Late Glacial-Holocene tephra from southern Patagonia and Tierra del Fuego (Argentina, Chile): a complete textural and geochemical fingerprinting for distal correlations in the Southern Hemisphere

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1. Abstract

Explosive volcanoes from the southern Andes are able to disperse ash over wide areas of the Southern Hemisphere, potentially as far as Antarctica. With the aim of improving correlations between sources and tephra in southernmost South America and, possibly, Antarctica, this work presents new field, textural and geochemical data on tephra layers from southern Patagonia and Tierra del Fuego (Argentina and Chile). Major- and trace-element data, obtained on single glass shards allowed to identify tephra sources in Late Glacial-Holocene eruptions from Hudson, Reclus and Mt Burney volcanoes, located in the Southern and Austral Volcanic Zone of the Andean Cordillera. Twelve new radiocarbon age determinations of charcoals, peats and soils have further constrained the correlations between the studied tephra layers and known eruptions from Hudson, Mt Burney and Reclus volcanoes. Therefore, this study contributes to expand the geochemical dataset on volcanic glasses valuable for tephra correlations in South America, and improves the current tephrostratigraphic framework of this region. Furthermore, we revised literature data by compiling a database including Neogene-Quaternary volcanic tephra found in Antarctic ice cores, marine sediments, blue ice and continental outcrops as well as tephra produced by volcanic sources located in Antarctica and circum-Antarctic areas. This revision shows that Antarctic tephra can be correlated with confidence to Antarctic and circum-Antarctic (South Shetlands and South Sandwich Islands) volcanic sources, whereas correlations with South American sources are arguable, and a complete geochemical fingerprinting is needed for validation.

2. Introduction

Tephra layers preserved in geological records represent a valuable tool for reconstructing the past volcanic activity of a given area. Moreover, they are isochronous marker horizons providing time-stratigraphic information whenever they are geochemically fingerprinted and tied to a known, dated eruption (Lowe, 2011; Lowe and Alloway, 2015). Volcanoes of southernmost South America have been proposed as possible extra-Antarctic sources of some tephra recovered in Antarctic glacial archives (Kurbatov et al., 2006; Narcisi et al., 2010; Narcisi et al., 2012), along with those from the South Sandwich Islands and New Zealand (Dunbar et al., 2017; Narcisi et al., 2005; Narcisi et al., 2012). Thus, in this perspective, tephra recovered from southern Patagonia and Tierra del Fuego (hereafter SPTF) have additional value as a tool for the correlation of geological, paleoclimatic and paleoenvironmental archives at intercontinental scale.

Late Glacial to Holocene tephra layers in SPTF (Argentina and Chile) have been recovered in different sedimentary archives including terrestrial outcrops, marine and lacustrine cores (Fontijn et al., 2014). They have been produced by several volcanoes during tens of eruptions some of which are characterized by intensities up to a Volcanic Explosive Index (VEI) of 6 (Naranjo and Stern, 1998). Some of these eruptions emplaced volumes of tephra larger than 20 km^3 (e.g., Hudson Ho eruption; Weller et al., 2014), with a dispersal area covering almost the whole SPTF and extending over the surrounding oceans.

Despite their significance, and with the exception of few cases (Haberle and Lumley, 1998; Kilian et al., 2003; Kratzmann et al., 2010; Stern, 2008; Weller et al., 2014), most of the eruptions occurred in the SPTF have been solely characterized by the chemical composition of the bulk tephra deposit or the bulk rock analysis of the juvenile component. Conversely, textural and mineralogical characterization, as well as major- and, even most, trace-element analyses of glasses are scarce. This issue represents a significant limitation when correlating tephra at both proximal to distal scale (i.e., SPTF) and distal to ultra-distal, Southern Hemisphere-wide scale (e.g., with the Antarctic ice records). In fact, the major- and trace-element compositions of the bulk deposit may significantly differ from that of individual glass shards, commonly recovered and analyzed in ultra-distal

locations, since the former may be variably affected by sample heterogeneity, and inter-shard variations (Pearce et al., 2004). Moreover, the bulk rock composition will correspond to that of glass fraction only if the first one is aphyric and formed only by juvenile material with no accidental lithics. Finally, many explosive eruptions are rhyolitic or dacitic in composition and almost indistinguishable using the major-element chemistry alone. In such cases, the study of textural and mineralogical features of tephra (e.g., nature and abundance of the components, particles morphology, vesicle size and distribution and crystal content) associated with single-glass-shard trace-element data is an invaluable help for the identification of their eruptive sources and for the correlation of different tephra layers (Pearce et al., 2004). This approach, typical of modern tephrostratigraphy, has never been fully applied to Patagonian tephra and only few papers report on the textural and physical features of studied deposits as well as on the mineralogical assemblage of distal tephra.

In this work, we present and discuss new data on texture, mineralogy, major- and trace-element geochemical composition performed on single glass shards of several tephra layers occurring in different, mostly unreported, stratigraphic sections in SPTF (Argentina and Chile). In addition, we provide new radiocarbon ages of charcoals, peats, and soils that further constrain the correlation between tephra layers and known volcanic eruptions. Findings of this investigation implement the existing tephrostratigraphic framework for the SPTF by also increasing the inventory of known outcrops. In the light of these results, we discuss the provenance of some tephra layers found in the Antarctic ice-records and previously attributed to the volcanoes of Southern and Austral Volcanic Zone of the Andean Cordillera.

3. Volcanological framework

In South America, most of the explosive Holocene volcanism is produced by the Andean Arc, a segmented volcanic arc along the Andean Cordillera (Stern, 2004). Volcanism formed as a result of the subduction of the Nazca and Antarctic plates underneath the South American Plate (Fig. 1), and is subdivided into four main volcanic zones separated from each other by volcanic gaps (Stern et al., 1984): the Northern (NVZ), the Central (CVZ), the Southern (SVZ), and the Austral Volcanic Zone (AVZ). The SVZ and AVZ are the closest to the area under study.

The SVZ comprises 60 volcanic centers aligned along a 1400 km-long, continuous volcanic arc active since the Late Quaternary. Similarly, the AVZ volcanic arc comprises six volcanic complexes active since the Late Quaternary: Lautaro, Viedma, Aguilera, Reclus, Mt Burney and Fueguino, also known as Cook (Corbella and Lara, 2008; Stern and Kilian, 1996).

Tephrostratigraphic and tephrochronological studies conducted in the Patagonia-Tierra del Fuego region have shown that explosive volcanism has been extremely active during the Holocene and Late Glacial period, often with high magnitude eruptions (Fontjin et al., 2104). In geological records, tephra layers have been correlated to large eruptions from four principal sources: Hudson, Mt Burney, Reclus and Aguilera volcanoes (Stern, 2008; Fig. 1).

The Hudson volcanic complex is the most active in the southern SVZ. Tephrostratigraphic records count at least a dozen of large-scale explosive eruptions since the Late Glacial period (Fontijn et al., 2014). The major explosive events of Hudson volcano occurred at ca.17,400 cal yrs BP (Ho) (Weller et al., 2014), at 7,750 cal yrs BP (H_1) (Fontijn et al., 2014; Prieto et al., 2013), at 3,920 cal yrs BP (H_2) (Naranjo and Stern, 1998), and in AD 1991 (H_3) (Scasso et al., 1994). All these eruptions produced a considerable volume of pyroclastic material, possibly ranging between >20 km^3 (Ho) to ca. 4.3 km^3 (H_3).

Mt Burney is a volcanic complex formed by a somma and an inner stratocone. The study of tephra over the Patagonia and Tierra del Fuego has yielded evidence for several eruptions from Mt Burney volcano, including two large Plinian eruptions named MB_1 and MB_2 (Stern, 2008). Radiocarbon dating indicates an age for MB_1 eruption comprised between 8,851 and 9,949 cal yrs BP (Kilian et

128 al., 2003; Stern, 2008). The age of MB_2 tephra has also been determined at several sites between

129 3,818 and 4,711 cal years BP (Kilian et al., 2003; McCulloch and Bentley, 1998; McCulloch and

130 Davies, 2001; Stern, 2008). Both the Plinian eruptions producing MB_1 and MB_2 tephra were VEI 5

131 and produced volumes of tephra exceeding 3 and 2.8 km^3, respectively (Stern et al., 2008). Some

132 other minor tephra layers have been identified possibly emplaced after smaller eruptions of Mt

133 Burney (Kilian et al., 2003). These have been dated from the oldest to the youngest at >9,511 cal yrs

134 BP, between 9,175±111 and 9,511±121 cal yrs BP and between 2,026±48 to 2,063±90 cal yrs BP

135 (Kilian et al., 2003).

136 Reclus is a small stratovolcano that has erupted mainly dacite lavas and pyroclastic ejecta

137 (Harambour, 1988). The present tephrostratigraphic and tephrochronologic framework in southern

138 Patagonia points to three main tephra layers sourced form Reclus volcano. The widespread R_1 tephra

139 layer (Tephra I of Auer, 1974) is attributed to a Plinian eruption of Reclus volcano dated at ~12,700

140 ^{14}C yrs BP (McCulloch and Davies, 2001; McCulloch et al., 2005; Stern, 2008; Stern et al., 2011)

141 and possibly involving a volume of ca. 5 km^3 of pyroclastic material (Stern et al., 2011). Several

142 other Holocene tephra layers chemically compatible with Reclus volcano, but much thinner and

143 considerably less spatially dispersed than R_1, have been identified in several localities of southern

144 Patagonia. In particular, two tephra, R_2 and R_3, derived from Reclus have been found in sediment

145 cores from Torres del Paine National Park, southern Chile (Villa-Martínez and Moreno, 2007) and

146 have been dated at 1789 cal yrs BP and 1035 cal yrs BP, respectively (Breuer et al., 2013; Moy et al.,

147 2008).

148 Aguilera is a remote stratovolcano identified in 1985 and indicated as the source of a regionally

149 widespread Holocene tephra named A_1, mostly found close to Lago Argentino just east of this

150 volcano. The A_1 tephra has an estimated age of~3,067-3,339 cal yrs BP (Stern, 2008). Several other

151 thinner and less widely distributed tephra layers have been identified in the vicinity of Lago

152 Argentino and Torres del Paine, and correlated to Aguilera volcano. The age obtained for one of

153 these layers is older than the age of A_1 tephra layer around <4,560 ^{14}C yrs BP. The age of tephra

154 layers younger than A_1 was not constrained.

155 The three remaining volcanoes of the AVZ, namely Lautaro, Viedma, and Fueguino (Fig. 1) erupted

156 in the Holocene and during historical time. Lautaro and Viedma are two stratovolcanoes located in

157 the northernmost AVZ (Corbella and Lara, 2008), yet no tephra layers in SPTF have attributed to

158 their activities. Fueguino represents the southernmost Holocene volcanic occurrence of the Andes

159 (Corbella and Lara, 2008). It produced a cluster of small pyroclastic cones (<150 m) and columnar-

160 jointed lava domes (Puig et al., 1984); this small to moderately energetic activity makes unlikely that

161 widely dispersed tephra sourced from this complex.

