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1 **Last millennium climate variability of the varved Lake Jeinimeni geochemical record**  
2 **from NE Chilean Patagonia**

3  
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20

21 **Highlights**  
22

- 23 • Lake Jeinimeni sediments in NE Patagonia records a detrital varved sequence over at least  
24 750 yr, from ~AD 1250 to 2008
- 25 • Seasonal clastic supplies are related to spring temperature and snowmelt discharge
- 26 • Correlation to instrumental record supports that varve thickness in Lake Jeinimeni is a proxy  
27 for precipitation
- 28 • The thicker (thinner) clastic varves characterize dry (wet) periods
- 29 • Few thick layers record exceptional erosive conditions responsible for major floods  
30

31 **Abstract (288 words)**

32 Paleoclimate studies in Patagonia show a high Holocene climate variability, strongly controlled  
33 by the intensity and latitudinal position of the Southern Westerly Winds. In this study,  
34 environmental and climate variability, and in particular winter precipitation, was reconstructed  
35 over the last centuries through sedimentological and geochemical analyses of a core from Lake  
36 Jeinimeni in North East Patagonia. Visual description, X-ray radiographies and thin section

37 observations point to finely laminated sediments, made by fine sands and light brown clayey  
38 silts forming an annual deposition (varves) occasionally interrupted by two Hudson volcano-  
39 related tephtras and 15 pluri-millimetre to pluri-centimetre coarser sandy to gravely layers.  
40 Varve counting confirmed by  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  indicates a detrital sequence of at least 750 yr.  
41 Based on a correlation with local meteorological data for the 1930-1988AD interval, varve  
42 thickness and statistical treatment of XRF geochemical data give information on transport  
43 pathway and sedimentary deposit conditions. The sandy laminae correspond to the deposition  
44 of high sedimentary load delivered by austral spring snowmelt whereas the clayey silt laminae  
45 result of particle settling in the water column during low hydrodynamical conditions. Thicker  
46 varves observed in dry conditions underline the importance of aeolian transport in sedimentary  
47 deposition. During locally dry and windy summer, the wind may erode and remobilise the  
48 sedimentary deposits along the lake margins. The sandy and gravely layers record massive  
49 erosional events due to proximal watershed perturbation driven by climatic or tectonic  
50 mechanisms. The clastic varves of Lake Jeinimeni document environmental decadal to  
51 multidecadal variability in East Patagonia over the last centuries. The more pronounced  
52 sediment transition around AD 1750 is consistent with the inception of the Little Ice Age-type  
53 event, in agreement with North Patagonian paleoclimate reconstructions derived from glacier  
54 advances, lacustrine varve thickness and tree-ring records.

55

56 **Keywords:**

57 Lacustrine sediment, clastic varves, climate variability, XRF-core scanner, Late Holocene

58

59 **1. Introduction**

60 Holocene climate variability at the southernmost tip of South America is strongly controlled  
61 by the latitudinal position and intensity of the Southern Westerlies Winds (SWW; Markgraf  
62 1993, Gilli et al., 2005, Garreaud et al., 2009; among others). SWW are associated to storm

63 tracks bringing heavy rainfalls (Trenberth 1991). At present, these winds bring precipitation  
64 over the western site of southern South America with a peak in precipitation around latitudes  
65  $52^{\circ}$ - $53^{\circ}$  S and generate arid conditions on the eastern side of the Andes (Garreaud, et al., 2013).  
66 The SWW are persistent throughout the year with limited seasonal latitudinal variations  
67 (Garreaud 2009). In austral winter (JJA), the SWW expand with a southerly position ( $\sim 55^{\circ}$ S)  
68 whereas it contracts in austral summer (DJF) in a northerly position ( $\sim 50^{\circ}$ S). During austral  
69 winters, the SWW extends, providing rainfall to central Chile ( $33^{\circ}$ - $40^{\circ}$  S) (Markgraf 1993;  
70 Garreaud 2007). The SWW expansion is associated with a decrease of the wind velocity,  
71 especially in its core zone in southernmost Chile ( $50^{\circ}$ - $55^{\circ}$  S) (Lamy et al. 2001, 2010). On the  
72 other hand, the wind speed increases in austral summer due to the contraction of the SWW  
73 (Garreaud 2009).

74 Located within the mid-latitude  $30$ - $60^{\circ}$ S belt, Patagonia is located between two main  
75 circulation systems, i.e. the Intertropical Convergence Zone (ITCZ) to the North and the  
76 Antarctic Convergence Zone (ACZ) to the South. Garreaud et al. (2013) emphasized that  
77 summer precipitation anomalies over Patagonia are correlated with Antarctic Oscillation  
78 (AAO) mode whereas winter anomalies are rather linked with El Niño-Southern Oscillation  
79 (ENSO)-controlled SWW anomalies over the SE Pacific (Montecinos and Aceituno 2003).

80 For the last decades, paleoclimate studies in Patagonia emphasized high temporal climate  
81 variability over the late glacial (Gilli et al., 2005; Markgraf et al., 1992, 2013; Mayr et al., 2013;  
82 Moreno et al., 2001), the Holocene (e.g., Markgraf et al., 1993, 2003; Moreno et al., 2009; Moy  
83 et al., 2009, 2011; Villa-Martínez et al., 2012; Zolitschka et al., 2019) and the last millennium  
84 (e.g., Mayr et al., 2013; Moy et al., 2008; Sepulveda et al., 2009; Schimpf et al., 2011; Villalba  
85 1994). Among the main variability, precipitation variations, derived from different paleoclimate  
86 proxies (e.g., pollen and terrestrial indexes, charcoal content, magnetic susceptibility signal,  
87 mineralogical or geochemical ratios) and archives (e.g., marine or lacustrine sediments, ice

88 cores, tree rings) were mainly used to reconstruct the evolution of SWW, in terms of wind  
89 intensity and latitudinal position over the Holocene (e.g., Villalba 1994; Villa-Martínez and  
90 Moreno 2007; Moy et al., 2008; Moreno et al., 2009; Lamy et al., 2010; Alvarez et al., 2015).  
91 According to vegetation distributions, divergent scenarios have been proposed for climate  
92 changes in Patagonia (44-49°S). Markgraf et al. (2003) suggested a northwards migration of  
93 SSW during the middle Holocene until they reached their modern position in the late Holocene  
94 (Markgraf et al., 1992). This latitudinal migration would be responsible for the Late Holocene  
95 higher climate variability in Patagonia (Markgraf et al., 2013). Villa-Martinez et al. (2012)  
96 rather suggested changes in the strength of the SWW at millennial and multi-millennial  
97 timescales since the last glaciation with no major latitudinal shifts.

98 For the last millennium however, the variability of the SWW remains less documented and  
99 poorly understood. It is particularly the case for the two major climate events, namely the  
100 Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) (e.g., Moy et al., 2008). The  
101 LIA was an apparently centuries-long climate state occurring around ca. AD 1400-1800 (Bradley  
102 et al., 2003) or AD1300-1850 (Masson-Delmotte et al., 2013; Mann et al., 2009; Neukom et al.,  
103 2019). It contrasts with a warm temperature period ranging between AD800 and AD1200,  
104 defined as the MCA (Neukom et al., 2019). In particular for those events, the strong variability  
105 revealed, for instance, in fjord sedimentary sequences from northwest Patagonia (Bertrand et  
106 al., 2014; Sepulveda et al., 2009) is inconsistent with paleoclimate reconstructions (Neukom et  
107 al., 2010). Those reconstructions display unequal and sparse proxy data distribution, especially  
108 for the Southern Hemisphere and for the last millennium (Neukom et al., 2010). However,  
109 paleoclimate reconstructions show poor coherency during these supposed cold and warm  
110 epochs over the past 2 kyr (Neukom et al., 2019). The LIA period, in particular, fails to present  
111 a spatio-temporal coherency with the coldest temperature ranging from the fifteen to the mid-  
112 nineteenth century according to the site location. Inconsistent results have also been derived from

113 the interpretation of different paleoclimate continental and marine Patagonian archives  
114 (Bertrand et al., 2014). As underlined by Moy et al. (2008), the scarcity of accurately-dated,  
115 continuous and unequivocally climate-related archives limit our understanding of recent and  
116 past Patagonian climate. In addition, the SWW fluctuations have mainly been studied in a  
117 latitudinal context, without taking account the influence of the Andes along a W-E longitudinal  
118 transect. Some interpretations of Westerlies fluctuations made on the western side of the Andes  
119 are indeed located in areas close to the eastern side generating contradictory results with  
120 previous studies (Lamy et al., 2010).

121 Therefore, this study aims to document environmental and climate variability, mainly related  
122 to the SWW influence, in a North Eastern Patagonian sector over the last millennium. The Lake  
123 Jeinimeni location provides a unique laminated record that contributes to better understanding  
124 the variability of SWW-related precipitation over the last centuries. Both sedimentological (i.e.,  
125 varve thickness) and geochemical data (represented by the two first principal components) are  
126 correlated with local meteorological data (i.e., temperature, precipitation) to identify the main  
127 drivers of the sedimentation and further to follow their temporal evolution. The main scientific  
128 questions we would like to address in this manuscript are the following ones:

129 (1) Does the sediment record any correlation with any meteorological variable associated with  
130 the SWW-related precipitation? (2) If any, how does it vary over the last millennium? (3) Is  
131 there any change in the sediment record associated with the manifestation of the MCA and the  
132 LIA in the region? (4) Is the climate evolution deduced from Lake Jeinimeni record consistent  
133 with the paleoclimate records available on a regional scale?

134

## 135 **2. Study area**

136 The Lake Jeinimeni (latitude 46.5°S 72°0W, Fig. 1) is located in the Aysen XI region of  
137 Chile (Fig. 1A), at ~50 km south of Chile Chico (Fig. 1B), close to the border with Argentina.

138 The geology of the Aysen region (Pankhurst et al., 1999) comprises three main units reported  
139 in Figure 1C: 1) the Meso-Cenozoic North Patagonian batholith (hornblende–biotite  
140 granodiorites and tonalities); (2) the Devonian-Carboniferous Eastern Andean metamorphic  
141 complex (clastic metasediments) and; (3) the Late Jurassic Ibanez Formation (volcanic rocks,  
142 dacite and rhyolite, andesitic lavas and sedimentary intercalations). Some Eocene and Mio-  
143 Pliocene continental flood basalts and Pliocene granodiorites also outcrop South West of Chile  
144 Chico (De la Cruz et al., 2003). Quaternary alluvial and fluvio-glacial deposits with some  
145 intercalations of volcanoclastic deposits occur along the rivers. The topography of the Aysen  
146 area includes the southern extension of the Andean Cordillera, which is characterized by eternal  
147 snow, numerous glacial valleys and is covered by two major mountain ice fields (Glasser et al.,  
148 2008). Patagonian glaciers are highly sensitive to climate variability and have expanded and  
149 contracted several times during the Quaternary (Glasser et al., 2012). They react to latitudinal  
150 migrations of the SWW that control precipitation (Trenbeth 1991, Lamy et al., 2010) and/or to  
151 temperature changes (e.g., Moreno et al., 2001; Heusser et al., 2006; Villa-Martinez et al.,  
152 2012). Major ice discharges are evidenced by moraine distributions at 1.1 Ma, 140-150 ka  
153 (MIS6), 16-23 ka (MIS2) (Hein et al., 2009). The Lago General Carrera/Buenos Aires is the  
154 regional largest moraine-dammed lake (see Fig. 1B - Glasser et al., 2012). It was formed during  
155 the final glacier retreat (ca 12.8 ka), as the Patagonian Ice Sheet decoupled into the Northern  
156 and Southern Patagonian Ice Sheets and drainage routes opened up towards the Pacific Ocean  
157 (Turner et al., 2005).

158 Located at ~150 km East of the Northern ice field (altitude 700-2500 m, ~4.000 km<sup>2</sup>), the  
159 Lake Jeinimeni watershed (Fig. 1B) corresponds to a mountainous system with steep slopes and  
160 small foothills cut by rivers and numerous streams. The lake altitude is 840 masl and in terms  
161 of its dimensions has a surface area of 0.045 km<sup>2</sup>, and the deepest point registered by this study  
162 was of 82 m. The Lake Jeinimeni with its narrow and elongated morphology belongs to the

163 glacial Lago General Carrera/Buenos Aires watershed (Hein et al., 2010). Its origin is related  
164 to glacial outlet that allows the drainage of the Northern Patagonian icefield and is controlled  
165 by the bedrock topography (Glasser et al., 2008).

166 Present day climate of the Lake Jeinimeni watershed is cold and humid, with a steppe  
167 environment characterized by a sharp orographic eastward decrease in precipitation (e.g.,  
168 Escobar et al., 1992). According to the closest meteorological station (i.e., Chile Chico station  
169 46.58°S, 71.69°W, altitude 306 m, see location on Fig. 1B), the annual average temperature is  
170 low, it oscillates between 7 and 9°C with a wide range between the coldest month (3°C) and  
171 the warmest one (14°C) (data reported in CONAF 2017). Likewise, the annual precipitation is  
172 low (< 500 mm; New et al., 2002). The Chile Chico reports a yearly average of cumulated  
173 precipitation of 293 mm ± 101 for the 1960-2014 interval (data from *Instituto de*  
174 *Investigaciones Agropecuarias* INIA - Hepp et al., 2018), with strong seasonal contrast between  
175 dry austral summer and wet austral winter. Such seasonal variability is mainly controlled by  
176 latitudinal migration and strength of the SWW. The measured wind velocity displays an annual  
177 average of 18 knots (7 to 25 knots) with a dominant W direction. The fastest wind speeds are  
178 observed during austral summer that are locally dry (data 2019 in Direccion General de  
179 Aeronautica Civil - DGAC 2020). Located on the eastern side of the Andes, the austral winter  
180 precipitation in the Lake Jeinimeni area fall mainly as snow above 1000 m (Villalba et al.,  
181 1997). The accumulation of snow reaches up to 6 to 10 m each year. The lake Jeinimeni is  
182 bordered by hills that are part of the called “Cordon La Gloria” (Fig. 1C), reaching altitudes  
183 above 1800 m. The main stream (i.e., La Gloria) that descends from the northwest carries a  
184 large amount of sediments that are deposited during spring in the valley between the Lake Verde  
185 and the Lake Jeinimeni. (Fig. 1C). These sediments can interrupt the flow of the Verde River,  
186 leading to a rise of the river and lake levels, eventually flooding the adjacent terranes  
187 (Henriquez and Alvear 1987). The sedimentary transport is characterized by a strong seasonal



188 control, evidenced by river discharge. Located at the outlet of the Lake Jeinimeni, the annual  
189 flow of the Jeinimeni River (Fig. 1D), measured monthly at the Chile Chico station since 2019  
190 (reported in Direccion General de Aguas - <https://dga.mop.gob.cl/>), displays a first increase  
191 related to precipitation in autumn (April-May), followed by a second one associated to snow  
192 melting in spring (Sept-Nov).

