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# The dynamics of mountain erosion: Cirque growth slows as landscapes age

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ABSTRACT: Glacial cirques are widely used palaeoenvironmental indicators, and are key to understanding the role of glaciers in shaping mountain topography. However, notable uncertainty persists regarding the rate and timing of cirque erosion. In order to address this uncertainty, we analyse the dimensions of 2208 cirques in Britain and Ireland and model ice accumulation to investigate the degree of coupling between glacier occupation times and cirque growth. Results indicate that during the last ~120 ka, cirques were glacier-free for an average of 52.0 ± 21.2 ka (43 ± 18%); occupied by small (largely cirque-confined) glaciers for 16.2 ± 9.9 ka (14 ± 8%); and occupied by large glaciers, including ice sheets, for 51.8 ± 18.6 ka (43 ± 16%). Over the entire Quaternary (i.e. 2.6 Ma), we estimate that cirques were glacier-free for 1.1 ± 0.5 Ma; occupied by small glaciers for 0.3 ± 0.2 Ma; and occupied by large glaciers for 1.1 ± 0.4 Ma. Comparing occupation times to cirque depths, and calculating required erosion rates, reveals that continuous cirque growth during glacier occupation is unlikely. Instead, we propose that cirques attained much of their size during the first occupation of a non-glacially sculpted landscape (perhaps during the timeframe of a single glacial cycle). During subsequent glacier occupations, cirque growth may have slowed considerably, with the highest rates of subglacial erosion focused during periods of marginal (small glacier) glaciation. We propose comparatively slow rates of growth following initial cirque development because a 'least resistance' shape is formed, and as cirques deepen, sediment becomes trapped subglacially, partly protecting the bedrock from subsequent erosion. In support of the idea of rapid cirque growth, we present evidence from northern British Columbia, where cirques of comparable size to those in Britain and Ireland developed in less than 140 ka. © 2019 John Wiley & Sons, Ltd.

KEYWORDS: cirques; glacial erosion; erosion rate; glacial buzzsaw; quaternary; Britain; Ireland

## Introduction

Glacial cirques (e.g. Figure 1) are armchair-shaped erosional hollows formed in upland environments (Evans and Cox, 1974, 1995). They are widely used as palaeoenvironmental indicators (Mîndrescu et al., 2010; Barr and Spagnolo, 2015), and are key to understanding the role of glaciers in shaping global-scale mountain topography (Oskin and Burbank, 2005; Egholm et al., 2009; Anders et al., 2010; Champagnac et al., 2012). Cirques are thought to form where glacial ice comes to occupy, erode and enlarge pre-existing mountainside depressions (Evans, 2006; Turnbull and Davies, 2006), eventually evolving to distinct shapes and relatively characteristic sizes (Barr and Spagnolo, 2015; Evans and Cox, 2017). However, one of the key uncertainties about cirque formation is how long they take to develop fully, with current estimates ranging from ~125 ka to a million years or more (Andrews and Dugdale, 1971; Anderson, 1978; Larsen and Mangerud, 1981; Sanders et al., 2013). Many cirques have been repeatedly occupied by glaciers during the Quaternary (Graf, 1976), but it remains unclear whether their size is the product of cumulative erosion through multiple glaciations, or is largely reached during a single glacial cycle. It is also unclear whether cirque growth continues throughout glacial occupation, even when small glaciers have evolved into valley glaciers/ice caps/ice sheets, or is focused during short windows of 'active' erosion when glaciers are solely confined to their cirques (Barr and Spagnolo, 2013; Crest et al., 2017). Addressing these issues is vital if cirques are to be used as robust palaeoenvironmental indicators, and is fundamental to understanding planetary-scale landscape evolution (Banks et al., 2008; Egholm et al., 2009; Mitchell and Humphries, 2015). With this in mind, here we analyse the dimensions of cirques in Britain and Ireland, and model former ice accumulation, to permit inferences about the rate and timing of cirque growth, supported by evidence from northern British Columbia.

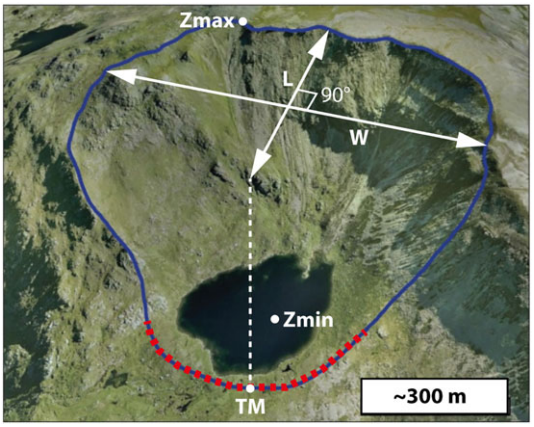


**Figure 1.** Example cirque (Choire Dheirg, Scotland, 58.197°N, 4.974°W), mapped as a blue polygon. Cirque length (*L*) is the line within the cirque polygon that intersects the cirque threshold midpoint (TM – the threshold is marked as a dashed red line) and splits the polygon into two equal halves. Cirque width (*W*) is the line perpendicular to the length and intersecting the length line midpoint. Cirque depth (*H*), not shown in the figure, is the altitudinal difference between the minimum and maximum altitude within the cirque (i.e. $Z_{max} - Z_{min}$). Spagnolo et al. (2017) provide further details of how these cirque metrics are calculated using their GIS tool. Background shows a getmapping™ aerial image, viewed obliquely in Google Earth™. [Colour figure can be viewed at wileyonlinelibrary.com]

## Methods

We adopt three different methods to investigate cirques in Britain and Ireland. First, we analyse cirque dimensions. Second, we model the spatial extent of the zone of ice accumulation within each cirque under different climate scenarios using a positive degree-day (temperature-index) mass balance approach. Third, we run our ice accumulation/mass balance model throughout the timespan of a typical glacial cycle, and over the Quaternary as a whole, to estimate the duration and style of former glacier occupation within each cirque.

### Analysing cirque dimensions

This work focuses on all recognizable ($n = 2208$) cirques in Britain and Ireland that were mapped from remotely sensed data (Barr et al., 2017; Clark et al., 2018). For each cirque, length (*L*), width (*W*) and depth (*H*) are calculated using ACME, a dedicated GIS tool (Spagnolo et al., 2017) (Figure 1). We primarily focus on *H*, since cirque depth is largely controlled by subglacial erosion (Gordon, 1977), while controls on *L* and *W* are more complex, and likely include both glacial and periglacial processes (Sanders et al., 2012; Barr and Spagnolo, 2015).

### Modelling former ice accumulation

To simulate the spatial extent of the zone of former ice accumulation (*Ac*) within each cirque, we use a positive degree-day (temperature-index) mass balance model (e.g. Laumann and Reeh, 1993; Hock, 2003; Braithwaite, 2008). We do not model glacier dimensions, nor allow ice to incrementally accumulate (or ablate) year-on-year, but simply model the spatial extent of the zone of net ice accumulation within each cirque at the end of the balance year (i.e. in September) under different temperature scenarios. To achieve this, we apply Equation (1) to each (30 × 30 m) pixel in a digital elevation model (DEM), and calculate *Ac* for each cirque by summing the surface area of the pixels that return positive values:

$$\sum P_m(snow) - (\sum T_m \times DDF) \quad (1)$$

where $\sum P_m(snow)$ is the annual sum of mean monthly precipitation (mm) for months with a mean near-surface temperature below a threshold value ($T_{crit}$). $\sum T_m$ is the annual sum of monthly positive degree-days (based on mean monthly temperatures above $T_{crit}$), and *DDF* is the degree-day melt factor.