162

4. Sampling and Methods

164 Stratigraphic logging and sampling of tephra layers were performed (February 2015 field work) in

165 SPTF (Fig. 1 and Table 1 for coordinates of stratigraphic sections). Sampling sites have been

166 selected in medial-distal locations, with respect to the potential Holocene volcanic sources of tephra,

167 and following criteria of easy accessibility and good exposure of the outcrops. From north to south,

168 the stratigraphic sections here reported are: Arroyo Robles close to the Potrok Aike Lake (Argentina;

169 section AR-1), Río Rubens (Argentina; section RR-1), Estancia Otway (Chile; sections EO-1, EO-2),

170 Río O'Higgins (Tierra del Fuego, Chile; section ROH-2); Punta Arenas (Chile; section PA-1), Río

171 Tres Brazos (Chile; sections RTB-1, RTB-2), Laguna de los Cisnes (Tierra del Fuego, Chile; section

172 LA-1). These are all unreported outcrops but one (ROH-2) (Stern, 1991). Tephra layers with a

173 thickness ranging from 1 to 16 cm have been identified mainly in natural exposures including banks

174 of alluvial and meandering channels, peat bogs, alluvial terraces, as well as in trenches dug for

175 livestock beverage and road cuts, yielding 16 samples.

176 Samples were first washed with deionized water in an ultrasonic bath to disaggregate them and to

177 remove impurities. Hydrochloric acid (10% v/v) was added to the samples to dissolve carbonates.

178 Afterward, hydrogen peroxide (35% v/v) was repeatedly added to the samples that were successively

179   heated at 120°C to further disaggregate the matrix, remove organic matter and soluble compounds.

180   Samples were then dried at 60°C, mounted with epoxy resin in 1-inch stubs, polished and prepared

181   for textural and geochemical analyses.

182   Tephra samples were described under a petrography microscope. The texture, components and

183   mineral assemblage of tephra were studied at the Istituto Nazionale di Geofisica e Vulcanologia,

184   Sezione di Pisa (INGV-Pisa) with a scanning electron microscope (SEM) Zeiss EVO MA and

185   images have been collected in back-scattered electrons (BSE) mode. Major-element glass

186   compositions were determined at the Laboratorio Microsonda Elettronica C.N.R.-I.G.G. of Florence

187   using a JEOL JXA-8600 microprobe (EMP) equipped with 4 wavelength dispersive spectrometers

188   (operating conditions:15 kV accelerating voltage, 10 nA beam current, 10 μm probe diameter and 20

189   s (10 s for Na and 40 s for Cl and F) and 20 s acquisition time for peak and background (40 s for Cl

190   and F), respectively) and at HPHT Laboratory INGV-Roma using a JEOL JXA 8200 electron

191   microprobe (EPMA) equipped with five wavelength-dispersive spectrometers (operating conditions:

192   15 kV accelerating voltage, 8 nA beam current, 5 μm probe diameter, 10 and 5 s acquisition time for

193   peak and background, respectively). Standards of glass and natural mineral phases were analyzed to

194   test the accuracy of data during the analyses (see Supplementary Material 1).

195   The trace-element concentrations were determined on single glass shards by Laser Ablation-

196   Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) at the Università di Perugia,

197   Dipartimento di Fisica e Geologia. The analyses were carried out with a Teledyne Photon Machine

198   G2 laser ablation system coupled to a Thermo Fisher Scientific iCAP-Q, quadrupole based, ICP-MS

199   (Petrelli et al., 2016a, 2016b; Petrelli et al., 2008). The LA-ICP-MS operating conditions were

200   optimized before each analytical session by continuous ablation of NIST SRM 612 glass reference

201   material (Pearce et al., 1997) to provide maximum signal intensity and stability for the ions of

202   interest while suppressing oxides formation (ThO^+/Th^+ below 0.5%). The U/Th ratio was also

203   monitored and maintained close to 1. The stability of the system was evaluated on ^{139}La, ^{208}Pb, ^{232}Th,

204   and ^{238}U by a short-term stability test. It consisted of 5 acquisitions (one minute each) on a linear

scan of NIST SRM 612 glass reference material (Petrelli et al., 2016a, 2016b). Tephra glasses were analyzed by using a circular laser beam with a diameter of 20 μm, a frequency of 8 Hz, and an energy density at the sample surface of 3.5 J/cm^2. NIST SRM 610 reference material (Pearce et al., 1997) was used as the calibrator and ^{29}Si as the internal standard. USGS BCR2G reference material was analyzed as unknown to provide a quality control (Jochum et al., 2005). Under these operating conditions, precision and accuracy are better than 10 % for all the investigated elements (Petrelli et al., 2008; Petrelli et al., 2016a, 2016b).

Age of tephra was obtained by ^{14}C-AMS radiometric dating of organic matter (charcoal, soil and peat samples) that are intercalated with tephra layers. Unfortunately, organic matter was present only in 9 of the studied sections. Analyses have been performed at the CIRCE laboratories, Caserta, Italy. Radiocarbon dates were converted to calendar years before present (cal years BP) with the CALIB 7.01 program (Stuiver et al., 2018), using the IntCal13 radiocarbon ages calibration curve (Reimer et al., 2013).

5. Results: chemical composition, tephra texture, mineral assemblage and age

A synoptic view of the features of the studied tephra layers is reported in Table 1 including grainsize, nature and relative abundance of components, texture of volcanic particles and mineral assemblage. Figures 2 and 3 report the photographs and the schematic representation of the studied stratigraphic sections, respectively. Figures 4, 5 and 6 show selected SEM-BSE images of the studied tephra. The major- and trace-element compositions of each sample are reported in Table 2 as averages of multiple point analyses by EPMA and LA-ICP-MS, and the whole analytical data set is reported in Supplementary Material 1.

The total alkali vs silica diagram (TAS, Fig. 7a; Le Bas et al., 1986) shows two main compositional clusters for the glasses of the studied tephra in the trachyte and rhyolite fields, respectively. In detail, samples EO-2H, EO-1B, ROH-2C and AR-F1 plot overall in the trachyte field, with SiO$_2$ ranging

230 between 63.7 and 68.6wt%. All the other samples plot into the rhyolite field with SiO_2 comprised

231 between 73.4 and 79.8 wt%.

232 In the K_2O vs SiO_2 diagram (Fig. 7b), which is commonly regarded as the most significant plot to

233 discriminate tephra from Patagonia and Tierra del Fuego (Stern, 2008), the samples form three main

234 compositional groups. The first one (Group Tr) consists of the four trachyte samples. The rhyolite

235 samples compositions define two distinct clusters. Among these, the Group Rh1 is characterized by a

236 SiO_2 ranging between 73.4 and 79.8 wt% and K_2O between 1.19 and 2.25 wt% (samples ROH-2B,

237 RTB-1B, EO-1C, EO-2D, EO-2L, AR-1B, AR-1D, RR-2B, and PA-1B). On the contrary, the Group

238 Rh2 shows more restricted SiO_2 values comprised between 77.1 and 78.4 wt% and higher K_2O,

239 ranging between 2.46 and 2.95 (samples EO-2B, RTB-2B, and LA-1B).

240 The distribution of the incompatible elements of the 16 samples analyzed by LA-ICP-MS (Fig. 8) is

241 that typical of orogenic magmas, with negative anomalies of Nb, Ta and Ti and positive anomalies of

242 Pb. However, some significant differences between samples belonging to groups Tr, Rh1 and Rh2

243 can be observed. On average Group Tr shows higher content for most incompatible elements than the

244 other two groups and particularly from Nd to Lu. Moreover, Rh1 glasses are less enriched in Rb than

245 those belonging to Groups Tr and Rh2 (Fig. 8).

246 These differences are emphasized in the diagrams Nb/Ba vs La/Zr, Rb/Ba vs Ti/Sm, Rb/Ba vs Sr/Nd

247 and Ce/Pb vs Ba/Th (Fig. 9). In these diagrams, samples belonging to Group Tr are well separated

248 from samples of groups Rh1 and Rh2. Indeed, these trachytes have distinctly higher Nb/Ba and

249 lower Sr/Nd and Ba/Th ratios. Rocks of Group Tr also have slightly higher Rb/Ba and Ce/Pb ratios.

250 The higher Nb/Ba and Ce/Pb ratios of Group Tr with respect to Groups Rh1 and Rh2 denotes a less

251 marked orogenic signature of the former. Groups Rh1 and Rh2 are less clearly discriminated from

252 each other, even though Rh1 samples have distinctly lower La/Zr and Rb/Ba, and higher Ba/Th with

253 respect to Rh2 samples. More in detail, the Rh1 samples PA-1B, RTB-1B, EO-1C and EO-2L have

254 lower La/Zr and higher Ti/Sm ratios, whereas samples RR-2B, AR-1B and AR-1D share higher

255   La/Zr and lower Ti/Sm ratios. Samples EO-2D and ROH-2B are characterized by intermediate

256   values of these trace element ratios (Fig. 9).

257   The textural features and the mineral assemblage of the studied samples (Table 1) are consistent with

258   the groups identified with the compositional data. In fact, Group Tr tephra are mainly composed of

259   blocky, y-shaped or platy-cuspate, poorly-vesicular glass fragments (<100 μm) along with a minor

260   amount of micropumices with spherical to slightly elongated and deformed vesicles. They contain

261   scarce amounts of loose crystals of plagioclase (pl), orthopyroxene (opx), clinopyroxene (cpx),

262   quartz (qz) and apatite (ap) (Table 1).

263   Group Rh1, conversely, is mostly composed of highly- to moderately-vesicular micropumices with

264   spherical to coalesced and collapsed vesicles; micropumices occasionally bear microlites of pl, qz,

265   opx, cpx and Fe-Ti oxides (Table 1). Samples from Group Rh1 commonly contain also abundant

266   loose crystals of pl, qz, opx, Fe-Ti spinels and ap coated with volcanic glass (Table 1).

267   Group Rh2 is composed of moderately- to poorly-vesicular, blocky and y-shaped glass shards,

268   bubble walls and bubble junctions together with a minor amount of micropumices with tubular,

269   coalesced and collapsed vesicles (Table 1). Glass fragments are mostly aphyric with rare microlites

270   of pl, opx and ap. The tephra also contains scarce loose crystals of pl, opx and ap and holocrystalline

271   volcanic rock fragments (Table 1).

272   Radiocarbon ages obtained from studied successions are reported in Table 3. Ages span from Late

273   Glacial (EO-2A) to modern age (RR-2B), yet mostly comprised within the Holocene.

274

275   **6. Discussion**

276   **6.1. Sources of tephra**

277   To assess the volcanic provenance of the studied tephra, we compared their glass compositions with

278   those available in the literature. Moreover, we used the nature and abundance of components and the

279   texture of juvenile particles (e.g. particle shape, vesicularity, type and abundance of microlites)

280   forming pyroclastic deposits and the relevant constraints provided by radiocarbon ages.

