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Stratigraphy, age and correlation of Lepué Tephra: a widespread c. 11,000 cal. a BP marker horizon sourced from the Chaitén Sector of southern Chile

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Stratigraphy, age and correlation of Lepué Tephra: a widespread c. 11,000 cal. a BP marker horizon sourced from the Chaitén Sector of southern Chile

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ABSTRACT

We describe the stratigraphy, age and correlation of a prominent tephra marker, named Lepué Tephra, extensively distributed in northwestern Patagonia. Lepué Tephra is well-dated at c.11,000 cal. a BP from numerous lake and soil cover-bed sequences and its recognition is useful for assessing the rate and timing of deglaciation as well as associated environmental changes in this region during the last glacial termination and early Holocene. Lepué Tephra has attributes typical of a complex and compositionally zoned phreatomagmatic eruptive. While the initial rhyolitic phase can be readily distinguished from multiple eruptive products sourced

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37 from the adjacent Volcán Chaitén, the main erupted end member is of basaltic-
38 andesite bulk composition - similar to younger tephra sourced from Holocene
39 monogenetic cones adjacent to the Volcán Michimahuida massif (tMim).

40 Lepué Tephra can be correlated to an equivalent-aged pyroclastic flow deposit
41 (Amarillo Ignimbrite) prominently distributed in the southeastern sector of tMim. The
42 source vent for these co-eruptive events is obscured by an extensive ice field and is
43 currently unknown. The widespread radially symmetrical distribution of Lepué
44 Tephra centred on tMim cannot be attributed solely to volcanological considerations.
45 Reduced Southern Hemisphere westerly wind influence interpreted from climate
46 proxies at the time of eruption are also implicated.

47 **[Words: 200]**

48
49 **Key Words:** northwest Patagonia, tephrostratigraphy, Lepué Tephra, Volcán
50 Michimahuida, Volcán Chaitén

52 INTRODUCTION

53 The ability to recognise, correlate and characterise tephra of mafic to
54 intermediate-silicic compositions that have been subjected to intense post-depositional
55 weathering and disturbance in temperate- to tropical-climate environments is a
56 significant obstacle to tephra studies in many proximal to distal volcanic settings. For
57 not only does the intense post-depositional pedogenic weathering effectively mask
58 fine-grained and/or thin tephra inter-beds within soil-dominated cover-beds, it
59 potentially compromises the morphological expression of the tephra as well as its
60 constituent geochemistry and grain-size characteristics - all attributes of which are
61 fundamental in tephra correlation. The characterisation of such tephra already
62 susceptible to post-depositional alteration can be further complicated by
63 compositional heterogeneity – that is, upward changes in tephra composition as an
64 eruption progresses. Such changes may reflect sequential surface discharge of either a
65 compositionally segregated magma body in the sub-volcanic system or a sudden
66 magmatic recharge event into an already fractionating body.

67 The principal objective of this study is to describe the stratigraphy, distribution,
68 age and geochemistry of a prominent tephra marker (here formally named Lepué
69 Tephra) located in the hyper-humid and high-weathering andic environment of
70 northwestern Patagonia (Fig. 1). The stratigraphy, age and chemistry of associated

71 rhyolitic tephra sourced from Volcán Chaitén will be presented in a companion paper
72 (see *Alloway et al., submitted*). Lepué Tephra is regionally important for three
73 reasons: First, it is one of the most widespread tephra marker beds to occur in this
74 sector and is therefore ideal for assessing the timing and rate of deglaciation and
75 associated environmental changes in this region during the Pleistocene-Holocene
76 transition. Second, Lepué Tephra can be recognised in high resolution lacustrine and
77 marine records and is therefore an important isochron potentially useful in assessing
78 proxy record synchronicity between equivalent-aged offshore and onshore sequences.
79 Third, Lepué Tephra is difficult to chemically characterise on account of the
80 ubiquitous occurrence of microphenocrysts and compositional heterogeneity of glassy
81 constituents. Hence, the application of a combination of grain discrete and bulk major
82 and trace elemental techniques may be a useful template by which other similarly
83 difficult tephra might be characterised. Finally, Lepué Tephra provides a unique
84 insight into a compositionally zoned and complex phreatomagmatic eruption
85 associated with a permanent Andean ice cap.

86
87 **Setting**

88 Northwestern Patagonia encompasses the Chilean Lake District and Chilotan
89 Archipelago (40° to 44°S), and is bounded in the east by the Andes Cordillera and a
90 lower lying coastal range in the west adjacent the Pacific Ocean (*Fig. 1*). This region
91 frequently experiences intermittent eruptions of varying magnitude from
92 compositionally diverse volcanoes situated within the Andean Southern Volcanic
93 Zone (SVZ). At least 60 active or potentially active volcanoes in Chile and Argentina,
94 as well as three caldera systems and numerous minor eruptive centres (*Stern, 2004*;
95 *Stern et al. 2007*) occur within this zone. Volcanism results from the subduction of the
96 Nazca Plate beneath the westward moving South American Plate (*Stern, 2004*), along
97 a narrow volcanic arc that follows the Liquiñe-Ofqui fault system in Chile between
98 33° and 46°S. Several volcanoes within this zone have recently erupted - the most
99 notable being Volcán Chaitén (VCha) in 2008, Puyehue-Cordon Caulle in 2011 and
100 Calbuco in 2015.

101 Over the last two decades, there has been a number of studies detailing the late
102 last glacial to Holocene tephrostratigraphy of northwestern Patagonia in order to
103 develop an inventory of eruptive events, determine source as well as characterize size,
104 composition and timing (i.e. *Naranjo and Stern, 2004*). While some eruptive histories

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of individual volcanic centres within the central portions of the SVZ have been described in detail (Lara *et al.* 2006; Singer *et al.* 2008), the eruptive histories of many centers particularly within the southern SVZ (SSVZ) are insufficiently known owing to their remote locations and inaccessibility (Watt *et al.* 2011). Tephra layers have been routinely recorded in lakes (i.e. Haberle and Lumley, 1998; Daga *et al.* 2010; Moreno *et al.* 2014) but in many studies the occurrence of tephra has been a subordinate focus in dominantly paleoecologically and paleoclimatically directed investigations (i.e. Abarzúa *et al.* 2004; Bertrand *et al.* 2008; Iglesias *et al.* 2012; Moreno and Videla, 2016). The need to better utilize tephra within sedimentary archives as an effective means to synchronize records was recently highlighted by Fontijn *et al.* (2016). Recent research efforts has also tended to focus on examining composite eruptive records in order to better assess region-wide hazards based on magnitude/frequency of historic and prehistoric eruptive events across large swaths of Patagonia (i.e. Watt *et al.* 2011; Fontijn *et al.* 2014; Rawson *et al.* 2015; Naranjo *et al.* 2017). Recent eruptions (i.e. Hudson, 1991; Chaitén, 2008; Puyehue Cordón-Caulle, 2011; Calbuco, 2015) have also served as a driver for renewed field-investigations so that eruptive histories and potential hazards posed to adjacent and downwind communities can be better clarified (i.e. Wilson *et al.* 2010, 2011; Amigo *et al.* 2013; Lara *et al.* 2013; Watt *et al.* 2013; Alloway *et al.* 2015, submitted).

Another dominant landscape feature is ubiquitous glacial landforms and ice-carved lake basins formed from Andean piedmont glaciers during episodes of cold (glacial) and/or temperate climate through the Quaternary. The configuration of these Andean piedmont ice lobes in northwestern Patagonia is well known largely based from the glacial morphologic mapping of moraines and outwash plains adjacent to lakes and ocean alongside the western margin of the Andes (Anderson *et al.* 1999; Denton *et al.* 1999). These seminal maps not only demarcated moraines and outwash plains deposited during the maximum phases of the last glaciation (locally referred to as Llanquihue glaciation) but also displayed older Casma and Colegual moraines and outwash plains first described by Mercer (1976). Radiocarbon dating of Llanquihue landforms show that the Andean ice lobes advanced into the moraine belt depicted in red in Fig. 1C numerous times during glacial and/or cool inter-stadial phases of Marine Isotope Stage (MIS) 4, 3 and 2, rather than simply being formed during the Last Glacial Maximum (LGM) in MIS 2. The chronology of the youngest advance is constrained by an extensive array of radiocarbon dates from sites tied to the former

139 Llanquihue, Reloncaví, Ancud and Golfo de Corcovado ice lobes (Denton *et al.* 1999;
140 Moreno *et al.* 2015). Overall this chronology shows a culmination of the glacial
141 readvance at 17,800 cal. a BP The advance of the two northern lobes (Llanquihue and
142 Reloncaví) reached the inner margin of the LGM moraine belt whereas the two
143 southern lobes (Ancud and Golfo de Corcovado) was either the most extensive, or
144 close to the most extensive, of MIS 2.

145 Of particular relevance to this study are sites located in areas formerly occupied
146 by ice lobes that overlie glacial deposits and contain the Lepué Tephra, as they can
147 assist in constraining the recessional chronology of ice lobes as climate warmed
148 abruptly during the Last Glacial Termination (LGT) (Moreno *et al.* 2015).

149
150 **STRATIGRAPHY**

151 In sections directly adjacent to the Volcán Michimahuida massif (tMim), Lepué
152 Tephra is typically characterised by compact, dark grey to brownish-grey, poorly
153 sorted, massive to weakly stratified, scoriaceous lapilli to lapilli-‘tuff’ (consolidated
154 ash, Fisher and Schmincke, 1984) beds often containing accretionary lapilli. These
155 textural and sorting characteristics, together with highly variable depositional
156 architecture between adjacent sections, suggest ‘molten fuel-coolant interactions’
157 (MFCI; Zimanowski, 1998) resulting in a complex succession of magmatic and
158 phreatomagmatic eruptive products (e.g. Cas and Wright, 1987; Ort and Carrasco-
159 Núñez, 2009; Ngwa *et al.*, 2010; van Otterloo and Cas, 2016).

160
161 *Proximal*

162 Within sections in the vicinity of Chaitén and Santa Barbara and those sections
163 further north towards Caleta Gonzalo (Fig. 2), a prominent decimetre(dm)-thick
164 reddish-brown crudely stratified medium to coarse scoriaceous fall unit is directly
165 overlain by a compact, dm-thick brownish-grey, crudely stratified, very poorly sorted
166 ash with conspicuous dispersed accretionary and scoriaceous lapilli layers. At Section
167 9B (Fig. 3-F) the upper phreatomagmatic unit, clearly over-thickened at the base of a
168 steeply inclined hillslope, infills an eroded lower scoriaceous fall unit suggesting a
169 brief hiatus between these two syn-eruptive events. At all other sections in this sector
170 both units appear conformable without any indication of an intervening break or soil
171 development. At Section 9D (Fig. 3-E) the basal scoriaceous lapilli bed is itself
172 underlain by a centimetre (cm)-thick surge deposit comprising compact, brownish-

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173 grey, low-angle cross-bedded fine to medium ash with few medium-scoriaceous
174 lapilli dispersed randomly throughout. This surge deposit appears localised and most
175 likely relates to its passage down an isolated stream tributary.

