



1 The case of a southern European glacier disappearing
2 under recent warming that survived Roman and Medieval
3 warm periods

4 Ana Moreno¹, Miguel Bartolomé², Juan Ignacio López-Moreno¹, Jorge Pey^{1,3}, Pablo
5 Corella⁴, Jordi García-Orellana^{5,6}, Carlos Sancho⁷, María Leunda⁷, Graciela Gil-
6 Romera^{8,1}, Penélope González-Sampériz¹, Carlos Pérez-Mejías⁹, Francisco Navarro¹⁰,
7 Jaime Otero-García¹⁰, Javier Lapazaran¹⁰, Esteban Alonso-González¹, Cristina Cid¹¹,
8 Jerónimo López-Martínez¹², Belén Oliva-Urcia¹², Sérgio Henrique Faria^{13,14}, María José
9 Sierra¹⁵, Rocío Millán¹⁵, Xavier Querol¹⁶, Andrés Alastuey¹⁶ and José M. García-Ruiz¹

- 10 1. Departamento de Procesos Geoambientales y Cambio Global, Instituto Pirenaico de Ecología – CSIC,
11 50059, Zaragoza, Spain
12 2. Departamento de Geología, Museo de Ciencias Naturales - CSIC, Madrid, 28034, Spain
13 3. Fundación Aragonesa para la Investigación y el Desarrollo, ARAID, Zaragoza, Spain
14 4. Université Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, 38000 Grenoble, France
15 5. Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Barcelona, Spain
16 6. Departament de Física, Universitat Autònoma de Barcelona, Barcelona, Spain
17 7. Institute of Plant Sciences & Oeschger Centre for Climate Change Research. Altenbergrain 21, 3013
18 Bern, Switzerland
19 8. Department of Ecology, Faculty of Biology, Philipps-Marburg University, Marburg, Germany
20 9. Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an, 710049, China
21 10. Departamento de Matemática Aplicada a las TIC, ETSI de Telecomunicación, Universidad Politécnica
22 de Madrid, Madrid, Spain
23 11. Centro de Astrobiología – CSIC-INTA, Madrid, Spain
24 12. Departamento de Geología y Geoquímica, Facultad de Ciencias, Universidad Autónoma de Madrid,
25 Madrid, Spain
26 13. Basque Centre for Climate Change (BC3), 48940, Leioa, Spain
27 14. IKERBASQUE, Basque Foundation for Science, 48011, Bilbao, Spain
28 15. CIEMAT — Environmental Department (DMA), Avenida Complutense 40, E-28040 Madrid, Spain
29 16. Institute of Environmental Assessment and Water Research – CSIC, 08034 Barcelona, Spain

30

31 † Deceased

32 **Corresponding author:** Ana Moreno (amoreno@ipe.csic.es) ORCID: 0000-0001-7357-
33 584X

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36



37 **Abstract**

38 Mountain glaciers have generally experienced an accelerated retreat over the last
39 three decades as a rapid response to current global warming. However, the response
40 to previous warm periods in the Holocene is not well-described for glaciers of the of
41 southern Europe mountain ranges, such as the Pyrenees. The situation during the
42 Medieval Climate Anomaly (900-1300 CE) is particularly relevant since it is not certain
43 whether the glaciers just experienced significant ice loss or whether they actually
44 disappeared. We present here the first chronological study of a glacier located in the
45 Central Pyrenees (N Spain), the Monte Perdido Glacier (MPG), carried out by different
46 radiochronological techniques and their comparison with geochemical proxies with
47 neighboring paleoclimate records. The result of the chronological model proves that
48 the glacier endured during the Roman Period and the Medieval Climate Anomaly. The
49 lack of ice from last 600 years indicates that the ice formed during the Little Ice Age
50 has melted away. The analyses of the content of several metals of anthropogenic
51 origin, such as Zn, Se, Cd, Hg, Pb, appear in low amounts in MPG ice, which further
52 supports our age model in which the record from the industrial period is lost. This
53 study confirms the exceptional warming of the last decades in the context of last two
54 millennia. We demonstrate that we are facing an unprecedented retreat of the
55 Pyrenean glaciers which survival is compromised beyond a few decades.

56

57



58 1. Introduction

59 Mountain glaciers are often sensitive to climate variations on temporal scales from
60 decades to centuries. It is well known that summer temperature and winter
61 precipitation are the most important climate parameters influencing glacier mass
62 balance (Oerlemans, 2001). Therefore, continuous records of past glacier size
63 fluctuations provide valuable information about the timing and magnitude of Holocene
64 climate shifts (Solomina et al., 2015, 2016), which contributed to explain the
65 characteristics and evolution of plant cover, human movements and land use. Several
66 glacier advances during the Neoglacial (which started around 6000-5000 yr ago) have
67 been identified and associated to sustained cooling periods across the North Atlantic
68 (Wanner et al., 2011). The most recent period of global glacier expansion took place
69 during the Little Ice Age (LIA), beginning in the 13th century and reaching a maximum
70 between the 17th and 19th centuries (Solomina et al., 2016). Afterwards, most glaciers
71 worldwide have retreated rapidly, as indicated by measurements of ice volume and
72 ice-covered area, and this trend seems to have accelerated over the last three decades
73 (Marzeion et al., 2014; Zemp et al., 2015, 2019).

74 Despite broad agreement on millennial-scale trends in global glacier fluctuations and
75 Holocene climate variability (Davis et al., 2009; Solomina et al., 2015), regional
76 variations are not so well constrained. For instance, for the Pyrenees, a mountain
77 range that currently hosts the majority of the southernmost glaciers in Europe, there is
78 a significant lack of knowledge about Holocene glacier fluctuations, as indicated scarce
79 evidences of glacier advances during the Neoglacial period (García-Ruiz et al., 2014;
80 Gellatly et al., 1992). Based on Pyrenean tree-ring chronologies, summer temperatures
81 during the Medieval Climate Anomaly (MCA, circa 900–1300 CE) were estimated to be
82 as warm as those of the 20th century (Büntgen et al., 2017), but no information has
83 been obtained on the glacier response to MCA warming. Conversely, glacier advance
84 during the LIA is well constrained in the Mediterranean mountains (García-Ruiz et al.,
85 2014; González Trueba et al., 2008; Hughes, 2018; Oliva et al., 2018) and a significant
86 deglaciation is also evident in recent times (López-Moreno et al., 2016; Rico et al.,
87 2017). Thus, Pyrenean glaciers have exhibited during the 20th and 21st centuries multi-
88 decadal variations similar to those of other mountain ranges in the world. In particular,



89 the period from the 1980s to present has been the most intense in terms of number of
90 glaciers that disappeared (from 39 inventoried Pyrenean glaciers in 1984 to 19 at
91 present) (Rico et al., 2017). Given the small size of the Pyrenean glaciers and their
92 current critical situation in the context of global warming, we hypothesize that they
93 could have disappeared completely during the aforementioned warm periods

94 This study is focused on Monte Perdido Glacier, located in the Spanish Central
95 Pyrenees, which is currently one of the best monitored small glaciers (<0.5 km²)
96 worldwide. Recent research based on different ground-based remote sensing
97 techniques has demonstrated a rapid retreat of this glacier, with an average loss of ice
98 thickness of about one meter per year since 1981 (López-Moreno et al., 2019). These
99 results, together with the evidences of long-term retreat since the LIA glacier position
100 indicated by pictures and moraines, suggest that this glacier could disappear over the
101 next few decades (López-Moreno et al., 2016). The present study relies on a variety of
102 dating techniques and on the analysis of several proxies associated to environmental
103 and anthropogenic changes to construct, for the first time, the chronology of an ice
104 sequence from a Pyrenean glacier. Such analyses will respond the key question of
105 whether Pyrenean glaciers may have survived previous Holocene warm periods.

106 **2. Study area**

107 The Monte Perdido Glacier (MPG, 42°40'50"N; 0°02'15"E.) is located in the Central
108 Spanish Pyrenees, in the Ordesa and Monte Perdido National Park (OMPNP) (Fig.1). It
109 currently consists of two separate ice bodies, which were connected in the past. Both
110 are north facing and lie on structural flats beneath the main summit of the Monte
111 Perdido Peak (3355 m a.s.l.) and are surrounded by vertical cliffs of 500–800 m in
112 height. At the base of the cliffs, the Cinca River flows directly from the glacier and the
113 surrounding slopes, and has created a longitudinal west–east basin called the Marboré
114 Cirque (5.8 km²). This is the area within the Pyrenees with the highest variety of recent
115 morainic deposits (García-Ruiz et al., 2014). Additionally, a 6-m thick sediment core
116 obtained in 2011 from a lake inside the cirque (Marboré Lake) contains valuable
117 information from the last 14,600 years of the depositional evolution of the lake (Oliva-
118 Urcia et al., 2018) and of the regional variations in the vegetation cover (Leunda et al.,



119 2017). The Marboré Lake (2595 m a.s.l.) is located in the Marboré or Tucarroya Cirque,
120 in the northern face of the Monte Perdido massif. The distance between the lake and
121 the MPG is approximately 1300 m and, therefore, both have been affected by similar
122 palaeoenvironmental conditions.

123 Recent measurements indicate that the total surface area of MP glacier in 2016 was
124 0.385 km² (López-Moreno et al., 2016). During the period 2011–2019, the glacier ice
125 thickness decreased by 7.4 m on average, though such losses exhibit a marked spatial
126 and temporal variability (Fig. S1, Supplementary Material). According to recent
127 measurements of air temperature (July 2014 to October 2017), the 0 °C isotherm lies
128 at 2945 m a.s.l., suggesting that the potential glacier accumulation area is very small,
129 even inexistent during warm years. In an average summer (June to September;
130 temperature measurements were conducted from 2014 to 2017), the temperature at
131 the foot of the glacier is 7.3 °C. No direct observations of precipitation are available at
132 the glacier location, but the maximum accumulation of snow in late April during the
133 three available years was 3.23 m, and average snow density was 454 kg m⁻³ measured
134 in the field, indicating that total water equivalent during the main accumulation period
135 (October to April) could be close to 1500 mm (López-Moreno et al., 2019).