193 The vegetation is characterized by a steppe ecotone. The catchment (212 km<sup>2</sup>) is covered by  
194 patches of Andean temperate deciduous forest leaded by *Nothofagus pumilio* and *Berberis*  
195 *ilicifolia* and temperate Mediterranean (so-called “Patagonian steppe” in Markgraf et al., 2007)  
196 dominated by Poaceae herbs (*Festuca pallescens*) and Apiacea (*Mulinum spinosum*) (Luebert  
197 and Pliscoff, 2006). The upper limit of the forest being located between 1200 and 1400 m, the  
198 low availability of vegetal cover up to the summit line favours erosion of the slopes and runoff  
199 (CONAF 2017).

200 Due to the combination of young landscapes modelled by glacier and rivers and cool climate  
201 associated with the Northern Patagonia Ice Field, the soils in the study area are weakly  
202 developed, dominated by entisols on fluvial terraces, inceptisols on the surfaces exposed after  
203 ice retreat and some histosols (Pfeiffer et al., 2010). The study area is at the Southern limit of  
204 andisol development. Weakly developed in the River Baker drainage Basin (27%, < 0.6 m of  
205 volcanic cover), andisols are for instance absent south of the Lake General Carrera, in Chile  
206 Chico (Vandekerkhove et al., 2015). There is no evidence of active volcanism in the area that  
207 corresponds to the “Patagonian volcanic gap”. The closest active volcano (Hudson Volcano) is  
208 the southernmost volcano of the Southern Volcanic Zone (Stern 2004), located 130 km to the  
209 north west of the study area. The ashes from the Hudson Quaternary explosive eruptions at 3.6  
210 kyr BP and 6.7 kyr BP may have reached the study area (Naranjo and Stern 1998) but according  
211 to Naranjo et al. (1993) recent eruptions in AD 1971 and 1991 did not deposit ash. In term of  
212 tectonic, Lake Jeinimeni is located at the south eastern side of the main structural strike-slip

213 lineaments in North Patagonia (i.e., Liquiñe-Ofqui Fault Zone, Río Mañihuales Fault, Thomson  
214 2002), responsible for crustal intraplate earthquakes (Vanneste et al., 2018). However, an  
215 additional tectonic influence is possible since a fault crossing the lake was recently inferred by  
216 Encinas et al. (2018).

217

### 218 **3. Material and methods**

#### 219 3.1. Sediment core

220 A 161 cm core (LJe14B, S46°50'42", W72°00'47") was taken in the eastern end of the lake  
221 (Fig. 1D), using an Uwitec® gravity corer at a water depth of 61 m in January 2014. A coring  
222 was attempted in a more distal site but it was not successful due to strong winds, frequent in  
223 austral summer.

224 The core was opened longitudinally and the archive half-core section was described and  
225 photographed. The sediment core is characterized by a fine sedimentary texture interrupted by  
226 several coarser layers named event and numbered from E1 to E8 according to increasing depth.  
227 As an exception the lowest part of the sediment core (155-161 cm) does not present any  
228 lamination. This section may be disturbed by coring and has not been further taken in account  
229 in the interpretation. The archive section was measured by non-destructive methods that include  
230 magnetic susceptibility, X-Ray imaging system (SCOPIX) and XRF core scanner. Magnetic  
231 susceptibility (MS) was measured with a Bartington® magnetic susceptibility meter MS2E  
232 point sensor with a 5 mm sampling interval. The working section was entirely subsampled  
233 utilizing aluminium boxes (25 cm length x 4 cm wide x 1.5 cm deep) that were slowly pushed  
234 into the cleaned sediment surface and was extruded with a knife, after a 180° rotation of the  
235 core section. The 25 cm long boxes were used to prepare the large thin section. The remaining  
236 sediment material was subsampled at 2.5 cm for loss-on-ignition (LOI) measurements.

#### 237 3.2. Sedimentological and mineralogical analyses

238 C/N ratio were measured at 1 cm sampling resolution for the upper 15 cm then at 10 cm.  
239 (Lab. Oceanology and AGEs, Université de Liège). After a HCl pre-treatment to remove any  
240 carbonates, ~30 mg of sediment sample powder was analysed for C/N ratio and  $\delta^{13}\text{C}$  with a  
241 Fisons® NA 1500NC elemental analyser coupled with an Optima IR-Mass Spectrometer  
242 (Hedges and Stern 1984).

243 LOI was measured at 60°C overnight for water content, at 550°C for 4h organic matter and  
244 then at 950°C for 2h for carbonates (following the technique described by Heiri et al. 2001).

245 X-ray diffraction (XRD) analyses were done at 5 to 10 cm sampling resolution. The sediment  
246 samples were dried at 40°C and crushed with an agate mortar to 150 microns. The powder was  
247 transferred into a sample holder according to the backside method (Moore and Reynolds 1997).  
248 XRD patterns were measured with a Bruker® D8- Advance Eco diffractometer (Copper  $K\alpha$   
249 radiance,  $\lambda=1.5418 \text{ \AA}$ ,  $V=40 \text{ KV}$ ,  $I=25 \text{ mA}$ ) coupled with a linear Lynxeye Xe energy  
250 dispersive detector. The non-oriented powder was scanned from 2 to 70° 2 $\theta$  with a step size of  
251 0.009°2 $\theta$ , and a time per step of 0.5 seconds. Semi-quantitative mineral abundance was  
252 estimated from the intensity of a diagnostic peak multiplied by a corrective factor defined by  
253 Cook et al. (1975) and Boski et al. (1998). The maximum intensity of the diffraction band at  
254 4.04Å was used to estimate the amorphous content in the sediments due to the occurrence of  
255 biogenic silica, volcanic glasses and/or organic matter (see more information in Fagel et al.,  
256 2017). The XRD mineralogy of the event layers was also done for comparison purposes with  
257 the background sediment.

258 In addition, the grain-size distribution was measured by a laser Malvern® Mastersizer 2000  
259 diffraction particle analyser (Chemical Department, Université de Liège) on a selection of 8  
260 samples from the coarse event layers evidenced by macroscopic description. The bulk sediment  
261 samples were sieved at 2 mm, dispersed in deionised water and introduced into the Hydro  
262 2000G dispersion unit filled by 100 ml of water. The sample amount was adjusted to 15%  $\pm 5$

263 of laser beam obscuration, homogenised and disaggregated with a 2000 rpm stirrer and 20% of  
264 ultrasonic waves. The analysis was repeated at least 3 times to ensure the reproducibility of the  
265 analysis. The results are reported as frequency distribution curves (Sperazza et al., 2004).

266 Scanning Electron Microscope (SEM/EDX) and Electron Microprobe (EMPA) analyses  
267 have been performed on 2 coarser and darker layers (E1 and E2) observed in the upper 10 cm  
268 of LJe14B. The dried bulk sediment was sieved at 105-425 microns, then separated by liquid  
269 density separation using bromoform and the glass-rich light fraction was mounted in epoxy  
270 resin. SEM observations and EDX analyses were performed with a Quanta 650-F QEMSCAN  
271 (FEI) equipped with a Bruker 630 mm<sup>2</sup> EDX detector at the Aachen University (Germany).  
272 We used an acceleration voltage of 15 kV and a working distance of 10 mm. Photos were taken  
273 with a dwell time of 10 µs and EDX spectra were collected from 0 to 10 keV. Quantitative  
274 EMPA analyses of glass beads were performed with a Cameca SX 5 with 5 WDS spectrometers  
275 at the Ruhr-Universität Bochum (Germany). We used a beam with an acceleration voltage of  
276 15 kV, a current of 8 nA and, for most analyses, a spot size of 10 µm. For EMPA calibration,  
277 the following standards were used for K $\alpha$  X-ray: Na on albite, Mg on olivine-SC\_233, Al, Si,  
278 K on orthoclase, Ca on wollastonite, P on apatite, Ti on rutile, Fe on hematite and Mn on  
279 rhodonite. The accuracy and reproducibility of the EMPA analyses were controlled by the  
280 repeated analyses (n=15) of the international glass standard A99 (average sum of oxides  
281 98.66%  $\pm$  0.53).

### 282 3.3. Laminae counting and geochronological analyses

283 Sediment micro-structure was detailed by thin section observations under the microscope  
284 according to the procol described in Żarczyński et al. (2018). The sedimentary material was  
285 subsampled from the 25 cm-long aluminium boxes for large thin sections of 10 to 12.5 x 2 x  
286 1.5 cm. The sediment was first shock-frozen in liquid nitrogen and, then freeze-dried at  
287 University of Liege. The next impregnation step with epoxy resin was done in specialized

288 laboratories. Two 12.5 cm-long thin sections were produced for the upper 25 cm at EPOC,  
289 Univ. Bordeaux (France). Fifteen 10 cm-long (with 2 cm overlapping) were produced between  
290 25 and 150 cm at MK factory in Potsdam (Germany).

291 All thin sections were scanned in polarized light with a resolution of 2400 DPI using a flatbed  
292 scanner and polarizing foils to identify, to count and to measure the thickness of the laminations.  
293 Axio Imager A2 (Zeiss, Germany) microscope was used to investigate thin sections under non-  
294 polarized and polarized light at the University of Gdansk.

295 After establishing a preliminary model of laminae succession representing annual  
296 sedimentation, couplets of laminae were counted on scanned images of thin sections. Counting  
297 was done twice by a single person for the whole sediment core with additional third counting  
298 restricted only to difficult core sections, in order to avoid possible misinterpretation. Finally,  
299 unclear couplets of laminae were included in the chronology as half a year and the counting  
300 uncertainty was increased by  $\pm 0.5$  years, respectively. Following this step, the uncertainty was  
301 cumulatively summed along the chronology.

302 The age model was corroborated by applying  $^{210}\text{Pb}$ ,  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{137}\text{Cs}$  data that were  
303 measured in the upper 16 cm of core LJe14b at EPOC (Univ. Bordeaux, France) using a low-  
304 background and high-efficiency well-type gamma detector. The analyses were performed on 1  
305 cm-thick samples ( $\sim 1.5$  g of dried sediment) retrieved from the archive section. The excess  
306  $^{210}\text{Pb}$  ( $^{210}\text{Pb}_{\text{xs}}$ ) activities were calculated as the difference of the measured  $^{210}\text{Pb}$  and  $^{226}\text{Ra}$ .  
307 Decrease with depth of  $^{210}\text{Pb}_{\text{xs}}$  is then converted into age by applying the Constant  
308 Flux/Constant Sedimentation (CF/CS) model according to Appleby and Oldfield (1978).

309 In addition, radiocarbon dates were measured on 4 bulk sediment samples (Gliwice, Poland).  
310 They were calibrated by the Southern Hemisphere calibration curve SHCal13 (Hogg et al.,  
311 2013) and corrected by a reservoir age of 540 years estimated from the average C/N ratio of the  
312 core (16.7 % at.) using the relationship established by Bertrand et al. (2012) for North

313 Patagonian lakes. The Clam 2.2 code (Blaauw 2010a, b) in the open source software R was  
314 used to perform an age-depth model by combining  $^{137}\text{Cs}$ , excess  $^{210}\text{Pb}$  and  $^{14}\text{C}$  data.

### 315 3.4. Elemental core scanning

316 An X-Ray imaging system composed with an X-ray tube and a linear X-Ray camera has  
317 been used at the EPOC laboratory (Univ. De Bordeaux, France) to obtain an X-Ray image of  
318 the core, and gray-scale level of the sediment (data SCOPIX). Both measurements were  
319 performed on the archive half-core section. Sediment core scanning was done at a resolution of  
320 2 mm an Avaatech XRF core scanner (Richter et al., 2006; Rothwell et al., 2006) equipped with  
321 a Rh tube on the Al boxes at the EPOC laboratory (Univ. Bordeaux, France). The XRF core  
322 scanning was done at 10, 30 and 50KV and 15, 20 and 25s exposure time, respectively. Fifteen  
323 elements have been measured: Al, Si, S, K, Ca, Ti, Mn, Fe, Zn, Br, Rb, Sr, Y, Zr and Ba. Semi-  
324 quantitative concentration profiles of the elements are plotted along the sediment core based on  
325 the variations of their peak areas on the XRF core scanner spectra.

### 326 3.5. Statistic section

327 Geochemical elements obtained from XRF core scanner were analysed through Principal  
328 Component Analysis (PCA). PCA produces new sets of variables, called Principal Components  
329 (PCs) and only the PCs with eigenvalues  $>1$  explain significantly the total variance of the  
330 dataset. Moreover, all the elements do not significantly contribute to the PCs and only those  
331 characterized by a communality values  $\geq 0.5$  are usually retained for PCA (Davis 2002).

332 Geochemical data series are compared to monthly-averaged temperature and precipitation  
333 records from the local Chile Chico meteorological station, which began reporting in AD 1960  
334 (Hepp et al., 2018). The calibration time window was extended down to AD 1930 by using the  
335 climate reconstruction CRU\_TS 4.03 (Harris and Jones 2020), retrieved for the geographical  
336 coordinates  $47^{\circ}.00$  to  $46.40^{\circ}$  latitude S and  $72.20$ - $71.51^{\circ}$  longitude W (<http://climexp.knmi.nl>).  
337 The retained calibration interval spans from AD1930 to AD1988. The oldest CRU\_TS 4.03

338 data for AD 1900-1930 interval was not retained for calibration since Elbert et al. (2012) have  
339 emphasized before AD 1930 a poor quality of the reanalysis in the area. The youngest interval  
340 1991-2014 AD, corresponding to the upper 5 cm of LJe14B record, has not been take into  
341 consideration due to the presence of a coarse event E1 (4.5-5 cm). Below the E1 event, the  
342 LJe14 data were linearly interpolated in order to compare the core proxies with yearly-averaged  
343 meteorological data. For the comparison of meteorological data and sedimentological proxies,  
344 we applied moving average filters of three, five and seven- years for the period 1930-1988 AD.

345 Pearson coefficients and p value ( $p < 0.05$ ) were used to evaluate the strength of the  
346 relationships for determining the main environmental controlling factors. All statistical analyses  
347 were performed in R (R Development Core Team 2016) using the *psych* and *corrplot* packages  
348 (Revelle 2017, Wei and Simko 2017).

