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1 **Climate patterns during former periods of mountain glaciation in Britain and Ireland:**
2 **inferences from the cirque record**

3

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16

17 **Abstract**

18 We map glacial cirques, and analyse spatial variability in their altitude and aspect to derive a
19 long-term, time-integrated, perspective on climate patterns during former periods of mountain
20 glaciation (likely spanning multiple Quaternary glaciations) in Britain and Ireland. The data reveal
21 that, although air temperatures were important, exposure to moisture-bearing air masses was the key
22 factor in regulating sites of former mountain glacier formation, and indicate that during such periods,
23 moisture supply was largely controlled by North Atlantic westerlies, with notable inland precipitation
24 gradients (precipitation decreasing inland), similar to present day. In places, trends in cirque altitude
25 may also reflect regional differences in the extent of cirque deepening, controlled by the dimensions
26 and dynamics of the glaciers that came to occupy them. Specifically, comparatively deep cirques in
27 coastal locations may reflect the former presence of dynamic (fed by moisture from the North
28 Atlantic), but comparatively small, glaciers (largely confined to their cirques). By contrast, decreasing

29 cirque depth further inland, may reflect the former presence of larger and/or less dynamic ice masses,
30 occupying comparatively continental climatic conditions.

31

32 **Keywords**

33 Quaternary; glaciation; NE Atlantic; precipitation; glacial cirque

34

35 **1. Introduction**

36 The synoptic climate of Britain and Ireland (Fig. 1) is dominated by the interaction of polar and
37 tropical air masses, and the mid-latitude westerlies that form at their boundary (Hurrell and Deser,
38 2010). The key variable in determining the region's climate is therefore the position, stability and
39 strength of this boundary, marked by the polar front jet stream (PFJS: a high-altitude band of strongest
40 air-flow within the zone of mid latitude westerlies). At present, the average track of the PFJS is to the
41 north of Scotland, meaning that Britain and Ireland lie in the direct path of mid-latitude moisture-
42 bearing westerlies. This results in strong W–E precipitation gradients, which, in Britain, are subject to
43 notable orographic enhancement, since much of the high ground is towards the North and West
44 (Mayers and Wheeler, 2013) (Fig. 1). As a result of this topographic control, the W–E precipitation
45 gradients are typically strongest in Scotland, and notably weaker across Ireland (Fig. 1B). Similarly,
46 trends in mean annual air temperature are largely determined by topography, with notable altitudinal
47 cooling (Fig. 1C). There is also a general cooling with latitude (Fig. 1C), but this latitudinal cooling is
48 often difficult to differentiate from the control exerted by topography.

49 Though these climatic patterns currently prevail, the position, stability and strength of the PFJS
50 vary not only seasonally and annually, but over much longer time periods (centuries to millennia).
51 This variability is linked to North Atlantic sea surface temperatures, sea-ice extent, thermohaline
52 circulation, and the extent of glaciation over North America and NW Europe (McManus et al., 1999).
53 As such, synoptic climate patterns over Britain and Ireland are subject to change over multiple
54 timescales. This is likely to have been particularly true during former periods of glaciation, when the
55 growth of glaciers, and the expansion of sea-ice had a dramatic impact on North Atlantic climate
56 (Renssen and Isarin, 1997; Renssen and Vandenberghe, 2003; Golledge et al., 2010). During the

57 Younger Dryas Stadial (c. 12.9–11.7 ka), for example, when much of Britain and Ireland experienced
58 mountain and ice cap glaciation, it has been suggested that the southward displacement of the PFJS
59 and associated increase in NE Atlantic sea-ice extent, resulted in accumulation season (winter) aridity
60 in NW Europe (Renssen and Isarin, 1998; Renssen and Vandenberghe, 2003; Golledge et al., 2010).

61 While glacial deposits (e.g., landforms and sediments) are useful for inferring full glacial
62 conditions, less is known about conditions during smaller scale glaciations, partly because relevant
63 evidence is commonly removed by subsequent, more extensive, glacial advances (Kirkbride and
64 Winkler, 2012). In Britain and Ireland, this is particularly true of evidence relating to periods prior to
65 the local Last Glacial Maximum (LGM, c. 27 ka), when much of the region was occupied by the
66 British-Irish Ice Sheet (BIIS) (Clark et al., 2012). Fortunately, the altitude and aspect of glacial
67 cirques (hereafter ‘cirques’), armchair-shaped hollows formed by the erosive action of mountain
68 glaciers (Fig. 2), are a potential source of this information, since their distribution is largely
69 determined by climatic patterns during periods of glacier initiation (Barr and Spagnolo, 2015a), while
70 their dimensions (including their depth) are largely determined by glacial erosion over tens of
71 thousands of years (often continued in successive glacial cycles), which is likely maximised during
72 the onset and termination of periods of glaciation (Crest et al., 2017). To make use of this potential,
73 we map cirques across Britain and Ireland, and analyse their distribution (altitude and aspect) to
74 obtain information about climate patterns during periods of mountain glaciation (when occupied by
75 small glaciers). We do not conduct detailed analysis of cirque morphometry (size and shape), though
76 these data are presented in Clark et al. (in press). Many of these cirques have been mapped previously
77 (Table 1), but most studies were conducted prior to the widespread development and implementation
78 of remote sensing and geographical information system (GIS) based techniques (e.g., Federici and
79 Spagnolo, 2004; Spagnolo et al., 2017). This is therefore the first study to systematically map and
80 analyse cirques across Britain and Ireland and to consider their regional palaeoclimatic implications.

81

82 **2. Methods**

83 **2.1. Cirque identification and mapping**

84 Cirques (defined according to Evans and Cox, 1974) were mapped from Bing Maps aerial
85 imagery, Google Earth, and three digital elevation models (DEMs): SRTM (horizontal resolution ~30
86 m, vertical accuracy ~16 m), ASTER GDEM (horizontal resolution 30 m, vertical accuracy ~17 m),
87 and NEXTMap Great Britain™ (horizontal resolution 5 m, vertical accuracy ~0.5 m). Each of these
88 sources was used to map or visualise every cirque, with the exception of the NEXTMap DEM, which
89 was not used in Ireland (due to lack of coverage). Cirques were identified as large hollows,
90 occupying valley-head or valley-side settings, bounded upslope by arcuate (in plan) headwalls but
91 open down-valley (Fig. 2). Cirque headwalls curve around floors which slope more gently than the
92 surrounding topography. Cirque lower limits are often marked by convex breaks-of-slope, referred to
93 as a ‘thresholds’ (Evans and Cox, 1995), sometimes occupied by frontal moraines, marking the
94 transition from shallow cirque floors to steeper topography below. Where thresholds were lacking,
95 lower limits were drawn to coincide with the extent of cirque lateral spurs (Evans and Cox, 1995; Barr
96 and Spagnolo, 2015a).

97 Though an attempt was made to map all cirques, some subtle examples will undoubtedly be
98 missing from the database. These cirques may resemble mass movement scars, or be difficult to
99 identify from the remotely-sensed sources used here. In addition, there are situations where features of
100 non-glacial origin (e.g., nivation hollows) will have been erroneously included in the database. To
101 minimise such errors, much of the mapping was validated through comparison with published sources
102 (Table 1).