136 **3. Material and methods**

137 *3.1. Ice sampling and storage*

138 Ice drilling in MPG was carried out in September 2017 using a Kovacs ice coring device
139 at three sites. These sites were selected based on previously obtained ground-
140 penetrating radar (GPR) results, which, combined with glacier dynamics modelling,
141 suggested that the oldest ice could be located at these locations since the thickness
142 was over 30 m and there was no movement of the ice (López-Moreno et al., 2019) (Fig.
143 1). Unfortunately, none of the glacio-meteorological and topographical criteria
144 required to obtain a preserved ice-core stratigraphy, such as low temperatures to
145 prevent water percolation, or a large extension and flat surface topography to
146 minimize the influence of glacier flow (Garzonio et al., 2018), are currently met in the
147 glacier. With this technique, only three short ice cores of 4, 3 and 2 m in length could
148 be recovered, which could not provide a complete chrono-stratigraphical ice sequence.



149 The cores were preserved intact and later stored at $-60\text{ }^{\circ}\text{C}$ at the BC3-IzotzaLab ice
150 core facility (Leioa, Spain) but not used in this study.

151 Based on the poor core recovery, we changed our drilling strategy and, to collect ice
152 samples in an ordered chrono-stratigraphical sequence covering from the oldest to the
153 newest ice preserved in the glacier, we took samples in an area with no evidence of
154 current ice movement, as confirmed by results from interferometric radar and GNSS
155 measurements (López-Moreno et al., 2019) (Fig.S2). This sector has been eroded to
156 form a current steady slope of 20° where it is possible to establish a relation between
157 the sample distances and the ice depth in a formerly much less steep glacier surface.
158 Due to the small size of this glacier, the ice needs to be frozen to bedrock, and hence
159 nearly stagnant, to become of substantial age, i.e., a few hundred years or more, as
160 indicated by previous studies in similar glaciers Gabrielli et al., 2016; Haerberli et al.,
161 2004). Therefore, we measured one-meter thickness using the Jacob's staff at every
162 sampling point to measure stratigraphic thicknesses since bedding was unclear (Fig.
163 S2). Once cleaned the most superficial ice to avoid new ice formed recently, we
164 recovered at every sampling position 3–4 small cores (6 cm in diameter and 25 cm in
165 length) using a custom stainless steel crown adaptor on a cordless power drill (see Fig.
166 S2 in Supplementary Material). Following that sampling procedure we recovered a
167 total of 100 samples, every one constituted by 3-4 cylinders, which represent the
168 whole ice sequence in MP glacier. Those ice samples were stored in a freezer room in
169 Zaragoza and further analysed to obtain their chronology (combining ^{210}Pb , ^{137}Cs and
170 ^{14}C techniques) and their geochemical composition (trace element and Hg
171 concentrations) (see below).

172 3.2. Dating by ^{210}Pb and ^{137}Cs .

173 The isotope ^{137}Cs usually associated to the fallout from nuclear tests during the 1950s
174 and the 1960s, as well as the Chernobyl (1986) and Fukushima (2011) accidents was
175 investigated by γ -spectrometry in the uppermost five samples in MPG, but no trace
176 could be detected (Table S1 in Supplementary Material). This implies that all samples
177 are older than 60–65 years and therefore they were not exposed to the atmosphere
178 after 1950 CE. Another possibility that was discarded once we had ^{14}C dates, is that all



179 samples were younger than 1950 CE. Additionally, up to ten samples were selected
180 from the 100 samples that constitute the whole ice sequence to carry out ^{210}Pb
181 analysis as an independent dating method to obtain chronologies for about the last
182 hundred years of glacier ice (Eichler et al., 2000; Herren et al., 2013). Those samples
183 were selected from the top of the sequence (Table S2). Determination of ^{210}Pb
184 activities was accomplished through the measurement of its daughter nuclide, ^{210}Po ,
185 by α -spectrometry following the methodology described in (Sanchez-Cabeza et al.,
186 1998) (Table S2 in Supplementary Material). Similarly, ^{210}Pb activity was also
187 undetectable in most cases, except in three samples (MP100, MP73 and MP76) with
188 concentrations above minimum detection activity (MDA; Table S2). Probably, the
189 MP100 sample contained the ^{210}Pb recently deposited because it was the most
190 superficial sample, therefore in contact with the atmosphere. However, this sample, as
191 well as samples MP73 and MP76 contained a large amount of lithogenic particulate
192 material from atmospheric dust or ash deposits. The absence of ^{210}Pb activity in the
193 analysed samples does not allow constructing an age-depth model for the last 100
194 years indicating that MPG ice samples were very likely older and the ^{210}Pb had
195 completely decayed. We then built up the proposed MPG chronology using AMS ^{14}C
196 dating.

197 3.3. Dating by ^{14}C method.

198 Sixteen accelerator mass spectrometry (AMS) ^{14}C dates from MPG ice were obtained
199 by combining bulk organic matter (9 samples), pollen concentrates (3 samples), bulk
200 sediment accumulated in filters (2 filters), and water-insoluble organic carbon (WIOC)
201 particles (2 samples) (Table 1). First, using a binocular microscope [x10], we selected
202 organic particles for dating from the nine selected bulk samples, once the ice sample
203 was melted. However, the small size prevented us from classifying the organic
204 remains. All the amorphous particles were sent to the dating laboratory (Direct AMS,
205 Seattle, USA). Pollen concentrates were prepared from three selected samples (30, 70
206 and 100 m depth) to complete the previous set of samples following the standard
207 palynological method, including a chemical treatment and mineral separation in heavy
208 liquid (Thoulet: density 2.0; Moore et al., 1991). Additionally, two ice samples
209 previously melted (67 and 81 m depth) were filtered throughout a filtration line



210 connected to a vacuum pump using 47 mm quartz fiber filters (PALL tissuquartz
211 2500QAT-UP), parameterized at controlled conditions (temperature: 22–24 °C; relative
212 humidity 25–35%) and weighted twice in different days. Abundant material was
213 obtained, but no control was made on the composition and amount of organic
214 material versus other type of inputs. Concentrated pollen samples and filters were
215 dated at the same laboratory (Direct AMS, Seattle, USA). Since organic fragments
216 (plants, wood, insects) are rarely found in mountain glaciers, a new, complementary
217 dating tool was recently developed based on extracting the microgram-amounts of the
218 water-insoluble organic carbon (WIOC) fraction of carbonaceous aerosols embedded in
219 the ice matrix for subsequent ¹⁴C dating (Uglietti et al., 2016). Two samples were dated
220 by the WIOC technique at the Laboratory of Environmental Chemistry, Paul Scherrer
221 Institute, Switzerland, following the usual procedures including removing the outer
222 part of the ice core segment for decontamination purposes (Jenk et al., 2009).

223 Finally, from the initial 16 dates, we had to discard seven (see the criteria in section 4.1
224 below) and the age model was developed including nine samples (eight from bulk
225 organic matter and one from the WIOC technique; Table 1). Those nine dates were
226 converted into calendar ages by the CALIB 5.0.2 software, which uses the most
227 updated dataset, INTCAL13 (Reimer et al., 2013) (Table 1). The median of the one- σ
228 probability interval was selected for these dates, resulting in large errors (230 years on
229 average) in the obtained calendar ages. The depth–age model was created using the R
230 package CLAM 2.2 (Blaauw, 2010; Blaauw et al., 2019) (Fig. 2). Given the scattered
231 depths at which dates concentrate, we chose to perform a non-smooth, second order
232 polynomial regression for preventing any model over-fitting and a spurious age–depth
233 relationship. In addition, we run the depth–age model setting a hiatus at 73 m depth
234 where we think an interruption in the ice accumulation was produced. This idea is
235 supported by the observation of several debris layers that increased their frequency
236 towards the top of the glacier. Those layers are interpreted as the result of several
237 phases of melting, dramatically changing the accumulation rates and concentrating
238 samples of similar ages (see section 4.1 below). Full details on how the model was
239 performed and a reproducible workflow with the current chronological dataset are available in
240 the Supplementary Material.



241 3.4. Trace elements in soluble and insoluble material.

