Tephrochronology of the southernmost Andean Southern Volcanic Zone, Chile

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Abstract. Correlations among and identification of source volcanoes for different Late-Glacial and Holocene tephra, preserved in eight lacustrine sediment cores taken from small lakes near Coyhaique (46°S), were made based on the stratigraphic position of tephra in the cores and tephra petrochemistry (glass color and morphology, phenocryst phases, and bulk-tephra trace-element contents determined by ICP-MS). The cores preserve a record of >60 explosive eruptions, since ~17,800 cal yrs BP, of volcanoes of the southernmost Andean Southern Volcanic Zone (SSVZ). Suggested source volcanoes for 55 of these tephra include Hudson (32 events), Mentolat (10 events), and either Macá, Cay or some of the many minor monogenetic eruptive centers (MEC; 13 events) in the area. Only four of these eruptions had been previously identified in tephra outcrops in the region, indicating the value of lake cores for identifying smaller eruptions. The tephra record preserved in these lake cores suggests that episodic explosive eruptions in this sector of the Andean arc have been regular from Late-Glacial to historic times. Tephra records in marine cores extends this conclusion back to 20,000 cal yrs BP, prior to the Last Glacial Maximum, and suggest that no significant temporal change in frequency of eruptions was associated with deglaciation.

Keywords: *tephra, Andean volcanism, explosive eruptions*

1 Introduction

The southernmost Andean Southern Volcanic Zone (SSVZ) consists of the five large volcanic centers Melimoyu, Mentolat, Macá, Cay, and Hudson (Fig. 1; Stern 2004), as well as numerous small monogenetic eruptive centers (MEC) located either along the Liquiñe-Ofqui Fault System (LOFS) or surrounding the larger volcanoes. We present a detailed tephrochronology of explosive eruptions of southernmost SSVZ volcanoes since the beginning of the last glacial termination based on the tephra record preserved in lacustrine sediment cores collected from eight small lakes to the southeast of these volcanoes near the town of Coyhaique (Fig. 1). This portion of the Andes was heavily glaciated during the last glaciation. Retreat of the glaciers, beginning at approximately 17,800 cal yrs BP (Miranda et al. 2013), generated many small shallow lakes with limited catchment areas in the semi-arid region to the southeast of the volcanic arc. These lakes provide favorable environments for the preservation of the tephra produced by explosive eruptions of the southernmost SSVZ volcanoes extending back into the Late-Glacial period. We have identified and characterized the tephra from >60 previously undocumented explosive eruptions of Hudson, Mentolat, Macá and possibly either Cay or one of the many minor monogentic eruptive centers in the región (Fig. 2). These results constrain a better understanding of both the eruption frequency of these volcanoes through time.

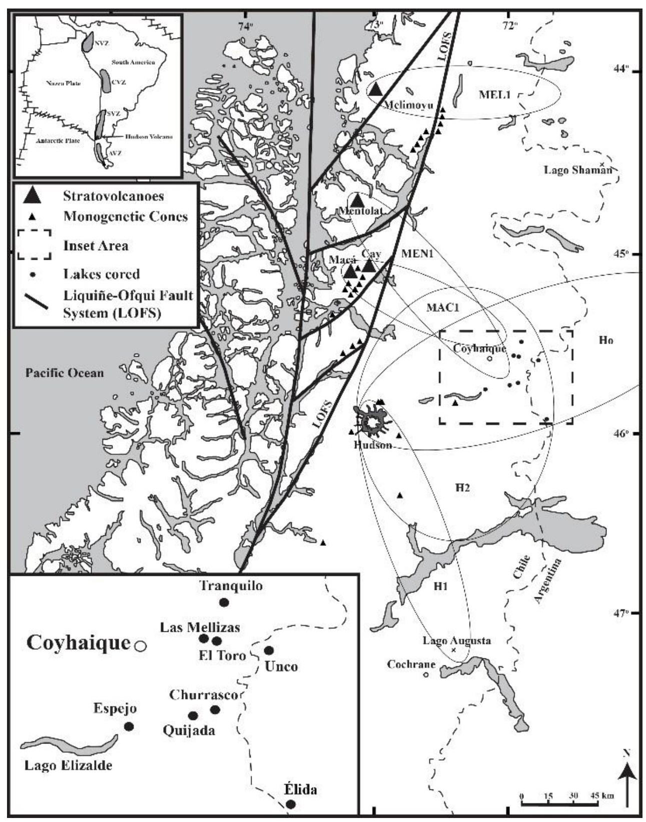

Figure 1. Location of the volcanoes in the Andean SSVZ (Stern 2004) and the eight lakes that were cored. Ten cm isopachs for some of the larger SSVZ explosive eruptions are taken from Naranjo and Stern (1998, 2004), Weller et al. (2014) and Stern et al. (2015b).

