Allometric Development of Glacial Cirques: An Application of Specific Geomorphometry

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1. Introduction

In geomorphometry many of the variables we measure describe size or shape of landforms. Taking the further step of analysis, a central question is whether shape varies with size. Here the hypothesis that larger cirques differ in shape from smaller ones is tested. First some general considerations about specific geomorphometry and allometry are outlined. Implications for cirque development and mountain glaciation are considered and, finally, the possibility that allometric development applies more generally to landforms is considered.

2. Specific Geomorphometry

Often we view the land surface as a continuous rough surface and analyse distributions of, for example, altitude derivatives: this is g**eneral geomorphometry**. On the other hand, we may recognize **discontinuities**. These relate to breaks in the continuity of form and process, and typically arise because of rock contrasts or events in the historical development of the landscape. These discontinuities can be joined up to outline **Elementary Forms** (segments, units, facets) of the land surface. Currently, this is a subjective, manual process: formulating a satisfactory automated routine is a continuing research challenge (Minar and Evans 2008).

Elementary forms in turn can be associated with neighbours, with which their development is related, to define **specific landforms** such as cirques, drumlins, dunes, landslides, and valley-sides. When completely delimited, landforms can be measured and their position, size and shape (including gradient) can be analysed. This is **specific geomorphometry**, of which a large part involves relating the shape and size of delimited forms – the study of **allometry** or isometry.

Evans (1987) recognized nine stages in a specific geomorphometric analysis. Techniques have changed, but all nine stages are still applicable:

1. **Conceptualisation** of landform types
2. Precise operational **definition**
3. Complete **delimitation** from surrounding land
4. **Measurement** of position, direction, size, gradient, shape and context
5. **Calculation** of derived indices, ratios
6. Assessment of **frequency distributions**; transformation - check effects
7. **Mapping** and spatial distributional analyses
8. **Interrelation** of attributes, e.g. shape v. size or position
9. **Interpretation** cf. genesis and chronology

3. Allometry

Many landforms develop **allometrically**, that is they change shape as size increases. In all but the most dynamic situations this can be tested only by considering variation with size at a given time, i.e. static allometry, as was proposed for **cirques** originally for a small population (15) in Colorado. It is now possible to test this for several cirque populations, each much bigger than in Olyphant's (1981) original study. This use of static allometry implies acceptance of the ergodic principle, substituting space for time.

First, several measures of cirque dimensions (components of overall size) are defined (Evans 2006); each is in units of length (metres):

Length = Horizontal distance from top to bottom of the median axis, which divides the cirque into two equal map areas and starts from the middle of the threshold, the division between the cirque floor and the valley below. Note that this definition is specific to this landform, and differs from the commonly used 'greatest separation between any two points'; thus length may be less than width;

Width = maximum map length of any line at right angles to the median axis;

Amplitude = vertical fall from top of median axis to lowest point on threshold;

Height range = overall, from highest altitude on crest to lowest (on threshold);

Wall height = maximum fall along a single slope line, from headwall crest to start of floor below.

Size (overall) = cube root of (length x width x amplitude).