242 35 selected ice samples from the altitudinal transect were melted and filtered through
243 a filtration ramp connected to a vacuum pump using 47 mm quartz fiber filters (PALL
244 tissuquartz 2500QAT-UP). Filters were pre-heated at 250 °C and thereafter prepared in
245 controlled conditions (temperature: 22–24 °C; relative humidity: 25–35 %) before and
246 after filtration. Subsequently, they were weighted in two different days. Mass
247 difference between blank and sampled filters was used to calculate the amount of
248 insoluble material entrapped in ice samples. For every sample, an aliquot and a filter
249 were obtained. From aliquots, anions and cations, as well as major and trace elements
250 were determined. From filters, we determined major and trace elements, as well as
251 organic and elemental carbon, following the method devised by (Pey et al., 2013)
252 (Table 2). Basically, an acidic digestion ($\text{HNO}_3\text{:HF:HClO}_4$) of half of each filter was
253 conducted, driven to complete dryness, being the remaining material re-dissolved in
254 HNO_3 . Inductively coupled plasma mass spectrometry (ICP-MS) and inductively
255 coupled plasma atomic emission spectroscopy (ICP-AES) were used to determine major
256 and trace elements. From the other half of each filter, a 1.5 cm^2 section was used to
257 determine Organic Carbon (OC) and Elemental Carbon (EC) concentrations by using a
258 SUNSET thermo-optical analyzer, following the EUSAAR_2 temperature protocol. Table
259 1 also contains the Enrichment Factors (EFs) calculated as follows:

$$260 \quad EF_{iCodd} = \frac{X_{iCodd}/Al_{Codd}}{X_{iUC}/Al_{UC}} \quad EF_{iMPGID} = \frac{X_{iMPGID}/Al_{MPGID}}{X_{iUC}/Al_{UC}} \quad EF_i = \frac{X_{iCodd}/Al_{Codd}}{X_{iMPGID}/Al_{MPGID}}$$

261 where EF_{iCodd} is the Al-normalised Enrichment Factor with respect to the Upper Crust
262 (UC, (Taylor and McLennan, 1995)) of an 'i' element in the current Ordesa's deposited
263 dust (Codd); EF_{iMPGID} is the Al-normalised Enrichment Factor with respect to the UC of
264 an 'i' element in the current MPG ice dust (MPGID); and EF_i is the Al-normalised
265 Enrichment Factor with respect to Codd of an 'i' element in the MPGID.

266 Regarding the Pb/Al ratio, we carried out a normalization with Al in both, ice and lake
267 records, to disentangle the anthropogenic lead variability from possible detrital inputs.



268 Aluminum has been selected for normalization since this lithogenic element is
269 immobile and abundant in carbonated watersheds.

270 3.5. Hg determination.

271 Total Hg concentration measurements were carried out in 21 selected samples by
272 Atomic Absorption Spectrophotometry using an Advance Mercury Analyzer (AMA 254,
273 LECO Company). This equipment is specifically designed for direct mercury
274 determination in solid and liquid samples without sample chemical pre-treatment.
275 Certified reference materials were used to determine the accuracy and precision of the
276 Hg measurements. These reference materials were ZC73027 (rice, $4.8 \pm 0.8 \mu\text{g kg}^{-1}$)
277 and CRM051–050 (Clay soil, $4.08 \pm 0.09 \text{ mg kg}^{-1}$). The repeatability was $S_r \leq 15 \%$ and
278 the relative uncertainty associated with the method ($k = 2$; confidence level of about
279 95%) was $\pm 20 \%$. All analyses were run at least three times. Total metal concentrations
280 were expressed in $\mu\text{g g}^{-1}$ of dry weight sediment due to the low amount detected.

281 4. Results and discussion

282 4.1. Dating of ice from the Monte Perdido Glacier

283 Dating of ice cores from temperate, non-polar glaciers is challenging and often
284 problematic as annual layer counting is precluded due to periods without net
285 accumulation, and to ice deformation caused by glacier flow (Festi et al., 2016;
286 Thompson et al., 2006). Hence, we have constrained the age of glacier ice within the
287 last 100 years by using ^{210}Pb and ^{137}Cs relative dating methods, and for the oldest
288 sections we used ^{14}C absolute dating from different materials (*Sect. Material and*
289 *methods* and Tables S1, S2 in Supplementary Material). Additionally, characteristics of
290 the ice stratigraphy, such as the presence of dark debris-rich layers, were integrated
291 into the chronology. Finally, proxy comparison with independently dated sediments of
292 the Marboré Lake located nearby (Corella et al., 2018; Oliva-Urcia et al., 2018) (Fig.1)
293 helped to support the obtained MPG age-depth model .

294 We took most of the ice samples for dating in sections where dark debris layers
295 alternated every ca. 5 m with cleaner and clearer ice (Fig. S2 in Supplementary
296 Material). The debris layers were composed of detrital, silty-sandy size deposits, likely



297 coming from wind-blown particles (e.g. black carbon-rich particles, dust) and from
298 erosive processes of the limestone catchment, including the fall of gravel-sized
299 particles from the surrounding cliffs. These debris layers contain more organic remains
300 than those formed by clear ice, making them ideal spots to find datable remains.
301 Interestingly, the frequency of debris layers increases towards the top of the glacier,
302 where these layers are most abundant. We consider the accumulation of debris layers
303 to be indicative of reduced ice accumulation and dominance of ablation periods. In
304 such situations, the detrital and organic material concentrates as the ice melts, giving
305 its characteristic dark colour to the ice layers.

306 The chronology for the last 100 years was not eventually constrained using ^{210}Pb and
307 ^{137}Cs as samples proved to be older than the decay period of both radionuclides
308 (Tables S1 and S2, Supplementary Material). Thus, the lack of ^{210}Pb activity indicated
309 the lack of ice formed during the last 100 years. Regarding the ^{14}C dated samples,
310 some sample limitations precluded the construction of a chronology (Table 1). The
311 sample from 48 m depth (D-AMS 025295) was the only one from the nine bulk organic
312 matter samples to be discarded due to probable contamination, since small plastic
313 debris coming from the painting used in the coring device were identified under the
314 microscope. From the two WIOC-dated samples, one was discarded (MP10m), as it had
315 too small amount of organic carbon (5.3 μg), thus providing too inaccurate results. The
316 other sample (MP59m), with higher organic carbon (28.7 μg), was incorporated into
317 the age model. The other two methods (pollen and filters) used to concentrate organic
318 matter to be dated by ^{14}C were, unfortunately, not successful. The three pollen
319 concentrates provided unreliably old datings. We hypothesize that these old datings
320 are likely associated to melting processes of older ice layers accumulated in the upper
321 ice body of MPG (Neoglacial or Roman times), which later percolated through the ice,
322 as observed in other glaciers (Ewing et al., 2014). Similarly, we discarded the two filter
323 samples from 67 m and 81 m depth (D-AMS 029894 and D-AMS 033972, respectively).
324 The material accumulated in the filters was a mixture of particles containing detrital
325 carbonate eroded from Eocene limestones or supplied by Saharan dust, which was not
326 removed and probably influenced the results incorporating dead carbon to the
327 samples.



328 Finally, from the original set of sixteen absolute dates obtained, we selected the nine
329 samples which did not present any problem related to the amount of carbon, possible
330 contamination, material from different sources or percolation within the ice sequence.
331 These nine samples were all chrono-stratigraphically coherent (eight from bulk organic
332 matter and one from WIOC-technique). The age-depth model obtained indicates the
333 presence of ice since 2000 years ago and allows distinguishing three main periods for
334 MPG (Fig. 2). First, an accumulation period from 0 to 700 CE. Second, an ablation-
335 dominated phase from 700 to 1200 CE, which corresponds to the dark-rich layers
336 interval. Third, a new accumulation period from 1200 to 1400 CE. Finally, no ice
337 formed during, at least, the last 600 years has been found today in MPG according to
338 this age model. This indicates that the LIA ice has been melted away, thus
339 demonstrating an intense ablation period since 1850 CE. The MPG chronology is
340 supported by, first, a quantitative comparison with present-day atmospheric
341 particulate matter (Table 2) and, second, by the comparison with the
342 paleoenvironmental sequence of the Marboré Lake for the last 2000 years (Fig. 3) (see
343 text below).

344 We have used the averaged concentration values of major and trace elements
345 currently obtained at a monitoring station located in Ordesa and Monte Perdido
346 National Park (8 km away from the MPG, at 1190 m a.s.l.), where deposited
347 atmospheric particulate matter is sampled monthly (Table 2). Interestingly, the
348 elements that abound nowadays in the Ordesa station are not so abundant in the ice
349 from MPG. Indicators such as organic carbon, Zn, Se and Cd concentrations, all of
350 which are potential proxies of current anthropogenic emissions, are much higher in the
351 samples from Ordesa, which are representative of today's atmosphere, than in the ice
352 samples from the MPG. The low concentration of these elements in MPG samples
353 could indicate their disappearance from glacier surface layers due to its continuous
354 melting. This supports our suggested age model (Fig. 2), in which the industrial period
355 has not been recorded. Contrariwise, the Al-normalised enrichment factor (EF) of Ti,
356 Mn, Cr, Co, Ni, Cu and Pb, elements linked to the natural fraction (dust deposition,
357 lithogenic elements) and mining activities (Corella et al., 2018), are more abundant in
358 the MPG ice samples than in the present-day Ordesa aerosols (Table 2). From them, Cu



359 and Pb were markedly enriched (by a factor >6) in the MPG ice samples compared with
360 the current deposited aerosols in Ordesa station.

361 Following previous studies on present-day atmospheric particulate matter composition
362 from natural, urban or industrial areas (Querol et al., 2007), the values of some
363 elemental ratios (e.g. Cu/Mn, As/Se, Pb/Zn) help to determine the origin of the
364 particulate matter accumulated today. The Ordesa site can accordingly be mostly
365 defined as remote in terms of atmospheric deposition (“rural background”) while the
366 average composition of MPG ice samples could be defined as a site under the influence
367 of Cu mining and smelting activities, due to the high values of the Cu/Mn, As/Se and
368 Pb/Zn ratios. It is noteworthy that Cu, Ag, and Pb mining and smelting have been
369 historically documented in Bielsa valley during pre-industrial times (Callén, 1996).
370 Indeed, MPG is only 7 km east from some of the largest lead and silver ore deposits in
371 the Pyrenees (historical mines of Parzan). The impact of ancient environmental
372 pollution in high alpine environments is archived in the lacustrine sequence of the
373 neighbouring Marboré Lake, providing first evidences of historical metal mining and
374 processing activities during the Roman Period (RP) (Corella et al., 2018, 2020).
375 Therefore, the enrichment of trace elements in MPG ice record most likely
376 corresponds to mining activities during ancient times. Recently, an ice core record
377 from the western Alps have also demonstrated the suitability of glacier ice to record
378 local and regional mining and smelting activities during RP and pre-Roman times
379 (Preunkert et al., 2019).