281 It is worth to note that the geochemical characterization and provenance of tephra layers from
282 southern Andes volcanoes have been mainly performed through the analysis of the major-element
283 compositions on bulk tephra up to recent times. The use of trace elements to improve the success of
284 the identification process is scarce. Furthermore, major- and trace-element determinations on single
285 glass shards analyses are even rarer. These latter should be preferred to bulk analyses because bulk
286 tephra often contain abundant phenocrysts, volcanic-lithic fragments, and non-volcanic material, and
287 therefore may not represent the actual composition of the melt fraction quenched at the time of
288 eruption (Pearce et al., 2004), which is indeed represented by glass shards (Shane et al., 2008).

289 The comparison between our microprobe major-element data on glass shards and the only available
290 literature data (see references in the legend of Figs. 10 and 11) on glass shards and bulk tephra as
291 well, shows that the three compositional groups Tr, Rh1 and Rh2 match very well three volcanic
292 sources located in the Southern and Austral Volcanic Zone of the Andean Cordillera (Figs. 10 and
293 11): Hudson (Tr), Mt Burney (Rh1) and Reclus (Rh2) volcanoes.

294

295 *Compositional Group Tr - Hudson*

296 The major- and trace-element glass compositions of samples belonging to Group Tr closely match
297 that of tephra erupted by Hudson volcano during the Holocene (Figs. 10a and 11a,b). Radiocarbon
298 determinations constrain the age of Tr-tephra between 7,026±49 and 4,219±241 yrs BP (Figs. 3 and
299 12), suggesting they were most likely produced by the mid-Holocene H_1 eruption. This represents the
300 largest Holocene volcanic event of the southern Andes, with a volume of erupted materials >18 km^3
301 (Naranjo and Stern, 1998; Stern, 2008) and an age of 7,750±95 cal yrs BP obtained as the best
302 average among several samples from TF (Prieto et al., 2013). Thickness of tephra belonging to
303 Group Tr is fully compatible with that of tephra previously identified in the SPTF region and
304 correlated with H_1 eruption (Prieto et al., 2013).

305

306 *Compositional Group Rh1 - Mt Burney*

Major element glass composition of samples belonging to Group Rh1, which includes the majority of the studied tephra, match that of the products erupted by Mt Burney volcano during the Holocene (Fig. 10b). Within compositional Group Rh1, samples EO-2D, ROH-2B and AR-1D are well bracketed in age between 9,299±65 and 7,325±46 yrs BP (Fig. 3). This age is compatible with the age of MB_1 eruption which is dated either at 8,851-9,949 cal yrs BP (Stern, 2008) or in the range of 9,009-9,175 cal yrs BP (Kilian et al., 2003). The compositions of Group Rh1 match also those of tephra layer 5022-2T1 identified between 12.32-12.34 m in the ICDP core 5022 from Laguna Potrok Aike in southern Patagonia, Argentina, correlated with the MB_1 tephra layer from Mt Burney (Wastegård et al., 2013). The age-depth model reported for the core (Kliem et al., 2013) indicates that the tephra layer has an age of ~9,545 cal yrs BP (2σ range 8851–10238 cal yrs BP) which overlaps the range reported for MB_1 eruption (Stern, 2008) (Fig.12). Thickness of studied tephra layer is compatible with that of tephra layers attribute to MB_1 eruption and previously identified in the SPTF region (Stern, 1991; Kilian et al., 2003; Stern, 2008).

Remarkably, in our Arroyo Robles section, a 2.5 cm thick tephra layer occurs under the MB_1 tephra separated by a 2 cm-thick peat horizon (Fig. 3). This tephra (AR-1B) has the same petro-chemical characteristics (Fig. 9) of the overlying MB_1 tephra (AR-1D) and can be attributed to an explosive activity of the Mt Burney slightly older than MB_1. Several pre-MB_1, tephra layers, dated between ~20 and ~50 ka, have been identified in the Laguna Potrok Aike lacustrine record (Wastegård et al., 2013) and attributed to Mt Burney activity. Accordingly, tephra AR-1B could represent the first report of a Mt Burney eruption occurred between MB_1 and the those documented in the Potrok Aike record.

The age of the rest of Group Rh1 samples (EO-2L, EO-1C, PA-1B, RR-2B, and RTB-1B) is not fully constrained. We obtained a maximum age of 4,219±241 yrs BP from a sample at the very base of sample EO-2L, but no age constraints at the top (Figs. 2, 3 and 12). In this regard, we do not observe any evidence of a sedimentological break or hiatus occurring between the dated peat sample and EO-2L tephra. EO-2L can be thus correlated with the Mid-Holocene Plinian eruption MB_2 of Mt Burney

333   volcano dated 3,818-4,711 cal yrs BP (Kilian et al., 2003; McCulloch and Bentley, 1998; McCulloch

334   and Davies, 2001; Stern, 2008). Similarly, sample EO-1C is separated by a few cm of sediment from

335   EO-1B tephra (Figs. 2 and 3), which is in turn correlated with the Hudson H_1 eruption dated at

336   7,750±95 cal yrs BP (Prieto et al., 2013). The age of the tephra EO-1C is thus younger than the age

337   of H_1 allowing a possible correlation to MB_2 eruption from Mt Burney, that in the investigated area

338   is reported to reach 5 cm of thickness (Stern, 2008), which is compatible with the 2-4 cm thickness

339   reported here. For PA-1B tephra, we obtained only a minimum age of 1,259±32 cal yrs BP, whereas

340   for RTB-1B tephra a modern age (Figs. 3 and 12). The RTB-1B age, however, is not coherent with

341   the stratigraphic framework, thus suggesting a considerably older age for this eruption. In addition,

342   we observe that samples PA-1B and RTB-1B have the same textural, mineralogical and

343   compositional characteristics as samples EO-2L and EO-1C (Fig. 10b). Thus we suggest their

344   correlation with MB_2 eruption.

345   Finally, sample RR-2B, which presents trace elements ratios different from EO-2L, EO-1C, PA-1B,

346   RTB-1B samples (Fig. 9) and a very young age (<200 yrs), may be correlated to the only known

347   historical eruption of Mt Burney occurred in 1910.

348   Comparing our compositional data for Mt Burney products with those available in the literature, we

349   observe a good correspondence with major-element compositions but not for trace-element

350   compositions (Fig. 11c and d). For instance, we observe a shift toward lower Rb content and a higher

351   Sr content in the literature data with respect to our compositions. This can be explained with the

352   different type of analyses performed: bulk-tephra and glass trace-element compositions determined

353   via energy dispersive XRF analysis (Stern, 2008; Stern and Kilian, 1996) could be affected by the

354   occurrence of microlites/crystals/lithics, whereas space-resolved single-shards LA-ICP-MS are

355   definitely representative of glass.

356

357   *Compositional Group Rh2 - Reclus*

Rhyolitic tephra of Group Rh2 can be correlated to the products erupted by Reclus volcano (Fig. 10c). In this case, the ^{14}C ages indicate two sub-groups, i.e., samples EO-2B and RTB-2B with age bracketed between 12,240±54 cal yrs BP and 9,299±65 cal yrs BP and LA-1B that is considerably much younger and has an age of <3,264±46 cal yrs BP.

The first sub-group (samples EO-2B, RTB-2B) is compatible in age with R_1 eruption from Reclus volcano that was dated between ca 12,700 yrs BP (McCulloch et al., 2005; Stern, 2008). Also the thickness of EO-2B, RTB-2B tephra layers is compatible with that R_1 tephra which in this region is > 5 cm (Stern, 2008). As mentioned above, sample LA-1B is considerably much younger and has an age of <3,385-3,585 cal yrs BP. This tephra is thus compatible in age with eruptions R_2 or R_3 dated at 2,000 cal yrs BP (Villa-Martínez and Moreno, 2007). The two groups have very similar trace-element signatures (Figs. 11e,f) apart from those compositions deriving from bulk analyses for the reasons above explained.

Samples EO-2B, RTB-2B of Group Rh2 match also the composition of tephra layers 5022-2T2, 5022-2T3, and 5022-2T4 recovered at 16.04-16.05 m, 16.48 m and 16.78-16.79 m in the Laguna Potrok Aike 5022 core and correlated with the Reclus R_1 tephra (Haberzettl et al., 2007; Wastegård et al., 2013).

6.2. South American tephra in Antarctica?

Southern Andes volcanoes, along with New Zealand and South Sandwich Islands volcanoes have been considered as potential sources for some Holocene ultra-distal tephra found in ice records at various sites of Antarctica (Dunbar et al., 2017; Kurbatov et al., 2006; Narcisi et al., 2010). Detecting whether these tephra layers are sourced from (i) mid-latitude volcanoes in the southern Andes or New Zealand, (ii) mid/high-latitude circum-antarctic volcanic islands (South Sandwich and South Shetlands) or (ii) high-latitude Antarctic volcanoes, is crucial to understand the atmospheric circulations able to transport tephra onto the Antarctic ice. In this perspective, it urges a detailed textural, mineralogical and geochemical fingerprinting, including major- and trace-element data of

tephra layers, in both ultra-distal and proximal-medial sites. This will offer a solid dataset in the framework of which possible stratigraphic correlations among different geological archives would be much more straightforward and reliable. To date, such a dataset is missing, while data are available on the major-element glass composition and on the age of tephra layers based on glacial proxies.

On these bases, it is only possible to define compositional lineages in order to distinguish the main sources of Antarctic tephra. To this aim, we collected major-element data of Neogene-Quaternary tephra from Antarctic ice cores, marine sediments, blue ice, continental outcrops as well as for potential sources located in Antarctica and circum-Antarctic areas (Supplementary Material 2). Then, we critically reviewed the obtained dataset discarding any analysis showing evidence of alterations. In detail, we applied the screening methods for altered specimens reported for Antarctic tephra (Di Roberto et al., 2012), also considering the criteria of alteration and alkali loss (Kilian et al., 2003). Figure 13 reports more than 2000 analyses in the widely used K_2O vs SiO_2 plot where the glass compositions define six clear geochemical lineages.

Lineage 1 is a typical alkaline lineage (Fig. 13); this includes glasses erupted by intraplate alkaline volcanoes of the West Antarctic rift system (e.g., McMurdo Volcanic Group, Marie Byrd Land volcanoes), most of the Andrill samples (Miocene to Quaternary), and marine and englacial tephra from Antarctica. At higher K_2O/SiO_2 relative to Lineage 1, nephelinites (1a) and phonolites (1b) are found. A scarcely populated trend is defined by high-silica glasses, with alkali-rhyolite to pantellerite compositions deriving from extreme fractionation of alkali feldspar and quartz (SiO_2>70 wt%, Lineage 1c; Fig. 13) (Armienti et al., 1998; Armienti et al., 2001; Di Roberto et al., 2012; Martin et al., 2010). Most of the tephra layers found in the Antarctic records show compositions that can be correlated with alkaline products, typical of Antarctic alkaline volcanoes.

A limited number of Antarctic tephra shows a subalkaline, low-K tholeiitic to calc-alkaline, major-element signature, typical of subduction zone igneous products. These tephra layers cannot be related to the Antarctic alkaline volcanism, and can potentially derive from subduction-related volcanoes of circum-Antarctic volcanic provinces, such as the Antarctic Peninsula area (South Shetland Islands),

the South Sandwich Islands in the southernmost Atlantic Ocean, the southern Andes and New Zealand volcanic provinces (Fig. 13). These glass compositions define five other sub-alkaline lineages.

