



**HAL**  
open science

## Climate sensitivity and geomorphological response of cirque glaciers from the late glacial to the Holocene

David Palacios, Marc Oliva, Antonio Gómez-Ortiz, Nuria Andrés, José Fernández-Fernández, Irene Schimmelpfennig, Laëtitia Léanni

### ► To cite this version:

David Palacios, Marc Oliva, Antonio Gómez-Ortiz, Nuria Andrés, José Fernández-Fernández, et al.. Climate sensitivity and geomorphological response of cirque glaciers from the late glacial to the Holocene. *Quaternary Science Reviews*, 2020, 248, pp.1-26. 10.1016/j.quascirev.2020.106617 . hal-02961582

**HAL Id: hal-02961582**

**<https://hal.science/hal-02961582>**

Submitted on 1 Dec 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Climate sensitivity and geomorphological response of cirque glaciers from the Late Glacial to the Holocene

David Palacios<sup>a\*</sup>, Marc Oliva<sup>b</sup>, Antonio Gómez-Ortiz<sup>b</sup>, Nuria Andrés<sup>a</sup>, José M. Fernández-Fernández<sup>c</sup>, Irene Schimmelpfennig<sup>d</sup>, Laëtitia Léanni<sup>d</sup>, ASTER Team<sup>d, e</sup>

<sup>a</sup> Department of Geography, Universidad Complutense de Madrid, Madrid, Spain

<sup>b</sup> Department of Geography, Universitat de Barcelona, Barcelona, Spain

<sup>c</sup> Instituto de Geografia e Ordenamento do Território, Universidade de Lisboa, Lisboa, Portugal.

<sup>d</sup> Aix Marseille Université, CNRS, IRD, INRAE, Coll. France, CEREGE, Aix-en-Provence, France

<sup>e</sup> Consortium: Georges Aumaître, Didier Bourlès, Karim Keddadouche

\*Corresponding author: [davidp@ucm.es](mailto:davidp@ucm.es) (D. Palacios)

## Abstract

Through a **detailed** geomorphological study, including thorough mapping of the geomorphic features as well as <sup>10</sup>Be Cosmic-Ray Exposure (CRE) dating, the geomorphological evolution of the Mulhacén cirque since the maximum ice extent of the last glacial cycle until nowadays was determined. This glacial cirque is shaped on the northern face of the Mulhacén peak (3479 m a.s.l., 37°03'12"N / 3°18'41"W), Sierra Nevada, southern Spain. It includes several depositional and erosional glacial landforms that allowed reconstructing its environmental evolution since the last glacial cycle. Furthermore, the sequence of glacial oscillations from this site was compared to **that** of other cirques of the massif, evidencing that: (i) new glaciers formed in these cirques during the Younger Dryas (YD), and (ii) disappeared at  $11.7 \pm 1.0$  ka. Depending on the altitude, orientation and height of the cirque walls, the final deglaciation of the cirques generated a diversity of landscapes, including a wide range of glacial and periglacial landforms, such as polished surfaces, sequences of moraines, proto-rock glaciers or large rock glacier systems. No glaciers existed in the Sierra Nevada during the Middle Holocene. Only the cirques whose summits exceed 3300 m, are north-exposed and whose walls exceed 300 m high (i.e. Mulhacén and Veleta) hosted glaciers during Neoglacial phases, including the Little Ice Age (LIA) (**approx. 1300-1850 CE**). During these periods, climate oscillations favoured the formation of small glaciers in these cirques, which generated large moraine systems with either one polygenic ridge or a sequence of spaced frontal arcs. The existence of glaciers impeded the formation of permafrost-related

35 landforms, such as rock glaciers and protalus lobes until the end of the LIA, when they  
36 started to form. These results are compared with the deglacial evolution in 55 cirques  
37 from Iberian mountains as well as from glacial cirques from other mid-latitude mountains  
38 and subpolar regions. The chronology of their deglaciation as well as the landforms  
39 generated during glacial retreat followed similar patterns, with no significant differences  
40 at regional scale. For each mountain range, the geomorphological diversity existing in  
41 each cirque depends on the local topographic characteristics although they formed during  
42 the same climatic phases.

43 *Key words:* Glacial Cirque, Rock Glacier, Sierra Nevada, Cosmic-Ray Exposure Dating,  
44 Late Glacial, Holocene.

## 45 **1. Introduction**

46 Glacial cirques are defined as armchair-shaped erosional hollows, typified by steep  
47 headwalls, typically arcuate and with lateral spurs, and with overdeepened floors, often  
48 occupied by a lake or bog (Evans and Cox, 1974, 1995; Barr and Spagnolo, 2015). The  
49 typology of cirques is extremely diversified and, therefore, the limits of this concept are  
50 difficult to define (Mîndrescu and Evans, 2014). Their origin is associated with the first  
51 steps of glaciation (Benn and Evans, 2010), although the mechanisms involved in their  
52 formation and upgrowth are still under debate (Sanders et al., 2012, 2013). Since the first  
53 studies, the importance of palaeoclimatic conditions driving the glacial and periglacial  
54 processes that shaped the heads of the valleys is highlighted (Benedict, 1973; Delmas et  
55 al., 2015; Barr et al., 2017). Consequently, several parameters such as the distribution,  
56 aspect, floor elevation and morphometry of the glacial cirques have been used to infer  
57 palaeotemperatures, precipitation gradients, cloud-cover and prevailing wind directions  
58 during glaciation (e.g. Dahl and Nesje, 1992; Barr and Spagnolo, 2015; Ipsen et al., 2018).  
59 However, other factors such as the geological structure, post-glacial erosion and the  
60 uncertainty regarding their origin make even more challenging to reconstruct past climate  
61 regimes using cirque morphometry (Barr and Spagnolo, 2015).

62 Moreover, it must be taken into account that enhanced by paraglacial dynamics, glacial  
63 cirques continue in many cases to evolve during the interglacial periods following the last  
64 phase of glaciation (Kleman and Stroeven, 1997; Ballantyne, 2002, 2013). This is  
65 especially important in the mountain ranges under Mediterranean influence, where glacial  
66 cirques are one of the most abundant glacial landforms, affected by the last glacial cycle

67 and subsequent deglaciation (Hughes et al., 2006; 2007). Over recent decades, in  
68 particular two palaeoenvironmental techniques, namely lake sediment record studies and  
69 Cosmic-Ray Exposure (CRE) dating of glacial landforms using cosmogenic nuclides,  
70 have provided evidence of the potential palaeoclimatic information preserved in alpine  
71 cirques.

72 Many mountain glaciers reached their maximum extent between 26.5 and 19 ka (Clark et  
73 al., 2009) or a few thousand years before (Hughes et al., 2013). This period is the so-  
74 called Last Glacial Maximum (LGM), which coincided with the minimum sea level at  
75 global scale (Clark et al., 2009; Hughes et al., 2013). However, this maximum extension  
76 was reached before or after the LGM in many other mountains, which is known as the  
77 Local Last Glacial Maximum (LLGM). In the Mediterranean region, particular attention  
78 has been paid to the reconstruction of the sequence of glacial phases recorded on cirque  
79 floors in the form of moraine systems revealing either (i) phases of stabilization during  
80 the long-term retreat since the LLGM, or (ii) short periods of glacial readvance. This is  
81 the case in the Rila mountains, Balkan Peninsula, where 2 km-long cirques include a large  
82 number of moraines that formed between the LGM and the Younger Dryas (YD) (12.9–  
83 11.7 ka, Walker et al. 2009; GS-1 Rasmussen et al., 2014), i.e. within the approx. 24-12  
84 ka period (Kuhlemann et al., 2013). One of the best examples of the geomorphological  
85 interest of these small glacial cirques comes from Mount Olympus, southern Balkan  
86 Peninsula, where moraines from the Late Glacial to the latest Neoglacial advances (from  
87  $15.6 \pm 2.0$  to  $0.64 \pm 0.08$  ka) are distributed over a distance of less than 500 m (Styllas et  
88 al., 2018). Similarly, in the Dinaric mountains, Žebre et al. (2019) summarized previous  
89 studies of numerous small cirques with a sequence of moraine systems dating back from  
90 Oldest Dryas (OD) to the YD (14.9 ka to 11.7 ka). Small cirques in the Apennines also  
91 retain geomorphic evidence in the form of moraine arcs formed between the LLGM and  
92 present-day (Giraudi, 2012; Baroni et al., 2018). There are many other examples of the  
93 potential of small cirques, including information about glacial oscillations occurred  
94 during Termination-1 (19 to 11.7 ka), such as in the Anatolian peninsula. Here, in Mount  
95 Geyikdag (Sarıkaya et al., 2017) and Mount Uludag (Zahno et al., 2010), ca. 1 km long  
96 cirques contain moraines from the LLGM to the Holocene. A similar pattern is found in  
97 small cirques of the High Atlas, Morocco, with moraine systems from different phases  
98 encompassing the entire deglaciation until the early Holocene (Hughes et al., 2019).

99 Small glacial cirques with rich palaeoclimatic information are not exclusive of the  
100 Mediterranean region. Cirques are also frequent glacial features in continental ranges as,  
101 for example, those in Central Europe. Similar glacial chronologies as those described  
102 above have been reported from cirques in the Krkonoše Mountains, Sudetes range (Engel  
103 et al., 2014), or in cirques of larger formerly glaciated ranges, such as the Tatra  
104 Mountains, Northern Carpathians (Engel et al., 2015; Makos et al., 2018; Zasadni et al.,  
105 2020), and Parang Mountains, Southern Carpathians (Gheorghiu et al., 2015), where  
106 moraines from the OD to the Holocene have been dated. Small cirques in the Alps also  
107 provided detailed information on glacial oscillations and the climatic evolution of the  
108 Late Holocene (Ribolini et al., 2007; Ivy-Ochs et al., 2009; Hippolyte et al., 2009; Moran  
109 et al., 2016; Ivy-Ochs, 2015; Le Roy et al., 2017). Well-known glacial oscillations from  
110 the last glacial phases in many cirques of several mountain ranges of the Western United  
111 States confirming previous results obtained in certain ranges such as the Sierra Nevada  
112 (Clark and Gillespie, 1997) have been recently published (Marcott et al., 2019; Laabs et  
113 al., 2020)

114 Glacial cirques in mountains that protruded from ice-sheet surfaces, such as those in  
115 nunataks, also include geomorphic evidence of glacial fluctuations during the last glacial  
116 cycle. This is the case of the Macgillicuddy's Reeks (South Ireland), where small cirques  
117 host moraines from the LLGM and even younger (Barth et al., 2016). Moreover, glacial  
118 cirques can also preserve accurate data on the last deglaciation phases of ice-sheets, as  
119 well as on Neoglacial advances during the current interglacial. For example, up to four  
120 glacial advances that occurred after the complete disappearance of the Scandinavian Ice-  
121 sheet have been evidenced in numerous cirques in Norwegian mountains (Dahl and Nesje,  
122 1992; Paasche et al., 2007). In Svalbard, small cirques contain moraines revealing that  
123 the YD was only a minor advance, smaller than those of the Little Ice Age (from 1300 to  
124 about 1850 CE, LIA) (Mangerud and Landvik, 2007). One of the best examples of the  
125 palaeoclimatic significance of these cirques can be found in the Tröllaskagi Peninsula,  
126 northern Iceland, formerly covered by the Icelandic Ice-Sheet (Ipsen et al., 2018). In this  
127 peninsula, small cirques a few km long host up to 12 Holocene moraine complexes  
128 corresponding to various stages of the LIA, and even different glacial advances over the  
129 last decades (Fernández-Fernández et al., 2019). Moreover, other cirques in the  
130 Tröllaskagi Peninsula include a set of erratic boulders, moraines, and several generations

131 of rock glaciers and debris-covered glaciers showing a complex glacial evolution from  
132 the OD to the present (Tanarro et al., 2019; Fernández-Fernández et al., 2020).

133 In the Iberian Peninsula, small glacial cirques including several moraine systems have  
134 been studied in the highest mountain ranges (Oliva et al., 2019). In the Eastern Pyrenees,  
135 very small cirques preserve erratic boulders, complex moraine systems and rock glaciers  
136 that reveal a complex glacial evolution from the LLGM to the Holocene (Pallàs et al.,  
137 2006, 2010; Delmas, 2015; Andrés et al., 2019; Jomelli et al., 2020). In the Central  
138 Pyrenees, small cirques include moraine complexes from the OD to the Holocene  
139 (Delmas, 2015; Palacios et al., 2017a; Crest et al., 2017; Tomkins et al., 2018), with only  
140 a few sites recording Neoglacial advances (García-Ruiz et al., 2014). In the Cantabrian  
141 Mountains, the heads of some cirques host rock glaciers and moraines from the OD to the  
142 Early Holocene (Rodríguez-Rodríguez, 2016, 2017). In the Iberian Range, cirques < 1  
143 km long preserved moraines from the LLGM, OD and remnants of fossil debris-covered  
144 glaciers, some of which were active until the Middle-Holocene due to their favourable  
145 orientation (Fernández-Fernández et al., 2017). Other cirques contain moraines from the  
146 LLGM to the OD, when the formation of rock glaciers occurs, and even subsequent  
147 deglaciated cirque steps, coetaneous with the YD (García-Ruiz et al., 2020a). In the  
148 Central Range, small cirques in the massifs of Guadarrama (Palacios et al., 2011, 2012a,  
149 2012b; Carrasco et al., 2016) and Gredos (Domínguez-Villar, 2013; Carrasco et al., 2013,  
150 2015) include moraine complexes from the LLGM to the OD, YD and even the Holocene,  
151 depending on the altitude and prevailing aspect of the cirques. Besides, a detailed study  
152 of the peatbogs from a glacial cirque in Gredos has provided valuable palaeoclimatic  
153 information from the deglaciation from the OD to the present (López-Sáez, et al., 2020).

154 The Sierra Nevada (South Iberia) contains 65 glacial cirques with geomorphic evidence  
155 indicative of the glacial and palaeoclimatic evolution from the LLGM to the recent times  
156 (Palacios et al., 2016; Palma et al., 2017) and, in some of these cirques, even from the  
157 previous glacial cycle (Palacios et al., 2019). Regarding the Holocene, several  
158 palaeoenvironmental archives such as lake records and peatbogs inside glacial cirques  
159 testify to a remarkable climatic variability (Oliva, 2009; Oliva and Gómez-Ortiz, 2012),  
160 as well as the impact of human activity (Anderson et al., 2011; García-Alix et al., 2013,  
161 2017). Two of these cirques held also small glaciers during the LIA, which were the  
162 southernmost in Europe (Gómez-Ortiz et al., 2009, 2015, 2018). One of them, the Veleta  
163 cirque, shaped on the northern slope of the Veleta peak, contains valuable information on

164 environmental dynamics from the first glacial phases of the LIA to the present-day, with  
165 evidence of: (i) the succession of several glacial advances and the gradual melting of the  
166 glacier, (ii) rock avalanches, (iii) landslides and, (iv) permafrost degradation. These  
167 processes, highly sensitive to small climatic variations, led to intense geomorphic  
168 readjustments typical of the paraglacial phase (Oliva et al., 2016; Palacios et al., 2019;  
169 Serrano et al., 2018; Gómez-Ortiz et al., 2019 and references therein). As a result,  
170 landforms from this cirque are considered key geoindicators for monitoring the impact of  
171 climate change on mountain geomorphological processes in southern Europe (Gómez-  
172 Ortiz et al., 2019). The other cirque that hosted a glacier during the LIA in the Sierra  
173 Nevada is located under the northern rock wall of Mulhacén peak. To date, although it  
174 contains a wide range of glacial depositional and erosional features, this cirque has been  
175 little studied. The only palaeoclimatic records from this cirque are those provided by the  
176 sediments of La Mosca Lake, which led to a detailed picture of the Mid-Late Holocene  
177 palaeoecological evolution as well as to the evidence of several glacial advances during  
178 the Late Holocene (Manzano et al., 2019; Oliva, 2009; Oliva et al., 2019).

179 On the other hand, the interpretation of the palaeoenvironmental records preserved in the  
180 interior of glacial cirques can come up against important difficulties, such as the alteration  
181 of glacial reliefs depending on the intensity of slope processes and the frequency of rock  
182 avalanches altering glacial landforms (Deline et al., 2015; Mercier et al., 2017; Knight et  
183 al., 2018) or the effects of neotectonic activity in cirque evolution (Oskin and Burbank,  
184 2005). Regarding CRE dating, these processes can hinder the presumed undisturbed  
185 exposure of bedrock surfaces, rock glacier and moraine boulders to be dated, or  
186 potentially lead to nuclide inheritance in these surfaces (Li et al., 2016; Çiner et al., 2017;  
187 Köse et al., 2019),

188 Therefore, the current state of knowledge still presents some open questions, such as:

- 189 (i) What is the origin of the complex moraine formations frequently found inside the  
190 cirques and covering a wide chronological range?
- 191 (ii) Why do glaciers, once confined within the cirques, tend to evolve in many different  
192 ways, forming, in some cases, debris-covered glaciers or rock glaciers, and, in other  
193 cases, multiple moraine ridges developing in short periods of time?

194 (iii) Is it possible to circumvent the impact of geomorphological processes occurring  
195 inside the glacial cirques to correctly extract the palaeoenvironmental significance  
196 preserved in their records?

197 In order to address these questions, the glacial landforms existing in one of the  
198 Mediterranean cirques housing the most detailed sequence of the environmental evolution  
199 since the LLGM, the Mulhacén cirque, have been analysed. To investigate the potential  
200 common behaviour and infer its palaeoclimatic implications on different spatial scales,  
201 the palaeoclimatic and geomorphological evolution of this cirque is compared to that of  
202 others in the whole massif of Sierra Nevada, the Iberian Peninsula and other mountains  
203 of the Northern Hemisphere for which geomorphological and CRE data are available.

## 204 **2. Study area**

205 Located in the southern fringe of Iberia at latitude of 37°N, the Sierra Nevada is the  
206 highest massif of the Betic Range (Fig.1). It includes the highest peaks in western Europe  
207 outside the Alps, with elevations exceeding 3000 m a.s.l. in its western fringe, such as  
208 Mulhacén (3479 m, 37°03'12"N 3°18'41"W) and Veleta (3396 m, 37°03'22"N,  
209 3°21'56"W). The landscape of the massif results from its bordering location between  
210 different climatic influences: continental (Europe/Africa), maritime  
211 (Atlantic/Mediterranean) and subtropical high pressure belt/mid-latitude westerlies  
212 (Oliva et al., 2011). Currently, the mean annual air temperature at 2500 m is 4.4 °C (1965-  
213 1992), whereas at the highest summits of the massif at 3400 it is 0 °C (2001-2016)  
214 (Gómez-Ortiz et al., 2019). Annual precipitation reaches 710 mm, mostly as snow  
215 between October and April (Oliva, 2009; Oliva et al., 2008). The bedrock of the summit  
216 area, the study site, is composed of micaschists which are intensely affected by periglacial  
217 processes. The vegetation cover is very sparse, typical of the high semi-arid  
218 Mediterranean mountains, and is mostly distributed across the valley floors near lakes  
219 and wetlands (Oliva et al., 2011).

220 The contemporary landscape of the Sierra Nevada is mostly a consequence of past  
221 glaciations. A wide range of depositional and erosional landforms of glacial origin are  
222 distributed in elevations above 2000 (northern slopes) and 2500 m (southern slopes).  
223 They result from the sequence of glacial phases that shaped the highest lands of the massif  
224 since the maximum ice extent of the penultimate glacial cycle (Palacios et al., 2019). The



225 LIA was the last period with the presence of glaciers in the Sierra Nevada (Gómez-Ortiz  
226 et al., 2009; 2012, 2015, 2018, Palacios et al., 2016).

227 The deglaciation of the cirques favoured the appearance of many mountain lakes and bogs  
228 which have been sampled for palaeoenvironmental and palaeoclimatic purposes  
229 (Anderson et al., 2011; García-Alix et al., 2013; 2017; Jiménez-Moreno and Anderson,  
230 2012; Oliva et al., 2011, 2010). At the northern foot of the Mulhacén peak, a glacial lake  
231 dammed by a moraine ridge is located next to the cirque mouth at 2892 m a.s.l.: the Mosca  
232 Lake (ca. 90 m wide, 160 m long, 1 ha, 3.2 m deep) (Oliva and Gómez-Ortiz, 2012) (Fig.  
233 1). A sequence of recessional moraines is connected to the large talus cones generated by  
234 frost shattering from the steep northern rock wall of the Mulhacén peak, almost 400 m  
235 high. These moraines show multiple collapses and subsidence features (Fig. 1) which  
236 evidence the degradation of the small isolated permafrost patches still existing today in  
237 the massif (Oliva et al., 2018; Serrano et al., 2018). The large talus cones are also being  
238 affected by widespread debris flows transporting sediments downslope during the melting  
239 season or during extreme rainfall events in late summer and early autumn. At the foot of  
240 the Mulhacén rock wall, there are a few semi-permanent snow-patches as well as a  
241 protalus lobe formed following the final deglaciation of the cirque (Fig. 2), which is also  
242 indicative of the existence of permafrost at this site (Serrano et al., 2018; Gómez-Ortiz et  
243 al., 2019).

244 As revealed by historical documents and lacustrine sedimentary records, the cirque was  
245 partly glaciated several times during the Holocene, namely at 2.8-2.7, 1.4-1.2 and 0.51-  
246 0.24 ka cal BP (Oliva and Gómez-Ortiz, 2012, Oliva et al., 2020). Lake sediment phases  
247 recorded peaks with large concentrations of sand and very low organic carbon content,  
248 which are attributed to colder and wetter conditions and the development of a glacier in  
249 the catchment. The last of these periods coincided with the LIA, which promoted the  
250 formation of the largest glacier over the three last millennia in the Mulhacén cirque (Oliva  
251 and Gómez-Ortiz, 2012). There are other longer sedimentary cores collected from this  
252 lake with radiocarbon dates up to 8.4 cal ka BP, which however do not come from the  
253 basal sediments, but give a minimum age of lake formation following glacial retreat  
254 (Manzano et al., 2019). No chronological evidence is reported about earlier glacial  
255 phases. Therefore, the moraines located upstream of the La Mosca Lake have probably  
256 developed throughout the Holocene, whereas the moraines closing the lake must be older.

### 257 3. Methodology

### 258 3.1 Geomorphological mapping

259 In order to reconstruct the palaeoenvironmental evolution of the Mulhacén cirque since  
260 the last glacial cycle, a detailed geomorphological analysis and mapping of the study area  
261 was first performed. Although we consider the last glacial cycle as a synonymous of the  
262 Late Pleistocene (approx. 123-14 ka; Hughes and Gibbard, 2018), most of the preserved  
263 glacial landforms formed during the LGM or later. The different geomorphological units  
264 were classified following the criteria used in previous studies of other glacial cirques in  
265 this massif focusing on the distribution of moraines, rock glaciers, protalus lobes, rock  
266 avalanches, debris flows and rock falls (Gómez-Ortiz et al., 2012; Palacios et al., 2016;  
267 Palma et al, 2017). The spatial distribution of the different features of glacial origin  
268 revealed in this cirque suggests a sequence of glacial events until the recent disappearance  
269 of the LIA glacier. The geomorphological map was also used for planning the sampling  
270 strategy for CRE dating in order to establish the chronology of the cirque deglaciation. In  
271 addition, historical sources provided information concerning the periods during which  
272 glaciers were present during the LIA in the Sierra Nevada (Gómez-Ortiz et al., 2009,  
273 2012, 2015, 2018). These were also used to interpret the final deglaciation phases of the  
274 Mulhacén cirque.

### 275 3.2 CRE sampling strategy

276 The sampling strategy for CRE dating is based on the sequence of the mapped landforms,  
277 from the bottom to the upper part of the cirque. In late summer 2016, when the cirque  
278 was snow-free and geomorphic features were clearly visible in the field, eight samples  
279 from the Mulhacén cirque at elevations between 2890 and 2950 m were collected. Two  
280 of the samples were taken from glacially polished outcrops (MOSCA-2 and MOSCA-3),  
281 while the others were taken from flat-topped surfaces of boulders located on moraine  
282 ridges. The characteristics of the sampling sites and complementary field data are  
283 summarized in Table 1.