In our model, $T_{crit}$ was set to 2°C (following Harrison et al., 2014) and the *DDF* ranged from 2.6 to 4.1 mm $d^{-1}°C^{-1}$ (following Braithwaite, 2008). These values are considered representative of conditions within cirques, where melt is restricted by notable topographic shading (Hannah et al., 2000). To account for the role of solar radiation (in addition to the role of air temperature) in regulating melt, *DDF* varied on a pixel-by-pixel basis, scaled according to modern annual solar radiation (calculated using the ArcGIS Solar Radiation tool). Thus, the pixel (across the entire dataset) with highest annual solar radiation was assigned a *DDF* of 4.1, and the pixel with the lowest, a value of 2.6. *DDF* was assumed to range linearly (with respect to solar radiation) between these extremes. Present-day monthly mean climatology (temperature and precipitation) was derived from gridded data (WorldClim v.2; Fick and Hijmans, 2017), which is representative of the period 1970 to 2000. Monthly climate grids were resampled from ~1 km to 30 m resolution using SRTM DEM data (vertical accuracy ~16 m). For temperature, this resampling assumed an altitudinal lapse rate of 6°C $km^{-1}$ (Rolland, 2003), whereas precipitation was resampled (to 30 m) without applying a lapse rate. The gridded climate data (Fick and Hijmans, 2017) were selected as they incorporate observations from a dense array of weather stations, and have been widely used for environmental modelling. In each cirque, ice was allowed to accumulate on all surfaces with gradients <30° (Harrison et al., 2014). Details of model validation and sensitivity are presented in the online Supporting Information.

### Estimating the duration and style of glacier occupation

The purpose of modelling the spatial extent of the zone of former ice accumulation (*Ac*) within each cirque is to estimate how long (during its history) each cirque has been: glacier-free ($t_{gf}$); glacier-occupied ($t$); occupied by small (largely cirque-confined) glaciers ($t_{marginal}$); and occupied by large glaciers (extending beyond cirque confines) ($t_{full}$). Here, we assume that the distinctions between these different conditions are approximated by differences in the proportion of each cirque's total surface area that is accumulating ice. Specifically, if $Ac < 10\%$

(i.e. if less than 10% of a cirque's surface area is accumulating ice), we classify cirques as glacier-free ($t_{gf}$) and if $Ac \geq 10\%$, we classify cirques as glacier-occupied ($t$). In the latter case, if $Ac$ = 10–90%, we classify cirques as occupied by small glaciers ($t_{marginal}$) and if $Ac > 90\%$, we classify cirques as occupied by large glaciers ($t_{full}$). The selection of 10% as a boundary within this scheme is justified on the assumption that when $Ac < 10\%$, any ice within a cirque is unlikely to form a coherent and rotationally flowing glacier. The selection of 90% as a boundary is justified on the assumption that when $Ac > 90\%$, any occupying glacier is likely to extend well beyond cirque confines. To analyse the duration and style of ice occupation during the last glacial cycle (i.e. 120 ka to present), we force Equation (1) with distal temperature depression ($\Delta T$) data from the Greenland Ice Core Project (GRIP; Dansgaard et al., 1993), scaled to account for precipitation reduction with cooling climate (following Seguinot et al., 2018) for all 2208 mapped cirques (Figure 2). To consider the duration and style of ice occupation over the Quaternary as a whole (i.e. 2.6 Ma to present), we use the composite benthic $\delta^{18}O$ stack from Lisiecki and Raymo (2005), and treat this as a proxy for temperature (thereby including the Mid-Pleistocene climate transition – Clark et al., 2006). Though there are limitations to this approach (since long-term records lack detail, and benthic $\delta^{18}O$ is not a direct proxy for terrestrial temperature), the results provide first-order estimates of Quaternary ice mass occupation times for British and Irish cirques.

## Results

### Cirque dimensions

For the entire population of cirques in Britain and Ireland (Figure 3a), $L$ (mean ± 1 standard deviation = 774 ± 426 m) and $W$ (786 ± 365 m) are comparable, but $H$ is approximately three times less (283 ± 108 m). All cirque size metrics have approximately log-normal frequency distributions – shown for $H$ in Figure 3b.

### Areas of former ice accumulation

Modelling the zone of ice accumulation indicates that for individual cirques in Britain and Ireland the $\Delta T$ required for $Ac \geq 10\%$ ranges from −0.2°C (Coire an Laoigh, Scotland, 56.81°N, 4.88°W, labelled 1 in Figure 3a) to −10.2°C (Keimeen, Ireland, 51.72°N, 9.27°W, labelled 2 in Figure 3a), with a mean of −5.0 ± 2.1°C (i.e. ±1σ) (Figure 4). The $\Delta T$ required for $Ac > 90\%$ ranges from −1.6°C (Sron a Gharbh-Choire, Scotland, 56.76°N, 4.92°W, labelled 3 in Figure 3a) to −12.3°C (Knocknahillan, Ireland, 53.52°N, 9.69°W, labelled 4 in Figure 3a), with a mean of −6.7 ± 2.0°C (Figure 4). The $\Delta T$ required for an individual cirque to transition from $Ac$ = 10% to $Ac$ = 90% ranges from −0.1°C (Fir Bhreugach, Scotland, 57.65°N, 6.28°W, labelled 5 in Figure 3a) to −6.9°C (Coire nan Arr, Scotland, 57.42°N, 5.66°W, labelled 6 in Figure 3a), with a mean of −1.7 ± 0.9°C (Figure 4).

### Duration and style of glacier occupation

Using ice accumulation modelling and published $\Delta T$ data, we estimate that during the last glacial cycle, cirques in Britain and Ireland were glacier-free ($t_{gf}$) for between 11.5 ka (Coire an Laoigh) and 93.6 ka (Keimeen), with a mean of 52.0 ± 21.2 ka (43 ± 18%) (Figure 5), and glacier-occupied ($t$) for between 26.4 and 108.5 ka, with a mean of 68.0 ± 21.2 ka (57 ± 18%). When occupied, cirques contained small (largely cirque-confined) glaciers ($t_{marginal}$) for between 0.9 ka (Lough Sallagh, Ireland, 54.74°N, 8.67°W, labelled 7 in Figure 3a) and 64.2 ka (Coire nan Arr, Scotland), with a mean of 16.2 ± 9.9 ka (14 ± 8%) (Figure 5), and large glaciers (extending beyond cirque confines), including ice sheets ($t_{full}$) for between 12.7 ka (Knocknahillan, Ireland, 53.51°N, 9.70°W) and 101.0 ka (Sron a Gharbh-Choire, Scotland, 56.76°N, 4.92°W), with a mean of 51.8 ± 18.6 ka (43 ± 16%) (Figure 5). To investigate possible relationships between the duration and style of glacier occupation and resulting cirque depth, $H$ is compared to $t_{gf}$, $t$, $t_{marginal}$ and $t_{full}$ (Figure 6). These plots show a weak, but statistically significant ($p < 0.01$), positive relationship between $t$ and $H$ ($r^2$ = 0.11; Figure 6a) and a statistically significant positive relationship between $t_{marginal}$ and $H$ ($r^2$ = 0.49; Figure 6b). However, in the latter case, caution should be applied when interpreting this relationship since it partly reflects the control that $H$ exerts on $t_{marginal}$ (i.e. due to altitudinal controls on temperature, deep cirques take comparatively long to transition from $Ac$ = 10% to $Ac$ = 90%), rather than vice versa. The control that $H$ exerts on $t_{marginal}$ is demonstrated by the statistically significant relationship between $H$ and the $\Delta T$ required for individual cirques to transition from $Ac$ = 10% to

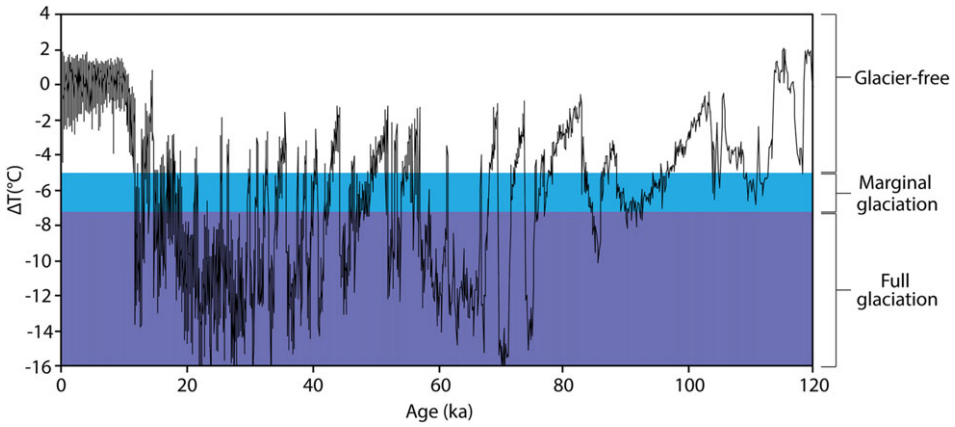


**Figure 2.** Temperature offset ($\Delta T$), relative to present, through the last glacial cycle (i.e. 120 ka to present), derived from the Greenland Ice Core Project (GRIP; Dansgaard et al., 1993), scaled to account for precipitation reduction with cooling climate (following Seguinot et al., 2018). This dataset is used to force Equation (1). Colours show periods of glacier-free conditions (white), marginal glaciation (light blue) and full glaciation (dark blue) for an example cirque (Cwm Marchlyn Mawr, Wales, 53.14°N, 4.07°W). [Colour figure can be viewed at wileyonlinelibrary.com]

