The erosion of glaciated mountains: evidence from hypsoclinometry

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ABSTRACT

Mountain glaciation involves the erosion of cirques and troughs, which increase steep slopes but also produce gentle slopes in cirque floors and trough floors. This is expected to increase the variability of slope gradients at related altitudes. Taking a whole mountain range, its distributions of altitude and slope can be analysed to establish a signal of glacial modification. Frequency distributions of altitude (hypsometry) and gradient (clinometry) alone do not seem adequate. Taking these two variables together – hypsoclinometry, plotting slope gradient against altitude – is more promising. Frequency distributions of slope gradient at different altitudes are exemplified here for mountain ranges in British Columbia and Romania, together with altitudinal variations of steep or gentle slopes.

Cirque headwalls give the clearest morphometric signature of glaciation. Steep (especially the steepest) slopes are concentrated at cirque altitudes, increasing mean, median, standard deviation (SD) and inter-quartile range (IQR) of gradients, especially above cirque floors. There is only a small increase in SD and IQR at cirque floor altitudes. Hypsometric maxima and increased proportions of gentle slopes at cirque floor altitudes are clear only in mountain ranges densely occupied by cirques. This relates to the small proportion of each cirque (about 28%) occupied by the floor. Concentrations of steep slope aspects in directions favoured by local glaciers provide further evidence of glacial modification. The most general morphometric effect of glaciation, however, is the increase in steep slopes at cirque headwall altitudes. Thus it is possible to rank mountain ranges by degree of glacial modification.

KEYWORDS
hypsoclinometry; clinometry; British Columbia; TanDEM–X; glacial erosion; cirque

1. Introduction

There are many differences between glaciated and unglaciated mountains, but how are these differences best expressed quantitatively? One way is to define and measure the specific landforms – cirques, arêtes, troughs and closed rock depressions – that
characterize glacial erosion (Barr and Spagnolo, 2015). Their sizes and densities show the degree of glacial modification of mountain landforms. The definition of specific landforms is progressing (in efficiency and objectivity) but remains subjective (Evans and Cox, 2017). For example, in some areas it is difficult to distinguish shallow glacial cirques from deep–seated rock slope failure scars, whose deposits may have been removed by glaciation. Glacial troughs are more difficult to define: an inverted parabola (U–) shape is characteristic but alluvial valley–floors obscure the distinction from fluvial valleys and make fitting a model to the bedrock surface problematic.

Analysis of the land surface (Minár and Evans, 2016) can employ either specific or general geomorphometry, or both. Thus in seeking greater objectivity it may be interesting to check for signals of glaciation in general geomorphometry, e.g. to take a whole mountain range and measure its distributions of altitude, slope gradient, slope aspect and curvatures. To start, frequency distributions of altitude (hypsometry) and slope gradient (clinometry) have been considered. It is widely believed that cirque erosion around glacial Equilibrium Line Altitudes (ELAs) has produced hypsometric maxima (high frequencies of altitude) (Mitchell and Montgomery, 2006; Egholm et al., 2009). This is one of the bases of the ‘glacial buzz-saw’ hypothesis that effective glacial erosion at such altitudes in the Late Cenozoic has worked to limit mountain altitudes (Mîndrescu and Evans, 2014). The strength of the hypsometric maximum should thus express at least one component of the glacial modification of mountains.

Hypsometric maxima, however, are somewhat fallible evidence as they may be produced in various ways (Evans et al., 2015; Robl et al., 2015, 2015a; Crest et al., 2017). It seems better to consider altitude and gradient together, rather than separately. Further evidence has thus been sought in the variation of mean or median slope gradient (slope angle) with altitude (elevation). Equilibrium models of fluvial topography predict steady increases in both channel gradient and hillslope gradient with altitude. In glaciated mountains, however, a flattening of this trend has been found at cirque floor altitudes (at least in the Alps: Kühni and Pfiffner, 2001; Robl et al., 2015a). Yet as glaciation produces gentle and reversed slopes (cirque floors and trough floors) as well as extra steep slopes (cirque headwalls and trough sides), plotting mean or median slope against altitude is not sufficient. It is necessary to plot frequency distributions of slope gradient at different altitudes. This combination of hypsometry and clinometry is logically labelled hypsoclinometry, and is more promising than the separate components, as the excellent work of Robl et al. (2015a) on the Alps has shown.