### 284 3.3 CRE laboratory procedures and exposure age calculation

285 The samples were crushed and sieved to the 0.25-1 mm fraction at the ‘Physical  
286 Geography Laboratory’ of the Universidad Complutense de Madrid. The following steps  
287 of the sample preparation process were carried out at the ‘Laboratoire National des  
288 Nucléides Cosmogéniques’ (LN2C) of the CEREGE (Centre Européen de Recherche et  
289 d’Enseignement des Géosciences de l’Environnement, Aix-en-Provence, France). To

290 extract the cosmogenic  $^{10}\text{Be}$  isotope, a first rough isolation of the quartz mineral fraction  
291 of the sieved samples was performed by means of a Frantz LB-1 magnetic separator  
292 removing the magnetic minerals. Subsequently, the remaining non-quartz minerals were  
293 dissolved through successive acid attacks (a mixture of concentrated hydrochloric (HCl)  
294 and hexafluorosilicic ( $\text{H}_2\text{SiF}_6$ ) acids in a proportion 1:2). Three consecutive partial  
295 dissolutions using concentrated hydrofluoric acid (HF) were performed to ensure removal  
296 of any non-quartz mineral from the treated samples and to decontaminate the pure quartz  
297 mineral fraction from meteoric  $^{10}\text{Be}$ . For the following steps, pure quartz masses ranged  
298 between 6 and 40 g. 150  $\mu\text{L}$  of an accurately weighted  $^9\text{Be}$  carrier solution manufactured  
299 in-house from a phenakite crystal ( $[^9\text{Be}] = 3025 \pm 9 \mu\text{g g}^{-1}$ ; [Merchel et al., 2008](#)) were  
300 added, and the quartz was totally dissolved in 48% HF (3.6 mL per g of quartz + 30 mL  
301 in excess). After the total dissolution, the resulting solution was evaporated until dryness  
302 and the solid residues were recovered in 7.1 M HCl. Samples were precipitated with  
303 ammonia before successive separations, first through an anion exchange column (Dowex  
304 1X8) to remove iron, and then through one or several cation exchange columns (Dowex  
305 50WX8) to discard boron (isobar) and to separate the Be from other elements (Merchel  
306 and Herpers, 1999). All samples contained a lot of muscovite, which was difficult to  
307 remove completely and complicated the treatment of some of the samples. Therefore 17  
308 cation exchange columns were performed for samples MOSCA-2, 3, 5 and 7.

309 The eluted Be was precipitated to beryllium hydroxide ( $\text{Be}(\text{OH})_2$ ) with ammonia and  
310 oxidized to BeO at 700 °C. As a final step, BeO were mixed with niobium powder in an  
311 approximate 1:1 proportion, and then loaded in cathodes for the subsequent measurement  
312 of the  $^{10}\text{Be}/^9\text{Be}$  ratio at the ASTER ('Accélérateur pour les Sciences de la Terre,  
313 Environnement et Risques') AMS (Accelerator Mass Spectrometry) national facility at  
314 CEREGE. A chemical blank was prepared along with the seven samples.

315 Sample  $^{10}\text{Be}/^9\text{Be}$  ratios were calibrated against the in-house standard STD-11, using an  
316 assigned  $^{10}\text{Be}/^9\text{Be}$  nominal ratio of  $(1.191 \pm 0.013) \times 10^{-11}$  ([Braucher et al., 2015](#)).

317 Analytical  $1\sigma$  uncertainties include uncertainties associated with AMS counting statistics,  
318 the standard  $^{10}\text{Be}/^9\text{Be}$  ratio, an external AMS error of 0.5% ([Arnold et al., 2010](#)) and the  
319 chemical blank measurement. A  $^{10}\text{Be}$  half-life of  $(1.387 \pm 0.0012) \times 10^6$  years was used  
320 ([Chmeleff et al., 2010](#); [Korschinek et al., 2010](#)). More details of analytical data are given  
321 in [Table 1](#).

322 <sup>10</sup>Be surface CRE ages were calculated using the CREp online calculator (Martin et al.,  
323 2017; available online at: <http://crep.crpq.cnrs-nancy.fr/#/>). The parameters used were:  
324 the LSD elevation latitude scaling scheme (Lifton et al., 2014), the ERA40 atmospheric  
325 model (Uppala et al., 2005) and the geomagnetic database based on the LSD framework  
326 (Lifton et al., 2014). This setting yielded a sea-level high latitude (SLHL) <sup>10</sup>Be production  
327 rate of  $3.98 \pm 0.22$  atoms g<sup>-1</sup> yr<sup>-1</sup>. Rock density was assumed to be 2.7 g cm<sup>-3</sup>. Partial  
328 shielding of the surrounding topography from the cosmic-ray flux was calculated through  
329 the Topographic Shielding Calculator v.2 of CRONUS-Earth Web Calculators (consulted  
330 2020). CRE ages are reported for the zero denudation scenario, and uncertainties included  
331 hereafter include analytical and production rate errors (Table 2).

332 The results of the analysis carried out in the Mulhacén cirque have been confronted with  
333 previous studies involving CRE dating, some using <sup>10</sup>Be and others <sup>36</sup>Cl, conducted in  
334 other cirques of the Sierra Nevada and in the rest of the Iberian mountains. In order to  
335 compare the results obtained from the two cosmogenic nuclides, all the CRE ages  
336 mentioned in the text were recalculated in accordance with the protocols proposed for the  
337 Iberian Peninsula in Oliva et al. (2019). Also, to compare our results with those obtained  
338 in cirques from other mountains outside Iberian Peninsula where CRE dating was  
339 performed, we have checked all the publications of the last five years that include a  
340 detailed description of the CRE age calculation protocols and only those with similar  
341 protocols to those applied to Iberian mountains were considered.

342 In addition, the information on the glacial chronological sequences provided by the new  
343 CRE ages were compared with the palaeoenvironmental evidences previously inferred  
344 from the sedimentary studies of La Mosca Lake (Oliva and Gómez-Ortiz, 2012; Manzano  
345 et al., 2019) as well as from other lakes and peatbogs of the massif (Anderson et al., 2011;  
346 García-Alix et al., 2013, 2017; Jiménez-Moreno and Anderson, 2012; Oliva et al., 2011,  
347 2010).

## 348 **4. Results**

### 349 *4.1 Geomorphological setting and CRE sample selection*

350 The results of the geomorphological analysis of the Mulhacén cirque are summarized in  
351 the geomorphological map (Fig. 2) as well as along a transect including the most  
352 remarkable glacial and periglacial features (Fig. 3).

353 For CRE dating, we focused on rocky outcrops with glacially polished surfaces that  
354 protrude above the bottom of the cirque and had probably not been covered with sediment  
355 after deglaciation; however, few suitable sites were found as debris cover is very abundant  
356 in the Mulhacén cirque floor. In addition, due to an efficient **weathering** of the micaschist  
357 bedrock, the original glacial surface of the few outcrops standing in the cirque floor is  
358 often not preserved and, therefore, only two polished surfaces were considered suitable  
359 for CRE dating. One sample was taken from a bedrock step below La Mosca Lake  
360 (MOSCA-2) and another one from a bedrock step above it (MOSCA-3) (Figs. 4 and 5).

361 The Mulhacén cirque ends downvalley in a large step that descends vertically from 2920  
362 to 2600 m to the Valdecasillas gorge. The sample MOSCA-2 is located just on the edge  
363 of this step, next to two moraine ridges damming the La Mosca Lake. Due to the highly  
364 weathered surface of the rocks, only three boulders from these ridges appeared suitable  
365 for CRE dating (not affected by denudation, and standing out above the cirque floor): one  
366 from the outermost moraine (MOSCA-1) and two from the ridge closest to the lake  
367 (MOSCA-6 and MOSCA-7). **The quartz content in sample MOSCA-1 was too low for**  
368 **<sup>10</sup>Be extraction and was considered non-suitable for further analyses.**

369 A bedrock step above the lake was sampled (MOSCA-3). Large boulders within fine-  
370 grained matrix are distributed **on this step**. In contrast to the majority of moraines in the  
371 Sierra Nevada, composed of abundant fine sediments due to the weathering of the  
372 micaschists (Gómez-Ortiz et al, 2012; Palacios et al., 2016), this ridge preserved metric-  
373 size boulders. However, most of them were intensely fractured by frost shattering after  
374 their deposition, and only one sample from this landform was collected (MOSCA-5).

375 Overlapping this ridge, there is a moraine including both boulders and fine sediments.  
376 One boulder from this ridge was sampled, whose surface showed glacial striations  
377 ensuring that it has not undergone major degradation since its deposition (MOSCA-4).

378 Above this ridge, there is a large area with a massive accumulation of boulders that  
379 corresponds to a large moraine system composed of several ridges. Due to the steep slope,  
380 the shape of some of these ridges has been altered by rock falls and slope readjustment,  
381 though they still show an arcuate morphology. All these moraines seem to be affected by  
382 slow flow of the surface sediments towards the base of the cirque, likely due to the  
383 presence of buried ice and permafrost patches such as those detected and monitored in  
384 the neighbouring Veleta cirque (Gómez-Ortiz et al., 2015; 2019). There are several

385 depressions of collapse and subsidence features (Fig. 2) related to the degradation of the  
386 frozen mass located below the debris cover, which also affected the stability of the  
387 boulders. In addition, there are also abundant rocks fallen from the steep north wall of the  
388 Mulhacén, located only at less than 300 m from these deposits. Consequently, it was  
389 difficult to find boulders suitable for CRE dating and indicative of the age of stabilization  
390 of this moraine system. In fact, only one likely appropriate boulder in an external ridge  
391 was sampled (MOSCA-8).

392 According to historical sources (Gómez-Ortiz et al., 2009, 2015, 2018), the LIA glacier  
393 did not reach these outermost moraines and only occupied the innermost moraine systems  
394 closer to the northern Mulhacén rock wall, which is very active supplying debris to the  
395 talus cones. Currently, an active protalus lobe at the foot of the rock wall indicates the  
396 occurrence of permafrost conditions at this site.

#### 397 *4.2 CRE results*

398 As usual, we highly recommend using only the internal (analytical) errors, when the  $^{10}\text{Be}$   
399 ages are compared amongst them (at the study site and at the other sites), because they  
400 are all equally impacted by the production rate uncertainty – the production rate  
401 uncertainty has to be considered when the  $^{10}\text{Be}$  ages are compared to other chronological  
402 data.

403 The CRE results are presented in Table 2, and Figs. 6 and 7. The two samples from  
404 polished bedrock lead to indistinguishable CRE ages:  $13.5 \pm 0.8$  ka (MOSCA-2) and  $14.2$   
405  $\pm 0.8$  (MOSCA-3). Assuming that the age of the bedrock samples reveals the age of the  
406 final ice retreat in the mouth of the cirque, this leads to a mean CRE age of  $13.8 \pm 0.8$  ka  
407 (n=2).

408 The two samples from the moraine just below La Mosca Lake yielded to CRE ages of  
409  $12.6 \pm 0.9$  ka (MOSCA-6) and  $16.4 \pm 1.1$  ka (MOSCA-7). Therefore, although from the  
410 same moraine, one boulder leads to an age 1.6 ka younger than the age of the bedrock  
411 surface where it rests, whereas the other leads to an age 2.2 ka older, respectively.  
412 Considering that the exposure age of the sample MOSCA-7 is older than that of the  
413 bedrock where it rests, it can be considered an outlier.

414 The samples taken above the lake - one located in a moraine of one of the lower ridges  
415 (MOSCA-4,  $9.8 \pm 0.8$  ka) and the other in a moraine of one of the highest ridges

416 (MOSCA-8,  $10.2 \pm 0.7$  ka) - lead to indistinguishable CRE ages whose mean value is  
417  $10.0 \pm 0.7$  ka ( $n = 2$ ). The deposition of these boulders resulted from different glacial  
418 events separated by only a few hundred years. The sample taken from the ridge formed  
419 by large boulders, located above the lake, leads to a CRE age of  $23.4 \pm 1.5$  ka (MOSCA-  
420 5). Significantly older than the landforms located more distant from the cirque wall (mean  
421 CRE age of  $14.1 \pm 0.9$  ka ( $n=4$ )), this age is inconsistent with the geomorphological  
422 sequence, probably due to nuclide inheritance.

## 423 **5. Discussion**

424 The results obtained in this work provide an approximate **chronology** of glacial retreat in  
425 the Mulhacén cirque, located at the foot of the highest peak in the Iberian Peninsula. The  
426 scarce number of landforms suitable to be sampled for the application of CRE dating  
427 impeded providing an accurate sequence of glacial oscillations for the transition from the  
428 Late Glacial to the Early Holocene, when most of the cirque became ice-free. This is due  
429 to the very intense geomorphological processes of the northern wall of the Mulhacén,  
430 with intense rock fall activity generating large talus cones that have covered some of the  
431 most recent moraines. In addition, the micaschist bedrock fractures very easily and it is  
432 therefore very difficult to find original glacial surfaces in boulders or bedrock outcrops.

### 433 *5.1 Sequence of geomorphological phases in the Mulhacén cirque*

434 Despite the small number of available samples to which the CRE dating method can be  
435 applied with confidence, the combination of the results obtained in this study with those  
436 from previous studies points to the occurrence of a number of geomorphological phases  
437 inside the Mulhacén cirque ([Table 2](#), and [Fig. 6 and 7](#)):

438 (i) The deglaciation of most of the cirque culminated approximately at 14 ka – including  
439 the area where La Mosca Lake is located –, which is related to the Bølling-Allerød  
440 Interstadial (B-A; 14.6-12.9 ka; GI-1 Greenland ice cores; [Rasmussen et al., 2014](#)). These  
441 results are compatible with the previous study that suggested that lake sedimentation  
442 started before 8.4 cal ka BP ([Manzano et al., 2019](#)).

443 (ii) Other published works focusing on La Mosca Lake sediments reported glacial  
444 oscillations during the Late Holocene. Three coarse-grained layers deposited in the lake  
445 bottom were interpreted as indicating the existence of a glacier in the catchment at 2.8-  
446 2.7, 1.4-1.2 and 0.51-0.24 ka cal BP ([Oliva and Gómez-Ortiz, 2012](#)). The presence of a  
447 glacier during the LIA in this cirque was also confirmed by historical sources ([Gómez-](#)

448 [Ortiz et al., 2009, 2015, 2018](#)). Our results show that the extent of these palaeoglaciers  
449 was spatially limited, with small features only located at the base of the wall in the  
450 concavities that are currently occupied by talus cones. According to our results, the last  
451 Early Holocene glacial advance that generated moraines reached a distance of only 300  
452 m from the foot of the wall.

453 (iii) The set of moraines located between the talus cones and the lake, with up to 6  
454 different ridges in less than 400 m, is indicative of repeated glacier advances and retreats  
455 in the early stages of the Holocene, towards ca. 10 ka. These Early Holocene glaciers had  
456 a significant debris cover provided by the northern rock wall of the Mulhacén cirque.  
457 Indeed, the abundance of boulders across this moraine system shows evidence of the very  
458 high debris supply on palaeoglaciers from the rock wall. During their retreat, the ice  
459 gradually melted leaving multiple collapse depressions.

460 The age difference between the samples that mark the deglaciation of the mouth of the  
461 cirque during the B-A Interstadial, and those of the moraines deposited at the bottom of  
462 the cirque during the Holocene, was also shown in a previous work ([Oliva et al., 2015](#))  
463 by the application of Schmidt Hammer Exposure Dating, with higher rebound (R values)  
464 indicative of less weathered surfaces and thus younger ages. The moraine that led to a  
465  $^{10}\text{Be}$  CRE age of 14 ka coincided with an R value of  $55 \pm 4$ , whereas the R values in the  
466 10 ka ridge were higher,  $64 \pm 6$  ([Oliva et al., 2015](#)).

467 (iv) There are some samples that show evidence of cosmogenic nuclide inheritance. In  
468 fact, the outlier sample MOSCA-5 is related to the unique moraine formed by large  
469 boulders with no fine-grained sediments. The overestimated exposure age may be related  
470 to boulders fallen from the wall and transported supraglacially on the ice surface with no  
471 or very little surface readjustment. This process has earlier been inferred in other  
472 mountain cirques, especially in small ones with limited distance between the headwall  
473 and the moraines ([Li et al. 2016](#); [Çiner et al, 2017](#); [Köse et al., 2019](#)).

474 (v) According to our results, there is no evidence of glacial activity during the Holocene  
475 Thermal Maximum (HTM: 9-5 ka, [Renssen et al., 2009](#)) in this cirque.

476 (vi) The current intense geomorphological activity of the rock wall is shown by the  
477 formation of large rock fall cones and talus since the disappearance of the LIA glacier.  
478 These rock fall cones are underlain by permafrost, as it is demonstrated by the recent  
479 development of a protalus lobe at the foot of such rock wall ([Serrano et al., 2018](#)).



480 *5.2 Common and diverse geomorphological phases in the Sierra Nevada cirques and*  
481 *their palaeoclimatic and topographic significance.*

482 In the Sierra Nevada, there is remnant evidence of two Late Pleistocene glacial cycles  
483 that are preserved in the form of moraine complexes in the southern valleys of the massif.  
484 During the last glacial cycle, the maximum ice extent slightly predated the LGM, as it has  
485 been shown by CRE dating of boulders from lateral moraines from the largest glacial  
486 valleys (Gómez-Ortiz et al., 2012; 2015; Palacios et al., 2016; 2019; Oliva et al., 2019).  
487 Moreover, the sequence of glacial phases inferred from several other cirques in the Sierra  
488 Nevada (Gómez-Ortiz et al., 2012; 2015; Palacios et al., 2016; 2019; Oliva et al., 2019)  
489 show a similar sequence of the last deglaciation to the one presented here from the  
490 Mulhacén cirque, whose main phases have been summarized in Table 3. It is important  
491 to consider that glacial cirques do not always form at the head of the valleys, such as in  
492 the Sierra Nevada where many develop on lateral slopes of the main valley more  
493 favourable for snow accumulation, especially on E- or NE-facing slopes.

494 Several common spatio-temporal patterns can be inferred with regards to the deglaciation  
495 evolution in cirques of the Sierra Nevada (Table 3 and Fig. 7):

496 (i) All the cirques studied in the Sierra Nevada were deglaciated at the beginning of the  
497 B-A, although glaciers either remained as small features or regenerated during the  
498 following cold phases. Six of the eight cirques studied Sierra Nevada show  
499 indistinguishable deglaciation ages based on samples obtained from polished bedrock  
500 surfaces, with an average of  $14.0 \pm 1.2$  ka (n=6) (samples from Palacios et al., 2016 and  
501 present work) (Fig. 7 and 8A). Therefore, these datasets suggest that shortly after the  
502 onset of the B-A the valley floors were ice-free and glaciers were confined within the  
503 cirques as small features at the foot of the highest rock walls and probably disappeared  
504 from many others (Fig. 8B and C).

505 (ii) There are only two cirques (Río Seco and Caldereta) including samples of polished  
506 bedrock surfaces that suggest a more recent deglaciation ( $12.0 \pm 1.1$  ka, n= 3) (Palacios  
507 et al., 2016). They do not preserve evidence of later moraine formations or the  
508 development of large rock glaciers. These younger ages would reveal the presence of  
509 glaciers after the main deglaciation at the bottom of the cirque, as in other cirques, but  
510 they did not generate moraines or rock glaciers when the ice melted, most likely due to  
511 the low debris supply from relatively stable rock walls.

512 (iii) In most cases, after the most important deglaciation phase following the LLGM,  
513 glaciers persisted in the cirques, or they regenerated during the YD (Fig. 8.D). Some inner  
514 moraines in the cirques have a stabilization age similar (considering their uncertainties)  
515 to polished bedrock surfaces, with an average age of  $11.4 \pm 1.0$  ka (n= 6) (Palacios et al.,  
516 2016 and present work).

517 (iv) The importance of topographical constraints controlling the geomorphological  
518 evolution in each cirque of the Sierra Nevada after its final deglaciation at the end of the  
519 YD. Moreover, the topographical conditions of each cirque favoured the generation of  
520 different type of landforms:

521 a) The cirques with summit altitudes >3300 m and floors > 2950 m, north exposed  
522 and with cirque walls > 300 m high were the most climatically sensitive considering  
523 the geomorphological setting. They include evidence of glacier changes from the YD  
524 to the present. This is the case of the Veleta and Mulhacén cirques. But it is  
525 noteworthy that each one evolved differently: in the case of the Veleta cirque, a large  
526 polygenic moraine was formed (Gómez-Ortiz et al., 2009; 2012, 2015; Palacios et al.,  
527 2019) (Fig. 8E.4), whereas in the Mulhacén cirque a sequence of moraine ridges  
528 developed (Fig. 8E.5). During the HTM glaciers probably melted away in these  
529 cirques, but regenerated under the cold Neoglacial conditions prevailing during the  
530 Late Holocene, namely during the LIA (Gómez-Ortiz et al., 2009; 2012, 2015, 2018;  
531 Oliva and Gómez-Ortiz, 2012; Palacios et al., 2016). These Neoglacial advances  
532 enlarged the polygenic moraine in the Veleta cirque, and must have generated new  
533 moraine ridges in the Mulhacén cirque. However, the very intense geomorphological  
534 processes of the Mulhacén wall accumulating large masses of debris at the foot of the  
535 steep slope of the cirque and the readjustment of the moraine boulders have hidden  
536 the associated evidence.

537 b) Cirques with summit altitudes between 3000 and 3200 m, floors located above  
538 2800 m, with small headwalls (elevation range < 200 m) and east-facing produced  
539 only small proto-rock glaciers. This is the case of the Peñón Colorado, Río Seco and  
540 Caldereta cirques. In these cirques, where proto-rock glaciers developed, their fronts  
541 stabilized shortly after they formed (Fig. 8E.1).

542 c) In cirques with summit altitudes < 3000 m and floors below 2800 m, the retreating  
543 glaciers left one or more moraines – or even none – depending on the intensity of the

544 paraglacial readjustment of their walls rather than the climate oscillations, and no rock  
545 glaciers formed. This is the case of the Hoya de la Mora, Mojón de Trigo and Moro  
546 cirques (Fig. 8.E.3). These moraines are located between 400-700 m away from the  
547 cirque walls, showing evidence of the small size of the YD glaciers.

548 (v) Except in the case of the Veleta and Mulhacén cirques, the landscape of the rest of the  
549 cirques is similar to that existing during the HTM. No new glacial landforms have formed  
550 since and they have been affected only by limited periglacial and slope processes during  
551 Late Holocene cold phases (Oliva, 2009; Oliva and Gómez-Ortiz, 2012; Oliva et al., 2010;  
552 2011 and 2020).

553 (vi) Based on the evolution and chronology of the Sierra Nevada glacial cirques, we  
554 assume that the origin of the rock glaciers they host are related to the process of  
555 deglaciation that occurred at the beginning of warm periods in connection with  
556 paraglacial processes which triggered an intense geomorphological activity of the rock  
557 walls (Kleman and Stroeven, 1997; Ballantyne, 2002; 2013, Knight et al., 2018; Serrano  
558 et al., 2018).

559 (vii) As in other cirques of the Sierra Nevada at the end of the Late Pleistocene glacial  
560 phases, the end of Neoglaciation with the disappearance of the LIA glaciers has favoured  
561 the development of a small rock glacier in the Veleta cirque (Gómez-Ortiz et al., 2015;  
562 2019) and a protalus lobe in the Mulhacén cirque (Serrano et al., 2018), where small  
563 isolated permafrost patches exist under the debris cover (Oliva et al., 2018; Serrano et al.,  
564 2018). These landforms are geoindicators of the end of cold periods and are out of balance  
565 with current climate conditions, and therefore, tend to become inactive (Oliva et al., 2018;  
566 Gómez-Ortiz et al., 2019).

