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

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Abstract

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

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

Keywords

Quaternary; glaciation; NE Atlantic; precipitation; glacial cirque

1. Introduction

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

Though these climatic patterns currently prevail, the position, stability and strength of the PFJS vary not only seasonally and annually, but over much longer time periods (centuries to millennia). This variability is linked to North Atlantic sea surface temperatures, sea-ice extent, thermohaline circulation, and the extent of glaciation over North America and NW Europe (McManus et al., 1999). As such, synoptic climate patterns over Britain and Ireland are subject to change over multiple timescales. This is likely to have been particularly true during former periods of glaciation, when the growth of glaciers, and the expansion of sea-ice had a dramatic impact on North Atlantic climate (Renssen and Isarin, 1997; Renssen and Vandenberghe, 2003; Golledge et al., 2010). During the Younger Dryas Stadial (c. 12.9–

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

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

2. Methods

2.1. Cirque identification and mapping

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

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

2.2. Cirque metrics and attributes

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

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

3. Results

3.1. Cirque distribution

A total of 2208 cirques were identified and mapped throughout the mountains of Scotland (n = 1139), Wales (n = 260), Northern England (n = 172) (plus one cirque in Exmoor), and around the periphery of Ireland (n = 637) (Fig. 1D). Given the uneven distribution of cirques, it is worth noting that patterns for the entire database (discussed below) are largely determined by cirques in Ireland and

Scotland (~80% of the total dataset). The cirque database has been incorporated in the BRITICE version 2 Glacial Map (Clark et al. in press) and is available for scrutiny or download from this source.

3.2. Cirque altitudes

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

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

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

3.3. Cirque aspect

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

When cirques are grouped by Z_{min}, a general altitudinal increase in population vector strength is evident (Fig. 6). This likely reflects spatial variability in both cirque aspect and altitude (with low vector strength and low Z_{min} in coastal populations, and high vector strength and high Z_{min} in interior regions). In other populations globally, cirques typically show an altitudinal decrease in vector strength (i.e., the opposite of the trend seen here), as marginal glacial conditions at low altitudes largely restrict glacier formation to poleward-facing slopes (resulting in high vector strength), whilst cooler temperatures at high altitudes allow glaciers to form on a range of slopes (resulting in low vector strength) (Olyphant, 1977; Barr and Spagnolo, 2013).

3.4. Cirque geology

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

4. Discussion

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

4.1. Climatic controls

Based on cirque distribution (Fig. 1D), it is clear that air temperature (Fig. 1C) was an important control on former sites of mountain glaciation in Britain and Ireland—with glaciation favoured in the highest mountains, where temperatures are lowest (Fig. 1C and D). However, patterns in Z_{min} and cirque aspect indicate that exposure to moisture from the North Atlantic was also a key control. For example, in Scotland and Ireland the strongest trends in Z_{min} are the rise from west to east; with distance from the coastline; and with distance from the closest coastline directly to the west (Fig. 4). Scotland and Ireland thus fit a pattern found in other regions globally, where the altitudes of former mountain glaciers (indicated by cirques) increases with distance from a dominant moisture source (Peterson and Robinson, 1969; Hassinen, 1998; Principato and Lee, 2014; Barr and Spagnolo, 2015b). This pattern is thought to reflect restricted precipitation in interior (non-coastal) regions, which confines mountain glaciers (and cirque formation) to higher altitudes, where cooler temperatures limit melt and thereby compensate for reduced accumulation. At first glance, eastern Ireland (i.e., the Mourne and Wicklow Mountains) and, to a lesser degree, south-central Ireland and South Wales appear to be an exception to this, as cirque altitudes are generally low, given their distant location from the closest coastline directly to the west (Fig. 4D). This may reflect the comparatively weak orographic precipitation gradient in Ireland (Fig. 1B), combined with the influence of moisture from the southwest.