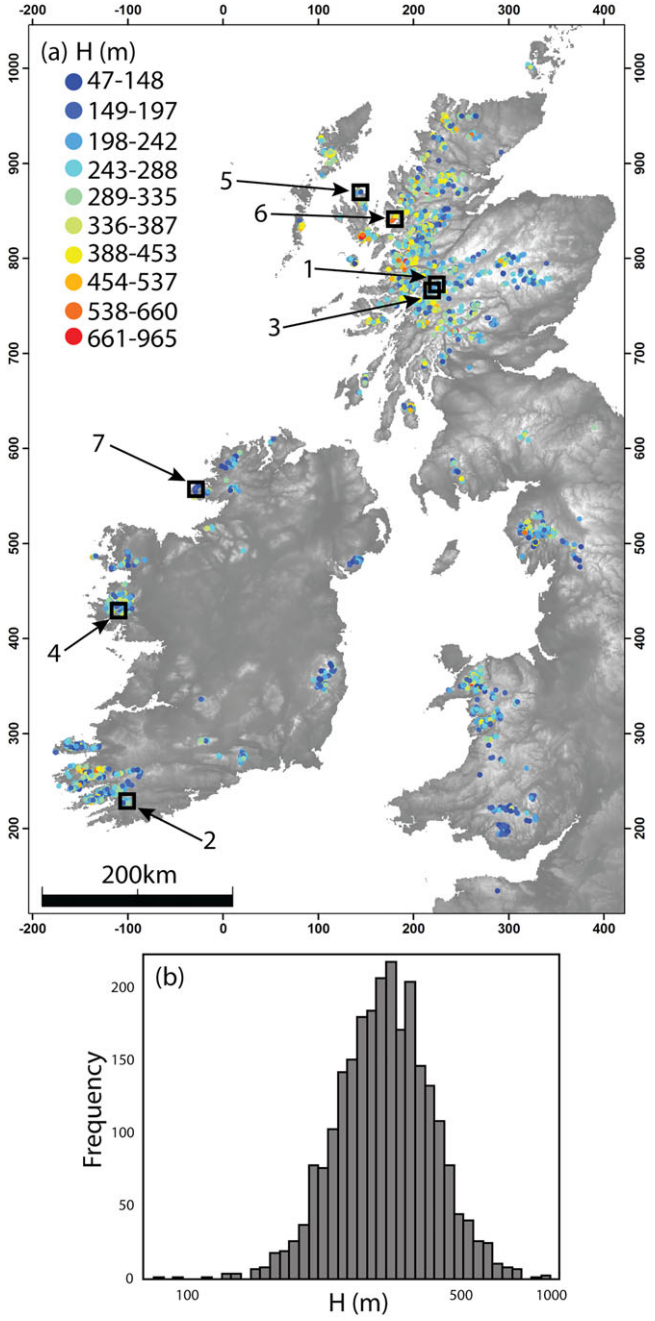


**Figure 3.** Cirques in Britain and Ireland (a) coloured according to depth (*H*) (scale plotted according to the natural breaks method, which best illustrates spatial differences in these data) and (b) with *H* plotted as a frequency distribution. *Note:* In (b) the *x*-axis is plotted on a logarithmic scale. Numbers in (a) refer to cirques mentioned in the text: 1 = Coire an Laoigh, 2 = Keimeen, 3 = Sron a Gharbh-Choire, 4 = Knocknahillan, 5 = Fir Bhreugach, 6 = Coire nan Arr, 7 = Lough Sallagh. [Colour figure can be viewed at wileyonlinelibrary.com]

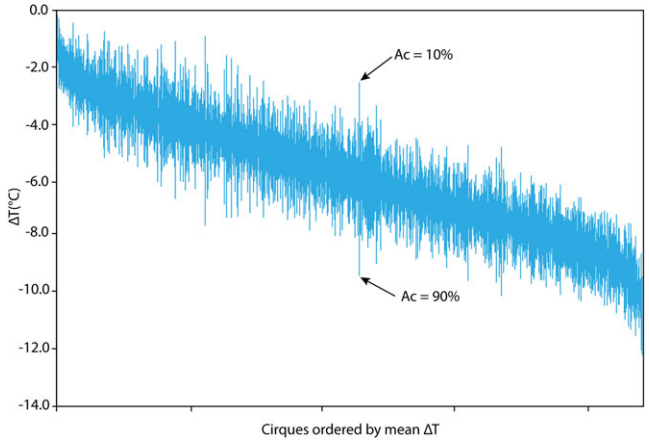


**Figure 4.** Modelled temperature offset ($\Delta T$), relative to present, required to accumulate ice within the cirques of Britain and Ireland. This figure shows the $\Delta T$ required for between 10 and 90% of each cirque's surface area to be accumulating ice. The example indicated by arrows is Coire nan Arr, Scotland (57.42°N, 5.66°W; labelled 6 in Figure 3a), which is the cirque that requires the greatest $\Delta T$ (i.e. −6.9°C) to transition from *Ac* = 10% to *Ac* = 90%. [Colour figure can be viewed at wileyonlinelibrary.com]

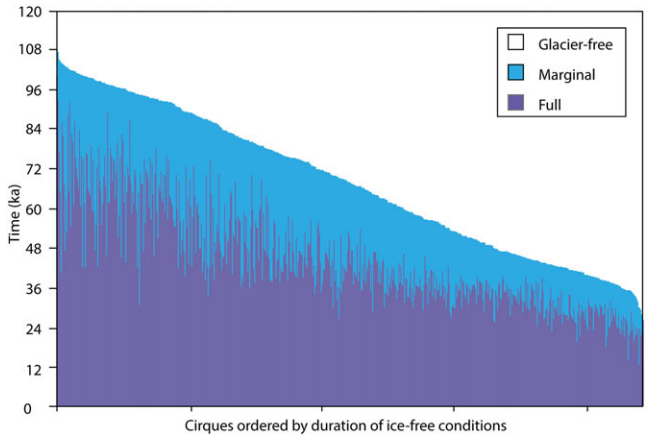


**Figure 5.** Cirques in Britain and Ireland, classified according to the duration of the last glacial cycle (120 ka to present), that our modelling suggests they were glacier-free (i.e. $t_{gf}$; *Ac* < 10%); occupied by small (marginal), largely cirque-confined, glaciers (i.e. $t_{marginal}$; *Ac* = 10–90%); and occupied by large glaciers (extending beyond cirque confines) (i.e. $t_{full}$; *Ac* > 90%). [Colour figure can be viewed at wileyonlinelibrary.com]

*Ac* = 90% ($r^2$ = 0.51; Figure 6d). There is no relationship between *H* and $t_{full}$ ($r^2$ = 0.00; Figure 6c).

There are clear regional patterns in *t* and $t_{full}$ (Figure 7), with cirques in Scotland, for example, having experienced ice occupation for most (>100 ka) of the last glacial cycle, and those in SW Ireland and south Wales having experienced occupation for a far shorter period (<40 ka) (Figure 7a). Notably, *H* does not show a correspondingly clear spatial pattern across Britain and Ireland (Figure 3a).

When considering the Quaternary as a whole (based on Lisiecki and Raymo, 2005), we estimate that cirques in Britain and Ireland were glacier-free ($t_{gf}$) for 1.1 ± 0.5 Ma and glacier-occupied (*t*) for 1.5 ± 0.5 Ma. When occupied, cirques contained small (largely cirque-confined) glaciers ($t_{marginal}$) for 0.3 ± 0.2 Ma and large glaciers, including ice sheets ($t_{full}$) for 1.1 ± 0.4 Ma. Given the long time period considered, these estimates are less precise than those based on the last glacial cycle alone.