349

## 350 **4. Results**

### 351 4.1. Core sedimentology and mineralogy

352 The core image, grey-scale level (SCOPIX), Al count (XRF core scanner), magnetic  
353 susceptibility, water and organic matter contents (LOI60 and LOI550, respectively) and  
354 geochemistry of organic matter (C/N and  $\delta^{13}\text{C}$ ) measured on the core LJe14B are presented in  
355 Fig. 2. The sediments retrieved in core LJe14B are mainly detrital and inorganic, with a water  
356 content ranging between 11 and 43% (average  $34 \pm 6\%$ ) and an averaged organic matter  
357 abundance of  $1.6 \pm 0.3\%$  ( $1.3 < \text{LOI at } 550^\circ\text{C} < 4.2\%$ ) (Fig. 2). The sediments of Lake Jeinimeni  
358 are made by finely laminated light brown clayey silt (fine silt mode at  $3 \mu\text{m}$ ) with a few  
359 remarkable layers, referred to event layer (E) and described in the next section. C/N and  $\delta^{13}\text{C}$   
360 values are relatively constant, with averages of  $16.7 \pm 3.8$  (atomic ratio) and  $-26.2 \pm 0.4\%$ ,  
361 respectively. The average high C/N ratio indicates an important contribution of reworked  
362 organic matter from the watershed (Meyers and Teranes 2001). Sparse benthic diatoms are  
363 observed in the thin sections, with *Eunotia*, *Cymbella*, *Nitzschia*, *Encyonema* and *Rhopalodia*

364 as the main representative genera. Central planktonic frustules are also detected in the upper  
365 part of the core (4-6 cm). Diatoms represent an estimated abundance  $< 1\%$ , they are indicative  
366 of a marshy-like environment (I. Israde Alcantara, personal communication 2/2019).

367 The mineralogical assemblages of core LJe14B are quite constant through the core (SM Fig.  
368 1). Clay minerals ( $36 \pm 4\%$ ) and quartz ( $31 \pm 3\%$ ) are the dominant phases, associated with  
369 similar abundance of K-feldspars ( $13 \pm 3\%$ ) and plagioclase ( $12 \pm 2\%$ ), mica ( $8 \pm 1\%$ ) and  
370 traces of chlorite and amphibole ( $< 2\%$ ). The total amorphous phases average  $11.8 \pm 1.9\%$  of  
371 the core mineralogy, with a maximum of 16% in the two tephra layers. It is made by organic  
372 matter content (1.3-4.2%), diatoms ( $\sim 1\%$ ), tephra glasses at 4.5-5 cm and 7-7.5 cm and  
373 reworked volcanic material from the watershed.

#### 374 4.2. Laminated sediments

375 The sedimentary sequence of Lake Jeinimeni in core LJe14B is made by millimetre-scale  
376 rhythmic alternations of coarse grained quartz- and feldspar-rich layers and fine grained clayey  
377 silt layers with minor organic contributions. This laminated pattern resembles clastic varves  
378 with typical particle-size differences between coarse- and fine-grained laminae deposited  
379 during spring/summer snowmelt and winter calm conditions, respectively (Sturm 1979).

380 The preservation quality of laminations is generally good except the sections adjacent to the  
381 event layers, where disturbances in the sediment structure appear. The base of coarse grained  
382 laminae forms sharp boundary with underlying fine grained laminae. In contrast, the contact  
383 between coarse grained and overlying fine-grained laminae is gradual and does not form a  
384 distinct boundary. Instead, a smooth fining upward is visible, which makes a reliable  
385 measurement of individual laminae (coarse vs. fine) thickness impossible. Thickness of laminae  
386 couplets ranges from 0.3 to 7.6 mm, although the majority (80%) is in the range 0.7-2.5 mm.  
387 The averaged thickness for the entire sediment sequence is  $1.54 \pm 0.89$  mm.

#### 388 4.3. Event layers



389 In the upper part of the core, two darker event layers are evidenced by naked eye at 4.5-5 cm  
390 and 7.4-7.9 cm (i.e., E1 and E2, respectively) and well-marked under the microscope by sharp  
391 bases with no or minimal erosion (Fig. 2). The uppermost layer displays the highest measured  
392 magnetic susceptibility value in the core (i.e., 486 SI, in contrast with the core average of  $54 \pm 36$   
393 SI). The samples at depths of 4-5 cm and 7-8 cm are dominated by silt (69%), yet are associated  
394 with 12-17% of sand and 14-18% of clay. They both present a fine silt mode (8.5-9.8  $\mu\text{m}$ ),  
395 darker grey-scale values and lower Al count (Fig. 2). Similar drops are observed in the Si, K  
396 and Rb core profile whereas Ti, Ca and Sr rather display a marked increase only at 4.5-5 cm  
397 (Fig. 1 and SM Fig. 2). Only the Zr profile evidences a second increase at 7-7.5 cm (SM Fig.  
398 2). The presence of glass shards was further confirmed by SEM observation and EDX analyses  
399 on both E1 and E2 samples (Fig. 3). In addition, the EMPA major geochemistry of the glass  
400 shards from E1 corresponds to an andesite with a high K content (averaged abundance of  $\text{SiO}_2$   
401 =  $62.39 \text{ wt.}\% \pm 1.07$ ,  $\text{K}_2\text{O} = 2.48 \text{ wt.}\% \pm 0.10$ ,  $n = 9$ ).

402 Between 34 and 67 cm, three pluri-centimetre event layers interrupt the laminated  
403 sedimentation: E3 from 34 to 38 cm, E4 from 44 to 48 cm and E7 between 65 and 67 cm (Fig.  
404 2). They are characterized by an irregular erosive base and a thinning upward graded bedding.  
405 Their grain-size corresponds to fine to medium sand with some gravels. According to the  
406 classification of Folk and Ward (1957) they are poorly to very poorly sorted, with sorting values  
407 ranging between 1.8 and 3. Samples 35-36 cm and 65-66 cm are made by > 82% of sand  
408 associated with 14% of silt and 4% of clay, with a mode at 307 and 184  $\mu\text{m}$ , respectively. Those  
409 layers are characterized by darker colour, a marked decrease in Al count and porosity, slightly  
410 lower magnetic susceptibility, lower water content and organic matter but no change in the C/N  
411 nor  $\delta^{13}\text{C}$  values (Fig. 2). The sample 44-45 cm presents a mode at 178  $\mu\text{m}$  with 32% of sand,  
412 46% of silt and 22% of clay particles (SM Fig. 3). Note there is no significant difference in the

413 mineral abundance of the event layers E3, E4 and E7 by comparison with the background  
414 sediment (SM Fig. 1).

415 In addition to the two pluri-millimetric E1 and E2 and the three pluri-centimetre layers E3,  
416 E4 and E7, twelve additional remarkable event layers have been observed under the microscope  
417 within the 150 cm of LJe14B (Fig. 2). They correspond to two groups identified on the thin  
418 sections: (1) non-erosive or representing minimal erosion only, and (2) layers of deformed  
419 laminations and cracks. First group is represented by eight thin (4-11 mm) layers with no or  
420 only minimal erosion (E5, E6, E8, E9, E12, E13, E14, E16). Low potential erosion was  
421 estimated based on the contact with underlying laminae, which were not disturbed. Second  
422 group consists of four layers (E10, E11, E15, E17), which partly result from cracks and  
423 sediment deformations. It is difficult to interpret unambiguously if these layers are original  
424 sedimentation structures or artefacts related to sediment impregnation.

#### 425 4.4. Core chronology

426 For the upper section of core LJe14B (0-16 cm), the age model was derived from  $^{210}\text{Pb}_{\text{xs}}$  and  
427  $^{137}\text{Cs}$  data (Fig. 4a, data reported in Table 1). The profile of  $^{210}\text{Pb}_{\text{xs}}$  displays drastic variations  
428 with low  $^{210}\text{Pb}_{\text{xs}}$  level in the uppermost 4 cm (Fig. 4b). Such low activity of  $^{210}\text{Pb}$  in the first  
429 centimeters could be related to rapid sedimentation event, that dilutes  $^{210}\text{Pb}_{\text{xs}}$  (e.g., Quiroz et  
430 al., 2005). This hypothesis is consistent with the occurrence of E1 event observed at 4.5-5 cm  
431 in LJe14B. Only the samples characterized by equivalent  $^{232}\text{Th}$  activities ( $\sim 70$  mBq/g) are  
432 retained (Table 1). This long-lived radionuclide is associated with the detrital fraction and then  
433 equivalent activities may indicate of rather equivalent lithological sources or proportions. The  
434 sample at 7-8 cm was discarded from the age model: this level was only measured to precise  
435 the shape of the  $^{137}\text{Cs}$  peak, and the counting session was not long enough to allow a reliable  
436 determination of  $^{210}\text{Pb}_{\text{x}}$  (low  $^{229}\text{Th}$  for event E2). The control points are: 1) the surface age (2013  
437 AD) and; 2) the maximum  $^{137}\text{Cs}$  activity (20 mBq/g) observed at 8.5 cm (Fig. 4b) and associated

438 to the most intense period of atmospheric nuclear tests fallout (Stupar et al., 2014). The  $^{137}\text{Cs}$   
439 peak is fixed at 1965 AD  $\pm$  5 yr.

440 For the upper 16 cm, ages were calculated every 2 mm with 95% confidence ranges assuming  
441 a linear regression (Fig.4a). The Pb-Cs age model gives a mean sedimentation rate of 1.43  
442 mm/yr for the upper 15.5 cm of core LJe14B. This value is fully consistent with the average  
443 thickness of laminae couplets of  $1.48\pm 0.86$  mm measured for the same depth interval.  
444 Moreover, there is a good consistency between laminae couplets counting and the  $^{210}\text{Pb}/^{137}\text{Cs}$   
445 age model (Fig. 4a). Assuming an annual sedimentation, the chronology based on varve-  
446 counting is reported for the whole core in Fig. 4c. Scanned images of the thin sections were  
447 correlated with core photographs to identify gaps in the thin sections and further refine the  
448 proposed age model. In Lake Jeinimeni the uppermost 150 cm sedimentary sequence recovered  
449 in core LJe14B encompasses  $759 \pm 62$  years (i.e., error of 8%), from 2013 down to 1254 AD  
450 ( $1193 \text{ AD} < \text{age} < 1318 \text{ AD}$ ), without taking account 15 cm of cumulative events (E1 to E17).  
451 The sedimentary sequence may be uncompleted due to the erosive action of the pluri-centimetre  
452 massive deposits, especially E4 and in a lesser proportion E3 and E7.

453 For the lower part of the core, only bulk sediment was available for radiocarbon dating as  
454 no terrestrial macroremain was found to be dated. Even taking account the reservoir correction  
455 established for the same Patagonian sector (Bertrand et al., 2012), the calibrated radiocarbon  
456 dates remain quite old (Table 2) and induce a sharp drop of the sedimentation rate between the  
457 upper part of the core (0.16 cm/yr) and the lower part of the core (0.03 cm/yr) (see SM Fig. 4).  
458 As such change was not supported by any lithological observation, the bulk sediment dates  
459 were discarded from the age model. Lacustrine bulk sediments may be contaminated by old  
460 “dead” carbon from the watershed (e.g., Abbott and Stafford 1996, Moy et al., 2011, Albéric et  
461 al., 2016).

462

463 **5. Discussion**

464 5.1. Annual character of the sedimentation

465 A set of observations attests for the annual character of the sedimentation retrieved in the  
466 core LJe14B. First, the annual character of the laminations is supported by a calculated  
467 significant correlation between the measured varve thickness and local meteorological data.  
468 The highest Pearson coefficient of -0.71 ( $p < 0.0001$ , Table 4) is obtained between austral spring  
469 (SON) precipitation and varve thickness. The coefficient is moderate but still significant  
470 between annual precipitation and varve thickness (-0.53,  $p < 0.0001$  - Table 4). The correlation  
471 is attested for the last century, i.e., from AD1930 and 1988.

472 Second, the number of laminae couplets observed on the thin section within the upper 16 cm  
473 of the LJe14B core is consistent with the  $^{210}\text{Pb}/^{137}\text{Cs}$  age model (Fig. 4a). This observation  
474 confirmed the annual character of the deposits at least for the upper core section, i.e, for the last  
475 120 years corresponding to the age window covered by the  $^{210}\text{Pb}$  geochronometer.

476 A third argument is related to the calculated age of the two event layers observed in the  
477 uppermost 8 cm of core LJe14B. The  $^{210}\text{Pb}/^{137}\text{Cs}$  age model gives an age of AD 1981-1996 for  
478 the event layer E1 and 1963-1977 for event E2. Given by Clam interpolation, the *best ages* of  
479 AD 1988 and AD 1970 for E1 and E2, respectively, are very close to the age of the two most  
480 recent explosive eruptions of the Hudson volcano (i.e., HU 1991 AD and HU 1971 AD, Scasso  
481 and Carey 2005). The activity of the Hudson volcano started at  $\sim 1$  Ma (Orihashi *et al.*, 2004)  
482 and the Holocene stratigraphy of its fallout deposits records at least twelve more explosive  
483 eruptions. Among them the most important eruption happened in August AD 1991 (Naranjo  
484 and Stern, 1998). Another historical eruption took place in August AD 1971, when an eruptive  
485 column rose 14 km high, leaving a wide scale tephra fall out deposit over the region  
486 (Fuenzalida, 1976). In addition to the age consistency, the glass shards-rich content detected by  
487 SEM observations of the E1 and E2 samples (Fig. 3) confirm their volcanic origin. The

488 microprobe analyses of the glass shards of the sample 4-5 cm gives a chemical composition  
489 similar to the signature of the Hudson eruptions, in particular with the AD 1991 eruption  
490 (Naranjo and Stern 1998) (Fig. 3).

491 Since the laminae couplets display the same structure under the microscope all along the  
492 core LJe14B depth, we assume that the sedimentary deposition in the lower part of the core also  
493 represents an annual character and are therefore interpreted as varves.

#### 494 5.2. Sedimentary deposit conditions

495 Lake Jeinimeni sediments are mostly clastic with a very minor biogenic component. The  
496 organic matter content is relatively low, ranging between 1.3 and 4.2% (Fig. 2). Its geochemical  
497 signature, with high C/N (mean  $16.7 \pm 3.8$  atomic ratio) and very negative  $\delta^{13}\text{C}$  values (-26.96  
498 to -25.39), reflects a mixing of lacustrine and terrestrial organic matter (Meyers and Terranes,  
499 2001). The stable mineralogical assemblages suggest that the source of detrital supplies remains  
500 constant through time. However, changes in grain-size, observed at both microscopic and  
501 macroscopic scales, reflect different modes of sediment transportation.