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

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

4.2. Non-climatic controls

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

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

The second factor to consider is geology, which has the potential to exert control on both cirque altitude and aspect (Battey, 1960; Mîndrescu and Evans, 2014). For example, the relationships between Z_{min} and lithology (noted in Section 3.4.) might indicate a geological control on cirque altitudes. However, since this relationship is comparatively weak, when detrended for the influence of northing, easting, and distance from the modern coastline, it is not considered a dominant factor regulating Z_{min} across the dataset. It is also probable that this relationship reflects spatial variability in both Z_{min} and lithology. For example, in the mountains of central and eastern Scotland, where Z_{min} is comparatively high, cirque lithology is dominated by Psammite or Pelite, whereas Granite or Gneiss cirques are typically found in lower altitude, coastal locations (Fig. 3). It is also possible that geological structure (i.e., the alignment of mountain ranges) exerts control on cirque aspect by regulating the orientation of slopes available for glacier development (Gordon, 2001; Evans, 2006; Bathrellos et al., 2014). However, as ridges in each sub-region have a broad range of orientations, structural controls are likely local and are not considered to affect the aspect statistics cited here.

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

The final factor to be considered here is the possibility that trends in Z_{min}, at least partly, reflect spatial variability in the extent of cirque deepening. This is based on the premise that Z_{min} is controlled not only by the altitudes at which former glaciers initiated, but also by the extent to which these glaciers eroded vertically. For example, given that documented cirque floor erosion rates range from ~ 0.076 mm yr^{-1} to 5.9 mm yr^{-1} (Barr and Spagnolo, 2015a), over 100,000 years of glacial occupation this would result in a ~580 m difference in depth between a heavily and minimally eroded cirque. This would be sufficient to account for some Z_{min} trends across Britain and Ireland. To test this possibility, here we analyse trends in cirque depth (H) (i.e., maximum – minimum altitudes, see Spagnolo et al., 2017), and make comparisons with trends in Z_{min}.

When the entire dataset is considered, H shows a significant reduction from north to south, and with distance from the modern coastline (Fig. 7). However, these relationships are not strong (typically,

$R^2 = 0.03–0.08$, Table 4), and the southward reduction in H (Fig. 7A), fails to explain the corresponding decline in Z_{min} (Fig. 4A). In Wales, relationships are stronger ($R^2 = 0.08–0.21$, Table 4), but, again, the dominant pattern is a southward reduction in H (Fig. 7A), which fails to explain the corresponding decline in Z_{min} (Fig. 4A).