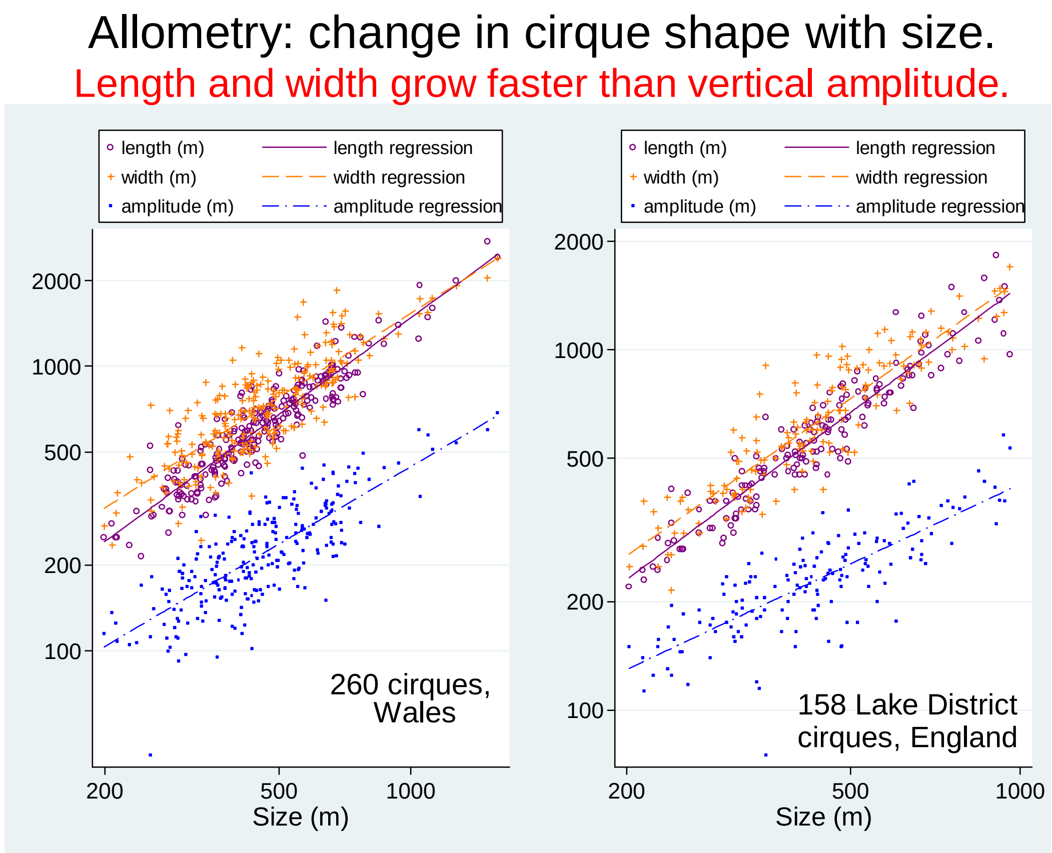

Figure 1. Allometric plots for Wales and the English Lake District.