502 The elemental data measured on core LJe14B allows to explain in further detail the  
503 sedimentation pattern (see Davies et al., 2015 for a review). In the following section the PCA  
504 scores of the main PCs (PC1, PC2) will be reported along core depth to track for lacustrine  
505 environmental variability. Among the XRF core scanner dataset, some elements (e.g., Al, Si,  
506 K, Ti and Fe) display similar trends (Fig. 2 and SM Fig. 2), and by applying a multivariate  
507 statistical analysis such as Principal Component Analysis (PCA), it is possible to disentangle  
508 the forcing mechanisms behind the temporal variability (e.g., Avsar et al., 2014). Four Principal  
509 Components (PC) were identified representing 70.3% of the total variance (Table 3). However,  
510 according to the communality values, the contribution of Mn (0.19) is lower than the other  
511 elements and was therefore removed from the analysis. After its exclusion, the four PCs explain  
512 74.6% of the total variance, with 42.4% of the variance explained by PC1 and 14.8% by PC2

513 (Table 3). PC1 is positively correlated with Al, Si, K, Ti, Fe, Ca, Sr and Y and negatively  
514 associated with S, Zn and Ba. Among these elements, Al, Si, K, Ti, Fe are indicators of detrital  
515 supplies. Abundant in clay minerals, micas and feldspars, they correspond to lithogenic  
516 elements, geochemically stable, hosted by resistant minerals with a conservative behaviour  
517 through the sedimentary cycle (Boës et al., 2011). In addition to their affinity for carbonates,  
518 Ca and Sr are also present in the detrital sedimentary fraction, mainly in plagioclase minerals.  
519 S is often associated to organic matter (e.g., Avsar et al., 2014) that may also include metallic  
520 element like Zn. PC2 explained the 14.8% of the variance and is positively associated with Sr,  
521 Ca and negatively with Rb, Ba. In addition to biogenic component, Sr and Ca are also present  
522 in detrital fraction mainly present in plagioclase feldspars (Davies et al., 2015, p. 196; Rothwell  
523 and Croudace 2015, p. 63). Rb is chemically similar to K that it substitutes in K-feldspars and  
524 micas (Davies et al., 2015, p. 196; Rothwell and Croudace 2015, p. 81), two minerals less easily  
525 chemically-weathered than plagioclase. Rb is rather enriched in fine clay and silt fraction  
526 (Kylander et al., 2011). In the PCA results, Ba is distributed in close proportion between PC1  
527 and PC2. According to its ionic ratio, Ba may substitute Ca and Sr in plagioclase, but also K in  
528 K-feldspars [e.g., in sanidine - cf. Cherniak (2002), Puchelt (1969-1978) cited in Rothwell and  
529 Croudace (2015), page 79].

530 The measured elements by the XRF provide hints about the sediment lithologies (i.e. tephra,  
531 fine clayey silt, fine to medium sand, coarse sand with some gravels). In the binary diagram  
532 PC1 vs. PC2 (Fig. 5), most samples are clustered along the PC1 axis and are distributed in three  
533 groups characterized by different grain sizes: (1) the highest positive values of PC1 fit with the  
534 field of the fine clay-rich samples; (2) the moderate negative PC1 values range within the field  
535 of the coarse sandy-rich samples; (3) the more negative PC1 values mainly correspond to the  
536 field of the three pluri-centimetre thick event layers E. Such sample distribution suggests that  
537 PC1 is sensitive to the hydrodynamics of the aquatic system; notably the energy of

538 hydrodynamics. All the elements associated to the PC1 have a detrital origin delivered by soils  
539 reworking and/or watershed erosion of the parental sediments and rocks. The river transports  
540 fine detrital-rich supplies that settle down at the coring site during calm conditions whereas  
541 coarser material is transported during periods of higher energy hydrodynamics. In addition to  
542 this main trend observed along PC1 axis, a few samples are rather aligned along the PC2 axis.  
543 These samples correspond to the tephra layers (i.e., events E1 and E2) observed in the upper  
544 core section and some type of detrital interference by them (i.e., labelled as tephra-influenced  
545 layer on Fig. 5). In the PC1-PC2 biplot, the distribution of Sr and Ca (and Zr in a lesser  
546 proportion) may be influenced by the tephra layers. Such observation is consistent with the  
547 results of Unkel et al. (2010) who evidenced enrichment in Zr associated to Ca, K, Ti and Sr in  
548 a Hudson volcano-related tephra layer from Laguna Cascada in South Chile.

549 Concerning the thick sandy to gravely event layers, similar coarse fining upward  
550 sedimentary deposits with an erosive base are often interpreted as resulting from floods  
551 deposited by hyperpycnal flows (e.g., Chapron et al., 2006). According to Mulder et al. (1998),  
552 the critical suspended-sediment concentration needed to produce a hyperpycnal plume in a lake  
553 is quite low and may result by river discharge into the lake. Among the event units observed in  
554 LJe14B, those layers with an erosive base (i.e. E3, E4 and E7) most probably record large flood-  
555 triggered turbidites. Only the upper sequence deposited during the falling limb of the flood is  
556 preserved, their basal coarsening upward sequence corresponding to the waxing flow being  
557 erased due to strong erosion (e.g., Guyard et al., 2007). In LJe14B, the event units are irregularly  
558 distributed over core depth, most of them being observed between 34 and 67 cm depth (Fig. 6).  
559 In particular, the event layers characterized by erosive bases may be triggered by different  
560 climate-related mechanisms (e.g., stormy winter conditions - Jenny et al., 2002 and/or  
561 exceptional snowmelt events, heavy rains, catastrophic drainage - Guyard et al., 2007) or  
562 tectonic-related mechanisms (e.g., slumps, earthquakes - Siegenthaler and Sturm 1991,

563 Waldmann et al., 2011, Moernaut et al., 2018). The climate-driven mechanism is the most  
564 probable as Lake Jeinimeni is located at the south eastern side of the influence area of the  
565 Liquiñe-Ofqui Fault Zone (Thomson 2002).

### 566 5.3. Meteorological calibration

567 The local instrumental data from Chile Chico station display a significant high correlation  
568 with CRU\_TS precipitation ( $R^2_{\text{INIA-Pwinter}} = 0.93$ ,  $p < 0.0001$ ;  $R^2_{\text{INIA-Pannual}} = 0.89$ ,  $p < 0.0001$ )  
569 and temperature data ( $R^2_{\text{INIA-Twinter}} = 0.83$ ,  $p < 0.0001$ ;  $R^2_{\text{INIA-Tannual}} = 0.79$ ,  $p < 0.0001$ ). The  
570 correlation analysis between meteorological parameters (i.e., annual and seasonal averaged  
571 temperature and precipitation) and sedimentological, geochemical proxies is shown in Table 4.  
572 In this, the varve thickness was retained as the main sedimentological proxy whereas the scores  
573 of the two first principal components PC1 and PC2 were chosen as geochemical proxies for  
574 grain-size (i.e., related to lake hydrodynamical conditions) and chemical weathering,  
575 respectively.

576 Among the selected proxies, the varve thickness was only sensitive to precipitation. The  
577 relationship between precipitation and varve was characterized by a Pearson correlation  
578 coefficient of -0.53 for annual precipitation and -0.71 in austral spring (i.e., September to  
579 November) (Table 4). As already presented in the first section of the discussion, such significant  
580 correlation supports the annually-resolved character of the sedimentation in LJe14B. The  
581 formation of clastic varves is mainly explained by seasonal runoff that carry suspended  
582 sediment into a stratified lake water body (Sturm, 1979). The thickness of the clastic varves,  
583 like the ones observed in core LJe14B, is strongly controlled by the amount of snowmelt-related  
584 runoff (e.g., Cockburn and Lamoureux 2008). Such seasonally-contrasted sedimentation is  
585 reported worldwide in proglacial lakes (e.g., Leemann and Niessen 1994, Guyard et al., 2007).  
586 The coarse layer results of sediment settling during high hydrodynamic conditions whereas the  
587 fine silt and clay layers result of particle settling in the water column during calm conditions.



588 For Lake Jeinimeni record, the correlation with meteorological parameters (SM Fig.7, Table  
589 4) showed that the varve thickness in core LJe14B was controlled by the precipitation  
590 abundance and its related surface runoff. However, the observed correlation is negative  
591 meaning that thicker (thinner) varves characterize dry (wet) periods. This observation suggests  
592 some contribution of an aeolian transport in the LJe14B sedimentation. The steep and narrow  
593 topography of the Lake Jeinimeni valley favours windy conditions throughout the year.  
594 However, the wind control on sediment transport is probably more pronounced, during the cold  
595 and locally dry austral summer corresponding to low runoff periods. A wind-control on varve  
596 thickness was proposed by Martin-Puertas et al. (2012) in the Meerfelder Maar record  
597 (Germany). In East Patagonia, the fastest winds that characterize the dry summer in the area  
598 may increase the erosive wave activity along the Lake Jeinimeni margins, providing detrital  
599 material to the lake. The fresh sedimentary deposits accumulated on the western margin of the  
600 Lake Jeinimeni during spring snowmelt could be especially sensitive to erosion and further  
601 transport by the lake hydrodynamic to the coring site.

602 Concerning the geochemical proxies, only PC1 presents a correlation with varve thickness,  
603 with thicker varves corresponding to higher PC1 scores ( $R^2_{\text{PC1-varve}} = 0.54$ , Table 4, SM Fig. 5).  
604 This correlation evidences an important contribution of sediment particle transport, and further  
605 settling, during calm hydrodynamic conditions expressed by positive PC1 score. Those  
606 conditions favour the transport of the finest clayey silt particles. This hypothesis would be  
607 confirmed by a counting of the individual thickness of the coarsest and the finest laminae that  
608 compose the clastic varves of Lake Jeinimeni sedimentary record. However, as said earlier in  
609 the laminae description, the core LJe14B does not allow to do such counting. Indeed, there is  
610 no clear distinction between the coarse grained and overlying fine-grained laminae but rather a  
611 gradual boundary.

612 In addition to varve thickness, the geochemical proxies were correlated to the first two  
613 principal components. PC1 score displays a negative correlation with austral winter temperature  
614 ( $R^2_{\text{JJA-PC1}} = -0.54$ , Table 4, SM Fig. 5). Lower austral winter temperatures favour snow  
615 accumulation and limits physical erosion. Only fine particulates (i.e., positive PC1) are  
616 transported to the lake, mostly by winter deflation. Again, the aeolian transport seems to  
617 contribute in a significant fraction of the particle settling in Lake Jeinimeni. The deployment of  
618 seasonal sediment traps within the water column would confirm this hypothesis.

619 On the contrary, PC2 score is positively correlated to temperature, but only with austral  
620 spring temperature ( $R^2_{\text{SON-PC2}} = 0.58$ , Table 4). For Lake Jeinimeni area, the austral spring  
621 warmer temperature is responsible for pronounced snow melting. The snowmelt delivers a high  
622 sedimentary load driven by La Gloria stream (reported on Fig. 1C) recorded by the high spring  
623 flow of the Jeinimeni River measured in Chile Chico station (Fig. 1B). The settling of such high  
624 sedimentary load explains the pluri-millimetre sandy-layers observed at the bottom part of the  
625 laminae couplet in LJe14B. In addition, the relationship between PC2 and SON temperature is  
626 marked by a lag of a few years (SM Fig. 5). An increase in the Sr and Ca content of the lake  
627 sediments (i.e., marked by a PC2 increase) occurs a few years later than a period of warmer  
628 SON temperatures. This observation suggests more influence of physical weathering than  
629 chemical one. Austral spring snowmelt upstream induces a downstream transport of less-  
630 chemically-weathered material to the coring site.

631 Another geochemical ratio, i.e. Si/Al, is also highly correlated with precipitation ( $R^2_{\text{annual P-}}$   
632  $\text{Si/Al}} = 0.72$ ), the highest correlation being observed in fall ( $R^2_{\text{MAM-Si/Al}} = 0.75$ ). In the literature  
633 Si/Al has been used as a proxy for grain-size (Davies et al., 2015; Kylander et al., 2011). In  
634 core LJe14B, the correlation of Si/Al with austral winter temperature ( $R^2_{\text{JJA-Si/Al}} = 0.50$ ) rather  
635 underlines a major runoff control. Indeed, the precipitation enhances physical weathering but

636 also increase lake level. The overbank flooding reduces the energy hydrodynamics and favours  
637 the settling of fine particles.

638

#### 639 5.4. Environmental variability over the last millennium

640 Various sedimentological, glacial and biological archives have been investigated in  
641 continental and also in marine settings from Southern America to reconstruct the climate  
642 variability over the last millennia. An overview of the regional information deduced from these  
643 different archives retrieved at different longitude is given for a 20° latitudinal transect from 33°  
644 to 53°S in South America (Table 5). Some studies depict a general overview of the changes  
645 over the Holocene whereas others present detailed reconstructions allowing to evidence short  
646 climate event like MCA or LIA-type events. In addition, historical archives may also provide  
647 information on pronounced environmental changes related to rapid climate events like the LIA.  
648 The temporal resolution of each archive is controlled by its accumulation rate or growth rate  
649 combined with the sampling step resolution.