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

4.3. Palaeoclimatic inferences

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

5. Conclusions

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

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

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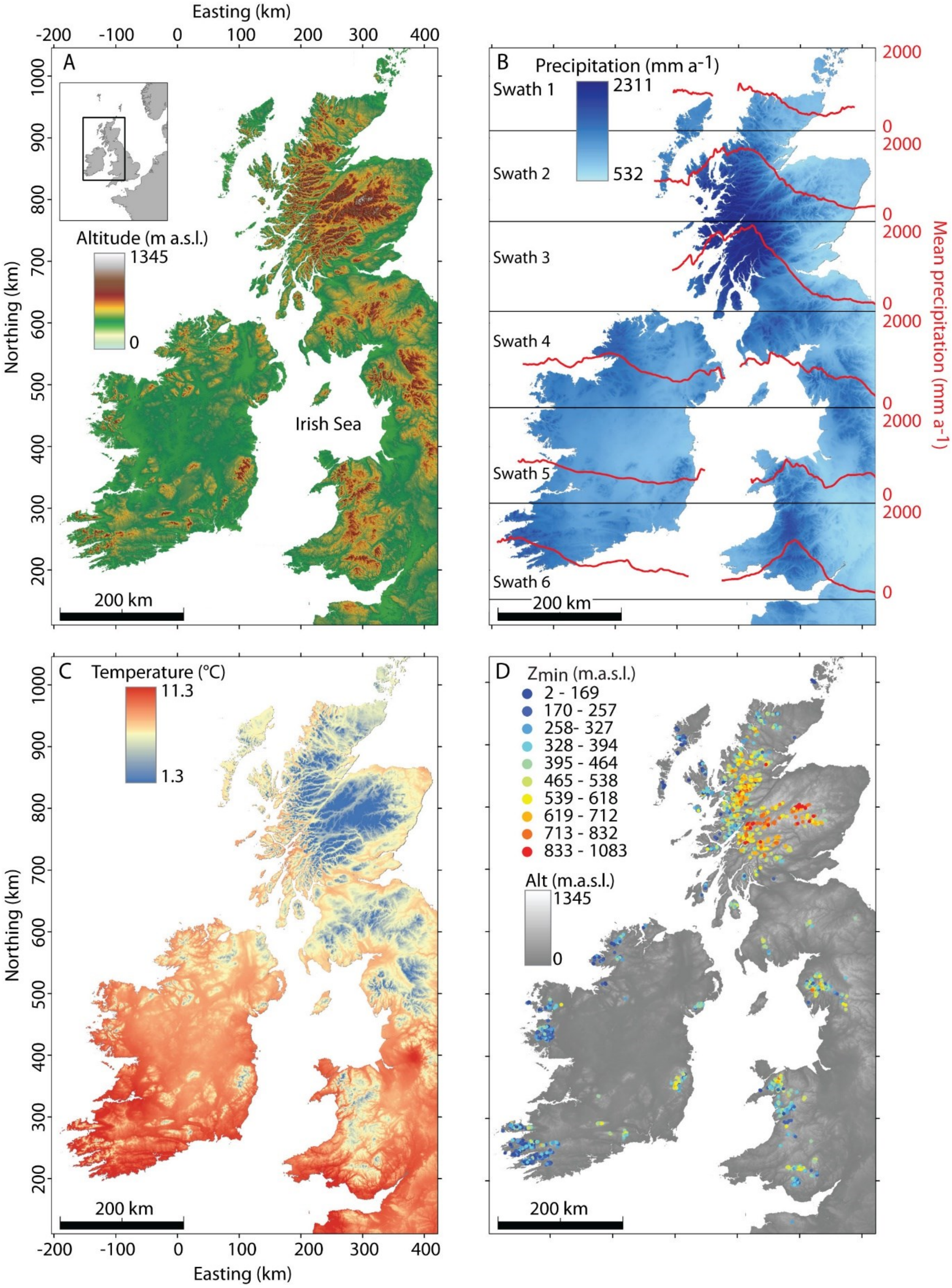

Fig. 1. Maps of the upland (cirque-occupied) regions of Britain and Ireland. (A) Topographic map (shown using SRTM DEM data). (B) Gridded annual average precipitation, and (C) mean annual temperature, for the 1950–2000 period (Hijmans et al., 2005). (D) Cirques (n = 2208), coloured

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

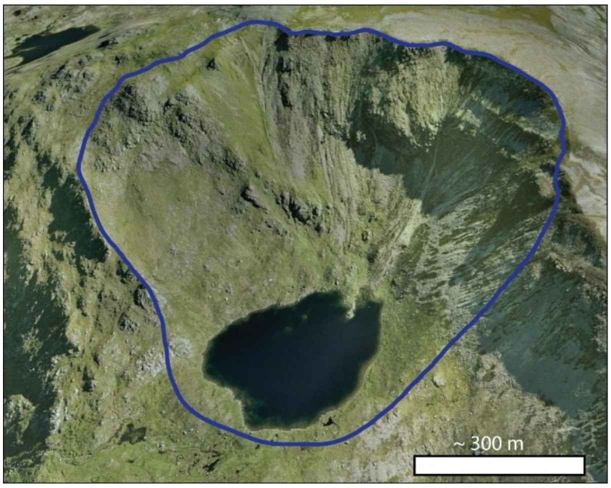

Fig. 2. Example cirque (Choire Dheirg, Scotland, 58.197°N, 4.974°W), mapped as a blue polygon, and shown in getmapping ™ aerial image, viewed obliquely in Google Earth ™.