176 Further north, at Section 4 on the southern side of a formerly glaciated mountain
177 pass (~264-m a.s.l) separating Lago Blanco (south) with Lago Negro (north) the
178 stratigraphy of Lepué Tephra is well exposed (Fig. 4). Here, the stratigraphy reveals a
179 prominent (metre-thick) rhyolitic pumiceous lapilli fall unit (Cha-1 *sensu stricto*
180 Naranjo and Stern, 2004; dated at c. 8700 ¹⁴C a BP, Watt *et al.* 2011) sourced from an
181 ancestral VCha, separated from a lower scoriaceous surge and fall couplet below by ~
182 0.4 m of medial-ashy andic material (paleosol). This lower couplet is characterised by
183 a basal fall sub-unit characterised by multiple, normal graded centimetre-thick beds of
184 well-sorted coarse to very-fine sand textured scoriaceous ash, grading upwards to a
185 more prominent fall sub-unit comprising weakly stratified, poorly sorted, scoriaceous
186 coarse lapilli. This fall unit is unconformably overlain by a surge unit containing
187 conspicuous, moderately sorted, inclined planar to low-angle cross-bedded,
188 scoriaceous ash and lapilli beds. Charcoal fragments retrieved from within this upper
189 surge unit were dated at 11483 ± 1034 cal. a BP (9960 ± 330 ¹⁴C a BP; UCIAMS-
190 145938) and are distinguishable from those radiocarbon ages acquired for Lepué
191 Tephra correlatives elsewhere (see Age Section). At Section-4, Lepué Tephra
192 (represented as a fall-flow couplet) is closely underlain by widespread and distinctive
193 layers of banded rhyolite breccia and rhyolitic ashy material unconformably overlying
194 basement bedrock. This layer of rhyolitic breccia underlying Lepué Tephra can be
195 correlated to Section 6 (Lago Blanco) and Section 7 (within Chaitén township) (see
196 Fig. 2) and likely represents explosive fragmental debris originating from a pre-Cha-1
197 lava dome (ancestral VCha). Such pre-Cha-1 rhyolitic sequences are rarely observed
198 proximal to inferred source due to deep burial and/or pervasive Andean glaciation
199 (Alloway *et al.* submitted).

200 Northwards along the continental coastline (see Fig. 5), Lepué Tephra can be
201 reliably traced from Section 5 at Puente Águila to sections in the vicinity of Seno
202 Reloncaví. In most sections, Lepué Tephra is subtly expressed within the andic soil
203 material as laterally discontinuous cemented aggregates of olive-brown to reddish-
204 brown fine to medium ash. Often Lepué Tephra is stratigraphically associated with
205 Cha-1 tephra above (Fig. 5). At Puente Pichileufú on the Hualaihue Peninsula, Lepué
206 Tephra is unconformably overlain by a scoriaceous coarse ash bed of presumed

207 Apagado-source (Ap-1? of Watt *et al.* 2011) whereas further north-eastwards (i.e.
208 Chapo-S1) towards Ralún, Lepué Tephra is enveloped by a steadily increasing
209 number of discontinuous weathered lapilli of presumed Calbuco-source dispersed in
210 andic medial material.

211

212 *Relationship with pyroclastic flow and surge deposits*

213 In sections along road W-887 located directly adjacent to Río Michimahuida (i.e.
214 Pumalín Section 1), a massive > 40 m-thick unconsolidated lithic-rich pyroclastic
215 density current (PDC) deposit can be observed with metre-sized oriented lithic intra-
216 clasts and rare, dispersed centimetre-sized charred wood fragments (Fig. 6A, B). At
217 other sections along road W-887 (i.e. Pumalín-4), syn-eruptive fall deposits that
218 overlie this PDC deposit can occasionally be observed. At these sections, the
219 uppermost co-eruptive scoriaceous fall deposits are separated from Cha-1 above (i.e.
220 Pum 4-T8) by a pervasive wedge of colluvial debris of mixed lithologies indicating
221 widespread landscape instability in the devastating aftermath of this eruption.
222 Northward from the W-887 road-end an extensive elevated sloping remnant valley-fill
223 surface can be clearly observed within the confines of the glacially dissected Río
224 Michimahuida valley and extending down to the Río Mallines–Michimahuida
225 confluence (Fig. 6C). This same PDC-deposit and surface was recognised by Amigo
226 *et al.* (2013) and named Amarillo Ignimbrite. Two radiocarbon samples acquired from
227 within and just above the Amarillo Ignimbrite were dated at 9260 ± 50 and 9510 ± 50
228 ^{14}C a BP respectively and are broadly in accord with an age of 9785 ± 30 ^{14}C a BP
229 (LLNL-122960) from our sample retrieved from Pumalín-1. These ages are also
230 indistinguishable from a radiocarbon age associated with the prominent surge deposit
231 occurring at Section 4 in the northwestern sector of Michimahuida (see Fig. 4). While
232 the voluminous scoriaceous-rich PDC-deposit can be clearly identified in both the
233 south-eastern and northwestern sectors of tMim, the precise location of the eruptive
234 source vent is obscured by ice fields and is currently unknown.

235

236 *Southern Sectors*

237 At sections 1, 13 and 14 located on Ruta 7 between Amarillo and Puerto
238 Cárdenas (see Figs. 7 and 8), Lepué Tephra (previously referred to as Cor-1 by
239 Naranjo and Stern, 2004) is enveloped by a sequence of at least six cm- to dm-thick,
240 basaltic-andesite to andesitic ash and lapilli inter-beds within dominantly reddish-

241 brown andic soil material that typically overlies glacial diamict (till) draping bedrock.
242 While some of these enveloping tephra (i.e. Unk-2) can be reliably traced northwards
243 towards Michimahuida, the eruptive origins of the majority (i.e. Yan-1, Cor-2 and
244 Cor-3 named by [Naranjo and Stern, 2004](#)) have yet to be determined. In this sector,
245 Lepu Tephra is typically characterised by a dm-thick weakly stratified, brownish-
246 grey, very poorly sorted cemented ash with indistinct centimetre-sized accretionary
247 lapilli and scoriaceous lapilli-rich ashy intrabeds. Cemented fine ash frequently
248 contains open interstitial pore spaces, which are typically indicative of syn-
249 depositional rain flushing ([Fig. 8](#)). Beneath this cemented grey ash are common,
250 highly weathered reddish-brown scoriaceous fine to very fine lapilli dispersed within
251 underlying medial andic material. Lepu Tephra can be traced south to the vicinity of
252 Santa Luca where it occurs as a laterally discontinuous, variably thick (8 to 13-cm)
253 grey cemented fine ash intervening between Yan-1 and Cor-2 correlatives above
254 clast-supported breccia (talus deposit).

255

256 *Eastern Sectors*

257 Lepu Tephra can be reliably correlated eastwards to distal sections in Chile
258 (Lago Espejo, Futaleuf) and Argentina (Alerce-6 and La Zeta) ([Fig. 9](#)). Correlation
259 is based on a combination of morphological expression, chronostratigraphic
260 association and correspondence of glass shard major element compositions. The
261 Lepu Tephra correlative at Lago Espejo, Alerce-6 and La Zeta is overlain by two
262 prominent rhyolitic coarse ash beds that are be correlated with Cha-2 and Cha-1
263 tephtras dated at *c.* 4950 and 9750 cal. a BP respectively ([Watt *et al.* 2013](#)). At La
264 Zeta, a ~11-cm thick tephra is prominently expressed within a ~ 5-metre-thick lake
265 sequence that contains numerous other mm- to cm-thick tephra inter-beds of basaltic
266 through to rhyolitic compositions. A radiocarbon age ($14,840 \pm 70$ ^{14}C a BP;
267 UCIAMS-145920) from basal lake sediments directly overlying glacial diamict (till)
268 establishes a maximum age of ~17,800 cal. a BP for the lake sequence. While the
269 Lepu Tephra correlative at La Zeta is not directly dated, it is loosely constrained by
270 radiocarbon dates obtained from enveloping tephra inter-beds within the lake
271 sequence. Certainty of correlation is achieved by glass shard major element chemistry
272 (see below).

273 At La Zeta, the Lepu Tephra correlative consists of three distinct fall units. The
274 lowermost unit consists of dark gray well-sorted coarse ash (< 1-cm thick, layer a in

Fig. 9 photo inset). This unit is overlain by a compact, subtly bedded, pale gray, moderately sorted fine to very fine ash (~2-cm thick, layer b in photo inset) which in turn is overlain by a ~8-cm thick uppermost unit (layer c in photo inset) comprising loose, well-sorted, very coarse to fine, grey scoriaceous ash. The internal architecture of Lepué Tephra at this locality affirms the complex phreatomagmatic to magmatic origin of this deposit.

Western Sectors

Through most of Isla Grande de Chiloé and its adjacent islands, Lepué Tephra is the only macroscopic tephra that can be systematically observed within the late last glacial to post-glacial andic cover-beds. Stratigraphic columns show the correlation of Lepué Tephra along a western transect from south-central Isla Grande de Chiloé northwards towards Puerto Montt in southernmost continental Chile (Fig. 10). Typically in this sector, Lepué Tephra forms highly irregular, discontinuous pods of crudely bedded, cemented fine- to medium-ash enveloped by reddish-brown andic soil material and closely overlying late last glacial to Last Glacial Maximum (LGM)-aged colluvium, bedded fluvio-glacial gravels and sands, and glacial diamicts (till). The morphological expression of Lepué Tephra within andic cover-bed sections of Isla Grande de Chiloé can be highly variable depending on the thickness of encapsulating andic material and the permeability of the underlying substrate. Where Lepué Tephra occurs within thin andic soil material closely overlying impermeable glacial diamicts (which seasonally perches the local water table), tephra colour is strongly altered to strong brown chromas (i.e. Queilen and Chonchi sections, Fig. 11), whereas Lepué Tephra overlain by a thicker interval of free-draining andic soil material typically have grey to pale brown chromas (i.e. Lago Natri, Castro, Puente Puntra and Chacao sections, Fig. 11). In northern sections (i.e. Huelmo and along Ruta 5 connecting Pargua with Puerto Montt; Figs. 10 and 12) Lepué Tephra is closely underlain by intensely weathered andesitic ash and lapilli ‘ghosts’ that are most likely sourced from either Volcán Calbuco or Volcán Yate located eastwards along the Andean mountain divide. These highly weathered tephra have yet to be geochemically characterized.