380 The comparison of Pb/Al ratios from the independently dated records of Marboré Lake
381 and MPG (Fig. 3) shows a reasonable agreement, supporting the obtained age model
382 for MPG ice. Particularly, the high Pb/Al values in both records between the 1st-5th
383 centuries can be explained by increased Pb emissions related to the aforementioned
384 regional mining and smelting activities during the RP. Maximum Pb/Al values have
385 been found in several natural archives in the Central Pyrenees since the onset of
386 Industrialization at 1800 CE as well as in other glacier ice core archives from the Alps
387 (Corella et al., 2017, 2018). Thus, the lack of a Pb/Al peak in the upper sequence of the
388 MPG again confirms the absence of the last two centuries in MP ice record. Similarly,
389 the Hg concentration in the glacier is very stable throughout the ice sequence (Fig.3).



390 Hg concentrations in other ice core records preserve an increase during the onset of
391 Industrialization at 1800 CE with maximum values typically 3–10 times higher than
392 preindustrial values (Cooke et al., 2020). In Marboré Lake, the mercury increase
393 occurred over the last 500 years associated to the maximum activity in the Spanish
394 Almaden mines during the Colonial Period (Corella et al., 2020). Again, these results,
395 lacking an expected increase in Hg levels, support the age model from the MPG record
396 where the last six centuries of ice deposition are missing.

397 *4.2. Evolution of the Monte Perdido glacier over the last 2000 years*

398 The analyzed ice from MPG provides remarkable information about the evolution of
399 the glacier in the last two millennia, which deserves be considered in the regional
400 context. Based on published results, the oldest paleoclimatic information in the
401 Marboré Cirque comes from the Marboré Lake, since no glacier deposits
402 corresponding to the Late Pleistocene have been found in the cirque (García-Ruiz et al.,
403 2014). There is sedimentological evidence that the Marboré Lake was already ice-free
404 at least since the onset of the Bølling period (Greenland Interstadial-1, 14,600 yr BP),
405 when clastic sediments were deposited in the lake basin (Leunda et al., 2017; Oliva-
406 Urcia et al., 2018). This is coherent with the nearby La Larri juxta-glacial sequence
407 which showed that the main Pineta glacier had already retreated further up in the
408 headwater by $13,245 \pm 120$ yr BP (Salazar et al., 2013). In fact, glaciological studies
409 performed in the Central Pyrenees confirm the sudden retreat of glaciers during the
410 Bølling period, when they were reduced to small ice tongues, cirque glaciers or rock
411 glaciers (Palacios et al., 2017).

412 Like other glaciers all over the world (Davis et al., 2009; Solomina et al., 2015), MPG
413 likely experienced numerous spatial fluctuations during the Holocene, although
414 absolute dates directly obtained from moraines are uncertain. A single boulder was
415 dated from the outermost moraine corresponding to the maximum glacier expansion
416 since the Younger Dryas (recalculated at 6900 ± 800 ^{36}Cl yr BP) (García-Ruiz et al.,
417 2020) in the Marboré Cirque. This is the oldest Holocene date available for glacial
418 deposits in Spain (García-Ruiz et al., 2014), and indicates a glacier advance during the
419 Neoglacial period (Fig. 4A). Other minor advances would have occurred in MPG prior to



420 the LIA, as inferred from three polished surfaces dated at 3500 ± 400 , 2500 ± 300 and
421 1100 ± 100 ^{36}Cl yr BP, indicating the occurrence of different deglaciation phases, and
422 therefore glacial re-advances prior to these dates (García-Ruiz et al., 2020). Most likely,
423 the voluminous moraine at the foot of the Monte Perdido Massif, which undoubtedly
424 was deposited during the LIA, incorporates minor moraines and till from prior
425 Neoglacial advances, as has been reported in other Pyrenean cirques (Crest et al.,
426 2017; Palacios et al., 2017).

427 With the new chronology of the MPG record, we can ascertain that MPG has persisted
428 at least since the RP (circa 2000 yr ago). At that time, which is a well known warm
429 period in the Iberian Peninsula as recorded in both continental (Martín-Puertas et al.,
430 2010; Morellón et al., 2009) and marine sequences (Cisneros et al., 2016; Frigola et al.,
431 2007; Nieto-Moreno et al., 2011), the glacier was still active, but probably smaller than
432 during Neoglacial times (Fig. 4B). This situation probably continued during the
433 following cold period, the Dark Ages (DA, Fig 4C) when the glacier advanced as
434 indicated by the polished surface dated at 1100 ± 100 ^{36}Cl yr BP (García-Ruiz et al.,
435 2020). In glaciers in the Alps, reconstructions based on dating trees found within and
436 at the edge of glacier forefields have revealed a minimum glacier extent during the
437 Iron Age and the RP (Holzhauser et al., 2005), when glaciers were estimated to be
438 smaller than during the 1920s (Ivy-Ochs et al., 2009). Afterwards, in the late RP and the
439 early Middle Ages numerous glaciers in the Alps advanced during the DA, also known
440 as the Göschenen II oscillation (Holzhauser et al., 2005).

441 The MCA (900–1300 CE) is the most recent preindustrial warm era in Europe (Mann et
442 al., 2009). For instance, in the Alps, a general glacier retreat has been observed during
443 this period, mainly associated with a decline in precipitation (Holzhauser et al., 2005).
444 According to the age-depth model, the MPG experienced a spectacular retreat (Fig.
445 4D), including the complete melting of some minor glaciers in the Marboré Cirque
446 (García-Ruiz et al., 2020). Nevertheless, during the MCA part of MPG was preserved, as
447 we find ice from 0 to 700 CE. No doubt the ice loss was significant, as evidenced by the
448 accumulation of dark strata over a long time interval (600–1200 CE) (Fig.2). On this
449 basis, we propose that the MPG was dominated by ablation processes during the MCA,
450 leading to considerable ice loss as deduced from just six meters of ice remaining from



451 this period (Fig. 2). We assume that, by this time, basal ice of Neoglacial age was
452 already removed, but at the end of the MCA the MPG still preserved ice from the RP
453 and the first half of the DA (Fig. 4D).

454 Over such a diminished MCA glacier, ice started to accumulate again at a rapid rate
455 during the LIA (1300–1850 CE). In most cases, the LIA was the period when mountain
456 glaciers recorded their maximum Holocene extent (Solomina et al., 2016), with
457 remarkable advances in the alpine glaciers (Ivy-Ochs et al., 2009). From a large variety
458 of proxies, several warm and cold periods have been identified in the Iberian Peninsula
459 during the LIA (Oliva et al., 2018). In the Marboré Cirque two generations of LIA
460 moraines have been mapped (García-Ruiz et al., 2014), whose emplacement coincided
461 with the coldest LIA phases, i.e. 1620-1715 CE, when the Pyrenean glaciers recorded
462 their maximum extent, and 1820-1840 CE, when a rapid advance of the ice mass
463 moved over the large moraine leaving parallel furrows, or flutes, as signs of erosion
464 (García-Ruiz et al., 2020; Serrano and Martín-Moreno, 2018). These two cold phases
465 are very well identified in the Marboré Cirque and were confirmed by the study of the
466 altitudinal fluctuations of the timberline in the neighboring Escuaín Valley (Camarero
467 et al., 2015). In fact, according to the map of Schrader from 1874 CE and other
468 historical sources, the MPG made direct contact with the large moraine in the second
469 half of the 19th century (García-Ruiz et al., 2014). Despite the MPG would have covered
470 an area of 5.56 km² at the end of the LIA (in 1894, (González Trueba et al., 2008), Fig.
471 4E), there is no record today of ice accumulated during the LIA, except for a few
472 meters at the top of the sequence corresponding to about 1400 CE. This means that
473 more than 600 years of ice accumulation have been lost associated to the warming
474 after ca. 1850 CE. This situation is not so common in the Alps, where ice from the LIA,
475 and even from the last two centuries, is still preserved in many studied glaciers (Eichler
476 et al., 2000; Gabrielli et al., 2016; Gäggeler et al., 1983; Preunkert et al., 2019).

477 Today the MPG is divided in two small ice bodies that together cover just 0.38 km²
478 (López-Moreno et al., 2016, Fig. 4F). Comparing the MPG extent at the end of the LIA
479 (ca. 1850 CE), thanks to the moraine location, and today, more than 5 km² of MPG
480 would have disappeared, thus indicating that the last 150 years have likely been the
481 period with the largest glacier melting in the last 2000 years.



482 **5. Conclusions**

483 This study presents for the first time the chronology of a glacier in the Pyrenees,
484 reconstructed from a set of ^{14}C dates on different organic remains and supported by
485 measurements on current atmospheric deposition and comparison with a nearby lake
486 sequence (Marboré Lake). The ice sequence from MPG covers the last 2000 years
487 allowing defining cold periods of ice advance and warm periods of retreat. We
488 demonstrate that the glacier was active during the RP, a well known warm period in
489 Iberia Peninsula. During the MCA, the MPG experienced a spectacular retreat marked
490 by the presence of dark debris layers indicative of successive years when ablation
491 processes predominated. The LIA was a period of glacier advance but not recorded
492 today in the ice from MPG since more than 600 years of ice accumulation have been
493 lost associated to the warming after ca. 1850 CE. This evidence from the age-depth
494 model is supported by the lack of anthropogenic indicators usually associated to the
495 Industrial Era abundant today in current atmospheric deposition in a nearby site.
496 Additionally, both Hg concentration and Pb/Al ratio appear much higher in the
497 Marboré Lake sediments whereas they don't reflect the anthropogenic increase in the
498 MPG record.