This leads me to a number of specific hypotheses:
1. There are more gradients <20° at cirque floor altitudes;
2. There are more gradients >35° above cirque floors (i.e. cirque headwalls);
3. Higher standard deviations (SDs) and interquartile ranges (IQRs) of gradients occur at cirque floor altitudes (because the altitude ranges of headwalls and floors overlap: headwalls are found immediately above the lowest cirque floors).

These hypotheses are tested here for two mountain ranges in British Columbia and compared with previous results from Romania.

2. Data and Methods
An increasing number of fairly accurate Digital Elevation Models (DEMs) are now available with near–worldwide coverage. For geomorphological interpretations, forest and human constructions can cause problems, but these are almost absent in mountains above timberline. In glaciated mountains, the main problems come from shadow (both solar shadow and radar shadow), glaciers and lakes.

The hypsoclinometry of 21 mountain ranges in Romania was analysed by Niculiţă and Evans (2018) from freely available SRTM data, gridded with 30 m horizontal resolution and analysed in ArcGIS. Here I focus on data for British Columbia, extracted from TanDEM–X 1–degree tiles supplied by DLR (project DEM–METH 1517). These provide higher resolution (30 arc–second), and were gridded (by D. Milledge) at 12.5 m grid mesh. Mountain range outlines were digitised, initially for the Shu-laps and Bendor Ranges on the interior side of the southern Coast Mountains, some 175 km north of
Vancouver. The data were extracted for whole mountain ranges down to the valleys and lakes on either side, and to passes separating them from other high ground. Note that below the ‘defining pass’ – the highest point on the range boundary – results for slope aspect become increasingly biased as contours are not closed on that side of the range. Above that pass, as each higher contour encompasses a smaller area, there is an expectation (but not an inevitability) that each contour may be shorter and that the area in each successive band (bin, class) of altitude will be less.

As the data are radar–based, return scatter over water produces false values, with differences of tens of metres between adjacent points which should be on the same level. Thus lakes had to be masked out, using available masks for large lakes but digitising other lake outlines. Lake areas were then treated as ‘missing data’. (Alternatively, with more work, each lake could be given its true altitude so that it shows up as zero gradients at the appropriate altitude). The altitude data were read into Stata as (x,y,z) trios and slope gradients and aspects were calculated with a program by N.J. Cox, based on the formulae in Evans (1979).

Available (map–based) data for each cirque floor in these ranges include lowest, modal and maximum altitudes. To exclude extreme values, the lowest 5% and highest 5% are ignored, and the 05 and 95 percentiles of Lowest altitude plus the 95 percentile of Maximum floor altitude are used to

Figure 1 The Bridge River District, British Columbia. Longitude grid lines are spaced 0.1°; latitude, 0.05°. Red outlines show the Shulaps Range (top), the Bendor Range (left) and the Mission Range (right). The long central lake is Carpenter Lake (a reservoir); the north–south valley on the right is of the Fraser River
represent the altitudinal range of cirque floors. By relating results for hypsoclinometry to these previous results for cirques, available on a comparable basis for British Columbia and Romania, it becomes clear that specific geomorphometry and general geomorphometry can be complementary.

3. Results

The Bendor and Shulaps Ranges (Fig. 1) in the Bridge River District of British Columbia are on the landward side of the southern Coast Mountains, which has a much less humid climate than the seaward side. At the last glacial maximum they were submerged in the Cordilleran Ice Sheet, which flowed southward and south–westward from the Interior (Fraser) Plateau to the coast, through several passes (Evans, 1990). The Ice Sheet produced little modification of the higher ground, where it was thinner and possibly cold–based. Instead, both Ranges preserve landforms of local glaciation (cirques and troughs) which developed during the build–up of ice and in numerous previous phases of glaciation intermediate between maximum and present–day. These were mainly valley glaciers, whereas those present today are cirque glaciers no longer than 2 km (Bendor) or 1 km (Shulaps).

3.1 Shulaps

The Shulaps Range has cirques and small glaciers mainly on its north or northeast side. Cirque lowest altitudes range from 1957 to 2456 m (05% to 95%) and the 95 percentile of Maximum floor altitude is 2610 m. Figure 2 shows the altitudinal distribution of steep and gentle slope gradients. The results for low gradients are disappointing in that there is no maximum at cirque floor altitudes. This is partly because cirque floors are on average only c. 28% of cirque areas (in Romania: Mindrescu and Evans, 2014, 2017), and partly because there is an extensive area of low–gradient bench or piedmont just below cirque altitudes, on the northeast (Yalakom) slope. Hence there is also no clear increase in SD or in IQR (Fig. 2).