### 567 *5.3 The typology of the cirques in Sierra Nevada in the context of the Iberian Peninsula*

568 Studies similar to those conducted in the Sierra Nevada have been carried out in other  
569 Iberian mountain ranges, although most of them focused on individual cirques, with the  
570 exception of some studies in the Pyrenees. The chronology of formation of different  
571 landforms in the cirques of the Sierra Nevada is highly similar to the periods of formation  
572 of analogous geomorphological features in other Iberian cirques (Table 4).

573 (i) Based on the available literature, we have analyzed a total of 26 Iberian cirques, where  
574 the maximum and minimum CRE ages of deglaciation at their mouth vary from  $16.3 \pm$

575 3.3 ka to  $13.2 \pm 0.7$  ka, considering either the time of stabilization of external moraines,  
576 or the outcropping of the bedrock due to the disappearance of the ice (Table 4). The  
577 average age of deglaciation taking into account all these cirques is  $15.1 \pm 1.3$  ka ( $n = 21$ )  
578 (Table 4 and Fig.9.A). According to marine and terrestrial records from the Iberian  
579 Peninsula and surrounding areas (Fletcher et al., 2010a, 2010b, Moreno et al., 2014;  
580 López-Sáez, et al., 2020), a sudden temperature increase that led to values similar to  
581 present is recorded at the beginning of B-A. The accelerated deglaciation of the cirques  
582 probably during the B-A has been detected in many other cirques in Iberian mountains  
583 (Palacios et al., 2017b), such as the Central Range (Palacios et al., 2011; Palacios et al.,  
584 2012a, 2012b; Carrasco et al., 2015), Iberian Range (Fernández-Fernández et al., 2017;  
585 García-Ruiz et al., 2020a), Central Cantabrian Mountains (Rodríguez-Rodríguez et al.,  
586 2017) and the Pyrenees (Pallàs et al., 2006, 2010; Delmas, 2015; Palacios et al., 2017a;  
587 Crest et al., 2017; Tomkins et al., 2018; Andrés et al., 2019; Jomelli et al., 2020).

588 (ii) Although they still need to be studied in much more detail, YD glaciers existed within  
589 the cirques of other Iberian mountain ranges (García-Ruiz et al., 2016). There are few  
590 studies on YD related moraines in the in the Pyrenees (Pallàs et al., 2006; Crest et al.,  
591 2017; Palacios et al., 2017a; Andrés et al., 2019) and one in the Central Range (Carrasco  
592 et al., 2015). However, dating of bedrock surfaces in nine other cirques shows that  
593 glaciers occupied the bottom of the cirques until the beginning of the Holocene (Palacios  
594 et al., 2011, 2012b, 2017a; García-Ruiz et al., 2020a; Crest et al., 2017 Andrés et al.,  
595 2019; Jomelli et al., 2020). Although the age of the bedrock surfaces and the moraines  
596 resting on them suggest the occurrence of different glacial phases, in this global analysis  
597 the mean of the two types of ages can be interpreted as indicative of the final ice  
598 disappearance from the cirques. The average age of the deglaciation of all these cirques  
599 is 11.2 ka ( $n=17$ ), which fits within the onset of the Holocene, once temperatures  
600 increased following the YD (Table 4 and Fig.9.A). In the rest of the cirques, there is a  
601 lack of information on the glacial impact of the YD due to lack of dating or because the  
602 bottoms are still occupied by rock glaciers. According to the 9 cirques with dated  
603 moraines, the glaciers in the YD never exceeded the limits of the cirque, with lengths  
604 between 500 and 1200 m (Table 4). The abrupt warming after the YD cold period is  
605 evidenced in marine and terrestrial records of the regional Iberian context (Fletcher et al.,  
606 2010a, 2010b, Moreno et al., 2014; García-Ruiz et al., 2016; López-Sáez, et al., 2020).

607 (iii) In some cases, boulder exposure ages from the front of the rock glaciers are provided.  
608 It is assumed that these ages represent the melting of the interstitial ice, i.e. the  
609 stabilization of the rock glacier fronts (Zasadni et al., 2020). In six cirques, rock glaciers  
610 likely stabilized somewhat before or at the start of the B-A Interstadial (Rodríguez-  
611 Rodríguez et al., 2016, 2017; Andrés et al, 2019; García-Ruiz et al., 2020a), but the roots  
612 of the large rock glacier complexes stabilized during the Middle to Late Holocene  
613 (Palacios et al., 2017a; Andrés et al, 2019; Jomelli et al., 2020). The stabilization periods  
614 (onset, duration and ending) of two debris-covered glaciers from the Iberian Range were  
615 determined by the aspect, and hence by solar radiation. They range from the beginning of  
616 the B-A to the Middle Holocene (Fernández-Fernández et al., 2017) (Table 4).

617 (iv) Neoglacial landforms are located in cirque floors only at the foot of the northern face  
618 of peaks above 3000 m in the Central Pyrenees (García-Ruiz et al., 2014; 2020b).

619 (v) In summary, in all highest Iberian mountains geomorphological features similar to  
620 those in the Sierra Nevada cirques have been observed, regarding both type and  
621 development period. The deglaciation of the cirques started at the beginning of the B-A  
622 and new glaciers developed during the YD. Following the glacial retreat at the onset of  
623 the B-A, as well as during the Early Holocene, shrinking glaciers triggered the formation  
624 of rock glaciers in areas of high sediment supply (e.g. at the foot of steep rock walls),  
625 with their fronts stabilizing shortly after forming. The sediment supply of the cirques  
626 depends on the rock types (see Table 4), but also on the persistence of weathered substrate  
627 of the cirque rock wall, especially in granitic areas (Palacios et al., 2017a; Andrés et al.,  
628 2019).

#### 629 *5.4 Diversity of landforms associated with cirque deglaciation in the Northern* 630 *Hemisphere*

631 In order to explore if the geomorphological evolution within glacial cirques in the Sierra  
632 Nevada and other Iberian ranges represents a local or a more widespread climatic pattern,  
633 we have examined dozens of glacial cirques in the Northern Hemisphere where CRE data  
634 are available. To this end, we have analysed chronological data from cirques from the  
635 Mediterranean region, Central Europe, the British Isles and subpolar regions. We have  
636 also included the analysis of numerous cirques in the western United States where precise  
637 chronologies are available (Marcott et al., 2019).

638 (i) Located between 31 and 37° N, 11 Mediterranean cirques from the Anatolian and  
639 Balkan peninsulas and north Morocco **benefitting from new detailed** CRE chronology  
640 were analysed (Table 5). Eight of the 11 cirques include chronological data on their initial  
641 deglaciation. All of them became ice-free at an averaged CRE age of  $14.1 \pm 1.4$  ka (n=8),  
642 in consistency with the findings from Iberia (Table 5, Fig. 9.B) (Köse et al., 2019;  
643 Sarıkaya et al., 2017; Styllas et al., 2018; Hughes et al., 2018; Žebre et al., 2019). Seven  
644 cirques include moraine ridges inside the cirques, five of which formed during the YD  
645 (Köse et al., 2019; Sarıkaya et al., 2017; Styllas et al., 2018; Hughes et al., 2018; Žebre  
646 et al., 2019). Only a few limestone cirques in the Anatolian peninsula reported  
647 significantly younger moraine ages (Sarıkaya et al., 2017). With the exception of these  
648 excluded cases, the average CRE age of these moraines is  $12.0 \pm 0.8$  ka (n=8) (Table 5,  
649 Fig. 9.B) and the glacier lengths ranged from 700 to 2500 m. There are only some CRE-  
650 dated rock glaciers in this region. Evidencing cosmogenic nuclide inheritance, they were  
651 not included in our analysis (Çiner et al., 2017). Neoglacial landforms appear only in  
652 cirques with peaks near 3000 m (Styllas et al., 2018), with the exception of Anatolia  
653 (Sarıkaya et al., 2017).

654 (ii) 17 cirques from Central Europe mountains located between 45° and 50° N were  
655 analysed (Table 6). Most of them are situated in the **Carpathian** Mountains, only two  
656 being low-altitude cirques from the Alps. In the Central Alps, the YD glaciers were  
657 beyond the cirque area and, hence, they are not considered in our analysis. Up to 15  
658 cirques include moraines with CRE ages ranging from  $15.5 \pm 0.4$  to  $13.2 \pm 1.0$  ka, leading  
659 to an averaged CRE age of  $14.7 \pm 0.9$  ka (n=14) (Table 6, Fig. 9C) (Engel et al., 2014,  
660 2017; Gheorghiu et al., 2015; Makos et al., 2018; Zasadni et al., 2020). Their stabilization  
661 might be related to the beginning of the B-A. Only 6 cirques included **moraine** formation  
662 during the YD/Early Holocene transition, whose CRE ages range between  $12.0 \pm 1.1$  and  
663  $10.9 \pm 0.6$  ka, leading to an averaged CRE age of  $11.6 \pm 0.7$  ka (n=6) (Table 6, Fig. 9.C)  
664 (Engel et al., 2017; Gheorghiu et al., 2015; Makos et al., 2018). **The YD glaciers had**  
665 **limited areas, with lengths between 500 and 800 m.** 6 cirques do not host YD moraines,  
666 but include rock glaciers, whose fronts stabilized at CRE ages ranging from  $12.9 \pm 0.7$  to  
667  $10.9 \pm 1.0$  ka, also during the YD/Early Holocene transition (Moran et al., 2016; Zasadni  
668 et al., 2020) (Table 6). There is no evidence of Neoglacial landforms.

669 (iii) Six cirques from the British Isles and three from northern Iceland were analyzed  
670 (Table 7). Only three British cirques provide information regarding their initial

671 deglaciation. They became ice-free prior to or during the B-A at an average age of  $15.2 \pm$   
672  $1.1$  ka (n=3) (Table 7, Fig. 9D) (Barth et al., 2018). Four British and two Icelandic cirques  
673 host moraines whose stabilization ages range from  $12.0 \pm 0.9$  to  $10.7 \pm 1.0$  ka, leading to  
674 an average age of  $11.6 \pm 1.1$  ka (n=6) (Table 7, Fig. 9D). Therefore, they probably formed  
675 during the YD (Barth et al., 2018; Hughes et al., 2019; Fernández-Fernández et al., 2020).  
676 The British YD cirque glaciers were between 300 and 950 m long while the Icelandic  
677 ones were longer, between 1500 and 3000 m. The stabilization of one rock glacier has  
678 been dated in Britain at  $12.5 \pm 1.1$  ka (n=5; Barth et al., 2018) and two others in Iceland  
679 lead to a reported average age of  $10.1 \pm 1.0$  ka (n=4; Fernández-Fernández et al., 2020).

680 (iv) Until very recently, chronological data about the formation of landforms inside  
681 glacial cirques from North America was very limited, but a recent study provides  
682 information about cirques from the Western United States (Marcott et al., 2019). Located  
683 between  $35^\circ$  to  $47^\circ$  N, 12 cirques were examined (Table 8). Six of these cirques provide  
684 deglaciation ages based on the chronology of the stabilization of their moraines that  
685 occurred during the B-A, their ages between  $15.2 \pm 0.7$  and  $13.4 \pm 0.7$  ka lead to an  
686 average age of  $14.4 \pm 0.8$  ka (n=6) (Table 8, Fig. 9E) (Marcott et al., 2019). Eight of the  
687 American cirques have internal moraines whose ages between  $12.8 \pm 0.7$  and  $10.7 \pm 0.6$   
688 ka lead to an average age of  $12.0 \pm 0.7$  ka (n=8) likely corresponding to the YD (Table 8,  
689 Fig. 9.E) (Marcott et al., 2019). These YD glaciers were between 700 and 2800 m long.  
690 Three of these cirques have rock glaciers whose ages of stabilization range between  $10.5$   
691  $\pm 0.6$  and  $9.6 \pm 0.5$  ka (Marcott et al., 2019).

692 (v) The comparison of the different deglaciation chronologies and of the development of  
693 rock glaciers allows inferring if there is a synchronic pattern across the Northern  
694 Hemisphere. The comparison of all the averaged ages of the rock glacier front  
695 stabilization reveals that they chronologically coincide with phases following the  
696 deglaciation of these cirques, i.e. fifteen of them (average age:  $10.8 \pm 0.7$  ka) after the  
697 YD, and 5 of them (average age:  $15.4 \pm 1.5$  ka) with the end of the OD (Table 3, 4, 5, 6,  
698 7 and 8 and Fig. 9.F). Since most of the analysed cirques were deglaciated after the YD,  
699 most of the rock glacier fronts stabilized shortly thereafter, around 1 ka after deglaciation  
700 (Palacios et al., 2016; Moran et al., 2016; Palacios et al., 2017a; Fernández-Fernández et  
701 al., 2020; Marcott et al., 2019; Zasadni et al., 2020).

702 (vi) Based on the typology and age of the landforms observed inside the cirques in the  
703 mid-latitude mountains of the Northern Hemisphere, we concluded that the

704 geomorphological dynamics of all these cirques were similar to those studied in the Sierra  
705 Nevada and in the rest of the Iberian Peninsula (Fig. 10). As in the Sierra Nevada, the  
706 diversity of geomorphic landforms in each cirque depends on the local topographic  
707 characteristics of the altitude of its summits and floors as well as on its orientation and  
708 prevailing lithology. However, most of the moraine systems and rock glaciers distributed  
709 inside glacial cirques formed during the same climatic phases throughout the Hemisphere,  
710 from the Last Termination to the present.

711 In fact, two distinct geomorphological phases are clearly linked to the warm phases during  
712 the Last Termination in the Northern Hemisphere: (i) The glacier margins receded from  
713 the mouth of the cirques – generating in many cases moraines – during the climate  
714 oscillations of the OD and the B-A transition; (ii) in most cirques, the glaciers expanded  
715 or remained during the YD and generated moraines within the limits of the cirques. These  
716 glaciers retreated up-valley and abandoned their moraines at the onset of the Holocene,  
717 when rock glacier fronts stabilized (Fig. 10).

## 718 6. Conclusions

719 This work provides robust evidence that glacial cirques reflect the climatic conditions  
720 prevailing during their formation (Benedict, 1973; Dahl and Nesje, 1992; Delmas et al.,  
721 2015; Barr et al., 2017; Barr and Spagnolo, 2015; Ipsen et al., 2018), and also preserve  
722 very valuable information on the climatic and geomorphological evolution that occurred  
723 during their deglaciation:

724 (i) All the examined cirques were deglaciated during the OD and the B-A transition. There  
725 are no geomorphic remnants in none of the examined cirques of the Northern Hemisphere  
726 supporting the existence of glaciers during the B-A. Although survival of glaciers through  
727 the B-A in the cirques is fully possible, it is not proven. While glaciers retreated during  
728 the OD and B-A transition in many cirques, in others the glaciers evolved into rock  
729 glaciers but their fronts stabilized soon after their formation.

730 (ii) There is widespread evidence of the existence of glaciers during the YD in many  
731 cirques, as shown by: (i) the age of glacier retreat revealed by the age of polished bedrock  
732 surfaces, and (ii) the age of moraine boulders stabilization. In both cases, results provide  
733 ages spanning the late YD and early Holocene.

734 (iii) The retreat of YD glaciers generated a wide variety of landforms within each cirque:  
735 (a) Sometimes, after the glaciers disappeared, only polished surfaces remained. This is a



736 widespread pattern in Iberian mountains, and probably in other mid-latitude mountains,  
737 although in other regions there are very few studies that have dated bedrock surfaces  
738 located at the bottom of the cirques. (b) In other cases, following the melting of glaciers,  
739 moraines rapidly stabilized. (c) Moraines did not form in many cirques, but the retreat of  
740 YD glaciers favoured the development of rock glaciers. In many cases, their fronts  
741 stabilized shortly after their formation, even in less than 1 ka (Zasadni et al., 2020). (d)  
742 In other cases, debris-covered glaciers could also form. In fact, many of the analysed rock  
743 glaciers may have originated from debris covered glaciers formed in previous phases of  
744 the long-term deglaciation process (Anderson et al., 2018). The detailed study conducted  
745 on the wide variety of cirques in the Sierra Nevada provided information about the  
746 topographical setting that determined every type of evolution. Similar studies should be  
747 done in other mountain systems to better determine every single type of  
748 geomorphological evolution and infer the role of climate, topography and lithology in  
749 their evolution.

750 (iv) In most cirques, no major changes have occurred on geomorphological dynamics  
751 since the HTM. Landscapes have only undergone minor transformations related to  
752 periglacial and slope processes. Neoglacial landforms only developed in the highest  
753 mountains, such as in the case of the Sierra Nevada, where glaciers developed in cirques  
754 with summits exceeding 3300 m. The diversity of cirque landforms depends on local  
755 conditions and, above all, on the geomorphological activity of their headwalls. In some  
756 cases, the retreat of small Neoglacial ice masses triggered the formation of incipient rock  
757 glaciers.

758 (v) This study highlights that the formation of rock glaciers inside the cirques is triggered  
759 by the onset of warm phases that accelerate the retreat of glaciers. Therefore, they are  
760 more associated with the paraglacial readjustment following glacial retreat (Ballantyne,  
761 2002) rather than with a periglacial origin driven by very cold temperatures. This explains  
762 the rapid stabilization of their fronts once the internal frozen body disappears (Gómez-  
763 Ortiz et al., 2014).

764 Glacial cirques have been shown to be highly climatically sensitive areas where small  
765 changes favoured the development or disappearance of glaciers. In addition, the activity  
766 of their walls is critical to generate a great variety of landforms, depending on their  
767 topographic characteristics. Glacial cirques are, therefore, a valuable source of

768 palaeoenvironmental information to better understand the landscape evolution of  
769 mountain systems since the last deglaciation to recent times.

## 770 Acknowledgements

771 This research article was supported by the project CGL2015-65813-R (Spanish Ministry  
772 of Economy and Competitiveness) and NUNANTAR (02/SAICT/2017 – 32002;  
773 Fundação para a Ciência e a Tecnologia, Portugal). It also complements the research  
774 topics examined in the project PALAEOGREEN (CTM2017-87976-P; Spanish Ministry  
775 of Economy and Competitiveness). The <sup>10</sup>Be measurements were performed at the  
776 ASTER AMS national facility (CEREGE, Aix-en-Provence), which is supported by the  
777 INSU/CNRS and the ANR through the “Projets thématiques d'excellence” program for  
778 the “Equipements d'excellence” ASTER-CEREGE action and IRD. Marc Oliva is  
779 supported by the Ramón y Cajal Program (RYC-2015-17597) and the Research Group  
780 ANTALP (Antarctic, Arctic, Alpine Environments; 2017-SGR-1102). The authors are  
781 deeply appreciative for the detailed analyses and excellent suggestions made by the two  
782 reviewers, Drs. Ian Evans and Philip Hughes, who helped to considerably improve many  
783 aspects of this work.

## 784 References

- 785 Anderson, R.S., Anderson, L.S., Armstrong, W.H., Rossi, M.W., Crump, S.E., 2018.  
786 Glaciation of alpine valleys: The glacier–debris-covered glacier–rock glacier  
787 continuum. *Geomorphology* 311, 127–142.  
788 <https://doi.org/10.1016/j.geomorph.2018.03.015>.
- 789 Anderson, R.S., Jiménez-Moreno, G., Carrión, J.S., Pérez-Martínez, C., 2011.  
790 Postglacial history of alpine vegetation, fire, and climate from Laguna de Río Seco,  
791 Sierra Nevada, southern Spain. *Quat. Sci. Rev.* 30, 1615–1629.  
792 <https://doi.org/10.1016/j.quascirev.2011.03.005>
- 793 Andrés, N., Gómez-Ortiz, A., Fernández-Fernández, J. M., Tanarro, L.M., Salvador, F.,  
794 Oliva, M., Palacios, D., 2019. Timing of deglaciation and rock glacier origin in  
795 the southeastern Pyrenees: a review and new data. *Boreas* 47, 1050–1071.  
796 <https://doi.org/10.1111/bor.12324>.
- 797 Arnold, M., Merchel, S., Bourlès, D.L., Braucher, R., Benedetti, L., Finkel, R.C.,  
798 Aumaître, G., Gott dang, A., Klein, M., 2010. The French accelerator mass  
799 spectrometry facility ASTER: Improved performance and developments. *Nuclear*  
800 *Instruments and Methods in Physics Research, Section B, Beam Interactions with*  
801 *Materials and Atoms*, 19th International Conference on Ion Beam Analysis 268,  
802 1954–1959. <https://doi.org/10.1016/j.nimb.2010.02.107>
- 803 Ballantyne, C.K. 2002. Paraglacial geomorphology. *Quaternary Science Reviews*, 21,  
804 1935–2017. [https://doi.org/10.1016/S0277-3791\(02\)00005-7](https://doi.org/10.1016/S0277-3791(02)00005-7)
- 805 Ballantyne, C.K., 2013. Paraglacial Geomorphology, in: *Encyclopedia of Quaternary*  
806 *Science: Second Edition*. Elsevier, pp. 553–565. [https://doi.org/10.1016/B978-0-](https://doi.org/10.1016/B978-0-444-53643-3.00089-3)  
807 [444-53643-3.00089-3](https://doi.org/10.1016/B978-0-444-53643-3.00089-3)

- 808 Baroni, C., Guidobaldi, G., Salvatore, M. C., Christl, M., Ivy-Ochs, S., 2018. Last  
809 glacial maximum glaciers in the Northern Apennines reflect primarily the influence  
810 of southerly storm-tracks in the western Mediterranean. *Quaternary Science*  
811 *Reviews* 197, 352–367. <https://doi.org/10.1016/j.quascirev.2018.07.003>.
- 812 Barr, I. D., Spagnolo, M. 2015. Glacial cirques as palaeoenvironmental indicators: Their  
813 potential and limitations. *Earth-science reviews*, 151, 48-78.  
814 <http://dx.doi.org/10.1016/j.earscirev.2015.10.004>
- 815 Barr, I. D., Ely, J. C., Spagnolo, M., Clark, C. D., Evans, I. S., Pellicer, X. M., ... & Rea,  
816 B. R. 2017. Climate patterns during former periods of mountain glaciation in  
817 Britain and Ireland: Inferences from the cirque record. *Palaeogeography,*  
818 *palaeoclimatology, palaeoecology*, 485, 466-475.  
819 <https://doi.org/10.1016/j.palaeo.2017.07.001>
- 820 Barth, A. M., Clark, P. U., Clark, J., McCabe, A. M., & Caffee, M. 2016. Last Glacial  
821 Maximum cirque glaciation in Ireland and implications for reconstructions of the  
822 Irish Ice Sheet. *Quaternary Science Reviews*, 141, 85-93.  
823 <https://doi.org/10.1016/j.quascirev.2016.04.006>
- 824 Barth, A. M., Clark, P. U., Clark, J., Roe, G. H., Marcott, S. A., McCabe, A. M., ... &  
825 Dunlop, P. 2018. Persistent millennial-scale glacier fluctuations in Ireland between  
826 24 ka and 10 ka. *Geology*, 46(2), 151-154. <https://doi.org/10.1130/G39796.1>
- 827 Benedict, J. B. 1973. Chronology of cirque glaciation, Colorado front range. *Quaternary*  
828 *Research*, 3(4), 584-599.
- 829 Benn, D.I., Evans, D.J.A., 2010. *Glaciers and Glaciation*. Hodder Education, London.
- 830 Braucher, R., Guillou, V., Bourlès, D.L., Arnold, M., Aumaître, G., Keddadouche, K.,  
831 Nottoli, E., 2015. Preparation of ASTER in-house  $^{10}\text{Be}/^9\text{Be}$  standard solutions.  
832 *Nuclear Instruments and Methods in Physics Research, Section B, Beam*  
833 *Interactions with Materials and Atoms, The Thirteenth Accelerator Mass*  
834 *Spectrometry Conference* 361, 335–340.  
835 <https://doi.org/10.1016/j.nimb.2015.06.012>
- 836 Carrasco, R.M., Pedraza, J., Dominguez-Villar, D., Willenbring, J.K., Villa, J., 2013.  
837 Supraglacial debris supply in the Cuerpo de Hombre palaeoglacier (Spanish  
838 Central System). Reconstruction and interpretation of a rock avalanche event.  
839 *Geogr. Ann. Ser. A Phys. Geogr.* 95, 211-266. <https://doi.org/10.1111/geoa.12010>
- 840 Carrasco R.M., Pedraza J., Dominguez-Villar D., Willenbring J.K., Villa J., 2015.  
841 Sequence and chronology of the Cuerpo de Hombre palaeoglacier (Iberian Central  
842 System) during the last glacial cycle. *Quat Sci Rev.* 129, 163–177.  
843 <https://doi.org/10.1016/j.quascirev.2015.09.021>
- 844 Carrasco, R.M, Pedraza, J., Willenbring, J. Karampaglidis, T., Soteres, R.L., Martín-  
845 Duque, J.F., 2016. Morfología glaciaria del Macizo de Los Pelados-El Nevero  
846 (Parque Nacional de la Sierra de Guadarrama). Nueva interpretación y cronología.  
847 *Bol. R. Soc. Esp. Hist. Nat. Sec. Geol.* 110, 49-66.
- 848 Çiner, A., Sarikaya, M.A., Yildirim, C., 2017. Misleading old age on a young landform?  
849 The dilemma of cosmogenic inheritance in surface exposure dating: Moraines vs.  
850 rock glaciers. *Quaternary Geochronology* 42, 76-88.  
851 <https://doi.org/10.1016/j.quageo.2017.07.003>
- 852 Chmeleff, J., von Blanckenburg, F., Kossert, K., Jakob, D., 2010. Determination of the  
853  $^{10}\text{Be}$  half-life by multicollector ICP-MS and liquid scintillation counting *Nuclear*  
854 *Instruments and Methods in Physics Research, Section B, Beam Interactions with*  
855 *Materials and Atoms* 268, 192–199. <https://doi.org/10.1016/j.nimb.2009.09.012>
- 856 Clark, D. H., Gillespie, A. R. 1997. Timing and significance of late-glacial and  
857 Holocene cirque glaciation in the Sierra Nevada, California. *Quaternary*

858 International, 38, 21-38. [https://doi.org/10.1016/S1040-6182\(96\)00024-9](https://doi.org/10.1016/S1040-6182(96)00024-9)

859 Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B.,  
860 Mitrovica, J.X., Hostetler, S.W., McCabe, A. 2009. The Last Glacial Maximum.  
861 Science 325, 710–714. 10.1126/science.1172873

862 Crest, Y., Delmas, M., Braucher, R., Gunnell, Y., Calvet, M., & Aster Team. 2017.  
863 Cirques have growth spurts during deglacial and interglacial periods: Evidence  
864 from <sup>10</sup>Be and <sup>26</sup>Al nuclide inventories in the central and eastern Pyrenees.  
865 Geomorphology, 278, 60-77. <http://dx.doi.org/10.1016/j.geomorph.2016.10.035>

866 CRONUS-Earth Web Calculators v2.0 2020: Available at:  
867 <http://cronus.cosmogenicnuclides.rocks/2.0/html/topo/> (accessed March 2020).