103

104 **2.2. Cirque metrics and attributes**

105 For each cirque, metrics were calculated using the Automated Cirque Metric Extraction
106 (ACME) GIS tool of Spagnolo et al. (2017). For the purposes of this investigation, we focus on cirque
107 minimum altitude (Z_{\min}) and mean aspect. Metric calculations are based on the SRTM DEM, since
108 these data provide coverage for the entire cirque dataset. In order to validate the use of this DEM,
109 metrics for cirques in Britain were also calculated using the ASTER GDEM and NEXTMap Great
110 Britain™ (Ireland was excluded because of lack of NEXTMap data). Analysis of variance revealed no
111 significant differences between results from the three DEMs ($p = 0.869$ for Z_{\min} and 0.503 for aspect).

112 In order to understand controls on cirque altitudes, and to assess the degree to which patterns
113 in Z_{\min} reflect palaeoclimatic conditions, relationships between Z_{\min} and aspect were analysed, as were
114 relationships between Z_{\min} and a number of cirque attributes. This approach of analysing statistical
115 relationships between cirque altitudes, aspect and attributes has been used previously to analyse the
116 palaeoclimatic implications of cirque populations elsewhere (Principato and Lee, 2014; Barr and
117 Spagnolo, 2015b). In the present study, the attributes recorded for each cirque include location
118 (coordinates), given by northing and easting, in km (measured from the centre point of each cirque,
119 and recorded as OS British National Grid coordinates, extended to cover Ireland); the shortest
120 distance from each cirque centre point to the modern coastline (in kilometres, calculated using the
121 ArcGIS Euclidean distance tool); the shortest distance from each cirque centre point to the coastline
122 directly to its west (270°N). Cirque northing is measured on the assumption that it represents a very
123 general proxy for spatial patterns in temperature, while easting, and distance from the coastline are
124 likely to reflect general proxies for patterns in precipitation (in this region dominated by North Atlantic
125 westerlies). In addition, the dominant bedrock lithology of each cirque (i.e., the geological unit which
126 accounts for the greatest surface area) was recorded. Information about bedrock lithology was based
127 on GIS data from the British Geological Survey 1:625,000 scale Digital Geological Map of Great
128 Britain (DiGMapGB-625, v.50, downloaded from the BGS) (2016) and the Geological Survey Ireland
129 (McConnell and Gatley, 2006) 1:500,000 bedrock geology map of Ireland (downloaded from the
130 GSI). To simplify the analysis, 34 geological units were categorised into 7 broader classes (Fig. 3).

131

132

133 **3. Results**

134 **3.1. Cirque distribution**

135 A total of 2208 cirques were identified and mapped throughout the mountains of Scotland (n
136 = 1139), Wales (n = 260), Northern England (n = 172) (plus one cirque in Exmoor), and around the
137 periphery of Ireland (n = 637) (Fig. 1D). Given the uneven distribution of cirques, it is worth noting
138 that patterns for the entire database (discussed below) are largely determined by cirques in Ireland and
139 Scotland (~80% of the total dataset). The cirque database has been incorporated in the BRITICE

140 version 2 Glacial Map (Clark et al. in press) and is available for scrutiny or download from this
141 source.

142

143 **3.2. Cirque altitudes**

144 Across the dataset, Z_{\min} ranges from 2 m to 1083 m, and shows notable spatial variability
145 (Fig. 1D). Z_{\min} shows statistically significant ($p < 0.01$) rises from west to east, south to north, and
146 with distance from the modern coastline (Fig. 4, Table 2). There is also a statistically significant
147 relationship between Z_{\min} and mean aspect, with Fourier (harmonic) regression (Evans and Cox, 2005)
148 revealing that Z_{\min} for WSW (259°) facing cirques is typically 71 m lower than those facing ENE
149 (079°) (Table 2). Multiple regression for easting, northing, and distance to the coastline (Table 2)
150 reveals that, for the entire dataset, the attribute most closely related to Z_{\min} is distance to the coastline
151 (t -value = 18.91), followed by northing (t -value = 15.91), then easting (t -value = 10.29). The
152 regression is not significantly improved by inclusion of aspect.

153 When sub-populations are considered independently, only cirques in Scotland and Wales
154 show statistically significant relationships between Z_{\min} and northing—with the former showing a
155 northward rise then strong decline in Z_{\min} , and the latter showing a weak, but statistically significant,
156 northward rise (Fig. 4A, Table 2). Cirques in Scotland and Ireland show statistically significant rises
157 in Z_{\min} from west to east, and with distance from the modern coastline (Fig. 4, Table 2). The eastward
158 rise in the altitudes of Scottish cirques was also illustrated and discussed by Linton (1959). Only
159 cirques in Scotland show a statistically significant relationship between Z_{\min} and mean aspect, with
160 Z_{\min} for WNW (284°) facing cirques typically 65 m lower than for those facing ESE (104°). Multiple
161 regression reveals that for Scotland, the attribute most closely related to Z_{\min} is distance to the
162 coastline (t -value = 7.66), followed by easting (t -value = 5.97); for Ireland, the attribute most closely
163 related to Z_{\min} is easting (t -value = 8.26), followed by distance to the coastline (t -value = 5.43); and
164 for Wales, the northward increase in Z_{\min} is the only statistically significant relationship (Table 2).
165 The English cirques, excluding Exmoor, are narrowly clustered in space and do not show significant
166 relationships.

167 When the shortest distance from each cirque centre point to the closest coastline directly to its
168 west is considered, Z_{\min} for the entire dataset shows a statistically significant rise then decline with
169 increasing distance (Fig. 4D). The rise in Z_{\min} is seen in both Scotland and Ireland, but the subsequent
170 decline is only seen in Ireland, and is largely controlled by comparatively low altitude cirques in
171 eastern Ireland (i.e., in the Mourne and Wicklow Mountains), although comparatively low altitude
172 cirques are also found in south-central Ireland and South Wales (Fig. 4D).

173

174 **3.3. Cirque aspect**

175 The entire cirque dataset shows a strong NE bias in aspect, with a population vector mean of
176 048.8° (Fig. 5). This NE bias is evident (with some variation) across the study area (Fig. 5), and is
177 observed for cirques in many other parts of the Northern Hemisphere (Evans, 1977). The entire
178 dataset has an aspect vector strength (VS, which highlights the extent of deviation from a uniform
179 distribution with aspect—see Evans, 1977) of 47% (Fig. 5). This is central to the range of results from
180 59 globally-distributed studies of cirque aspect summarised by Barr and Spagnolo (2015a) (table 4 in
181 their paper), where vector strength (excluding studies from Britain and Ireland) ranges from 18 to
182 91%, with a mean value of 54%. Cirque sub-populations in central and eastern Scotland, Wales and
183 England have vector strengths (46–59%) which are similar to this (biased) ‘global’ mean, whilst the
184 vector strength of cirques in Ireland and the islands of western Scotland are notably lower (30–37%)
185 (Fig. 5). Thus, vector strength generally increases from west to east (Fig. 5). Lower aspect vector
186 strengths along the Atlantic coast indicate that cirques in these areas have a greater tendency to face
187 varied directions. For example, by quadrant, Irish cirques account for 50% of the SW-facing total ($n =$
188 142), but only 23% of NE-facing total ($n = 1073$) (Table 3).