Lake Records

A large number of cores over many years have been retrieved from bogs (Heusser

309 *et al.* 2003) and shallow lakes throughout northwestern Patagonia in order to elucidate
310 vegetation-climate change, fire regime shifts and volcanic disturbance (i.e. *Moreno*
311 *and León, 2003; Pesce and Moreno, 2014; Henríquez et al. 2015*). A key priority for
312 these ongoing investigations has been to disentangle the role of paleofires and
313 explosive volcanism from climate drivers of past vegetation change. Until recently,
314 the occurrence of Lepué Tephra has been a subordinate focus in dominantly
315 paleoecologically directed investigations. However, there is growing appreciation of
316 the utility this tephra is able to play in terms of vegetation-climate synchronization
317 within equivalent-aged lake records of diverse latitude and elevation.

318 Lepué Tephra can be readily identified in most sediment cores as a macroscopic
319 layer (centimetre-thick) showing primary fall deposition with minimal post-
320 depositional reworking. However, in some lakes (i.e. Lago Lepué; *Pesce and*
321 *Moreno, 2014*) Lepué Tephra shows evidence of reworking and is substantially
322 overthickened compared with adjacent lake sequences. In all cases, Lepué Tephra can
323 be readily identified as a very prominent down-core inorganic density (gr/cc) peak
324 (Fig. 13). For cores throughout Isla Grande de Chiloé (i.e. Lago (L.) Quilque, L.
325 Tarumán, L. Lepué, L. Melli and L. Tahui) this peak occurs at ~750-cm depth with a
326 subordinate inorganic peak at ~650-cm likely representing a VCha-sourced tephra,
327 which is not typically expressed macroscopically in adjacent andic soil cover-beds
328 (*Alloway et al. submitted*). For continental cores south of Puerto Montt (i.e. L.
329 Condorito, Huelmo mire, L. El Salto), Lepué Tephra occurs at ~650-cm depth
330 whereas at L. Proschle and Puelche Section Lepué Tephra occurs at ~350-cm depth,
331 and is associated with minor inorganic spikes likely representing tephra additions
332 from Volcán (V.) Chaitén, V. Apagado and V. Calbuco. In all lake cores throughout
333 the region, the ages of Lepué Tephra are well-constrained by numerous radiocarbon
334 dates (see Age Section below).

335 So far the northern-most occurrence of Lepué Tephra within lake sediments is
336 found at Lago Pichilaguna, located immediately west of Llanquihue township and
337 ~178-km north-west of V. Michimahuida. Here, Lepué Tephra occurs at 382 to 390-
338 cm depth within core 1402AT3 as a ~8-cm-thick dark olive-grey, normal graded
339 coarse to very fine ash (see photo inset Fig. 10) and is chronologically constrained by
340 bracketing radiocarbon dates of 8905 ± 35 ^{14}C a BP (CAMS-158137; 9989 ± 113 cal.
341 a BP) above and $10,100 \pm 25$ ^{14}C a BP (UCIAMS-177595; $11,576 \pm 109$ cal. a BP)
342 below. In this same vicinity, Lepué Tephra is not macroscopically preserved within

the andic soil-forming environment.

In lakes close to its presumed Michimahuida source, only sediments and tephra post-dating Lepué Tephra have been retrieved since it forms a prominent hardpan and a significant obstacle for further core penetration. For example, at Lago Teo located near Chaitén (Moreno *et al.* 2014), no core penetration beyond 3.02 m depth was achieved. Lepué Tephra was not encountered despite being prominently expressed in all adjacent road sections. An age of 8925 ± 30 ^{14}C a BP of organic sediments from the base of the Lago Teo core provides a minimum age of 10,021 cal. a BP for Lepué Tephra in this sector.

Offshore Record

Site 1233 was drilled during ODP Leg 202 off southern continental Chile ($41^{\circ}0.01'S$, $74^{\circ}26.99'W$; 40-km offshore; 838-m water depth) in a small basin on the upper continental slope away from the pathway of major turbidity currents. This offshore site is located at the northern margin of the Antarctic Circumpolar Current (ACC) and at the origin of the Perú-Chile Current (PCC), the most latitudinally extensive Eastern Boundary Current system in the world, driven by along-shore parallel winds along the Pacific coast of South America. This offshore core yielded high-resolution alkenone-based sea surface temperature (SST) and vegetation records extending over the last 50-70,000 years (Kaiser *et al.* 2005; 2008; Heusser *et al.* 2006; Lamy *et al.* 2007). A prominent macroscopic tephra layer was registered in core 1233D within clay and silty clays between 14.52-14.83 mcd and was accompanied by a prominent spike in magnetic susceptibility (916.8 m.mol^{-1} (SI)) (Fig. 14). Unfortunately, no radiocarbon dates were obtained directly associated with the upper and lower contacts of this tephra but bracketing radiocarbon samples from 12.94 and 17.01 mcd yielded calibrated ages of 10,040 and 12,260 cal. a BP, respectively.

AGE

A weighted mean age determination of 9588 ± 20 ^{14}C a BP (95% probability: 10,080 to 10,714 cal. a BP) was modeled for Lepué Tephra based on four R-combine-statistically grouped samples (UCIAMS-145938, LLNL-158290, LLNL-123032 and LLNL-12329) from Sections 4, 12A, Pichileufú and Puelche, respectively (Fig. 15; Table 1). Three sample outliers from Sections 9, 12A and Pumalín -1, (LLNL-158125, LLNL-158291 and LLNL-122960) were rejected. This modeled age of Lepué

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3 377 Tephra compares closely with a similarly modeled age of 9725 ± 23 ^{14}C a BP based
4 378 on samples retrieved from Huelmo (Moreno and Leon, 2003), Lago (L.) Condorito
5 379 (Moreno, 2004), L. Tahui (Abarzúa *et al.* 2004), L. Melli (Abarzúa and Moreno,
6 380 2008) and L. Lepué (Pesce and Moreno, 2014) (Fig. 16; Table 1). The associated
7
8 381 mean calendar age of $10,994 \pm 124$ cal. a BP collated from previous research is
9 382 indistinguishable from a mean calendar age of $10,909 \pm 228$ cal. a BP determined for
10 383 Lepué Tephra in this study from Chaitén (S-4, S-12A), Puelche and Pichileufú (see
11 384 Fig. 5).
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18 386 ISOPACH

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20 387 Lepué Tephra is extensively distributed from the Chaitén Section of southern
21 388 Chile in a wide arc from Isla Grande de Chiloé in the west to Esquel, Argentina across
22 389 the Andes in the east (Fig. 17). Lepué Tephra can also be traced northwards to the
23 390 vicinity of Seno Reloncaví and immediately south of Puerto Montt. In routinely
24 391 measuring the thickness of Lepué Tephra two problems are encountered. Thicknesses
25 392 recorded in the soil-forming (andic) environment bear little resemblance to those
26 393 determined from lake/peat records. We consider that the most accurate thicknesses are
27 394 likely to be derived from lakes and organic-rich lens, though bedding characteristics
28 395 need to be carefully scrutinised to distinguish between primary and secondary
29 396 depositional features. For example in L. Lepué (Pesce and Moreno, 2014) – Lepué
30 397 Tephra is recorded as being ~ 44-cm thick with this thickness being significantly at
31 398 odds with those from adjacent cored lakes (i.e. L. Melli, 11-cm; L. Tahui, 16-cm),
32 399 with no mention of bedding characteristics that might distinguish primary airfall
33 400 products from secondary redeposition and reworking.
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43 401 Within the andic soil environment Lepué Tephra typically forms a highly
44 402 irregular and laterally intermittent layer of well-cemented ashy material. This lateral
45 403 distribution is presumably coincident with the density and distribution of vegetation
46 404 that likely existed at the time of deposition with continued biological disturbance
47 405 since (i.e. interference by roots, tree-throw). At any one particular section within the
48 406 Chaitén sector, thickness values for Lepué Tephra are highly variable and are for the
49 407 most part, interpreted as being over-thickened within the valleys and lower slopes
50 408 adjacent the Andean range-front (along which most roads follow). This pervasive
51 409 over-thickening certainly restricts the production of a reliable isopach map and by
52 410 proxy - any accurate estimate of eruptive volume. However, these thickness
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measurement obstacles certainly do not diminish the utility of this tephra as one of the most important early Holocene stratigraphic markers in this sector.

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414 **GEOCHEMISTRY**

415 We report major- and trace-element chemistry of pumice and matrix glass from
416 Lepu Tephra utilising grain-discrete EMPA and LA-ICP-MS techniques (see [Tables](#)
417 [2, 3 and SI Methods](#)) as well as bulk solution nebulisation inductively coupled plasma
418 mass spectrometry (SN-ICP-MS) analyses (see [Table 4 and SI Methods](#)). The key
419 objective for this paper is to demonstrate its utility in supporting field correlations and
420 is not intended to detail the genesis of the melt body (or melt bodies) involved. Thus,
421 while a (micro)phenocryst assemblage dominated by plagioclase, with subordinate
422 pyroxene and Fe-Ti oxide phases was noted, their routine analysis was not undertaken
423 as mineral compositions, and their implications for petrogenesis of the deposit, were
424 not considered central to this particular study. The grain specific major- and trace-
425 element characterisation of the pure glass phase of the Lepu Tephra has proven to be
426 difficult because of the progressive increase in the concentration of microphenocrysts
427 (dominantly plagioclase) occurring within the tephra glass shards as the eruption
428 proceeded.

429

430 Back-scatter electron (BSE) images of selected glass shards from Lepu Tephra
431 correlatives indicate low microlite concentrations are observed within glassy grains at
432 the base of the tephra sequence referred to as “microlite-poor glass” which are
433 broadly rhyolitic in composition (onset of the Lepu eruption; [Fig. 18-A to -C](#)).
434 Higher up in the tephra sequence, the microlite concentration within the glassy grains
435 significantly increases ([Fig. 18-D to -F](#)) giving “intensely microlitic glass” which
436 typically have a basaltic andesite composition. Analysing the intensely microlitic
437 glass either by EMPA and/or LA-ICP-MS is highly problematic in that microlites are
438 inevitably included in the material analysed (i.e. [Fig. 18-G, -H](#)), even when using a 10
439 m diameter EMPA, or LA-ICP-MS, spot. However, with sufficient analyses, glass
440 chemistry can be determined as an end-member to a trend of analyses contaminated
441 by (dominantly) plagioclase phenocrysts, and in some cases “microlite-free” analyses
442 can be produced, particularly so from the microlite-poor glass shards. Coinciding with
443 the increase in microlite concentration, the proportion of well-formed oriented

444 vesicles also decreases with a corresponding increase in irregular shaped (collapsed)
445 and coalesced voids (Fig. 18-D, -F).