## Discussion

### Evidence against continuous cirque growth

Ice accumulation modelling suggests that during the last glacial cycle, cirques in Britain and Ireland experienced glacier/ice-sheet occupation (*t*) for an average of 68.0 ± 21.2 ka. Over the Quaternary as a whole (based on Lisiecki and Raymo, 2005), modelling suggests 1.5 ± 0.5 million years of glacier/ice occupation. Given a mean cirque depth of 283 ± 108 m, and assuming a fluvial valley head with an

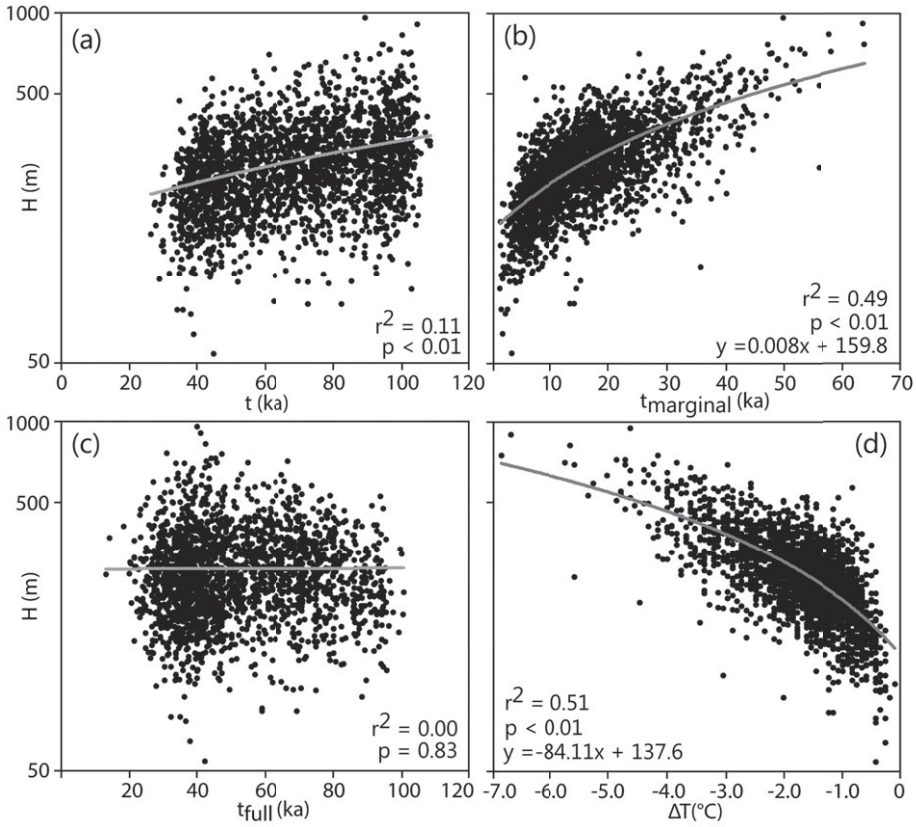


**Figure 6.** Cirque depth (*H*) in Britain and Ireland plotted against the duration of the last glacial cycle (120 ka to present) that our modelling suggests were: (a) glacier-occupied (*t*); (b) occupied by small (largely cirque-confined) glaciers ($t_{marginal}$); and (c) occupied by large glaciers (extending beyond cirque confines) ($t_{full}$). (d) *H* plotted against the $\Delta T$ required for individual cirques to transition from $Ac = 10\%$ to $Ac = 90\%$. *Note:* In all examples, the *y*-axes are plotted on logarithmic scales.

initial depth of 50–100 m (Lewis, 1949), continuous cirque growth throughout this period of occupation would imply an average vertical erosion rate of ~0.14 mm $a^{-1}$. Such an erosion rate is possible, but lies towards the low end of published estimates, and modern cirque glaciers suggest that vertical erosion rates can be an order of magnitude higher (Table I). In addition, since our estimate of cirque erosion is based on *H* – that is, the altitudinal difference between the minimum and maximum altitude of a cirque (Figure 1) – it likely represents the maximum erosion rate per cirque, since other parts of the cirque have lower maximum and/or higher minimum elevations, and therefore require the excavation of less bedrock. Importantly, if cirque growth is continuous during ice occupation, then cirque depth would be expected to scale linearly with *t* and match clear spatial patterns in *t*. However, the relationship between *H* and *t* is weak (Figure 6a) and the match in spatial patterns is not present (Figure 7a vs. Figure 3a). Thus, our results indicate that constant and continuous vertical erosion of cirques throughout glacier occupation is an unlikely scenario.

## Evidence for episodic cirque growth

There is evidence from published literature (Barr and Spagnolo, 2013; Crest et al., 2017) to suggest that during glacier occupation, the rate of cirque growth fluctuates considerably. This suggest that cirque erosion predominantly occurs during periods of marginal glaciation and may reduce (or even stop) when the landscape is occupied by larger ice masses (Barr and Spagnolo, 2013; Crest et al., 2017). The logic behind this assumption is that when glaciers are small, subglacial erosion is focused at the cirque floor and the base of the cirque headwall (Barr and Spagnolo, 2015). By contrast, larger glaciers and ice sheets extend well beyond cirque confines, and focus erosion further down-valley (Derbyshire and Evans, 1976). Under such conditions, cirques themselves may become occupied by cold-based, low-gradient and therefore minimally erosive glacial ice (Cook and Swift, 2012; Barr and Spagnolo, 2013, 2015; Crest et al., 2017), as the glacier surface slope becomes decoupled from the bed slope, and basal sheer stresses are reduced (Pedersen et al., 2014). At present, the only observational evidence to support this idea comes from the east-central Pyrenees, where Crest et al. (2017) found erosion rates during periods of cirque-type glaciation to be notably greater than when cirques were occupied by an extensive icefield (i.e. 0.03–0.35 vs. 0–0.03 mm $a^{-1}$) – though still generally low when compared to the values in Table I. In Britain and Ireland, ice accumulation modelling suggests that during the last glacial cycle, cirques experienced marginal glacial conditions for an average of 16.2 ± 9.9 ka and full (extensive) glacial conditions for 51.8 ± 18.6 ka. If erosion rates from the east-central Pyrenees (Crest et al., 2017) are applied to Britain and Ireland, and we focus on cirque deepening alone, this implies that during the last glacial cycle, cirque depth increased by 3.1 ± 1.9 m during periods of marginal glaciation and only 0.8 ± 0.3 m during full glacial conditions. The minimal impact of full glacial conditions might explain the clear lack of a relationship between $t_{full}$ and cirque size (Figure 6c). Over the Quaternary as a whole, this approach implies a cumulative 66 ± 40 m of cirque deepening during periods of marginal glaciation, and 23 ± 8 m of deepening during full glacial conditions. Assuming a fluvial valley head with an