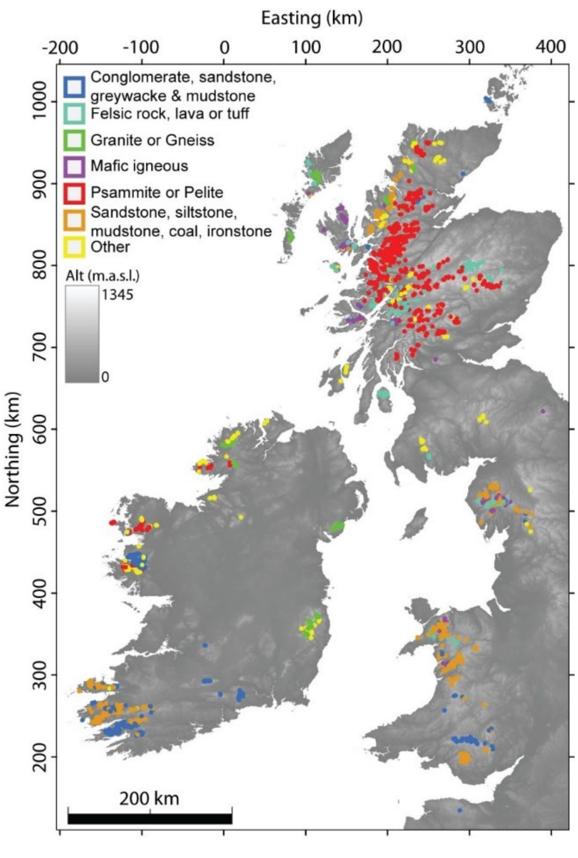

Fig 3. Cirques classified according to their dominant geological class.

