Size and shape of glacial cirques: comparative data in specific geomorphometry

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Abstract — **When comparably defined, cirque size and shape vary modestly but significantly between regions. Differences in vertical dimensions (height range, amplitude, wall height) are greater than those in horizontal dimensions. A broader set of data from various authors shows greater variability, especially in mean values, for which there are several possible explanations.**

I. Introduction

Studies of the morphometry of landforms normally deal with single regions. When regions are compared, differences can be attributed both to subjective differences between authors in their understanding of definitions, and to differences in source material and methods, as well as to real differences. Scientific progress in specific geomorphometry has thus been held back by the vagueness of definitions, leading to data sets produced by different authors lacking comparability. We require precise, repeatable operational definitions permitting replicable closed outlines to be drawn around each land-form. Ardelean et al. [1] showed that the considerable differences between different authors can be reduced if a common precise definition is applied. An attempt is being made, for glacial cirques, to produce a series of data sets based on the same definition [2] [3]. Initial results are reported here, and comparisons with differently produced data sets are made.

We consider the distributions of cirque size and shape especially for nine well-studied regions. A particular question in the development of cirques by glacial erosion is whether there is an upper limit on cirque size: Evans [4] suggested that cirques are scale-specific, with upper and lower limits to their size. Another is whether the form of glacial cirques is produced essentially by deep-seated rock avalanches [5]. A third question is the variation of shape with size and age: Evans [6] reported work confirming the static allometry of glacial cirques in several European and British Columbian areas.

II. Data

Here we test for differences in cirque size and shape between nine regions with complete inventories: three divisions of Romania, three in Britain (Wales and England), and three adjacent ranges in south-west British Columbia. The first six data sets were produced by Evans, while the Romanian coverage was produced by Marcel Mîndrescu following the same definitions, with checks by Evans [7]. The Lake District (England) data are from Evans and Cox [3], but with two deletions; those for the two divisions of Wales are from Evans [8]; and the British Columbian data were used in Evans [4]. Each data set is based on detailed fieldwork, air photo interpretation, and large-scale topographic maps. We thus have a cluster sample, with complete coverage of Romania, of Wales and the Lake District, and of three contiguous mountain ranges in British Columbia (Cayoosh, Bendor and Shulaps). Wales is divided into the old volcanic and metamorphic terrain of the northwest (‘Snowdonia’) and the mainly sedimentary or weakly metamorphosed terrain of central, southern and eastern Wales. In Romania, the threefold division is achieved by separating the largest glaciated range, the Făgăraş Mountains, from the mountains to the west, and from those to the east and north.

III. Size analyses

Median values for the two horizontal dimensions (length and width), and for three ways of defining the vertical dimension, are given in Table I. As all these size variables are positively skewed, the median is more representative than the mean (which is always higher) (Fig. 1). The effects of skewness are avoided by performing all further analyses on logarithms of these size variables, reducing skewness (per region) to between −0.75 and +0.63 (from initial values between +0.52 and +4.30).

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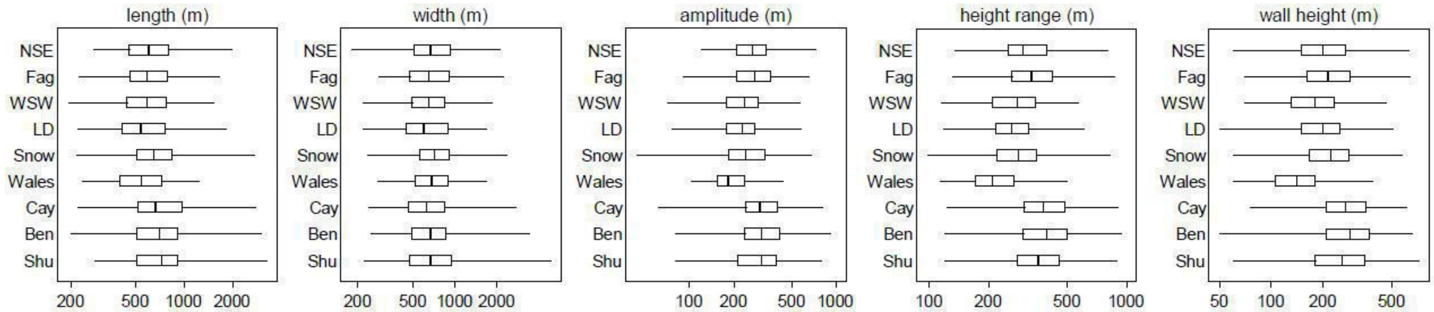

Figure 1. Box plots of five morphometric measures on logarithmic scale. The plots show minimum, quartiles and median (central box) and maximum. These measures are all commutative with logarithmic scale as (e.g.) median of logarithms is logarithm of median.

Note that length is greatest for the three British Columbian regions, and least for the Lake District and 'Wales C., S. and E'. Width is greatest for Snowdonia and least for the Lake District. Vertical dimensions are strongly inter-correlated, and much more variable between regions. All three vertical variables are greatest in British Columbia and least in Wales (C, S & E).