189 When cirques are grouped by Z_{\min} , a general altitudinal increase in population vector strength
190 is evident (Fig. 6). This likely reflects spatial variability in both cirque aspect and altitude (with low
191 vector strength and low Z_{\min} in coastal populations, and high vector strength and high Z_{\min} in interior
192 regions). In other populations globally, cirques typically show an altitudinal decrease in vector
193 strength (i.e., the opposite of the trend seen here), as marginal glacial conditions at low altitudes
194 largely restrict glacier formation to poleward-facing slopes (resulting in high vector strength), whilst

195 cooler temperatures at high altitudes allow glaciers to form on a range of slopes (resulting in low
196 vector strength) (Olyphant, 1977; Barr and Spagnolo, 2013).

197

198 **3.4. Cirque geology**

199 One-way analysis of variance (ANOVA) was used to estimate the variability in Z_{\min}
200 accounted for by different geological classes. These data indicate a statistically significant relationship
201 between Z_{\min} and geology (F-ratio = 97.7, F-crit = 2.1), though this is weakened (F-ratio = 8.9, F-crit
202 = 2.1) when detrended for the influence of northing, easting, and distance from the modern coastline
203 (using the regression equation from Table 2).

204

205 **4. Discussion**

206 The cirque record presented here indicates former sites of mountain glaciation in Britain and
207 Ireland. However, it is not possible to establish when glaciers first generated each cirque, not how
208 long they were ice-occupied, and this likely varied across the dataset (by region and altitude). Thus,
209 the record represents a time-integrated pattern of conditions during periods of mountain glaciation
210 (likely spanning multiple Quaternary glaciations). With this in mind, here we assess evidence for
211 climatic and non-climatic controls on the altitude and aspect of cirques in Britain and Ireland, before
212 considering the palaeoclimatic implications of the record.

213

214 **4.1. Climatic controls**

215 Based on cirque distribution (Fig. 1D), it is clear that air temperature (Fig. 1C) was an
216 important control on former sites of mountain glaciation in Britain and Ireland—with glaciation
217 favoured in the highest mountains, where temperatures are lowest (Fig. 1C and D). However, patterns
218 in Z_{\min} and cirque aspect indicate that exposure to moisture from the North Atlantic was also a key
219 control. For example, in Scotland and Ireland the strongest trends in Z_{\min} are the rise from west to
220 east; with distance from the coastline; and with distance from the closest coastline directly to the west
221 (Fig. 4). Scotland and Ireland thus fit a pattern found in other regions globally, where the altitudes of
222 former mountain glaciers (indicated by cirques) increases with distance from a dominant moisture

223 source (Peterson and Robinson, 1969; Hassinen, 1998; Principato and Lee, 2014; Barr and Spagnolo,
224 2015b). This pattern is thought to reflect restricted precipitation in interior (non-coastal) regions,
225 which confines mountain glaciers (and cirque formation) to higher altitudes, where cooler
226 temperatures limit melt and thereby compensate for reduced accumulation. At first glance, eastern
227 Ireland (i.e., the Mourne and Wicklow Mountains) and, to a lesser degree, south-central Ireland and
228 South Wales appear to be an exception to this, as cirque altitudes are generally low, given their distant
229 location from the closest coastline directly to the west (Fig. 4D). This may reflect the comparatively
230 weak orographic precipitation gradient in Ireland (Fig. 1B), combined with the influence of moisture
231 from the southwest.

232 Cirque aspect data (Fig. 5) reveal that former mountain glaciation was promoted on NE-
233 facing slopes, where direct solar radiation is minimised (limiting melt). However, in coastal areas
234 (i.e., in Ireland, and the islands of western Scotland), comparatively low vector strengths (Fig. 5)
235 appear to indicate that variations in direct solar radiation were less important, and that mountain
236 glaciers were able to occupy, and thereby form cirques on, other slopes, albeit in smaller numbers. In
237 regions further from the Atlantic coastline, vector strengths are higher, and there is a notable N/NE/E
238 bias in vector means (Fig. 5). The strong bias in these regions suggests that variations in direct solar
239 radiation (i.e., controls on ablation) were the dominant control on glacier aspect, with mountain
240 glacier development promoted on north-facing slopes, where direct solar radiation is lowest, and on
241 NE-facing slopes, which receive much of their direct solar radiation in the morning, when air
242 temperatures are relatively low (Evans, 1977, 2006). The eastward bias, particularly evident in areas
243 such as NW Wales (Fig. 5), potentially indicates that away from the North Atlantic, westerlies were
244 more important in the redistribution of snow, thereby promoting the formation of mountain glaciers
245 on leeward (east-facing) slopes, as well as acting as a source of direct precipitation. This implies that
246 North Atlantic westerlies, though still important in regulating sites of glacier development, were
247 comparatively moisture-starved by the time they reached such areas—implying a notable W–E
248 precipitation gradient. In addition, cirque aspect shows a tendency somewhat more eastward of NE at
249 higher altitudes, where lower temperatures and drier snow likely facilitated redistribution by wind
250 (Fig. 5).

251 In eastern and south-central Ireland, there is considerable variability in cirque aspect (VS =
252 34%, Fig. 5). Again, this likely reflects the comparatively weak precipitation gradients across Ireland,
253 combined with the influence of moisture from the southwest. Similarly, in South Wales, the strong
254 E/NE aspect bias in cirque aspect (VS = 69%, Fig. 5) may reflect the role of southwesterlies in
255 promoting glaciation on leeward (NE-facing) slopes (though it is difficult to differentiate between this
256 potential control and the role of direct solar radiation in promoting glacier formation on these slopes).
257 A broad distribution of aspects may also relate to the greater cloudiness of maritime climates.

258

259 **4.2. Non-climatic controls**

260 Despite potential climatic controls on cirque altitude and aspect (Section 4.1.), non-climatic
261 factors also need to be considered (Barr and Spagnolo, 2015a).

262 The first factor considered is topography, since high- and low-altitude mountain glaciers can
263 only form, and thereby generate cirques, where high- and low-altitude topography (respectively) exist.
264 Thus, the inland increase in Z_{\min} across Britain and Ireland (Fig. 4C), might, at least partly, reflect a
265 corresponding increase in topography (Peterson and Robinson, 1969; Hassinen, 1998). To assess this
266 potential, we compare Z_{\min} to the minimum and maximum altitudes within a 5 km radius of each
267 cirque, and plot values relative to distance from the modern coastline (Fig. 4C), on the assumption
268 that these data reflect regional trends in topography. Minimum altitudes show a general inland rise,
269 but maximum altitudes show no clear inland trend, and topography often extends well above Z_{\min}
270 (Fig. 4C). There is, therefore, little evidence to suggest that topography exerts a strong control on
271 cirque altitudes, and is not considered to fully account for observed trends in Z_{\min} .

272 The second factor to consider is geology, which has the potential to exert control on both cirque
273 altitude and aspect (Battey, 1960; Mîndrescu and Evans, 2014). For example, the relationships
274 between Z_{\min} and lithology (noted in Section 3.4.) might indicate a geological control on cirque
275 altitudes. However, since this relationship is comparatively weak, when detrended for the influence of
276 northing, easting, and distance from the modern coastline, it is not considered a dominant factor
277 regulating Z_{\min} across the dataset. It is also probable that this relationship reflects spatial variability in
278 both Z_{\min} and lithology. For example, in the mountains of central and eastern Scotland, where Z_{\min} is

279 comparatively high, cirque lithology is dominated by Psammite or Pelite, whereas Granite or Gneiss
280 cirques are typically found in lower altitude, coastal locations (Fig. 3). It is also possible that
281 geological structure (i.e., the alignment of mountain ranges) exerts control on cirque aspect by
282 regulating the orientation of slopes available for glacier development (Gordon, 2001; Evans, 2006;
283 Bathrellos et al., 2014). However, as ridges in each sub-region have a broad range of orientations,
284 structural controls are likely local and are not considered to affect the aspect statistics cited here.