Headwalls, however, give a clear ‘glacial’ signal – mainly above 2456 m. At 1530–1957 m, below cirque floors, only 1.5% of gradients are >45°; at 1957–2456 m the percentage rises to 2.5, at 2456–

![Figure 2 Shulaps Range gradient statistics by altitude: dispersion measured by Standard Deviation (SD) and Inter–quartile Range (IQR), and percentages (in each 50 m altitude bin) of gentle and steep slopes. The left red line is the defining pass; the two central lines at 1957 and 2456 m are the 05 and 95 percentiles of cirque floor Lowest altitude, and the right line at 2610 m is the 95 percentile of Maximum floor altitude per cirque](image-url)
2610 m it is 8.5 and above 2610 m it is 7.5 (Fig. 2). This is a clear representation of steep cirque headwalls. Figure 3 shows the density (frequency in relation to total) of slope gradients >45°: the strong secondary mode above 2100 m altitude shows cirque headwalls even more clearly.

![Figure 3](image_url) Density of steep gradients (>45°) in the Shulaps Range by altitude (50 m bins)

Figure 4 Density of altitude in the Bendor Range (25 m bins). The red lines at 1790, 2300 and 2425 m show the extent of cirque floors, covering the hypsometric maximum

Vector analyses of aspects of steep slopes provide further evidence of glacial modification of the Shulaps Range. Using the same altitude classes as above, but subdividing the large 1957–2456 m class, vector means are consistently northward (351–001°) above 2200 m (Table 1). This compares with a mean of 007° for cirques. Vector strength increases, to over 0.24, only above 2456 m, where headwalls are dominant. Below 2150 m various mean directions occur.

### 3.2 Bendor

The Bendor Range is well glaciated, with glacial troughs and 222 cirques (Evans and Cox, 2017). Cirque floors average 150 m lower than in Shulaps. Bendor has a ‘glacial’ hypsometric maximum at cirque floor altitudes (Fig. 4). This contrasts with the ‘fluvial’ trend of area increasing linearly downward, at least to the ‘defining pass’ (at 1865 m).

Overall, Bendor gradients peak sharply at 35°. Coinciding with the 05 and 95 percentiles of cirque floor Lowest altitudes at 1790 to 2300 m there is a strong maximum of low gradients, from the extensive cirque floors (Fig. 5). This is complemented by a strong maximum of steep gradients at the same altitudes (Fig. 6). Subdivision (not shown) of steep gradients reveals that for increasingly steep slopes the maximum shifts upwards, peaking around 2300 m – above the mid-altitude of cirque floors – for both 55–65° and >65°. Slopes steeper than 55° are infrequent below 1700 m. Gradients below 20° become more important especially below 1400 m, where there are benches above Cadwallader Creek.

Statistics in Figure 7 show the greater proportions of gradients <20° between 1790 and 2300 m (more noteworthy considering the trend of the proportion reducing with increasing altitude), and of those >45° above 2080 and especially above 2300 m, reflecting floors and headwalls respectively. This is supported by high IQRs between 1790 and 2300 m, but not by SDs.

Although the aspects of cirques and glaciers in Bendor are less azimuthally concentrated than in Shulaps, the glaciation is still strongly asymmetric. Hence above 1900 m, vector means of steep (>40°) slopes are consistently northward, and above 2100 m their vector strengths are above 0.14. The northward mean of 008° is very close to the vector means of cirques (018°) and of modern glaciers (011°). Thus strong and consistent asymmetry of steep slopes, restricted to appropriate altitudes, is a further geomorphometric indicator of cirque headwalls, and therefore of glacial modification.
Table 1  Vector strength and vector mean (with confidence limits) for aspect, by altitude bands, for slope gradients over 40° in the Shulaps Range: from the 12.5 m DEM

| Altitude       | Strength | Mean | 95% limits       | Observations |
|----------------|----------|------|------------------|--------------|
| Over 2610 m    | 0.287    | 001.0| 358.1 – 003.9    | 7314         |
| 2456 – 2610    | 0.240    | 359.6| 357.6 – 001.6    | 24433        |
| 2350 – 2456    | 0.180    | 356.5| 353.9 – 359.1    | 25443        |
| 2250 – 2350    | 0.179    | 351.0| 348.0 – 354.0    | 20074        |
| 2150 – 2250    | 0.214    | 341.9| 339.0 – 344.8    | 15095        |
| 2050 – 2150    | 0.136    | 285.9| 280.0 – 291.8    | 10554        |
| 1957 – 2050    | 0.208    | 216.8| 212.9 – 220.7    | 10385        |
| Over 2200 m    | 0.208    | 356.4| 355.1 – 357.6    | 85615        |

