GEOMORPHOMETRY 2020 PERUGIA, ITALY JUNE 22 - 26 2020

Hypsoclinometric evidence of the degree of modification of mountains by glacial erosion

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Abstract— **Analyses of slope gradient distributions as functions of altitude are described as hypsoclinometry. They show strong distinctions between glaciated and unglaciated mountains, analysing each mountain range as a whole, bounded by low passes. The denser and better-developed the glacial cirques, the greater the proportion of steep slopes among slopes at cirque altitudes, representing cirque headwalls. This is accompanied by increased variability of slope gradient and by consistent directions of vector mean aspects. There may also be a concentration of gentle slopes at cirque floor altitudes. General geomorphometry can thus provide objective measures of the degree of modification by local glaciers.**

I. INTRODUCTION

Hypsometric maxima have been used as evidence of the importance of glaciation in eroding mountain ranges (Egholm et al., 2009). It is inferred that these represent glacial cirque floors: however, summit plateaux and other low-gradient areas also produce maxima in altitude frequency distributions (Crest et al., 2017). Robl et al. (2015) showed that more information can be obtained by combining altitude and slope gradient frequency distributions, an approach labelled hypsoclinometry by Niculița and Evans (2018), and Evans (2019). Here we apply this approach to several ranges in British Columbia and make some comparisons with Romania and England. Note that it is important to take a whole mountain range and to focus on altitudes above the lowest closed contour, given by a 'defining pass'. Data on the specific geomorphometry of cirques are used to interpret the results of hypsoclinometry, which is a part of general geomorphometry (Minár et al., 2013).

In British Columbia we used TanDEM-X 0.5 arc-second data gridded at 12.5 m, after digitising lake outlines and replacing lakes with 'missing data' because their radar returns suffered water speckle errors. We compared the well-glaciated Bendor Range with the adjacent, drier, moderately-glaciated Shulaps Range and the lightly-glaciated Mission Ridge. (Later, comparisons will be made with the Ninemile and Clear Ranges, with just a few cirques, and the South Camelsfoot Range that did not suffer local glaciation). The 'glacial signal' comes mainly from the development of glacial cirques (Barr and Spagnolo, 2015; Evans and Cox, 2017; Evans, 2020), hence we relate gradient distributions to altitudes of cirque floors. The Bendor Range has a strong signal for both cirque floors and headwalls; Shulaps shows a signal mainly for headwalls.

II. GRADIENT DISTRIBUTIONS BY ALTITUDE

In the Shulaps Range (122.5° W, 51° N, highest summit 2877 m), only headwalls give a clear 'glacial' signal – mainly above 2456 m (see steeper than 45°, Table I). Floors do not, probably because in general they are only c. 28 % of cirque areas whereas headwalls are 72%. Any low-gradient (see gentler than 20°) signal is blurred by extensive benches just below cirques, on the northeast (Yalakom) slope.

TABLE I. SHULAPS RANGE, B.C.: GRADIENT STATISTICS FOR ALTITUDE BANDS

Altitude (m)	Mean (°)	Median (°)	SD (°)	IQR (°)	<20° %	>45° %	Observations
Above 2610**	28.6	28.8	11.5	14.7	22.8	**7.5** headwalls	53k
2456-*	29.8	29.7	11.4	14.3	**19.1** floors	**8.5**	156k
1957-*	23.9	24.1	10.8	15.8	**36.9**	2.5	1465k
1530-	21.2	20.5	10.7	16.2	48.3	1.5	1946k
Below	25.4	25.0	12.5	16.1	35.7	6.1	1887k

*1957 & 2456 m are 05 and 95 percentiles of lowest altitude per cirque.
**2610 m is the 95 percentile of maximum floor altitude per cirque. k=thousand.

Ian Sylvester Evans, Nicholas J. Cox, Mihai Niculita and David Milledge (2020) Hypsoclinometric evidence of the degree of modification of mountains by glacial erosion:

in Massimiliano Alvioli, Ivan Marchesini, Laura Melelli & Peter Guth, eds., Proceedings of the Geomorphometry 2020 Conference, doi:10.30437/GEOMORPHOMETRY2020_21.