499 Comparing the present-day glacier situation with that of previous warm intervals, such
500 as the RP or the MCA, we conclude that the MPG is nowadays greatly reduced in area
501 and volume. Additionally, the recent ice mass loss rate is definitely more rapid than
502 during the four centuries spanned by the MCA, thus suggesting that present day
503 warming in the Pyrenees is faster and more intense than in any previous warm phase
504 occurred during the last 2000 years. Under such climatic conditions, it is reasonable to
505 expect the disappearance of this glacier, as well as other glaciers in the Pyrenees and
506 in Southern Europe, over the next few decades.

507 **6. Data availability**

508 The input data file for CLAM, as well as the output results are stored in this journal for
509 reviewing process and will be permanently deposited in the journal upon the
510 acceptance of this manuscript. The other data are included in the tables and in the
511 Supplementary.



512 **7. Author contributions**

513 The paper was conceived by A.M., M.B., C.S. and J.I.L.M. and F.N., J.O.G., J.L., P.G.S.,
514 C.C., J. L.M., B.O., S.H.F and J.G.R. contributed to design this research project. J.G.O.
515 carried out the ^{210}Pb and ^{137}Cs analyses; J.P., X.Q. and A.A. provided the geochemical
516 data from Ordesa site and MPG; P.C., M.J.S. and R.M. provided the Hg data from
517 Marboré Lake and MPG, C.P., M.L., E.A. helped during field work and G.G.R. run the R
518 package CLAM 2.2 to build the age model. All authors contributed to the writing of the
519 paper.

520 **8. Competing interest**

521 The authors declare that they have no conflict of interest.

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536 **10. References**

537 Blaauw, M.: Methods and code for ‘classical’ age-modelling of radiocarbon sequences,
538 *Quaternary Geochronology*, 5(5), 512–518, doi:10.1016/j.quageo.2010.01.002, 2010.

539 Blaauw, M., Christen, J. A., Vázquez, J. E. and Goring, S.: clam: Classical Age-Depth Modelling of
540 Cores from Deposits. CRAN 2019, [online] Available from: [https://CRAN.R-](https://CRAN.R-project.org/package=clam)
541 [project.org/package=clam](https://CRAN.R-project.org/package=clam), 2019.



- 542 Büntgen, U., Krusic, P. J., Verstege, A., Sangüesa-Barreda, G., Wagner, S., Camarero, J. J.,
543 Ljungqvist, F. C., Zorita, E., Oppenheimer, C., Konter, O., Tegel, W., Gärtner, H., Cherubini, P.,
544 Reinig, F. and Esper, J.: New Tree-Ring Evidence from the Pyrenees Reveals Western
545 Mediterranean Climate Variability since Medieval Times, *J. Climate*, 30(14), 5295–5318,
546 doi:10.1175/JCLI-D-16-0526.1, 2017.
- 547 Callén, J. J. N.: El proceso sidero-metarlúrgico altoaragonés: los valles de Bielsa y Gistain en la
548 Edad Moderna (1565-1800), *Llull: Revista de la Sociedad Española de Historia de las Ciencias y*
549 *de las Técnicas*, 19(37), 471–508, 1996.
- 550 Camarero, J. J., García-Ruiz, J. M., Sangüesa-Barreda, G., Galván, J. D., Alla, A. Q., Sanjuán, Y.,
551 Beguería, S. and Gutiérrez, E.: Recent and Intense Dynamics in a Formerly Static Pyrenean
552 Treeline, *Arctic, Antarctic, and Alpine Research*, 47(4), 773–783, doi:10.1657/AAAR0015-001,
553 2015.
- 554 Cisneros, M., Cacho, I., Frigola, J., Canals, M., Masqué, P., Martrat, B., Casado, M., Grimalt, J.
555 O., Pena, L. D., Margaritelli, G. and Lirer, F.: Sea surface temperature variability in the central-
556 western Mediterranean Sea during the last 2700 years: a multi-proxy and multi-record
557 approach, *Clim. Past*, 12(4), 849–869, doi:10.5194/cp-12-849-2016, 2016.
- 558 Cooke, C. A., Martínez-Cortizas, A., Bindler, R. and Sexauer Gustin, M.: Environmental archives
559 of atmospheric Hg deposition – A review, *Science of The Total Environment*, 709, 134800,
560 doi:10.1016/j.scitotenv.2019.134800, 2020.
- 561 Corella, J. P., Valero-Garcés, B. L., Wang, F., Martínez-Cortizas, A., Cuevas, C. A. and Saiz-Lopez,
562 A.: 700 years reconstruction of mercury and lead atmospheric deposition in the Pyrenees (NE
563 Spain), *Atmospheric Environment*, 155, 97–107, doi:10.1016/j.atmosenv.2017.02.018, 2017.
- 564 Corella, J. P., Saiz-Lopez, A., Sierra, M. J., Mata, M. P., Millán, R., Morellón, M., Cuevas, C. A.,
565 Moreno, A. and Valero-Garcés, B. L.: Trace metal enrichment during the Industrial Period
566 recorded across an altitudinal transect in the Southern Central Pyrenees, *Science of The Total*
567 *Environment*, 645, 761–772, doi:10.1016/j.scitotenv.2018.07.160, 2018.
- 568 Corella, J. P., Sierra, M. J., Garralón, A., Millán, R., Rodríguez-Alonso, J., Mata, M. P., Wilhem,
569 B., Vivez, P., Duval, B., Amouroux, D., Vicente de Vera, A., Moreno, A., Cuevas, C. A., Adame, J.
570 A., Saiz-Lopez, A. and Valero Garcés, B.: Legacy pollution from roman and medieval mining in
571 the Iberian Peninsula recorded in high mountain ecosystems, *Science of The Total*
572 *Environment*, under review, 2020.
- 573 Crest, Y., Delmas, M., Braucher, R., Gunnell, Y. and Calvet, M.: Cirques have growth spurts
574 during deglacial and interglacial periods: Evidence from ¹⁰Be and ²⁶Al nuclide inventories in
575 the central and eastern Pyrenees, *Geomorphology*, 278, 60–77,
576 doi:10.1016/j.geomorph.2016.10.035, 2017.
- 577 Davis, P. T., Menounos, B. and Osborn, G.: Holocene and latest Pleistocene alpine glacier
578 fluctuations: a global perspective, *Quaternary Science Reviews*, 28(21–22), 2021–2033,
579 doi:10.1016/j.quascirev.2009.05.020, 2009.
- 580 Eichler, A., Schwikowski, M., Gäggeler, H. W., Furrer, V., Synal, H.-A., Beer, J., Saurer, M. and
581 Funk, M.: Glaciochemical dating of an ice core from upper Grenzgletscher (4200 m a.s.l.),
582 *Journal of Glaciology*, 46(154), 507–515, doi:10.3189/172756500781833098, 2000.



- 583 Ewing, M. E., Reese, C. A. and Nolan, M. A.: The potential effects of percolating snowmelt on
584 palynological records from firn and glacier ice, *Journal of Glaciology*, 60(222), 661–669,
585 doi:10.3189/2014JoG13J158, 2014.
- 586 Festi, D., Carturan, L., Kofler, W., dalla Fontana, G., de Blasi, F., Cazorzi, F., Bucher, E., Mair, V.,
587 Gabrielli, P. and Oeggli, K.: Linking pollen deposition, snow accumulation and isotopic
588 composition on the Alto dell’Ortles glacier (South Tyrol, Italy) for sub-seasonal dating of a firn
589 temperate core, *The Cryosphere Discussions*, 1–16, doi:10.5194/tc-2016-221, 2016.
- 590 Frigola, J., Moreno, A., Cacho, I., Canals, M., Sierro, F. J., Flores, J. A., Grimalt, J. O., Hodell, D. A.
591 and Curtis, J. H.: Holocene climate variability in the western Mediterranean region from a
592 deepwater sediment record, *Paleoceanography*, 22(doi:10.1029/2006PA001307), 2007.
- 593 Gabrielli, P., Barbante, C., Bertagna, G., Bertó, M., Binder, D., Carton, A., Carturan, L., Cazorzi,
594 F., Cozzi, G., Dalla Fontana, G., Davis, M., De Blasi, F., Dinale, R., Dragà, G., Dreossi, G., Festi, D.,
595 Frezzotti, M., Gabrieli, J., Galos, S. P., Ginot, P., Heidenwolf, P., Jenk, T. M., Kehrwald, N.,
596 Kenny, D., Magand, O., Mair, V., Mikhalenko, V., Lin, P. N., Oeggli, K., Piffer, G., Rinaldi, M.,
597 Schotterer, U., Schwikowski, M., Seppi, R., Spolaor, A., Stenni, B., Tonidandel, D., Uglietti, C.,
598 Zagorodnov, V., Zanoner, T. and Zennaro, P.: Age of the Mt. Ortles ice cores, the Tyrolean
599 Ice man and glaciation of the highest summit of South Tyrol since the Northern Hemisphere
600 Climatic Optimum, *The Cryosphere*, 10(6), 2779–2797, doi:10.5194/tc-10-2779-2016, 2016.
- 601 Gäggeler, H., Gunten, H. R. von, Rössler, E., Oeschger, H. and Schotterer, U.: 210Pb-Dating of
602 Cold Alpine Firn/Ice Cores From Colle Gnifetti, Switzerland, *Journal of Glaciology*, 29(101),
603 165–177, doi:10.1017/S0022143000005220, 1983.
- 604 García-Ruiz, J. M., Palacios, D., Andrés, N. de, Valero-Garcés, B. L., López-Moreno, J. I. and
605 Sanjuán, Y.: Holocene and ‘Little Ice Age’ glacial activity in the Marboré Cirque, Monte Perdido
606 Massif, Central Spanish Pyrenees, *The Holocene*, 24(11), 1439–1452,
607 doi:10.1177/0959683614544053, 2014.
- 608 García-Ruiz, J.M., Palacios, D., Andrés, N., López-Moreno, J.I.: Neoglaciation in the Spanish
609 Pyrenees: A multiproxy challenge. *Mediterranean Geoscience Reviews*.
610 <https://doi.org/10.1007/s42990-020-00022-9>, 2020.
- 611 Garzonio, R., Di Mauro, B., Strigaro, D., Rossini, M., Colombo, R., De Amicis, M. and Maggi, V.:
612 Mapping the suitability for ice-core drilling of glaciers in the European Alps and the Asian High
613 Mountains, *J. Glaciol.*, 64(243), 12–26, doi:10.1017/jog.2017.75, 2018.
- 614 Gellatly, A. F., Grove, J. M. and Switsur, V. R.: Mid-Holocene glacial activity in the Pyrenees, *The*
615 *Holocene*, 2(3), 266–270, doi:10.1177/095968369200200309, 1992.
- 616 González Trueba, J. J., Moreno, R. M., Martínez de Pisón, E. and Serrano, E.: ‘Little Ice Age’
617 glaciation and current glaciers in the Iberian Peninsula, *The Holocene*, 18(4), 551–568,
618 doi:10.1177/0959683608089209, 2008.
- 619 Haeberli, W., Frauenfelder, R., Käab, A. and Wagner, S.: Characteristics and potential climatic
620 significance of “miniature ice caps” (crest- and cornice-type low-altitude ice archives), *Journal*
621 *of Glaciology*, 50(168), 129–136, doi:10.3189/172756504781830330, 2004.
- 622 Herren, P.-A., Eichler, A., Machguth, H., Papina, T., Tobler, L., Zapf, A. and Schwikowski, M.: The
623 onset of Neoglaciation 6000 years ago in western Mongolia revealed by an ice core from the