285 The third factor considered here is the role of post-glacial uplift and subsidence and their
286 potential to displace cirques from the altitudes at which they were formed. This influence is most
287 important in tectonically active areas (Bathrellos et al., 2014), and, fortunately, both Britain and
288 Ireland have been tectonically stable during the Quaternary. However, glacial isostatic adjustment has
289 occurred, and its extent has been spatially and temporally variable (Bradley et al., 2011; Kuchar et al.,
290 2012). Of potential note for this study is the disparity between SW Ireland, where isostasy currently
291 results in subsidence rates of $\sim 0.5 \text{ mm a}^{-1}$, and central Scotland, where uplift is occurring at $\sim 1.5 \text{ mm}$
292 a^{-1} (Shennan et al., 2009). Assuming that glacier initiation occurred on a land surface unaffected by
293 glacial loading, this spatial variability is likely to have had some impact on trends in Z_{\min} . However,
294 Z_{\min} also varies even over comparatively small spatial scales (e.g., in western Scotland), where
295 differences in uplift are likely modest. Also, cirques in central Scotland (where glacial isostatic
296 depression was greatest) are presumably still depressed below the altitudes at which they formed,
297 while cirques in SW Ireland (where subsidence is currently occurring) are presumably elevated above
298 the altitudes at which they formed. Thus, if cirque altitudes were corrected for residual glacial
299 isostatic adjustment, this would strengthen the general SW–NE Z_{\min} gradient currently observed.

300 The final factor to be considered here is the possibility that trends in Z_{\min} , at least partly,
301 reflect spatial variability in the extent of cirque deepening. This is based on the premise that Z_{\min} is
302 controlled not only by the altitudes at which former glaciers initiated, but also by the extent to which
303 these glaciers eroded vertically. For example, given that documented cirque floor erosion rates range
304 from $\sim 0.076 \text{ mm yr}^{-1}$ to 5.9 mm yr^{-1} (Barr and Spagnolo, 2015a), over 100,000 years of glacial
305 occupation this would result in a $\sim 580 \text{ m}$ difference in depth between a heavily and minimally eroded
306 cirque. This would be sufficient to account for some Z_{\min} trends across Britain and Ireland. To test this

307 possibility, here we analyse trends in cirque depth (H) (i.e., maximum – minimum altitudes, see
308 Spagnolo et al., 2017), and make comparisons with trends in Z_{\min} .

309 When the entire dataset is considered, H shows a significant reduction from north to south,
310 and with distance from the modern coastline (Fig. 7). However, these relationships are not strong
311 (typically, $R^2 = 0.03\text{--}0.08$, Table 4), and the southward reduction in H (Fig. 7A), fails to explain the
312 corresponding decline in Z_{\min} (Fig. 4A). In Wales, relationships are stronger ($R^2 = 0.08\text{--}0.21$, Table
313 4), but, again, the dominant pattern is a southward reduction in H (Fig. 7A), which fails to explain the
314 corresponding decline in Z_{\min} (Fig. 4A).

315 Given the above, spatial trends in H are not considered to fully account for trends in Z_{\min} .
316 However, the consistent pattern of increasing H with proximity to the coastline (Fig. 7C and D) might
317 indicate that moisture availability in these areas not only promoted the initiation of comparatively low
318 altitude glaciers, but may also have resulted in glaciers that were comparatively efficient at cirque
319 deepening. Cirque deepening is often thought to be promoted by long-lasting (and/or repeated)
320 occupation by cirque-type glaciers (i.e., small glaciers confined to their cirques), and/or occupation by
321 particularly dynamic glaciers (Bathrellos et al., 2014; Barr and Spagnolo, 2015a). Thus, the increase
322 in H with proximity to the coastline might indicate that, during glacial cycles, cirques in these
323 locations were occupied by comparatively small glaciers (often confined to their cirques). This might
324 reflect marginal glacial conditions in these climatically less favourable (in terms of solar radiation)
325 low-altitude locations. By contrast, in regions such as central Scotland, cirques may have readily
326 become occupied by large (non cirque-type) glaciers (Golledge et al., 2008), which are often
327 considered inefficient at cirque deepening (Barr and Spagnolo, 2013). In addition, glaciers in coastal
328 locations may have been comparatively dynamic, with greater mass turnover and greater basal
329 velocities than elsewhere, since they occupied comparatively maritime climatic conditions. Thus,
330 cirque depth data might indicate that, during glacial cycles, cirques in coastal locations were more
331 often occupied by dynamic and/or cirque-type glaciers, while larger and/or less dynamic glaciers
332 dominated further inland.

333

334 **4.3. Palaeoclimatic inferences**

335 We suggest that patterns in cirque altitude and aspect across Britain and Ireland are not
336 controlled by variations in topography, geology or glacial isostasy, but largely reflect climatic
337 conditions during former periods of mountain glaciation, and are perhaps enhanced (in places) by
338 regional differences in the extent of cirque deepening. On this basis, the cirque record appears to
339 indicate that during periods of mountain glaciation, moisture supply across Britain and Ireland was
340 dominated by westerlies. The data suggest that during such periods precipitation patterns very similar
341 to present, with a general W–E gradient (strongest in Western Scotland), a S–N gradient in Wales, and
342 a more complex picture in eastern and South-Central Ireland. In addition, cirque depth data potentially
343 indicate former maritime conditions in coastal locations (promoting dynamic glaciation and cirque
344 deepening), with more continental conditions further inland (resulting in less dynamic glaciation and
345 limited cirque deepening)

346

347 **5. Conclusions**

348 In this study, glacial cirques are mapped and their altitudes and aspect analysed. These
349 attributes provide information about climate patterns during former periods of mountain glaciation in
350 Britain and Ireland. The main study findings are summarised as follows:

- 351 1. Cirque altitude and aspect indicate that although air temperatures were important,
352 exposure to moisture-bearing air masses was the key factor in regulating sites of former
353 mountain glaciation in Britain and Ireland (as would be expected in a maritime
354 environment). Non-climatic factors (including topography, geology, and isostasy) are also
355 likely to have had an impact, but do not explain region-wide patterns.
- 356 2. The record indicates that climatic patterns in Britain and Ireland were similar to present,
357 with moisture largely derived from North Atlantic westerlies, resulting in a notable W–E
358 precipitation gradient, which was strongest in western Scotland.
- 359 3. Trends in cirque altitude may also reflect regional differences in the extent of cirque
360 deepening—largely controlled by the dimensions and dynamics of the glaciers that came
361 to occupy them (likely during multiple Quaternary glaciations). Specifically,
362 comparatively deep cirques in coastal locations may reflect the former presence of

363 dynamic and/or cirque-type glaciers (occupying a maritime climate), while less-deep
364 cirques further inland may reflect the former presence of larger and/or less dynamic ice
365 masses (occupying more continental conditions).