650 Among the numerous archives, varve thickness is commonly used as a high-resolution proxy  
651 of climate change (e.g., Zolitschka 1996, Kemp et al., 2001, Nederbragt and Thurow 2001,  
652 Haberzettl et al., 2005). For Lake Jeinimeni setting, the meteorological calibration evidences that  
653 varve thickness of core LJe14B mainly reflects precipitation intensity. Varve counting in  
654 LJe14B allows a reconstruction of precipitation over, at least,  $759 \pm 62$  years, i.e., from ~AD  
655 1250 to 2008. Note this time-window may be longer due to possible erosive influence of the  
656 events E3, 4 and 7 (Fig. 4C). The uncertainty on the age model precludes any time-series  
657 analysis. The sedimentary record of Lake Jeinimeni displays a pronounced multidecadal  
658 variability in varve thickness, by a factor of 1 to 8, over core depth (Fig. 6). This observation  
659 that claims for strong variability in local precipitation is consistent with Late Holocene climate  
660 variability observed in North Patagonia (e.g., Villalba et al., 1990; Markgraf et al., 2013,  
661 Sepulveda et al., 2009; Masiokas et al., 2009). The reconstructed annual precipitation curve in

662 LJe14B (Fig. 7) evidences a succession of wet (ca. AD 1259-1350, AD 1400-1450, AD 1480-  
663 1490, AD 1580-1610, AD 1650-1690, AD 1750-1800, AD 1820-1850, AD 1860-1920 and AD  
664 1960-1990) and dry (ca. AD 1380-1400, 1700-1750 AD) intervals of variable, decadal to  
665 multidecadal, duration. Those climate fluctuations are roughly consistent to the Glacial Frias  
666 ( $41^{\circ}09'S$ ,  $71^{\circ}48'W$  - Fig. 7) fluctuations. Its dendrochronological-derived chronology is marked  
667 by 8 re-advances over the last 4 centuries at ca. AD 1638, 1717-1727, 1742-1752, 1835-1843,  
668 1875-1884, 1912-1916, 1942-1943, and 1977-1978 (reported in Fig. 7), each of those been  
669 characterized by a cold and rainy interval recorded by a wider tree ring (Villalba et al., 1990).  
670 In LJe14B, the most marked drier interval is characterized by a sharp drop of precipitation ca.  
671 AD 1700 and a more gradual return to wetter conditions at ca. AD 1750. This dry interval  
672 precedes a wetter and colder phase reported from various North Patagonian archives such as  
673 tree rings (Villalba et al., 1990; Villalba 1994; Luckman and Villalba 2001; Villalba et al.,  
674 2003), extensive glacier advances (Masiokas et al., 2009, 2010), marine (e.g., core GeoB3313-  
675 1, Fig. 7 - Lamy et al., 2001), fjord (Jacaf, Fig. 7 - Sepulveda et al., 2009) and lacustrine (Lago  
676 Plomo, Fig. 7 - Elbert et al., 2012) sediments between ca. AD 1780 and 1850) and attributed to  
677 the LIA-like interval. North Patagonian glacial fluctuations over the last 1000 years have been  
678 studied by Rabassa et al. (1979, 1984), Villalba et al. (1990) and Masiokas et al. (2010). Villalba  
679 et al. (1990) emphasized the major glacial advances of the Frias Glacier (Fig. 7) between AD  
680 1800-1850 as the LIA event. Likely tree-ring dating indicated that the most extensive expansion  
681 of the Glacier Río Manso, ( $41^{\circ}12'S$ ,  $71^{\circ}51'W$ ) over the past several centuries took place  
682 between the late 1700s and the 1830-40s as the glacier thickened and advanced into adjacent  
683 forests (Masiokas et al. 2009). Further south the LIA-like event has been identified by the  
684 evolution of the Glacier San Rafael ( $46^{\circ}7'S$   $73^{\circ}80'W$  - Fig. 7) located at similar latitude than  
685 Lake Jeinimeni but on the western side of the North Patagonian Icefield. Based on documentary  
686 archives, Araneda et al. (2007) reconstructed the minimal and maximal extension of the Glacier

687 San Rafael within the adjacent laguna (see location on Fig. 1). They identified the interval  
688 comprised between AD 1766-1865 and AD 1871-1904 (Fig. 6) as an interval corresponding to  
689 the LIA-type event in North Patagonia. The coldest interval ca. AD 1857-1871 is consistent  
690 with literature compilation from Northern Patagonian Icefield (Masiokas et al., 2009). Indeed,  
691 the dating of moraines and trimlines associated with 12 North Patagonian glaciers outlets  
692 indicated major glacial advances between AD 1820-1850 (Masiokas et al., 2009), whereas the  
693 LIA is identified  $\leq 100$  to 300 yr earlier in South Patagonia (Koch and Killian 2005), e.g.,  
694 between AD 1550-1800 (Moy et al., 2008). Therefore, the transition observed in LJe14B around  
695 AD 1750 is consistent with the oldest limit of the LIA-type event in North Patagonia, i.e. a  
696 youngest limit by comparison to the LIA interval for the Northern Hemisphere (i.e., AD 1570-  
697 1900 - Matthews and Briffa 2005).

698 The regional significance of the climate variability of Lake Jeinimini record has been further  
699 assessed by the comparison with two varve sequences documented in North Chilean and  
700 Argentinean Patagonia (Fig. 7). In 2012, Elbert et al. (2012) reported an annually-laminated  
701 sedimentary record for 1530-2002 AD from a proglacial lake (Lago Plomo 46°59'S, 72°52'W,  
702 203 masl - Fig. 7) located east of the Northern Patagonian Ice Field, at 75 km WSW of Lake  
703 Jeinimeni. Since no local meteorological station was available for the calibration, the mass  
704 accumulation rate (MAR) derived from the varves thickness were calibrated against austral  
705 winter (JJA) precipitation climate reconstruction data retrieved 47.0°S 72.5°W for the period  
706 AD 1930-2002). By reference to the calibration period, the reconstructed winter precipitation  
707 curve (Fig. 7) evidenced 3 wetter intervals around AD 1600, AD 1630-1690 and AD 1780-  
708 1850, and a drier period AD 1690-1780 with a minimum at AD 1770. Those intervals are  
709 roughly consistent with the wet and dry intervals identified in LJe14B (i.e., AD 1580-1610, AD  
710 1650-1690, AD 1750-1800 and AD 1700-1750). The time lag of 10 to 30 years remains within  
711 the calculated uncertainty of the varve counting in LJe14B (i.e.,  $\pm 62$  years).

712 Likely Ariztegui et al. (2007) investigated a 180 year-varve thickness record in a proglacial  
713 lake (Laguna Frias, Argentina, 40°S - Fig. 7). The authors emphasized that varve thickness  
714 variations mimick the Frias glacier (41°09'S, 71°48'W - Fig. 7) fluctuations (Villalba et al.  
715 1990), with thicker varves during glacial re-advances. Most of those glacier readvances have  
716 been recorded in Lago Frias by the sedimentation of a thicker detrital clayey to silty laminations,  
717 linked to the abrasion of the bedrock by the glacier.

718 Moreover, some regional-scale coherency with the LJe14B record is even observed with  
719 lacustrine sequences from Central Chile. A 600 year-varve sequence retrieved from Lago  
720 Puyehue (40°S, Fig. 7) was divided by 8 periods (Boës and Fagel 2008; Fagel et al., 2008). The  
721 thin varve thickness from ca. AD 1400-1510 in Lake Puyehue is consistent with the dry period  
722 observed in LJe14B between AD 1400-1450, had been interpreted as low lake level during the  
723 late MCA interval. The interval ca. AD 1510-1630, characterized by thicker varves, indicated  
724 more humid conditions in central Chile in comparison with the present-day regional climate  
725 conditions. It covers two successive wet phases evidenced in LJe14B (i.e., AD 1480-1490 and  
726 1580-1610) and was also recorded in Lake Plomo (ca. AD 1600). Between ca. AD 1630 to 1730  
727 and AD 1780-1820, two significant increases in varve thickness attested for another wetter  
728 phases, consistent with the wet LJe14B intervals at AD 1650-1690 and AD 1750-1800 but also  
729 with those recorded in the Lake Plomo record at AD 1630-1690 and AD 1780-1850. There are  
730 interrupted by a drop in the precipitations from ca. AD 1730 to 1780 that corresponds to dry  
731 intervals in LJe14B (~AD 1700-1750) and in Lake Plomo (~ AD 1690-1780). The nineteen  
732 century mainly recorded wetter conditions in Lake Puyehue sequence, with a wet interval over  
733 AD 1820-1920 that covers 2 wet intervals evidenced in LJe14B at ca. AD 1820-1850 and AD  
734 1860-1920. The next wet interval evidenced in Lake Puyehue between AD1920-1950 is not  
735 observed in LJe14B. Note the uppermost interval in the Lake Puyehue record was perturbed by  
736 an earthquake deposit at AD 1960.

737 For a northern site, a multiproxy study of the sedimentary sequence of Laguna Aculeo (33°S,  
738 see location on Fig. 7) emphasized several clastic layers over the last 2 millennia (Jenny et al.,  
739 2002). Those deposits that occurred around ca. AD 200-400, 500-700, AD 1300-1700, and AD  
740 1850-1998 were interpreted as floods and correlated with winter rains from the SWW (Jenny  
741 et al., 2002). The termination of the AD 1300-1700 flood event is consistent with the inception  
742 of the dry interval recorded between ca. AD 1700-1750 in LJe14B. The inception of the next  
743 flood event coincides with the end of the maximum extent of LIA as reported in North Patagonia  
744 (e.g., Araneda et al., 2007; Masiokas et al., 2009).

745 To summarize the regional overview, the precipitation record of Lake Jeinimeni is consistent  
746 with published paleoclimate reconstructions derived from different climate archives studied in  
747 Southern America.

748

## 749 **Conclusion**

750 The sedimentological and geochemical study carried out on Lake Jeinimeni sediments  
751 emphasizes environmental and climate variabilities in NE Chilean Patagonia, in agreement with  
752 climate reconstructions deduced from both marine and continental North Patagonian archives.  
753 The varved core LJe14B records recurrent hydrodynamical changes in the lake watershed, with  
754 seasonal clastic flood supplies related to austral spring temperature and snowmelt discharge. In  
755 addition, the presence of a few thick layers between 1700 and 1850AD underlines exceptional  
756 erosive conditions with the watershed responsible for major floods. The inverse relationship  
757 between varve thickness and precipitation indicates a contribution of aeolian transport within  
758 the LJe14b record during cold and dry austral summer. This could be especially true in lakes  
759 located in the forest-steppe ecotone like Lake Jeinimeni which is located in the lee side of the  
760 Patagonian Andes where an increase in the SWW could be reflected as an increase in aeolian  
761 transport of particles producing a thicker varve.

762 The climate interpretation is limited by the potential disturbance due to the deposition of  
763 those massive events. A distal coring site would bring a more continuous varved-record  
764 allowing to count individual laminae but also to perform spectral analyses on time-series and  
765 therefore further investigate the climate forcing. Precipitation-sensitive proxies (i.e., varve-  
766 thickness, Si/Al) display a high variability in the LJe14B sequence over at least  $759\pm 62$  years.  
767 The highest variability is reported for the oldest part of the LIA-type event (ca. 1750AD), in  
768 agreement with tree-ring records and glacial advances reported in North Patagonia, and  
769 quantitative precipitation reconstructions derived from lacustrine laminated sequences from  
770 both North Patagonia and Central Chile.

771

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#### 780 **References**

781 Abbott M.B. and Stafford T.W. (1996). Radiocarbon Geochemistry of Modern and Ancient  
782 Arctic Lake Systems, Baffin Island, Canada. *Quat. Res.*, 45, 300-311.  
783 Albéric P., Jézéquel D., Bergonzini L., Chapron E., Viollier E., Massault M. and Michard G.  
784 (2016). Carbon Cycling and Organic Radiocarbon Reservoir Effect in a Meromictic Crater  
785 Lake (Lac Pavin, Puy-de-Dôme, France). *Radiocarbon*, 55, 1029-1042.



786 Alvarez D., Fagel N., Araneda A., Jana-Pinninghoff P., Keppens E., Urrutia R. (2015). Late  
787 Holocene climate variability on the eastern flank of the Patagonian Andes (Chile): A  $\delta^{18}\text{O}$   
788 record from mollusks in Lago Cisnes (47°S). *The Holocene* 25 (8), 1220-1230.

789 Appleby P.G. and Oldfield F. (1978). The Calculation of Lead-210 Dates Assuming a Constant  
790 Rate of Supply of Unsupported  $^{210}\text{Pb}$  to the Sediment. *CATENA* 5, 1-8.

791 Aritzigui D., Bösch P., Davaud E. (2007). Dominant ENSO frequencies during the Little Ice  
792 Age in Northern Patagonia: The varved record of proglacial Lago Frías, Argentina.  
793 *Quaternary International* 161, 46-55.

794 Araneda A., Torrejón F., Aguayo M., Torres L., Cruces F., Cisternas M. and Urrutia R. (2007).  
795 Historical records of San Rafael glacier advances (North Patagonia icefield): another clue  
796 to 'Little Ice Age' in southern Chile? *The Holocene* 17(7), 989–1000.

797 Avşar U., Hubert-Ferrari A., De Batist M., Fagel N. (2014). A 3400 years lacustrine  
798 paleoseismic record from the North Anatolian Fault, Turkey: Implications for bimodal  
799 recurrence behaviour. *Geophysical Research Letters* 41, 3773-84,  
800 doi:10.1002/2013GL058221.

801 Bertrand S., Boës X., Castiaux J., Charlet F., Urrutia R., Espinoza C., Lepoint G.,  
802 Charlier, B., Fagel, N. (2005). Temporal evolution of sediment supply in Lago  
803 Puyehue (Southern Chile) during the last 600 yr and its climatic significance.  
804 *Quaternary Research* 64, 163-175.

805 Bertrand S., Araneda A., Vargas P., Jana P., Fagel N., Urrutia R. (2012). Using the N/C ratio  
806 to correct bulk radiocarbon ages from lake sediments: Insights from Chilean Patagonia.  
807 *Quaternary Geochronology* 12, 23-29. doi: 10.1016/j.quageo.2012.06.003.

808 Bertrand S., Huguen K., Sepúlveda J., Pantoja S. (2014). Late Holocene covariability of the  
809 southern westerlies and sea surface temperature in northern Chilean Patagonia  
810 *Quaternary Science Reviews* 105,195-208.

811 Blaauw M. (2010a). Methods and code for 'classical' age-modelling of radiocarbon sequences.  
812 Quaternary Geochronology 5(5), 512-518. <https://doi.org/10.1016/j.quageo.2010.01.002>.

813 Blaauw M. (2010b). R-Code for 'classical' age-modelling (CLAM V1.0) of radiocarbon  
814 sequences. PANGAEA, <https://doi.org/10.1594/PANGAEA.873023>.

815 Boës X. and Fagel N. (2008). Relationships between southern Chilean varved lake sediments,  
816 precipitation and ENSO for the last 600 years. Journal of Paleolimnology 39, 237-252. Doi:  
817 10.1007/s10933-007-9119-9.

818 Boës X, Rydberg J, Martinez-Cortizas A, Bindler R, Renberg I (2011) Evaluation of  
819 conservative lithogenic elements (Ti, Zr, Al, and Rb) to study anthropogenic element  
820 enrichments in lake sediments. Journal of Paleolimnology 46, 75-87.

821 Boski T., Pessoa J., Pedro P., Thorez J., Dias J.M.A., Hall I.R. (1998). Factors governing  
822 abundance of hydrolysable amino acids in the sediments from the N.W. European  
823 Continental Margin (47–50°N). Progress in Oceanography 42, 145–164.

824 Bradley R.S., Briffa K.R., Cole J., Hughes M.K., Osborn T.J. (2003). The climate of the  
825 last millennium. In: Alverson K.D., Bradley R.S., Pederson T.F. (Eds.), Paleoclimate, Global  
826 Change and the Future. Springer, New York, pp. 105-141.

827 Chapron E., Ariztegui D., Mulsow S., Villarosa G., Pino M., Outes V., Juvigné E., Crivelli E.,  
828 (2006). Impact of the 1960 major subduction earthquake in Northern Patagonia. Quaternary  
829 International 158, 58–71.

830 Cherniak D.J. (2002), Ba diffusion in feldspars. Geochimica et Cosmochimica Acta 66(9),  
831 1641-1650.

832 Cockburn J.M.H. and Lamoureux S.F. (2008). Inflow and lake controls on short-term mass  
833 accumulation and sedimentary particle size in a High Arctic lake: implications for  
834 interpreting varved lacustrine sedimentary records. Journal of Paleolimnology 40 (3), 923-  
835 942. <http://dx.doi.org/10.1007/s10933-008-9207-5>.