868 Dahl, S. O., Nesje, A. 1992. Palaeoclimatic implications based on equilibrium-line  
869 altitude depressions of reconstructed Younger Dryas and Holocene cirque glaciers  
870 in inner Nordfjord, western Norway. Palaeogeography, Palaeoclimatology,  
871 Palaeoecology, 94(1-4), 87-97. [https://doi.org/10.1016/0031-0182\(92\)90114-K](https://doi.org/10.1016/0031-0182(92)90114-K)

872 Deline, P., Akçar, N., Ivy-Ochs, S., Kubik, P.W., 2015. Repeated Holocene rock  
873 avalanches onto the Brenva Glacier, Mont Blanc massif, Italy: A chronology. Quat.  
874 Sci. Rev. 126, 186-200 <http://dx.doi.org/10.1016/j.quascirev.2015.09.004>

875 Delmas, M., 2015. The last maximum ice extent and subsequent deglaciation of the  
876 Pyrenees: an overview of recent research. Cuadernos de Investigación Geográfica  
877 41 (2), 359-387. <http://dx.doi.org/10.18172/cig.2708>

878 Delmas, M., Gunnell, Y., Calvet, M., 2015. A critical appraisal of allometric growth  
879 among alpine cirques based on multivariate statistics and spatial analysis.  
880 Geomorphology 228, 637–652. <https://doi.org/10.1016/j.geomorph.2014.10.021>

881 Domínguez-Villar, D., Carrasco, R.M., Pedraza, J., Cheng, H., Edwards, R.L.,  
882 Willenbring, J.K. 2013. Early maximum extent of palaeoglaciers from  
883 Mediterranean mountains during the last glaciation. Sci. Rep. 3, 2034.  
884 <https://doi.org/10.1038/srep02034>

885 Engel, Z., Braucher, R., Traczyk, A., & Laetitia, L. 2014. <sup>10</sup>Be exposure age chronology  
886 of the last glaciation in the Krkonoše Mountains, Central Europe. Geomorphology,  
887 206, 107-121. <http://dx.doi.org/10.1016/j.geomorph.2013.10.003>

888 Engel, Z., Mentlík, P., Braucher, R., Minár, J., Léanni, L., Aster Team 2015.  
889 Geomorphological evidence and <sup>10</sup>Be exposure ages for the Last Glacial  
890 Maximum and deglaciation of the Velká and Malá Studená dolina valleys in the  
891 High Tatra Mountains, central Europe. Quaternary Science Reviews, 124, 106-123.  
892 <http://dx.doi.org/10.1016/j.quascirev.2015.07.015>

893 Engel, Z., Braucher, R., Traczyk, A., & Laetitia, L. 2014. <sup>10</sup>Be exposure age chronology  
894 of the last glaciation in the Krkonoše Mountains, Central Europe. Geomorphology,  
895 206, 107-121. <https://doi.org/10.1016/j.geomorph.2013.10.003>

896 Evans, I.S., Cox, N.J., 1974. Geomorphometry and the operational definition of cirques.  
897 Area 6, 150–153.

898 Evans, I.S., Cox, N.J., 1995. The form of glacial cirques in the English Lake District,  
899 Cumbria. Z. Geomorphol. 39, 175–202.

900 Fernández-Fernández, J.M., Palacios, D., García-Ruiz, J.M., Andrés, N.,  
901 Schimmelpfennig, I., Gómez-Villar, A., Santos González, J., Álvarez-Martínez, J.,  
902 Arnáez, J., Úbeda, J., Léanni, L., ASTER Team, 2017. Chronological and  
903 geomorphological investigation of fossil debris-covered glaciers in relation to  
904 deglaciation processes: A case study in the Sierra de la Demanda, northern Spain.  
905 Quaternary Science Reviews 170, 232–249.  
906 <https://doi.org/10.1016/j.quascirev.2017.06.034>

907 Fernández-Fernández, J.M., Palacios, D., Andrés, N., Schimmelpfennig, I.,

- 908 Brynjólfsson, S., Sancho, L.G., Zamorano, J.J., Heiðmarsson, S., Sæmundsson, Þ.,  
 909 ASTER Team 2019. A multi-proxy approach to Late Holocene fluctuations of  
 910 Tungnahryggsjökull glaciers in the Tröllaskagi peninsula (northern Iceland)  
 911 Science of the Total Environment, 664, 499-517. Citations: 1.  
 912 <https://doi.org/10.1016/j.scitotenv.2019.01.364>
- 913 Fernández-Fernández, J.M., Palacios, D., Andrés, N., Schimmelpfennig, I., Tanarro,  
 914 L.M., Brynjólfsson, S., López-Acevedo, F.J., Sæmundsson, Þ., Team, A.S.T.E.R.,  
 915 2020. Constraints on the timing of debris-covered and rock glaciers: An  
 916 exploratory case study in the Hólar area, northern Iceland. *Geomorphology* 361,  
 917 107196. <https://doi.org/10.1016/j.geomorph.2020.107196>
- 918 Fletcher, W.J., Sánchez Goñi, M.F., Allen, J.R.M., Cheddadi, R., Cambourieu-Nebout,  
 919 N., Huntley, B., Lawson, I., Londeix, L., Magri, D., Margari, V., Muller, U.C.,  
 920 Naughton, F., Novenko, E., Roucoux, K., Tzedakis, P.C., 2010a. Millennial-scale  
 921 variability during the last glacial in vegetation records from Europe. *Quaternary*  
 922 *Science Reviews* 29 (21-22), 2839-2864.  
 923 <https://doi.org/10.1016/j.quascirev.2009.11.015>
- 924 Fletcher, W.J., Sánchez-Goñi, M.F., Peyron, O., Dormoy, I., 2010b. Abrupt climate  
 925 changes of the last deglaciation. Western Mediterranean forest record. *Climate of*  
 926 *the Past* 6, 245–264. <https://doi.org/10.5194/cp-6-245-2010>
- 927 García-Alix, A., Jimenez-Espejo, F.J., Lozano, J.A., Jiménez-Moreno, G., Martínez-  
 928 Ruiz, F., García Sanjuán, L., Aranda Jiménez, G., García Alfonso, E., Ruiz-  
 929 Puertas, G., Anderson, R.S., 2013. Anthropogenic impact and lead pollution  
 930 throughout the Holocene in Southern Iberia. *Sci. Total Environ.* 449, 451–460.  
 931 <https://doi.org/10.1016/j.scitotenv.2013.01.081>
- 932 García-Alix, A., Jiménez-Espejo, F.J., Toney, J.L., Jiménez-Moreno, G., Ramos-  
 933 Román, M.J., Anderson, R.S., Ruano, P., Queralt, I., Delgado Huertas, A., Kuroda,  
 934 J., 2017. Alpine bogs of southern Spain show human-induced environmental  
 935 change superimposed on long-term natural variations. *Sci. Rep.* 7, 1–12.  
 936 <https://doi.org/10.1038/s41598-017-07854-w>
- 937 García-Ruiz, J. M., Palacios, D., de Andrés, N., Valero-Garcés, B.L., López-Moreno,  
 938 J.I., Sanjuán, Y., 2014. Holocene and ‘little ice age’ glacial activity in the Marboré  
 939 cirque, Monte Perdido massif, central Spanish Pyrenees. *The Holocene* 24 (11),  
 940 1439–1452. <https://doi.org/10.1177/0959683614544053>.
- 941 García-Ruiz, J. M., Palacios, D., González-Sampériz, P., De Andrés, N., Moreno, A.,  
 942 Valero-Garcés, B., & Gómez-Villar, A. 2016. Mountain glacier evolution in the  
 943 Iberian Peninsula during the Younger Dryas. *Quaternary Science Reviews*, 138,  
 944 16-30. <https://doi.org/10.1016/j.quascirev.2016.02.022>
- 945 García-Ruiz, J.M., Palacios,D., Fernández-Fernández, J.M., Andrés, N. Arnáez, J.  
 946 Gómez-Villar A., Santos-González, J., Álvarez-Martínez, J., Lana-Renault, N.  
 947 Léanni, L. ASTER Team 2020a. Glacial stages in the Peña Negra valley, Iberian  
 948 Range, northern Iberian Peninsula: Assessing the importance of the glacial record  
 949 in small cirques in a marginal mountain area. *Geomorphology (revision)*.
- 950 García-Ruiz, J.M., Palacios,D., Andrés, N., López-Moreno,J.I., 2020b. Neoglaciation in  
 951 the Spanish Pyrenees: A multiproxy challenge. *Mediterranean Geoscience*  
 952 *Reviews*. <https://doi.org/10.1007/s42990-020-00022-9>
- 953 Gheorghiu, D. M., Hosu, M., Corpade, C., & Xu, S. 2015. Deglaciation constraints in  
 954 the Parâng Mountains, Southern Romania, using surface exposure dating.  
 955 *Quaternary International*, 388, 156-167.  
 956 <http://dx.doi.org/10.1016/j.quaint.2015.04.059>
- 957 Giraudi, C., 2012. The campo felice late pleistocene glaciation (Apennines, Central

- Italy). *J. Quat. Sci.* 27, 432e440. <https://doi.org/10.1002/jqs.1569>
- 959 Gómez-Ortiz, A., Palacios, D., Schulte, L., Salvador-Franch, F., Plana-Castellví, J.A.,  
 960 2009. Evidences from historical documents of landscape evolution after little ice  
 961 age of a mediterranean high mountain area, Sierra Nevada, Spain (eighteenth to  
 962 twentieth centuries). *Geogr. Ann. Ser. A Phys. Geogr.* 91, 279–289.  
 963 <https://doi.org/10.1111/j.1468-0459.2009.00370.x>
- 964 Gómez-Ortiz, A., Oliva, M., Salvador-Franch, F., Salvà-Catarineu, M., Plana-Castellví,  
 965 J.A., 2018. The geographical interest of historical documents to interpret the  
 966 scientific evolution of the glacier existing in the Veleta cirque (Sierra Nevada,  
 967 Spain) during the Little Ice Age. *Cuadernos de Investigación Geográfica* 44, 267–  
 968 292.
- 969 Gómez-Ortiz, A., Oliva, M., Salvador-Franch, F., Palacios, D., Tanarro, L.M., Sanjosé-  
 970 Blasco, J.J., Salvà-Catarineu, M., 2019. Monitoring permafrost and periglacial  
 971 processes in Sierra Nevada (Spain) from 2001 to 2016. *Permafr. Periglac. Process.*  
 972 <https://doi.org/10.1002/PPP.2002>
- 973 Gómez-Ortiz, A., Oliva, M., Palacios, D., Salvador-Franch, F., Vázquez-Selem, L.,  
 974 Salvà-Catarineu, M., De Andrés, N., 2015. The deglaciation of Sierra Nevada  
 975 (Spain), synthesis of the knowledge and new contributions. *Cuad. Investig.*  
 976 *Geográfica* 41, 409. <https://doi.org/10.18172/cig.2722>
- 977 Gómez-Ortiz, A., Palacios, D., Palade, B., Vázquez-Selem, L., Salvador-Franch, F.,  
 978 2012. The deglaciation of the Sierra Nevada (Southern Spain). *Geomorphology*  
 979 159–160, 93–105. <https://doi.org/10.1016/j.geomorph.2012.03.008>
- 980 Hippolyte, J.C., Bourlès, D., Braucher, R., Carcaillet, J., Léanni, L., Arnold, M.,  
 981 Aumaitre, G., 2009: Cosmogenic <sup>10</sup>Be dating of a sackung and its faulted rock  
 982 glaciers, in the Alps of Savoy (France). *Geomorphology* 108, 312-320  
 983 <http://www.springer.com/us/book/9783642800955>.
- 984 Hughes, P.D., Woodward, J.C., Gibbard, P.L., Macklin, M.G., Gilmour, M.A., Smith,  
 985 G.R., 2006. The glacial history of the Pindus Mountains, Greece. *J. Geol.* 114,  
 986 413–434. <https://doi.org/10.1086/504177>
- 987 Hughes, P.D., Gibbard, P.L., Woodward, J.C., 2007. Geological controls on Pleistocene  
 988 glaciation and cirque form in Greece. *Geomorphology* 88 (3), 242–253.  
 989 <https://doi.org/10.1016/j.geomorph.2006.11.008>
- 990 Hughes, P.D., Gibbard, P.L., Ehlers, J. 2013. Timing of glaciation during the last glacial  
 991 cycle: Evaluating the concept of a global ‘Last Glacial Maximum’ (LGM). *Earth-*  
 992 *Sci. Rev.* 125, 171–198. <https://doi.org/10.1016/j.earscirev.2013.07.003>
- 993 Hughes, P.D., Fink, D., Rodés, A., Fenton, C.R., Fujioka, T., 2018. Timing of  
 994 Pleistocene glaciations in the High Atlas, Morocco: New <sup>10</sup>Be and <sup>36</sup>Cl exposure  
 995 ages. *Quaternary Science Reviews*, 180, 193–213.  
 996 <https://doi.org/10.1016/j.quascirev.2017.11.015>.
- 997 Hughes, P. D., Gibbard, P. L. 2018. Global glacier dynamics during 100 ka Pleistocene  
 998 glacial cycles. *Quaternary Research*, 90(1), 222-243.  
 999 <https://doi.org/10.1017/qua.2018.37>
- 1000 Hughes, P.D., Tomkins, M.D., Stimson, G.A. 2019. Glaciation of the English Lake  
 1001 District during the Late-glacial: a new analysis using <sup>10</sup>Be and Schmidt hammer  
 1002 exposure dating. *North West Geography*, 19(2), 8-20.
- 1003 Ipsen, H.A., Principato, S.M., Grube, R.E., Lee, J.F., 2018. Spatial analysis of cirques  
 1004 from three regions of Iceland: implications for cirque formation and palaeoclimate.  
 1005 *Boreas* 47, 565–576. <https://doi.org/10.1111/bor.12295>
- 1006 Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., Schlüchter, C.,  
 1007 2009. Latest Pleistocene and Holocene glacier variations in the European Alps.

1008 Quat. Sci. Rev. 28, 2137–2149. <https://doi.org/10.1016/j.quascirev.2009.03.009>.

1009 Ivy-Ochs, S., 2015. Glacier variations in the European Alps at the end of the last  
1010 glaciation. Cuadernos de Investigación Geográfica, 41 (2), 295-315. Doi:  
1011 <https://doi.org/110.18172/cig.2750>

1012 Jiménez-Moreno, G., Anderson, R.S., 2012. Holocene vegetation and climate change  
1013 recorded in alpine bog sediments from the Borreguiles de la Virgen, Sierra Nevada,  
1014 southern Spain. Quat. Res. 77, 44–53. <https://doi.org/10.1016/j.yqres.2011.09.006>

1015 Jomelli V., Chapron E., Favier V., Rinterknecht V., Braucher R., Tournier N., Gascoin  
1016 S., Marti R., Galop D., Binet S., Deschamps-Berger C., Tissoux H., ASTER Team.  
1017 2020. Glacier fluctuations during the Late Glacial and Holocene on the Ariege  
1018 valley, northern slope of the Pyrenees and reconstructed climatic conditions.  
1019 Mediterranean. Geosci. Rev. 1-15 <https://doi.org/10.1007/s42990-020-00018-5>

1020 Kleman, J., Stroeven, A.P., 1997. Preglacial surface remnants and Quaternary glacial  
1021 regimes in northwestern Sweden. Geomorphology 19 (1), 35–54.  
1022 [https://doi.org/10.1016/S0169-555X\(96\)00046-3](https://doi.org/10.1016/S0169-555X(96)00046-3)

1023 Knight, J., Harrison, S., Jones, D.B., 2018. Rock glaciers and the geomorphological  
1024 evolution of deglaciating mountains. Geomorphology 311, 127–142.  
1025 <https://doi.org/10.1016/j.geomorph.2018.09.020>

1026 Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G.,  
1027 Wallner, A., Dillmann, I., Dollinger, G., von Gostomski, C.L., Kossert, K., Maiti,  
1028 M., Poutivtsev, M., Remmert, A., 2010. A new value for the half-life of <sup>10</sup>Be by  
1029 Heavy-Ion Elastic Recoil Detection and liquid scintillation counting. Nuclear  
1030 Instruments and Methods in Physics Research, Section B, Beam Interactions with  
1031 Materials and Atoms 268, 187–191. <https://doi.org/10.1016/j.nimb.2009.09.020>

1032 Köse, O., Sarıkaya, M. A., Çiner, A., Candaş, A., 2019. Late Quaternary glaciations and  
1033 cosmogenic <sup>36</sup>Cl geochronology of Mount Dedegöl, south-west Turkey. Journal of  
1034 Quaternary Science, 34 (1), 51–63. <https://doi.org/10.1002/jqs.3080>.

1035 Kuhlemann, J., Gachev, E., Gikov, A., Nedkov, S., Krumrei, I., Kubik, P. 2013.  
1036 Glaciation in the Rila Mountains (Bulgaria) during the last glacial maximum.  
1037 Quaternary International, 293, 51-62.  
1038 <http://dx.doi.org/10.1016/j.quaint.2012.06.027>

1039 Laabs, B. J., Licciardi, J. M., Leonard, E. M., Munroe, J. S., & Marchetti, D. W. 2020.  
1040 Updated cosmogenic chronologies of Pleistocene mountain glaciation in the  
1041 western United States and associated palaeoclimate inferences. Quaternary Science  
1042 Reviews, 242, 106427. <https://doi.org/10.1016/j.quascirev.2020.106427>

1043 Le Roy, M., Deline, P., Carcaillet, J., Schimmelpfennig, I., Ermini, M., ASTER Team,  
1044 2017. <sup>10</sup>Be exposure dating of the timing of Neoglacial glacier advances in the  
1045 Ecrins-Pelvoux massif, southern French Alps. Quaternary Science Reviews, 178,  
1046 118-138. <https://doi.org/10.1016/j.quascirev.2017.10.010>

1047 Li, Y., Li, Y., Harbor, J., Liu, G., Yi, C., Caffee, M.W., 2016. Cosmogenic <sup>10</sup>Be  
1048 constraints on Little Ice Age glacial advances in the eastern Tian Shan, China.  
1049 Quat. Sci. Rev. 138, 105-118. <https://doi.org/10.1016/j.quascirev.2016.02.023>

1050 Licciardi, J. M., Pierce, K. L. 2008. Cosmogenic exposure-age chronologies of Pinedale  
1051 and Bull Lake glaciations in greater Yellowstone and the Teton Range, USA.  
1052 Quaternary Science Reviews, 27(7-8), 814-831.  
1053 <https://doi.org/10.1016/j.quascirev.2007.12.005>

1054 Lifton, N., Sato, T., Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production  
1055 rates using analytical approximations to atmospheric cosmic-ray fluxes. Earth  
1056 Planet. Sci. Lett. 386, 149–160. <https://doi.org/10.1016/j.epsl.2013.10.052>

