2014).

4.10. Cisnes 263A

This 6 cm thick dark colored tephra contains brown glass with a small amount of rounded vesicle (Fig. 8D) and phenocrysts of plagioclase and two pyroxenes. Its High Abundance type chemistry is identical to that of tephra ‘a’ from the two cores and its source volcano in likely to have been the Melimoyu volcano. It is the first pre-Late-Glacial Maximum age tephra reported in this region of the southern Andes.

5. Discussion and Conclusions

In general, the 17 tephra from the Lago Shaman and Mallín El Embudo cores fall into two easily distinguishable groups; one with abundant brown glass with a few rounded vesicles (Fig. 8A), a smaller proportion of plagioclase and pyroxene phenocrysts, and High Abundance type chemistry (Fig. 6; Table 3), and another group with clear glass with rounded vesicles (Fig. 8B), abundant phenocrysts of plagioclase, pyroxenes, brown amphibole and minor olivine, and Very Low Abundance type chemistry (Fig. 6; Table 3). We attribute the first group to eruptions of the Melimoyu volcano and the second to eruptions of the Mentolat volcano. One tephra (v) from Lago Shaman has tan to brown glass with abundant stretched vesicles (Fig. 8C), few phenocrysts and High Abundance chemistry (Fig. 6), and this tephra is attributed to the large Late-Glacial age Ho eruption of the Hudson volcano (Weller et al., 2014). The glacial age tephra from the outcrop (CIS-263A) is similar to those with brown glass (Fig. 8D) and High Abundance chemistry (Fig. 6) and is attributed to an eruption of the Melimoyu volcano.

Based on their petrography, chemistry and age, we conclude that the 17 tephra analyzed from the Lago Shaman and Mallín El Embudo cores have been derived from nine different eruptions of the Mentolat volcano, three of the Melimoyu volcano, and one from the Hudson volcano. Although, there is still not enough spatial coverage to constrain isopach maps for the eruptions that produced all the tephra, some of these tephra do appear to correspond chronologically and petrochemically to some of the larger eruptions identified previously by Naranjo and Stern (1998, 2004), Mella et al. (2012), Stern et al. (2013) and Weller et al. (2014), while others occurred at times when no such large eruption has been previously identified. Tephras ‘a’ in the two cores may correspond to Late-Holocene eruption MEL2 of Melimoyu (Table 1) previously documented by Naranjo and Stern (2004). Either tephra ‘d’ or ‘e’ in the Lago Shaman core may have formed from a Late-Holocene explosive eruption of Mentolat documented by Mella et al. (2012). Tephra ‘b’ from Mallín El Embudo and ‘f’ in Lago Shaman do not result from the H2 eruption of Hudson as previously suggested (de Porras et al., 2012, 2014), but rather from a mid-Holocene eruption of the Melimoyu...
volcano not previously described. Tephra ‘i’ from the Lago Shaman core and ‘h’ from the Mallín El Embudo core may have been deposited during the mid-Holocene MEN1 eruption of Mentolat (Table 1; Naranjo and Stern, 2004; Stern et al., 2013). Tephra ‘v’ in Lago Shaman was produced by the Late-Glacial Ho eruption of Hudson (Table 1; Weller et al., 2014). Tephra ‘y’ in the Lago Shaman core may correspond to the Late-Glacial MENo eruption of Mentolat documented in cores from lakes near Coyhaique (Weller et al., 2014). The one pre-Late-Glacial Maximum tephra Cisnes 263A also formed from an eruption of Melimoyu volcano.

This information confirms the repeated episodic explosive eruption of the Mentolat and Melimoyu volcanoes beginning from, in the case of Mentolat the earliest Late-Glacial period at approximately >17340 cal yrs BP, and in the case of Melimoyu before the Last Glacial Maximum at >19,670 BP. The petrochemical data suggest that the eruptive products of each of these two volcanic provinces has been relatively constant in character over this time period, although they differ significantly from each other despite being located within only 70 km of each other along strike on the volcanic front of the SSVZ arc.