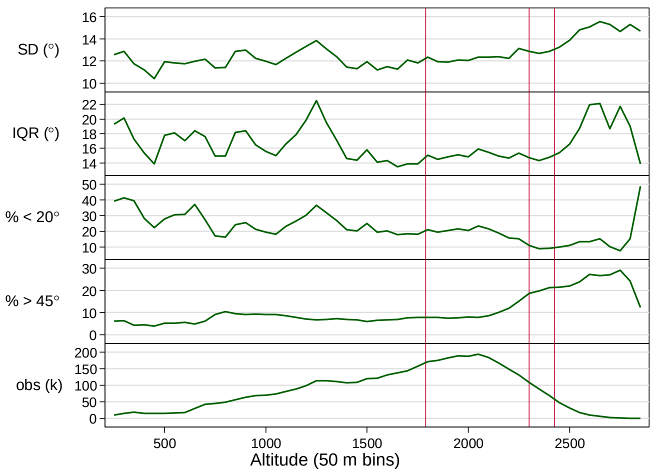

Figure 1. Gradient statistics by altitude (x axis, 25 m bands) for the Bendor Range, British Columbia. Red lines at 1790 and 2300 m are the 05 and 95 percentiles of lowest floor altitude, whereas the right-hand line at 2425 m is the 95 percentile of maximum floor altitude per cirque; obs (k) is the number of observations in thousands.

TABLE II. BENDOR RANGE, B.C.: GRADIENT STATISTICS FOR ALTITUDE BANDS

Altitude (m)	**Mean (°)**	**Median (°)**	**SD (°)**	**IQR (°)**	**<20° %**		**>45° %**		**Observations**
Above 2425	36.2	35.7	13.8	16.8	11.3		22.6	headwalls	153k
2300-	35.8	35.2	12.8	14.5	9.9	floors	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

1790 and 2300 m are 05 and 95 percentiles of lowest altitude per cirque.
2425 m is the 95 percentile of maximum floor altitude per cirque.
k= thousand. (From Evans, 2019.)

The Bendor Range (highest summit 2911 m) shows a strong maximum of high gradients above the mid-altitude of cirque floors (Fig. 1). Low gradients, very variable at lower altitudes, do show a broad maximum from the extensive floors of 222 cirques. This is accompanied by a hypsometric maximum (see obs(k)). Variability, expressed by Standard Deviation and Inter-Quartile Range, is high at cirque floor levels but even higher above these.

Fig. 2 shows that all classes of slopes over 35° in the Bendor Range have a strong maximum towards the top of cirque floor levels. This concentration increases for steeper slopes, especially above 55°. It appears that the sides of glacial troughs, down-valley from cirques, are mainly between 35° and 55°; not as steep as some cirque headwalls.

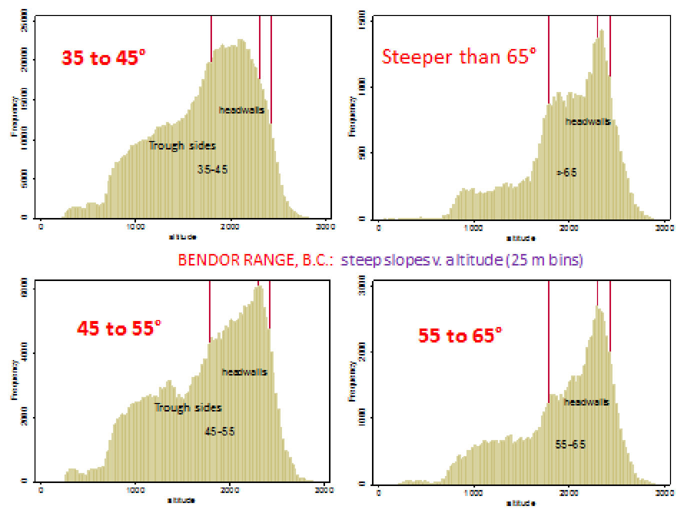

Figure 2. Frequencies of four classes of steep slopes in the Bendor Range, B.C., by 25 m bins of altitude (x axis). Red lines at 1790 and 2300 m are the 05 and 95 percentiles of modal floor altitude, whereas the right-hand lines at 2425 m are the 95 percentile of maximum floor altitude per cirque.