446 Selected major element compositions (weight percent SiO₂ vs Na₂O + K₂O and
447 FeO vs K₂O and CaO) of glass shards from Lepu Tephra correlatives are presented in
448 Fig. 19A to C. Two glass shard types can be clearly distinguished by differences in
449 the major element analyses, viz. (i) the rhyolitic composition of glass from the
450 microlite-poor shards and (ii) the broadly basaltic-andesite composition of the
451 intensely microlitic shards, which represent analyses of mixed glass and phenocrysts,
452 approximating to a “bulk” (modal) analyses of the glass shard, and not the glass phase
453 only (*cf.* Platz *et al.* 2007). The insets on Fig. 19 show the tight compositional
454 clustering of rhyolitic glass shards erupted at the onset of the Lepu eruption and
455 these likely represent the initial magma withdrawal from the top of a melt body
456 dominated by fractionated magma (~71 wt % SiO₂). Note that the rhyolitic end-
457 member composition of Lepu Tephra can be clearly differentiated from all post
458 18,000 cal. a BP rhyolitic tephra sourced from V. Chaitn-sourced tephra (indicated in
459 greyscale).

460 Selected trace element (Nd vs Th and Sr vs Y, Ho, Nd, Zr) compositions of glass
461 shards from Lepu Tephra correlatives as determined by grain discrete LA-ICP-MS
462 analyses are presented in Fig. 20. Data for glass shards from proximal sites at La Zeta,
463 Puente guila (S5) and Paso Lago Blanco (S4) sites are broadly coincident, showing
464 strong linear relationships between the data in all plots. Samples from the more distal
465 locations of Lago Lepu (020DT8-1804-cm) and ODP-1233D (14.68-m) plot slightly
466 away from the trend displayed in the other Lepu samples, but the low Sr end-point of
467 this compositional array is coincident, and the differences result from issues
468 associated with the volume of material sampled during LA-ICP-MS microanalysis of
469 microcryst-bearing glass shards.

470 All data display a range of compositions ranging from pure rhyolitic glass with a
471 composition of ~ 72 to 113-ppm Sr (i.e. microlite-free analyses from microlite-poor
472 glass shards) to high Sr compositions (~1000-ppm Sr) where the glasses become
473 increasingly microlite-rich, with the highest Sr compositions coming from analyses
474 which will have ablated almost entirely feldspar, with very little glass in the intensely
475 microlitic shards. With increasing Sr, incompatible element concentrations decrease,
476 associated with low incompatible element concentrations in feldspar. All analyses
477 were calculated using the glass SiO₂ composition from the shards (determined by

EPMA) as the internal standard (I.S.). This will give accurate analyses for the pure glass component (i.e. low Sr analyses), but the change in glass composition by inclusion of feldspar in the analyses will mean that, as more feldspar is ablated, the true SiO₂ content of the ablated mixture (the I.S. composition) moves further from the pure glass composition and the analyses will become progressively less accurate (see [Pearce, 2014](#)). Incorporation of plagioclase in rhyolitic glass causes the SiO₂ content in the ablated mixture to drop, and thus, using the glass SiO₂ composition as I.S., analysed elements will be marginally overestimated. It is not possible to correct the internal standard concentration for this effect unless the amount of feldspar ablated with glass and the SiO₂ composition of feldspar and glass are both accurately known. The effect of ablation of feldspar increases the reported Sr (compatible in feldspar) considerably and decreases incompatible element concentrations (by dilution, as feldspar has very low incompatible element contents), and this dilution effect competes with the increase in concentration from the change in I.S. composition, with the overall effect depending strongly on exactly how much phenocryst has been ablated (see [Pearce, 2014](#)), however without knowing its composition, the amount cannot be calculated. The offset of the Sr-rich analyses of microcryst-bearing glasses from the distal sites at Lago Lépue and ODP-1233D when compared with data from the more proximal sites may relate to differences in glass composition and phenocryst assemblage/content associated with deposition at different stages of the eruption, and the effects these variables may introduce into the LA-ICP-MS analyses described above. What is apparent though is that the microcryst-poor and microcryst-free glass analyses (i.e. where Sr <~ 150-ppm) from the more distal localities have the same glass composition as the microcryst-free glass analyses from the proximal localities, which establishes the correlation between these deposits ([see Table 3](#)) consistent with the well constrained chronologies at these sites. This microcryst-free glass composition (Sr 73 to 113-ppm) defines the composition (and compositional range) of the rhyolitic component of the Michimahuida magma at the onset of the eruption.

Solution-nebulisation-ICP-MS analyses were also conducted on bulk ash material and individual accretionary lapilli from a number of proximal- to distal-sites. Plots of the highly immobile elements (i.e. Th vs Zr) from Lépue Tephra correlatives from six proximal sites and sixteen distal sites located on Isla Grande de Chiloé and the coastal Chilean mainland are presented in [Fig. 21A](#). These results are compared with

individually analysed accretionary lapilli from seven proximal Lepué Tephra localities (Fig. 21B). While bulk ash analyses exhibit a wide elemental range (even between duplicate samples) and predominantly along a tightly clustered linear fractional crystallization pathway, accretionary lapilli samples exhibit a narrower elemental range positioned on the same linear pathway as the bulk ash samples. Lepué analyses were compared with similar analyses from Holocene-aged tephra beds (13) of tMim and its adjacent monogenetic satellite cones (here named Michimahuida Volcanic Complex, MimVC) (Fig. 21C). The elemental spread and orientation of tephra points are coincident along the Lepué Tephra linear evolutionary trend. These results indicate the limited utility of bulk analyses in the absence of associated chrono-stratigraphic contexts to be able to adequately differentiate MimVC-sourced eruptives. Results also indicate that all MimVC-sourced tephra irrespective of age, are fractionating under broadly similar phase equilibria constraints.

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526 *Confirming Michimahuida as the eruptive source*

527 Glass shard major-element chemistry indicates that the initial eruptive phase of
528 Lepué Tephra is rhyolitic in composition but distinguishable from all post-18,000 cal.
529 a BP Chaitén-sourced tephra. As the Lepué eruption progresses the composition
530 steadily becomes more basic and terminates in a compositional field that broadly
531 straddles the Trachyte-andesite, Andesite, Basaltic-trachyte-andesite and Basaltic-
532 andesite fields (see Fig. 19). This trend suggests a zoned magma body with a volatile-
533 rich aphyric cap above a more mafic and phenocryst-rich magma. This more mafic
534 end member of Lepué Tephra is similar to the composition (Basaltic-andesite) of
535 proximal MimVC deposits exposed at Campo Grande, Pumalín-2 and Pumalín-4 (see
536 Fig. 22). At these localities, dm-thick lapilli beds (CG-T3, Pum 2-T4, and Pum 4-T5)
537 can be directly associated with adjacent MimVC monogenetic scoria cone complexes
538 and lava flows. Two coarse-grained pumiceous lapilli and ash beds (Pum 2-T5 and
539 Pum 4-T7) have distinct compositions that straddle the Trachyte and Dacite fields and
540 on the same compositional trend as MimVC-sourced tephra (see Fig. 23). While these
541 two tephra cannot be associated with an identifiable MimVC source vent - coarse
542 grain-size and thickening characteristics would tend to indicate a putative MimVC-
543 source. The three compositional groups identified from proximal MimVC-sites are
544 similar to those identified from L. Teo (Moreno *et al.* 2014) and indicate a diverse
545 range of discrete small-volumed silicic to mafic melt bodies resident at different

levels within the MimVC sub-volcanic system and may reflect contributions from different upper mantle components (i.e. Hickey *et al.* 1986; Hickey-Vargas *et al.* 2002), differences in rates of crustal stagnation and differentiation as well as structural controls (i.e. Lopez-Escobar *et al.* 1995).

DISCUSSION

Relationship of Lepué Tephra to deglaciation

Lepué Tephra is one of the most widespread tephra marker beds to occur in this sector in the last 11,000 years and its early Holocene age is ideal for assessing the timing and rate of deglaciation and associated environmental changes as the climate ameliorated at the transition between the LGM and early Holocene.

Radiocarbon dates of organic material retrieved from the base of cores and sections through lacustrine and organic-rich sediments that overlie glacial deposits situated in areas formerly covered by ice lobes have been pivotal in terms of assessing the temporal-spatial extent of glaciers in this region and of relevance to this study, the timing of rapid ice lobe recession that followed the LGT advance into the LGM moraine belt. For example, a basal radiocarbon date from a low-elevation stratigraphic section containing Lepué Tephra at Puelche (see Fig. 5) indicates a minimum-limiting age of $14,070 \pm 35$ ^{14}C a BP ($17,107 \pm 99$ cal. a BP) for recession of the Seno Reloncaví ice lobe. Similarly a radiocarbon date from a coastal roadside outcrop just north of Chaitén (section 12A, Fig. 2) (also containing Lepué Tephra) indicates a minimum-limiting age of $13,830 \pm 50$ ^{14}C a BP ($16,737 \pm 125$ cal. a BP) for recession of the Golfo de Corcovado ice lobe. The persistence of ice lobes within low-elevation Cordilleran valley sites is indicated from minimum ages of c. 12,500 ^{14}C a BP ($14,600$ cal. a BP) from basal organic mud sequences overlying glacial till (i.e. Sta. Lucía, Fig. 7). Certainly, the spatial range of dates presented in this study support the findings of Moreno *et al.* (2015) that wholesale glacial recession in this region following the final advance of Andean ice lobes during a cold and wet LGT episode ($17,700$ - $18,100$ cal. a BP) was very abrupt with diminished lobes recessed within the confines of continental Andean valleys in less than 1000 years.

Synchronisation of late last glacial to early post-glacial vegetation and climate records

Pollen percentage curves of selected key taxa from six sites (arranged south to

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3 580 north; L. Melli, L. Tahui, L. Lepué, L. El Salto, Huelmo mire and L. Condorito)
4 581 between 8000 and 15,000 cal. a BP are shown in Fig. 24. While sediment cores from
5 582 these sites have been individually described in the literature, the recognition of the
6 583 widespread Lepué Tephra within these cores enable us to effectively time-slice and
7 584 synchronise vegetation/climate records across a broad latitudinal swath of
8 585 northwestern Patagonia and west of the Cordillera de los Andes. An intra-regional
9 586 summary of these synchronised records is presented here.