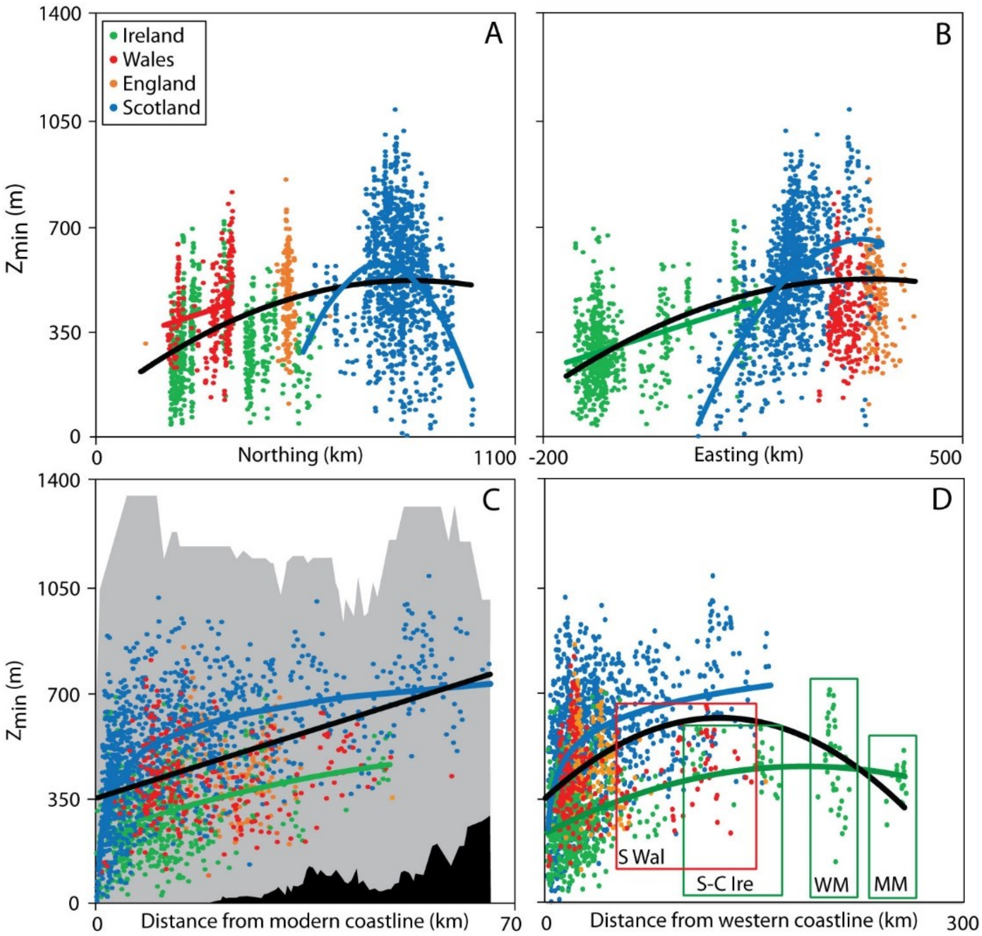

Fig. 4. Cirque minimum altitude (Z_{min}) plotted against (A) northing; (B) easting; (C) distance from the modern coastline; and (D) distance from the closest coastline directly to the west. In each case, the solid black line reflects the regression line for the entire cirque dataset, whilst coloured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