Lineage 2 is potassic calc-alkaline (Fig. 13); this comprises glass compositions of tephra produced or attributed to the Hudson volcano (including also four samples from this study). Also, Hudson volcano has been proposed as the source for a trachybasaltic sample TD193 identified in the Talos Dome core with an assigned age of 2.02 ka BP (Narcisi et al., 2012). This has been correlated to a tephra with basaltic composition that is assumed to be regionally significant and bracketed between uncalibrated radiocarbon ages 1,910±70 and 2,235±130 yrs BP (Naranjo and Stern, 1998). A few Plinian eruptions fed by mafic magmas have been identified worldwide, able to spread ash to ultra-distal sites, i.e., Etna 122 B.C. (Coltelli et al., 1998), Fontana Lapilli (ca. 60 ka BP), the Masaya Triple Layer and the Masaya Tuff from Masaya caldera (2.1 and 1.8 ka BP), Nicaragua (Pérez et al., 2009), and Tarawera, New Zealand in 1886 (Houghton and Gonnermann, 2008). For the Hudson volcano, there is no evidence reported for such an eruption during the Late Glacial period and in the Holocene, thus the correlation between TD193 tephra and Hudson volcano should be reconsidered. Sample TD216, also from Talos Dome ice core, and dated 2,355±54 yrs BP, has been correlated to evolved products from Hudson, based on glass composition (Narcisi et al., 2012) slightly more evolved than most evolved Hudson tephra. In the known volcanological record of this volcano, the HW7 eruption has an age comparable to the one attributed to sample TD216 (Haberle and Lumney, 1998; Carel et al. 2011). However, the Ti content of TD216 tephra is significantly lower than that present in Hudson samples with comparable SiO_2, and also the ratios K_2O/TiO_2 and CaO/Al_2O_3 are different. Therefore, the attribution of this tephra layer to Hudson volcano is not based on solid ground.

Lineage 3 is rather K-rich calc-alkaline (Fig. 13) and includes the product erupted by Fueguino, Macá, Cay, and Aguilera volcanoes and also the products from Antarctic Peninsula area (Seal Nunataks) (Kraus et al., 2013). The glass compositions from Siple Dome ice core attributed to an

unreported eruption from Hudson volcano (Kurbatov et al., 2006), together with shards from Talos Dome (Narcisi et al., 2012; Narcisi et al., 2017) ice cores, overlap the compositions of Aguilera rhyolites. Nevertheless, these rhyolitic compositions also plot on the rhyolitic extension of the Antarctic alkaline trend (Lineage 1c), and can therefore represent the extremely evolved alkaline products of an Antarctic volcano. Tephra VK3311-2 and VK3311-4 from Vostok ice core have been potentially attributed to a southern Andes or South Shetland source. Nevertheless, its rather old age (414 ka) and the CaO and TiO_2 content make it difficult to correlate this tephra with either a Macá or Cay source. Layers 1117.1 and 1868.3 from Dome C ice core have been attributed to a South Shetland source (Narcisi et al., 2005) that, despite a rather low Al_2O_3 content, could be a plausible correlation.

Lineage 4 is a rather K-poor calc-alkaline lineage (Fig. 13) that includes products erupted by the Reclus volcano (Kilian et al., 2003; Stern and Kilian, 1996)(this work) and by volcanoes in the South Shetlands and South Sandwich Islands. No shards from tephra recognized in Antarctic records plot along this lineage, with the significant exception of a cryptotephra found in the WDC06A ice core, recovered from central West Antarctica and attributed to the Oruanui supereruption from Taupo volcano, at ca. 25.6 ka (Dunbar et al., 2017). Interestingly, the WDC06A ash layer has an average composition closely matching that of Reclus tephra (Fig. 13). The only difference between WDC06A ash layer and Reclus products is a pronounced spread in K_2O concentration (1.87 to 3.27 wt%), an unusual feature for a strongly evolved, far-distal tephra. Tephra TD282 from Talos Dome ice core, dated at 3,392±82 yrs BP (Narcisi et al., 2012) has K_2O vs SiO_2 relationships compatible with Reclus compositions, but a correlation with Chile's Puyehue-Cordón Caulle has been suggested (Narcisi et al., 2012). However, the K_2O/TiO_2 ratio (2.63) points out a composition far removed from typical trends of southern Andes volcanoes for which the value of K_2O/TiO_2 expected at comparable SiO_2 content would be around 7, and overlapping instead South Shetlands compositions (Supplementary Material 2).

461 Lineage 5 is a low-K tholeiitic trend (Fig. 13); this includes glass shards from Mt Burney and South

462 Sandwich Islands volcanic arc (Hubberten et al., 1991; Pearce et al., 2014). This lineage overlaps the

463 composition of some tephra layers found in Siple Dome, Vostok, and Talos Dome ice cores. Among

464 the latter, the majority of glass compositions with SiO_2 <70 wt% is consistent with a provenance

465 from South Sandwich Islands (Basile et al., 2001). Conversely, glass with SiO_2 ranging between 70

466 and 75 wt%, cannot be definitively correlated with products of any known volcanic source. More in

467 detail, the SDMA2571 tephra in Siple Dome ice-core, dated at 1805 B.C., was related to the products

468 of Mt Burney (Kurbatov et al., 2006). According to these authors, the age of SDMA2571 tephra is

469 comparable to the MB_2 eruption from Mt Burney dated at 3,818-4,711 cal yrs BP (Kilian et al., 2003;

470 McCulloch and Bentley, 1998; McCulloch and Davies, 2001; Stern, 2008). However, the chemical

471 compositions of SDMA 2571 tephra do not match with the published composition of MB_2 eruption

472 tephra (Kilian et al., 2003; Stern, 2008; Wastegård et al., 2013). Our data also confirm this evidence.

473 In fact, although the glass composition of SDMA 2571 tephra lies on the compositional trend defined

474 by the Group Rh1 attributed to Mt Burney eruption, only a partial overlap exists between the most

475 evolved glass of SDMA2571 tephra and less evolved compositions measured in our samples (Fig.

476 13). In Talos Dome ice core, the cryptotephra layer TD299 dated at 3,677±92 yrs BP was correlated

477 to this SDMA2571 tephra, thus in turn possibly correlated to the activity of Mt Burney, even though

478 not to a definite eruption. As reported for SDMA2571, no clear match exists between compositions

479 of TD299 tephra and products of Mt Burney eruptions (Kilian et al., 2003; Stern, 2008; Wastegård et

480 al., 2013) (Fig. 13). The glass composition with SiO_2 ranging between 70 and 75 wt% falling on this

481 trend and deriving from Antarctic ice records (mostly Siple Dome) can be correlated either with

482 evolved products from Mt Burney or with the most evolved compositions of the South Sandwich

483 Islands. Nevertheless, the drop in Al_2O_3 contents with increasing SiO_2 is not compatible with a Mt

484 Burney trend, making a South American source poorly feasible also in this case.

485 Also Lineage 6 is again a low-K tholeiitic lineage (Fig. 13), with a slightly lower K content and a

486 modest spread of SiO_2 concentrations than the Lineage 5. This lineage is defined by products of

487 South Sandwich Islands and Fueguino volcano. Tephra layers from Dome C, Siple Dome, Dome Fuji

488 and Vostok ice cores plot on this trend. In more detail, the andesitic layer 9008 from the Antarctic

489 SDMA (Siple Dome) ice core, dated 9,216 yrs B.C., and tentatively attributed to an eruption of the

490 Hudson volcano using geochemical and chronological data (Kurbatov et al., 2006), distinctively plot

491 on this trend (Fig. 13). Additionally, a Hudson tephra characterized by this composition and by a

492 large dispersion such as to justify its transport up to the Antarctic it is not known in Patagonia-Tierra

493 del Fuego. It is therefore plausible this tephra is sourced in South Sandwich volcanic activity.

494 The result of the comparison between our data and those available in the literature indicates that

495 Antarctic tephra mostly derives from Antarctic or circum-Antarctic volcanoes. For subalkaline

496 tephra, proposed correlations with South American volcanoes are either unfeasible or at least

497 alternative origins are equally feasible. In summary, for Holocene tephra found in Antarctica there is

498 no straightforward need to invoke a source at latitude lower than the circum-Antarctic volcanoes. A

499 possible exception could be represented by the cryptotephra found in WDC ice core correlated with

500 Oruanui supereruption, from Taupo (Dunbar et al., 2017). However, atmospheric dispersal modeling

501 indicates a significant ash accumulation of 30 g/m^2 on the core site (Dunbar et al., 2017), quite at

502 odds with the extremely fine grain-size of the cryptotephra and the convolute atmospheric path

503 followed by the particles arriving on site more than eight days after the eruption.

504 Possible explanations for the lack of South American tephra in Antarctica can be given in the light of

505 results recently published dealing with the potential ash impact from Antarctic volcanoes (Geyer et

506 al., 2017). Findings indicate that the potential impact of volcanic ash from Antarctic eruptions is

507 linked to volcano locations and eruption intensities. Eruptions with eruptive plumes <10 km in height

508 and from latitude >70° are likely to be confined in Antarctica due to moderated wind zones encircled

509 by the polar jet stream. Conversely, eruptive plumes >10 km in height have a higher potential for

510 extra-Antarctic ash dispersal. Also, eruptions from lower-latitude Antarctic volcanoes as Deception

511 Island are more likely to encircle the globe with ash, even for moderate size eruptions, reaching

512 tropical latitudes (Geyer et al., 2017). This because they are located out of the control of the polar jet

stream. The lack of ash produced by Austral mid-latitude volcanoes can be due to the effect of the polar jet stream, which acts as a physical barrier on its two sides, hampering their dispersal to Antarctica.

7. Conclusions

New field occurrences of tephra layers produced by Andean large-scale Holocene eruptions are reported from SPTF. These findings considerably expand the present knowledge of the areal dispersion of these tephra and offer new tie points for future precise eruption volume calculation. A complete stratigraphic, geochronological (whenever possible), textural, mineralogical and compositional characterization of tephra has been carried out including the determination of major and trace elements on single glass shards by EPMA and LA-ICP-MS. These results significantly strengthen the tephrostratigraphic framework of the Patagonia-Tierra del Fuego for the last ca. 13 ka by applying, for the first time in this area, the multidisciplinary approach of the modern tephrostratigraphy and tephrochronology. On this solid ground, we correlated tephra layers across the studied stratigraphic sections and found the volcanic source of studied tephra layers in Hudson, Mt Burney and Reclus volcanoes in the southern Andes. In detail, we correlate the tephra layers with major explosive eruptions that affected SPTF during the Late Glacial to Holocene, namely the H_1 eruption from Hudson, MB_1 and MB_2 eruptions from Mt Burney and R_1 and R_2/R_3 eruptions from Reclus.