366

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370

371

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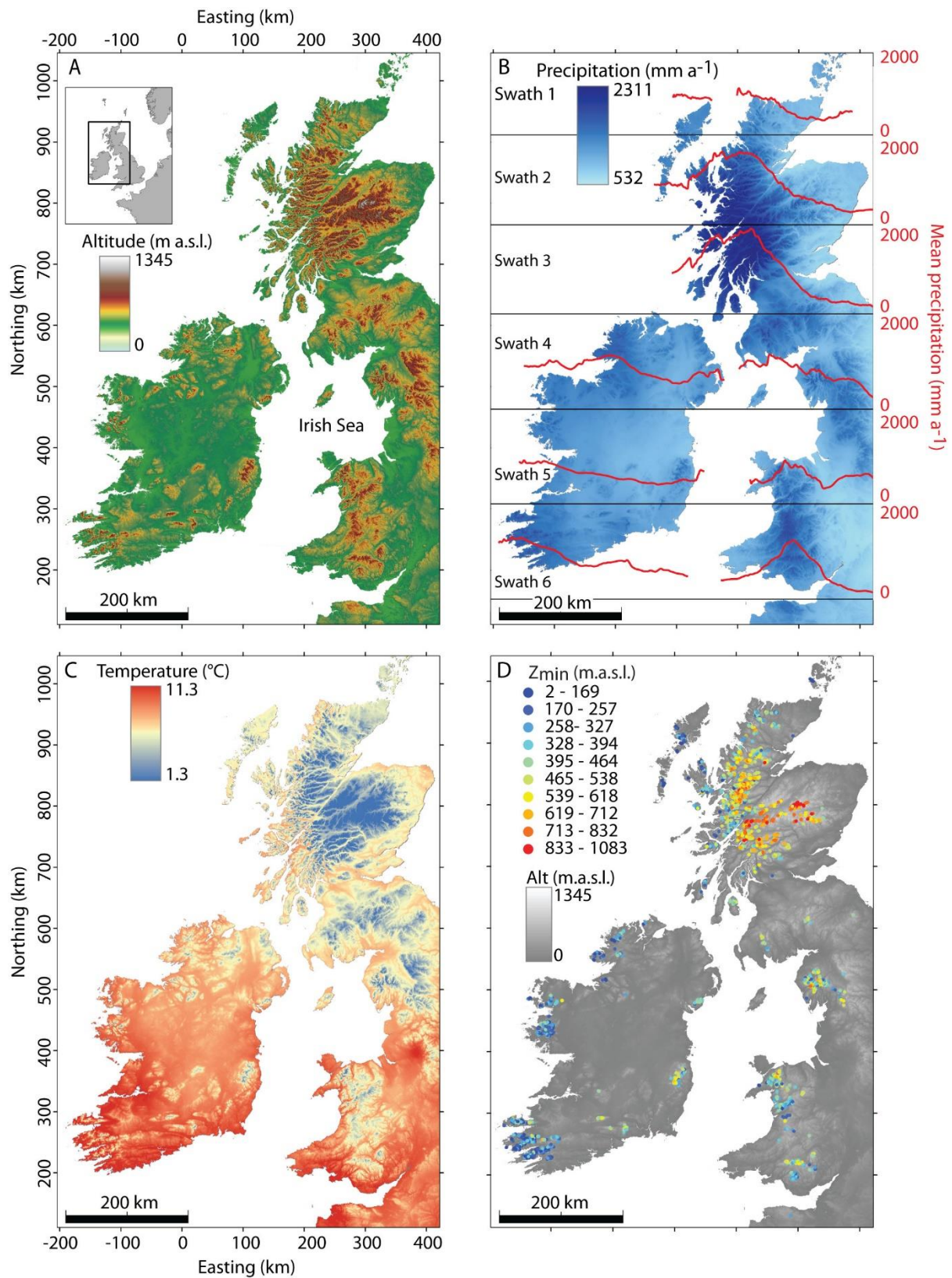
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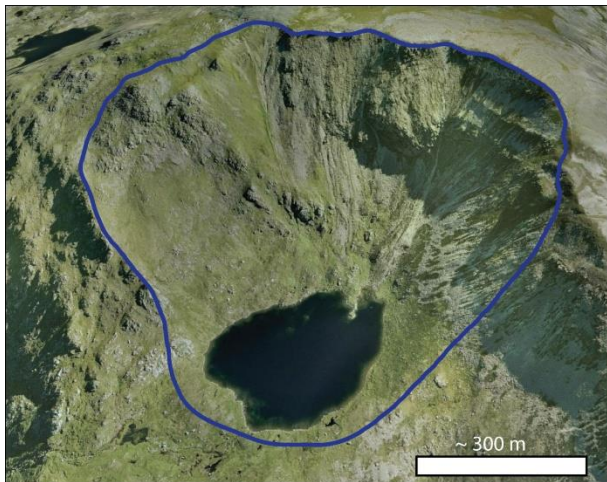


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550 Fig. 1. Maps of the upland (cirque-occupied) regions of Britain and Ireland. (A) Topographic map
 551 (shown using SRTM DEM data). (B) Gridded annual average precipitation, and (C) mean annual
 552 temperature, for the 1950–2000 period (Hijmans et al., 2005). (D) Cirques (n = 2208), coloured

553 according to minimum altitude above sea level (Z_{\min}). In (B), the red cross-sections show mean
 554 precipitation values for the different swaths (values shown in red at the right side of the image).
 555 Coordinates in this figure represent the OS British National Grid, extended to cover Ireland.