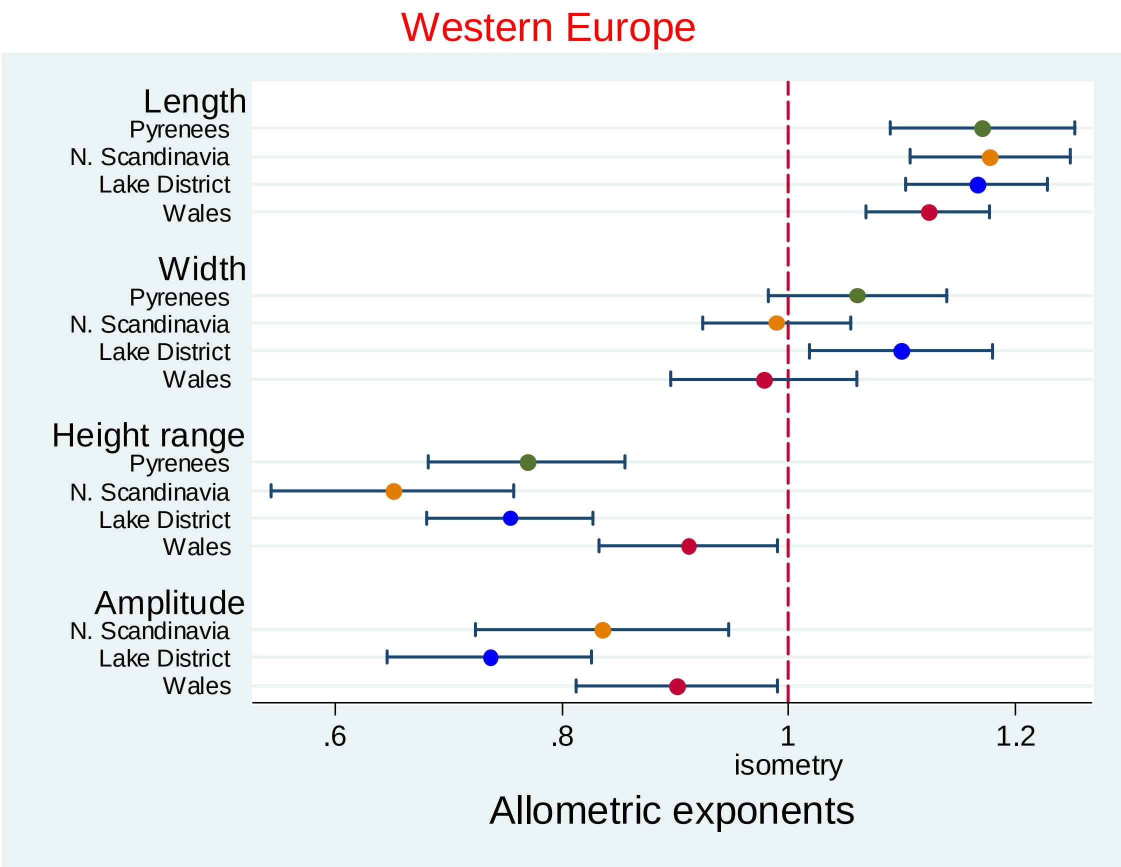

Figure 2. 95% Confidence limits on exponents for Western Europe.
Data as for Table 1.

4. Results

Exponents are fitted as the gradients of ordinary least squares regressions of size variables against overall size. This ensures that exponents for the three components of overall size sum to 3.0. Logarithmic plots of horizontal and vertical dimensions against overall size (e.g. Fig. 1) show that, as size increases, cirque length increases at a greater rate than vertical dimensions. This is confirmed wherever the 95% confidence intervals on exponents do not overlap – which is consistent across regions (Fig. 2 and Table 1). For isometry, all **power coefficients** (exponents) must be statistically indistinguishable from 1.0.

Exponents for-	**Exponent**	**95% Confidence limits**		R^2
Length				
Pyrenees	1.170	1.089	1.251	.798
N. Scandinavia	1.177	1.106	1.248	.662
Lake D.	1.166	1.103	1.228	.897
Wales	1.122	1.067	1.176	.863
Width				
Pyrenees	1.060	0.982	1.139	.774
N. Scandinavia	0.988	0.923	1.054	.619
Lake D.	1.099	1.018	1.179	.823
Wales	0.977	0.895	1.060	.678
Height range				
Pyrenees	0.769	0.682	0.856	.597
N. Scandinavia	0.650	0.543	0.757	.208
Lake D.	0.754	0.680	0.827	.721
Wales	0.911	0.832	0.990	.667
Amplitude				
N. Scandinavia	0.835	0.723	0.947	.285
Lake D.	0.736	0.646	0.825	.625
Wales	0.901	0.812	0.990	.605

Table 1. Size exponents (power coefficients) for four regions in Western Europe [Pyrenees (C. Spanish) 206 cirques *(data: J.M. Garcia-Ruiz et al. 2000)*; Northern. Scandinavia 541 *(a transect through Narvik; data: S. Hassinen 1998)*; Lake District 158; Wales 260].

Results for different regions of **British Columbia, Britain, Romania, Scandinavia, and Spain** are consistent in confirming the static allometry of glacial cirques: larger cirques are relatively longer and broader, more than they are deeper. Observed exponents include: length 0.99, 1.08, 1.08, 1.10, 1.10, 1.12, 1.17 and 1.18 ; width 0.98, 0.99, 1.00, 1.01, 1.04, 1.05, 1.08 and 1.10; and depth 0.74, 0.84, 0.85, 0.86, 0.90 and 0.91. Coefficients for length and width are generally **above 1.0**, while those for depth are significantly below. In most regions the length exponent exceeds the width exponent: hence the allometry cannot be explained by lateral coalescence of cirques. All length exponents are significantly above 1.0, and **all depth exponents** are significantly **below,** whether vertical dimension is expressed as height range or axial amplitude (Table 1), or headwall height. Isometry is observed only in one region (out of 14): the Ben Ohau Range in New Zealand (Brook et al. 2006).