We compiled a database including major- and trace-element compositional data of Neogene-Quaternary tephra found in Antarctic ice cores, marine sediments, blue ice and continental outcrops as well as tephra produced by volcanic sources located in Antarctica and circum-Antarctic areas. We revised the chemical and petrological soundness of the attribution of some of these tephra to South American volcanic sources. Results indicate that most, if not all, tephra layers identified in Antarctic

539 records can be correlated with Antarctic or circum-Antarctic volcanic sources (South Sandwich and

540 South Shetland Islands). No clear need exists to invoke South American volcanic sources. If

541 confirmed, this result calls for additional unequivocal new data to infer Holocene atmospheric

542 circulation and transport of tephra from mid-latitudes to Antarctica.

543

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734

Table captions

Table 1 Synoptic scheme of the features of studied tephra layers.

Table 2 Major and trace element compositions of glass in studied samples.

Table 3 Radiocarbon age results.

Figure captions

Figure 1 - Map of southernmost South America showing the locations of the Holocene volcanoes, the extent of the Austral Volcanic Zone of the Andes, and the tephra outcrops studied in this work. Abbreviations: AR, Arroyo Robles; RR, Río Rubens; EO, Estancia Otway; ROH, Río O'Higgins; PA, Punta Arenas; LA, Laguna de los Cisnes; RTB, Río Tres Brazos. The inset shows the Southern Hemisphere with the localities mentioned in the text: F, Dome Fuji; V, Vostok Station; C, Dome C; T, Taylor Dome; A, Andrill; S, Siple Dome; W, WAIS Divide.

Figure 2 - Photographs of the studied stratigraphic sections. a: Estancia Otway 1; b: Estancia Otway 2; c: Punta Arenas; d: Río Tres Brazos 1; e: Río Tres Brazos 2; f: Laguna de los Cisnes; g: Río O'Higgins; h: Arroyo Robles; i: Río Rubens.

Figure 3 - Logs of studied stratigraphic sections and their correlations.

Figure 4 - Scanning electron microscope back-scattered (SEM-BSE) images of tephra samples. a: EO-1B tephra; b: EO-1C tephra; c: EO-2B tephra; d: EO-2D tephra; e: EO-2H tephra; f: EO-2l tephra.

Figure 5 - Scanning electron microscope back-scattered (SEM-BSE) images of tephra samples. a: PA-1B tephra; b: RTB-2B tephra; c: RTB-1B tephra; d: LA-1B tephra.

Figure 6 - Scanning electron microscope back-scattered (SEM-BSE) images of tephra samples. a: ROH-2B tephra; b: ROH-2C tephra; c: AR-1B tephra; d: AR-1D tephra; e: AR-1F tephra; f: RR-2B tephra.

Figure 7 - a: Total alkali vs Silica diagram (TAS) (Le Bas et al., 1986); b: K_2O versus SiO_2 diagram.

Figure 8 - Primordial mantle-normalized multi-element patterns (McDonough and Sun, 1995). a: all studied samples; b: Group Tr samples; c: Group Rh1 samples; d: Group Rh2 samples.

Figure 9 - a: Nb/Ba vs La/Zr; b: Rb/Ba vs Ti/Sm; c: Rb/Ba vs Sr/Nd; d: Ce/Pb vs Ba/Th for the glass shards of tephra layers studied in this work. Each data point represents a single LA-ICP-MS point analysis.

Figure 10 - K_2O vs SiO_2 diagrams reporting literature data compared with data of this work in which the volcanic sources are unambiguously distinguished; a: Hudson (Group Tr); b: Mt Burney (Group Rh1); c: Reclus (Group Rh2).

Figure 11 - Selected trace element diagrams for comparison of volcanic sources with this work data.

Figure 12 - Volume and age of the major eruptions from Hudson, Mt Burney and Reclus (Watt et al., 2013; Weller et al., 2015) in comparison with the age of eruptions here discussed. Red lines represent intervals for eruption ages defined by two ^{14}C ages (Table 3), red arrows represent intervals for eruption ages defined by only one ^{14}C ages bounding the possible oldest or youngest age (Table 3).

786 Figure 13 - K_2O vs SiO_2 plot comparing compositional groups of tephra collected in Antarctic, Peri-

787 Antarctic and South American regions. Antarctic tephra come from (i) englacial layers from Marie

788 Byrd Land (MBL) and northern Victoria Land (NVL) (Dunbar et al., 2008; Wilch et al., 1999),

789 http://www.tephrochronology.org/AntT/about.html, and East Antarctica (Curzio et al., 2008; Harpel

790 et al., 2008); in this group highly evolved samples of Lineage 1c are included (Martin et al., 2010;

791 Martin, 2009), (ii) ice cores drilled in Fuji Dome (Fujii et al., 1999; Kohno et al., 2004), Taylor

792 Dome (Dunbar et al., 2003), Siple Dome (Dunbar and Kurbatov, 2011; Kurbatov et al., 2006),

793 http://www.tephrochronology.org/AntT/about.html, West Antarctic Divide-WDC (Dunbar et al.,

794 2017), Vostok (Basile et al., 2001; Narcisi et al., 2010), Dome C (Narcisi et al., 2010; Narcisi et al.,

795 2005), Talos Dome (Narcisi et al., 2010; Narcisi et al., 2012; Narcisi et al., 2017; Narcisi et al., 2001)

796 and (iii) offshore ANDRILL deep cores (Del Carlo et al., 2009; Di Roberto et al., 2012; Nyland et

797 al., 2013) and gravity cores (Del Carlo et al., 2015). Peri-Antarctic tephra are from South Shetland

798 Islands (Hole et al., 1993; Kraus et al., 2013) and from marine tephra attributed to South Sandwich

799 sources (Hubberten et al., 1991). Tephra from South America are from semi-distal to distal layers

800 collected in Patagonia and Tierra del Fuego and attributed to an Andean sources, i.e. the volcanoes

801 Hudson (Gutiérrez et al., 2005; Kratzmann et al., 2010; Naranjo and Stern, 1998; Weller et al.,

802 2014), Reclus (Kilian et al., 2003; Stern and Kilian, 1996), Mt Burney (Kilian et al., 2003; Stern,

803 2008; Stern and Kilian, 1996), Aguilera (Kilian et al., 2003; Stern, 2008), Cook (Stern and Kilian,

804 1996), Macá and and Cay (Gutiérrez et al., 2005), as well as from layer studied in this work. For

805 locations see Figure 1. Specific samples mentioned in the text are labeled (same color as symbol).