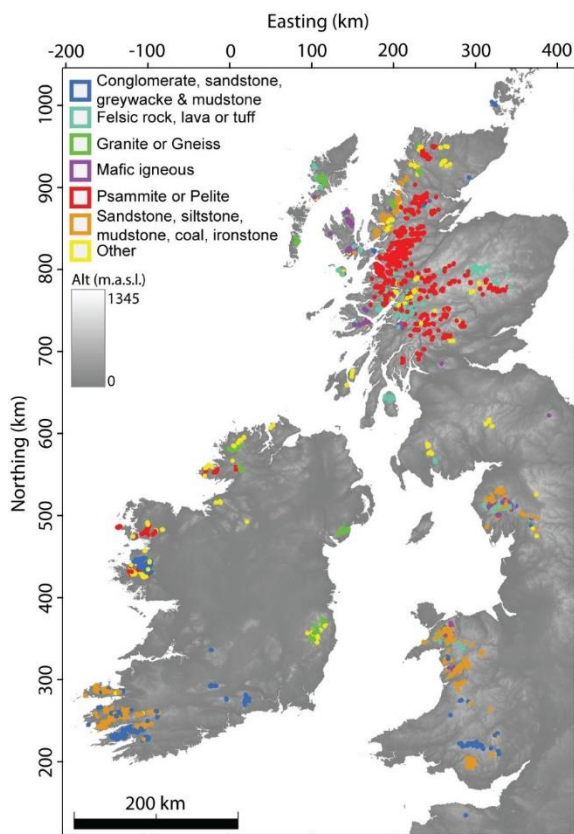
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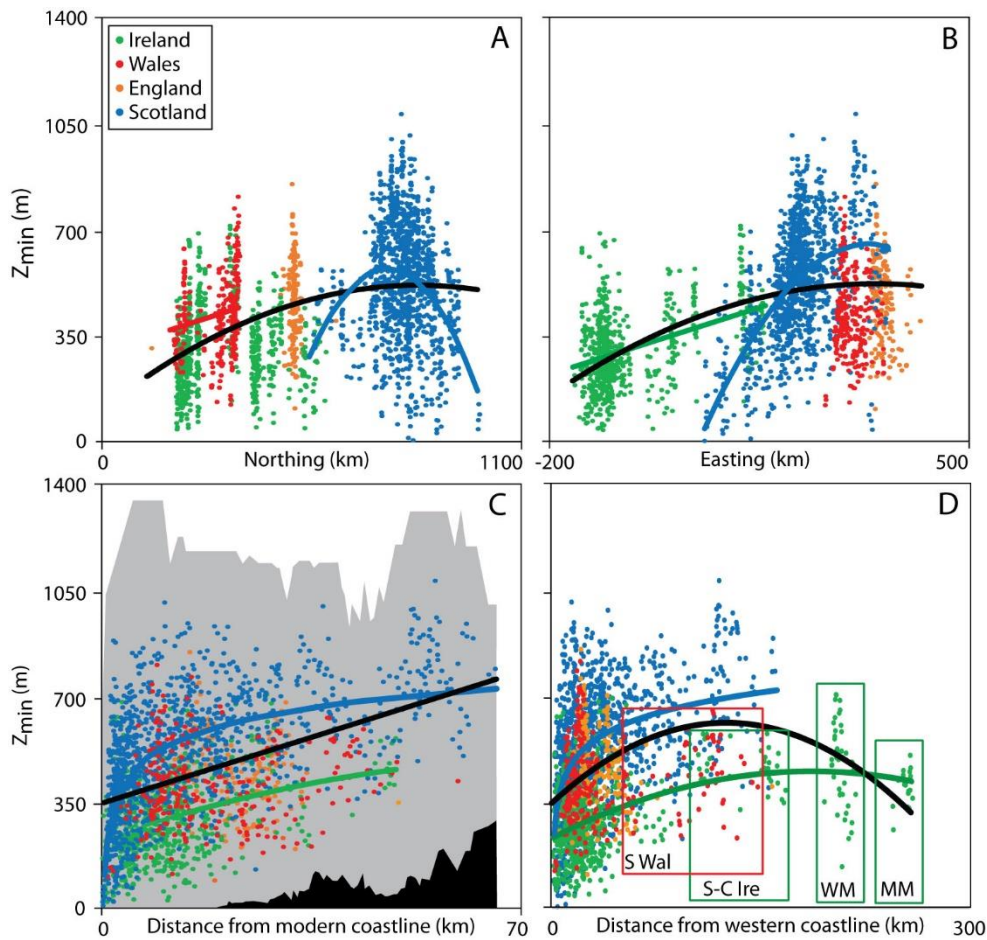
558 Fig. 2. Example cirque (Choire Dheirg, Scotland, 58.197°N, 4.974°W), mapped as a blue polygon,
 559 and shown in getmapping™ aerial image, viewed obliquely in Google Earth™.

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562 Fig 3. Cirques classified according to their dominant geological class.

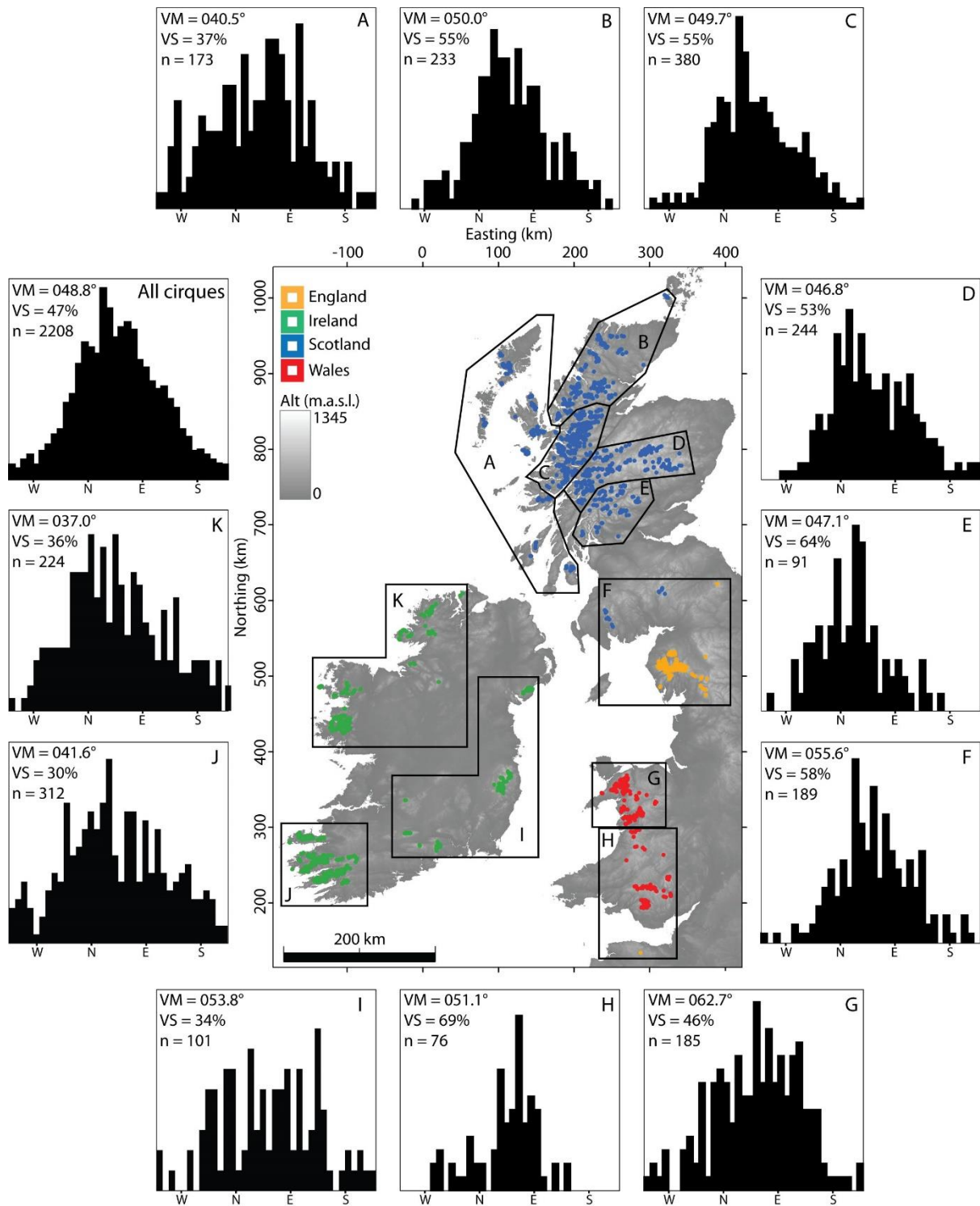


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565 Fig. 4. Cirque minimum altitude (Z_{\min}) plotted against (A) northing; (B) easting; (C) distance from the
566 modern coastline; and (D) distance from the closest coastline directly to the west. In each case, the
567 solid black line reflects the regression line for the entire cirque dataset, whilst coloured lines reflect
568 national cirque populations (lines are only plotted where relationships are significant, i.e., $p < 0.01$,
569 see Table 2). In (C), the maximum (grey shaded area) and minimum (black shaded area) topography
570 (based on the region within a 5 km radius of each cirque) are also plotted. In (D), regions labelled in
571 boxes are: the Mourne Mountains (MM), Wicklow Mountains (WM), South-central Ireland (S-C Ire)
572 and South Wales (S Wales).