These results are robust in that they are found for different grades and types of cirque (Table 2). The length exponent is significantly greater than amplitude and height range exponents, but the width exponent for Wales (unusually) is not. The results on the right show consistency for different grades and types of cirque. Relations between length and width, however, vary between ranges.

Variable	*expon.*	*95% conf.*	R^2	*better*	*no outer*	*v-side*	*v-head*
Length	1.12	1.07-1.18	.86	1.10	1.12	1.13	1.01
Width	0.98	0.89-1.06	.68	0.98	0.99	0.97	0.94
Amplitude	0.90	0.81-0.99	.61	0.91	0.89	0.90	1.05
Height range	0.91	0.83-0.99	.67	0.89	0.90	0.90	0.93
Wall height	0.97	0.86-1.09	.52	0.85	0.97	1.02	0.99

Table 2. Exponents for logarithmic (power) regressions of size variables on overall size for Wales. 95% **confidence intervals** and R^2 measures of fit for all 260 cirques in Wales are given on the left. These are followed by exponents for 142 **better** cirques (graded **definite, well-defined or classic**), for the 249 cirques **excluding 'outer'** cirques, for 157 **valley-side** and for 75 valley-head cirques.

This study shows the importance of considering **confidence intervals** when making conclusions about relative rates of change. This permits size of data set to be given due weight, and prevents conclusions based on random variations. Detailed subdivision is seen to be counter-productive, as results become insignificant. Confidence intervals are also an aid in checking consistency of results between regions and between types of landform.

5. Cirque Development and the 'Buzzsaw'

It is inferred that cirque **headwall retreat is faster** than cirque deepening. Yet many cirques have **deep lakes** that attest to considerable cirque deepening (Lewis, 1960); this means that cirque development in all three dimensions is considerable (Evans 2007). Faster headwall recession implies support for the 'buzzsaw hypothesis' (Mitchell and Montgomery 2006) of rapid glacial erosion limiting the height of many mountain ranges. Instances of complete range truncation are, however, hard to find: coalescent and back-to-back cirques are common, but only occasionally do intervening ridges seem to have been removed. Cirques are rarely more than 2 km long or wide. It is interesting that cirques in plateau areas, where range truncation has clearly not occurred, are not dissimilar in size to those in more dissected mountains with back-to-back cirques, where the buzzsaw hypothesis might be applicable.

6. Conclusions

a: cirque allometry –

- Taking larger cirques as having developed further, each dimension can be plotted against an overall size measure to express static **allometry** or **isometry**.
- Large cirques differ in shape and gradient from small ones.
- Vertical dimensions increase more slowly than do horizontal.
- The allometric nature of cirque development is thus confirmed on the basis of a set of large inventories of cirques.
- Length usually increases faster than width, but length – width relations vary between areas. (*Exponents: length > width > height.*)

b: broader context: scaling -

- Many **fluvial** features scale over many orders of magnitude. Scaling (e.g. with a fractal model) is more important for hydrology and fluvial landforms, but always has limits (if only grain size, and size of Earth!)
- **Cirques** are scale-specific (Evans 2003) but also scale allometrically within one decimal order of magnitude.
- **Bedforms** (dunes, drumlins…) are also scale-specific. Whether allometry is general also for them has yet to be established.
- Scale specificity is important because it relates either to **process thresholds** or to the scale of controlling **frameworks** (e.g. whole valley-side, for mass movements)
- I hypothesize that all landforms show some scale-specificity: there are good process reasons for limits to their scaling behaviour.

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