Analysis of variance between and within the nine regions produced highly significant differences ($P < 0.0001$) for all size dimensions except width ($P = 0.1452$) (Table II). Judging by either F ratio or R^2, between-region contrasts were greatest for vertical dimensions, especially height range. Similar results were obtained with and without logarithmic transformation.

IV. Shape and Gradient Analyses

Table III gives median values for gradient and shape variables. The gradient and closure variables are almost unskewed (−0.47 to +1.00 per region) and means are not far from medians: but medians are given for compatibility with the two ratios (skews +0.49 to +1.65) and with Table I. Profile closure is controlled mainly by maximum gradient: Snowdonian cirques are best developed (with especially gently-sloping floors), followed by Lake District and Cayoosh, while 'North and southeast Romania' has the poorest. It may be that Romanian gradients are distorted by relatively poorly-contoured maps, mainly at 1:25,000, with contours interrupted at cliff symbols. In plan, Făgăraş has the best-developed cirques, and Shulaps plus 'Wales central, southern and eastern' have the poorest. Wales (C, S & E) has the highest W/L and L/H ratios, while the British Columbian ranges have the lowest, accompanied by Făgăraş for L/H. This reflects the poor showing of Wales (C, S & E) on length and especially on height range.

Analysis of variance demonstrated highly significant differences between regions (Table II) for all seven shape variables (gradient, closure and ratio variables). Differences, as shown by F ratio and R^2 values, are greatest for gradient variables and thus for profile closure, and for the Length/Height ratio which is an inverse gradient measure.

TABLE I. Median dimensions (m) and numbers of cirques, per region.

Region	*Number*	*Length*	*Width*	*Amplitude*	*Height range*	*Wall height*
N & SE Romania	132	610	666	270	300	200
Făgăraş	206	592	652	280	330	215
W & SW Romania	293	591	644	240	280	180
Lake District	156	545	600	230	261	200
Snowdonia	143	655	720	242	285	222
Wales C, S & E	117	550	685	185	210	140
Cayoosh	198	670	625	305	381	270
Bendor	222	705	670	312	395	285
Shulaps	126	730	670	310	360	260
TOTAL	**1593**	**625**	**656**	**260**	**310**	**210**

TABLE II. Analysis of variance results for variance accounted for the division into nine regions. All except width are highly significant (P<0.0001). The *SD* (overall standard deviation) is given for comparison with the *RMSE* (root mean square deviation) within regions. Logarithms are used for the first five variables (dimensions).

Variable	*F*	R^2	*Adjusted* R^2	*rmse*	*SD*
Length	9.37	.045	.040	.188	.192
Width	1.52	.008	.003	.192	.192
Amplitude	26.77	.119	.115	.166	.177
Height range	48.39	.196	.192	.155	.172
Wall height	42.10	.175	.171	.182	.200
Max gradient	80.51	.289	.285	8.97	10.62
Min gradient	20.71	.095	.090	5.39	5.65
Plan closure	9.67	.047	.042	48.11	49.15
Profile closure	55.80	.220	.216	11.40	12.87
Axial gradient	13.39	.063	.059	6.51	6.71
Width/length	12.82	.061	.056	.365	.375
Length/height range	24.73	.111	.106	.643	.681

TABLE III. MEDIAN GRADIENT AND SHAPE VARIABLES (°, EXCEPT LAST TWO) AND NUMBERS OF CIRQUES, PER REGION. 'GRAD' = GRADIENT.

Region	*Number*	*Max grad*	*Min grad*	*Plan closure*	*Profile clos.*	*Axial grad*	*Width/Length*	*Length/Height*
N & SE Romania	132	48	10.2	137	37.6	23.8	1.10	2.04
Fagaras	206	55	8.7	145	46.5	24.6	1.03	1.81
W & SW Romania	293	51	7.5	134	42.3	22.5	1.11	2.10
Lake District	156	63	7.1	123	56.0	22.7	1.10	2.09
Snowdonia	143	65	3.5	121	61.5	20.6	1.07	2.29
Wales C, S & E	117	56	5.2	110	50.0	20.0	1.27	2.52
Cayoosh	198	68	9.7	135	55.6	25.4	0.91	1.88
Bendor	222	63	8.2	124	50.6	24.4	0.97	1.79
Shulaps	126	53	7.3	100	45.4	23.3	0.97	2.01
TOTAL	**1593**	**57**	**7.7**	**128**	**49.2**	**23.1**	**1.05**	**2.03**

The size and shape variables may thus be ranked in order of inter-regional contrast, measured by F in Table II, as: Maximum gradient; Profile closure; Height range; Wall height; Amplitude; (Length/Height range) ratio; Minimum gradient; Axial gradient; (Width/Length) ratio; Plan closure; Length; Width. The first six all include a vertical dimension, and it is clearly this that varies most between regions. Minimum gradient and shape measures come next, followed by Length and (insignificant) Width.

