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

3
4 Fagel N.¹, P. Pedreros², D. Alvarez²⁻³, W. Tylmann⁴, O. Namur⁵, A.C. Da Silva⁶, P. Jana², A.
5 Araneda², I. Billy⁷, S. Schmidt⁷ and R. Urrutia²
6

7 1. Université de Liège, AGEs - Argiles, Géochimie et Environnements sédimentaires,
8 Department of Geology, 4000 Liège, Belgium

9 2. University of Concepcion, Faculty of Environmental Sciences and EULA - Chile
10 Environmental Sciences Centre, Concepcion, Chile

11 3. Universidad Santo Tomás, Facultad de Ciencias, Concepcion, Chile.

12 4. University of Gdansk, Faculty of Oceanography and Geography, Poland

13 5. KU Leuven University, Department of Earth and Planetary Sciences, 3001 Heverlee,
14 Belgium

15 6. Université de Liège, Sedimentary Petrology. Department of Geology, 4000 Liège Belgium

16 7. Université de Bordeaux, UMR Environnements et Paléoenvironnements Océaniques et
17 Continentaux, France
18

19 Contact e-mail address: nathalie.fagel@uliege.be
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 tephras and 15 pluri-millimetre to pluri-centimetre coarser sandy to gravely layers.
40 Varve counting confirmed by ^{210}Pb and ^{137}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°-53° 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 (~55°S)
68 whereas it contracts in austral summer (DJF) in a northerly position (~50°S). During austral
69 winters, the SWW extends, providing rainfall to central Chile (33°-40° 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°-55° 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°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 km²), 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 km², 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 km²) 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 θ with a step size of
251 0.009°2 θ , 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 mm² 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 μ s 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 μ m. For EMPA calibration,
277 the following standards were used for K α 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 ± 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}Pb , ^{226}Ra , ^{232}Th and ^{137}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 (~ 1.5 g of dried sediment) retrieved from the archive section. The excess
306 ^{210}Pb ($^{210}\text{Pb}_{\text{xs}}$) activities were calculated as the difference of the measured ^{210}Pb and ^{226}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}Cs , excess ^{210}Pb and ^{14}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 ≥ 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° latitude S and 72.20 - 71.51° 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 ± 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 (~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 ± 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 ± 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 μm),
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 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 μm , 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 μm 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}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}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}Th activities (~ 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}Cs peak, and the counting session was not long enough to allow a reliable
436 determination of $^{210}\text{Pb}_{\text{x}}$ (low ^{229}Th for event E2). The control points are: 1) the surface age (2013
437 AD) and; 2) the maximum ^{137}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}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 ± 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 ± 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}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 ~ 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 ± 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 Lamoureaux 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 ± 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 ≤ 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., ± 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 ± 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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1170

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}Cs and excess ^{210}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}Cs and excess ^{210}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}Th and ^{137}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}Pb - ^{137}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