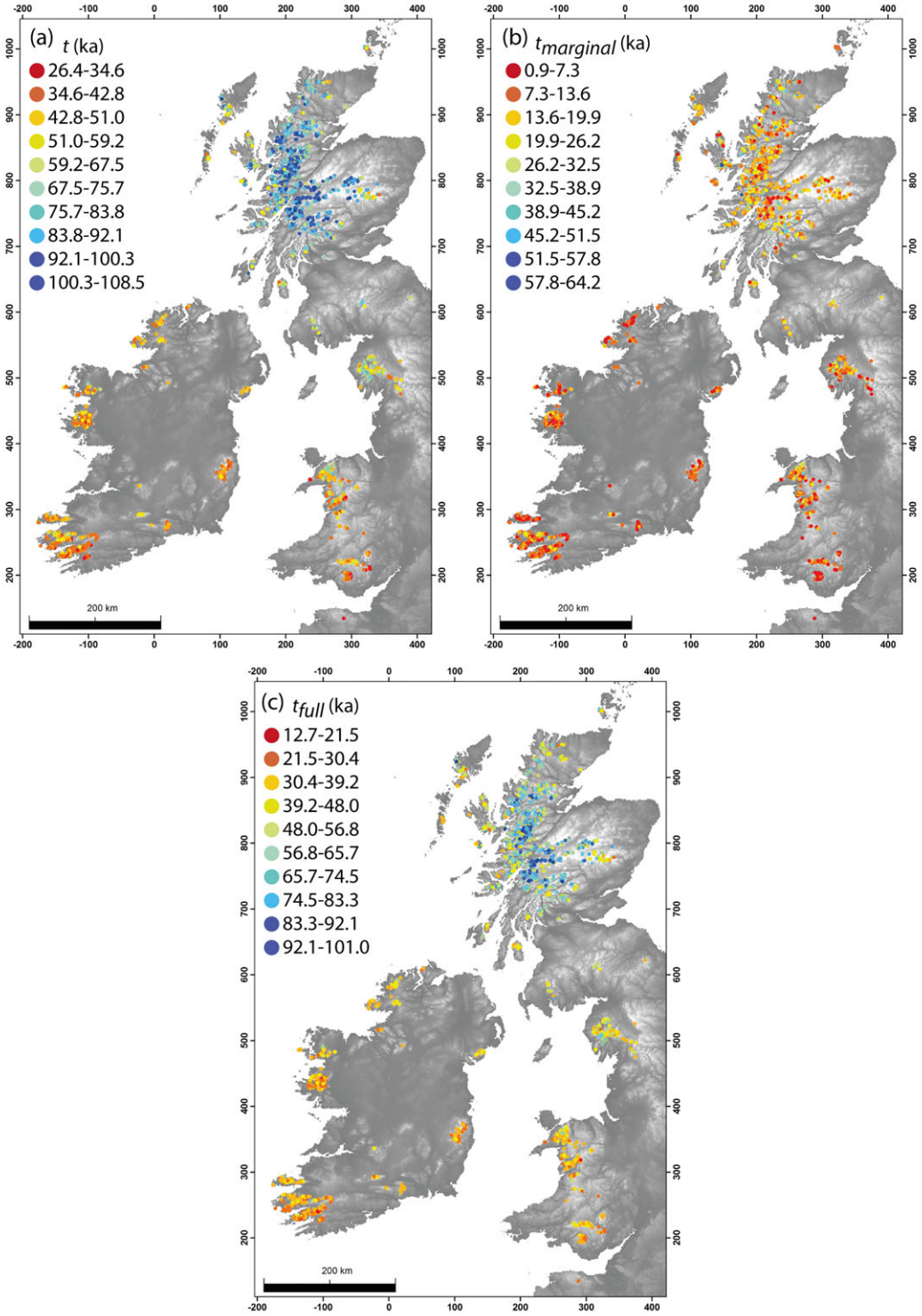


**Figure 7.** Spatial variability in the duration of the last glacial cycle (120 ka to present) that our modelling suggests cirques in Britain and Ireland were: (a) glacier-occupied ($t$); (b) occupied by small (largely cirque-confined) glaciers ($t_{marginal}$); and (c) occupied by large glaciers (extending beyond cirque confines) ($t_{full}$). [Colour figure can be viewed at wileyonlinelibrary.com]

initial depth of 50–100 m (Lewis, 1949), these estimates of cumulative Quaternary erosion result in cirque depths lower than the mean cirque depth of 283 ± 108 m observed in Britain and Ireland. This might indicate that overall cirque erosion rates in Britain and Ireland were higher than in the Pyrenees, though cirque depths in these regions are typically comparable (Delmas *et al.*, 2014). An alternative explanation is that erosion rates from 'recent' glaciations are not representative of earlier periods, and that cirque growth slows as they age. Thus, using erosion rates from 'recent' glaciations to extrapolate throughout the Quaternary is likely to underestimate total cirque erosion.

## A conceptual model for cirque growth

Evidence from the present study supports the idea that cirque growth is episodic, focused during periods of marginal glaciation and slowing considerably during full glacial conditions. However, we also propose that when cirques first initiate (i.e.

**Table I.** A global dataset of published cirque erosion rates, modified from Barr and Spagnolo (2015)

| Location | Vertical erosion (mm $a^{-1}$) | Headward erosion (mm $a^{-1}$) | Sidewall erosion (mm $a^{-1}$) | Citation |
|---|---|---|---|---|
| Marie Byrd Land, Antarctica | 0.4 | 5.8 | 0.8 | Andrews and LeMasurier (1973) |
| Arapaho Glacier, Front Range, Colorado, USA | 0.095–0.17 | – | – | Reheis (1975) |
| Pangnirtung Fiord, Baffin Island, Canada | 0.008–0.076 | – | – | Anderson (1978) |
| Kråkenes, Norway | 0.5–0.6 | 0.1 | – | Larsen and Mangerud (1981) |
| Rocky Mountains | 0.147–1.811 | – | – | Olyphant (1981) |
| Ivory Lake, Southern Alps, New Zealand | 5.3–5.9 | – | – | Hicks et al. (1990) |
| Ovre Beiarbreen, Norway | 0.18 | – | – | Bogen (1996) |
| Ben Ohau Range, New Zealand | 0.29 | 0.44 | – | Brook et al. (2006) |
| Nisqually Glacier, Washington, USA | 5.0 | – | – | Mills (1979) |
| Canadian Rocky Mountains, British Columbia | 0.5–0.9 | 1.2 | – | Sanders et al. (2013) |

when sizable glaciers first come to occupy a non-glacially sculpted landscape), erosion rates are likely to be particularly rapid, allowing cirques to attain much of their size very quickly. Our suggestion is that as cirques grow rapidly from pre-existing topographic depressions (driven by high erosion rates), they start to attain 'least-resistance' shapes (i.e. armchair-shaped hollows), which allow ice to be evacuated efficiently with minimal erosional impact. In attaining 'least-resistance' shapes, cirques often become overdeepened, thereby trapping subglacial sediment at their floors (Cook and Swift, 2012). This sediment may further reduce cirque erosion (deepening) by acting as a protective layer between the ice and bedrock at the cirque floor (Hooke, 1991; Gądek et al., 2015). In this scenario, spatial differences in the duration of glacier occupation become less important in regulating cirque size. This might explain why there is a limited spatial pattern in cirque depth across Britain and Ireland (Figure 3a), despite clear, and order of magnitude, differences in $t$ (Figure 7a). However, cirque depth does vary locally, and this variability might reflect: differences in $t_{marginal}$; differences in glacier dynamics during periods of marginal glaciation; differences in the efficiency of sediment evacuation; and/or other factors such as bedrock structure and lithology (Barr and Spagnolo, 2015).

Evidence to support the notion that cirques grow rapidly (as suggested above) is rare, often because the timing of cirque initiation is extremely difficult to constrain (Turnbull and Davies, 2006; Barr and Spagnolo, 2015). Developments in surface exposure dating potentially allow the timing of cirque deactivation (i.e. deglaciation) to be determined (Barth et al., 2016, 2017). However, there are very few locations where the timing of cirque initiation can be constrained with any certainty. One circumstance where chronologies of cirque initiation can be constrained is where cirques are eroded into tuyas (flat-topped volcanoes formed subglacially), which often have a clear and chronologically constrainable history. A classic example is Tuya Butte, northern British Columbia, which formed c. 140 ka (Smellie and Edwards, 2016). Two glacial cirques are present at its northern end (Mathews, 1947; Allen et al., 1982) (Figure 8) which, given the tuya's history, must have formed within the past 140 ka (i.e. during a single glacial cycle). These cirques have depths of 185 and 210 m. The lithology of this area is not directly comparable to that of the cirques of Britain and Ireland, which comprise 34 distinct geological units, ranging in strength from granites to mudstones (Barr et al., 2017). However, it is not obviously much weaker, as Tuya Butte is composed of weak palagonitized hyaloclastite agglomerate capped by ~80 m of thick, massive lava flow basalt, likely comparatively resistant to glacial erosion (Allen et al., 1982; Smellie, 2017). If cirques in Britain and Ireland attained similar dimensions to those at Tuya Butte during a single glacial cycle (from an initial depression depth of 50–100 m), this would suggest erosion rates (during this period) of 1.0–3.4 mm $a^{-1}$, if continuous during ice occupation and 3.3–25.4 mm $a^{-1}$, if confined to periods of marginal glaciation. Attaining such sizes during a single glacial cycle would also imply that cirque erosion rates were an order of magnitude lower over the rest of the Quaternary (i.e. 0.05–0.16 mm $a^{-1}$, if continuous during ice occupation and 0.16–1.24 mm $a^{-1}$, if confined to periods of