806

807 **Supplementary Material Table 1**

808 Dataset of major and trace elements data and secondary standard analyses.
809

810

811 **Supplementary Material Table 2**

812   Major- and trace-element data for tephra from Antarctic ice cores, marine sediments, blue ice,

813   continental outcrops as well as for potential sources located in Antarctica and circum-Antarctic areas.
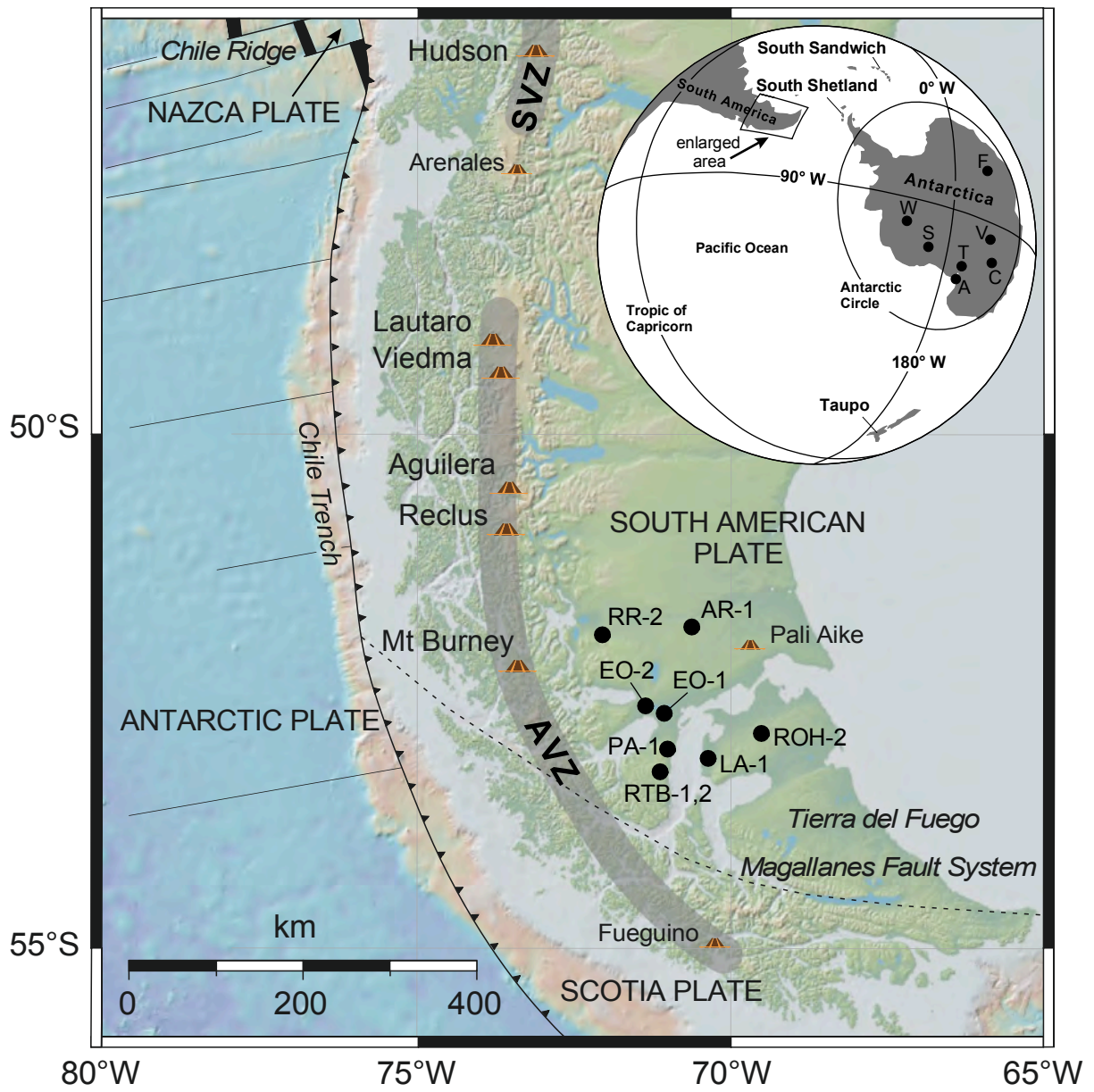
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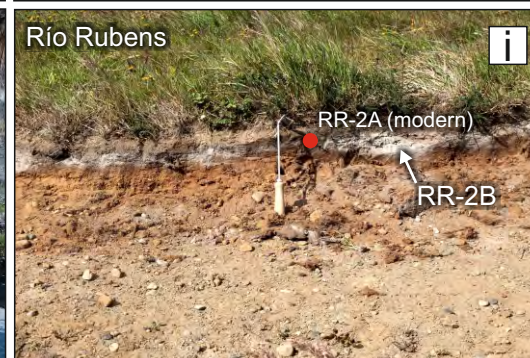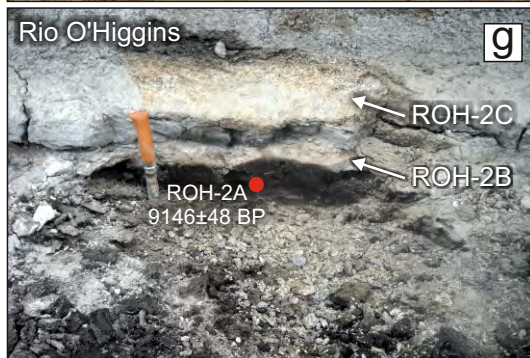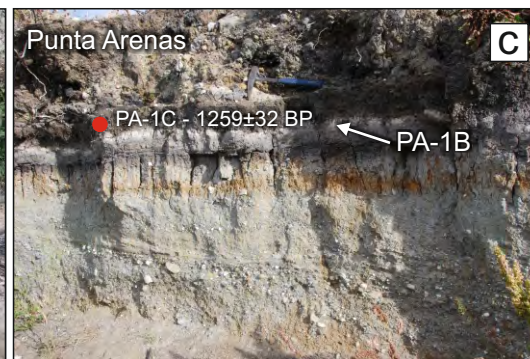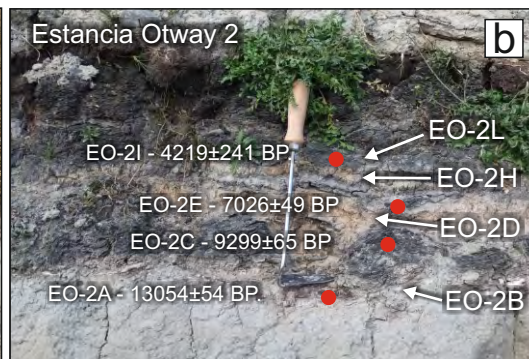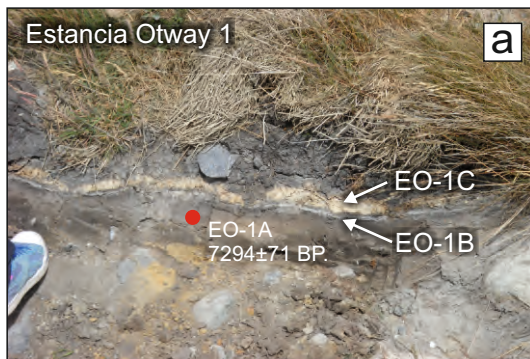|	PA-1B	RTB-1B	RTB-2B	LA-1B	EO-1B	EO-1C	EO-2B	EO-2D	EO-2H	EO-2L	ROH-2B	ROH-2C	AR-1B	AR-1D	AR-1F	RR-2B
Section	PA-1	RTB-1	RTB-2	LA-1	EO-1		EO-2				ROH-2		AR-1			RR-2
Lat. S	53°10'14.9"	53°17'23.70"	53°17'25.26"	53°14'43.20"	52°47'28.58"		52°44'44.64"				52°56'12.60"		51°51'27.77"			52° 3'37.14"
Long. W	070°56'19.3"	71° 1'12.60"	71° 1'12.66"	70°18'58.74"	71° 5'19.41"		71°20'58.98"				69°25'48.00"		70°25'37.54"			71°59'24.78"
Sample	PA-1B	RTB-1B	RTB-2B	LA-1B	EO-1B	EO-1C	EO-2B	EO-2D	EO-2H	EO-2L	ROH-2B	ROH-2C	AR-1B	AR-1D	AR-1F	RR-2B
Thickness (cm)	2-5	12-15	1-3	3-7, discontinuous	1-3	2-4	1-2	2-5	2	2	3-5	12	2.5	10-12	1-16, discontinuous	7, discontinuous
Color	grey-white (Fig. 2c)	white-grey (Fig. 2d)	white (Fig. 2d)	grey (Fig. 2f)	grey (Fig. 2a)	pale yellow (Fig. 2b)	milky white (Fig. 2b)	honey (Fig. 2b)	grey (Fig. 2b)	grey (Fig. 2b)	pale white (Fig. 2g)	pale yellow (Fig. 2g)	white (Fig. 2h)	pale grey (Fig. 2h)	pale yellow (Fig. 2h)	grey-white (Fig. 2i)
Grain size	very fine	fine	very fine	very fine	very fine	fine	very fine	fine to coarse ash	very fine	very fine	fine	very fine	fine to coarse ash	fine to coarse ash	very fine	fine to coarse ash
Glass shards	blocky, Y-shaped and cuspate glass shards, bubble walls and bubble junctions; size from few μm up to ~100 μm (Fig. 5a)	<20 μm blocky to y-shaped or cuspate glass shards (Fig. 5c)	<20 μm, bubble junctions and y-shaped glass shards; poorly-vesicular blocky glass fragments <100 μm with spherical to ellipsoidal and coalesced vesicles	<50 μm, moderately- to poorly-vesicular, blocky glass particles and y-shaped, bubble walls and junctions shards (Fig. 5d); mostly aphyric with scarce pl, opx, ap	blocky, y-shaped or platy-cuspate glass fragments; size from few μm up to ~100 μm (Fig. 4a)	blocky, <100 μm shards; dense fragments with crystal-rich (pl+ox±opx) groundmass (Fig. 4b)	<30 μm, y-shaped, bubble walls and bubble junctions glass hards (Fig. 4c) and blocky particles		low to moderately vesicular, blocky shards <100 μm with spherical to slightly elongated and deformed vesicles; pl, opx microlites; bubble walls and junctions <50 (Fig. 4e)		bubble walls and bubble junctions, y-shaped glass shards; moderately-vesicular blocky glass few to ~100 μm in size	<100 μm colorless, moderately- to poorly-vesicular blocky glass particles and y-shaped glass shards (Fig. 6b); mostly aphyric with scarce microlites of			<100 μm, moderately- to poorly-vesicular, blocky particles and shards, bubble walls and bubble junctions; mostly aphyric with sparse pl, opx microlites	
Micropumices	some highly vesicular and almost aphyric micropumices, <300 μm in size with coalesced and collapsed vesicles	moderately- to highly-vesicular micropumices <200 μm	minor highly- to moderately-vesicular micropumices <200 μm (Fig. 5b); micropumices with microlites of pl, opx, cpx, Fe-Ti ox, ap	minor <100 μm micropumices occur with tubular, coalesced and collapsed vesicles	few micropumices with tubular vesicles and occasional microlites of pl, opx, Fe-Ti ox, ap	few moderately to highly-vesicular micropumices	abundant ~100 μm to 1 mm, highly-vesicular micropumices with coalesced and collapsed vesicles. Some of the micropumices show microlite–rich groundmass	minor, <2 mm, highly- to moderately-vesicular with coalesced and collapsed vesicles, bearing microcrystals of pl, qz, opx, Fe-Ti spinels, cpx and ap (Fig. 4d).		few high- to moderately-vesicular micropumices	<300 μm, highly- to moderately-vesicular micropumices with spherical to amoeboid vesicles, coalesced, collapsed, rarely tubular; aphyric, occasionally including microlites of opx, pl, cpx, Ti-oxides	some poorly- to moderately-vesicular micropumices with amoeboid to collapsed vesicles	abundant, highly- to moderately-vesicular micropumices with spherical to coalesced and collapsed vesicles; micropumices occasionally bear microlites of pl, qz, opx, Fe-Ti oxides (Fig. 6c)	abundant highly- to moderately-vesicular micropumices <500 μm in size, with spherical to coalesced and collapsed vesicles	Minor, <200 μm micropumices with elongated, coalesced and collapsed vesicles	highly- to moderately-vesicular micropumices <1 mm with spherical to coalesced and collapsed vesicles; glass groundmass is aphyric to crystalline with abundant microlites of feldspar and minor
Crystals	loose crystals of cpx, opx, pl and Fe-Ti ox often coated with vesicular glass	loose crystals of pl (strongly zoned), opx, cpx wetted by vesicular glass	loose crystals of pl, opx, cpx, Fe-Ti oxides, ap, wetted by vesicular volcanic glass	scarce loose crystals of pl, opx, ap	scarce loose crystals of pl <150 μm	<200 μm, loose euhedral to subhedral crystals of pl, opx, cpx, ap, Fe-Ti oxides coated with highly-vesicular glass; crystals with cracks and perforation patterns (channels or tunnels)	pl, opx, Fe-Ti spinels and cpx are abundant, and often coated with vesicular to dense glass	<1 mm-sized, loose crystals of pl, qz, opx, Fe-Ti spinels, cpx and ap coated with highly-vesicular glass	scarce loose crystals of pl, opx, cpx and ap	abundant loose crystals of pl, qz, opx, Fe-Ti spinels and ap coated with volcanic glass and few μm blocky glass shards, bubble walls and bubble junctions (Fig. 4f)	<300 μm, loose crystals of pl, cpx, opx and qz <400 μm occur coated with highly- to poorly-vesicular glass	loose crystals of pl, opx, cpx, qz and apatite	<500 μm, loose crystals of pl, qz, opx, Fe-Ti spinels, cpx and ap coated with vesicular glass (Fig. 6a)	<500 μm, loose crystals of pl, qz, opx, Fe-Ti spinels, cpx and ap often coated with moderately vesicular glass	loose crystals of cpx, pl and opx	<2 mm, loose crystals of pl, opx, cpx, qz often coated with moderately vesicular glass (Fig. 6f); crystals with cracks and alteration textures along the cracks
Lithics	well rounded volcanic rock grains and abundant diatoms	abundant fragments and crystals with cracks and perforation patterns (channels or tunnels)	volcanic rock grains	scarce holocrystalline volcanic rock fragments			present	present	present		well-rounded lithic fragments of holocrystalline volcanic rocks	rare fragments of holocrystalline rocks		holocrystalline volcanic rocks	holocrystalline rock fragments are scarce	
Stratigraphic notes	layer sandwiched between two soils (PA-1C, above and PA-1A, below), with desiccation cracks (Fig. 2c)	top of bottom of the layer slightly reworked and diffuse; charcoal fragments (sample RTB-1C) dispersed in the uppermost 3 cm of the tephra	deposited over a cm-thick peat layer (sample RTB-2A), resting on the top of a metres-thick conglomerate (Fig. 2e)	tephra lies on a dark brown soil several cm-thick (sample LA-1A; Fig. 2f)	emplaced over a peat layer (Fig. 2a)	emplaced over a peat layer (Fig. 2a)	layer interbedded with peat layer (Fig. 2b)	layer interbedded with peat layer (Fig. 2b)			lowest layers, lying with wavy basal contact over a peat layer several cm-thick (sample ROH-2A; Fig. 2g)		lowermost layer in the section; embedded between two peat layers (samples AR-1A, AR-1C, Fig. 2h)	mid layer in the section; sandwiched betwen two peat layers (samples AR-1C, AR-1E, Fig. 2h)	uppermost layer in the section (Fig. 2h)	tephra tooped by a soil layer rich in organic matter with dispersed charcoals has been observed (sample RR-2A; Fig. 2i)