The data also suggest that none of the tephra in these cores were the products of the eruption of the small monogenetic basaltic cones near Puyuhuapi and Palena (Fig. 1), as these basalts have abundant olivine and lack orthopyroxene and amphibole. The eruption of the small monogenetic basalt cones in the Palena and Puyuhuapi group may have been too small to generate regional tephra falls. Nor is there any unambiguous indication of tephra in the upper Río Cisne valley being derived from the Maca, Cay and/or Yanteles volcanoes, which are Low Abundance type centers (Fig. 6). One tephra (MAC1) observed close to Puerto Aisén has been attributed to an explosive eruption of Maca (Naranjo and Stern, 2004), and Mella et al. (2012) attribute another tephra observed in this area to Cay volcano, but neither of these volcanoes have summit craters/calderas as do Hudson, Mentolat and Melimoyu, and they have may had more effusive and less explosive eruptive histories.

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References

Carel, M.; Siani, G.; Delpech, G. 2011. Tephrostratigraphy of a deep-sea sediment sequence off the south Chilean margin: New insight into the Hudson volcanic activity since the last glacial period. Journal of Volcanology and Geothermal Research 208: 99-111.

de Porras, M.E.; Maldonado, A.; Abarzúa, A.M.; Cárdenas, M.L.; Francois, J.P.; Martel-Cea, A.; Stern, C.R.; Méndez, C.; Reyes, O. 2012. Postglacial vegetation, fire and climate dynamics at Central Chilean Patagonia (Lake Shaman, 44°S). Quaternary Science Reviews 50: 71-85.

de Porras, M.E.; Maldonado, A.; Quintana, F.A.; Martel-Cea, A.J.; Reyes, O.; Méndez, C. 2014. Environmental and climatic changes in Central Chilean Patagonia since the Late Glacial (Mallín El Embudo, 44°S). Climate of the Past 10: 1063-1078.

D’Orazio, M.; Innocenti, F.; Manetti, P.; Tamponi, M.; Tonarini, S.; González-Ferrán, O.; Lahren, A.; Omarini, R. 2003. The Quaternary calc-alkaline volcanism of the Patagonian Andes close to the Chile triple junction: geochemistry and petrogenesis of volcanic rocks from the Cay and Maca volcanoes (~45°S, Chile). Journal of South American Earth Sciences 16: 219-242.

Fontijn, K.; Lachowycz, S.M.; Rawson, H.; Pyle, D.M.; Mather, T.A.; Naranjo, J.A.; Moreno-Roa, H. 2014. Late Quaternary tephrostratigraphy of southern Chile and Argentina. Quaternary Science Reviews 89: 70-84.

Futa, K.; Stern, C.R. 1988. Sr and Nd isotopic and trace element compositions of orogenic Quaternary volcanic centers of the southern Andes. Earth and Planetary Science Letters 88: 253-262.

García, J.L.; Strelin, J.A.; Vega, R.M.; Hall, B.L.; Stern, C.R. 2015. Deglacial Ice-marginal glaciolacustrine environments and structural moraine building in Torres del Paine, south Patagonia. Andean Geology 42 (2): 190-212. doi: 10.5027/andgeoV42n2-a03.

Gutiérrez, F.; Gioncada, A.; González-Ferrán, O.; Lahsen, A.; Mazzuoli, R. 2005. The Hudson volcano and surrounding monogenetic centres (Chilean Patagonia): an example of volcanism associated with ridge-trench collision environment. Journal of Volcanology and Geothermal Research 145: 207-233.

Hickey, R.L.; Frey, F.A.; Gerlach, D.C. 1986. Multiple sources for basaltic arc rocks from the Southern Volcanic Zone of the Andes (34-41°S): Trace element and isotopic evidence for contributions from subducted
oceanic crust, mantle, and continental crust. Journal of Geophysical Research 91: 5963-5983.