10 587 Palynological studies of organic sediments from numerous lake cores and cover-
11 588 bed sections that overlie glacial deposits or bedrock situated in areas formerly covered
12 589 by ice lobes indicate that the interval preceding Lepué Tephra (11,700-15,000 cal. a
13 590 BP) features dominance of closed-canopy temperate rainforests. Palynological records
14 591 from lowlands sites indicate a prominent increase in the cold-resistant conifer
15 592 *Podocarpus nubigena* starting at ~14,500 cal. a BP, concomitant with a decline in
16 593 thermophilous rainforest trees (*Myrtaceae*) and vines (*Hydrangea*) (Moreno 1997,
17 594 2004; Moreno *et al.* 1997, 2004; Moreno *et al.* 1999, Moreno *et al.* 2001; Moreno and
18 595 Leon, 2003). The species *P. nubigena* attained its maximum abundance between
19 596 12,700-13,000 cal. a BP, declined between 11,000-12,700 cal. a BP and then reached
20 597 minimum abundance until 8000 cal. a BP These changes suggest a cooling trend and
21 598 increase in precipitation between ~12,700-14,500 cal. a BP, followed by a decline in
22 599 precipitation and/or enhanced precipitation seasonality with intense fire activity
23 600 between ~11,000 -12,700 cal. a BP. Mainland sites show that fire disturbance
24 601 promoted forest gaps and colonization of the opportunistic, shade-intolerant tree
25 602 *Weinmannia trichosperma* over a cold and highly variable interval between ~11,000-
26 603 12,700 cal. a BP. Over the same interval, sites in Isla Grande de Chiloé (Abarzúa and
27 604 Moreno 2008; Abarzúa *et al.* 2004; Pesce and Moreno, 2014) show diversification of
28 605 the forest canopy, lake-level lowering and encroachment of species of the myrtle
29 606 family along the lake periphery. Deposition of the Lepué Tephra at ~11,000 cal. a BP
30 607 occurred when *P. nubigena* had already reached low abundance in mainland
31 608 palynological sites (L. Condorito, Huelmo mire), and at the culmination of a rapid
32 609 decline of this conifer in Chilotan sites (L. Lepué, L. Melli, L. Tahui). Chilotan sites
33 610 show abrupt increases in *W. trichosperma* following deposition of the Lepué Tephra;
34 611 likewise, mainland sites exhibit a secondary expansion of this species. These changes
35 612 have been interpreted as changes in temperature and precipitation, the latter associated
36 613 with variation in intensity in the southern westerly winds (SWW) attributable to

latitudinal shifts or intensity variations. Recent studies (Moreno *et al.* 2015; Moreno *et al.* 2010; Moreno *et al.* 2012) have proposed that the SWW intensified during the Antarctic Cold Reversal (~12,700-14,500 cal. a BP), shifted pole-ward during Younger Dryas time (~11,500-12,700 cal. a BP) and then weakened during the early Holocene (~7800-11,500 cal. a BP). These changes covaried with temperature and paleofires, with warm/dry conditions featuring enhanced fire activity and cold/wet climates inhibiting paleofires. Deposition of the Lepué Tephra occurred at the beginning of the warmest/driest interval of the last glacial-interglacial cycle, when the SWW attained their weakest condition and when SST's from core ODP-1233 reach a maximum of 15.6°C in the early Holocene (11,000 to 9000 cal. a BP) (Kaiser *et al.* 2005, 2008; Heusser *et al.* 2006).

Prevailing warm/dry climate conditions coupled with weak SWW flow might account for the broad distribution of Lepué Tephra west of Volcán Michimahuida at a time when zonal atmospheric flow did not impede its northwestward distribution toward the SE Pacific. However, the distribution of Lepué Tephra may have also been influenced by volcanological factors - in particular - a hybrid dry/wet plume that expands outward as a powerfully spreading umbrella cloud (see section below).

Eruption style and hazard implications

A schematic representation of the Lepué eruptive sequence centred at tMim is represented in Fig. 25. Dark grey, poorly-sorted, fine-grained sub-units of Lepué Tephra with accretionary lapilli and rain-flushed pore spaces within the ashy matrix clearly indicate the involvement of external water within the erupted mixture. The eruption comprising Lepué Tephra and its co-eruptive PDC (Amarillo Ignimbrite) is an excellent example of an early Holocene dominantly phreatomagmatic eruption derived from a volcanic massif presently mantled by an extensive area of permanent ice. Such eruptions are less usual compared with the more typical background of Strombolian to Plinian volcanism frequently experienced in this region during the Holocene. Thus, in the absence of proximal exposures on Volcán Michimahuida, it's not known if Lepué eruption was point-sourced and derived from a single magma reservoir, or alternatively, derived from a network of coalescing and/or discrete multiple co-genetic melt bodies (i.e. similar to the 2011 Puyehue-Cordón Caulle eruption, see Alloway *et al.*, 2015).

Within most sections adjacent to tMim, metre-thick accretionary lapilli bearing ash deposits with weak stratification between coarser and finer components can be observed and indicate fluctuating multilevel deposition – that is – coarse ash and lapilli transported farther during stable phases of the eruption (less water content with higher vertical velocities), yet deposited closer to source during periods of unstable water-rich plumes where moist convection simultaneously occurs both vertically and laterally away from the vent. If moist convection was a dominant feature of the Lepué plume, then a substantial portion of the initially erupted mass was likely ejected and maintained in the troposphere where temperature inversions inhibit the rise of the weaker, less stable portions of the eruption column. Under such circumstances, the ash plume would have had the tendency to spread outward as a broad, umbrella-shaped cloud. The combination of fluctuating multilevel transport/deposition and upwind/cross wind expansion at the troposphere would have likely favored the formation of a radially symmetrical ash cloud (see Houghton *et al.* 2015). Indeed, recorded thicknesses of Lepué Tephra over such an extensive area in all directions from source appear to support this scenario (see Fig. 17). While eruptive conditions were likely conducive to the broad radial distribution noted for Lepué Tephra, this distribution could also be attributed to the reduced SWW intensity interpreted from equivalent-aged environmental records.

In the advent of a future sustained eruption of similar magnitude to the Lepué eruption centred upon the ice-capped tMim, a centimetre-thick wet ash fall could be reasonably expected up to ~ 200-km from volcanic source and potentially affecting communities and critical infrastructure westward in Isla Grande de Chiloé, northwards towards the city of Puerto Montt and east and south-eastwards towards the communities of Futaleufú on the Chilean frontier and Esquel and Trevelin located in Argentina. Eruption-induced sub-glacial and surface melting of ice and snow on tMim is also likely to occur and lead to significant melt-water formation, jökulhlaups, and lahars extending down adjacent tributaries. Such events have already been shown to be a significant hazard in areas of Iceland (i.e. Katla, 1918; Eyjafjallajökull 2010), Alaska (i.e. Redoubt, 2009), Cascades (i.e. Mt. Rainier), Antarctica (i.e. Deception Island, 1969) and in parts of the Andes (i.e. Nevado del Ruiz, 1985). Although the area surrounding Volcán Michimahuida is sparsely populated with little critical infrastructure, melt-water floods and/or water-supported mass-flows would inundate picturesque and increasingly popular low-lying river-side tourist campgrounds within

681 Parque Pumalín and scattered farm dwellings farther down-stream. The community of
682 Amarillo would likely be affected, though inundation is likely to be minimized by
683 recent engineering works that have elevated and armored adjacent river-banks.

684
685 In summary, while Lepué Tephra is temporally associated with rhyolitic products
686 from nearby Volcan Chaitén, its physical and geochemical attributes are typical of
687 a complex (zoned) phreatomagmatic eruption sourced from tMim. We propose that
688 the eruption commenced with initial magma withdrawal from the top of a melt body
689 dominated by fractionated Si-rich magma (~71 wt % SiO₂), which propagated
690 downwards into the hosting crystalline-rich magma and ultimately resulted in the Si-
691 rich magma being rapidly and almost entirely replaced by microphenocrysts with very
692 minor interstitial melt (~55 wt % bulk SiO₂). Despite compositional heterogeneity, we
693 were still able to characterise both the aphyric and microlitic glass of the Lepué
694 Tephra by grain discrete and bulk analytical techniques to define a broad
695 compositional array enabling us to distinguish and widely correlate this tephra marker
696 in both terrestrial and marine realms of northwestern Patagonia. While discrete and
697 bulk glass shard trace element analyses may be of significant use in petrogenetic
698 studies, this study also illustrates its utility in substantiating correlation beyond that
699 already established from major element (EMP) analyses.

700 Lepué Tephra with its phreatomagmatic style and its compositional heterogeneity
701 is exceptional in the context of other documented eruptions known from this Andean
702 sector. We consider that our integrative approach of intensive mapping supported by
703 multi-technique geochemical analysis is a useful template for the characterisation and
704 correlation of such complex and compositionally variable tephra deposits elsewhere.
705 Ultimately, our approach applied to weathered tephra in wet, hyper-humid
706 environments, like that of northwestern Patagonia, will be of great assistance in the
707 synchronisation of different equivalent-aged sedimentary archives.

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709 [Words 7418]

710
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729

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911 **FIGURES**

912 **Fig. 1. A, B.** The location of the study area in Llanquihue-Puerto Montt, Hornopirén,
913 Chaitén, Isla Grande de Chiloé and Esquel Sectors of northwestern Patagonia.
914 Coloured insets within Fig. 1B indicate the location of key transects presented in this
915 paper that detail the stratigraphy of Lepué Tephra. **C.** Extent of ice lobes within the
916 study area during the Last Glacial Maximum (LGM) (modified from Plates 1-4 in
917 **Denton *et al.* 1999**). Moraine ridges or hills are indicated in red and areas of present-
918 day permanent ice are indicated in black. The location of core ODP Site 1233

offshore of southern continental Chile is also indicated.

920

Fig. 2. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section 7 located within Chaitén township northward to Section 5 at Puente Águila on Ruta 7 ~ 8.2-km south of Caleta Gonzalo.

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Fig. 3. Lepué Tephra at Sections 7 (A), 8 (B, C), 9 (D), 9D (E), 9B (F, G) and 5 (H) that illustrate the complex internal architecture of magmatic (LT-m) and phreatomagmatic (LT-phr-m) fall and flow (LT-sur) co-eruptive phases (see Fig. 2).

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Fig. 4. The stratigraphy of Section 4 located on Ruta 7 on the southern side of the pass connecting Lago Blanco (south) with Lago Negro (north). The stratigraphy at this section reveals a prominent rhyolitic pumiceous lapilli (Cha-1 *sensu stricto*) dated at *c.* 8700 ¹⁴C a BP and sourced from an ancestral Chaitén Volcano. Cha-1 tephra (now formally renamed Chana Tephra; Alloway *et al.* submitted) closely overlies a lower fall and surge co-eruptive couplet (Lepué Tephra) of presumed Michimahuida-source. The surge deposit is directly dated at 11,483 ± 1034 cal. a BP (9960 ± 330 ¹⁴C a BP; UCIAMS-145938). The spade is 1-m length; (B) Low-angle cross-bedding and cross-cutting relationship of the surge across its co-eruptive fall deposit; (C) The entire sequence is underlain by a widespread and distinctive layer of banded rhyolite breccia (indicated by arrows) that likely represent an explosion of a pre-Cha-1/Chana Tephra lava dome (ancestral VCha).