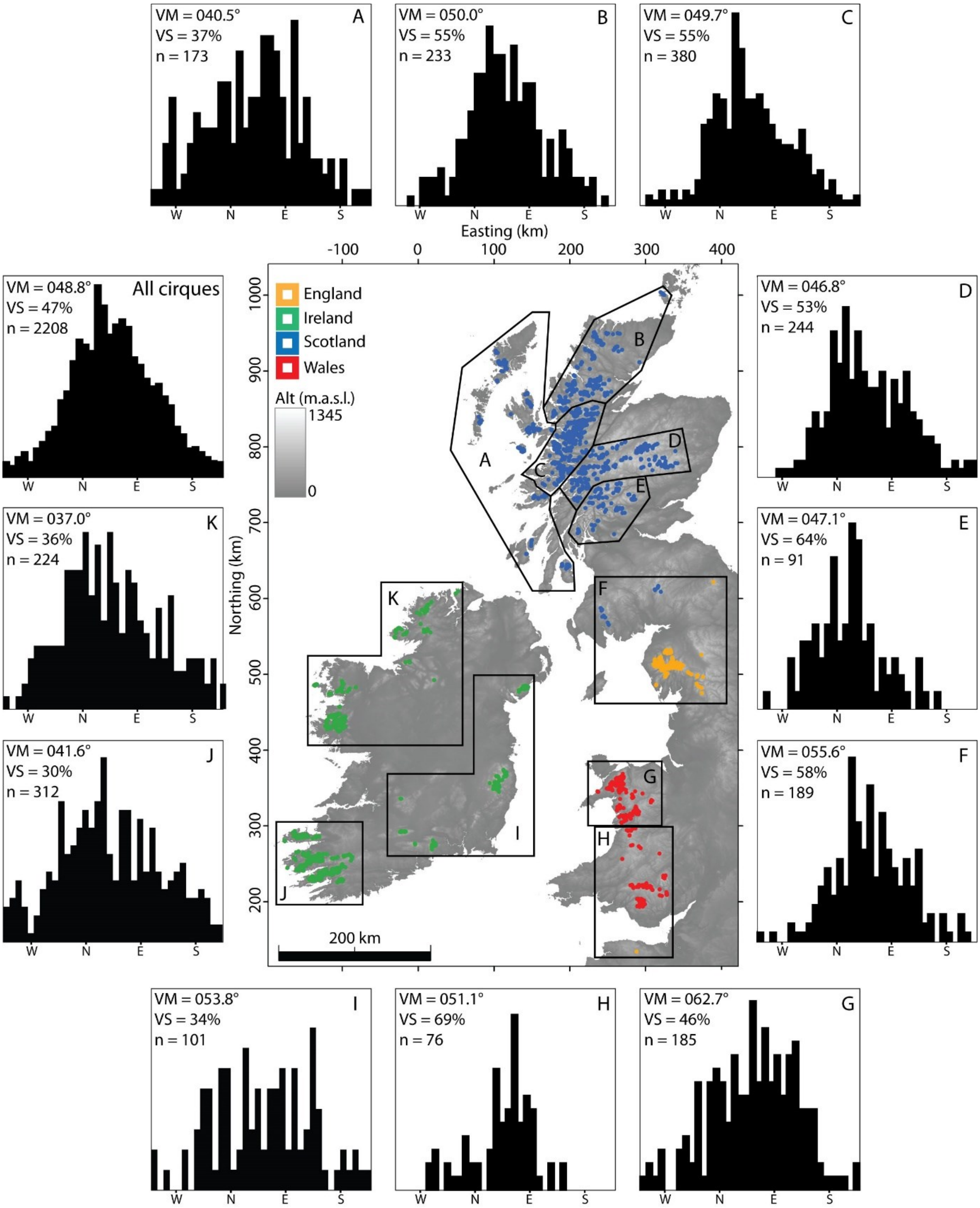

Fig. 5. Histograms of aspect for all cirques in Britain and Ireland, and for different sub-populations (defined visually, on the basis of cirque clustering). (A) The Hebrides and Arran. (B) Northern Highlands and Hoy. (C) Western Highlands. (D) Cairngorms and Central Highlands. (E) Southern Highlands. (F) Northern England and Southern Uplands of Scotland. (G) NW Wales. (H) Central and South Wales, and Exmoor. (I) Eastern and south-central Ireland. (J) SW Ireland. (K) West and NW

Ireland. For each population, the aspect vector mean (VM), vector strength (VS, which highlights the extent of deviation from a uniform distribution with aspect), and number of cirques (n) are recorded