- 624 Tsambagarav mountain range, *Quaternary Science Reviews*, 69, 59–68,
625 doi:10.1016/j.quascirev.2013.02.025, 2013.
- 626 Holzhauser, H., Magny, M. and Zumbühl, H. J.: Glacier and lake-level variations in west-central
627 Europe over the last 3500 years, *The Holocene*, 15(6), 789–801, 2005.
- 628 Hughes, P. D.: Little Ice Age glaciers and climate in the Mediterranean mountains: a new
629 analysis, *CIG*, 44(1), 15, doi:10.18172/cig.3362, 2018.
- 630 Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P. W. and Schlüchter, C.: Latest
631 Pleistocene and Holocene glacier variations in the European Alps, *Quaternary Science Reviews*,
632 28(21–22), 2137–2149, 2009.
- 633 Jenk, T. M., Szidat, S., Boliuss, D., Sigl, M., Gäggeler, H. W., Wacker, L., Ruff, M., Barbante, C.,
634 Boutron, C. F. and Schwikowski, M.: A novel radiocarbon dating technique applied to an ice
635 core from the Alps indicating late Pleistocene ages, *Journal of Geophysical Research:*
636 *Atmospheres*, 114(D14), doi:10.1029/2009JD011860, 2009.
- 637 Leunda, M., González-Sampériz, P., Gil-Romera, G., Aranbarri, J., Moreno, A., Oliva-Urcia, B.,
638 Sevilla-Callejo, M. and Valero-Garcés, B.: The Late-Glacial and Holocene Marboré Lake
639 sequence (2612m a.s.l., Central Pyrenees, Spain): Testing high altitude sites sensitivity to
640 millennial scale vegetation and climate variability, *Global and Planetary Change*, 157, 214–231,
641 doi:10.1016/j.gloplacha.2017.08.008, 2017.
- 642 López-Moreno, J. I., Revuelto, J., Rico, I., Chueca-Cía, J., Julián, A., Serreta, A., Serrano, E.,
643 Vicente-Serrano, S. M., Azorin-Molina, C., Alonso-González, E. and García-Ruiz, J. M.: Thinning
644 of the Monte Perdido Glacier in the Spanish Pyrenees since 1981, *The Cryosphere*, 10(2), 681–
645 694, doi:10.5194/tc-10-681-2016, 2016.
- 646 López-Moreno, J. I., Alonso-González, E., Monserrat, O., Del Río, L. M., Otero, J., Lapazaran, J.,
647 Luzzi, G., Dematteis, N., Serreta, A., Rico, I., Serrano-Cañadas, E., Bartolomé, M., Moreno, A.,
648 Buisan, S. and Revuelto, J.: Ground-based remote-sensing techniques for diagnosis of the
649 current state and recent evolution of the Monte Perdido Glacier, *Spanish Pyrenees, J. Glaciol.*,
650 65(249), 85–100, doi:10.1017/jog.2018.96, 2019.
- 651 Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C.,
652 Faluvegi, G. and Ni, F.: Global Signatures and Dynamical Origins of the Little Ice Age and
653 Medieval Climate Anomaly, *Science*, 326(5957), 1256–1260, 2009.
- 654 Martín-Puertas, C., Jiménez-Espejo, F., Martínez-Ruiz, F., Nieto-Moreno, V., Rodrigo, M., Mata,
655 M. P. and Valero-Garcés, B. L.: Late Holocene climate variability in the southwestern
656 Mediterranean region: an integrated marine and terrestrial geochemical approach, *Clim. Past*,
657 6(6), 807–816, doi:10.5194/cp-6-807-2010, 2010.
- 658 Marzeion, B., Cogley, J. G., Richter, K. and Parkes, D.: Attribution of global glacier mass loss to
659 anthropogenic and natural causes, *Science*, 345(6199), 919–921,
660 doi:10.1126/science.1254702, 2014.
- 661 Moore, P. D., Webb, J. A. and Collinson, M. E.: *Pollen Analysis, Second.*, Blackwell Scientific
662 Publications., 1991.
- 663 Morellón, M., Valero-Garcés, B., Vegas-Vilarrúbia, T., González-Sampériz, P., Romero, Ó.,
664 Delgado-Huertas, A., Mata, P., Moreno, A., Rico, M. and Corella, J. P.: Lateglacial and Holocene



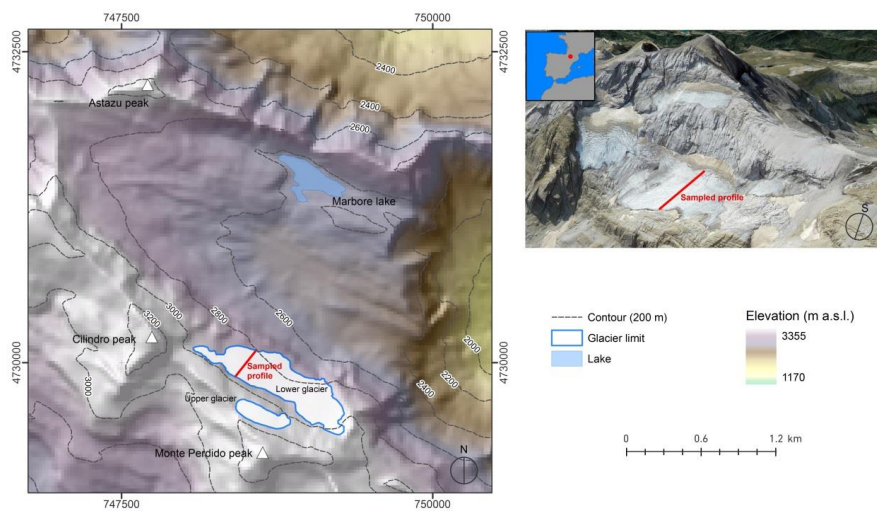
- 665 palaeohydrology in the western Mediterranean region: The Lake Estanya record (NE Spain),
666 *Quaternary Science Reviews*, 28(25–26), 2582–2599, 2009.
- 667 Nieto-Moreno, V., Martínez-Ruiz, F., Giralt, S., Jiménez-Espejo, F., Gallego-Torres, D., Rodrigo-
668 Gámiz, M., García-Orellana, J., Ortega-Huertas, M. and de Lange, G. J.: Tracking climate
669 variability in the western Mediterranean during the Late Holocene: a multiproxy approach,
670 *Clim. Past Discuss.*, 7(1), 635–675, doi:10.5194/cpd-7-635-2011, 2011.
- 671 Oerlemans, J.: *Glaciers and Climate Change*, CRC Press., 2001.
- 672 Oliva, M., Ruiz-Fernández, J., Barriendos, M., Benito, G., Cuadrat, J. M., Domínguez-Castro, F.,
673 García-Ruiz, J. M., Giralt, S., Gómez-Ortiz, A., Hernández, A., López-Costas, O., López-Moreno,
674 J. I., López-Sáez, J. A., Martínez-Cortizas, A., Moreno, A., Prohom, M., Saz, M. A., Serrano, E.,
675 Tejedor, E., Trigo, R., Valero-Garcés, B. and Vicente-Serrano, S. M.: The Little Ice Age in Iberian
676 mountains, *Earth-Science Reviews*, 177, 175–208, doi:10.1016/j.earscirev.2017.11.010, 2018.
- 677 Oliva-Urcia, B., Moreno, A., Leunda, M., Valero-Garcés, B., González-Sampériz, P., Gil-Romera,
678 G., Mata, M. P. and Group, H.: Last deglaciation and Holocene environmental change at high
679 altitude in the Pyrenees: the geochemical and paleomagnetic record from Marboré Lake (N
680 Spain), *J Paleolimnol*, 59(3), 349–371, doi:10.1007/s10933-017-0013-9, 2018.
- 681 Palacios, D., García-Ruiz, J. M., Andrés, N., Schimmelpfennig, I., Campos, N., Léanni, L.,
682 Aumaitre, G., Bourlès, D. L. and Keddadouche, K.: Deglaciation in the central Pyrenees during
683 the Pleistocene–Holocene transition: Timing and geomorphological significance, *Quaternary
684 Science Reviews*, 162, 111–127, doi:10.1016/j.quascirev.2017.03.007, 2017.
- 685 Pey, J., Pérez, N., Cortés, J., Alastuey, A. and Querol, X.: Chemical fingerprint and impact of
686 shipping emissions over a western Mediterranean metropolis: Primary and aged contributions,
687 *Science of The Total Environment*, 463–464, 497–507, doi:10.1016/j.scitotenv.2013.06.061,
688 2013.
- 689 Preunkert, S., McConnell, J. R., Hoffmann, H., Legrand, M., Wilson, A. I., Eckhardt, S., Stohl, A.,
690 Chellman, N. J., Arienzo, M. M. and Friedrich, R.: Lead and Antimony in Basal Ice From Col du
691 Dome (French Alps) Dated With Radiocarbon: A Record of Pollution During Antiquity,
692 *Geophysical Research Letters*, 46(9), 4953–4961, doi:10.1029/2019GL082641, 2019.
- 693 Querol, X., Viana, M., Alastuey, A., Amato, F., Moreno, T., Castillo, S., Pey, J., de la Rosa, J.,
694 Sánchez de la Campa, A., Artíñano, B., Salvador, P., García Dos Santos, S., Fernández-Patier, R.,
695 Moreno-Grau, S., Negral, L., Minguillón, M. C., Monfort, E., Gil, J. I., Inza, A., Ortega, L. A.,
696 Santamaría, J. M. and Zabalza, J.: Source origin of trace elements in PM from regional
697 background, urban and industrial sites of Spain, *Atmospheric Environment*, 41(34), 7219–7231,
698 doi:10.1016/j.atmosenv.2007.05.022, 2007.
- 699 Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Cheng,
700 H., Edwards, R. L., Friedrich, M. and others: IntCal13 and Marine13 radiocarbon age calibration
701 curves 0–50,000 years cal BP, *Radiocarbon*, 55(4), 1869–1887, 2013.
- 702 Rico, I., Izagirre, E., Serrano, E. and López-Moreno, J. I.: Superficie glaciar actual en los Pirineos:
703 Una actualización para 2016, *Pirineos*, 172(0), 029, doi:10.3989/Pirineos.2017.172004, 2017.
- 704 Salazar, A., Mata, M. P., Rico, M., Valero-Garcés, Oliva-Urcia, B. and Rubio, F. M.: El paleolago
705 de La Larri (Valle de Pineta, Pirineos), *Cuadernos de Investigación Geográfica*, 39(1), 97–116,
706 2013.