III. ASPECT CONCENTRATION

Slope aspects show greater concentration at the altitudes of headwalls. Focusing on steep slopes (>40°), the vector statistics of aspect can be compared with those of cirques. Vector means are consistently northward above 2200 m in Shulaps and 1900 m in Bendor (Tables III and IV). These are similar to vector means for cirque headwall aspects and glacier aspects. Shulaps means are 342-001°, 356° overall above 2200 m; and Bendor means are 012-014°, 008° overall above 1900 m. Headwall vector mean aspects are 007° and 018° respectively, and glaciers average 011° in both ranges. In lower altitude belts, various mean directions of steep slopes occur.

Steep slopes show relatively high vector strengths of 18-29%, 21% overall above 2200 m in Shulaps; and 14% overall above 1900 m in Bendor but 14-22% in belts above 2100 m. The comparison reflects the broader range of cirque aspects in the more heavily glaciated Bendor Range.

Similarly in the English Lake District, slopes >45° at high altitude (above 300 m; Fig. 3) have a vector mean aspect of NE, (033°) as do the 157 cirques(048°): the vector strengths are 37% and 54%. These results are characteristic of mountains glaciated asymmetrically, and give further objective evidence of a glacial imprint. As yet it is not known whether asymmetry of steep slopes is found in mountain ranges where cirques face all directions and have no significant resultant vector. Consistency of steep slope aspects and cirque aspects is not found in the lightly glaciated Mission Ridge, east of Bendor and south of Shulaps but with a highest summit of only 2427 m. This ridge has a very steep southwest slope, part of the Seton Lake trough.

TABLE III. VECTOR MEAN AND STRENGTH FOR ASPECT OF SLOPES OVER 40°, BY ALTITUDE BANDS IN SHULAPS RANGE, B.C.;
the boundaries at 1957 and 2456 m are 05 and 95 percentiles of lowest altitude per cirque; 2610 m is the 95 percentile of maximum floor altitude per cirque; consistent northward tendency above 2200 m (in italics, bottom line) reflects cirque headwalls

Altitude (m)	**Mean (°)**	**Strength (%)**	**Observations**
Above 2610	**001**	**29**	7314
2456-2610	**360**	**24**	24433
2350-2456	**357**	**18**	25443
2250-2350	**351**	**18**	20074
2150-2250	**342**	**21**	15095
2050-2150	286	14	10554
1957-2050	219	21	10385
Above 2200	***356***	***21***	***85615***

In Romania, the gradient frequency distributions can be related to modal floor altitudes in the data of Mîndrescu and Evans (2014). In Table V the resulting signals for cirque floors (a decline in lower quartile: LQR) and cirque headwalls (increased standard deviations and inter-quartile ranges: SD & IQR) are related to the low (05) and high (95) percentiles of modal cirque floor altitudes, for the twelve ranges with more than four cirques. Although only six mountain ranges show a 'floor' signal of declining LQR, all but Bucegi show a 'headwall' signal. The ranges are listed in order of 'degree of glacial modification' calculated from seven cirque variables by Mîndrescu and Evans. The headwall signal is strongest for the 'most glaciated' ranges (the first three). Rodna, Maramureş and Ţarcu also give strong 'glacial' signals.

The innovative paper of Robl et al. (2015) graphed the hypsoclinometry of many massifs in the Alps, using a DEM with 50 m resolution. The continuing presence of glaciers is a complication, reducing gradients of the lower parts of cirque headwalls. Clear signals of both headwalls and cirque floors are found especially in the external massifs (Mont Blanc, Pelvoux-Écrins, Aar, Belledonne and Argentera), and in the Ligurian Alps and Dora Maira Massif (Robl et al., 2015, Figs. 6 & 8).