TABLE IV. MEAN CIRQUE SIZE DATA (m) FROM OTHER AUTHORS (* MEAN AMPLITUDE).

Region	*Number*	*Length*	*Width*	*Height range*	*Source*
Kintail-Affric-Cannich, W. Scotland	231	625	586	(276*)	[16] (simple cirques)
N. Scandinavia transect	537	845	888	400	[17]
High Tatra	116	570	550	311	[18]
Bohemia	27	788	700	272	[19]
Maritime Alps	432	672	663	355	[20]
E. Pyrenees	1071	489	482	(223*)	[10]
C. Pyrenees	206	519	691	364	[13]
SW. Asturias	70	487	594	255	[12]
W. Picos de Europa	59	295	467	294	[12]
NE. USA	49	1687	954	442	[21]
W.-C. Yukon	331	802	736	214	[22]
Kamchatka	3520	868	992	421	[11]
Fiordland, N.Z.	1296	855	882	463	[14]
Westland, N.Z.	480	1069	961	580	[14]
Ben Ohau Ra., N.Z.	90	489	536	216	[15]
N. Greece	166	530	737	289	[23]
S. Greece	99	376	460	173	[23]

V. FURTHER DATA

As the three clusters were selected as study areas for their feasibility and accessibility, they are obviously not representative of cirques globally. They cover intrusive, old volcanic, metamorphic and sedimentary rock areas in old crystalline massifs and young orogenic belts, but not young volcanic areas or the highest-relief mountains.

It might be expected that cirques around the world's highest mountain have been eroded vigorously for a considerable time period, and should thus be larger than those in areas of more marginal local glaciation. There are difficulties due to the presence of thick glaciers masking cirque floors, but these do not hinder measurement of cirque width and length. Preliminary measurements from the 1: 50,000 'National Geographic' 1986 map of Everest show that the mean width of 35 cirques around Mount Everest is 2.23 km (median 2.0 km). The largest cirque, with Lhotse Glacier, is 4.6 km wide, followed by the Western Cwm at 3750 m: both are 3.9 km long. This is not out of line with the largest cirques elsewhere: what are lacking, on this highest terrain, are small cirques. 22 cirques on the lower Nuptse-Dingboche ridge average 727 m wide (median 625 m), comparable to the nine regions in Table I. It seems that widths and lengths around 4 km are the limiting dimensions for mid-latitude glacial cirques, developing from previously fluvial topography.

Antarctica is a special case, where very long-continued glaciation may have developed larger cirques. Thus the 56 mapped in the 'Dry Valleys' by Aniya and Welch [9] have a mean length of 2116 m, mean width of 1679 m, and mean height range of 849 m: they dominate compiled graphs of cirque size, as in Delmas et al. [10].

Barr and Spagnolo [11] tabulated cirque size means from various authors, for 16 areas, although 5 of these had less than 40 cirques. These further data sets show a greater range of sizes (see also Table IV) than the nine comparable regions. Excluding Antarctica, those with more than 40 ranged in mean length from 295 to 1687 m, more than five-fold, and much more varied than the 577 to 798 m (545 to 730 m in medians) here in Table I. Their mean widths varied from 467 to 954 m, two-fold and considerably more than the 681 to 797 m (600 to 720 in medians) here. Mean height ranged from 236 to 442 m (their 209 m refers to wall height): this is somewhat greater than the 225 to 419 m (210 to 395 m in medians) here. Barr and Spagnolo's tabulated ranges for individual cirques were 100 to 4000 m in length (191 to 3280 here), 125 to 3100 m in width (180 to 4870 here), and 57 to 1328 m (97 to 953 here) in height range. The greatest subjectivity probably concerns recognition of cirques 100 to 200 m long or wide, and those < 100 m in height.

In Table IV, cirques in the western Picos de Europa [12], have a remarkably low mean length (295 m), the same as their 294 m mean height range. These are steeper than cirques elsewhere, possibly because this is a high-relief limestone massif. Garcia-Ruiz et al. [13] also have some very steep cirques, as high as long, in the central Spanish Pyrenees.

The greater contrasts between regions in Table IV might be because a greater variety of regions has been included. However, the three greatest height ranges come from studies based on satellite imagery [11] or automatic cirque identification [14]: Richter [14] included only features > 0.1 km^2 in area, giving 35 cirques in the Ben Ohau Range where Brook et al. [15] found 90. Fieldwork and use of higher-resolution DEMs or maps identifies smaller cirques and reduces average sizes.

VI. Conclusions

Three clear conclusions emerge from this analysis. When a clear, consistent operational definition is applied, differences in cirque size and shape are small between regions, compared with the variation within each region. Nevertheless the differences between regions in length, all vertical dimensions, gradients and closures are highly significant; only width does not differ significantly between regions. Second, differences are greatest for vertical dimensions, due more to differences in tectonic setting than in geology. Third, means of cirque populations can be compared where measured by the same author, but those from different authors cannot as yet be taken as real differences between regions. It is hoped that the results in Tables I and III provide a starting point for a consistent multi-regional data set to which future measurements of cirques can be related.

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