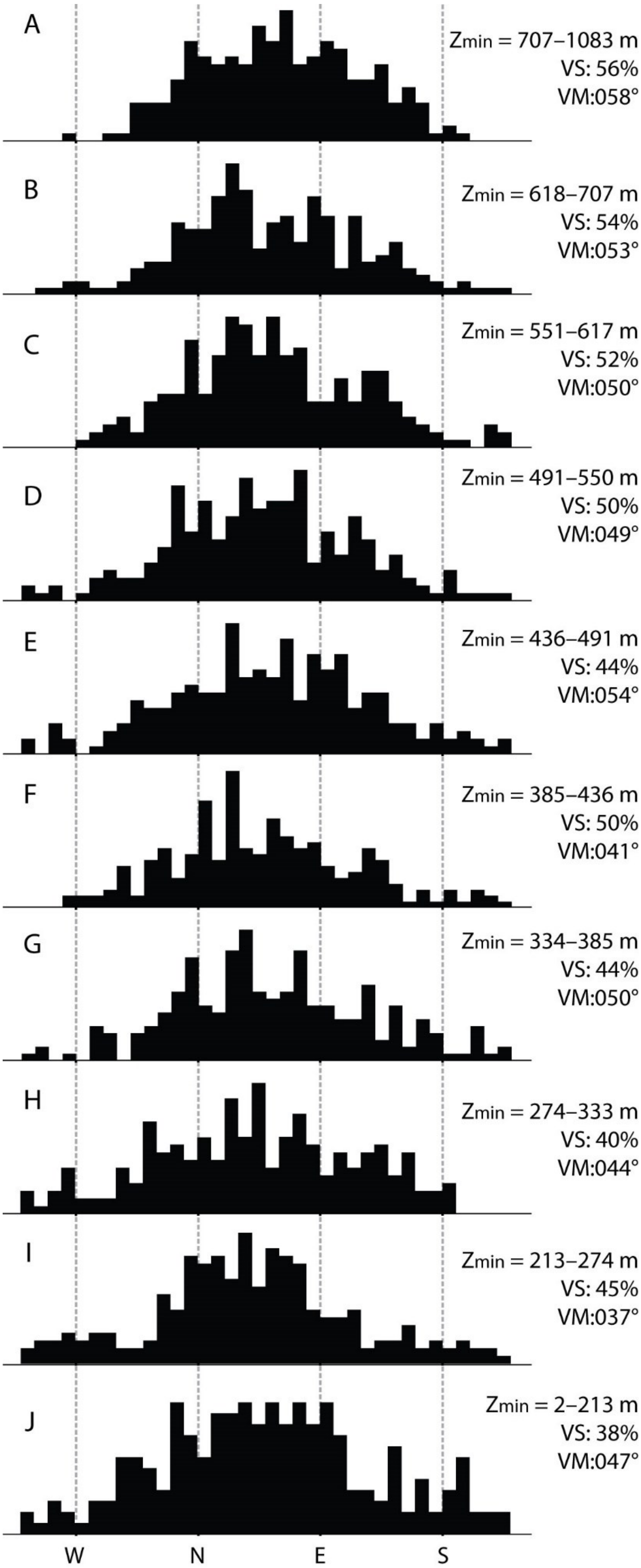
A
Zmin = 707–1083 m
VS: 56%
VM:058°
B
Zmin = 618–707 m
VS: 54%
VM:053°
C
Zmin = 551–617 m
VS: 52%
VM:050°
D
Zmin = 491–550 m
VS: 50%
VM:049°
E
Zmin = 436–491 m
VS: 44%
VM:054°
F
Zmin = 385–436 m
VS: 50%
VM:041°
G
Zmin = 334–385 m
VS: 44%
VM:050°
H
Zmin = 274–333 m
VS: 40%
VM:044°
I
Zmin = 213–274 m
VS: 45%
VM:037°
J
Zmin = 2–213 m
VS: 38%
VM:047°
W
N
E
S

Fig. 6. Aspect histograms for cirque populations grouped according to Z_{min} (221 cirques are represented in each diagram, with the exception of (A) where 219 are represented). Groups range from (A) the highest cirques, to (J) the lowest. For each group, the aspect vector strength (VS), vector mean (VM), and range in Z_{min} are recorded.