Abbreviations: cpx, clinopyroxene; opx, orthopyroxene; pl, plagioclase; ox, oxides; ap, apatite

Table 2. Major and trace element compositions of glass in the studied samples

	AR-1F	st.dev	EO-1B	st.dev	EO-2H	st.dev	ROH-2C	st.dev	AR-1B	st.dev	AR-1D	st.dev	EO-1C	st.dev	EO-2D	st.dev	EO-2L	st.dev	PA-1B	st.dev	ROH-2B	st.dev	RR-2B	st.dev	RTB-2B	st.dev	EO-2B	st.dev	LA-1B	st.dev	RTB-1B	st.dev
Compositional Group	Tr		Tr		Tr		Tr		Rh1		Rh1		Rh1		Rh1		Rh1		Rh1		Rh1		Rh1		Rh1		Rh2		Rh2		Rh2	
	n=11	st.dev	n=14	st.dev	n=12	st.dev	n=13	st.dev	n=10	st.dev	n=23	st.dev	n=17	st.dev	n=6	st.dev	n=11	st.dev	n=11	st.dev	n=10	st.dev	n=15	st.dev	n=7	st.dev	n=11	st.dev	n=23	st.dev	n=15	st.dev
SiO_2	65.4	1	64.6	0.6	65.5	1	65.4	1	77.6	2	78.3	0.3	77.2	2	76.6	2	78.2	0.6	77.9	0.5	78.1	2	78.1	0.3	77.9	0.5	77.6	0.5	78.0	0.2	78.2	0.8
TiO_2	1.17	0.08	1.29	0.09	1.22	0.1	1.15	0.07	0.19	0.08	0.16	0.05	0.24	0.1	0.29	0.11	0.27	0.1	0.27	0.05	0.22	0.2	0.16	0.04	0.06	0.07	0.12	0.1	0.14	0.04	0.22	0.07
Al_2O_3	15.9	0.2	15.7	0.2	15.9	0.2	15.8	0.4	13.3	0.7	12.6	0.1	12.9	0.9	13.4	1	12.8	0.3	12.7	0.2	12.7	0.6	12.7	0.2	12.8	0.2	12.9	0.1	12.6	0.1	12.5	0.5
MnO	0.28	0.1	0.16	0.04	0.17	0.07	0.29	0.1	0.13	0.08	0.04	0.02	0.05	0.02	0.09	0.1	0.05	0.06	0.03	0.02	0.10	0.1	0.05	0.03	0.20	0.2	0.14	0.1	0.06	0.03	0.04	0.02
MgO	1.41	0.1	1.52	0.1	1.39	0.2	1.41	0.4	0.30	0.1	0.23	0.04	0.36	0.2	0.46	0.2	0.34	0.08	0.32	0.04	0.44	0.3	0.24	0.03	0.23	0.03	0.23	0.08	0.20	0.02	0.27	0.05
FeO	4.87	0.3	5.04	0.3	4.82	0.4	4.89	0.6	1.26	0.4	1.16	0.1	1.51	0.5	1.73	0.6	1.28	0.3	1.35	0.1	1.48	0.6	1.22	0.3	1.34	0.1	1.33	0.1	1.26	0.06	1.19	0.2
CaO	2.79	0.2	3.12	0.3	2.81	0.3	2.91	0.7	1.45	0.5	1.26	0.1	1.73	0.6	2.03	0.8	1.46	0.3	1.63	0.1	1.54	0.5	1.33	0.08	1.44	0.1	1.55	0.1	1.47	0.06	1.39	0.2
Na_2O	4.67	1	5.29	0.2	4.78	0.6	4.46	0.3	3.96	0.2	4.17	0.1	4.16	0.3	3.65	0.2	3.50	0.4	4.08	0.1	3.64	0.5	4.19	0.1	3.25	0.2	3.43	0.2	3.53	0.1	4.28	0.4
K_2O	2.95	0.1	2.87	0.1	2.96	0.2	2.98	0.3	1.75	0.3	2.01	0.1	1.79	0.4	1.50	0.2	1.99	0.9	1.73	0.06	1.66	0.2	1.99	0.2	2.68	0.2	2.60	0.1	2.74	0.07	1.87	0.6
P_2O_5	0.52	0.1	0.39	0.05	0.41	0.09	0.68	0.4	0.10	0.07	0.04	0.02	0.05	0.03	0.19	0.1	0.05	0.1	0.05	0.02	0.07	0.06	0.05	0.02	0.09	0.1	0.15	0.4	0.03	0.02	0.03	0.02
Total	98.8	1	99.4	0.5	98.4	0.8	97.7	0.9	97.4	1	97.6	1	98.3	0.9	96.5	0.9	95.3	2	98.5	0.6	96.4	3	98.3	0.8	94.9	1	96.7	2	96.1	0.9	94.6	0.7
	n=10	st.dev	n=33	st.dev	n=10	st.dev	n=12	st.dev	n=7	st.dev	n=17	st.dev	n=8	st.dev	n=8	st.dev	n=7	st.dev	n=8	st.dev	n=2	st.dev	n=13	st.dev	n=7	st.dev	n=17	st.dev	n=17	st.dev	n=4	st.dev
Sc	23.7	2	23.8	2	23.9	2	23.9	2	12.7	1	11.9	1	13.6	2	9.7	1	13.0	1	13.6	0.72	11.5	2	11.3	0.9	13.6	1	11.5	2	10.9	1	15.4	2
Ti	6821	510	6894	700	6594	788	6594	990	849	71	939	75	1578	735	1152	520	1103	144	1451	220	1386	482	898	43	1344	160	877	181	725	76	743	111
V	67	11	60	8	61	12	61	29	4.7	0.7	7.5	3	12.7	8	10.0	9	10.7	2	14.0	3	9.4	4	6.0	1	14.2	5	4.7	3	7.3	4	9.6	6
Cr	bdl		bdl		bdl		bdl		14.0		bdl		bdl		bdl		bdl		bdl		bdl		bdl		bdl		bdl		31.0		bdl	
Mn	1287	84	1283	59	1376	90	1376	139	326	19	320	14	341	116	353	72	277	36	335	31	425	125	321	16	306	43	359	26	386	50	597	212
Co	6.0	1	6.2	1	5.4	0.9	5.4	2	0.97		1.61	0.5	2.45	1	2.70	1	2.52	1	3.6	1	2.10		1.23	0.2	1.39	0.3	2.54	1	3.7	1	4.1	1
Cu	8.3	3	9.2	3	7.8	2	7.8	5	14.6	4	12.7	4	19.1	12	16.6	7	21.4	3	22.3	4	17.9	6	11.1	3	11.9	6	6.9	3	7.8	2	14.0	3
Ga	20.6	0.6	24.6	4	20.4	0.7	20.4	0.9	13.8	1	13.9	2	13.8	1	14.9	2	13.1	2	15.6	2	14.6	0.7	14.1	2	13.5	1	15.5	2	17.0	2	17.8	1
Rb	66	3	69	3	69	4	69	10	28.2	2	28.2	2	27.7	5	26.0	3	19.3	2	23.7	2	24.6	2	27.7	2	22.8	3	45	4	50	4	50	2
Sr	292	31	268	23	283	57	283	100	174	13	187	15	199	53	206	54	189	50	222	25	247	89	187	24	216	48	275	56	255	43	234	9
Y	46	2	46	4	47	6	47	7	12.0	1.0	12.4	1	15.1	3	11.2	2	8.8	0.9	12.7	2	11.7	1	12.6	1	9.0	1	14.6	3	11.7	1	17.0	5
Zr	469	13	471	41	475	48	475	61	92	10	99	6	133	39	103	23	115	12	139	20	133	41	99	8	119	14	105	26	78	7	78	8
Nb	19.5	0.7	20.1	1	19.8	2	19.8	2	5.1	0.3	5.3	0.4	5.2	1	4.4	0.6	3.7	0.6	4.7	0.3	4.5	0.6	5.1	0.4	4.0	0.5	9.3	0.8	8.1	0.9	8.4	0.4
Cs	1.63	0.1	1.78	0.2	1.66	0.2	1.66	0.2	0.51	0.05	0.51	0.1	0.55	0.1	0.55	0.2	0.40	0.1	0.54	0.1	0.52	0.05	0.46	0.1	0.67	0.4	0.68	0.1	1.00	0.3	0.81	0.1
Ba	766	28	745	43	788	61	788	84	561	22	563	34	525	40	480	48	352	25	434	42	475	22	559	36	384	33	660	64	679	58	621	42
La	49	2	50	3	50	5	50	6	15.1	0.6	15.9	1	18.5	2	13.6	2	10.7	0.9	14.8	1	15.7	4	15.3	1	10.7	1	28.3	2	25.1	2	25.6	2
Ce	103	5	105	8	103	9	103	10	29.5	2	30.6	2	36	5	27.1	3	21.4	1	28.7	1	30.3	5	29.7	2	21.8	2	52	5	47	4	44	2
Pr	12.1	0.5	12.4	1	12.3	1	12.3	1	3.19	0.2	3.4	0.3	4.1	0.6	3.01	0.4	2.44	0.2	3.4	0.4	3.12	0.3	3.4	0.3	2.35	0.3	5.5	0.5	5.0	0.6	5.1	0.6
Nd	50	3	51	4	51	5	51	6	12.9	1	13.0	1	16.4	3	11.6	2	9.7	0.7	13.3	2	11.7	1	13.4	2	9.6	1	20.2	2	17.5	3	18.9	2
Sm	10.4	1	10.7	2	10.2	2	10.2	1	2.50	0.3	2.72	0.6	3.29	0.9	2.24	0.7	1.99	0.4	2.63	0.7	2.47	0.7	2.88	0.7	1.84	0.4	3.6	0.8	3.13	0.6	3.6	0.8
Eu	2.72	0.2	2.73	0.3	2.62	0.5	2.62	0.3	0.46	0.07	0.54	0.2	0.57	0.3	0.45	0.1	0.45	0.05	0.71	0.2	0.54	0.1	0.48	0.1	0.47	0.1	0.81	0.2	0.73	0.2	0.68	0.2
Gd	9.3	1	9.4	1	9.3	0.7	9.3	1	2.09	0.4	2.46	0.7	2.73	1	2.25	0.7	1.59	0.3	2.44	0.4	1.92	0.1	2.05	0.4	1.81	0.3	3.21	0.9	2.56	0.7	3.26	0.9
Tb	1.40	0.1	1.37	0.2	1.37	0.2	1.37	0.2	0.34	0.06	0.33	0.09	0.37	0.1	0.28	0.1	0.24	0.05	0.35	0.06	0.28	0.06	0.34	0.07	0.24	0.06	0.44	0.1	0.35	0.08	0.50	0.09
Dy	8.3	0.5	8.4	1	8.5	1	8.5	1	1.96	0.1	2.14	0.4	2.56	0.7	1.68	0.3	1.44	0.1	2.14	0.2	1.83	0.04	2.02	0.4	1.55	0.5	2.42	0.5	1.94	0.5	2.62	0.9
Ho	1.77	0.1	1.72	0.2	1.82	0.4	1.82	0.2	0.38	0.06	0.45	0.1	0.49	0.08	0.38	0.1	0.30	0.06	0.45	0.09	0.38	0.03	0.44	0.1	0.30	0.03	0.51	0.2	0.41	0.1	0.52	0.2
Er	4.9	0.3	4.9	0.4	4.9	0.6	4.9	0.6	1.05	0.3	1.33	0.3	1.67	0.4	1.05	0.2	0.92	0.2	1.38	0.3	0.93	0.2	1.24	0.3	0.85	0.2	1.41	0.4	1.23	0.3	1.48	0.3
Tm	0.74	0.05	0.71	0.1	0.74	0.2	0.74	0.1	0.18	0.03	0.20	0.07	0.25	0.07	0.14	0.05	0.15	0.03	0.22	0.08	0.20	0.07	0.21	0.05	0.17	0.04	0.22	0.05	0.16	0.06	0.26	0.02
Yb	5.1	0.4	4.9	0.8	5.3	0.8	5.3	1	1.33	0.3	1.50	0.5	1.61	0.5	1.29	0.5	0.95	0.3	1.36	0.4	1.13	0.3	1.55	0.4	1.05	0.3	1.38	0.3	1.26	0.4	1.81	0.6
Lu	0.83	0.08	0.78	0.1	0.82	0.1	0.82	0.2	0.20	0.03	0.22	0.1	0.25	0.05	0.19	0.08	0.18	0.03	0.25	0.09	0.12	0.06	0.23	0.05	0.16	0.05	0.19	0.07	0.17	0.07	0.29	0.08
Hf	10.7	0.6	10.5	1	10.7	2	10.7	2	3.32	0.3	3.5	0.5	4.0	1	2.97	0.6	3.28	0.6	4.0	0.9	3.6	0.7	3.4	0.6	3.11	0.6	3.08	0.8	2.37	0.4	2.33	0.3
Ta	1.16	0.1	1.17	0.2	1.18	0.2	1.18	0.2	0.44	0.07	0.40	0.1	0.39	0.1	0.33	0.05	0.28	0.03	0.34	0.09	0.25	0.1	0.40	0.2	0.32	0.07	0.78	0.2	0.72	0.1	0.72	0.1
Pb	14.9	0.3	18.2	3	15.5	2	15.5	1	8.4	2	8.0	1	12.5	9	8.2	0.8	6.7	1	9.3	3	7.6	2	8.3	0.8	6.7	1	11.4	2	14.0	3	11.9	1
Th	7.7	0.4	8.0	1	7.9	0.9	7.9	1	2.38	0.3	2.28	0.3	2.49	0.3	1.92	0.3	1.39	0.09	2.14	0.2	2.55	1	2.28	0.3	1.47	0.2	5.9	0.6	5.4	0.6	5.3	0.4
U	1.90	0.1	2.03	0.3	1.85	0.4	1.85	0.2	0.64	0.04	0.67	0.2	0.73	0.2	0.71	0.2	0.59	0.2	0.64	0.1	0.60	0.2	0.66	0.1	0.43	0.08	2.05	0.7	1.52	0.3	2.00	0.4