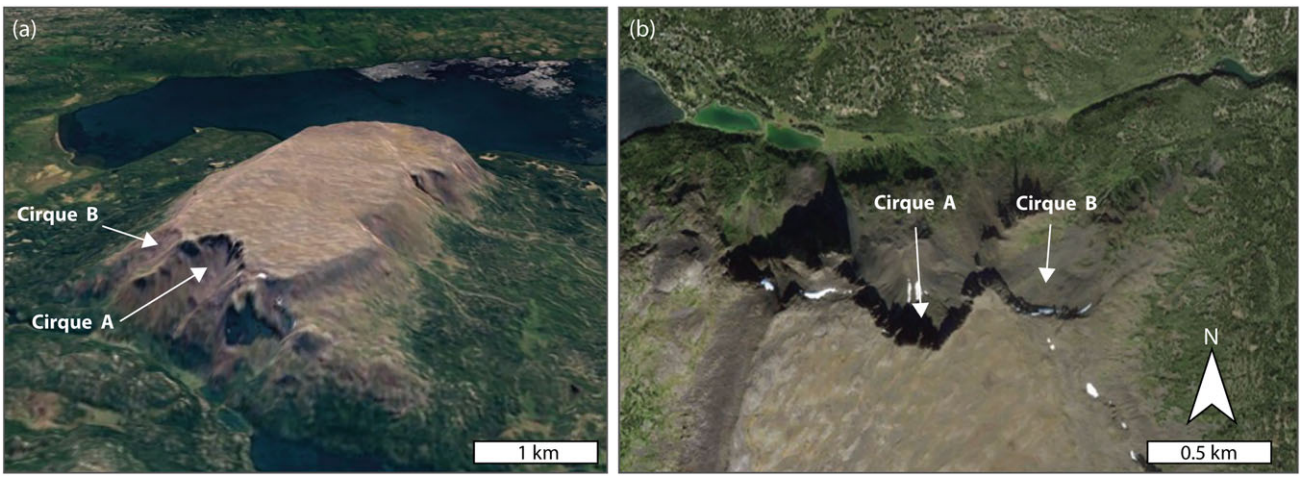


**Figure 8.** Tuya Butte, northern British Columbia. (a) Landsat image viewed obliquely (from the northwest) in Google Earth™. (b) PlanetScope satellite image, clearly showing the two cirques (A = 59.136°N, 130.570°W; B = 59.137°N, 130.560°W) eroded into the tuya's northern flank. [Colour figure can be viewed at wileyonlinelibrary.com]

marginal glaciation). It is worth emphasizing, since these erosion rates are based on *H*, that they likely represent the maximum values per cirque.

### Implications for understanding cirque erosion rates

The conceptual model we propose here is that cirques grow quickly when they first initiate – perhaps attaining much of their size, and reaching a least-resistance shape, during a single glacial cycle. Thereafter (i.e. during subsequent phases of glaciation), cirque growth slows by an order of magnitude, and is perhaps focused during periods of marginal glaciation. This model is partly supported by broader-scale glacial erosion rate data (i.e. not derived from cirques explicitly) (Hallet et al., 1996; Koppes and Montgomery, 2009) and modelling of glacial erosion over multiple glacial–interglacial cycles (MacGregor et al., 2009; Egholm et al., 2012). For example, Koppes and Montgomery (2009) note that both fluvial and glacial erosion rates are typically highest for landscapes forced out of equilibrium (e.g. following volcanic eruptions, or during glacial retreat). We suggest that the first glacial occupation of a non-glacially sculpted landscape is an extreme example of a shift in equilibrium state – explaining high erosion rates during such periods. Koppes and Montgomery (2009) report that modern temperate tidewater glaciers (i.e. retreating glaciers, not in climatic equilibrium) typically have erosion rates in the 10–100 mm $a^{-1}$ range. In Britain and Ireland, we suggest that erosion rates of comparable magnitude (i.e. 3.3–25.4 mm $a^{-1}$) would be required to allow cirques the size of those at Tuya Butte to form during a single glacial cycle (if erosion was confined to periods of marginal glaciation) – such rates are up to an order of magnitude higher than observed for modern cirque glaciers (Table I). Over the rest of the Quaternary, we suggest erosion rates (i.e. 0.16–1.24 mm $a^{-1}$) that are generally comparable with estimates from the Pyrenees (Crest et al., 2017) and derived from modern cirque glaciers globally (Table I), with some exceptions that are notably higher (i.e. up to 6.0 mm $a^{-1}$; Table 1). However, these exceptionally high published erosion rate estimates are often based on sediment volumes within proglacial streams/forelands (Reheis, 1975; Anderson, 1978; Larsen and Mangerud, 1981; Hicks et al., 1990; Bogen, 1996; Sanders et al., 2013), and some of this sediment may have been stored under glaciers for a considerable period (as noted by Koppes and Montgomery, 2009). It is therefore possible that such estimates are a measure of the rate at which sediment is being evacuated from the cirque, rather than the rate at which bedrock is being eroded.

In all, we suggest that erosion rate estimates derived from modern cirque glaciers are representative of periods of marginal glaciation, rather than longer-term averages, and may be biased by temporal decoupling of bedrock erosion and sediment evacuation.

### Implications for understanding landscape evolution

The discussion above supports the idea that cirque erosion largely occurs during comparatively short periods of marginal (small-scale) glacier occupation, and that cirques attain much of their size during the first occupation of a non-glacially sculpted landscape (particularly susceptible to erosion). This raises questions about the role of glaciers in long-term landscape evolution, particularly in relation to the buzzsaw hypothesis, which suggests that glacial erosion can keep pace with rates of tectonic uplift, and act as a fundamental limit to mountain height at a near-global scale (Brozović et al., 1997; Egholm et al., 2009; Pedersen et al., 2010; Mitchell and Humphries, 2015). The suggestion that cirque erosion is largely focused during an early phase of glaciation is difficult to reconcile with the buzzsaw hypothesis; however, the suggestion that subsequent erosion may be episodic is not. For example, during periods of marginal glaciation, rates of erosion may (in some cases) be comparable to uplift rates (e.g. Crest et al., 2017). By contrast, during full glacial conditions, rates of erosion are likely to be significantly lower but, during such periods, tectonic uplift is also likely to be reduced due to glacio-isostatic depression. Thus, a cycle might develop whereby low erosion rates are tied to periods of low uplift, and vice versa, allowing the glacial buzzsaw to operate, limiting mountain height, throughout cycles of Quaternary glaciation.

### Implications for interpreting cirque depth

Spatial variability in cirque depth (within and between regions) has been used previously to infer palaeoenvironmental conditions, on the assumption that cirque size is largely dictated by the duration of glacier occupation and by ice dynamics (i.e. the intensity of erosion) during such periods (e.g. Barr and Spagnolo, 2015). However, results from the present study suggest that cirque size is largely determined during an early stage of glaciation and (to a lesser degree) during short phases of subsequent active erosion when glaciers are small. Given the suggestion that growth continues, but slowly, following an initial phase of glaciation, it is likely that the ergodic principle, whereby variation in feature size can be substituted (to some degree) for variation with time, can still be applied to cirques (Olyphant, 1981; Evans, 2006). However, spatial differences in cirque depth will reflect differences in bedrock lithology and structure (Barr and Spagnolo, 2015), as well as differences in conditions (e.g. differences in glacier dynamics) during the initial phase of glaciation, and perhaps during short (active) periods during subsequent glacier occupation. Thus, spatial differences in cirque depth may reflect the complex interplay of controls, leading to difficulties with using cirque depth as a robust source of palaeoenvironmental information.