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Fig. 5. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section 5 at Puente Águila northwards to sections located in the vicinity of Seno Reloncaví and Ralún. Note the closely overlying occurrence of Cha-1 (now formally named Chana Tephra, see Alloway *et al.* submitted) sourced from VCha.

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Fig. 6. A. Massive > 40-m thick pyroclastic density current (PDC) deposit exposed at Pumalín-1 (Pum-1) section along road W-887 located directly adjacent to Río Michimahuida. This PDC-deposit correlates with Amarillo Ignimbrite of Amigo *et al.* (2013) and is considered contemporaneous with Lepué Tephra on the basis of its equivalent stratigraphic position and age. Arrow indicates oriented, metre-sized, lithic

clast transported within this PDC; **B.** Typical PDC-internal architecture with dispersed poorly sorted, angular, lithic clasts and rare charcoal fragments that are dated at $11,190 \pm 88$ cal. a BP (9785 ± 30 ^{14}C a BP; LLNL-122960); **C.** Remnant Amarillo Ignimbrite valley-infill surface viewed northwest from W-887 roadside lookout ($42^{\circ} 55' 18.33''$ S; $72^{\circ} 23' 46.99''$ W); ~ 436 -m asl). Note that this surface is clearly inclined towards the Michimahuida massif (tMim).

Fig. 7. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section Pumalín-3 southward to Santa Lucía-3 ~ 2.4 -km north of the Sta. Lucía-Futaleufú junction. Note the occurrence of a diamict (1.82 to 2.68-m below surface) within Sta. Lucía-1 containing fragmental rock clasts, wood and organic rip-up clasts (dated at *c.* 9400 ^{14}C a BP; *c.* 10,600 cal. a BP). The internal architecture strongly suggests deposition from a debris avalanche event. Although the erosional base of this debris avalanche deposit is associated with a prominent tephra, the two events do not appear to be chronologically related. On this basis it seems more likely that this catastrophic avalanche event was probably triggered by tectonic seismicity.

Fig. 8. Lepué Tephra at Sections 1 (A), 13 (B) and 14 (C, D, E) of the southern transect (see Fig. 7). Here, Lepué Tephra is dominated by compact grey, poorly-sorted and crudely stratified ‘lapilli-tuff’ deposits (phreatomagmatic phase) containing dispersed centimetre-sized accretionary lapilli (D) and obvious open interstitial pore spaces (E) indicative of rain flushing. No co-eruptive magmatic phase was identified.

Fig. 9. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section Pumalín-2 eastwards to La Zeta 3-km west of Esquel in Argentina. A lake record from Lago Espejo, Futaleufú, Chile is also included to show correlation of Lepué Tephra as well as rhyolitic tephra sourced from an ancestral Volcan Chaitén. The inset photo shows Lepué Tephra as preserved enveloped by paleolake sediments at La Zeta. Note the well-defined shower bedding with a thin, well-sorted coarse ash base (initial magmatic phase) overlain by compact, grey-coloured poorly-sorted massive structured very fine ash (phreatomagmatic phase) followed by proportionally thicker normal-graded moderately well sorted very coarse to fine ash (magmatic phase). This eruptive architecture is in accord with

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3 987 features from more proximal localities that similarly indicate a complex
4 988 phreatomagmatic-magmatic eruption style for Lepué Tephra.

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8 990 **Fig. 10.** Stratigraphic columns showing the correlation of Lepué Tephra along the
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10 991 western transect from south-central Isla Grande de Chiloé northward towards Puerto
11 992 Montt in southernmost continental Chile. In northern sections (i.e. Huelmo and along
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13 993 Ruta 5 connecting Pargua with Puerto Montt) Lepué Tephra is closely underlain by
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15 994 intensely weathered andesitic ash and lapilli ‘ghosts’ that are most likely derived from
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17 995 either Volcanes Calbuco or Yate located to the eastward along the Andean mountain
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19 996 divide. These weathered tephra have yet to be geochemically characterized. At the La
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21 997 Paloma site located between Puerto Montt and Alerce, Lepué Tephra forms a
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23 998 continuous layer ~12-cm thick within peat and is closely overlain (~20-cm) by
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25 999 discontinuous and irregularly thick (< 1-cm) of Cha-1 (Chana Tephra). The other
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27 1000 photo inset shows the Lepué Tephra at its northernmost occurrence within Lago
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29 1001 Pichilaguna, immediately west of Llanquihue township and 180-km northwest of
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31 1002 Volcán Michimahuida. Here, Lepué Tephra occurs within core 1402AT3 at 382 to
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33 1003 390-cm depth as a ~8-cm thick dark olive-grey, normal graded coarse to very fine ash.
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35 1004 In this same vicinity, Lepué Tephra is not recognized macroscopically within the
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37 1005 andic soil-forming environment.

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39 1007 **Fig. 11.** The variable morphological expression of Lepué Tephra within cover-bed
40 1008 sections (Queilen, Lago Natri, Chonchi, Castro, Puente Puntra and Chacao) in Isla
41 1009 Grande de Chiloé (see Fig. 10). The position of Lepué Tephra is indicated by yellow
42
43 1010 arrows. At all sections in this sector Lepué Tephra is the only macroscopic tephra
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45 1011 observable within the cover-bed sequence and forms highly irregular, discontinuous
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47 1012 pods of cemented fine ash. Typically in this sector, Lepué Tephra is enveloped by
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49 1013 andic soil material and closely overlies colluvium, bedded fluvio-glacial gravels and
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51 1014 sands and glacial diamictons (till). In cases where Lepué Tephra closely overlies
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53 1015 impermeable glacial diamictons which seasonally perch the local water table, tephra
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55 1016 colour is strongly altered to strong brown chromas, whereas Lepué Tephra enveloped
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57 1017 by thicker successions of free-draining andic soil material typically have grey to pale
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59 1018 brown chromas.

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1020 **Fig. 12.** Lepué Tephra occurring within cover-bed sections in southernmost

1021 continental Chile (San Augustin, Huelmo and Ruta 5 connecting Pargua with Puerto
1022 Montt). Sections (Caleta La Arena, 13-S7, 13-S8, Chapo S1) in the vicinity of Seno
1023 Reloncaví are also shown (see Figs. 5 and 10). Note that Cha-1 is now formally
1024 renamed Chana Tephra (Alloway *et al.*, submitted).

1025
1026 **Fig. 13.** Down-core inorganic densities (gr/cc) of lake sediments retrieved from Isla
1027 Grande de Chiloé (i.e. Quilque, Tarumán, Lepué, Melli and Tahui), coastal
1028 continental lakes and mires east of Golfo de Ancud (Lago Proschle and Puelche),
1029 south (i.e. Condorito, Huelmo, El Salto) and north (i.e. Pichilaguna) of Puerto Montt.
1030 The occurrence of Lepué Tephra is strongly indicated in all records and is closely
1031 overlain by a subordinate peak. This lesser peak (i.e. Isla Grande de Chiloé sites)
1032 likely coincides with a c. 8 cal. ka Chaitén-sourced rhyolitic cryptotephra (Puma
1033 Verde Tephra, see Alloway *et al.*, submitted), which unlike Lepué Tephra is not
1034 typically expressed macroscopically in adjacent andic soil cover-beds.

1035
1036 **Fig. 14.** Magnetic susceptibility (SI units; indicated in green) and alkenone-based Sea
1037 Surface Temperature estimates (°C) of ODP-202 Site-1233 (indicated in red). The
1038 position of calibrated radiocarbon ages are indicated on the right. The inset shows a
1039 prominent macroscopic tephra encapsulated within clay and silty clays between 14.52
1040 and 14.83-mcd and is accompanied by a prominent spike in magnetic susceptibility
1041 (916.8-m.mol⁻¹ (SI)). Unfortunately, no radiocarbon dates were obtained directly
1042 associated with the upper and lower contacts of this tephra but bracketing radiocarbon
1043 samples from 12.94 and 17.01-mcd yielded calibrated ages of 10,040 and 12,260 cal.
1044 a BP, respectively.

1045
1046 **Fig. 15.** Weighted mean modeled age determination (9588 ± 20 ¹⁴C a BP) for Lepué
1047 Tephra based on four R-combine-statistically grouped samples (UCIAMS-145938,
1048 LLNL-158290, LLNL-123032 and LLNL-12329) from Sections 4, 12A, Pichileufú
1049 and Puelche, respectively. Three ¹⁴C sample outliers from Sections 9, 12A and
1050 Pumalín -1, (LLNL-158125, LLNL-158291 and LLNL-122960) were rejected. The
1051 Southern Hemisphere terrestrial calibration curve (SHCal13) and OxCal Program
1052 (v.4.2.4) were used for all samples radiocarbon dated in this study.

1053
1054 **Fig. 16.** Modeled ages determinations of Lepué Tephra from Huelmo mire (Moreno

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1055 and Leon, 2003), L. Condorito (Moreno, 2004), L. Tahui (Abarzúa *et al.*, 2004), L.
1056 Melli (Abarzúa and Moreno, 2008) and L. Lepué (Pesce and Moreno, 2014).
1057 Modelled ages are arranged according to intervals (cm) sampled with respect to the
1058 basal contact of Lepué Tephra. Error bars represent $\pm 2 \sigma$. A weighted mean modeled
1059 age determination of 9725 ± 23 ^{14}C a BP for Lepué Tephra is based on eight R-
1060 combine-statistically grouped samples from Huelmo mire (ETH-20386), L. Condorito
1061 (A8069), L. Tahui (NSRL-12473 and GX28215), L. Melli (ETH-25249) and L. Lepué
1062 (CAMS-125915 and ETH-25451). The associated mean age of $10,994 \pm 124$ cal. a BP
1063 is indistinguishable from a mean age of $10,909 \pm 228$ cal. a BP determined for Lepué
1064 Tephra from Chaitén (S-4, S-12A), Puelche and Pichileufú (this study; Fig. 5).

1065
1066 **Fig. 17.** Map of the study area indicating the maximum-recorded thicknesses (in
1067 centimetres) of Lepué Tephra occurring within andic soil cover-bed sections. At any
1068 one site, it is usually very difficult to derive a representative thickness for the
1069 pocketed, highly irregular and variably thick Lepué Tephra. Thickness values from
1070 lake cores are also shown and indicate considerable thickness differences between
1071 adjacent soil and lacustrine depositional environments. Large thickness variations
1072 were also noted between closely situated closed basin lakes suggesting that either
1073 tephra thickness measurements made from previous studies may not have
1074 distinguished between primary and secondarily tephric inputs or perhaps, the
1075 existence of more complex sedimentary inputs to these lake systems.