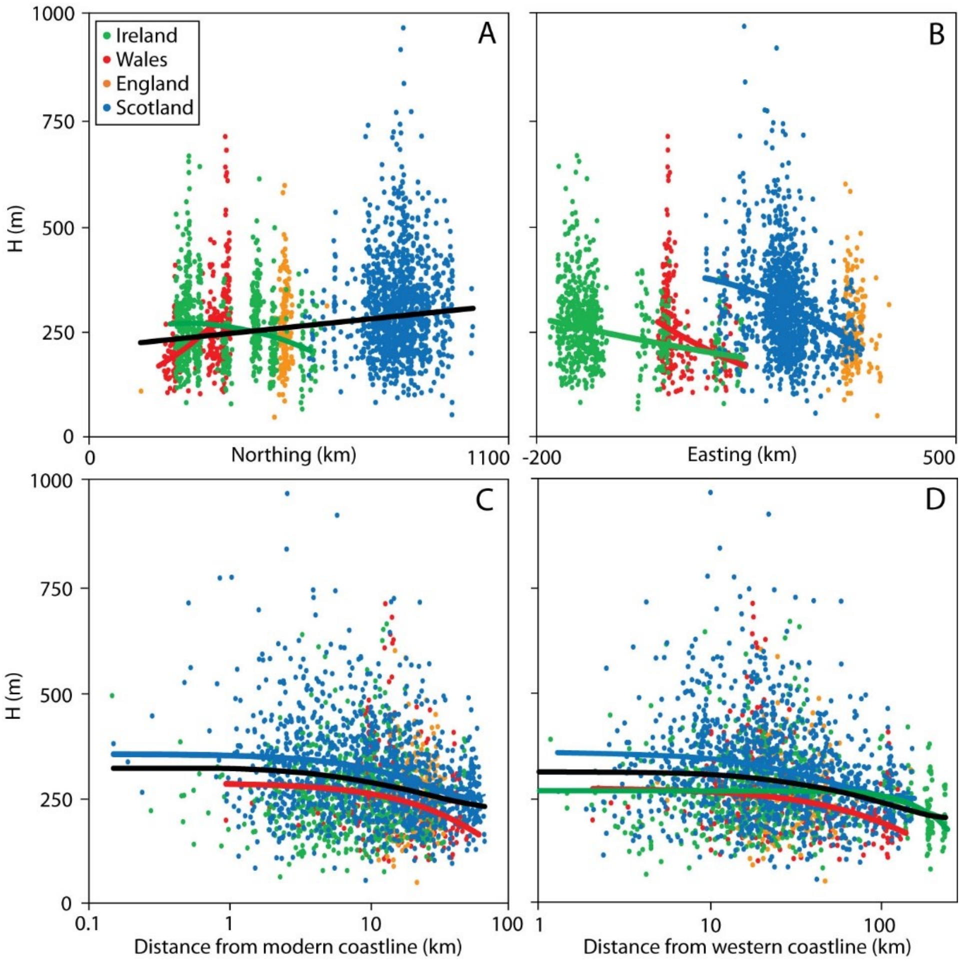

Fig. 7. Cirque depth (H) plotted against (A) northing; (B) easting; (C) distance from the modern coastline; and (D) distance from the closest coastline directly to the west. In each case, the solid black line reflects the regression line for the entire cirque dataset, whilst coloured lines reflect national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

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

Table 2. Regression of minimum altitude (Z_{min}) against northing (N), easting (E), distance from the modern coastline (dist), and aspect (θ) for cirques across Britain and Ireland. Significant relationships (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.	$Z_{min} = 6.552dist + 349.210$	<0.01	0.205
	Aspect	$Z_{min} = 6.791\cos\theta + 34.834\sin\theta + 434.79$	<0.01	0.011
	N, E, dist.	$Z_{min} = 0.246N + 0.264E + \mathbf{5.065dist} + 187.39$	<0.01	0.403
	N, E, dist., aspect	$Z_{min} = 0.247N + 0.263E + \mathbf{5.049dist} - 5.699\cos\theta + 2.411\sin\theta + 188.11$	<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.	$Z_{min} = 101.57 \ln(dist) + 303.74$	<0.01	0.339
	Aspect	$Z_{min} = -7.745\cos\theta + 31.61\sin\theta + 524.19$	<0.01	0.001
	N, E, dist.	$Z_{min} = -0.133N + 1.048E + \mathbf{3.87dist} + 354.48$	<0.01	0.295
	N, E, dist., aspect	$Z_{min} = -0.141N + 1.030E + \mathbf{3.86dist} - 2.416\cos\theta + 19.251\sin\theta + 358.13$	<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.	$Z_{min} = -0.033dist^2 + 6.656dist + 240.36$	<0.01	0.131
	Aspect	Not stat. sig.	0.739	n/a
	N, E, dist.	$Z_{min} = -0.149N + \mathbf{0.558E} + 3.21dist + 368.70$	<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

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

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

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.	$H = 0.038dist^2 – 3.421dist + 319.63$	<0.01	0.041
	DistW	$H = 0.002distW^2 – 0.860distW + 311.09$	<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.	$H = 0.037dist^2 – 3.918dist + 352$	<0.01	0.077
	DistW	$H = 0.007distW^2 – 1.777distW + 354.64$	<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	$H = 0.002distW^2 + 0.108distW + 264.13$	<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.	$H =284.22e^{-0.009dist}$	<0.01	0.080
	DistW	$H = 271.14e^{-0.003distW}$	<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