836 Corporación Nacional Forestal CONAF (2017). Plan de uso público Reserva Nacional Lago  
837 Jeinimeni. República de Chile-Ministerio de Agricultura, p. 27-30.

838 Cook H.E., Johnson P.D., Matti J.C., Zemmels I. (1975). Methods of sample preparation and  
839 X-ray diffraction data analysis in: X-ray mineralogy laboratory. In: Kaneps AG (ed.) *Initial*  
840 *Reports of the DSDP*. Washington, DC: Printing Office. pp. 997–1007.

841 Croudarce I.W. and Rothwell R.G. (2015). Micro-XRF studies of sediment cores.  
842 *Developments in paleoenvironmental Research* 17, Springer Science, Dordrecht, 189-226.  
843 DOI 10.1007/978-94-017-9849-5-7.

844 Davies S.J., Lamb H. F., Roberts S.J. (2015). Micro-XRF Core scanning in paleolimnology:  
845 recent developments. In I.W. Croudarce and R.G. Rothwell (eds.), *Micro-XRF studies of*  
846 *sediment cores. Developments in paleoenvironmental Research* 17, Springer Science,  
847 Dordrecht, 189-226.

848 Davis J.C. (2002). *Statistics and data analysis in Geology*. J. Wiley & sons, New York, 638 pp.

849 De la Cruz R., Suarez M. and Formato M. (2003) *Geología del area puerto guadal-puerto*  
850 *sanchez, region aisen del general carlos ibanez del campo, escala 1. 100000. n° mapa:*  
851 *m113*. Santiago: Servicio Nacional de Geología y Minería-Chile.

852 Dirección General de Aeronáutica Civil (DGAC) (2020). Anuario Meteorológico 2019.  
853 Editorial Dirección Meteorológica de Chile, Santiago de Chile., 85-86.  
854 <https://climatologia.meteochile.gob.cl/application/index/anuarios>.

855 Elbert J., Grosjean M., von Gunten L., Urrutia R., Fischer D., Wartenburger R, Ariztegui D.,  
856 Fujak M. and Hamann Y. (2012). Quantitative high-resolution winter (JJA) precipitation  
857 reconstruction from varved sediments of Lago Plomo 47°S, Patagonian Andes, AD 1530-  
858 2002. *The Holocene* 22(4) 465–474. DOI: 10.1177/0959683611425547.

859 Encinas A., Folguera A., Riffo R., Molina P., Fernandez Paz L., Litvak V.D., Colwyn D.A.,  
860 Valencia V.A., Carrasco, M. (2018). Cenozoic basin evolution of the Central Patagonian

861 Andes: Evidence from geochronology, stratigraphy, and geochemistry, *Geoscience Frontiers*  
862 <https://doi.org/10.1016/j.gsf.2018.07.004>.

863 Escobar, F., Vidal, F., Garin, C., Naruse, R. (1992). Water balance in the Patagonian Icefield.  
864 In: Naruse, R., Aniya, M. (Eds.), *Glaciological Researches in Patagonia*, 1990. Japanese  
865 Society of Snow and Ice, 109–119.

866 Fagel N., Boës X., Loutre M. F. (2008). Climate oscillations evidenced by spectral analysis of  
867 Southern Chilean lacustrine sediments: the assessment of ENSO over the last 600 years.  
868 *Journal of Paleolimnology* 39, 253–266.

869 Fagel N., Alvarez D., Namur O., Devidal J.L., Nuttin L., Schmidt, S., Jana P., Torrejon F.,  
870 Bertrand S., Araneda A. and R. Urrutia (2017). Lacustrine record of last millenia eruptions  
871 in Northern Chilean Patagonia (45-47°S). *The Holocene*. Doi 10.1177/0959683616687380.

872 Folk R.L. and Ward W.C. (1957). A study in the significance of grain-size parameters. *Journal*  
873 *of Sedimentary Petrology* 27, 3-26.

874 Fuenzalida R. (1976). The Hudson volcano. *Proceedings of the IA VCEI Symposium on Andean*  
875 *and Antarctic Volcanology Problems*, 78-87. Santiago, Chile, 1974.

876 Garreaud R.D. (2007). Precipitation and circulation covariability in the extratropics. *Journal of*  
877 *Climate* 20, 4789–4797, doi: 10.1175/JCLI4257.1.

878 Garreaud R.D., Vuille M., Compagnucci R., Marengo J. (2009). Present-day South America  
879 climate. *Paleogeography, Paleoclimatology, Palaeoecology* 281, 180-195.

880 Garreaud R.D., Lopez P., Minvielle M., Rojas M. (2013). Large-Scale Control on the  
881 Patagonian Climate. *Journal of Climate* 26, 215-230. doi: 10.1175/JCLI-D-12-00001.1

882 Gilli A., Ariztegui D., Anselmetti F.S., McKenzie J., Markgraf V., Hajdas I., McCulloch R.D.  
883 (2005). Mid-Holocene strengthening of the southern westerlies in South America—  
884 sedimentological evidences from Lago Cardiel, Argentina (49°S). *Global and Planetary*  
885 *Change* 49, 75-93.

886 Glasser N.F., Jansson K.N., Harrison S., Kleman J. (2008). The glacial geomorphology and  
887 Pleistocene history of South America between 38° and 56°S, *Quaternary Science Reviews*  
888 27, 365–390.

889 Glasser N.F., Harrison S., Schnabel C., Fabel D., Jansson K.N. (2012). Younger Dryas and  
890 early Holocene age glacier advances in Patagonia, *Quaternary Science Reviews* 58, 7-17.

891 Gyuard H., Chapron E., St-Onge G., Anselmetti F. S., Arnaud F., Magand O., Francus P.,  
892 Mélières M.A. (2007). High-altitude varve records of abrupt environmental changes and  
893 mining activity over the last 4000 years in the Western French Alps (Lake Bramant, Grandes  
894 Rousses Massif). *Quaternary Science Reviews* 26, 2644-2660.

895 Haberzettl T., Fey M., Lücke A., Maidana N., Mayr C., Ohlendorf C., Schäbitz F., Schleser  
896 G.H., Wille M., Zolitschka B. (2005). Climatically induced lake level changes during the  
897 last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia  
898 Patagonia (Santa Cruz, Argentina). *Journal of Paleolimnology* 33, 283–302.

899 Harris I.C., Jones P.D. (2020). CRU TS4.03: Climatic Research Unit (CRU) Time-Series (TS)  
900 version 4.03 of high-resolution gridded data of month-by-month variation in climate (Jan.  
901 1901- Dec. 2018). Centre for Environmental Data Analysis, 22 *January 2020*.  
902 doi:10.5285/10d3e3640f004c578403419aac167d82. [http://dx.doi.org/10.5285/10d3e3640f](http://dx.doi.org/10.5285/10d3e3640f004c578403419aac167d82)  
903 [004c578403419aac167d82](http://dx.doi.org/10.5285/10d3e3640f004c578403419aac167d82)

904 Hepp C., Reyes C., Muñoz R. (2018). Análisis de datos históricos de cinco estaciones  
905 meteorológicas de la región de Aysén. Boletín Técnico N°365. Instituto de Investigaciones  
906 Agropecuarias, Centro de Investigación INIA Tamel Aike, Coyhaique, Aysén-Patagonia,  
907 Chile. 200 pp (In Spanish).

908 Hedges J.I. and Stern J.H. (1984). Carbon and nitrogen determinations of carbonate-containing  
909 solids. *Limnology and Oceanography* 29(3), 1984, 657-663.

910 Henríquez M. and Alvear N. (1987). Guía de Manejo Reserva Nacional Lago Jeinimeni.  
911 República de Chile-Ministerio de Agricultura, Corporación Nacional Forestal (CONAF), p.  
912 42. (In Spanish).

913 Hein A. S., Hulton N. R. J., Dunai T. J., Schnabel C., Kaplan M. R., Naylor M., Xu S. (2009).  
914 Middle Pleistocene glaciation in Patagonia dated by cosmogenic-nuclide measurements on  
915 outwash gravels. *Earth and Planetary Science Letters* 286 (1–2), 184-197.

916 Hein A.S., Hulton N.R.J., Dunai T.J., Sugden D.E., Kaplan M.R., Xu S. (2010). The chronology  
917 of the Last Glacial Maximum and deglacial events in central Argentine Patagonia,  
918 *Quaternary Science Reviews* 29, 1212-1227.

919 Heiri A., Lotter F. and Lemcke G. (2001) Loss on ignition as a method for estimating organic  
920 and carbonate content in sediments: Reproducibility and comparability of results. *Journal of*  
921 *Paleolimnology* 25(1), 101–110.

922 Hepp, C., Reyes, C. y Muñoz, R. 2018. Análisis de datos históricos de cinco estaciones  
923 meteorológicas de la región de Aysén. Boletín Técnico N°365. Instituto de Investigaciones  
924 Agropecuarias, Centro de Investigación INIA Tamel Aike, Coyhaique, Aysén-Patagonia,  
925 Chile. 200 pp.

926 Heusser L., Heusser, C., Piasias, N. (2006). Vegetation and climate dynamics of southern Chile  
927 during the past 50,000 years: results of ODP Site 1233 pollen analysis. *Quaternary Science*  
928 *Reviews* 25, 474-485.

929 Hogg A. G., Hua Q., Blackwell P.G., Niu M., Buck C. E., Guilderson T. P., Heaton T.J., Palmer  
930 J. G., Reimer P. J., Reimer R. W., Turney C. S. M., Zimmerman S. R. H. (2013). SHCal13  
931 Southern Hemisphere Calibration, 0–50,000 Years cal BP. *Radiocarbon* 55(4), 1889-1903.

932 Jenny B., Valero-Garces B. L., Urrutia R., Kelts K., Veit H., Appleby P. G., Geyh M. (2002).  
933 Moisture changes and fluctuations of the Westerlies in Mediterranean Central Chile during

934 the last 2000 years: The Laguna Aculeo record (33°50'S). *Quaternary International* 87, 3-  
935 18.

936 Kemp A.E.S, Dean J., Pearce R.B., Pike J. (2001). Recognition and analysis of bedding and  
937 sediment fabric features. In: Last, Smol (eds) *Tracking environmental change using lake*  
938 *sediments. Physical and geochemical Methods*, vol 2, Kluwer Academic Publishers,  
939 Dordrecht, The Netherlands, 7–22.

940 Kylander M., Ampel L., Wohlfarth B., Veres. D. (2011). High-resolution X-ray fluorescence  
941 core scanning analysis of Les Echets (France) sedimentary sequence: new insights from  
942 chemical proxies; *J. Quat. Sci.* 26, 109-117.

943 Koch, J. and Kilian, R. (2005). “Little Ice Age” glacier fluctuations, Gran Campo Nevado,  
944 southernmost Chile. *The Holocene* 15, 20-28.

945 Lamy F., Hebbelm D., Rohl U., Wefer G. (2001). Holocene rainfall variability in southern  
946 Chile: A marine record of latitudinal shifts of the southern westerlies. *Earth and Planetary*  
947 *Science Letters* 185, 369–382.

948 Lamy, F., Kilian, R., Arz, H.W., Francois, J.P., Kaiser, J., Prange, M., Steinke, T. (2010).  
949 Holocene changes in the position and intensity of the southern westerly wind belt. *Nature*  
950 *Geoscience* 3, 695-699.

951 Leemann A. and Niessen F. (1994). Varve formation and the climatic record in an Alpine  
952 proglacial lake: calibrating annually laminated sediments against hydrological and  
953 meteorological data. *The Holocene* 4, 1–8.

954 Luckman B.H. and Villalba R. (2001). Assessing the synchronicity of glacier fluctuations in the  
955 western cordillera of the Americas during the last millennium. In: Markgraf V. (Ed.),  
956 *Interhemispheric Climate Linkages*. Academic Press, New York, 119-137.

957 Luebert F. and Pliscoff P. (2006). *Sinopsis bioclimática y vegetacional de Chile*. Editorial  
958 *Universitaria: Santiago*.

959 Mann M E., Zhang Z.H., Rutherford S., Bradley R.S., Hughes M.K., Shindell D., Ammann C.,  
960 Faluvegi G., Ni F.B. (2009). Global signatures and dynamical origins of the Little Ice Age  
961 and Medieval climate anomaly. *Science* 326, 1256-1260.

962 Markgraf, V. (1993). Paleoenvironments and paleoclimates in Tierra del Fuego and  
963 southernmost Patagonia, South America. *Palaeogeography, Palaeoclimatology,*  
964 *Palaeoecology* 102 (1-2), 53-68.

965 Markgraf, V., Dodson, J.R., Kershaw, A.P., McGlone, M.S., Nicholls, N. (1992). Evolution of  
966 Late Pleistocene and Holocene climates in the circum-South Pacific land areas. *Climate*  
967 *Dynamics* 6, 193-211.

968 Markgraf, V., Bradbury, J.P., Schwalb, A., Burns, S.J., Stern, C., Ariztegui, D., Gilli, A.,  
969 Anselmetti, F.S., Stine, S., Maidana, N. (2003). Holocene palaeoclimates of southern  
970 Patagonia: limnological and environmental history of Lago Cardiel, Argentina (49°S).  
971 *Holocene* 13 (4), 581– 591.

972 Markgraf V., Iglesias V., Whitlock C. (2013). Late and postglacial vegetation and fire history  
973 from Cordón Serrucho Norte, northern Patagonia. *Palaeogeography, Palaeoclimatology,*  
974 *Palaeoecology* 371, 109-118.

975 Martin-Puertas C, Brauer A, Dulski P. (2012). Testing climate–proxy stationarity throughout  
976 the Holocene: an example from the varved sediments of Lake Meerfelder Maar (Germany).  
977 *Quaternary Science Reviews* 58, 56–65.

978 Masiokas M.H., Luckman B.H., Villalba R., Delgado S., Skvarca P., Ripalta A. (2009). Little  
979 Ice Age fluctuations of small glaciers in the Monte Fitz Roy and Lago del Desierto areas,  
980 south Patagonian Andes, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*  
981 281, 351–362.



982 Masiokas M.H., Luckman B.H., Villalba R., Ripalta A., Rabassa J. (2010). Little Ice Age  
983 fluctuations of Glaciar Río Manso in the north Patagonian Andes of Argentina. *Quaternary*  
984 *Research* 73, 96-106.

985 Masson-Delmotte V. et al. in *Climate Change* (2013). The Physical Science Basis  
986 Contribution of Working Group I to the Fifth Assessment Report of the  
987 Intergovernmental Panel on Climate Change (eds. Stocker T. F. et al.), Cambridge Univ.  
988 Press, 383-464.

989 Matthews J.A and Briffa K.R. (2005). The ‘Little Ice Age’: Re-evaluation of an evolving  
990 concept. *Geogr. Ann* 87, 17–36.