1076
1077 **Fig. 18.** Selected back-scatter electron (BSE) images of glass shards from Lepué
1078 Tephra correlatives showing the varying concentration of dominantly plagioclase
1079 microlites within their glassy matrix (A, B – lowermost Lepué, Section 4; C –
1080 lowermost Lepué, Section 5; D – uppermost Lepué, Section 5; E - 1819-1821 cm, L.
1081 Lepué; F - 1831-1838 cm, L. Lepué; G – Lepué Tephra, Puente Puntra, Isla Grande
1082 de Chiloé; H – 14.68 m, ODP-1233D). Low microlite concentrations were observed
1083 within glassy grains at base of the tephra (onset of the Lepué eruption; A, B, C),
1084 however, the microlite concentration within the matrix of glassy grains significantly
1085 increases (D, E, F) progressively upwards within the tephra deposit. In distal
1086 localities, the overwhelming dominance of glass grains containing profuse microlites
1087 made it very difficult and in many cases, impossible for 10-20 μm diameter electron

1088 and laser beams to be positioned on glass and without any obvious microlite
1089 contamination (i.e. **G, H**). Note that as the microlite concentration increases, the
1090 proportion of well-formed oriented vesicles decrease with a corresponding increase in
1091 irregular shaped (collapsed) and coalesced voids (**D, F**).

1092
1093 **Fig. 19.** Selected major element compositions (weight percent SiO_2 vs $\text{Na}_2\text{O} + \text{K}_2\text{O}$
1094 and FeO vs K_2O and CaO) of glass shards from Lepu Tephra correlatives. Two glass
1095 end members, microlite-poor and microlitic, are plotted to show compositional and
1096 elemental concentration differences occurring between these two end members. All
1097 post-18,000 cal. a BP Chaitn-sourced tephra are plotted for comparison.

1098
1099 **Fig. 20.** Nd vs Th and Sr vs Y, Ho, Nd, Zr compositions of glass shards from Lepu
1100 Tephra correlatives determined by grain discrete LA-ICP-MS analysis. Microlite-poor
1101 and microlitic glass data are plotted and show significant concentration differences
1102 between these two glass types associated with the ablation of (dominantly)
1103 plagioclase with glass. The microlite-poor glass compositions occur between 73 -113
1104 ppm Sr, and these analyses are indicated on the plot of Nd vs Th. See text for
1105 explanation.

1106
1107 **Fig. 21.** Th vs Zr (ppm) plots as determined by bulk sample solution-ICP-MS analysis
1108 showing Lepu Tephra correlatives from proximal and distal (continental Chile and
1109 Isla Grande de Chilo). These results are compared with individually analysed
1110 accretionary lapilli from seven proximal Lepu Tephra localities. Tephra beds of
1111 presumed MimVC-source stratigraphically associated with Lepu Tephra are plotted
1112 for comparison.

1113
1114 **Fig. 22.** Sections containing analysed proximal tephra beds sourced from satellite
1115 MimVC monogenetic scoria cones. Inset map shows the location of associated
1116 satellite MimVC monogenetic scoria cone complexes and lava flows, sections
1117 containing analysed Lepu Tephra and Amarillo Ignimbrite and its remnant valley-fill
1118 surface.

1119
1120 **Fig. 23.** SiO_2 vs $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (wt. %) compositions of glass shards from **A.** proximal-
1121 distal Lepu Tephra compared with proximal tephra beds sourced from satellite

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MimVC monogenetic scoria cones, and **B.** post-11,000 cal. a BP tephra beds from L. Teo (Moreno *et al.*, 2014). All tephra beds (except Pum 4-T7) as well as Group 2 and 3 tephra inter-beds from L. Teo occur on the same fractional crystallisation pathway as analysed Lepué Tephra. The compositions of all post-18,000 cal. a BP. Chaitén-sourced tephra are indicated for comparison.

Fig. 24. Pollen percentage curves of key taxa from 6 sites (arranged south to north; L. Melli, L. Tahui, L. Lepué, L. El Salto, Huelmo mire and L. Condorito; see Fig. 17) between 8000 and 15,000 cal. a BP Background blue represents an interval of interpreted cold/wet climate, green - an interval of cold and seasonally dry climate, and pink – an interval of warm and dry climate. Lepué Tephra occurs at all sites and its position within each record is indicated (LT).

Fig. 25. A schematic model for Lepué Tephra and its co-eruptive PDC (Amarillo Ignimbrite). **A.** A zoned magma body within the MimVC sub-volcanic system comprising a volatile-rich cap of dominantly fractionated glass occurring on top of a more mafic phenocryst-rich magma; **B.** Explosive phreatomagmatic eruption involving snow and ice from tMim and dominantly upward thrust of volatile-rich fractionated magma forming a stable column with associated fall dominated by aphyric glass; Episodic moist convection generates flanking PDC deposits; **C.** As the eruption continues, magma withdrawal steadily propagates downwards into the underlying crystal-rich magma and results in a fall increasingly dominated by microphenocrysts with very minor interstitial melt; Intensified water vaporisation results in heightened convection and plume instability; **D.** Continued oscillations between buoyant (dry) and wet eruptive phases leads to the development of a multilevel plume; Continued sustained moist convection and climactic plume collapse generates the Amarillo Ignimbrite.

Table Captions

Table 1. Radiocarbon dates and ages associated with Lepué Tephra and its distal correlatives. The Southern Hemisphere terrestrial calibration curve (SHCal13) and OxCal Program (v.4.2.4) were used for all radiocarbon samples dated in this study.

Table 2. Summary of individual glass shard major-element compositions (normalised to an anhydrous basis) of proximal to distal Lepué Tephra in the Chaitén, Isla Grande de Chiloé and Esquel Sectors of NW Patagonia.

Table 3. Summary of individual glass shard trace-element compositions of proximal to distal Lepué Tephra in the Chaitén, Isla Grande de Chiloé and Esquel Sectors of NW Patagonia obtained by LA-ICP-MS at Aberystwyth. All concentrations in ppm unless otherwise stated.

Table 4. All trace-element concentrations from bulk Lepué Tephra correlative samples obtained by Solution-nebulisation-ICP-MS at Aberystwyth University, Wales. All concentrations in ppm unless otherwise stated.

SUPPLEMENTARY INFORMATION

METHODS

Electron Microprobe (EMP) technique

Major-element determinations were made on a JEOL Superprobe (JXA-8230) housed at Victoria University of Wellington, using the ZAF correction method. Analyses were performed with 15 kV accelerating voltage, 8 nA beam current, and an electron beam defocused to between 20 to 10 µm. Standardization was achieved by means of mineral and glass standards. A rhyolitic glass standard (ATHO-G) was routinely used to monitor calibration in all analytical runs, and used to evaluate any day-to-day differences in the calibration. The large number of samples precluded conducting all analyses in a single batch. All analyses are normalized to 100 wt. % anhydrous, with H₂O by difference being given, and total Fe is reported as FeO. Glass shard major-element analyses are presented in [Table 2](#). All analyses are available upon request to the corresponding author.

Laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) technique

Trace-element analyses on individual glass shards were performed by laser ablation (LA) ICP-MS in the Department of Geography and Earth Sciences,

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1188 Aberystwyth University, using a Coherent GeoLas ArF 193 nm Excimer LA system
1189 coupled to a Thermo Finnegan Element 2 sector field ICP-MS. Trace element data
1190 were collected for individual shards with the majority of analyses performed using 20
1191 μm ablation craters. Laser fluence was 10 Jcm^{-2} at a repetition rate of 5 Hz for a 24
1192 second acquisition. The minor ^{29}Si isotope was used as the internal standard, with
1193 SiO_2 (determined by EMPA) used to calibrate each analysis, after normalization to an
1194 anhydrous basis. The NIST 612 reference glass was used for calibration, taking
1195 concentrations from [Pearce *et al.* \(1997\)](#). A fractionation factor was applied to the
1196 data to account for analytical bias related to the different matrices of the reference
1197 standard and the sample. For this factor as well as ICP-MS and laser operating
1198 conditions see [Pearce *et al.* \(2011\)](#), and references therein. The MPI-DING reference
1199 glass ATHO-G ([Jochum *et al.* 2006](#)) was analysed as an unknown under the same
1200 operating conditions at the same time. Analytical precision is typically between ± 5 -
1201 10%, and accuracy is typically around $\pm 5\%$, when compared with the published
1202 GeoReM concentrations for ATHO-G. Glass shard trace-element analyses are
1203 presented in [Table 3](#).

1204

1205 **Solution nebulisation inductively coupled plasma mass spectrometry (ICP-MS)** 1206 **technique**

1207
1208 Dried bulk samples were crushed and homogenised using an agate mortar and
1209 pestle to a fine powder and bagged. To ensure no sample cross-contamination
1210 occurred, all crushing equipment was washed with $18.2 \text{ M}\Omega$ deionised H_2O
1211 (MilliQ®), 5% HCl (hydrochloric acid) and 5% HNO_3 (nitric acid) between the each
1212 sample. Subsequently, 0.25 g of each homogenised sample was weighed into
1213 polytetrafluoroethylene (PTFE) beakers ready for standard HF/ HClO_4 acid digestion
1214 (performed by Andy Brown in the Geochemistry Laboratory, DGES). Initially
1215 samples were treated with 5 mL concentrated HCl and evaporated to dryness,
1216 followed by an open HF/ HClO_4 digestion (15 mL/4 mL) which was left cold
1217 overnight before evaporation to dryness at about 170°C . A second HF/ HClO_4
1218 digestion was used if needed. Once dry, 4 mL of HClO_4 was added to each sample
1219 and evaporated to dryness to remove any residual HF, and the samples were then
1220 taken up to a final volume of 250 ml in 2.5% HCl and stored in Nalgene™ sample
1221 bottles ready for analysis by solution nebulisation Inductively Coupled Plasma – Mass
1222 spectrometry (SN-ICP-MS) to determine their trace-element content in the

1223 Department of Geography and Earth Sciences, Aberystwyth University. All acids
1224 were AnalaR grade or better, and blanks were prepared with all batches of samples.
1225 Analyses were performed on an Agilent 7700 ICP-MS, which determined a range of
1226 trace elements, with low masses (<52) determined using He as a collision gas to
1227 reduce polyatomic interferences (He-mode). Calibration was achieved against multi-
1228 element synthetic standards produced from stock single element standard solutions,
1229 and Te was used as the internal standard for analyses. Some samples were prepared in
1230 triplicate and dispersed through the analytical run, and indicate analytical precision is
1231 better than 4% on average (although this varies with within element concentration
1232 etc., see [Pearce *et al.* 2004](#)). Two reference materials (USGS QLO-1 Quartz Latite
1233 and GSJ JA-3 Andesite) were routinely analysed to check accuracy. Analyses are
1234 presented in [Table 4](#).
1235
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1245 Jochum, KP, Stoll B, Herwig K. *et al.* 2006. MPI-DING reference glasses for in situ
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Pumalín-3
10.3 km from Ruta 7-
Termas El Amarillo
road junction
(10.020 road marker)
S 42° 57' 49.6"
W 72° 24' 06.4"