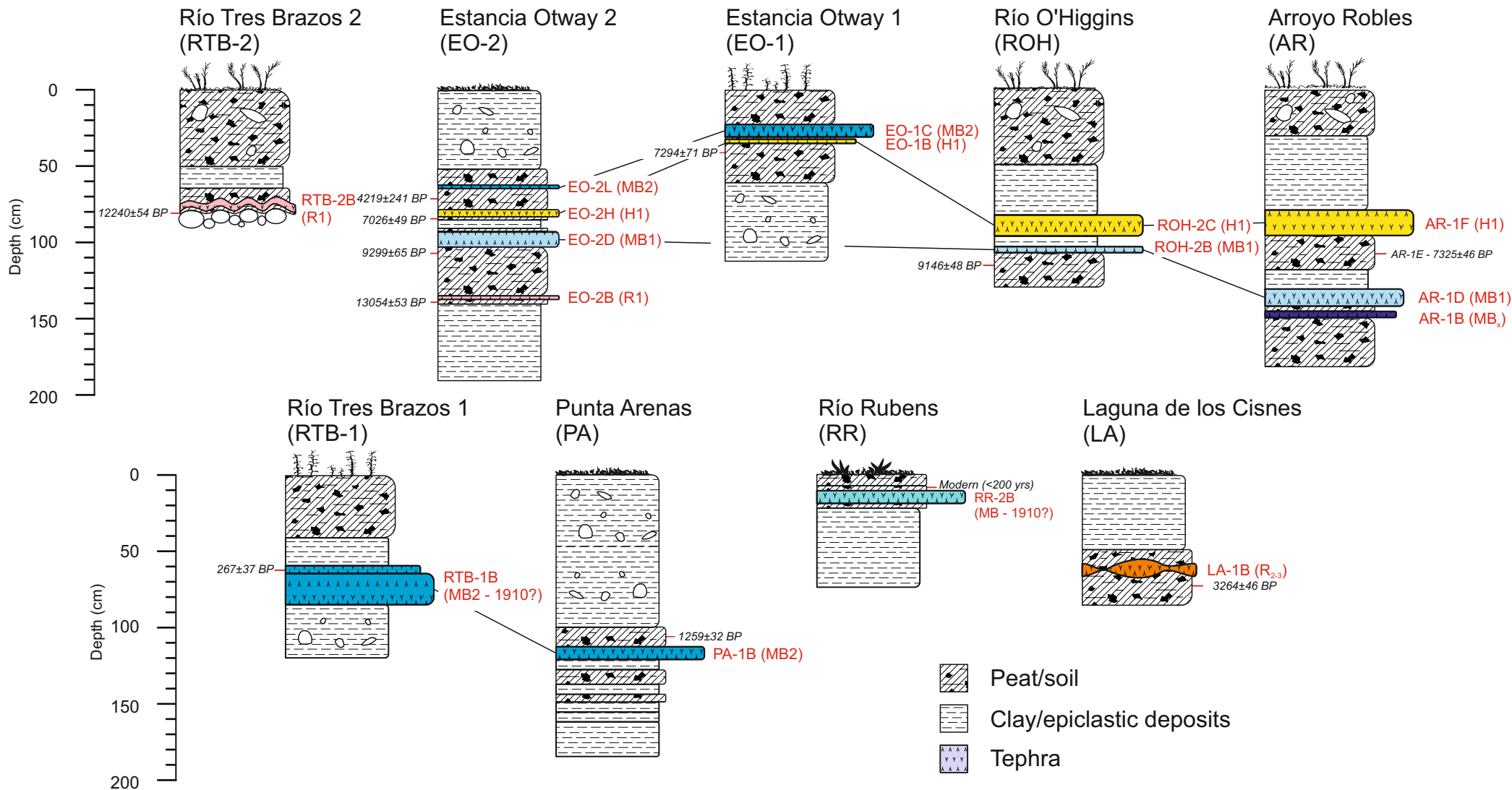Abbreviations: n, number of analyses; st.dev, standard deviation; bdl, below detection limit

Table 3. Radiocarbon age results

Sample Label	Laboratory code	Material	^{14}C yrs BP	^{14}C cal yrs BP (range 2σ)	median cal year BP	∂^{13}C‰ V-PDB
RTB-1C	RC479	Charcoal	267±37	277-459	321	-38.13±1.43
RTB-2A	RC491	SOM	12240±54	13966-14402	14143	-26.54±2.04
PA-1C	RC475	Charcoal	1259±32	1084-1281	1216	-14.07±0.80
LA-1A	RC494	SOM	3264±46	3385-3585	3495	-24.78±4.40
EO-1A	RC486	SOM	7294±71	7965-8303	8106	-37.29±1.25
EO-2I	RC490	SOM	4219±241	4090-5461	4762	-29.60±0.84
EO-2C	RC488	SOM	9299±65	10276-10661	10490	-24.12±4.63
EO-2E	RC489	SOM	7026±49	7744-7955	7865	-36.02±1.35
EO-2A	RC477	Charcoal	13054±54	15359-15861	15643	-30.77±1.26
ROH-2A	RC493	SOM	9146±48	10224-10482	10308	-33.42±1.73
AR-1E	RC485	SOM	7325±46	8014-8291	8119	-22.32±1.68
RR-2A	RC481	SOM	9±38	Modern	Modern	-24.39±4.54

Abbreviations: SOM, soil organic matter

Río Tres Brazos 2 (RTB-2)

12240±54 BP

RTB-2B (R1)

Estancia Otway 2 (EO-2)

EO-2L (MB2)
4219±241 BP
EO-2H (H1)
7026±49 BP
EO-2D (MB1)
9299±65 BP
EO-2B (R1)
13054±53 BP

Estancia Otway 1 (EO-1)

7294±71 BP
EO-1C (MB2)
EO-1B (H1)

Río O'Higgins (ROH)

ROH-2C (H1)
ROH-2B (MB1)
9146±48 BP

Arroyo Robles (AR)

AR-1F (H1)
AR-1E - 7325±46 BP
AR-1D (MB1)
AR-1B (MBx)

Río Tres Brazos 1 (RTB-1)

267±37 BP
RTB-1B (MB2 - 1910?)

Punta Arenas (PA)

1259±32 BP
PA-1B (MB2)

Río Rubens (RR)

Modern (<200 yrs)
RR-2B (MB - 1910?)

Laguna de los Cisnes (LA)

LA-1B (R2-3)
3264±46 BP

Depth (cm): 0, 50, 100, 150, 200

Legend:
- Peat/soil
- Clay/epiclastic deposits
- Tephra

EO-1B **a** — 100 μm
EO-1C **b** — 100 μm
EO-2B **c** — 100 μm
EO-2D **d** — 200 μm
EO-2H **e** — 100 μm
EO-2L **f** — 100 μm

PA-1B   a   100 µm

RTB-2B   b   100 µm

RTB-1B   c   100 µm

LA-1B   d   200 µm

ROH-2B **a** 100 µm

ROH-2C **b**

AR-1B **c** 100 µm

AR-1D **d** 100 µm

AR-1F **e** 100 µm

RR-2B **f** 200 µm

Hudson

Mt. Burney

Reclus

Legend (inset box):
- Tephra volume 10 km³
- 1 km³
- 0.1 km³
- Unknown tephra volume

Rows (right labels): Reclus, Mt Burney, Hudson

Labels within figure: R1, R2, R3, MB1, MB2, Hb, H1, H2, H3

X-axis: Eruption age (cal yrs BP)
18,000   14,000   10,000   6,000   2,000   2018 A.D.

Antarctica	englacial		MBL-NVL
		+	Fuji Dome
	ice cores	✕	Taylor Dome
			Siple Dome
		◇	WDC06A
		○	Vostok
			Dome C
			Talos Dome
	off shore	○	Andrill deep core
			gravity cores

Peri-Antarctic			South Shetland
			South Sandwich
	South America	○	Hudson
		◇	Reclus
			Mt Burney
		+	Aguilera
		✕	Fueguino-Macá-Cay
	this work	○	Group Tr
		□	Group Rh1
		◇	Group Rh2