IV. CONCLUSIONS

From analyses of slope, aspect and altitude in British Columbia, Romania, England and the Alps, the best geomorphometric indication of glacial modification of mountains (by erosion) is the concentration of steep slopes, representing headwalls, around and above the altitudes of cirque floors. This is supported, in the common situation of asymmetric local glaciation, by consistent favoured directions of steep slopes at similar altitudes, with vector means comparable to those of cirques and present or former glaciers. There is also an increased standard deviation and inter-quartile range of slope gradients at these altitudes. The expected concentration of gentle slopes at altitudes of cirque floors is clear only where there are numerous well-developed cirques. Hypsometry alone – the concentration of area at certain altitudes – is not a reliable indicator of altitudes of glacial erosion.

TABLE IV. VECTOR MEAN AND STRENGTH FOR ASPECT OF SLOPES OVER 40°, BY ALTITUDE BANDS IN BENDOR RANGE, B.C.;
the boundaries at 1790 and 2300 m are 05 and 95 percentiles of lowest altitude per cirque; 2425 m is the 95 percentile of maximum floor altitude per cirque; consistent northward tendency above 1900 m (in italics, below) reflects cirque headwalls, and is stronger above 2100 m (black horizontal line)

Altitude (m)	**Mean (°)**	**Strength (%)**	**Observations**
Above 2425	**012**	**21.7**	51871
2300-2425	**007**	**15.9**	73199
2100-2300	**002**	**14.3**	125046
1900-2100	**014**	8.9	114425
1790-1900	061	7.4	59306
1500-1790	110	8.4	114671
Above 1900	***008***	***13.9***	***364541***

TABLE V. ALTITUDES WITH SLOPE GRADIENTS RELATED TO CIRQUE ALTITUDES, FOR 12 RANGES IN ROMANIA WITH MORE THAN FOUR CIRQUES

Mountain range	LQR rises	Modal Floor (p5……p95)	Increased SD & IQR	Max. altitude	n
Retezat	1800-2100	1760…2190	1800-2400	2509	84
Parâng	-	1830…2150	1850-2350	2518	51
Făgăraș	1875-2175	1830…2230	1900-2500	2544	206
Bucegi*	-	1940…2320	-	2505	11
Rodna	1700-1800	1520…1910	1700-2300	2303	45
Lotru*	-	1700…1960	1875-2150	2242	10
Cindrel*	-	1701…2020	1825-2200	2244	8
Godeanu*	-	1640…2010	1850-2200	2291	69
Maramureș	1475-1675	1465…1690	1475-1825	1956	27
Iezer*	-	1870…2170	1925-2200	2470	38
Țarcu*	1750-2050	1630…1980	1850-2100	2192	58
Călimani	1725-1975	1725…1975	1675-1875	2100	7

*ranges with summit plateaux. LQR = lower quartile, p = percentile, SD = standard deviation, IQR = inter-quartile range, n = number of cirques.

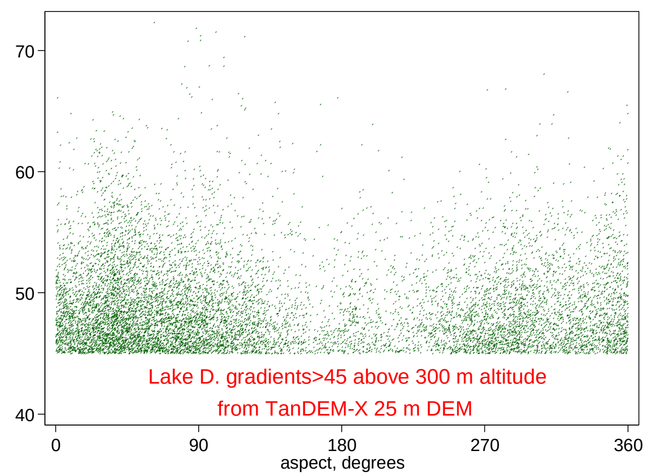

Figure 3. Gradients steeper than 45°, above 300 m altitude, in the English Lake District, from a gridded 25 m TanDEM-X DEM. Concentrations around north and northeast give a vector mean of 033°, with a strength of 37%.

ACKNOWLEDGEMENT

We are grateful to the German Aerospace Centre (DLR) for providing TanDEM－X DEM data for the Bridge River District under project DEM_METH1517.

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