1057 López-Sáez, J. A., Carrasco, R. M., Turu, V., Ruiz-Zapata, B., Gil-García, M. J.,

- 1058 Luelmo-Lautenschlaeger, R., ... & Pedraza, J., 2020. Late Glacial-early holocene  
 1059 vegetation and environmental changes in the western Iberian Central System  
 1060 inferred from a key site: The Navamuño record, Béjar range (Spain). *Quaternary*  
 1061 *Science Reviews*, 230, 106167. <https://doi.org/10.1016/j.quascirev.2020.106167>
- 1062 Makos, M., Rinterknecht, V., Braucher, R., Tołoczko-Pasek, A., Arnold, M., Aumaître,  
 1063 G., ... Keddadouche, K. 2018. Last Glacial Maximum and Lateglacial in the Polish  
 1064 High Tatra Mountains-Revised deglaciation chronology based on the <sup>10</sup>Be  
 1065 exposure age dating. *Quaternary Science Reviews*, 187, 130-156.  
 1066 <https://doi.org/10.1016/j.quascirev.2018.03.006>
- 1067 Mangerud, J. A. N., Landvik, J. Y. 2007. Younger Dryas cirque glaciers in western  
 1068 Spitsbergen: smaller than during the Little Ice Age. *Boreas*, 36(3), 278-285  
 1069 <https://doi.org/10.1080/03009480601134827>
- 1070 Manzano, S., Carrión, J.S., López-Merino, L., Jiménez-Moreno, G., Toney, J.L.,  
 1071 Armstrong, H., Anderson, R.S., García-Alix, A., Pérez, J.L.G., Sánchez-Mata, D.,  
 1072 2019. A palaeoecological approach to understanding the past and present of Sierra  
 1073 Nevada, a Southwestern European biodiversity hotspot. *Glob. Planet. Change* 175,  
 1074 238–250. <https://doi.org/10.1016/j.gloplacha.2019.02.006>
- 1075 Martin, L., Blard, P.-H., Balco, G., Lave, J., Delunel, R., Lifton, N., Laurent, V., 2017.  
 1076 The CREP program and the ICE-D production rate calibration database: a fully  
 1077 parameterizable and updated online tool to compute cosmic-ray exposure ages.  
 1078 *Quat. Geochronol.* 38, 25–49. <https://doi.org/10.1016/j.quageo.2016.11.006>
- 1079 Marcott, S.A., Clark, P.U., Shakun, J.D., Brook, E.J., Davis, P.T., Caffee, M.W. 2019.  
 1080 <sup>10</sup>Be age constraints on latest Pleistocene and Holocene cirque glaciation across the  
 1081 western United States. *Clim. Atmos. Sci.* 2(5). [https://doi.org/10.1038/s41612-019-](https://doi.org/10.1038/s41612-019-0062-z)  
 1082 [0062-z](https://doi.org/10.1038/s41612-019-0062-z)
- 1083 Mercier, D., Coquin, J., Feuillet, T., Decaulne, A., Cossart, E., Jónsson, H.P.,  
 1084 Sæmundsson, Þ., 2017. Are Icelandic rock-slope failures paraglacial? Age  
 1085 evaluation of seventeen rock-slope failures in the Skagafjörður area, based on  
 1086 geomorphological stacking, radiocarbon dating and tephrochronology.  
 1087 *Geomorphology* 296, 45–58. <https://doi.org/10.1016/j.geomorph.2017.08.011>
- 1088 Merchel, S., Hergers, U. 1999. An update on radiochemical separation techniques for  
 1089 the determination of long-lived radionuclides via accelerator mass spectrometry.  
 1090 *Radiochimica Acta*, 84(4), 215-220. <https://doi.org/10.1524/ract.1999.84.4.215>
- 1091 Merchel, S., Arnold, M., Aumaître, G., Benedetti, L., Bourlès, D.L., Braucher, R.,  
 1092 Alfimov, V., Freeman, S.P.H.T., Steier, P., Wallner, A., 2008. Towards more  
 1093 precise <sup>10</sup>Be and <sup>36</sup>Cl data from measurements at the 10–14 level: Influence of  
 1094 sample preparation. *Nuclear Instruments and Methods in Physics Research,*  
 1095 *Section B, Beam Interactions with Materials and Atoms* 266, 4921–4926.  
 1096 <https://doi.org/10.1016/j.nimb.2008.07.031>
- 1097 Mîndrescu, M., Evans, I. S. 2014. Cirque form and development in Romania: Allometry  
 1098 and the buzzsaw hypothesis. *Geomorphology*, 208, 117-136.  
 1099 <https://doi.org/10.1016/j.geomorph.2013.11.019>
- 1100 Moran, A.P., Ivy-Ochs, S., Vockenhuber, C., Kerschner, H., 2016. Rock glacier  
 1101 development in the Northern Calcareous Alps at the Pleistocene-Holocene  
 1102 boundary. *Geomorphology* 273, 178–188.  
 1103 <https://doi.org/10.1016/j.geomorph.2016.08.017>.
- 1104 Moreno, A., Svensson, A., Brooks, S.J., Connor, S., Engels, S., Fletcher, W., Genty, D.,  
 1105 Heiri, O., Labuhn, I., Persoiu, A., Peyron, O., Sadori, L., Valero-Garcés, B., Wulf,  
 1106 S., Zanchetta, G., 2014. A compilation of Western European terrestrial records 60-  
 1107 8 ka BP: towards an understanding of latitudinal climatic gradients. *Quaternary*



- 1108 Science Reviews 106, 167-185. <https://doi.org/10.1016/j.quascirev.2014.06.030>
- 1109 Oliva, M., Schulte, L., Gómez-Ortiz, A., 2008. Solifluction Lobes in Sierra Nevada  
1110 (Southern Spain ): Morphometry and Palaeoenvironmental Changes. Proc. Ninth  
1111 Int. Conf. Permafrost. 1321–1326.
- 1112 Oliva, M., 2009. Holocene alpine environments in Sierra Nevada (southern Spain).  
1113 University of Barcelona.
- 1114 Oliva, M., Gómez-Ortiz, A., Schulte, L., 2010. Tendencia a la aridez en Sierra Nevada  
1115 desde el holoceno medio inferida a partir de sedimentos lacustres. Increasing Arid.  
1116 Sierra Nevada since Mid-Holocene inferred from lake sediments. Boletín de la  
1117 Asociación de Geógrafos Españoles, (52) 27–42.
- 1118 Oliva, M., Schulte, L., Ortiz, A.G., 2011. The role of aridification in constraining the  
1119 elevation range of Holocene solifluction processes and associated landforms in the  
1120 periglacial belt of the Sierra Nevada (southern Spain). Earth Surf. Process.  
1121 Landforms 36, 1279–1291. <https://doi.org/10.1002/esp.2116>
- 1122 Oliva, M., Gómez-Ortiz, A., 2012. Late-Holocene environmental dynamics and climate  
1123 variability in a Mediterranean high mountain environment (Sierra Nevada, Spain)  
1124 inferred from lake sediments and historical sources. Holocene 22, 915–927.  
1125 <https://doi.org/10.1177/0959683611434235>
- 1126 Oliva, M., Gómez-Ortiz, A., Salvador, F., Ramos, M., Palacios, D., Pereira, P., 2016.  
1127 Inexistence of permafrost at the Veleta peak (Sierra Nevada). Science of Total  
1128 Environment 550, 484-494. <https://doi.org/10.1016/j.scitotenv.2016.01.150>
- 1129 Oliva, M., Žebre, M., Guglielmin, M., Hughes, P.D., Çiner, A., Vieira, G., Bodin, X.,  
1130 Andrés, N., Colucci, R.R., García-Hernández, C., Mora, C., Nofre, J., Palacios, D.,  
1131 Pérez-Alberti, A., Ribolini, A., Ruiz-Fernández, J., Sarıkaya, M.A., Serrano, E.,  
1132 Urdea, P., Valcárcel, M., Woodward, J.C., Yıldırım, C., 2018. Permafrost  
1133 conditions in the Mediterranean region since the Last Glaciation. Earth-Science  
1134 Rev. 185, 397–436. <https://doi.org/10.1016/j.earscirev.2018.06.018>
- 1135 Oliva, M., Palacios, D., Fernández-Fernández, J.M., Rodríguez-Rodríguez, L., García-  
1136 Ruiz, J.M., Andrés, N., Carrasco, R.M., Pedraza, J., Pérez-Alberti, A., Valcárcel,  
1137 M., Hughes, P.D., 2019. Late Quaternary glacial phases in the Iberian Peninsula.  
1138 Earth-Science Reviews 192, 564–600.  
1139 <https://doi.org/10.1016/j.earscirev.2019.03.015>.
- 1140 Oliva, M.; Gómez-Ortiz, A.; Vidal, J.; Salvador-Franch, F.; Salvà-Catarineu, M. 2015.  
1141 El martillo de Schmidt como un instrumento de datación relativa. Aplicación  
1142 preliminar a los arcos morrénicos del Corral del Veleta y Hoya del Mulhacén  
1143 (Sierra Nevada). In: Gómez-Ortiz, A.; Salvador-Franch, F.; Oliva, M. & Salvà-  
1144 Catarineu, M. (eds.). Avances, métodos y técnicas en el estudio del  
1145 periglacialismo. Publicacions i Edicions de la Universitat de Barcelona, Barcelona,  
1146 pp. 323-331.
- 1147 Oliva, M., Gómez-Ortiz, A., Palacios, D., Salvador-Franch, F., Andrés, N., Tanarro, L.  
1148 M., Fernández-Fernández, J.M., Barriocanal, C. 2020. Multiproxy reconstruction  
1149 of Holocene glaciers in Sierra Nevada (south Spain). Mediterranean Geoscience  
1150 Reviews, 1-15. <https://doi.org/10.1007/s42990-019-00008-2>
- 1151 Oskin, M., Burbank, D. W. 2005. Alpine landscape evolution dominated by cirque  
1152 retreat. Geology, 33(12), 933-936. <https://doi.org/10.1130/G21957.1>
- 1153 Paasche, Ø., Dahl, S. O., Bakke, J., Løvlie, R., & Nesje, A. 2007. Cirque glacier activity  
1154 in arctic Norway during the last deglaciation. Quaternary Research, 68(3), 387-  
1155 399. <https://doi.org/10.1016/j.yqres.2007.07.006>
- 1156 Palacios, D., Marcos, J. Vázquez-Selem, L. 2011. Last Glacial Maximum and  
1157 Deglaciation of Sierra de Gredos, Central Iberian Peninsula. Quaternary

- 1158 International, 233: 16-26. <https://doi.org/10.1016/j.quaint.2010.04.029>.
- 1159 Palacios D, de Andrés N, de Marcos J, Vázquez-Selem L., 2012a. Glacial landforms  
1160 and their palaeoclimatic significance in Sierra de Guadarrama, Central Iberian  
1161 Peninsula. *Geomorphology* 139–140, 67–78.  
1162 <https://doi.org/10.1016/j.geomorph.2011.10.003>.
- 1163 Palacios D, Andrés N, Marcos J, Vázquez-Selem L., 2012b. Maximum glacial advance  
1164 and deglaciation of the Pinar Valley (Sierra de Gredos, Central Spain) and its  
1165 significance in the Mediterranean context. *Geomorphology* 177–178, 51–61.  
1166 <https://doi.org/10.1016/j.geomorph.2012.07.013>
- 1167 Palacios, D., Gómez-Ortiz, Andres, N., Salvador, F., Oliva, M. 2016. A Timing and  
1168 new geomorphological evidence of the last deglaciation stages in Sierra Nevada  
1169 (southern Spain) *Quaternary Science Reviews* 150, 110-129  
1170 <https://doi.org/10.1016/j.quascirev.2016.08.012>
- 1171 Palacios, D., García-Ruiz, J.M., Andrés, N., Schimmelpfennig, I., Campos, N. Leanni,  
1172 L., ASTER Team, 2017a. Deglaciation in the central Pyrenees during the  
1173 Pleistocene-Holocene transition: Timing and geomorphological significance.  
1174 *Quaternary Science Reviews* 162, 111-127. [https://doi.org/10.1016/j.quascirev.](https://doi.org/10.1016/j.quascirev.2017.03.007)  
1175 [2017.03.007](https://doi.org/10.1016/j.quascirev.2017.03.007)
- 1176 Palacios D., Andrés N., Gómez-Ortiz A. & García-Ruiz G. 2017b. Evidence of glacial  
1177 activity during the Oldest Dryas in the Mountain of Spain. In: Hughes P. and  
1178 Woodward J. *Quaternary glaciation in the Mediterranean Mountains*. Geological  
1179 Society of London, Special Publication, 433(1), 87-110  
1180 <https://doi.org/10.1144/SP433.10>
- 1181 Palacios, D., Gómez-Ortiz, A., Alcalá-Reygosa, J., Andrés, N., Oliva, M., Tanarro, L.,  
1182 Salvador-Franch, F., Schimmelpfennig, I., Fernández-Fernández, J.M., Léanni, L.,  
1183 2019. The challenging application of cosmogenic dating methods in residual  
1184 glacial landforms: The case of Sierra Nevada (Spain). *Geomorphology* 325, 103–  
1185 118. <https://doi.org/10.1016/j.geomorph.2018.10.006>.
- 1186 Pallàs, R., Rodés, A., Braucher, R., Carcaillet, J., Ortuño, M., Bordonau, J., Bourlès, D.,  
1187 Vilaplana, J.M., Masana, E., Santanach, P., 2006. Late Pleistocene and Holocene  
1188 glaciation in the Pyrenees: A critical review and new evidence from <sup>10</sup>Be exposure  
1189 ages, south-central Pyrenees. *Quaternary Science Reviews* 25, 2937–2963.  
1190 <https://doi.org/10.1016/j.quascirev.2006.04.004>.
- 1191 Pallàs, R., Rodés, A., Braucher, R., Bourlès, D., Delmas, M., Calvet, M., Gunnell, Y.,  
1192 2010. Small, isolated glacial catchments as priority targets for cosmogenic surface  
1193 exposure dating of Pleistocene climate fluctuations, southeastern Pyrenees.  
1194 *Geology* 38 (10), 891–894. <https://doi.org/10.1130/G31164.1>.
- 1195 Palma, P., Oliva, M., García-Hernández, C., Ortiz, A. G., Ruiz-Fernández, J., Salvador-  
1196 Franch, F., & Catarineu, M. 2017. Spatial characterization of glacial and  
1197 periglacial landforms in the highlands of Sierra Nevada (Spain). *Science of the*  
1198 *Total Environment*, 584, 1256-1267.  
1199 <https://doi.org/10.1016/j.scitotenv.2017.01.196>
- 1200 Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.  
1201 B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V.,  
1202 Guillevic, M., Hoek, W.Z., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K.,  
1203 Steffensen, J.P., Svensson, A.M., Vallenga, P., Vinther, B.M., Walker, M.J.C.,  
1204 Wheatley, J.J., Winstrup, M. 2014. A stratigraphic framework for abrupt climatic  
1205 changes during the Last Glacial period based on three synchronized Greenland ice-  
1206 core records: Refining and extending the INTIMATE event stratigraphy. *Quat. Sci.*  
1207 *Rev.* 106, 14–28. <https://doi.org/10.1016/j.quascirev.2014.09.007>

- 1208 Renssen, H., Seppä, H., Heiri, O., Rotche, D. M., Goosse, H., & Fichefet, T. 2009. The  
 1209 spatial and temporal complexity of the Holocene thermal maximum. *Nature*  
 1210 *Geoscience*, 2(6), 411. <https://doi.org/10.1038/NGEO513>
- 1211 Ribolini, A., Chelli, A., Guglielmin, M., Pappalardo, M., 2007. Relationships between  
 1212 glacier and rock glacier in the Maritime Alps, Schiantala Valley, Italy. *Quat. Res.*  
 1213 68, 353–363. <https://doi.org/10.1016/j.yqres.2007.08.004>
- 1214 Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M. J.,  
 1215 Rinterknecht, V., Pallas, R., & Bourles, D. 2016. Chronology of glaciations in the  
 1216 Cantabrian Mountains (NW Iberia) during the Last Glacial Cycle based on in situ-  
 1217 produced <sup>10</sup>Be. *Quaternary Science Reviews*, 138, 31-48.  
 1218 <https://doi.org/10.1016/j.quascirev.2016.02.027>
- 1219 Rodríguez-Rodríguez, L., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J.,  
 1220 Rinterknecht, V., Pallàs, R., Aster Team, 2017. Timing of last deglaciation in the  
 1221 Cantabrian Mountains (Iberian Peninsula; North Atlantic region) based on in situ-  
 1222 produced <sup>10</sup>Be exposure dating. *Quat. Sci. Rev.* 171, 166-181.  
 1223 <https://doi.org/10.1016/j.quascirev.2017.07.012>
- 1224 Sanders, J.W., Cuffey, K.M., Moore, J.R., MacGregor, K.R., Kavanaugh, J.L., 2012.  
 1225 Periglacial weathering and headwall erosion in cirque glacier bergschrunds.  
 1226 *Geology* 40 (9),779–782. <https://doi.org/10.1130/G33330.1>
- 1227 Sanders, J.W., Cuffey, K.M., MacGregor, K.R., Collins, B.D., 2013. The sediment  
 1228 budget of an alpine cirque. *Geol. Soc. Am. Bull.* 125, 229–248.  
 1229 <https://doi.org/10.1130/B30688.1>
- 1230 Sarıkaya, M. A., Çiner, A., Yıldırım, C., 2017. Cosmogenic <sup>36</sup>Cl glacial chronologies of  
 1231 the Late Quaternary glaciers on Mount Geyikdağ in the Eastern Mediterranean.  
 1232 *Quaternary Geochronology* 39, 189–204.  
 1233 <https://doi.org/10.1016/j.quageo.2017.03.003>
- 1234 Serrano, E., Oliva, M., González-García, M., López-Moreno, J.I., González-Trueba, J.,  
 1235 Martín-Moreno, R., Gómez-Lende, M., Martín-Díaz, J., Nofre, J., Palma, P., 2018.  
 1236 Post-little ice age paraglacial processes and landforms in the high Iberian  
 1237 mountains: A review. *L. Degrad. Dev.* 29, 4186–4208.  
 1238 <https://doi.org/10.1002/ldr.3171>
- 1239 Styllas, M. N., Schimmelpfennig, I., Benedetti, L., Ghilardi, M., Aumaître, G., Bourlès,  
 1240 D., Keddadouche, K., 2018. Late-glacial and Holocene history of the northeast  
 1241 Mediterranean mountain glaciers-New insights from in situ-produced <sup>36</sup>Cl-based  
 1242 cosmic ray exposure dating of palaeo-glacier deposits on Mount Olympus, Greece.  
 1243 *Quaternary Science Reviews* 193, 244–265.  
 1244 <https://doi.org/10.1016/j.quascirev.2018.06.020>
- 1245 Tanarro, L. M., Fernández, J.M., Andres, N., Zamorano, J.J., Sæmundsson, Þ.,  
 1246 Brynjólfsson, S., Palacios, D. 2019. Unchanged surface morphology of debris-  
 1247 covered glacier and rock glaciers in Tröllaskagi Peninsula (Northern Iceland).  
 1248 *Science of the Total Environment* 648, 218–235  
 1249 <https://doi.org/10.1016/j.scitotenv.2018.07.460>
- 1250 Tomkins, M. D., Dortch, J. M., Hughes, P. D., Huck, J. J., Stimson, A. G., Delmas, M.,  
 1251 ... & Pallàs, R. 2018. Rapid age assessment of glacial landforms in the Pyrenees  
 1252 using Schmidt hammer exposure dating (SHED). *Quaternary Research*, 90(1), 26-  
 1253 37. <https://doi.org/10.1017/qua.2018.12>
- 1254 Uppala, S.M., Kållberg, P., Simmons, A., Andrae, U., Bechtold, V., Fiorino, M.,  
 1255 Gibson, J., Woollen, J., 2005. The ERA-40 reanalysis. *Q.J.R. Meteorol. Soc.* 131,  
 1256 2961–3012. <https://doi.org/10.1256/qj.04.176>
- 1257 Walker, M., Johnsen, S., Rasmussen, S. O., Popp, T., Steffensen, J. P., Gibbard, P., ... &

- 1258 Cwynar, L. C. (2009). Formal definition and dating of the GSSP (Global  
1259 Stratotype Section and Point) for the base of the Holocene using the Greenland  
1260 NGRIP ice core, and selected auxiliary records. *Journal of Quaternary Science*,  
1261 24(1), 3-17. <https://doi.org/10.1002/jqs.1227>
- 1262 Zahno, C., Akçar, N., Yavuz, V., Kubik, P. W., & Schlüchter, C. 2010. Chronology of  
1263 late Pleistocene glacier variations at the Uludağ Mountain, NW Turkey.  
1264 *Quaternary Science Reviews*, 29(9-10), 1173-1187.  
1265 <https://doi.org/10.1016/j.quascirev.2010.01.012>
- 1266 Zasadni, J., Kłapyta, P., Broś, E., Ivy-Ochs, S., Świąder, A., Christl, M., &  
1267 Balážovičová, L. 2020. Latest Pleistocene glacier advances and post-Younger  
1268 Dryas rock glacier stabilization in the Mt. Kriváň group, High Tatra Mountains,  
1269 Slovakia. *Geomorphology*, 107093.  
1270 <https://doi.org/10.1016/j.geomorph.2020.107093>
- 1271 Žebre, M., Sarıkaya, M. A., Stepišnik, U., Yıldırım, C., & Çiner, A. 2019. First <sup>36</sup>Cl  
1272 cosmogenic moraine geochronology of the Dinaric mountain karst: Velež and  
1273 Crvanj Mountains of Bosnia and Herzegovina. *Quaternary Science Reviews*, 208,  
1274 54-75. <https://doi.org/10.1016/j.quascirev.2019.02.002>
- 1275

1276 **Table captions**

1277 Table 1. Field data of sampling sites, topographic shielding factor, sample thickness and  
1278 distance from the headwall.

1279 Table 2. Analytical data and cosmic-ray exposure (CRE) ages.  $^{10}\text{Be}/^9\text{Be}$  ratios were  
1280 measured at the ASTER AMS facility. The numbers in italics correspond to the internal  
1281 (analytical) uncertainty at  $1\sigma$  level.

1282 Table 3. Location, main topographic characteristics, geomorphologicalal units, and  
1283 average CRE ages from the cirques studied in the Sierra Nevada compared to the  
1284 Mulhacén cirque.

1285 Table 4. Location, main topographic characteristics, geomorphologicalal units, and  
1286 average CRE ages of the cirques studied in the rest of Iberian Peninsula (outside Sierra  
1287 Nevada). All CRE ages are updated following [Oliva et al. \(2019\)](#).

1288 Table 5. Location, main topographic characteristics, geomorphologicalal units, and  
1289 average CRE ages of the cirques studied in the Mediterranean region (Iberian Peninsula  
1290 not included). All CRE ages are updated.

1291 Table 6. Location, main topographic characteristics, geomorphologicalal units, and  
1292 average CRE ages of the cirques studied in the Central European region (outside Sierra  
1293 Nevada). All CRE ages are updated.

1294 Table 7. Location, main topographic characteristics, geomorphologicalal units, and  
1295 average CRE ages of the cirques studied in the British Isles and Iceland. All CRE ages  
1296 are updated.

1297 Table 8. Location, main topographic characteristics, geomorphologicalal units, and  
1298 average CRE ages of the cirques studied in the Western North America. All CRE ages  
1299 are updated.

1300

1301 **Figure captions**

1302 Figure 1. Location map of the study area. A) Location of the Sierra Nevada in the context  
1303 of the Iberian Peninsula. B) Glacier extent of the Sierra Nevada glaciers during their  
1304 LLGM. C) Western sector of the Sierra Nevada where the main peaks and the cirques  
1305 cited throughout the text are distributed.

1306 Figure 2. Mulhacén cirque and location of the CRE sampling sites and  $^{10}\text{Be}$  ages. A)  
1307 Aerial orthophoto. B) Geomorphological map.

1308 Figure 3. Geomorphological transect along the Mulhacén cirque (S-N direction) showing  
1309 the  $^{10}\text{Be}$  CRE ages (in ka).

1310 Figure 4. Photos of the Mulhacén cirque floor, with the location of the CRE sampling  
1311 sites and  $^{10}\text{Be}$  ages. Panels A) and B) are oblique views of La Mosca Lake taken from the  
1312 SE and E, respectively.

1313 Figure 5. Photos of the Mulhacén cirque floor, location of the CRE sampling sites and  
1314  $^{10}\text{Be}$  CRE ages. A) Oblique view of La Mosca Lake from the W. B) Blocky moraine  
1315 where the sample MOSCA-5 (with nuclide inheritance) was collected.

1316 Figure 6. CRE age correlation with: A) elevation, and B) distance to the Mulhacén  
1317 headwall. In the panel B) we have removed the sample MOSCA-5 as being an outlier  
1318 (cosmogenic nuclide inheritance). In the panel A) the correlation with altitude is very  
1319 weak as all the samples are located on the flat floor of the cirque.

1320 Figure 7. Probability density plots of CRE ages for different chronostratigraphic units in  
1321 the A) Mulhacén cirque (data shown in Table 3) and B) in the Sierra Nevada cirques (data  
1322 shown in Table 4). Panels correspond to different stages according to the  
1323 chronostratigraphy: a) Deglaciation of the Mulhacén cirque floor after the Younger  
1324 Dryas. b) Deglaciation of the cirque mouth at the beginning of the Bølling-Allerød  
1325 interstadial. We have included two outlier samples, probably with cosmogenic nuclide  
1326 inheritance (MOSCA-5 and MOSCA-7). The number associated with each averaged CRE  
1327 age refers to the number of CRE ages from each geomorphological unit considered. We  
1328 assume that this average is indicative of the age for each geomorphological phase detected  
1329 in each cirque.