Figure 5 Frequency of gentle slopes (<20°) in the Bendor Range (50 m bins). The red lines at 1790, 2300 and 2425 m show the extent of cirque floors, with frequency peaking at average floor altitude. The lower peak, around 1300 m, relates to valley-side benches along Cadwallader Creek.

Figure 6 Frequency of steep slopes (>35°) in the Bendor Range (50 m bins). The red lines at 1790, 2300 and 2425 m show the extent of cirque floor altitudes, at which there is a broad maximum of steep (as well as gentle) gradients. Headwalls start from the lowest cirque floors and extend to the highest summits.

3.3 Romania

Results from Niculiţa and Evans (2018), using SRTM data for Romania, support those for British Columbia. At present there are no glaciers in the Romanian mountains, but at the Last Glacial Maximum there were many cirque and valley glaciers, in numerous mountain ranges. In the Retezat Mountains of southwest Romania, the 84 cirque floors are mainly 1760–2190 m (5 to 95 percentiles of Modal floor altitude: Mindrescu et al., 2010; Mindrescu and Evans, 2014, 2017). This shows in the hypsometric plot as a decline in the lower quartile of gradient, from 1800 to 2100 m altitude (Fig. 8). Median gradient declines (gently) from 1600 to 2050 m, the latter being the median gradient of cirque floor altitudes. The upper quartile and the 95 percentile of gradient rise steeply from 1850 to 2350 m, and the median increases from 2100 to 2400 m: all these show the effects of high gradients from cirque
headwalls. The quartiles diverge above 1850 m: the increase in SD and IQR reflects the presence of both low-gradient cirque floors and high-gradient cirque headwalls. There is a relatively small area above 2350 (to 2500 m) and the declining gradients there are due to smoothing as gradients were calculated from a quadratic fitted to a 90 x 90 m window.

Similar results were found for other well–glaci-ated ranges. The 45 cirque floors of the Rodna

| Altitude (m) | Mean (°) | Median (°) | SD (°) | IQR (°) | <20° % | >45° % | Observations |
|--------------|----------|------------|--------|---------|--------|--------|--------------|
| above 2425   | 36.2     | 35.7       | 13.8   | 16.8    | 11.3   | 22.6%  | 153k         |
| 2300         | 35.8     | 35.2       | 12.8   | 14.5    | 9.9    | 19.4%   | 235k         |
| 2080         | 31.0     | 31.4       | 12.6   | 15.2    | 18.9   | 10.7%   | 708k         |
| 1790         | 29.6     | 30.1       | 12.1   | 14.9    | 21.0%  | 7.8%   | 1053k        |
| 1600         | 29.8     | 30.4       | 11.7   | 13.9    | 18.8%  | 7.3%   | 538k         |
| 1400         | 28.8     | 29.5       | 11.5   | 14.7    | 21.7%  | 6.5%   | 457k         |
| Below        | 28.2     | 29.1       | 12.7   | 17.9    | 27.0%  | 8.6%   | 1236k        |

Figure 7 Statistics for Bendor altitudinal classes of gradient, including 1790–2300–2425 m (cirque floors) and 2080–2300 m and up (cirque headwalls)

The Parâng Mountains in the southwest Carpa-thians have 51 cirques. Again headwalls are more evident than cirque floors, with the 95 percentile of gradient increasing from 0.85 at 1775 m to 1.13 at 2275 m: the upper quartile rises similarly. Median gradient increases from 1950 to 2300 m. SD and IQR increase from 1850 to 2350 m (and 2450 m for SD).