## Conclusions

In this study, we analyse the size characteristics of cirques in Britain and Ireland, to reveal information about the rate and timing of their growth. Ice accumulation modelling indicates that the temperature depression, relative to present, required for ≥ 10% of a cirque's surface area to be accumulating ice ranges from −0.2 to −10.2°C, with a mean of −5.0 ± 2.1°C. These temperature depression data suggest that during the last glacial cycle (i.e. 120 ka to present), cirques in Britain and Ireland were glacier-free for an average of 52.0 ± 21.2 ka, occupied by small (largely cirque-confined) glaciers for 16.2 ± 9.9 ka and occupied by large glaciers for 51.8 ± 18.6 ka. Over the Quaternary as a whole, modelling indicates that cirques were glacier-free for 1.1 ± 0.5 Ma, occupied by small glaciers for 0.3 ± 0.2 Ma and occupied by large glaciers for 1.1 ± 0.4 Ma. We suggest that continuous cirque growth during periods of glacier occupation is unlikely, since spatial patterns in cirque size fail to match patterns in glacier-occupation time. A more realistic proposition is that during glacier occupation cirque growth is episodic, maximized during periods of marginal glaciation and greatly reduced, or even stopped, when the landscape is occupied by larger ice masses. We propose a conceptual model for cirque growth, whereby cirques attain much of their size when they first initiate (i.e. when glaciers first

come to occupy a non-glacially sculpted landscape). This might occur during a single glacial cycle. Following this period (and despite potentially repeated glacier occupation), cirque growth slows by an order of magnitude and, even then, is largely focused during periods of marginal glaciation. We propose generally slow rates of growth following initial cirque development, because a least-resistance shape is likely to form and, as cirques deepen, sediment becomes trapped subglacially, partly protecting the bedrock from subsequent erosion. In support of the idea that much of a cirque's growth can occur during a single glacial cycle, we present evidence from northern British Columbia, where cirques are eroded into Tuya Butte – a flat-topped, formerly subglacial, volcano formed c. 140 ka. Based on this evidence, we suggest that erosion rates derived from modern cirque glaciers are unlikely to be representative of longer-term conditions and primarily measure the rate at which sediment is being evacuated from cirques, which relates only indirectly to the rate at which bedrock is being eroded. Finally, our modelling suggests that palaeoenvironmental inferences made from cirque depth should be treated with caution, as cirque characteristics are primarily controlled by the initial phase of glaciation and are perhaps modified during short periods of marginal glaciation.

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## References

Allen CC, Jercinovic MJ, Allen JS. 1982. Subglacial volcanism in north-central British Columbia and Iceland. *Journal of Geology* **90**(6): 699–715. https://doi.org/10.1086/628725.

Anders AM, Mitchell SG, Tomkin JH. 2010. Cirques, peaks, and precipitation patterns in the Swiss Alps: connections among climate, glacial erosion, and topography. *Geology* **38**(3): 239–242. https://doi.org/10.1130/G30691.1.

Anderson LW. 1978. Cirque glacier erosion rates and characteristics of Neoglacial tills, Pangnirtung Fiord area, Baffin Island, NWT, Canada. *Arctic and Alpine Research* **10**(4): 749–760. https://doi.org/10.1080/00040851.1978.12004012.

Andrews JT, Dugdale RE. 1971. Late Quaternary glacial and climatic history of northern Cumberland Peninsula, Baffin Island, NWT, Canada. Part V: factors affecting corrie glacierization in Okoa Bay. *Quaternary Research* **1**: 532–551. https://doi.org/10.1016/0033-5894(71)90063-9.

Andrews JT, LeMasurier WE. 1973. Rates of Quaternary glacial erosion and corrie formation, Marie Byrd Land, Antarctica. *Geology* **1**(2): 75–80. https://doi.org/10.1130/0091-7613(1973)1<75:ROQGEA>2.0.CO;2.

Banks ME, McEwen AS, Kargel JS, Baker VR, Strom RG, Mellon MT, Gulick VC, Keszthelyi L, Herkemhoff KE, Pelletier JD, Jaeger WL. 2008. High Resolution Imaging Science Experiment (HiRISE) observations of glacial and periglacial morphologies in the circum-Argyre Planitia highlands, Mars. *Journal of Geophysical Research, Planets* **113**(E12). https://doi.org/10.1029/2007JE002994.

Barr ID, Spagnolo M. 2013. Palaeoglacial and palaeoclimatic conditions in the NW Pacific, as revealed by a morphometric analysis of cirques upon the Kamchatka Peninsula. *Geomorphology* **192**: 15–29. https://doi.org/10.1016/j.geomorph.2013.03.011.

Barr ID, Spagnolo M. 2015. Glacial cirques as palaeoenvironmental indicators: their potential and limitations. *Earth-Science Reviews* **151**: 48–78. https://doi.org/10.1016/j.earscirev.2015.10.004.

Barr ID, Ely JC, Spagnolo M, Clark CD, Evans IS, Pellicer XM, Pellitero R, Rea BR. 2017. Climate patterns during former periods of mountain glaciation in Britain and Ireland: inferences from the cirque record. *Palaeogeography, Palaeoclimatology, Palaeoecology* **485**: 466–475. https://doi.org/10.1016/j.palaeo.2017.07.001.

Barth AM, Clark PU, Clark J, McCabe AM, Caffee M. 2016. Last Glacial Maximum cirque glaciation in Ireland and implications for reconstructions of the Irish Ice Sheet. *Quaternary Science Reviews* **141**: 85–93. https://doi.org/10.1016/j.quascirev.2016.04.006.

Barth AM, Clark PU, Clark J, Roe GH, Marcott SA, McCabe AM, He F, Cuzzone JK, Dunlop P. 2017. Persistent millennial-scale glacier fluctuations in Ireland between 24 ka and 10 ka. *Geology* **46**(2): 151–154. https://doi.org/10.1130/G39796.1.

Bogen J. 1996. Erosion rates and sediment yields of glaciers. *Annals of Glaciology* **22**: 48–52. https://doi.org/10.3189/1996AoG22-1-48-52.

Braithwaite RJ. 2008. Temperature and precipitation climate at the equilibrium-line altitude of glaciers expressed by the degree-day factor for melting snow. *Journal of Glaciology* **54**(186): 437–444. https://doi.org/10.3189/002214308785836968.

Brook MS, Kirkbride MP, Brock BW. 2006. Cirque development in a steadily uplifting range: rates of erosion and long-term morphometric change in alpine cirques in the Ben Ohau Range, New Zealand. *Earth Surface Processes and Landforms* **31**(9): 1167–1175. https://doi.org/10.1002/esp.1327.

Brozović N, Burbank DW, Meigs AJ. 1997. Climatic limits on landscape development in the northwestern Himalaya. *Science* **276**(5312): 571–574. https://doi.org/10.1126/science.276.5312.571.

Champagnac JD, Molnar P, Sue C, Herman F. 2012. Tectonics, climate, and mountain topography. *Journal of Geophysical Research - Solid Earth* **117**(B2). https://doi.org/10.1029/2011JB008348.

Clark PU, Archer D, Pollard D, Blum JD, Rial JA, Brovkin V, Mix AC, Pisias NG, Roy M. 2006. The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric $pCO_2$. *Quaternary Science Reviews* **25**(23–24): 3150–3184. https://doi.org/10.1016/j.quascirev.2006.07.008.

Clark CD, Ely JC, Greenwood SL, Hughes AL, Meehan R, Barr ID, Bateman MD, Bradwell T, Doole J, Evans DJA, Jordan CJ, Monteys X, Pellicer XM, Sheehy M. 2018. BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet. *Boreas* **47**(1): 11–27. https://doi.org/10.1111/bor.12273.

Cook SJ, Swift DA. 2012. Subglacial basins: their origin and importance in glacial systems and landscapes. *Earth-Science Reviews* **115**(4): 332–372. https://doi.org/10.1016/j.earscirev.2012.09.009.

Crest Y, Delmas M, Braucher R, Gunnell Y, Calvet M, Team ASTER. 2017. Cirques have growth spurts during deglacial and interglacial periods: evidence from $^{10}$Be and $^{26}$Al nuclide inventories in the central and eastern Pyrenees. *Geomorphology* **278**: 60–77. https://doi.org/10.1016/j.geomorph.2016.10.035.

Dansgaard W, Johnsen SJ, Clausen HB, Dahl-Jensen D, Gundestrup NS, Hammer CU, Hvidberg CS, Steffensen JP, Sveinbjörnsdottir AE, Jouzel J, Bond G. 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* **364**(6434): 218–220. https://doi.org/10.1038/364218a0.

Delmas M, Gunnell Y, Calvet M. 2014. Environmental controls on alpine cirque size. *Geomorphology* **206**: 318–329. https://doi.org/10.1016/j.geomorph.2013.09.037.

Derbyshire E, Evans IS. 1976. The climatic factor in cirque variation. In *Geomorphology and Climate*, Derbyshire E (ed). Wiley: Chichester; 447–494.

Egholm DL, Nielsen SB, Pedersen VK, Lesemann JE. 2009. Glacial effects limiting mountain height. *Nature* **460**: 884–887. https://doi.org/10.1038/nature08263.

Egholm DL, Pedersen VK, Knudsen MF, Larsen NK. 2012. Coupling the flow of ice, water, and sediment in a glacial landscape evolution model. *Geomorphology* **141**: 47–66. https://doi.org/10.1016/j.geomorph.2011.12.019.