Section 13
S 43° 08' 34.9"
W 72° 26' 26.1"

Section 1
(south-side)
S 43° 09' 49.3"
W 72° 25' 44.8"

Sta. Lucía-1
24.3-km south of
Puente Yelcho
(70.060 Road Marker)
S 43° 21' 43.3"
W 72° 23' 28.7"

Sta. Lucía-2
25-km south of
Puente Yelcho
(70.760 Road Marker)
S 43° 22' 01.1"
W 72° 23' 09.9"

Sta. Lucía-3
2.4-km north of
Sta. Lucia-Futaléufú
junction
S 43° 23' 25.0"
W 72° 22' 22.3"

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Lepuë Tephra

Microlite-poor glass

- ▲ Section 4, 14J13S4-2 (n=18)
- Lago Lepuë, 020DT8 1831 (n=2)
- Section 5, 14J13S5-1 (n=16)
- La Zeta, LAZ-T7 (n=30)
- ✚ 1233D, 14.68-m (n=5)

Microlitic glass

- ☆ Lago Lepuë, 020DT8 1804 (n=8)
- Lago Lepuë, 020DT8 1831 (n=6)
- ★ Pumalin 4-9 (n=5)
- ✚ Lago Espejo, F19 (n=22)
- 1233D, 14.68-m (n=20)

all post-18 cal. ka BP Chaitén-sourced tephra

Proximal Localities

- ◆ Section 1 (Fig. 7)
- ▽ Section 4 (Figs. 2 and 4)
- ▼ Section 5 (Fig. 2)
- ◇ Section 6 (Fig. 2)
- ⬢ Section 9C
- ◇ Section 9D (Fig. 2)
- ⬢ Pumalin 4-9 (Fig. 9)

- Accretionary lapilli - 32 samples
7 localities (see Fig. 21B)
- ◆ light blue assorted symbols -
tephra beds of presumed MimVC-
source stratigraphically associated
with Lepué Tephra (see Fig. 21C)

Distal Localities -
Continental Chile

- Puelche (Fig. 5)
- ⬢ Puente Pichileufu (Fig. 5)
- ◇ Cholgo (Fig. 5)
- ⬢ Seno Reloncavi 13-S7 (Figs. 5 and 10)
- Pto.M-Pargua - 0.2 km
- Pto.M-Pargua - 4.1 km (Figs. 10 and 12)
- ☆ Huelmo - 7.8 km (Figs. 10 and 12)
- ◇ Huelmo - Quarry
- ▲ Caleta La Arena (Fig. 12)
- 1233D (n=6), (Fig. 14)

Distal Localities -
Isla Grande de Chiloé

- ★ Chacao
- ⬢ Puente Puntra - basal (Figs. 10 and 11)
- ⬢ Puente Puntra - upper
- ⬢ Lago Natri (Figs. 10 and 11)
- ⬢ Chonchi (Figs. 10 and 11)
- Lago Lepué (n=5), (Fig. 13)

Accretionary Lapilli

- ▲ Section 4 (n=1)
- Section 5 (n=1)
- ⬢ Section 8 (n=4)
- ◇ Section 9 (n=6)
- △ Section 1 (n=6)
- ⬢ Section 13 (n=9)
- ⊗ Section 14 (n=5), (Fig. 8)

(Fig. 2)

(Fig. 7)

(Fig. 8)

Tephra beds of presumed MimVC-source
stratigraphically associated with Lepué Tephra

- Section 1 Cor-3b
- Section 1 Cor-3a
- ◇ Section 1 Unk-2 (n=2)
- ⬢ Section 1 Cor-2
- ⬢ Section 1 Unk-1 (n=2)
- ⬢ Section 1 Yan-1
- △ Pumalin 2-4
- ⬢ Pumalin 2-11
- Pumalin 4-5
- ⬢ Pumalin 4-7
- ⬢ Alérce-6-2
- ◇ Campo Grande (Fig. 22)
- ⬢ Raya-2 (lithic debris flow clasts (n=3),
(see Fig. 7 of Alloway *et al.* in press)

(Fig. 7)

(Fig. 9)

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Proximal-distal Lep Tephra

- Section 4, 14J13S4-2 (aphyric, $n=18$)
- Section 5, 14J13S5-1 (aphyric, $n=16$)
- Pumalin 4-9 (microlitic, $n=5$)
- La Zeta, LAZ-T7 (aphyric, $n=30$)
- Lago Lepu, 020DT8 1831 (aphyric, $n=8$)
- Lago Lepu, 020DT8 1804 (microlitic, $n=8$)
- 1233D, 14.68-m (aphyric, $n=5$)
- 1233D, 14.68-m (microlitic, $n=20$)

Proximal Michimahuida Volcanic Complex (MimVC) deposits

- Pum 2-T4 ($n=17$)
- Pum 2-T5 ($n=17$)
- Pum 4-T5 ($n=13$)
- Pum 4-T7 ($n=3$)
- Campo Grande T3 ($n=17$)
- All post-18 cal. ka BP Chaitn (VCha)-sourced tephra

Lago Teo - post 11 cal. ka tephra interbeds

GROUP-1 (VCha-sourced)

- LTT-1 ($n=70$)
- LTT-2 ($n=102$)
- LTT-4 ($n=18$)
- LTT-5 ($n=138$)
- LTT-6 ($n=37$)
- LTT-12 ($n=48$)
- LTT-17 ($n=62$)
- LTT-22 ($n=31$)
- LTT-23 ($n=16$)
- LTT-25 ($n=15$)

GROUP-2

- LTT-8 ($n=33$)
- LTT-18 ($n=15$)
- LTT-20 ($n=30$)

GROUP-3

- LTT-3 ($n=30$)
- LTT-7 ($n=33$)
- LTT-9 ($n=16$)
- LTT-10 ($n=15$)
- LTT-14 ($n=13$)
- LTT-15 ($n=8$)
- LTT-26 ($n=9$)

Location	Lab ID	Sample type	Sample position	¹⁴ C AMS age (¹⁴ C a BP)	Calibrated ‡ Age (± 2σ) (cal. a BP)	95% HPDF * (cal. a BP)
Onshore						
<i>(this study)</i>						
S-4, Chaitén *	UCIAMS-145938	Charcoal (twig)	Within surge deposit (co-eruptive correlative)	9,960 ± 330	11,483 ± 1,034	10,561-12,552
Pumalín-1, Chaitén	LLNL-122960	Charcoal (outer small tree)	Within pyroclastic deposit (co-eruptive correlative)	9,785 ± 30	11,190 ± 88	11,108-11,237
Pte Pichileufú *	LLNL-123032	Bulk carbonac. muds	Immediately below lower contact	9,635 ± 35	10,934 ± 118	10,753-11,134
Puelche *	LLNL-123029	Bulk highly carbonac. muds	Immediately below lower contact	9,570 ± 30	10,862 ± 250	10,595-11,080
S- 9, Chaitén	LLNL-158125	Bulk carbonac. muds	Immediately below lower contact	10,330 ± 40	12,033 ± 280	11,825-12,383
S-12A, Chaitén *	LLNL-158290	Bulk carbonac. muds	Immediately below lower contact	9,560 ± 35	10,841 ± 262	10,563-11,081
	LLNL-158291	Wood in growth position	Immediately below lower contact	9,970 ± 35	11,321 ± 170	11,234-11,500
R_combine modelled age (n=4 *)				9,588 ± 20	10,909 ± 228	10,714-11,080
<i>(Previous studies)</i>						
Huelmo (Moreno & Leon, 2003)	NSRL-12478	Wood	901B-601A, 666.5- cm	9,030± 60	10,139 ± 214	9,914-10,246
	Lepúe tephra correlative (10-cm thick), 700-cm depth (basal contact)					
	ETH-20386	Bulk gyttja	901B-601A, 702-cm	9,695± 90	10,982 ± 290	10,735-11,225
	ETH-18856	Wood	901B-601A, 706-cm	9,415± 80	10,595 ± 286	10,289-11,063
	AA23236	Wood	901B-601A, 706-cm	9,635± 85	10,938 ± 284	10,696-11,196
	ETH-188857	Bulk gyttja	901B-601A, 710-cm	9,545± 70	10,820 ± 308	10,580-11,100
	ETH-24476	Bulk gyttja	901B-601A, 712-cm	9,830± 75	11,208 ± 244	10,800-11,399
Lago Condorito (Moreno, 2004)	A8070	Bulk gyttja	PM10, 685-688-cm	9,680± 85	10,967 ± 282	10,732-11,211
	A8069	Bulk gyttja	PM10, 710-713-cm	10,060± 80	11,527 ± 328	11,245-11,917
	Lepúe tephra correlative (27-cm thick), 726-cm depth (basal contact)					
	A8068	Bulk gyttja	PM10, 821-824-cm	11,265 ± 65	13,090 ± 148	12,928-13,258
Laguna Tahui (Abarzúa et al., 2004)	GX28215		004D, 891-895-cm	8,990 ± 110	10,029 ± 332	9,635-10,367
	Lepúe tephra correlative (16-cm thick), 932-cm depth (basal contact)					
	NSRL-12473	Bulk gyttja	004D, 934-936-cm	10,150± 50	11,703 ± 296	11,403-11,960
Lago Meli (Abarzúa and Moreno, 2008)		Terrestrial macrofossil	818-819-cm	9,105 ± 70	10,227 ± 218	9,930-10,479
	Lepúe tephra correlative (11-cm thick), 843-cm depth (basal contact)					
	CAMS-115814	Bulk gyttja	844-cm	10,000± 40	11,377 ± 218	11,247-11,610
Lago Lepúe (Pesce & Moreno, 2014)	ETH-25451	Bulk gyttja	0201 DT8, 786-cm	8,965 ± 65	10,033 ± 234	9,781-10,227
	Lepúe Tephra (44-cm thick), 870-cm depth (basal contact)					
	CAMS-125915	Bulk gyttja	0201 DT9, 904-cm	10,360 ± 40	12,123 ± 272	11,948-12,401
Offshore						
ODP Site 1233D (Lamy et al. 2004)	KIA 21451	Mixed planktonic foraminifera	12.94 mcd	9, 340 ± 80	10,175 ± 288	9,916-10,387
	Lepúe Tephra (12-cm thick), 14.80 mcd (basal contact)					
	KIA21473	Mixed planktonic foraminifera	17.01 mcd	10,800 ± 70	12,276 ± 280	12,019-12,534

‡ The Southern Hemisphere terrestrial calibration curve (SHCal13) and OxCal Program (v. 4.2.4) were used for all samples; * Highest Probability Density Function Radiocarbon laboratories used in this study: UCIAMS - University of California at Irving AMS Facility; LLNL – Lawrence Livermore National Laboratory.