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575 Fig. 5. Histograms of aspect for all cirques in Britain and Ireland, and for different sub-populations

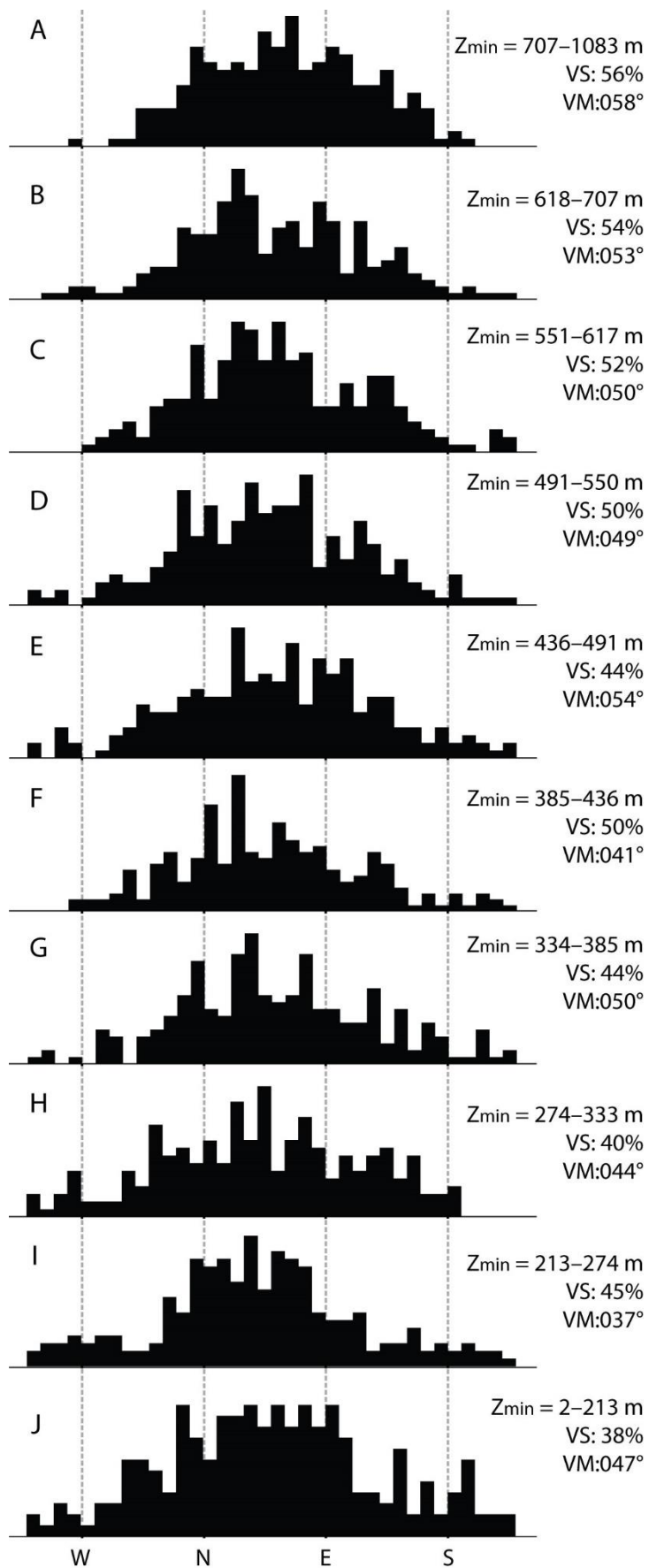
576 (defined visually, on the basis of cirque clustering). (A) The Hebrides and Arran. (B) Northern

577 Highlands and Hoy. (C) Western Highlands. (D) Cairngorms and Central Highlands. (E) Southern

578 Highlands. (F) Northern England and Southern Uplands of Scotland. (G) NW Wales. (H) Central and

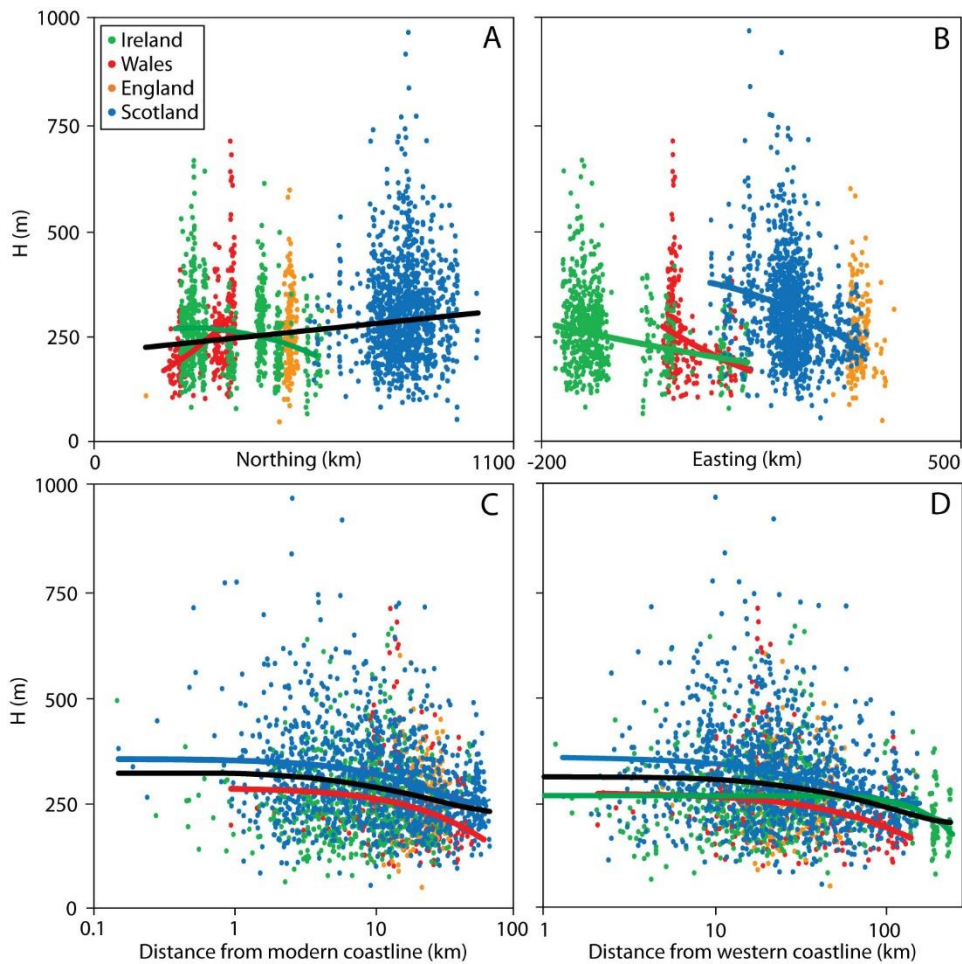
579 South Wales, and Exmoor. (I) Eastern and south-central Ireland. (J) SW Ireland. (K) West and NW

580 Ireland. For each population, the aspect vector mean (VM), vector strength (VS, which highlights the
581 extent of deviation from a uniform distribution with aspect), and number of cirques (n) are recorded
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588 Fig. 6. Aspect histograms for cirque populations grouped according to Z_{\min} (221 cirques are
589 represented in each diagram, with the exception of (A) where 219 are represented). Groups range
590 from (A) the highest cirques, to (J) the lowest. For each group, the aspect vector strength (VS), vector
591 mean (VM), and range in Z_{\min} are recorded.