991 Mayr C., Lücke A., Wagner S., Wissel H., Ohlendorf C., Haberzettl T., Oehlerich M.,  
992 Schäbitz F., Wille M., Zhu J. (2013). Intensified Southern Hemisphere Westerlies  
993 regulated atmospheric CO<sub>2</sub> during the last deglaciation. *Geology* 41, 831-834.

994 Mayr C., Fey M., Haberzettl T. et al. (2005). Palaeoenvironmental changes in southern  
995 Patagonia during the last millennium recorded in lake sediments from Laguna Azul  
996 (Argentina). *Palaeogeography, Palaeoclimatology, Palaeoecology* 228, 203-227.

997 Mayr C, Wille M, Haberzettl T et al. (2007). Holocene variability  
998 of the Southern Hemisphere westerlies in Argentinean Patagonia (52°S). *Quaternary Science*  
999 *Reviews* 26, 579-584.

1000 Meyers P. A. and Teranes J. L. (2001). Sediment organic matter. *In* W. M. Last & J. P. Smol  
1001 (Eds). *Tracking environmental change using lake sediments*, vol. Volume 2, Physical and  
1002 geochemical methods, p. 239–269. Kluwer Academic Publishers: Dordrecht, Netherlands.

1003 Moernauts J., Van Daele M., Fontijn K., Kempf P., Pino M., Valdebenito G., Urrutia R.,  
1004 Strasser M., De Batist M. (2018), Larger earthquakes recur more periodically: New insights  
1005 in the megathrust earthquakes cycle in lacustrine turbidite records in south-central Chile.  
1006 *Earth Planetary Science Letters* 481, 9-19.

1007 Montecinos A. and Aceituno P. (2003). Seasonality of the ENSO-Related Rainfall Variability  
1008 in Central Chile and Associated Circulation Anomalies. American Meteorological Society  
1009 16, 281-296.

1010 Moore D. and Reynolds R.C. Jr. (1997). *X-Ray Diffraction and the Identification and Analysis*  
1011 *of Clay Minerals*. Oxford: Oxford University Press, 332 pp.

1012 Moreno, P.I., Jacobson, G.L., Lowell, T.V., and Denton, G.H. (2001). Interhemispheric climate  
1013 links revealed by a late-glacial cooling episode in southern Chile. *Nature* 409, 804–808, doi:  
1014 10.1038/35057252.

1015 Moreno P.I., Francois J.P., Villa-Martinez R.P., Moy C.M. (2009). Millennial-scale variability  
1016 in Southern Hemisphere westerly wind activity over the last 5000 years in SW Patagonia:  
1017 *Quaternary Science Reviews* 28, 25–38, doi: 10.1016/j.quascirev.2008.10.009.

1018 Moy C.M., Dunbar R.B., Moreno P.I., Francois J.P., Villa-Martínez R., Mucciarone D.M.,  
1019 Guilderson T.P., Garreaud R.D. (2008). Evidence for hydrologic change related to the  
1020 westerlies in SW Patagonia, Chile, during the last millennium. *Quaternary Science Reviews*  
1021 27, 1335–1349, doi: 10.1016/j.quascirev.2008.03.006.

1022 Moy C.M., Moreno P.I., Dunbar R.B., Kaplan M.R., Francois J.P., Villalba R., Haberzettl T.  
1023 (2009). Climate change in Southern South America during the last 2 millennia. In: Vimeux  
1024 et al. (eds.). *Past Climate variability in South America and surrounding regions*.  
1025 *Developments in Paleoenvironmental Research* 14, 353-387. doi 10.1007/978-90-481-2672-  
1026 9\_15.

1027 Moy C.M., Dunbar, R.B., Guilderson T.P., Waldmann N., Mucciarone D.A., Recasens C.,  
1028 Ariztegui D., Austin Jr J.A. and Anselmetti F.S. (2011). A geochemical and sedimentary  
1029 record of high southern latitude Holocene climate evolution from Lago Fagnano, Tierra del  
1030 Fuego. *Earth and Planetary Science Letters* 302, 1-13

1031 Mulder T., Syvitski J.P.W., Skene K.I. (1998). Modelling of erosion and deposition by turbidity  
1032 currents generated at river mouths. *Journal of Sedimentary Research* 68, 124–137.

1033 Naranjo J.A. and Stern C.R. (1998). Holocene Explosive Activity of Hudson Volcano, Southern  
1034 Andes, *Bull. Volcanol.* 59, 291-306.

1035 Naranjo J.A., Moreno H., N. G. Banks (1993). La erupción del volcán Hudson en 1991 (46°S),  
1036 Región de Aisén, Chile, Servicio Nacional de Geología y Minería, Boletín 44 Santiago, 50  
1037 pp.

1038 National Center for Atmospheric Research Staff (2017). The Climate data Guide CRU TS  
1039 gridded precipitation and other meteorological variables since 1900. Retrieved from  
1040 [https://climatedataguide.ucar.edu/climate-data/cru-ts-gridded-precipitation-and-other-](https://climatedataguide.ucar.edu/climate-data/cru-ts-gridded-precipitation-and-other-meteorological-variables-1901)  
1041 [meteorological-variables-1901.](https://climatedataguide.ucar.edu/climate-data/cru-ts-gridded-precipitation-and-other-meteorological-variables-1901)

1042 Nederbragt A.J. and Thurow J.W. (2001). A 6000 years varve record of Holocene climate in  
1043 Saanich Inlet, British Columbia, from digital sediment colour analysis of ODP Leg 169S  
1044 cores. *Marine Geology* 174, 95–110.

1045 Neukom R., Luterbacher J., Villalba R., Kuttel M., Frank D., Jones P.D., Grosjean M.,  
1046 Esper J., Lopez L., Wanner H. (2010). Multi-centennial summer and winter  
1047 precipitation variability in southern South America. *Geophysical Research Letters* 37.

1048 Neukom R., Steiger N., Gómez-Navarro J.J. et al. (2019). No evidence for globally coherent  
1049 warm and cold periods over the preindustrial Common Era. *Nature* 571, 550-554.  
1050 [https://doi.org/10.1038/s41586-019-1401-2.](https://doi.org/10.1038/s41586-019-1401-2)

1051 New M., Lister D., Hulme M., Makin I. (2002). A high-resolution data set of surface climate  
1052 over global land areas. *Climate Research* 21, 1-25. doi:10.3354/cr021001.

1053 Orihashi Y., J.A. Naranjo, A. Motoki, H. Sumino, D. Hirata, R. Anma, K. Nagao (2004).  
1054 Quaternary volcanic activity of Hudson and Lautaro volcanoes, Chilean Patagonia: New

1055 constraints from K-Ar ages. *Revista Geológica de Chile* 31(2), 207-224.  
1056 <http://dx.doi.org/10.4067/S0716-02082004000200002>.

1057 Pankhurst R.J., Weaver S. D., Hervé F., Larrondo P. (1999). Mesozoic-Cenozoic evolution of  
1058 the North Patagonian Batholith in Aysen, southern Chile. *Journal of the Geological Society*  
1059 156(4), 673-694.

1060 Pfeiffer M., Mascayano C., Aburto F. (2010). Soils of Chilean Patagonia in glacial and  
1061 periglacial environments. *Eurasian Soil Sciences* 43(13), 1430-1438.

1062 Quade J. and Kaplan M.R. (2017). Lake-level stratigraphy and geochronology revisited at Lago  
1063 (Lake) Cardiel, Argentina, and changes in the Southern Hemispheric Westerlies over the last  
1064 25 ka. *Quaternary Science Reviews* 177, 173-188.

1065 Quiroz R., Popp P., Urrutia R., Bauer C., Araneda A., Treutler H.C., Barra R. (2005). PAH  
1066 fluxes in the Laja Lake of south central Chile Andes over the last 50 years: Evidence from a  
1067 dated sediment core. *Science of total Environment* 349, 150-160.

1068 Rabassa J., Rubulis, S. Suarez J. (1979). Rate of formation and sedimentology of (1976–1978)  
1069 push-moraines, Frias Glacier, Mount Tronador (41°10S, 71°53W), Argentina. In:  
1070 Schlüchter, Ch. (Ed.), *Moraines and Varves*. Rotterdam, Balkema, pp. 65-79.

1071 Rabassa J., Brandani A., Boninsegna J.A., Cobos D.R. (1984). Cronología de la “Pequeña  
1072 Edad del Hielo” en los glaciares Río Manso y Castaño Overo, Cerro Tronador, Provincia de  
1073 Río Negro. *Noveno Congreso Geológico Argentino, Actas* 3, 624–639.

1074 R Development Core Team (2016). *R: A Language and Environment for Statistical*  
1075 *Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-  
1076 0, URL <http://www.R-project.org/>.

1077 Revelle W. (2017). *Psych: Procedures for Personality and Psychological Research*. North-  
1078 Western University, Evanston. R package version 1.7.12. URL [http://personality-](http://personality-project.org/r/psych)  
1079 [project.org/r/psych](http://personality-project.org/r/psych).

1080 Richter T.O., Van der Gaast S., Koster B., Vaars A., Gieles R., De Stigter H., De Haas H., van  
1081 Weering T.C.E. (2006). The Avaatech XRF core scanner: technical description and  
1082 applications to NE Atlantic sediments. In: Rothwell, R.G. (Ed.), *New Techniques in*  
1083 *Sediment Core Analysis*. Special Publication, vol. 267. Geological Society, London, 39–50.

1084 Röhlisberger E., 1986. 1000 Jahre Gletschergerichte der Erde. Verlag Sauerlander,  
1085 Salzburg.

1086 Rothwell R.G. and Rack F.R. (2006). New techniques in sediment core analysis: an  
1087 introduction. In: Rothwell, R.G. (Ed.), *New Techniques in Sediment Core Analysis*. Special  
1088 Publication, vol. 267. Geological Society, London, 1-29.

1089 Rothwell R.G. and Croudarce I.W. (2015). Twenty Years of XRF Core Scanning Marine  
1090 Sediments: What Do Geochemical Proxies Tell Us? In: Croudarce I.W. and Rothwell R.G.  
1091 (eds.). *Micro-XRF studies of sediment cores. Developments in paleoenvironmental*  
1092 *Research 17*, Springer Science, Dordrecht, 189-226. DOI 10.1007/978-94-017-9849-5-7.

1093 Schimpf D., Kilian R., Kronz A., Simon K., Spötl C., Worner G., Deininger M.,  
1094 Mangini A. (2011). The significance of chemical, isotopic, and detrital components in three  
1095 coeval stalagmites from the superhumid southernmost Andes (53S) as high-resolution  
1096 palaeo-climate proxies. *Quaternary Science Review* 30, 443-459.

1097 Sepulveda J., Pantoja S., Hughen K.A., Bertrand S., Figueroa D., León T., Drenzek, N.J.,  
1098 Lange, C. (2009). Late Holocene sea-surface temperature and precipitation variability in  
1099 northern Patagonia, Chile (Jacaf Fjord, 44°S). *Quaternary Research* 72, 400-409.

1100 Siegenthaler C. and Sturm M. (1991). Slump induced surges and sediment transport in Lake  
1101 Uri, Switzerland. *Int. Assoc. Theor. Applied Limnology Proceedings*, 24(2), 955-958.

1102 Sperazza M., Moore J., Hendrix M. (2004). High-resolution particle size analysis of naturally  
1103 occurring very fine-grained sediment through laser diffractometry. *Journal of Sedimentary*  
1104 *Research* 74 (5) 736-743.

- 1105 Stern C.R. (2004). Active Andean Volcanism: Its Geologic and Tectonic Setting, *Rev. Geol.*  
1106 *Chile* 31 (2), 161–206.
- 1107 Stern C.R., de Porras M.E., Maldonado A. (2015). Tephrochronology of the upper Río Cisnes  
1108 valley (44°S), southern Chile. *Andean Geology* 42 (2), 173-189.
- 1109 Stupar Y.V., Schäfer J., García M.G., Schmidt S., Piovano E., Blanc F., Huneau G., Le  
1110 Coustumer P. (2014). Historical mercury trends recorded in sediments from the Laguna del  
1111 Plata, Córdoba, Argentina. *Chemie der Erde Geochimistry* 74, 353-363.
- 1112 Sturm M. (1979). Origin and composition of clastic varves. In: Schlüchter, C. (Ed.),  
1113 *Moraines and Varves: Origin, Genesis, Classification*. A.A. Balkema, Rotterdam,  
1114 The Netherlands, pp. 281-285. [http://www.worldcat.org/title/moraines-andvarves-origin-  
1115 genesis-classification/oclc/5542145](http://www.worldcat.org/title/moraines-andvarves-origin-genesis-classification/oclc/5542145).
- 1116 Thomson S. N. (2002). Late Cenozoic geomorphic and tectonic evolution of the Patagonian  
1117 Andes between latitudes 42°S and 46°S: An appraisal based on fission-track results from the  
1118 transpressional intra-arc Liquiñe-Ofqui fault zone. *Geological Society of America Bulletin*  
1119 114(9), 1159–1173.
- 1120 Trenbeth K.E. (1991). Storm tracks in the Southern Hemisphere. *Journal of the Atmospheric*  
1121 *Sciences*, 48 (19), 2159–2178.
- 1122 Unkel I., Fernandez M., Bjorck S., Ljung K., Wohlfarth B. (2010). Records of environmental  
1123 changes during the Holocene from Isla de los Estados (54.4°S), southeastern Tierra del  
1124 Fuego. *Global Planetary Change* 74, 99-113.
- 1125 Vandekerkhove E., Bertrand S., Reid B., Bartels A., Charlier B. (2015). Sources of dissolved  
1126 silica to the fjords of northern Patagonia (44-48°S): the importance of volcanic ash soil  
1127 distribution and weathering *Earth Surf. Process. Landforms*. DOI: 10.1002/esp.3840.
- 1128 Vanneste K., Wils K., Van Daele M. (2018). Probabilistic evaluation of fault sources based on  
1129 paleoseismic evidence from mass-transport deposits: The example of Aysén Fjord, Chile.

1130 Journal of Geophysical Research: Solid Earth 123, 9842–9865.  
1131 <https://doi.org/10.1029/2018JB016289>.

1132 Villalba R. (1994). Tree-ring and glacial evidence for the Medieval Warm Epoch and the Little  
1133 Ice Age in Southern South America. *Climate Change* 26, 183-197.

1134 Villalba R., Leiva J.C., Rubulis S., Suarez J., Lenzano L. (1990). Climate Tree-rings and Glacial  
1135 Fluctuations in the Rio Frias Valley, Rio Negro, Argentina, *Arctic and Alpine Research*  
1136 22(3), 215–232. <https://doi.org/10.1080/00040851.1990.12002786>

1137 Villalba R., Boninsegna J.A., Veblen T.T., Schmelter A., Rubulis S. (1997). Recent trends in  
1138 tree-rings records from high elevation sites in the Andes of Northern Patagonia. *Climatic*  
1139 *Change* 36, 425-454.