- 707 Sanchez-Cabeza, J. A., Masqué, P. and Ani-Ragolta, I.: 210Pb and 210Po analysis in sediments
708 and soils by microwave acid digestion, *J Radioanal Nucl Chem*, 227(1), 19–22,
709 doi:10.1007/BF02386425, 1998.
- 710 Serrano, E. and Martín-Moreno, R.: Surge glaciers during the Little Ice Age in the Pyrenees,
711 *Cuadernos de Investigación Geográfica*, 44(1), 213–244, doi:10.18172/cig.3399, 2018.
- 712 Solomina, O. N., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N.,
713 Nesje, A., Owen, L. A., Wanner, H., Wiles, G. C. and Young, N. E.: Holocene glacier fluctuations,
714 *Quaternary Science Reviews*, 111, 9–34, doi:10.1016/j.quascirev.2014.11.018, 2015.
- 715 Solomina, O. N., Bradley, R. S., Jomelli, V., Geirsdottir, A., Kaufman, D. S., Koch, J., McKay, N. P.,
716 Masiokas, M., Miller, G., Nesje, A., Nicolussi, K., Owen, L. A., Putnam, A. E., Wanner, H., Wiles,
717 G. and Yang, B.: Glacier fluctuations during the past 2000 years, *Quaternary Science Reviews*,
718 149, 61–90, doi:10.1016/j.quascirev.2016.04.008, 2016.
- 719 Taylor, S. R. and McLennan, S. M.: The geochemical evolution of the continental crust, *Reviews*
720 *of Geophysics*, 33, 241–265, 1995.
- 721 Thompson, L. G., Mosley-Thompson, E., Brecher, H., Davis, M., Leon, B., Les, D., Lin, P.-N.,
722 Mashiotta, T. and Mountain, K.: Abrupt tropical climate change: Past and present, *Proceedings*
723 *of the National Academy of Sciences*, 103(28), 10536–10543, doi:10.1073/pnas.0603900103,
724 2006.
- 725 Uglietti, C., Zapf, A., Jenk, T. M., Sigl, M., Szidat, S., Salazar, G. and Schwikowski, M.:
726 Radiocarbon dating of glacier ice: overview, optimisation, validation and potential, *The*
727 *Cryosphere*, 10(6), 3091–3105, doi:10.5194/tc-10-3091-2016, 2016.
- 728 Wanner, H., Solomina, O., Grosjean, M., Ritz, S. P. and Jetel, M.: Structure and origin of
729 Holocene cold events, *Quaternary Science Reviews*, 30(21–22), 3109–3123,
730 doi:10.1016/j.quascirev.2011.07.010, 2011.
- 731 Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W.,
732 Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B.
733 E., Casassa, G., Cobos, G., Dávila, L. R., Granados, H. D., Demuth, M. N., Espizua, L., Fischer, A.,
734 Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte,
735 P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurdsson, O.,
736 Soruco, A., Usabaliyev, R. and Vincent, C.: Historically unprecedented global glacier decline in
737 the early 21st century, *Journal of Glaciology*, 61(228), 745–762, doi:10.3189/2015JoG15J017,
738 2015.
- 739 Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H.,
740 Nussbaumer, S. U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S. and Cogley,
741 J. G.: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016,
742 *Nature*, 568(7752), 382–386, doi:10.1038/s41586-019-1071-0, 2019.
- 743



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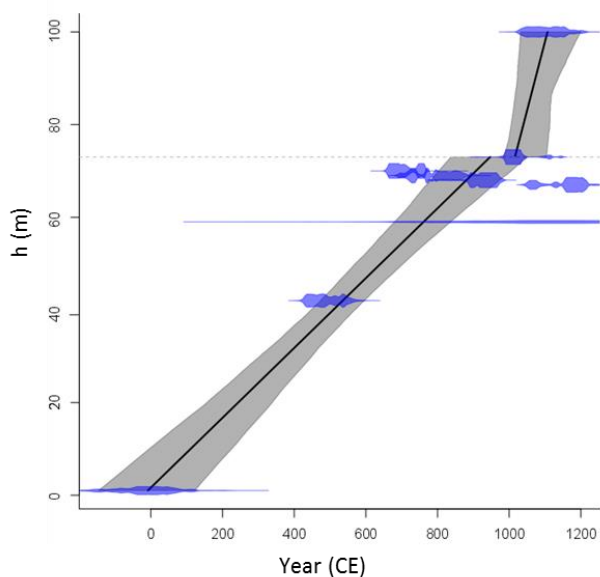
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747 **Figure 1.** (left) Location of Monte Perdido Glacier (MPG) within a digital elevation map
748 of Marboré Cirque. (right) Picture (©Google Earth) of MPG where the location of the
749 samples is indicated. Note the different orientation of both figures.