1330 Figure 8. Synthetic evolution model of the deglaciation phases in the cirques of the Sierra  
1331 Nevada. A) The glaciers filled the cirques during the OD, until just before the onset of

1332 the B-A Interstadial. B) The mouth of most of the cirques was deglaciated during the B-  
1333 A Interstadial. C) Glaciers might have disappeared from the Sierra Nevada cirques. D)  
1334 Most of the cirques hosted new small glaciers during the YD. After this phase, the cirques  
1335 evolved differently, according to their topographic characteristics. E.1) Cirques with  
1336 summits at 3000-3200 m and floors at >2800 m, with small headwalls (< 200 m of altitude  
1337 range) and east-facing produced only small proto-rock glaciers. E.2) Cirques with  
1338 summits at 3000-3200 m and floors at > 2800 m, with steep and long headwalls (> 300 m  
1339 of altitude range) developed larger rock glacier complexes, especially if they are north  
1340 facing. E.3) Cirques with summits at < 3000 m and floors at < 2800 m. The shrinking  
1341 glaciers left one or more moraines – or even none – depending on the intensity of the  
1342 paraglacial readjustment of their surrounding walls. Cirques with summits at > 3300 m  
1343 and floors at > 2950 m, north-facing and with > 300-m-high walls recorded geomorphic  
1344 evidence from glacier changes from the YD to present. This is the case of the Veleta and  
1345 Mulhacén cirques, but their evolution was different. E.4) Veleta palaeoglacier formed  
1346 only a large polygenic moraine. E.5) Mulhacén palaeoglacier developed a sequence of  
1347 moraine ridges.

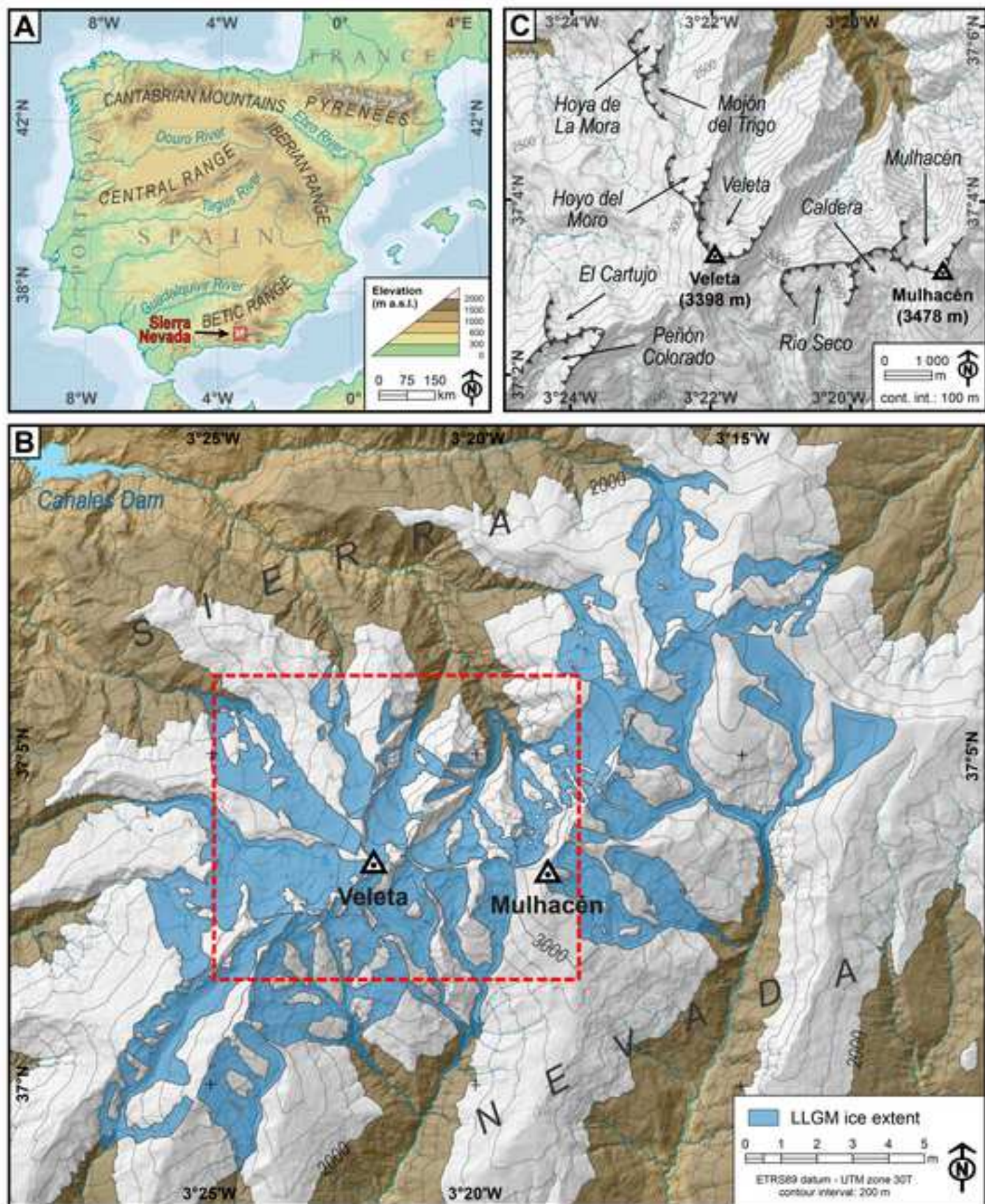
1348 Figure 9. Probability density plots of CRE ages for different chronostratigraphical units  
1349 in A) The Iberian Peninsula cirques (data shown in Table 4); B) The Mediterranean  
1350 cirques (outside Iberian Peninsula) (data shown in Table 5); C) The Central European  
1351 cirques (data shown in Table 6); D) The British Isles and Iceland cirques; E) The Western  
1352 North America cirques (data shown in Table 8); F) Rock glacier front stabilization in the  
1353 cirques analysed in the North Hemisphere (data shown in Tables 3, 4, 5, 6, 7 and 8). For  
1354 Figure 9, B), C), D) and E) the plots are clustered in a) Deglaciation of the cirque floor  
1355 after the YD (ages of the stabilization of the youngest moraine and polished bedrock  
1356 surfaces); b) Deglaciation of the mouth of the cirque, at the beginning of the B-A  
1357 Interstadial (ages of the stabilization of the oldest moraine inside the cirque and polished  
1358 bedrock surfaces). For the Panel F) the plots are clustered in a) Rock glacier front  
1359 stabilization after Neoglacial advances; b) Rock glacier front stabilization after the  
1360 Younger Dryas; c) Rock glacier front stabilization after at the beginning of the B-A  
1361 Interstadial. The number associated with each averaged CRE age refers to the number of  
1362 CRE ages from each geomorphological unit considered.

1363 Figure 10. Probability density plots of CRE ages for different chronostratigraphical units,  
1364 comparing all the results from the six regions. The plots are clustered in a) Rock glacier

1365 front stabilization after the YD; b) Deglaciation of the cirque floor after the YD (ages of  
1366 the stabilization of the youngest moraine and polished bedrock surfaces); c) Deglaciation  
1367 of the mouth of the cirque, at the beginning of the B-A Interstadial (ages of the  
1368 stabilization of the oldest moraine inside the cirque and polished bedrock surfaces). The  
1369 number associated with each averaged CRE age refers to the number of cirques with  
1370 available CRE ages in a given region analysed. The average CRE age of each  
1371 geomorphological unit is compared with the Greenland ice core chronology ([Rasmussen](#)  
1372 [et al., 2014](#)).

1373





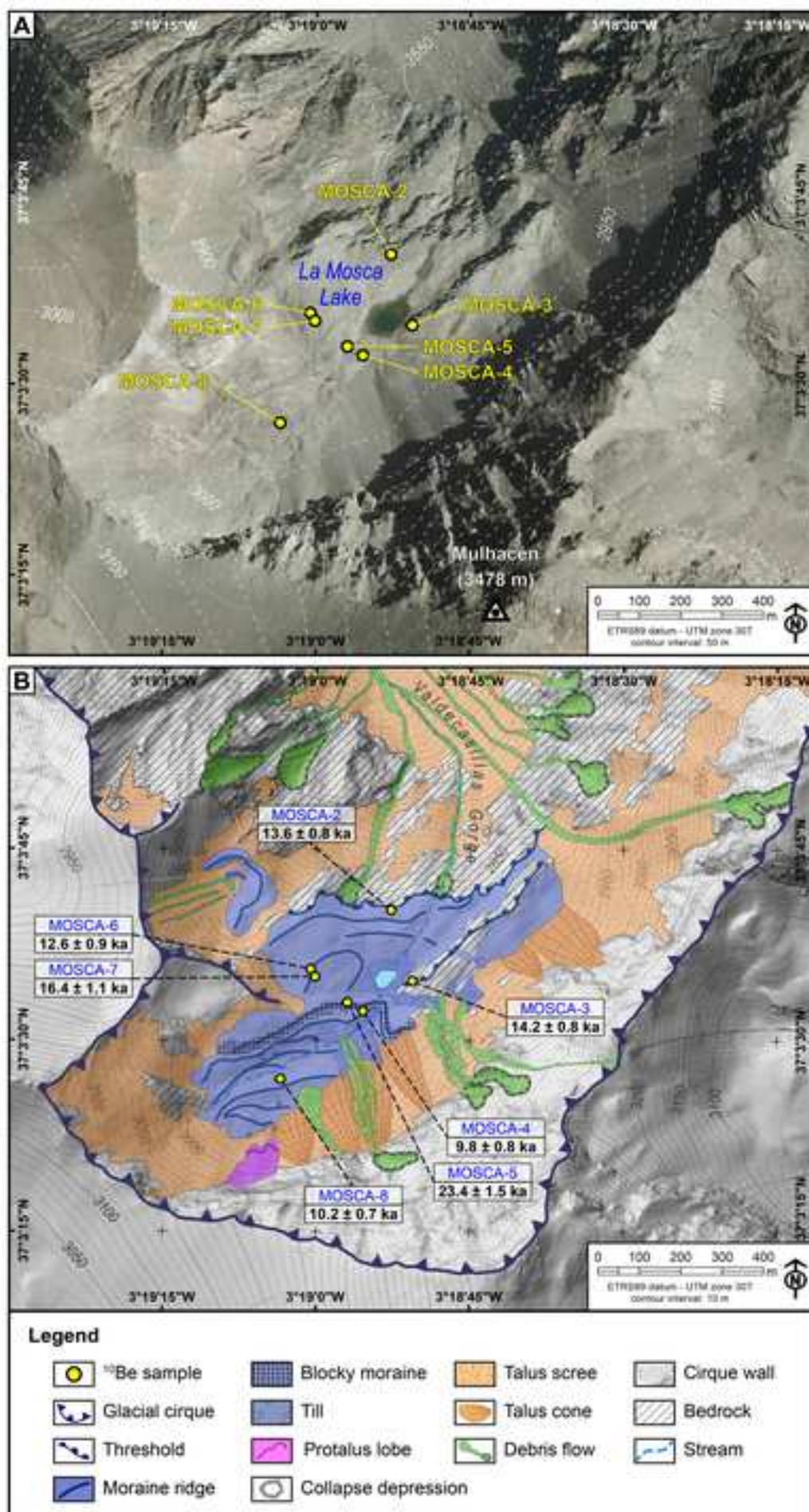
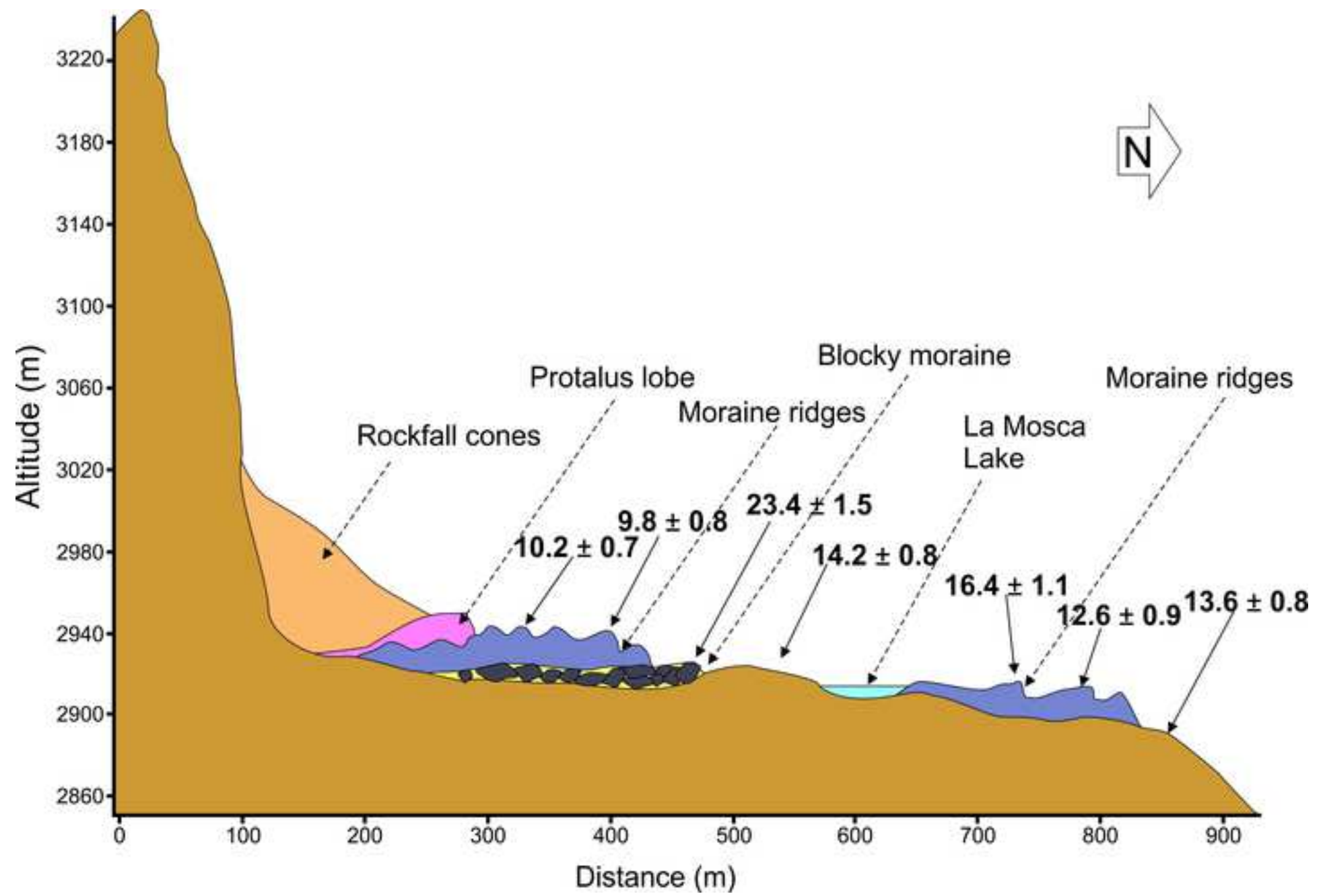
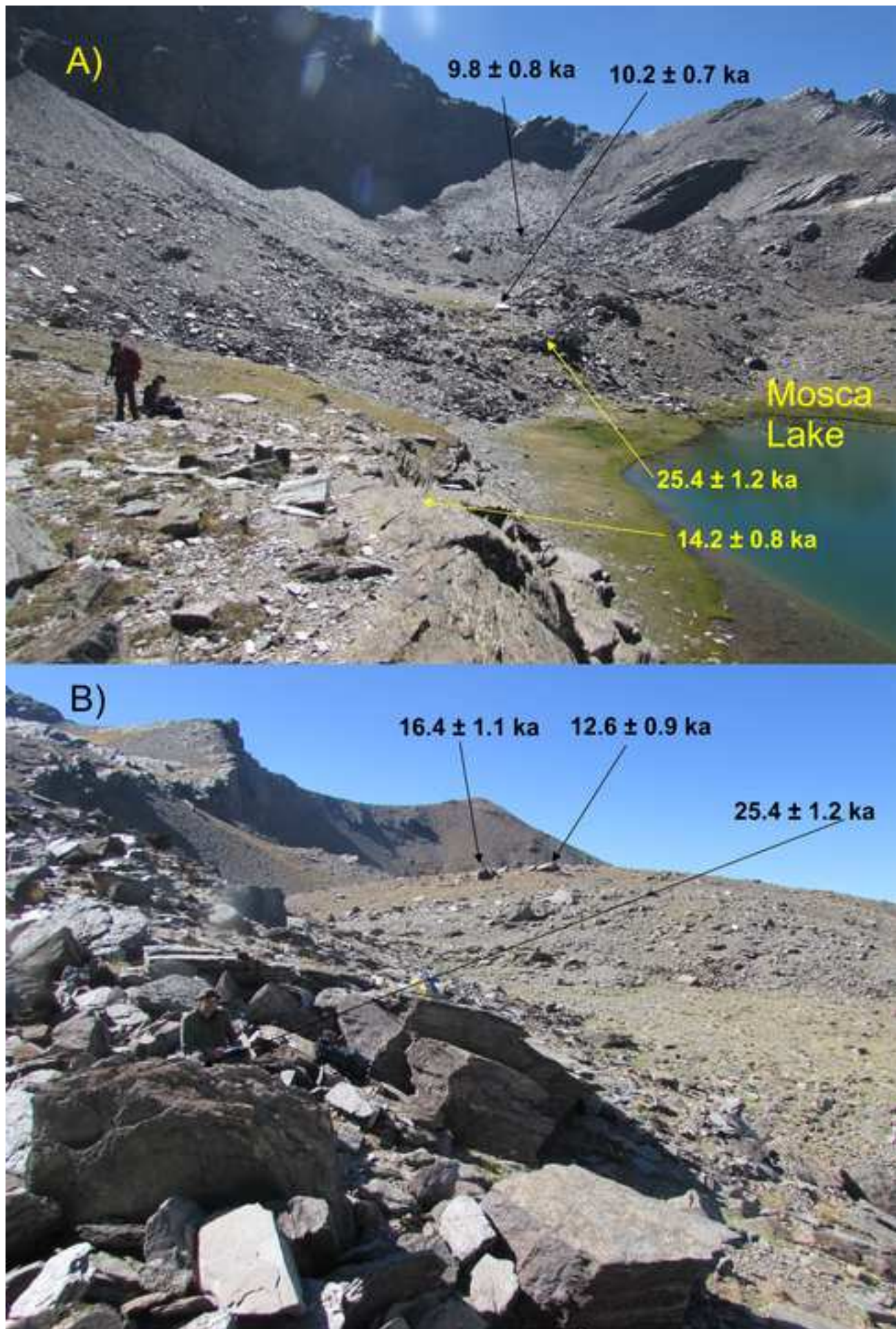
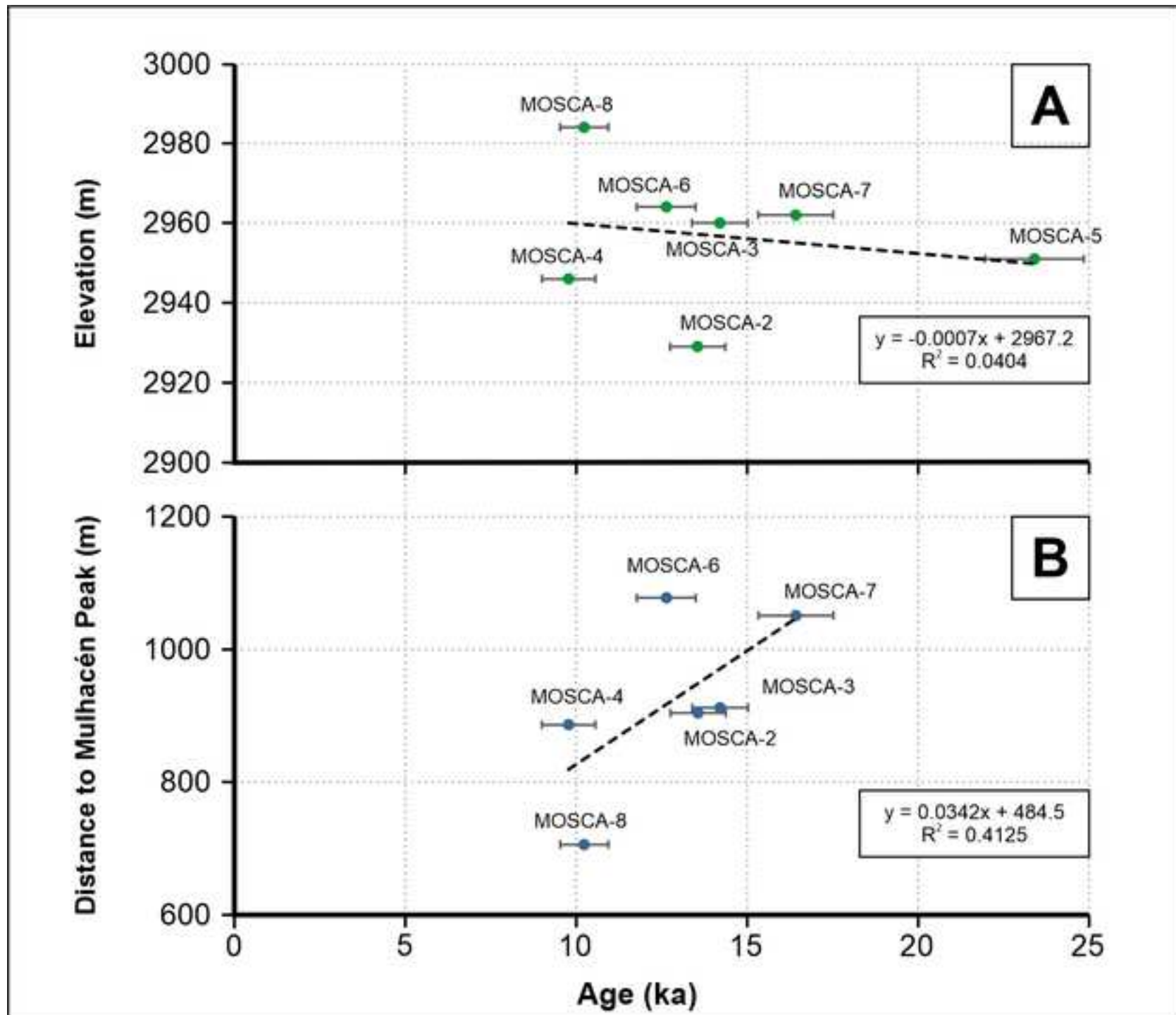