1140 Villalba R., Lara A., Boninsegna J.A. et al. (2003). Large-scale temperature changes across the  
1141 southern Andes: 20th-century variations in the context of the past 400 years. In: *Climatic*  
1142 *change climate variability and change in high elevation regions: Past, Present and Future*,  
1143 25–28 June 2001, vol 59. Davos, Switzerland, 177-232.

1144 Villa-Martínez R., Villagrán C., Jenny B. (2003). The last 7500 cal yr BP of westerly rainfall  
1145 in Central Chile inferred from a high-resolution pollen record from Laguna Aculeo (34°S).  
1146 *Quaternary Research* 60, 284-293. doi: 10.1016/j.yqres.2003.07.007.

1147 Villa-Martínez, R., Moreno, P.I (2007). Pollen evidence for variations in the southern margin  
1148 of the westerly winds in SW Patagonia over the last 12,600 years. *Quaternary Research* 68,  
1149 400-409. doi: 10.1016/j.yqres.2007.07.003.

1150 Villa-Martínez R., Moreno P.I., Valenzuela M.A. (2012). Deglacial and postglacial vegetation  
1151 changes on the eastern slopes of the Patagonian Andes (47°S). *Quaternary Science Reviews*  
1152 32, 86-99.

1153 Waldmann N., Anselmetti F.S., Ariztegui D., Austin J.A., Pirouz M., Moy C.M., Dunbar R.  
1154 (2011). Holocene mass-wasting events in Lago Fagnano, Tierra del Fuego (54°S):

1155 implications for paleoseismicity of the Magallanes-Fagnano transform fault. *Basin Research*  
1156 23 (2), 171-190. DOI: 10.1111/j.1365-2117.2010.00489.

1157 Wei T. and Simko V. (2017). R package "corrplot": Visualization of a Correlation Matrix  
1158 (Version 0.84). Available from <https://github.com/taiyun/corrplot>.

1159 Żarczyński M., Tylmann W., Goslar T. (2018). Multiple varve chronologies for the last  
1160 2000 years from the sediments of Lake Żabińskie (northeastern Poland) – comparison of  
1161 strategies for varve counting and uncertainty estimations. *Quat. Geochronol.*  
1162 47, 107–119. <https://doi.org/10.1016/j.quageo.2018.06.001>.

1163 Zolitschka B. (1996). High resolution lacustrine sediments and their potential for palaeoclimatic  
1164 reconstruction. In: Jones, Bradley and Jouzel (Eds), *Climatic variations and forcing*  
1165 *mechanisms of the last 2000 years*. NATO ASI series 141, 453–478.

1166 Zolitschka B., Fey M., Janssen S., Maidana N., Mayr C., Wulf S.  
1167 Haberzettl T., Corbella H., Lücke A., Ohlendorf C. and Schäbitz F. (2019). Southern  
1168 Hemispheric Westerlies control sedimentary processes of Laguna Azul (south-eastern  
1169 Patagonia, Argentina). *The Holocene* 29(3), 403-420.

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1171 **Figure captions**

1172 Figure 1. (A) Location of Lake Jeinimeni within the Aysén region of Chile. The location of the  
1173 Hudson volcano is reported on the map. (B) Simplified map of the regional geology, showing  
1174 the North Patagonian batholith, the Eastern Andean metamorphic complex and the Late  
1175 Jurassic volcano-sedimentary Ibañez Formation (Pankhurst et al. 1999). NPI: Northern  
1176 Patagonian Ice Sheet, LGC/BA: Lago General Carrera/Buenos Aires. Lake Jeinimeni  
1177 watershed is marked by a blue contour. (C) A lake watershed DEM (Digital Elevation  
1178 Model) showing the main geomorphological features. The lake water body is reported in  
1179 blue. (D) Map of basic bathymetric measurements and coring site, reported as a red dot, at  
1180 the northern sector of Lake Jeinimeni. Images C and D, modified from Google Earth© 2019.

1181 Figure 2. Core image, simplified lithological column with the event layers depths and major  
1182 measurements, which include: GL=X-ray grayscale, AI counts, MS=magnetic susceptibility,  
1183 water (LOI60) and organic matter content (LOI550), carbon/nitrogen atomic ratio (C/N) and  
1184 carbon stable isotope ( $\delta^{13}\text{C}$ ) measurements of core LJe14B. The simplified lithological  
1185 column indicates the positions of 17 event layers, noted E1 to E17, which interrupt the  
1186 background sedimentation. The three types of events are plotted with different symbols: the  
1187 thickest and coarsest layers with erosive base in brown; the coarse layers without any erosion  
1188 in black; the questionable layer resulting from cracks and sediment deformation in pale  
1189 brown. E1 at 4.5-5 cm and E2 at 7.4-7.9 cm correspond to two tephras layers. B) Images  
1190 illustrating the background sedimentation and different event types. The scale of each picture  
1191 is approx. 20 mm. Note the reported MS curve represents an average of three profiles.

1192 Figure 3 - On the left panel, Electron Microprobe (EMPA) characterisation of glass shards  
1193 extracted from E1 and E2 event layers in core LJe14B. All the analysed glasses fit with the  
1194 field of the High Abundance Magma Field of the eruptive products from the Southern  
1195 Volcanic Zone (SVZ) as reported in Stern et al. (2015). Moreover, the glass chemistry is

1196 consistent with the signature of the Hudson 1991 eruption (data from Naranjo and Stern  
1197 2004). On the right panel, Scanning Electron Microscope photographs and elemental EDX  
1198 composition of representative glassy samples with circular or elongated gas bubbles: A. E1  
1199 4.5-5 cm, B - E2 7.4-7.9 cm. The EDX major chemistry of the observed glasses from both  
1200 E1 and E2 layer is consistent with a plagioclase composition.

1201 Figure 4. Age model for the upper 16 cm of core LJe14B. A. Comparison between the age-  
1202 depth model derived from varve counting and its uncertainty reported as black lines and the  
1203 age-depth model based on  $^{137}\text{Cs}$  and excess  $^{210}\text{Pb}$  data and its uncertainty marked as blue  
1204 lines. For varve counting, maximum age takes in account all varves, minimum age does not  
1205 include uncertain varves and mean age represents the half of uncertain varves added to  
1206 chronology. The grey bars indicate events E1 and E2 correspond to the two Hudson eruptions  
1207 of 1991 and 1971 AD, respectively. B. The curve corresponds to the exponential fit of the  
1208  $^{210}\text{Pb}_{\text{xs}}$  decrease. Note the two uppermost samples (0-1 cm and 2-3 cm) and the sample at 7-  
1209 8 cm (tephra E2) were excluded from the age model since they present no or low  $^{210}\text{Pb}_{\text{xs}}$ .  
1210 The age model derived from  $^{137}\text{Cs}$  and excess  $^{210}\text{Pb}$  activities (B) is elaborated by linear  
1211 interpolation with Clam 2.2 code (Blaauw 2010a,b). C. Age model for core LJe14B as  
1212 derived from varve counting. The events labelled E1 to E17 are marked. The enclosed photo  
1213 gives an example of the laminated sediment texture, with an alternation of thicker quartz and  
1214 feldspar-rich coarse-grained lamina and thinner fine-grained lamina.

1215 Figure 5. PCA biplot of XRF core scanner dataset (except Mn) reported as a binary diagram of  
1216 the first two principle components PC1 and PC2. The samples are reported with different  
1217 symbols according to their dominant lithology. This diagram emphasizes the distribution of  
1218 the samples in 4 groups according to their lithology. The three groups distributed along the  
1219 PC1 axis correspond to sedimentary samples dominated by fine-grained lamina (red  
1220 diamond), coarse-grained lamina (blue circle), and the massive, sandy to gravely, event E3,

1221 E4 and E7 (open blue square). The fourth group plots along the PC2 axis and corresponds to  
1222 the tephra (dark grey triangle) and tephra-influenced (light grey triangle) layer.

1223 Figure 6. A. Selected sedimentological and geochemical data of LJe14B reported vs. depth, i.e.,  
1224 PC1 and PC2 scores, and varve thickness in mm) The reported numbers correspond to the  
1225 event layers observed in the core sedimentary features. B. Varve thickness is also reported  
1226 vs. varve number (upper horizontal axis) and varve age model (lower horizontal axis) for  
1227 comparison. The bold line represents a 5-years moving average curve. The horizontal bar  
1228 underlines the interval characterized by the thickest varves. Its estimated age ca. AD 1750  
1229 is consistent with the oldest limit of the LIA-type event in North Patagonia, as reported by  
1230 maximal and minimal extension of the Glacier San Rafael (GSR) in the Laguna San Rafael  
1231 (Araneda et al., 2007). See text for more explanation.

1232 Figure 7. Comparison of the varve thickness evolution of Lake Jeinimeni LJe14B with some  
1233 regional records from lacustrine and glacial archives. (a) Varve thickness sequence back to  
1234 AD 1530 obtained from the short core PUII of Lago Puyehue (40°S) by Boës and Fagel  
1235 (2008). The varve thickness has been correlated to precipitation, the highest correlation  
1236 being obtained for May, i.e. autumn/winter transition. The grey line represents the annual  
1237 variations of the varve thickness, the dark grey line the 5-year filtered record and, the dashed  
1238 black line the 30-year filtered. (b) Evolution of varve thickness of LJe14B for the last 500  
1239 years. The grey line represents the annual variations of the varve thickness, the black line  
1240 the 10-year filtered record. (c) Reconstruction of austral winter (JJA) precipitation for varved  
1241 sediments of Lago Plomo (46°59'S) derived from mass accumulation rate back to AD 1530.  
1242 The thin black line represents 5-year filtered precipitation data. The dashed line shows the  
1243 30 years filtered reconstruction. (d) Variations of tree-ring index on *Nothofagus pumilio* over  
1244 the last 500 years (Villalba et al., 1990). The formation of wider tree-rings has been  
1245 correlated to cold and rainy summers and to Glacial Frias re-advances. On the curve, the

1246 black arrows indicate the position of the Glacier Frias advances, their thickness being  
1247 indicative of the event extension. Note all the curves indicate higher precipitation upwards.  
1248 The location of the different records cited in the text is reported on the adjacent map on the  
1249 right side of the figure. See text for more explanation.

1250

### 1251 **Table captions**

1252 Table 1. Measured activities of  $^{210}\text{Pb}_{\text{xs}}$ ,  $^{232}\text{Th}$  and  $^{137}\text{Cs}$  in sediment samples of the uppermost  
1253 16 cm of core LJe14B.

1254 Table 2. AMS radiocarbon ages obtained on bulk sediment samples. An age reservoir correction  
1255 of 540 years was applied taking in account a C/N ratio of 16.7 (% at.) following the equation  
1256 proposed by Bertrand et al. (2012). Four intervals (4.5-4.9, 34-39 cm, 44-48 cm, 65-67 cm)  
1257 were considered as events and were removed for the calibration. Radiocarbon dates were  
1258 calibrated by Clam calibration program (Blauw et al., 2010 a, b) using atmospheric SHCal13  
1259 calibration curve (Hogg et al., 2013). Samples were measured at the Gadam Radiocarbon  
1260 Laboratory.

1261 Table 3. Results of principal component analysis (PCA) on raw XRF core scanner dataset. The  
1262 table gives the contribution of each principal component in total variance. PCA was  
1263 performed without Mn because its communality value was lower than 0.5.

1264 Table 4. Calibration of varve thickness and geochemical data (principal components PC1 and  
1265 PC2, Si/Al) with CRU-TS reconstruction over 1930-1988 AD. Meteorological data retrieved  
1266 from National Center for Atmospheric Research Staff (2017). Statistically significant  
1267 correlations, according to Pearson's correlation coefficient with p-value  $< 0.05$ , are reported  
1268 in color (positive in red, negative in blue). The number of asterisks gives the degree of  
1269 significance: \*p  $< 0.01$ , \*\*p  $< 0.001$  and \*\*\*p  $< 0.0001$ . Note the same correlations are  
1270 observed for averaged or accumulated precipitation.

1271 Table 5. Overview of regional paleoenvironmental information deduced from published climate  
1272 archives reported over a 20° latitudinal transect from 33° to 53°S in South America.

1273

#### 1274 **Supplementary material**

1275 SM Figure 1. XRD mineralogy on bulk sediment. The sample are reported along the x-axis.

1276 Each sample correspond to 1 cm of sediment thickness and the label represents the mid-

1277 depth of the sample expressed in cm. The T at the end of the label indicates the two tephra

1278 layers. The cumulated mineral abundance is given along the y-axis. Each mineral is

1279 represented by a distinct color, the color code being given on the right site of the diagram.

1280 OM corresponds to the organic matter deduced from the loss-of-ignition at 550°C (LOI550).

1281 OM abundance was removed from the XRD-estimated total amorphous content in the

1282 sediments (i.e., sum of biogenic silica, volcanic glasses and/or organic matter).

1283 SM Figure 2. XRF core scanner elemental profile for Si, K, S, Ca, Sr, Rb and Zr.

1284 SM Figure 3. Grain-size distribution measured by a laser Malvern® Mastersizer 2000

1285 diffraction particle analyser. The selected samples correspond to different event layers,

1286 evidenced by macroscopic description. The samples are identified by their depth interval

1287 expressed in cm. Note the three samples characterize by the highest abundance of coarse

1288 sand grains (i.e. samples 35-36, 44-45 and 65-66) correspond to the coarsest layers E3, E4

1289 and E7. The samples 4-5 and 7-8 corresponding to the tephra layers E1 and E2 display a

1290 broad range of grain size with a clear influence of the fine background sedimentation.

1291 SM Figure 4. Age model for core LJe14B derived from  $^{210}\text{Pb}$ - $^{137}\text{Cs}$  data (data in Table 1) and

1292 AMS radiocarbon dates on bulk sediment (data in Table 2). The linear interpolation between

1293 the dated samples does not take into account the observed event layers (i.e., E1 4-4.5 cm, E2

1294 7.4-7.9 cm, E3 35-36 cm, E4 44-45 cm and, E7 65-66 cm), marked by the horizontal grey

1295 bars. The dashed red line corresponds to an extrapolation of the sedimentation rate measured  
1296 for the upper 16 cm of core LJe14B and consistent with varve counting.

1297 SM Figure 5. Correlation between local meteorological data (i.e., precipitation, temperature)  
1298 retrieved from Instituto de Investigaciones Agropecuaria (INIA - Hepp et al., 2018) and  
1299 sedimentological (varve thickness) or selected geochemical proxies of LJe14B discussed in  
1300 the text (PC1 and PC2 scores, Si/Al). All curves correspond to a 7-years moving average.

1301 Data from Table 4.

1302