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594 Fig. 7. Cirque depth (H) plotted against (A) northing; (B) easting; (C) distance from the modern
595 coastline; and (D) distance from the closest coastline directly to the west. In each case, the solid black
596 line reflects the regression line for the entire cirque dataset, whilst coloured lines reflect national
597 cirque populations (lines are only plotted where relationships are significant, i.e., $p < 0.01$, see Table
598 4). Note: in (C) and (D), the x-axes are plotted on logarithmic scales.

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601

602 Table 1. Summary of previous investigations of cirques in Britain and Ireland.

Citation	Region	Number of cirques mapped
Evans (2006)	Wales	260
Evans (1999)	Wales	228
Gordon (1977)	Kintail-Aifric-Cannich, NW Scotland	260
Clough (1974, 1977)	Cumbria, England	198
Unwin (1973)	Snowdonia, NW Wales	81
Lewis (1970)	Brecon Beacons, Wales	13
Sale (1970)	Scotland	876
	Cumbria, England	104
	North Wales	118
	South Wales	15
Sugden (1969)	Cairngorms, Scotland	30
Pippan (1967)	Cumbria, England	28
Sissons (1967)	Scotland	347
Godard (1965)	NW Scotland	437
Temple (1965)	West-Central Cumbria, England	73
Spencer (1959)	Cumbria, England	67
Seddon (1957)	Snowdonia, NW Wales	34
Harker (1901)	Cuillin, Scotland	52

603
604 Table 2. Regression of minimum altitude (Z_{\min}) against northing (N), easting (E), distance from the
605 modern coastline (dist), and aspect (θ) for cirques across Britain and Ireland. Significant relationships
606 (i.e., where $p < 0.01$) for N, E and dist are plotted in Fig. 3.

Region	Variable	Equation	p-value	R^2
Total	Northing	$Z_{\min} = -0.001N^2 + 0.998N + 93.65$	<0.01	0.197
	Easting	$Z_{\min} = -0.001E^2 + 0.737E + 375.72$	<0.01	0.271
	Dist.	$Z_{\min} = 6.552\text{dist} + 349.210$	<0.01	0.205
	Aspect	$Z_{\min} = 6.791\cos\theta + 34.834\sin\theta + 434.79$	<0.01	0.011
	N, E, dist.	$Z_{\min} = 0.246N + 0.264E + \mathbf{5.065}\text{dist} + 187.39$	<0.01	0.403
	N, E, dist., aspect	$Z_{\min} = 0.247N + 0.263E + \mathbf{5.049}\text{dist} - 5.699\cos\theta + 2.411\sin\theta + 188.11$	<0.01	0.404
Scotland	Northing	$Z_{\min} = -0.007N^2 + 11.362N - 3782$	<0.01	0.110
	Easting	$Z_{\min} = -0.013E^2 + 7.793E - 507.47$	<0.01	0.310
	Dist.	$Z_{\min} = 101.57 \ln(\text{dist}) + 303.74$	<0.01	0.339
	Aspect	$Z_{\min} = -7.745\cos\theta + 31.61\sin\theta + 524.19$	<0.01	0.001
	N, E, dist.	$Z_{\min} = -0.133N + 1.048E + \mathbf{3.87}\text{dist} + 354.48$	<0.01	0.295
	N, E, dist., aspect	$Z_{\min} = -0.141N + 1.030E + \mathbf{3.86}\text{dist} - 2.416\cos\theta + 19.251\sin\theta + 358.13$	<0.01	0.299
Ireland	Northing	Not stat. sig.	0.588	n/a
	Easting	$Z_{\min} = 0.001E^2 + 0.651E + 344.01$	<0.01	0.152
	Dist.	$Z_{\min} = -0.033\text{dist}^2 + 6.656\text{dist} + 240.36$	<0.01	0.131
	Aspect	Not stat. sig.	0.739	n/a
	N, E, dist.	$Z_{\min} = -0.149N + \mathbf{0.558}E + 3.21\text{dist} + 368.70$	<0.01	0.215
Wales	Northing	$Z_{\min} = 0.393N + 297.72$	<0.01	0.031
	Easting	Not stat. sig.	0.733	n/a
	Dist.	Not stat. sig.	0.157	n/a
	Aspect	Not stat. sig.	0.243	n/a
England	Northing	Not stat. sig.	0.367	n/a
	Easting	Not stat. sig.	0.023	n/a
	Dist.	Not stat. sig.	0.182	n/a
	Aspect	Not stat. sig.	0.130	n/a

607 For equations based on multiple regression, the coefficient and variable with the strongest t value is in
608 **bold face**.

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Table 3. Cirque frequency by quadrant, illustrating differences between Ireland and the rest of the cirque population.

	NE	SE	SW	NW	Total
Total	1072	535	142	459	2208
Ireland	250	153	71	163	637
Rest	822	382	71	296	1571
Ireland (%)	23	29	50	36	29

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Table 4. Regression of cirque depth (H) against northing (N), easting (E), distance from the modern coastline (dist), and distance from the closest coastline directly to the west (distW) for cirques across Britain and Ireland. Significant relationships (i.e., where $p < 0.01$) are plotted in Fig. 6.

Region	Variable	Equation	p-value	R ²
Total	Northing	$H = 215.44e^{0.0003N}$	<0.01	0.049
	Easting	Not stat. sig.	0.362	n/a
	Dist.	$H = 0.038\text{dist}^2 - 3.421\text{dist} + 319.63$	<0.01	0.041
	DistW	$H = 0.002\text{distW}^2 - 0.860\text{distW} + 311.09$	<0.01	0.049
Scotland	Northing	Not stat. sig.	0.120	n/a
	Easting	$H = -0.001E^2 - 0.062E + 386.17$	<0.01	0.068
	Dist.	$H = 0.037\text{dist}^2 - 3.918\text{dist} + 352$	<0.01	0.077
	DistW	$H = 0.007\text{distW}^2 - 1.777\text{distW} + 354.64$	<0.01	0.070
Ireland	Northing	$H = -0.001N^2 + 0.334N + 221.44$	<0.01	0.027
	Easting	$H = 219.79e^{-0.001E}$	<0.01	0.082
	Dist.	Not stat. sig.	0.268	n/a
	DistW	$H = 0.002\text{distW}^2 + 0.108\text{distW} + 264.13$	<0.01	0.049
Wales	Northing	$H = 93.574e^{0.003N}$	<0.01	0.213
	Easting	$H = 1832.8e^{-0.007E}$	<0.01	0.133
	Dist.	$H = 284.22e^{-0.009\text{dist}}$	<0.01	0.080
	DistW	$H = 271.14e^{-0.003\text{distW}}$	<0.01	0.102
England	Northing	Not stat. sig.	0.024	n/a
	Easting	Not stat. sig.	0.361	n/a
	Dist.	Not stat. sig.	0.571	n/a
	Dist. W	Not stat. sig.	0.694	n/a

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