The Romanian results, for 21 ranges, show strong concentrations of high gradients at altitudes of cirque headwalls in fourteen ranges with more than a few cirques. Cirque floors are less evident in hypsoclinometry, presumably because they cover on average only 28% of the map area of a cirque (Mîn-drescu and Evans, 2014, 2017). The relevant falling lower quartile is found in six ranges, with weaker indications in five others. ‘Glacial signals’ in altitudi-nal distributions of gradients are clearest in the Re-tezat, Făgăraș, Țârcu, Maramureș and Rodna Mountains. This is comparable to the ranking (of twelve regions) from seven attributes of cirque quality in Mindrescu and Evans (2014): from most glacially modified to least, Retezat, Parâng, Făgăraș, Bucegi, Rodna, Lotru–Cindrel, Godeanu, Maramureș, Iezer, Țârcu, Bihor, Călimani.

Unglaciated ranges in Romania show a variety of altitudinal trends of gradient (Niculiță and Evans, 2018).
4. Further work

The work on British Columbia is at an early stage and will be extended to further mountain ranges, with differing degrees of past and present glaciation. (Large present-day glaciers cause problems as it is the unknown subglacial topography that is of interest). Data quality needs more detailed study, and it will be useful to compare results from 25 m resolution DEMs with results from these 12.5 m DEMs. Aspect distributions should be analysed in relation to gradient as well as altitude. Finally, several measures of surface curvature can be analysed in relation to altitude.

5. Conclusions

The strong glacial modification of the Bendor Range shows in a high percentage of steep slopes (headwalls) at and above cirque floor altitudes, and of gentle slopes (above the upward decreasing trend) at cirque floor altitudes.

![Figure 8](from Mihai Niculita) Combined boxplots and density distributions for the Retezat Mountains, southwest Carpathians. The boxes represent the Interquartile Range (IQR), from lower to upper quartile. The circles show one standard deviation (SD) above the mean (black) and one below (open). Colour shows percentage of observations, for bins of 50 m altitude x 0.025 gradient. Note that gradient (tangent) of 1.0 = 45°

Steep (and especially steepest) slopes are concentrated at cirque altitudes, increasing mean, median, SD and IQR especially above cirque floors. There is only a small increase of IQR and SD at cirque floor altitudes. The hypsometric maximum is at cirque floor altitudes, unlike the expectation for fluvial topography.

The Shulaps Range is asymmetrically glaciated with fewer cirques and very short troughs. It shows a strong secondary mode of steep slopes above 2100 m altitude; but the ‘glacial’ signal in mor-
phometry is much weaker than for Bendor, reflecting its lesser degree of glacial modification. This is due to a former ELA which is higher in Shulaps, whereas summits are of comparable altitude. The present-day ELA is also higher in the Shulaps, and its lower precipitation may also make its glaciers less effective both today and in the past.

These results are supported by the Romanian evidence in Niculiță and Evans (2018). Romanian ranges can thus be ranked by degree of glacial modification, comparably to the ranking from specific geomorphometry of cirques in Mindrescu and Evans (2014). In general, low gradients at cirque floor altitudes become clear only in well-glaciated ranges with high densities of cirques. The most general morphometric effect of glaciation is the increase in steep slopes at cirque headwall altitudes. This usually feeds through to increased variability and averages of gradient: SD, IQR, mean and median. Complications can arise where there are low-gradient summit surfaces, as in the Godeanu and Țarcu Mountains, or where extensive gentle slopes are found below cirque floors as in the Shulaps Range.

Slope aspects are much more azimuthally concentrated at the altitudes of headwalls. Vector means are northward above 1900 m in Bendor and 2200 m in Shulaps. Vector strengths for slopes on headwalls are >14% in Bendor above 2100 m and >18% in Shulaps above 2200 m. These are similar to vector means for cirque aspects and glacier aspects. Likewise in the English Lake District, slopes >45° at high altitude have a vector mean aspect of northeast, as do cirques and a vector strength of 37%. These results are characteristic of mountains glaciated asymmetrically, and give further objective evidence of a glacial imprint.

Although these results are preliminary, and analyses of further mountain ranges are required, it is possible to arrive at judgements on the three hypotheses. The first, that there are more gradients <20° at cirque floor altitudes, is weakly confirmed. The second, that there are more gradients >35° above cirque floors (representing cirque headwalls) is strongly confirmed, and in the British Columbian examples applies especially to gradients >45°. The third, that higher standard deviations and interquartile ranges of gradients occur at cirque floor altitudes (because the altitude ranges of headwalls and floors overlap), is strongly confirmed. Thus it may be possible to rank mountain ranges by the degree of glacial modification, using several approaches of general geomorphometry.

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