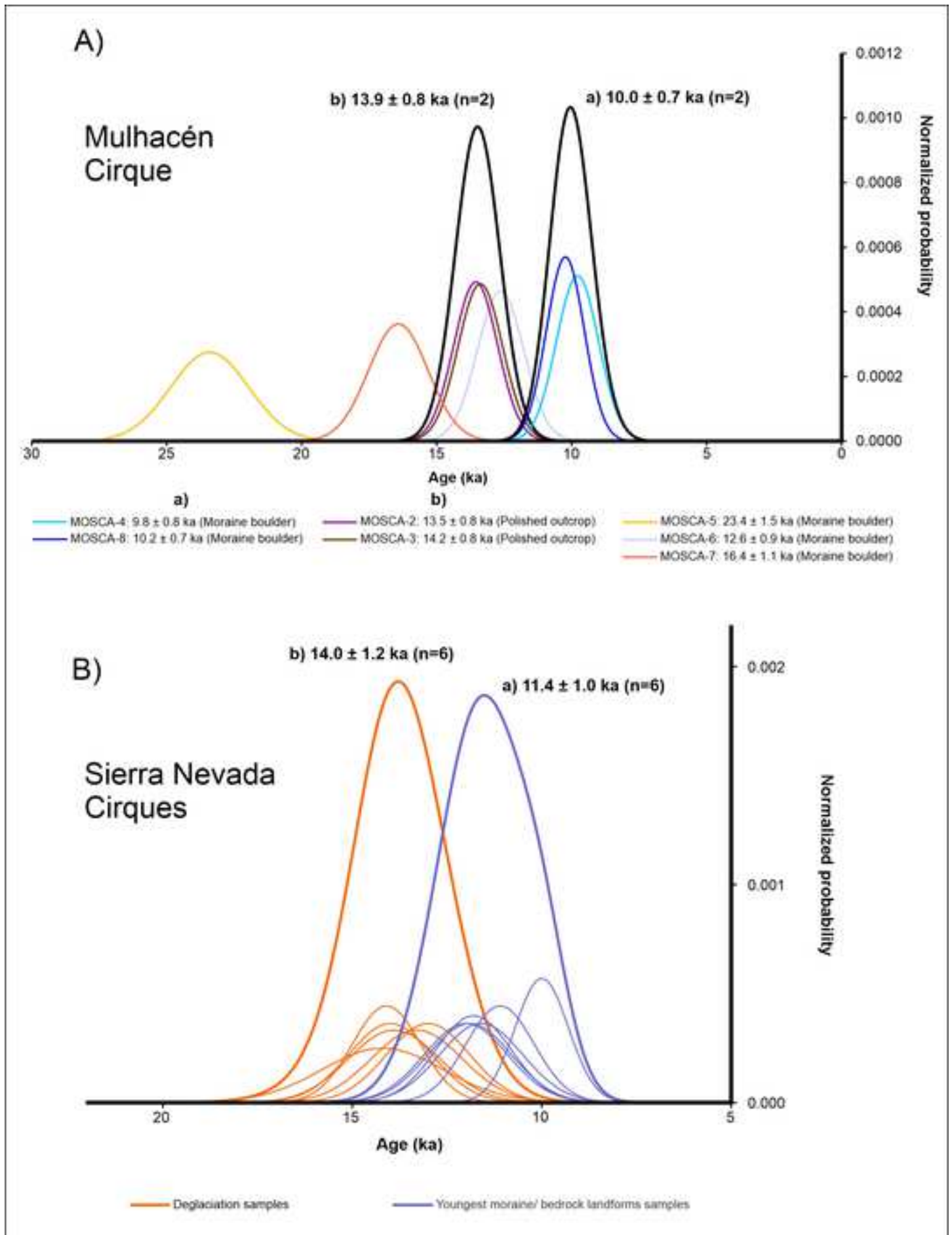
Figure 3

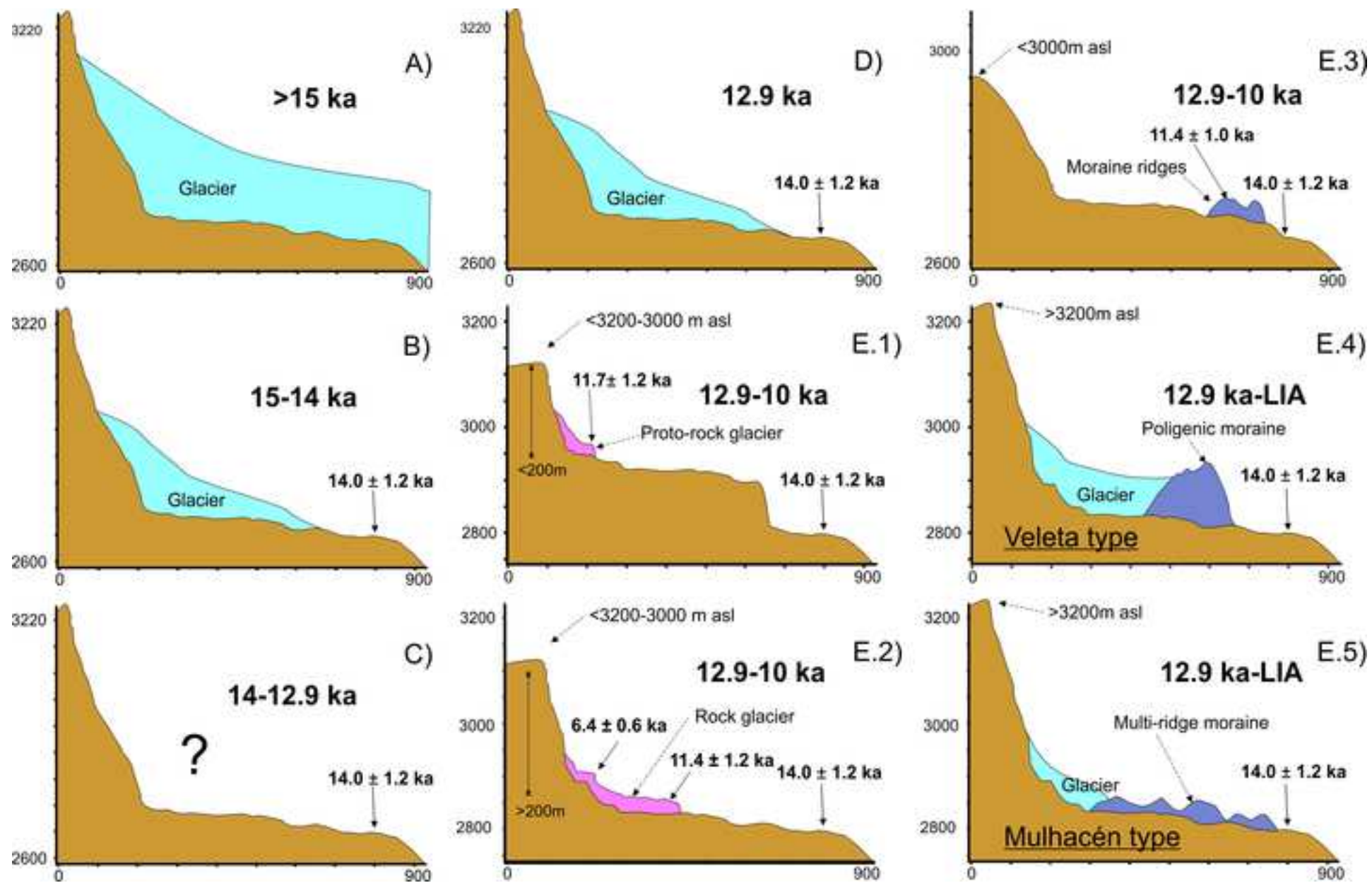




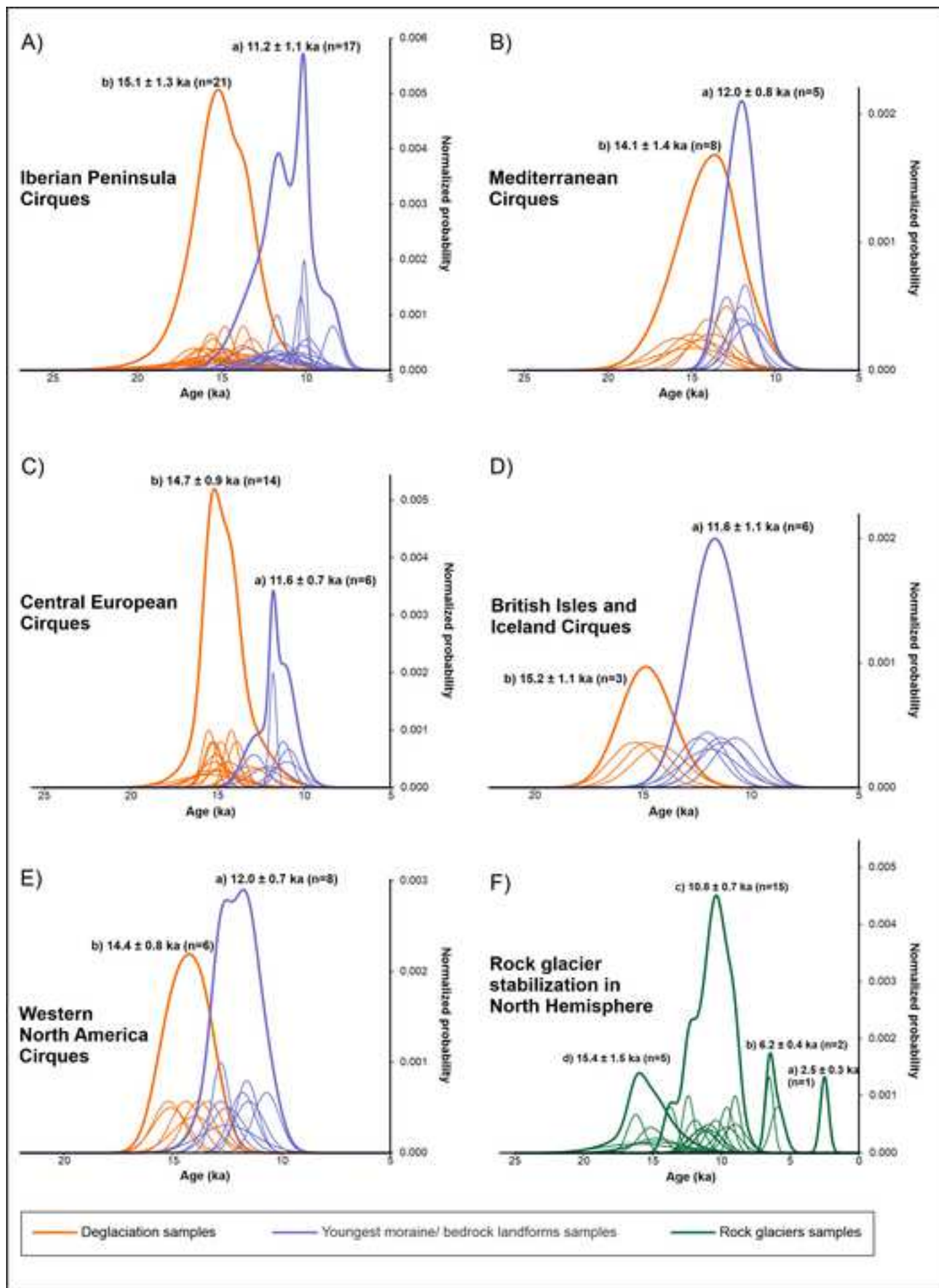


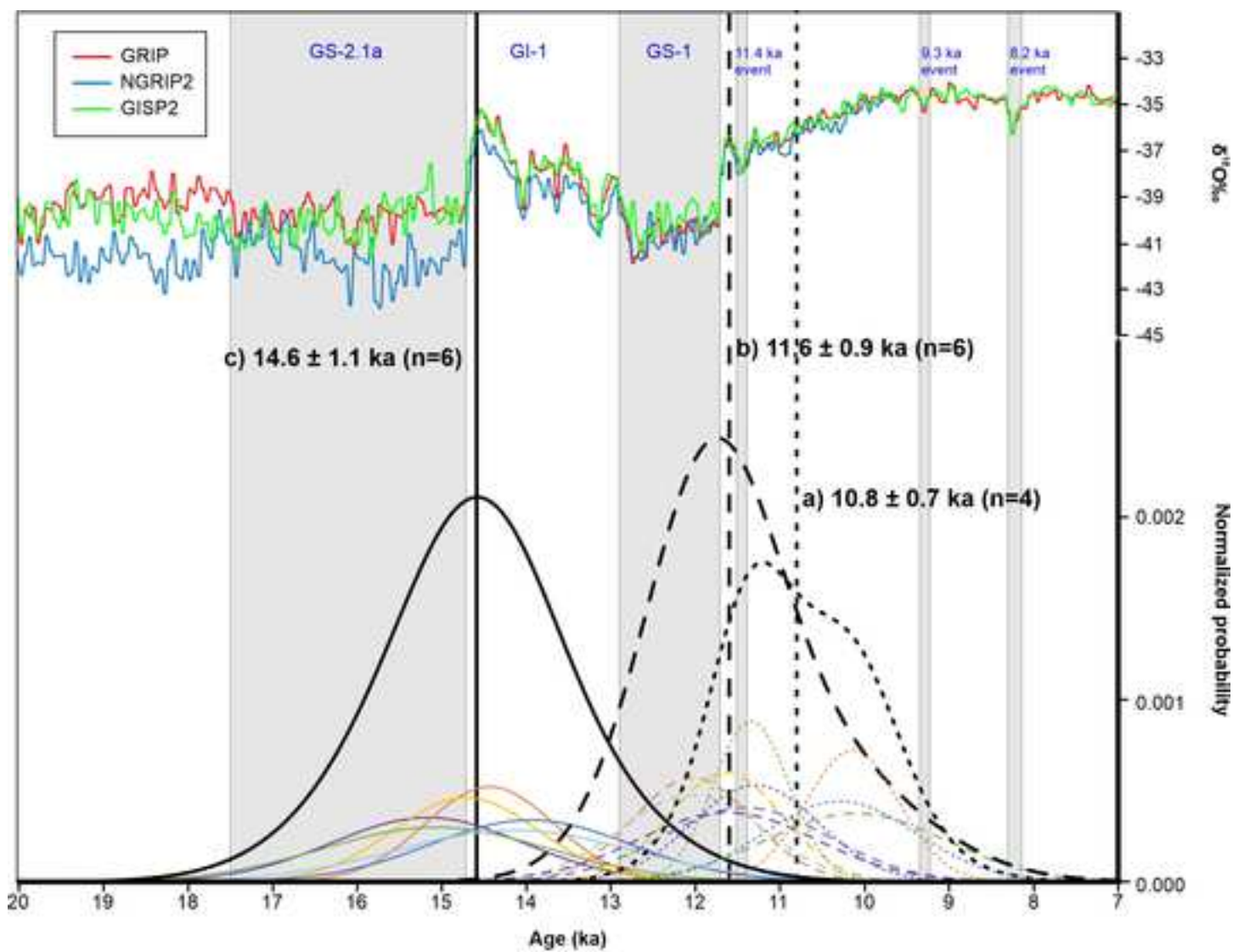












	Deglaciation of the cirque ———	Youngest moraine/bedrock - - -	Rock glacier landforms - - - -
Sierra Nevada	—————	- - - -	.....
Iberian Peninsula	—————	- - - -	.....
Mediterranean region	—————	- - - -	
Central European region	—————	- - - -	
British Isles and Subpolar regions	—————	- - - -	.....
Western North America	—————	- - - -	.....

Table 1. Field data of sampling sites, topographic shielding factor, sample thickness and distance from the headwall.

<b>Sample name</b>	<b>Sample type</b>	<b>Latitude (DD)</b>	<b>Longitude (DD)</b>	<b>Elevation (m a.s.l.)</b>	<b>Topographic shielding factor</b>	<b>Thickness (cm)</b>	<b>Distance from the headwall (m): map vs ground length</b>
MOSCA-2	Polished outcrop	37.06117	-3.31463	2929	0.9757	3.0	904 / 1058
MOSCA-3	Polished outcrop	37.05963	-3.31405	2960	0.9545	2.0	911 / 1049
MOSCA-4	Moraine boulder	37.05897	-3.31539	2946	0.9579	2.5	886 / 1034
MOSCA-5	Moraine boulder	37.05916	-3.31581	2951	0.9579	2.5	932 / 1071
MOSCA-6	Moraine boulder	37.05989	-3.31681	2964	0.9572	3.0	1077 / 1194
MOSCA-7	Moraine boulder	37.05972	-3.31669	2962	0.9579	4.0	1050/ 1170
MOSCA-8	Moraine boulder	37.05749	-3.31763	2984	0.9460	4.0	706 / 862

Table 2. Analytical data and cosmic ray exposure (CRE) ages.  $^{10}\text{Be}/^9\text{Be}$  ratios were measured at the ASTER AMS facility. The numbers in italics correspond to the internal (analytical) uncertainty at  $1\sigma$  level.

Sample name	Quartz weight (g)	Mass of carrier ( $^9\text{Be}$ mg)	ASTER cathode ID	$^{10}\text{Be}/^9\text{Be}$ ( $10^{-13}$ ) corrected of chemical blank	Blank correction (%)	$[^{10}\text{Be}]$ ( $10^4$ atoms $\text{g}^{-1}$ )	Age (ka)
MOSCA-2	39.7779	155.9	ICYQ	$4.7124 \pm 0.1461$	0.52	$37.321 \pm 1.163$	$13.55 \pm 0.8$ (0.4)
MOSCA-3	29.2882	155.5	ICYR	$3.6722 \pm 0.1148$	0.67	$39.418 \pm 1.238$	$14.20 \pm 0.8$ (0.4)
MOSCA-4	8.4979	158.3	ICYS	$0.7182 \pm 0.0350$	3.31	$27.047 \pm 1.321$	$9.78 \pm 0.8$ (0.5)
MOSCA-5	5.9343	156.3	ICYT	$1.2924 \pm 0.0571$	1.87	$68.786 \pm 3.045$	$23.41 \pm 1.5$ (0.9)
MOSCA-6	40.4572	153.2	ICYU	$4.5547 \pm 0.2008$	0.54	$34.864 \pm 1.541$	$12.63 \pm 0.9$ (0.5)
MOSCA-7	21.5507	155.5	ICYV	$3.1261 \pm 0.1501$	0.78	$45.598 \pm 2.194$	$16.42 \pm 1.1$ (0.7)
MOSCA-8	40.1676	156.3	ICYW	$3.5672 \pm 0.1130$	0.68	$28.061 \pm 0.893$	$10.23 \pm 0.7$ (0.4)
<i><math>^{10}\text{Be}</math> Blank</i>							
MOSCA-BK	-	157.8	ICYP	-	-	-	-

Table 3. Location, main topographic characteristics, geomorphological units, and average CRE ages from the cirques studied in the Sierra Nevada compared to the Mulhacén cirque.

Cirque/ valley	Location <sup>1</sup>	Cirque elevation range <sup>2</sup> (m a.s.l.) and (m)	Length <sup>3</sup> (m)	Aspect <sup>4</sup>	Deglaciation (ka) <sup>5</sup>	Youngest moraine/ bedrock (ka) <sup>6</sup>	Distance from headwall to the youngest moraine (m) <sup>7</sup>	Rock glacier and protalus lobe landforms (ka) <sup>8</sup>	Neoglacial landforms (ka/CE) <sup>9</sup>	References
La Mora/ San Juan	37°5'43"N 3°22'57"W	2609-2350 (259)	600	NE	<b>13.9 ± 1.2</b> (n=2)	4 moraine ridges <b>11.6 ± 1.1</b> (n=2)	400	-		Palacios et al. (2016)
Mojón del Trigo/ San Juan	37°5'22"N 3°22'36"W	2609-2350 (259)	800	E	<b>14.5 ± 1.2</b> (n=2)	3 moraine ridges <b>11.8 ± 1.0</b> (n=2)	600	-		Palacios et al. (2016)
El Moro/ San Juan	37°4'28"N 3°22'22"W	2925-2790 (135)	700	E	<b>14.0 ± 1.1</b> (n=2)	1 ridge <b>11.1 ± 0.9</b> (n=1)	500			Palacios et al. (2016)
Cartujo/ Dílar	37°3'9"N 3°22'57"W	3152-2700 (452)	1400	N	<b>14.2 ± 1.6</b> (n=2)	No data		Rock glacier From <b>11.4 ± 1.0</b> to <b>6.4 ± 0.6</b>		Palacios et al. (2016)
Peñón Colorado/ Lanjarón	37°1'56"N 3°24'23"W	3113-2950 (163)	600	E	<b>13.0 ± 1.1</b> (n=4)	3 ridges No data		Proto-rock glacier <b>10.5 ± 0.9</b>		Palacios et al. (2016)
Río Seco/ Río Seco	37°2'55"N 3°20'39"W	3141-3000 (141)	600	E		Bedrock <b>11.9 ± 1.1</b> (n=1)		Proto-rock glacier <b>9.0 ± 0.8</b>		Palacios et al. (2016)
Caldereta/ Mulhacén	37°3'5"N 3°19'32"W	3182-3000 (182)	900	E		Bedrock <b>12.0 ± 1.1</b> (n=2)		Rock glacier from <b>13.1 ± 1.2</b> to <b>6.3 ± 0.5</b>		Palacios et al. (2016)
Corral del Veleta/ Guarmón	37°3'35"N 3°21'57"W	3396-3000 (396)	500	N	No data	Large poligenic ridge		Rock glacier from <b>1950 CE</b>	Poligenic LIA ridge <b>From 1355</b> <b>to 1900 CE</b>	Palacios et al. (2019)

<b>Mulhacén cirque</b>	<b>37° 3'36"N 3°18'57"W</b>	<b>3479-2900 (579)</b>	<b>950</b>	<b>N</b>	<b>14.1 ± 0.9 (n=1) (a)</b>	<b>6 ridges 10.0 ± 0.7 (n=2)(a)</b>	<b>700</b>	<b>Protalus lobe from 1900 CE (b)</b>	<b>(a) Present work (b) Serrano et al. (2018)</b>
------------------------	---------------------------------	----------------------------	------------	----------	---------------------------------	---	------------	---	---

<sup>1</sup>Geographic coordinates of the center point of the cirque floor.

<sup>2</sup>Maximum and minimum elevation of the cirque and elevation range.

<sup>3</sup>Cirque length. From the summit to the lower sector measured on the map. It is necessary to consider that many cirques are wider than they are long.

<sup>4</sup>Aspect. It is necessary to consider that many cirques do not coincide with the head of the valley where they are located, but rather they are housed on one of its slopes with a more appropriate orientation for the accumulation of snow.

<sup>5</sup>Deglaciation age of the cirque according to the CRE ages obtained from bedrock outcrops on its bottom.

<sup>6</sup>Number of moraines and their CRE age in ka or CE located into the cirque. When no moraine ages are available, the age corresponds to dated bedrock surfaces.

<sup>8</sup>Rock glaciers and protalus lobe located in the cirque and the stabilization CRE age of its front and its root, when available.

<sup>9</sup>Neoglacial landforms present in the cirque.

Table 4. Location, main topographic characteristics, geomorphological units, and average CRE ages of the cirques studied in the rest of Iberian Peninsula (outside Sierra Nevada). All CRE ages are updated following [Oliva et al. \(2019\)](#).