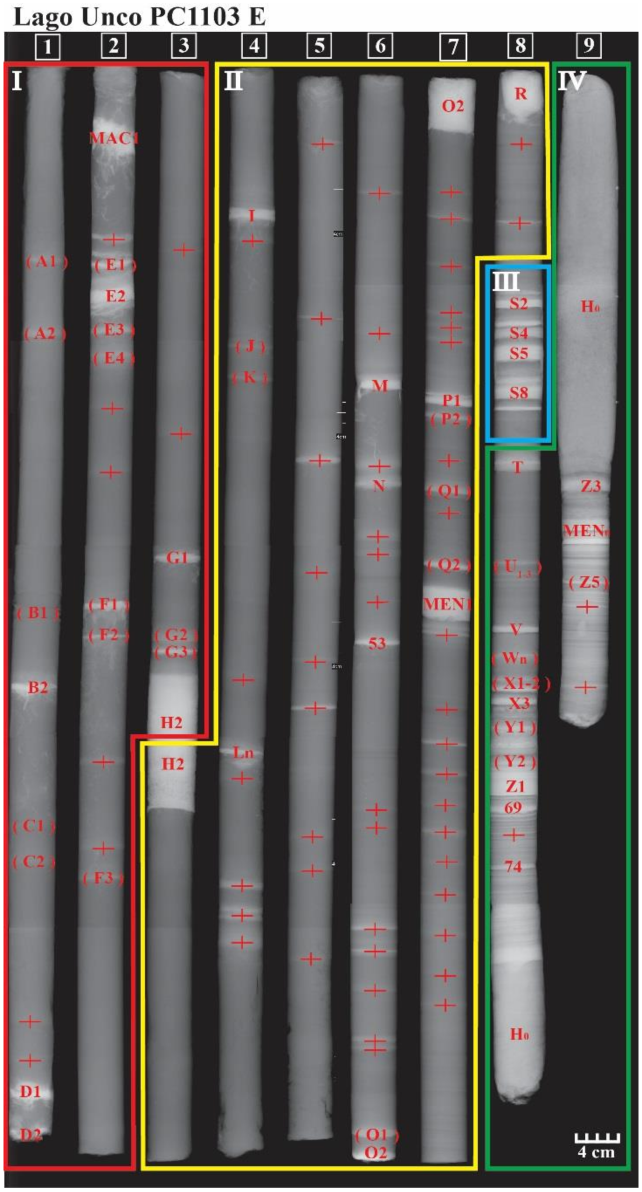

Figure 2. X-ray image of the 8.5 x 1 meter sections of the core from Lago Unco. The >70 different tephra in this core appear as white layers due to their higher density compared to the predominantly organic lake sediments in which they are preserved. Sampled and unsampled (in parentheses) tephra from 59 eruptions that have been correlated with tephra in other cores are labeled A1 through Z3, and numerous thin unsampled dense layers, most probably tephra, are indicated by the + symbols. The core has been divided into four zones (Zone I from the top to tephra H2; Zone II from tephra H2 to the top of the sequence of 10 tephra S1-10; Zone III the sequence S1-10; Zone IV from S10 to the bottom of the core) for the purpose of describing the different tephra.

2 Method, Samples, Results

Each core segment was X-rayed to aid in the identification of the tephra deposits (Fig. 2). In these images the darker layers are the less dense organic material rich post-glacial lacustrine sediments, while the white layers within the cores are denser tephra. The chronology of some of the different tephra identified in the cores, specifically Ho (Weller et al. 2014) and the S1-10 sequence of tephra (Fig. 2), has been controlled by AMS radiocarbon dates of organic material in the sediments above and below these tephra (Miranda et al. 2013). Radiocarbon dates were converted to calendar years before present (cal yrs BP) using the CALIB7 program and the SHCal13 data set (Stuiver et al. 1998). The age of other tephra (D3=MAC1 from Maca, F3=T6 and H2 from Hudson volcano, and MEN1 from Mentolat) are controlled by previously determined ages from outcrops (Naranjo and Stern 1998, 2004) and other cores in the region (Elbert et al. 2013; Stern et al. 2015b). Ages of all the other previously unknown tephra in these cores have not been determined directly, but can be roughly estimated based their depth in the cores relative to these five dated tephra.

Over 400 of the thicker visually identifiable tephra layers were removed from the lake cores with a knife. A portion of each tephra sample was mounted on a slide and examined under a petrographic microscope to characterize it petrography. Approximately 300 bulk tephra samples were powdered and dissolved for trace-element analysis using an ELAN D CR ICP-MS. Glass compositions were determined by eletron microprobe.