Hickey-Vargas, R.L.; Moreno-Roa, H.; López-Escobar, L.; Frey, F.A. 1989. Geochemical variations in Andean basaltic and silicic lavas from the Villarrica-Lañín volcanic chain (39.5°S): an evaluation of source heterogeneity, fractional crystallization and crustal assimilation. Contributions to Mineralogy and Petrology 103: 361-386.

Hickey-Vargas, R.L.; Sun, M.; López-Escobar, L.; Moreno-Roa, H.; Reagan, M.K.; Morris, J.D.; Ryan J.G. 2003. Multiple subduction components in the mantle wedge: evidence from eruptive centers in the Central Southern volcanic zone, Chile. Geology 30 (3): 199-202.

Kratzmann, D.J.; Carey, S.; Scasso, R.A.; Naranjo, J.A. 2009. Compositional variations and magma mixing in the 1991 eruptions of Hudson volcano, Chile. Bulletin of Volcanology 71 (4): 419-439.

Kratzmann, D.J.; Carey, S.; Scasso, R.A.; Naranjo, J.A. 2010. Role of cryptic amphibole crystallization in magma differentiation at Hudson volcano, Southern Volcanic Zone, Chile. Contributions to Mineralogy and Petrology 159: 237-264.

López-Escobar, L.; Kilian, R.; Kempton, P.; Tagiri, M. 1993. Petrology and geochemistry of Quaternary rocks from the southern volcanic zone of the Andes between 41°30’ and 46°00’S, Chile. Revista Geológica de Chile 20 (1): 33-55. doi: 10.5027/andgeoV20n1-a04.

López-Escobar, L.; Cembrano, J.; Moreno, H. 1995a. Geochemistry and tectonics of the chilean Southern Andes basaltic Quaternary volcanism (37°-46°S). Revista Geológica de Chile 22 (2): 219-234. doi: 10.5027/andgeoV22n2-a06.

López-Escobar, L.; Parada, M.A.; Hickey-Vargas, R.; Frey, F.A.; Kempton, P.D.; Moreno, H. 1995b. Calbuco Volcano and minor eruptive centres distributed along the Liquiñe-Ofqui Fault Zone, Chile (41°-42°S): contrasting origin of andesitic and basaltic magma in the Southern Volcanic Zone of the Andes. Contributions to Mineralogy and Petrology 119: 345-361.

Lowe, D.J. 2011. Tephrochronology and its application: a review. Quaternary Geochronology 6: 107-153.

Mella, M.; Ramos, A.; Kraus, S.; Duhart, P. 2012. Datos tefroestratigráficos de erupciones Holocenas del Volcán Mentolat, Andes del Sur (44°40’S), Chile. In Congreso Geológico Chileno, No. 13, Actas, Antofagasta.

Méndez, C.; Reyes, O. 2008. Late Holocene human occupation of Patagonian forests: a case of study at Cisnes River basin (44°S, Chile). Antiquity 317: 560-570.

Méndez, C.; Reyes, O.; Maldonado, A.; Francois, J.P. 2009. Ser humano y medio ambiente durante la transición Pleistoceno Holoceno en las cabeceras del río Cisnes (44°S, Aisén Norte). In Arqueología de Patagonia: una mirada desde el último confín (Salemme, M.; Santiago, F.; Álvarez, M.; Piana, E.; Vázquez, M.; Mansur, E., editors). Editorial Utopíasis: 75-83. Ushuaia.

Naranjo, J.A.; Stern, C.R. 1998. Holocene explosive activity of Hudson Volcano, southern Andes. Bulletin of Volcanology 59: 291-306.

Naranjo, J.A.; Stern, C.R. 2004. Holocene tephrochronology of the southernmost part (42-45°S) of the Andean Southern Volcanic Zone. Revista Geológica de Chile 31 (2): 225-240. doi: 10.5027/andgeoV31n2-a03.

Peccerillo, A.; Taylor, S.R. 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from Kastamonu area, Northern Turkey. Contributions to Mineralogy and Petrology 58: 39-63.