Cirque/ Valley and rock type	Massif/ range <sup>1</sup>	Elevation (m a.s.l.) and geographic coordinates <sup>2</sup>	Aspect <sup>3</sup>	Deglaciation of the cirque (ka) <sup>4</sup>	Youngest: moraine/ bedrock landforms (ka) <sup>5</sup>	Distance from headwall to the youngest moraine (m)	Rock glacier/debris- covered glacier/other landforms (ka) <sup>6</sup>	Neoglacial landforms (ka) <sup>7</sup>	References
Cinco Lagunas/ Pinar (Granite)	Sierra de Gredos/ Central Range	2572 40°15'22"N 5°18'24"W	NNE	<b>16.3 ± 3.3</b> (n=2)	Bedrock <b>10.3 ± 1.3</b> (n=3)		Protalus rampart,	-	<a href="#">Palacios et al. (2011)</a>
Gredos (Granite)	Sierra de Gredos/ Central Range	2591 40°14'56"N 5°17'58"W	N	<b>15.9 ± 1.0</b> (n=2)				-	<a href="#">Palacios et al. (2012a)</a>
Cuerpo de Hombre (Granite)	Sierra de Gredos/ Central Range	2399 40°17'32"N 5°45'14"W	NW	<b>15.1 ± 1.0</b> (n=3)	Moraine <b>12.1 ± 1.2</b> (n=1)	600	Rock avalanche	-	<a href="#">Carrasco et al. (2015)</a>
Peñalara/ Lozoya (Gneis)	Sierra de Guadarrama/ Central Range	2428 40°50'60"N 3°58'1" W	ESE	<b>15.9 ± 1.0</b> (n=2)	Bedrock <b>11.7 ± 0.4</b> (n=1)		Proto-rock glacier <b>16.1 ± 2.5</b> (n=1)	-	<a href="#">Palacios et al. (2012b)</a>
Hoyo Grande/ Lozoya (Gneis)	Sierra de Guadarrama/ Central Range	2209 40°58'46"N 3°50'51"W	SE	<b>15,6 ± 0,6</b> (n=2)					<a href="#">Carrasco et al. (2016)</a>
San Lorenzo/ Najerilla (Conglomerat es)	Sierra de la Demanda/ Iberian Range	2271 42°14'33" N 2°58'22" W	SE	<b>16.1 ± 1.0</b> (n=2)			Debris-covered glacier <b>9.0 ± 0.4 (n=3)</b>	-	<a href="#">Fernández-Fernández et al. (2017)</a>
Mencilla/ Arlanzón (Conglomerat es)	Sierra de la Demanda/ Iberian Range	1932 42°11'9"N 3°18'44"W	NNE				Debris-covered glacier <b>6.5 ± 0.3 (n=8)</b>	-	<a href="#">Fernández-Fernández et al. (2017)</a>
Peña Negra/ Mayor (Conglomerat es)	Sierra de la Cebollera/ Iberian Range	2023 m 42°2'39" 2°45'35"W	ENE	<b>16.6 ± 1.0</b> (n=2)	Bedrock <b>13.5 ± 1.0</b> (n=1)		Rock glacier <b>15.1 ± 0.9</b> (n=3)	-	<a href="#">García-Ruiz et al. (2020a)</a>

Monasterio (Quartzites)	Montaña Central/Cantabria n Mountains	2019 43°5'1"N 5°20'24"W	N	<b>14.8 ± 0.5 (n=5)</b>			Rock glacier <b>13.7 ± 0.5 (n=5)</b>	-	Rodríguez- Rodríguez et al. (2017)
Silván (Quartzites)	Montaña Central/Cantabria n Mountains	1935 43°2'31"N 5°21'14"W	ENE				Rock glacier <b>16.2 ± 0.6 (n=5)</b>	-	Rodríguez- Rodríguez et al. (2016)
Malniu-Guils cirques (Granite)	Cerdanya/ Eastern Pyrenees	2692 42°29'8"N 1°47'31"E	S	<b>14.8 ± 2.0 (n=1)</b>			Rock glacier <b>14.7 ± 1.6 (n=1)</b>	-	Andrés et al. (2019)
Perafita/ Arànsér (Granite)	Cerdanya/ Eastern Pyrenees	2761 42°26'59"N 1°34'53"E	E	<b>13.7 ± 0.5 (n=1)</b>	Moraine <b>12.6 ± 1.7 (n=1)</b>		Rock glacier From <b>14.7 ± 2.1</b> to <b>8.6 ± 1.1</b>	-	Andrés et al, (2019)
Bassiès/ Escale (Granite)	Eastern Pyrenees	2763 42°37'0"N 1°57'34"E	N	<b>15.8 ± 1.7 (n=2)</b>	Moraine <b>11.7± 1.5(n=2)</b>	1200		-	Crest et al. (2017); Tomkins et al. (2018)
Rec de la Grava/ (Granite)	Cerdanya/ Eastern Pyrenees	2763 42°37'7"N 1°57'16"E	S		Bedrock <b>11.5 ± 2.0 (n=3)</b>	1100		-	Crest et al. (2017); Tomkins et al. (2018)
Picot Ariège valley (Granite)	Eastern Pyrenees	2797 42°40'34"N 1°28'55"E	NW	<b>15.5 ± 0.7 (n=4)</b>	Bedrock <b>8.4± 0.5 (n=1)</b>		Rock glacier From <b>7.2± 0.4</b> to <b>1.4 ± 0.2</b>	-	Jomelli et al. (2020)
Médécourbe/ Ariège valley (Granite)	Eastern Pyrenees	2914 42°36'13"N 1°26'31"E	N	<b>13.2 ± 0.7 (n=2)</b>	Bedrock /moraine <b>9.9± 0.7 (n=3)</b>			-	Jomelli et al. (2020)
Mulleres* /Noguera Ribagorçana (Granite)	Central Pyrenees	3010 42°37'44"N 0°41'54"E	E	<b>13.7 ± 0.9 (n=3)</b>	Moraine <b>10.3 ± 0.3 (n=2)</b>			-	Pallàs et al. (2006)
Bessiberri* /Noguera Ribagorçana (Granite)	Central Pyrenees	3017 42°35'41"N 0°49'13"E	W	<b>16.3 ± 2.2 (n=1)</b>	Moraine <b>10.1 ± 0.2 (n=2)</b>			Rock glacier (active)	Pallàs et al. (2006)



Maladeta/ Esera (Granite)	Central Pyrenees	3323 42°38'47"N 0°38'25" E	N	<b>13.7 ± 1.4</b> (n=2)	Bedrock /moraine <b>11.8 ± 1.1</b> (n=2)	1200		From <b>4.5 to LIA</b> moraine	Crest et al. (2017); Tomkins et al. (2018)
Marboré/ Pineta (Sandstones)	Central Pyrenees	3348 42°40'32"N 0°2'4E	N					<b>5.6 ± 0.6</b> <b>3.6 ± 0.4</b> <b>1.1 ± 0.1</b> and <b>LIA</b> moraines	García-Ruiz et al. (2014)
Arrémoulit/ Osseau (Granite)	Central Pyrenees	2821 42°50'5" N 0°19'51"W	N		Bedrock <b>10.2 ± 0.9</b> (n=2)			-	Palacios et al. (2017a)
Balaitus/ Aguas Limpías (Granite)	Central Pyrenees	3147 42°50'20"N 0°17'25"W	S	<b>14.6 ± 2.0</b>	Bedrock <b>11.0 ± 1.4</b> (n=2)			LIA moraine	Palacios et al. (2017a)
Bachimaña/ Caldarés (Granite)	Central Pyrenees	2728 42°47'54"N 0°13'2"W	S	<b>12.9 ± 1.5</b> (n=3)				-	Palacios et al. (2017a)
Brazato/ Caldarés (Granite)	Central Pyrenees	2722 42°44'21"N 0°12'33"W	NNW	<b>14.5 ± 1.2</b>	Bedrock <b>11.4 ± 0.8</b>		Rock glacier <b>6.1 ± 0.3 (n=2)</b>	-	Palacios et al. (2017a)
Catieras/ Caldarés (Granite)	Central Pyrenees	2564 42°43'4"N 0°11'18"W	W	<b>15.9 ± 1.6</b>	Moraine <b>10.9 ± 1.2</b>	600	Rock glacier <b>12.0 ± 1.3 (n=3)</b>	-	Palacios et al. (2017a)
Piniecho/ Caldarés (Granite)	Central Pyrenees	2696 42°43'43"N 0°12'12"W	W	<b>15.6 ± 2.3</b> (n=4)	Moraine <b>12.4 ± 1.9</b>	500	Rock glacier <b>13.0 ± 1.3 (n=4)</b>	-	Palacios et al. (2017a)

<sup>1</sup>Name of the cirque within the mountain range.

<sup>2</sup> Elevation and geographic coordinates of the highest summit of the cirque.

<sup>3</sup>Main aspect of the cirque.

<sup>4</sup>CRE age showing the deglaciation of the cirque. Note that small glaciers may have remained at the foot of the cirque walls. All ages are related to the bedrock and/or moraines distributed at the mouth of the cirque.

<sup>5</sup>CRE ages indicating the final deglaciation of the cirque. All ages correspond to bedrock or moraines located in the highest parts of the cirque.

<sup>6</sup>CRE ages reporting the stabilization of the rock glacier fronts. If there are two ages, the second one corresponds to the stabilization of the roots of the rock glacier. Other debris landforms (debris-covered glacier, protalus rampart, rock avalanches, etc.) located in the cirque floor are also included, with their age of stabilization.

<sup>7</sup>Existence of landforms generated by Neoglacial advances with the available CRE ages, if existing.

Table 5. Location, main topographic characteristics, geomorphological units, and average CRE ages of the cirques studied in the Mediterranean region (Iberian Peninsula not included). All CRE ages are updated.

Cirque/ Valley	Massif/ range <sup>1</sup>	Elevation (m a.s.l.) and coordinates <sup>2</sup>	Aspect <sup>3</sup>	Deglaciation of the cirque (ka) <sup>4</sup>	Youngest moraine (ka) <sup>5</sup>	Distance from headwall to the youngest moraine (m)	Rock glacier landforms (ka) <sup>6</sup>	Neoglacial landforms (ka) <sup>7</sup>	References
Kisbe/ Sayacak	Mt. Dedegol Mts Taurus Anatolia Pen.	2750 37°40'40"N 31°15'16"E	N		<b>11.5 ± 1.1</b> (n=2)	2500			Köse et al. (2019)
Karagol	Mt. Dedegol Mts Taurus Anatolia Pen.	2900 37°38'35"N 31°17'25"E	E	<b>15.8 ± 1.6</b> (n=1)	<b>12.0 ± 1.0</b>	1800			Köse et al. (2019)
North Çimi	Central Taurus Anatolia Pen.	2411 36°57'21"N 31°59'32"E	E	<b>13.7 ± 0.8</b> (n=1)	<b>8.1 ± 0.9*</b> (n=2)	1500			Sarıkaya et al. (2017)*
South Çimi	Central Taurus Anatolia Pen.	2411 36°57'28"N 31°58'55"E	E	<b>14.9 ± 1.4</b> (n=5)	<b>7.3 ± 0.6*</b> (n=4)	2500			Sarıkaya et al. (2017)*
Güneycik	Central Taurus Anatolia Pen.	2440 37°1'41"N 31°59'24"E	E	<b>14.5 ± 1.7</b> (n=4)				<b>5.9 ± 0.5</b> (n=4)	Sarıkaya et al. (2017)
Çündüre	Central Taurus Anatolia Pen.	2638 36°58'40"N 32°1'46"E	NE	<b>14.9 ± 2.3</b> (n=3)					Sarıkaya et al. (2017)
Megala Kazania	Mount Olympus Balkans	2918 40°05'0"N 22°21'0"E	NNE	<b>13.8 ± 1.4</b> (n=3)	<b>12.0 ± 0.8</b> (n=2)	800			Styllas et al. (2018)
Throne of Zeus	Mount Olympus Balkans	2918 40°05'30"N 22°21'30"E	NNW	<b>14.0 ± 1.0</b> (n=4)				<b>2.5 ± 0.3</b> (n=4) and <b>LIA</b>	Styllas et al. (2018)
Velez Mountain	Dinaric Mts.	1965 43°19'02"N 18°2'6"E	N	<b>14.9 ± 1.1</b> (n=2)					Zebre et al. (2019)

Irhzer n'Likemt	Akusal Atlas Mts. Morocco	3555 31°7'39"N 7°49'56"W	N		<b>12.9 ± 0.7</b> <b>(n=2)</b>	1200			Hughes et al. (2018)
Azib Mzik	Akusal Atlas Mts. Morocco	3129 31°6'53"N 7°56'28"W	NE		<b>11.8 ± 0.6</b> <b>(n=3)</b>	800			Hughes et al. (2018)

<sup>1</sup>Name of the cirque within the mountain range.

<sup>2</sup> Elevation and geographic coordinates of the highest summit of the cirque.

<sup>3</sup>Main aspect of the cirque.

<sup>4</sup>CRE age showing the deglaciation of the cirque, though small glaciers may have remained at the foot of the cirque walls. All ages are related to the bedrock and/or moraines distributed at the mouth of the cirque.

<sup>5</sup>CRE ages indicating the final deglaciation of the cirque. All ages correspond to bedrock or moraines located in the highest parts of the cirque.

<sup>6</sup>CRE ages reporting the stabilization of the rock glacier fronts. If there are two ages, the second one corresponds to the stabilization of the roots of the rock glacier.

<sup>7</sup>Existence of landforms generated by Neoglacial advances with the available CRE ages, if existing.

\* These moraines are not included in the statistical analysis of the Fig. 11, as they are considered exceptional. Ages obtained in limestone under heavy erosion.

Table 5. Location, main topographic characteristics, geomorphological units, and CRE ages of the cirques studied in the Central European region (outside Sierra Nevada). All CRE ages are updated.

Cirque/ Valley	Massif/ range <sup>1</sup>	Elevation (m a.s.l.) and coordinates <sup>2</sup>	Aspect <sup>3</sup>	Deglaciation of the cirque (ka) <sup>4</sup>	Youngest moraine (ka) <sup>5</sup>	Distance from headwall to the youngest moraine (m)	Rock glacier landforms (ka) <sup>6</sup>	Neoglacial landforms (ka) <sup>7</sup>	References
North Mohoru	Parâng Mts. Romanian Carpathians	2365 45°20'27"N 23°36'25"E	N	<b>13.2 ± 1.1 ka</b> (n=5)	<b>11.8 ± 0.2 ka</b> (n=2)	500			Gheorghiu et al. (2015)
Zanoaga Mare	Parâng Mts. Romanian Carpathians	2278 45°21'4"N 23°31'60"E	N	<b>13.7 ± 1.2 ka</b> (n=4)	<b>11.0 ± 0.9 ka</b> (n=2)	800			Gheorghiu et al. (2015)
Galcescu	Parâng Mts. Romanian Carpathians	2519 45°20'24"N 23°32'25"E	N	<b>15.2 ± 1.3</b> (n=1)	<b>12.0 ± 1.1 ka</b> (n=3)	800			Gheorghiu et al. (2015)
Spitze Rumer Spitze	Karwendel Mts. North Alps	2454 47°19'13"N 11°25'35"E	N				<b>From 12.4 ± 0.4 to 9.6 ± 0.6</b> (n=7)		Moran et al. (2016)
Mandlspitze	Karwendel Mts. North Alps	2370 47°19'7"N 11°24'25"E	N				<b>10.9 ± 0.8</b> (n=4)		Moran et al. (2016)
Nefcerská	High Tatra Western Carpathians	2428 49°10'14"N 20°1'37"E	N	<b>14.2 ± 0.4</b> (n=2)			<b>11.3 ± 0.9</b> (n=3)		Zasadni et al. (2020)
Suchá važecká	High Tatra Western Carpathians	2350 49°9'47"N 20°0'48"E	S	<b>14.9 ± 1.4</b> (n=2)			<b>10.9 ± 1.0</b> (n=3)		Zasadni et al. (2020)
Mlynická	High Tatra Western Carpathians	2428 49°10'14"N 20°1'37"E	N				<b>10.4 ± 0.7</b> (n=3)		Zasadni et al. (2020)
Hincova	High Tatra Western Carpathians	2438 49°11'11"N 20°3'38"E	SE	<b>14.8 ± 0.5</b> (n=1)			<b>11.9 ± 0.7</b> (n=3)		Zasadni et al. (2020)

Kasprowy Wierch Bystra	High Tatra Western Carpathians	1987 49°13'55"N 19°58'54"E	N	<b>14.4±0.9 ka (n=4)</b>					Makos et al. (2018)
Sucha Woda	High Tatra Western Carpathians	2235 49°13'6"N 20°1'45"E	N	<b>15.5±0.4 ka (n=5)</b>					Makos et al. (2018)
Biata Woda	High Tatra Western Carpathians	2300 49°13'10"N 20°0'34"E	N	<b>15.2±0.9 ka (n=10)</b>					Makos et al. (2018)
Piec Stawow Polskich valley	High Tatra Western Carpathians	2503 49°10'46"N 20°5'16"E	N	<b>15.1±0.7 ka (n=5)</b>	<b>10.9±0.6 ka (n=5)</b>	700			Makos et al. (2018)
Velká Studená	High Tatra Western Carpathians	2383 49°10'59"N 20°8'40"E	E	<b>15.2 ± 0.5 (n=4)</b>					Engel et al. (2015)
Malá Studená	High Tatra Western Carpathians	2627 49°12'9"N 20°11'46"E	SE	<b>13.9 ± 0.5 (n=1)</b>	<b>11.2 ± 0.5 (n=1)</b>	500			Engel et al. (2015)
Sněžka Úpa valley	Krkonoše Mountains	1602 50°44'10"N 15°44'25"E	S	<b>15.3 ± 0.5 (n=1)</b>					Engel et al. (2017)
Snowy cirque	Krkonoše Mountains	1509 50°46'39"N 15°34'03"E	NE	<b>15.4 ± 1.8 (n=1)</b>	<b>12.9 ± 0.7 (n=1)</b>	400			Engel et al. (2017)

<sup>1</sup>Name of the cirque within the mountain range.

<sup>2</sup> Elevation and geographic coordinates of the highest summit of the cirque.

<sup>3</sup>Main aspect of the cirque.

<sup>4</sup>CRE age showing the deglaciation of the cirque, though small glaciers may have remained at the foot of the cirque walls. All ages are related to the moraines distributed at the mouth of the cirque.

<sup>5</sup>CRE ages indicating the final deglaciation of the cirque. All ages correspond to moraines located in the highest parts of the cirque.

<sup>6</sup>CRE ages reporting the stabilization of the rock glacier fronts. If there are two ages, the second one corresponds to the stabilization of the roots of the rock glacier.

<sup>7</sup>Existence of landforms generated by Neoglacial advances with the available CRE ages, if existing.

Table 7. Location, main topographic characteristics, geomorphological units, and average CRE ages of the cirques studied in the British Isles and Iceland. All CRE ages are updated.

Cirque/ Valley	Massif/ Range <sup>1</sup>	Elevation (m a.s.l.) and coordinates <sup>2</sup>	Aspect <sup>3</sup>	Deglaciatio n of the cirque (ka) <sup>4</sup>	Youngest moraine/ bedrock (ka) <sup>5</sup>	Distance from headwall to the youngest moraine (m)	Rock glacier landforms (ka) <sup>6</sup>	Neoglacial landforms <sup>7</sup>	References
Corranabinna Lough	Mayo Western Ireland	670 53°57'40"N 9°41'15"W	NNE	<b>15.4 ± 1.1 (n=4)</b>					<a href="#">Barth et al. (2018)</a>
Glascairns Hill	Donegal NW Ireland	580 54°46'15"N 8° 1'42"W	NE	<b>15.9 ± 1.1 (n=8)</b>	<b>12.0 ± 0.9 (n=4)</b>	850			<a href="#">Barth et al. (2018)</a>
Logaharry Lough	Mayo Western Ireland	620 53°37'38"N 9°42'10"W	NE	<b>14.2 ± 1.2 (n=4)</b>					<a href="#">Barth et al. (2018)</a>
Sruhauncullin more	Mayo Western Ireland	803 53°38'29"N 9°47'31"W	NE		<b>11.4 ± 1.0 (n=4)</b>	950	<b>12.5 ± 1.1 (n=5)</b>		<a href="#">Barth et al. (2018)</a>
Keskadale/ Newlands	Derwent Fells/ Lake District British Isles	734 54°32'30"N 3°14'8"W	N		<b>12.4±1.0 ka (n=2)</b>	600			<a href="#">Hughes et al. (2019)</a>
Ling Comb	Derwent Fells/ Lake District British Isles	737 54°31'52"N 3°18'24"W	E		<b>11.9±1.3 ka (n=4)</b>	300			<a href="#">Hughes et al. (2019)</a>
Fremri- Grjótárdalur West	Tröllaskagi Northern Iceland	1183 65°42'47"N 19°0'6.32"W	N		<b>11.3 ± 1.1 (n=2)</b>	1500	<b>10.8 ± 1.0 (n=2)</b>	Active rock glaciers	<a href="#">Fernández- Fernández et al. (2020)</a>
Fremri- Grjótárdalur East	Tröllaskagi Northern Iceland	1183 65°42'47"N 19°0'6.32"W	N				<b>9.4 ± 1.1 (n=2)</b>	Active rock glaciers	<a href="#">Fernández- Fernández et al. (2020)</a>
Hólajökull	Tröllaskagi Northern Iceland	65°42'7"N 18°57'2"W	N		<b>10.7 ± 1.0 (n=2)</b>	3000		Active debris covered glacier	<a href="#">Fernández- Fernández et al. (2020)</a>



<sup>1</sup>Name of the cirque within the mountain range.

<sup>2</sup> Elevation and geographic coordinates of the highest summit of the cirque.

<sup>3</sup>Main aspect of the cirque.

<sup>4</sup>CRE age showing the deglaciation of the cirque. Note that small glaciers may have remained at the foot of the cirque walls. All ages are related to the bedrock and/or moraines distributed at the mouth of the cirque.

<sup>5</sup>CRE ages indicating the final deglaciation of the cirque. All ages correspond to bedrock or moraines located in the highest parts of the cirque.

<sup>6</sup>CRE ages reporting the stabilization of the rock glacier fronts. If there are two ages, the second one corresponds to the stabilization of the roots of the rock glacier.

<sup>7</sup>Existence of landforms generated by Neoglacial advances with the available CRE ages, if existing.

Table 8. Location, main topographic characteristics, geomorphological units, and average CRE ages of the cirques studied in the Western North America. All CRE ages are updated.

Cirque/ valley	Massif/ range <sup>1</sup>	Elevation (m a.s.l.) and coordinates <sup>2</sup>	Aspect <sup>3</sup>	Deglaciation of the cirque (ka) <sup>4</sup>	Youngest moraine/ bedrock (ka) <sup>5</sup>	Distance from headwall to the youngest moraine (m)	Rock glacier landforms (ka) <sup>6</sup>	Neoglacial landforms <sup>7</sup>	References
Little Anapurna/ Inspiration Lake	Central Cascades Washington	2660 47°28'8"N 120°48'50"W	NE		<b>10.7 ± 0.6</b> (n=5)	1200			Marcott et al. (2019)
Solicitude Lake	Teton Range Wyoming	3209 43°48'14"N 110°50'52"W	E		<b>12.8 ± 0.4</b> (n=3)	1300			Licciardi et al. (2008); Marcott et al. (2019)
Roaring Fork Stough Creek	Wind River Range Wyoming	3720 42°38'2"N 109°1'29"W	NE		<b>12.8 ± 0.7</b> (n=4)	700	<b>Proto-rock glacier</b> <b>9.6 ± 0.5</b> (n=7)	Active rock glacier	Marcott et al. (2019)
Temple lake	Wind River Range Wyoming	3953 42°41'55"N 109°10'15"O	NW	<b>14.0 ± 1.0</b> (n=7)					Marcott et al. (2019)
Medicine Bow	Rocky Mts, Wyoming	3580 41°20'36"N106° 19'51"W	E	<b>14.5 ± 0.7</b> (n=6)	<b>11.5 ± 0.7</b> (n=6)	600	<b>Proto-rock glacier</b> <b>10.5 ± 0.6</b> (n=6)		Marcott et al. (2019)
Agassiz/ Blue Lake	Uinta Mts., Utah	3788 40°42'39"N 110°49'30"W	E	<b>14.4 ± 0.7</b> (n=6)					Marcott et al. (2019)
Dead Horse Lake	Uinta Mts., Utah	3650 40°44'24"N 110°40'48"W	NE	<b>13.4 ± 0.7</b> (n=6)	<b>11.8 ± 0.6</b> (n=6)	600	<b>Proto-rock glacier</b> <b>10.5 ± 0.5</b> (n=6)		Marcott et al. (2019)
Arapahoe Cirque	Colorado Front Range	4115 40°01'35"N 105°39'01"W	E		<b>11.6 ± 0.5</b> (n=6)	1800	<b>Inner moraine</b> <b>10.0 ± 0.6</b> (n=6)		Marcott et al. (2019)

Warren Mt. Chicago lakes	Colorado Front Range	4055 39°36'19"N 105°37'59"W	NE	<b>15.2 ± 0.7 (n=5)</b>					Marcott et al. (2019)
Wheeler	South Snake Range Nevada	3982 38°59'10"N 114°18'48"W	NE		<b>12.5 ± 1.3 (n=6)</b>	1800		Active rock glacier	Marcott et al. (2019)
Mount Thompson Boon lakes	Sierra Nevada California	4112 37°8'35"N 118°36'48"W	N		<b>12.5 ± 0.8 (n=5)</b>	2800			Marcott et al. (2019)
Badly/ Katherine	Sangre de Cristo Mts, New Mexico.	3840 35°49'57"N105° 45'28"W	SE	<b>15.1 ± 0.8 (n=10)</b>					Marcott et al. (2019)

<sup>1</sup>Name of the cirque within the mountain range.

<sup>2</sup> Elevation and geographic coordinates of the highest summit of the cirque.

<sup>3</sup>Main aspect of the cirque.

<sup>4</sup>CRE age showing the deglaciation of the cirque. Note that small glaciers may have remained at the foot of the cirque walls. All ages are related to the bedrock and/or moraines distributed at the mouth of the cirque.

<sup>5</sup>CRE ages indicating the final deglaciation of the cirque. All ages correspond to bedrock or moraines located in the highest parts of the cirque.

<sup>6</sup>CRE ages reporting the stabilization of the rock glacier fronts. If there are two ages, the second one corresponds to the stabilization of the roots of the rock glacier.

<sup>7</sup>Existence of landforms generated by Neoglacial advances with, if existing, the available CRE ages.