Correlation of tephra deposits across cores were based on three criteria; 1) the stratigraphic position of tephra in the cores; 2) bulk-tephra trace-element compositions; and 3) the color, morphology and abundance of their volcanic glass along with the identity and abundance of mineral microlites and phenocrysts. Identification of the source volcanoes of tephra were also based on bulk-tephra and glass (Fig. 3) chemistry and petrology as outlined below for each individual posible source volcano.

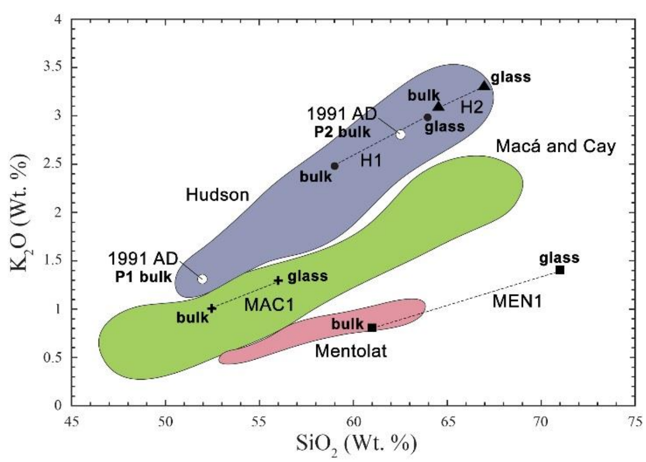

Figure 3. K_2O vs SiO_2 for SSVZ volcanoes from published data and both bulk and glass compositions of selected tephra (Kratzmann et al. 2010; Stern et al. 2015b), illustrating one aspect of the chemical differences between both bulk tephra and tephra glasses erupted from High Abundance (HA; Hudson), Low Abundance Mafic (LAM; Macá and Cay), and Low Abundance Felsic (LAF; Mentolat) source volcanoes.

2.1. Hudson tephra

All published analysis of lavas and tephra derived from explosive eruptions of Hudson volcano are High Abundance (HA) chemical types (Fig. 3; López-Escobar et al. 1993), with distinctly higher incompatible large-ion-lithophile (LIL; K, Cs, Rb, Ba, Sr, Th), rare-earth-element (REE) and high-field-strength element (HFSE; Ti, Zr, Nb, Hf, U) contents than other SSVZ centers, and all tephra with HA chemistry in the cores are considered to be derived from Hudson volcano. Tephra derived from previously documented explosive eruptions of Hudson also have other distinctive morphologic and petrologic characteristics used to distinguish the smaller eruptions from Hudson, such as the presence of pale orange-brown, vesicle-rich glass, which generally lacks plagioclase microlites. Vesicles are often highly deformed into elongated cylindrical shape reflecting the rapid extrusion of magma during these explosive eruption. Minor plagioclase feldspar, clinopyroxene, orthopyroxene, and small amounts of olivine are present in Hudson tephra deposits, but not amphibole.

2.2. Mentolat tephra

In contrast, Mentolat lavas (López-Escobar et al. 1993) and MEN1 tephra (Naranjo and Stern 2004; Stern et al. 2015a, 2015b) are Low Abundance (LA; Fig. 3) chemical types, with relatively low LIL (K, Rb, Ba) for intermediate (Ti <6000 ppm; Fig. 3) compositions compared to other LA type basalts. MEN1 tephra is characterized by the presence of colorless rhyolitic (Stern et al. 2015b) glass with abundant circular undeformed vesicles and no mineral microlites. Other tephras in the cores with LA character and containing clear colorless glass are referred to as Low Abundance Felsic petrochemical types (LAF) and interpreted as being derived from the Mentolat volcano. These other LAF chemical type tephra layers have, as does MEN1 tephra, abundant plagioclase, clinopyroxene and highly pleochroic orthopyroxene (hypersthene) phenocrysts, minor olivine, along with variable amounts of dark brown amphibole, and in two cases (tephras O_1 and R) biotite. López-Escobar et al. (1993) also recognized biotite in one Mentolat lava sample.

2.3. Macá, Cay and MEC tephra

Many of the tephra deposits within the sediment cores are LA chemical types, but are petrographically distinct from Mentolat tephras. These have dark brown to black glass with low to moderate vesicle abundances and often high abundances of microlites, but lack any clear vesicle-rich rhyolitic glass. The most abundant mineral phenocrysts are plagioclase with minor clinopyroxene, orthopyroxene and trace olivine. Amphibole is absent. These tephras with LA character with dark black glass, but no clear glass or amphibole, which are referred to as Low Abundance Mafic petrochemical types (LAM), are chemically and petrologically similar to MAC1 tephra derived from the Macá volcano (Naranjo and Stern 2004), but they may also have been derived from Cay volcano or one of the many small Holocene minor eruptive centers (MEC) in the region, which both also erupted LAM type magmas. These tephra are not assigned to a specific one of these possible sources, with the exception of the one tephra in group D (D_3) which is correlated directly with MAC1.