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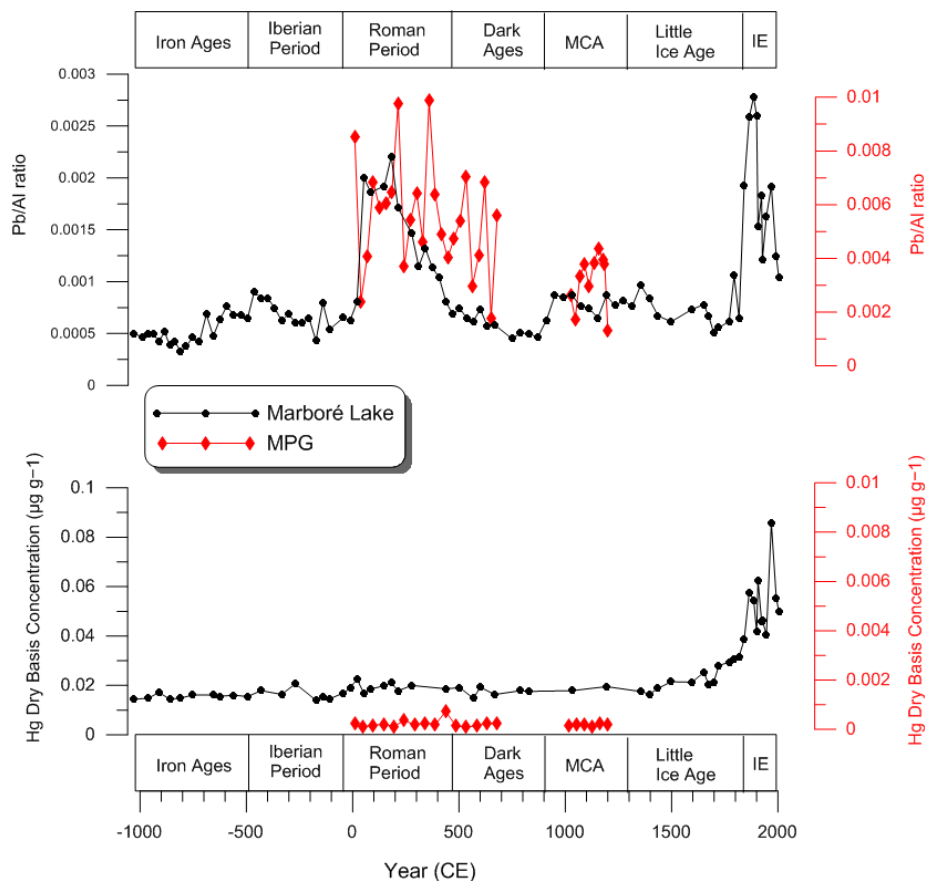
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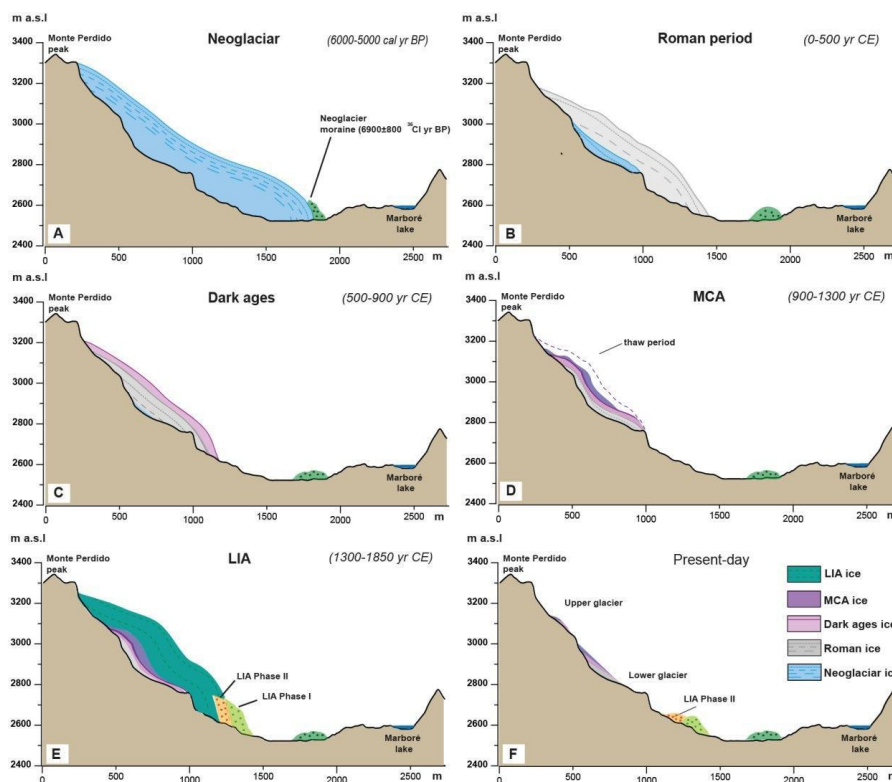
753 **Figure 2.** Composite depth-age model for the Monte Perdido ice sequence based on
754 linear interpolation of ^{14}C data (Table 1), obtained using the Clam software (Blaauw,
755 2010; Blaauw et al., 2019). The dates appear as the calendar-age probability
756 distributions in blue, while the black line is the resulting depth-age model and the gray
757 envelope shows the 95% confidence interval. Note the hiatus located at 73m indicated
758 by a dashed line.

759



760
761 **Figure 3.** Comparison of Pb/Al ratio and Hg concentration ($\mu\text{g g}^{-1}$ of dry weight
762 sediment) in MPG samples with data obtained from Marboré Lake sediments (Corella
763 et al., 2020). Note the differences in the vertical axis.

764



765

766 **Figure 4.** Geomorphic transects (south to north) taken from the Marboré Cirque,
767 showing the schematic reconstruction of MPG during the six main stages discussed in
768 the text. A) Neoglacial Period (ca 5000 – 6000 cal yr BP) where the Neoglacial moraine
769 is indicated (García-Ruiz et al., 2014); (B) Roman Period (0-500 CE) when the glacier is
770 shown considerably retreated; (C) Dark Ages (500-900 CE); (D) Medieval Climate
771 Anomaly (900-1300 CE), a period when the glacier retreated and ablation made
772 condensing debris and organic remains form dark layers in the glacier ice
773 (discontinuous line aims to highlight the importance of melting processes); (E) Little Ice
774 Age (1300-1850 CE), with the MPG reaching the LIA moraines position and (F) present-
775 day situation characterized by the MPG divided into two ice bodies, no ice remaining
776 from the LIA, and very steep slopes.

777



778 **Table 1.** Radiocarbon dating of MPG samples indicating their origin, the radiocarbon
 779 age (^{14}C age BP) and the calibrated date using INTCAL13 curve and presented in
 780 calendar years Common Era (CE). Samples in **red** and *italics* were not included in the
 781 age model (see text for explanation).

Laboratory ID	Sample depth (m from base)	Sample description	^{14}C age BP	Cal age (CE)
D-AMS 025291	1	Bulk organic matter	2000±64	8±66
MP10m	10	WIOC	812±755	<i>854±721</i>
D-AMS 031464	30	pollen concentration	3906±42	<i>-2384±1332</i>
D-AMS 025294	42	bulk organic matter	1554±27	462±32
D-AMS 025295	48	bulk organic matter	73±33	<i>1897±20</i>
MP59m	59	WIOC	926±268	1046±242
D-AMS 025296	67	bulk organic matter	876±29	1185±31
D-AMS 029894	67	bulk material (filter)	485±40	<i>1429±15</i>
D-AMS 026592	68	bulk organic matter	1128±22	942±24
D-AMS 026593	69	bulk organic matter	1230±23	730±14
D-AMS 025297	70	bulk organic matter	1308±28	680±16
D-AMS 031465	70	pollen concentration	1787±37	<i>237±255</i>
D-AMS 025298	73	bulk organic matter	1011±25	1012±16
D-AMS 033972	81	bulk material (filter)	1758±25	<i>287±68</i>
D-AMS 025299	100	bulk organic matter	923±39	1074±31
D-AMS 031466	100	pollen concentration	1854±30	<i>158±807</i>

782



783 **Table 2.** Elemental concentration (ppm) of major and trace metals in both Ordesa's
 784 current deposited dust and MPG ice deposits (averaged values for the 35 analyzed
 785 samples); Upper Crust elemental contents (Taylor and McLennan, 1995); and Al-
 786 normalised Enrichment Factors (EF) for dust components and elements for: EF_i , the
 787 MPG ice dust versus the current Ordesa's deposited dust (CODD); EF_{iCODD} , the CODD
 788 versus the Upper Crust (UC); and EF_{iMPGID} , the MPG ice dust versus the UC.

Ordesa 2016-2017 (2 years atmospheric deposition)				Monte Perdido (ice dust: 35 filter samples)				U. Crust				
ppm	Max	Min	Average	1mg dust	Max	Min	Average	EF_i	EF_{iCODD}	EF_{iMPGID}		
	OC	443270	49659		206814	OC	436343					14793
EC	114519	12506	39995	EC	112769	14668	40605	0,6			EC	
Al	122401	7883	60410	Al	506467	19611	98808	80400	1,0	1,0	1,0	Al
Ca	22578	3182	9663	Ca	119648	256,7	11984	30000	0,8	0,4	0,3	Ca
Fe	63218	2901	32665	Fe	183957	12504	59477	35000	1,1	1,2	1,4	Fe
K	27478	3907	14839	K	57038	4001	18505	28000	0,8	0,7	0,5	K
Mg	27286	2105	12265	Mg	72210	3513	16645	13300	0,8	1,2	1,0	Mg
Na	5380	1,2	1413	Na	25750	593	5126	28900	2,2	0,1	0,1	Na
Ti	5035	257	2334	Ti	52192	3243	13662	3000	3,6	1,0	3,7	Ti
Mn	1656	128	582	Mn	3835	174	979	600	1,0	1,3	1,3	Mn
Sr	170	19	78	Sr	200	20	80	350	0,6	0,3	0,2	Sr
Be	7	0	2,1	Be	2,3	0	0,4	3	0,1	0,9	0,1	Be
V	208	10	76	V	257	28	107	60	0,9	1,7	1,5	V
Cr	720	5	118	Cr	2915	12	441	35	2,3	4,5	10,3	Cr
Co	32	0	7,6	Co	49	5,4	20	10	1,6	1,0	1,6	Co
Ni	414	7	55	Ni	1046	4,3	228	20	2,5	3,6	9,3	Ni
Cu	683	33	127	Cu	26451	92	3786	25	18,3	6,7	123,2	Cu
Zn	9391	164	1316	Zn	3826	171	988	71	0,5	24,7	11,3	Zn
As	26	2	10	As	51	5,3	18	1,5	1,0	9,1	9,6	As
Se	90	0	22	Se	30	0	5,2	50	0,1	0,6	0,1	Se
Cd	100	0	14	Cd	1,5	0	0,3	0,98	0,0	18,8	0,2	Cd
Sb	26	0	4,5	Sb	59	2	11	0,2	1,5	29,7	43,3	Sb
Ba	1010	15	287	Ba	870	67	317	550	0,7	0,7	0,5	Ba
Tl	1	0	0,1	Tl	1,1	0	0,2	0,75	1,7	0,1	0,2	Tl
Pb	175	8	53	Pb	2989	86	495	17	5,7	4,2	23,7	Pb
Th	37	1	12	Th	26	1,6	9,7	10,7	0,5	1,5	0,7	Th
U	8	0	2,5	U	15	0	3,7	2,8	0,9	1,2	1,1	U

789