Prieto, A.; Stern, C.R.; Esterves, J. 2013. The peopling of the Fuego-Patagonian fjords by littoral hunter-gatherers after the mid-Holocene H1 eruption of Hudson volcano. Quaternary International 317: 3-13.

Reyes, O.; Méndez, C.; Maldonado, A.; Velásquez, H.; Trejo, V.; Cárdenas, M.; Abarzia, A.M.; 2009. Uso del espacio de cazadores recolectores y paleoambiente Holoceno en el valle del Río Cisnes, región de Aisén, Chile. Magallania 37: 91-107.

Saadat, S.; Stern, C.R. 2011. Petrochemistry and genesis of olivine basalts from small monogenetic parasitic cones of Bazman stratovolcano, Makran arc, south-eastern Iran. Lithos 125: 609-617.

Sellés, D.; Rodriguez, A.C.; Dungan, M.A.; Naranjo, J.A.; Gardeweg, M. 2004. Geochemistry of Nevados de Longaví volcano (36.2°S): a compositionally atypical arc volcano in the Southern Volcanic Zone of the Andes. Revista Geológica de Chile 31 (2): 293-315. doi: 10.5027/andgeoV31n2-a08.

Stern, C.R. 2004. Active Andean Volcanism: its geologic and tectonic setting. Revista Geológica de Chile 31 (2): 161-206. doi: 10.5027/andgeoV31n2-a01.

Stern, C.R.; Skewes, M.A.; Duran, M. 1976. Volcanismo orogénico en Chile austral. In Congreso Geológico Chileno, No. 1, Actas 2: 195-212. Santiago.

Stern, C.R.; Moreno, H.; López-Escobar, L.; Clavero, J.E.; Lara, L.E.; Naranjo, J.A.; Parada, M.A.; Skewes, M.A. 2007. In The Geology of Chile (Moreno, T.; Gibbons, W.; editors). Geologic Society of London: 149-180. Bath.

Stern, C.R.; Moreno, P.I.; Henrique, W.I.; Villa-Martínez, R.P.; Sagredo, E.; Aravena, J.C. 2013. Tephrochronology in
the area around Cochrane, southern Chile. Bollettino di Geofisica 54, Supplement 2: 199-202.

Stuiver, M.; Reimer, P.J.; Braziunas, T.F. 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40 (3): 1127-1151.

Vargas, G.; Rebolledo, S.; Sepúlveda, S.A.; Lahsen, A.; Thiele, R.; Townley, B.; Padilla, C.; Rauld, R.; Herrera, M.J.; Lara, M. 2013. Submarine earthquake rupture, active faulting and volcanism along the major Liquiñe-Ofque Fault Zone and implications for seismic hazard assessment in the Patagonian Andes. Andean Geology 40 (1): 141-171. doi: 10.5027/andgeoV40n1-a07.

Völker, D.; Kutterolf, S.; Wehrmann, H. 2012. Comparative mass balance of volcanic edifices at the southern volcanic zone of the Andes between 33°S and 46°S. Journal of Volcanology and Geothermal Research 205: 114-129.

Watt, S.F.L.; Pyle, D.M.; Mather, T.A. 2011. Geology, petrology and geochemistry of the dome complex of Huequi volcano, southern Chile. Andean Geology 38 (2): 335-348. doi: 10.5027/andgeoV38n2-a05.

Watt, S.F.L.; Pyle, D.M.; Mather, T.A.; Naranjo, J.A. 2013. Arc magma compositions controlled by linked thermal and chemical gradients above the subducting slab. Geophysical Research Letters 40 (11): 2550-2556.

Weller, D.; Miranda, C.G.; Moreno, P.I.; Villa-Martínez, R.; Stern, C.R. 2014. A very large (>20 km³) late-glacial eruption (Ho) of the Hudson volcano, southern Chile. Bulletin of Volcanology 76: 831-849.

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