3 Discussion

Some of the many dense layers observed as white bands in the X-ray images (Fig. 2) of the multiple lakes cores from near Coyhaique, Chile, may be sand or re-worked tephra, but >60 tephra all occur in similar stratigraphic relations to each other in cores from multiple lakes, and we therefore consider them to be derived from independent eruptions. The chemistry and petrology of 55 of these >60 tephra are consistent with and support the correlations based on stratigraphy alone. We therefore conclude that >60 eruptions of various sizes of southernmost SSVZ volcanoes (including possibly MEC) have occurred since glacial retreat at approximately 17,800 cal yrs BP (Fig 4).

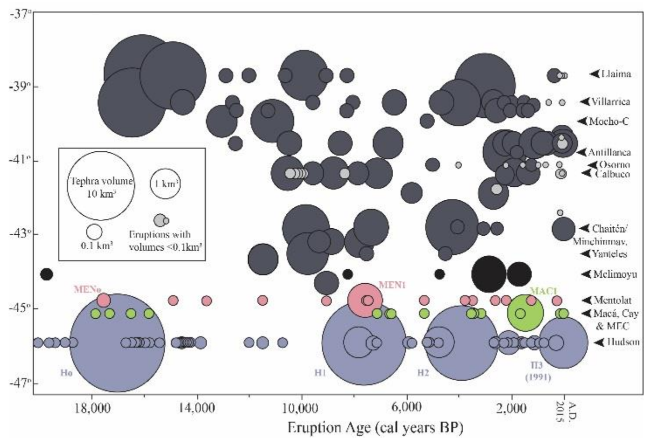

Figure 4. Eruption volumes for volcanic centers of the SVZ between 37 to 47ºS from Late-Glacial to Holocene time. Modified from Watt et al. (2013) to include the many small volume (<<1 km^3) eruptions from Hudson, Mentolat and either Macá, Cay or one of the MEC documented in this study, eruptions of Melimoyu and Montolat identified by Stern et al. (2015a) in Lago Shaman (Fig. 1) and Mallín el Embudo east of the arc, and from Hudson identified by Haberle and Lumley (1998) along the western coast and by Carel et al. (2011) in Pacific Ocean marine cores.

Most of the eruptions observed in these cores must have been small (<0.1 km^3), since only four of the tephra preserved in these lakes (MAC1; H2, F3=Hudson T6, and MEN1) have been correlated with tephra previously reported in outcrops in the region. Nevertheless, it is clear that although tephrochronology studies based solely on outcrops, such as those of Naranjo and Stern (1998, 2004), are satisfactory for identifying large eruptions, they are only seeing a minor proportion with regard to all eruptions. On the other hand, it is also significant to note that tephra from one of the largest Holocene eruptions of Hudson, the H1 event at 8,170 ± 60 cal yrs BP (Stern 1991, 2004, 2008; Naranjo and Stern 1998; Prieto et al. 2013; Stern et al.

2015b), does not occur in any of these cores because it was distributed more towards the south (Fig. 1).

The large number of eruptions documented from the lake cores near Coyhaique represent a significant contribution to the record of eruptions from volcanoes in this region during Late-Glacial and Holocene times (Fig. 4). These new results indicate that although explosive eruptions within the SSVZ are episodic, they have on the average been regularly repetitive throughout Late-Glacial to historic times without any significant change in the frequency. This conclusion extends back to 20,000 cal yrs BP, before the Last Glacial Maximum, when the tephra from Pacific Ocean marine cores are also considered (Carel et al. 2011), and suggests that deglaciation did not enhance the rates of explosive eruptions.

The new information, combined with previously published data concerning tephra derived from the Hudson volcano (Naranjo and Stern 1998; Haberle and Lumley 1998; Carel et al. 2011; Weller et al. 2014) indicate that this volcano has had >55 explosive eruptions since 20,000 cal yrs BP (Fig. 4). These eruptions have produced >45 km^3 of pyroclastic material based on previously published volume estimates of its larger eruptions (Weller et al. 2014). This makes Hudson one of the most active volcano in the SSVZ in terms of both frequency and volume of explosive eruptions, comparable to Volcán Mocho-Choshuenco (Rawson et al. 2015), perhaps as a result of its location just east of the Chile Rise-Trench triple junction. The tephra record indicates that local population centers such as Coyhaique (Fig. 1) could also be profoundly affected by future eruptions from Macá and Mentolat volcanoes similar in magnitude to those that occurred in the past.

Acknowledgements

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