Evans IS. 2006. Allometric development of glacial cirque form: geological, relief and regional effects on the cirques of Wales. *Geomorphology* **80**(3–4): 245–266. https://doi.org/10.1016/j.geomorph.2006.02.013.

Evans IS, Cox NJ. 1974. Geomorphometry and the operational definition of cirques. *Area* **6**: 150–153.

Evans IS, Cox NJ. 1995. The form of glacial cirques in the English Lake District, Cumbria. *Zeitschrift für Geomorphologie* **39**: 175–202.

Evans IS, Cox NJ. 2017. Comparability of cirque size and shape measures between regions and between researchers. *Zeitschrift für Geomorphologie* **61**(Suppl. 2): 81–103. https://doi.org/10.1127/zfg_suppl/2016/0329.

Fick SE, Hijmans RJ. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* **37**(12): 4302–4315. https://doi.org/10.1002/joc.5086.

Gądek B, Grabiec M, Kędzia S. 2015. Application of ground penetrating radar to identification of thickness and structure of sediments in postglacial lakes, illustrated with an example of the Mały Staw Lake (the Karkonosze Mountains). *Studia Geomorphologica Carpatho-Balcanica* **49**(1): 5–13. https://doi.org/10.1515/sgcb-2015-0006.

Gordon JE. 1977. Morphometry of cirques in the Kintail–Affric–Cannich area of northwest Scotland. *Geografiska Annaler. Series A, Physical Geography* **59**(3–4): 177–194. https://doi.org/10.2307/520798.

Graf WL. 1976. Cirques as glacier locations. *Arctic and Alpine Research* **8**: 79–90. https://doi.org/10.2307/1550611.

Hallet B, Hunter L, Bogen J. 1996. Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. *Global and Planetary Change* **12**(1–4): 213–235. https://doi.org/10.1016/0921-8181(95)00021-6.

Hannah DM, Gurnell AM, McGregor GR. 2000. Spatio-temporal variation in microclimate, the surface energy balance and ablation over a cirque glacier. *International Journal of Climatology* **20**(7): 733–758. https://doi.org/10.1002/1097-0088(20000615)20:7<733::AID-JOC490>3.0.CO;2-F.

Harrison S, Rowan AV, Glasser NF, Knight J, Plummer MA, Mills SC. 2014. Little Ice Age glaciers in Britain: glacier-climate modelling in the Cairngorm mountains. *The Holocene* **24**(2): 135–140. https://doi.org/10.1177/0959683613516170.

Hicks DM, McSaveney MJ, Chinn TJH. 1990. Sedimentation in proglacial Ivory Lake, Southern Alps, New Zealand. *Arctic and Alpine Research* **22**(1): 26–42. https://doi.org/10.1080/00040851.1990.12002763.

Hock R. 2003. Temperature index melt modelling in mountain areas. *Journal of Hydrology* **282**(1–4): 104–115. https://doi.org/10.1016/S0022-1694(03)00257-9.

Hooke RL. 1991. Positive feedbacks associated with erosion of glacial cirques and overdeepenings. *Geological Society of America Bulletin* **103**(8): 1104–1108. https://doi.org/10.1130/0016-7606(1991)103<1104:PFAWEO>2.3.CO;2.

Koppes MN, Montgomery DR. 2009. The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales. *Nature Geoscience* **2**(9): 644–647. https://doi.org/10.1038/ngeo616.

Larsen E, Mangerud J. 1981. Erosion rate of a Younger Dryas cirque glacier at Krakenes, western Norway. *Annals of Glaciology* **2**(1): 153–158. https://doi.org/10.3189/172756481794352216.

Laumann T, Reeh N. 1993. Sensitivity to climate change of the mass balance of glaciers in southern Norway. *Journal of Glaciology* **39**: 656–665. https://doi.org/10.3189/S0022143000016555.

Lewis WV. 1949. Glacial movement by rotational slipping. *Geografiska Annaler* **31**(1–4): 146–158. https://doi.org/10.1080/20014422.1949.11880800.

Lisiecki LE, Raymo ME. 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography* **20**: PA1003. https://doi.org/10.1029/2004PA001071.

MacGregor KR, Anderson RS, Waddington ED. 2009. Numerical modeling of glacial erosion and headwall processes in alpine valleys. *Geomorphology* **103**(2): 189–204. https://doi.org/10.1016/j.geomorph.2008.04.022.

Mathews WH. 1947. "Tuyas," flat-topped volcanoes in northern British Columbia. *American Journal of Science* **245**(9): 560–570. https://doi.org/10.2475/ajs.245.9.560.

Mills HH. 1979. Some implications of sediment studies for glacial erosion on Mount Rainier, Washington. *Northwest Science* **53**(3): 190–199.

Mîndrescu M, Evans IS, Cox NJ. 2010. Climatic implications of cirque distribution in the Romanian Carpathians: palaeowind directions during glacial periods. *Journal of Quaternary Science* **25**(6): 875–888. https://doi.org/10.1002/jqs.1363.

Mitchell SG, Humphries EE. 2015. Glacial cirques and the relationship between equilibrium line altitudes and mountain range height. *Geology* **43**(1): 35–38. https://doi.org/10.1130/G36180.1.

Olyphant GA. 1981. Allometry and cirque evolution. *Geological Society of America Bulletin* **92**(9): 679–685. https://doi.org/10.1130/0016-7606(1981)92<679:AACE>2.0.CO;2.

Oskin M, Burbank DW. 2005. Alpine landscape evolution dominated by cirque retreat. *Geology* **33**(12): 933–936. https://doi.org/10.1130/G21957.1.

Pedersen VK, Egholm DL, Nielsen SB. 2010. Alpine glacial topography and the rate of rock column uplift: a global perspective. *Geomorphology* **122**(1–2): 129–139. https://doi.org/10.1016/j.geomorph.2010.06.005.

Pedersen VK, Huismans RS, Herman F, Egholm DL. 2014. Controls of initial topography on temporal and spatial patterns of glacial erosion. *Geomorphology* **223**: 96–116. https://doi.org/10.1016/j.geomorph.2014.06.028.

Reheis MJ. 1975. Source, transportation and deposition of debris on Arapaho glacier, Front Range, Colorado, USA. *Journal of Glaciology* **14**(7): 407–420. https://doi.org/10.3189/S0022143000021936.

Rolland C. 2003. Spatial and seasonal variations of air temperature lapse rates in Alpine regions. *Journal of Climate* **16**(7): 1032–1046. https://doi.org/10.1175/1520-0442(2003)016<1032:SASVOA>2.0.CO;2.

Sanders JW, Cuffey KM, Moore JR, MacGregor KR, Kavanaugh JL. 2012. Periglacial weathering and headwall erosion in cirque glacier bergschrunds. *Geology* **40**(9): 779–782. https://doi.org/10.1130/G33330.1.

Sanders JW, Cuffey KM, MacGregor KR, Collins BD. 2013. The sediment budget of an alpine cirque. *Geological Society of America Bulletin* **125**: 229–248. https://doi.org/10.1130/B30688.1.

Seguinot J, Ivy-Ochs S, Jouvet G, Huss M, Funk M, Preusser F. 2018. Modelling last glacial cycle ice dynamics in the Alps. *The Cryosphere* **12**(10): 3265–3285. https://doi.org/10.5194/tc-12-3265-2018.

Smellie JL. 2017. Glaciovolcanism: a 21st century proxy for palaeo-ice. In *Past Glacial Environments*, Menzies J, van der Meer J (eds), 2nd edn. Elsevier: Amsterdam; 335–375.

Smellie JL, Edwards BR. 2016. *Glaciovolcanism on Earth and Mars*. Cambridge University Press: Cambridge.

Spagnolo M, Pellitero R, Barr ID, Ely JC, Pellicer XM, Rea BR. 2017. ACME, a GIS tool for automated cirque metric extraction. *Geomorphology* **278**: 280–286. https://doi.org/10.1016/j.geomorph.2016.11.018.

Turnbull JM, Davies RH. 2006. A mass movement origin for cirques. *Earth Surface Processes and Landforms* **31**: 1129–1148. https://doi.org/10.1002/esp.1324.

## Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Figure S1.** Supporting information

**Figure S2.** Supporting information

**Table S1.** Comparison between geomorphologically derived (published) and modelled (from the present study) equilibrium-line altitude (ELA) estimates for 88 former cirque glaciers in Britain and Ireland.