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Cirque form and development in Romania: Allometry and the buzzsaw hypothesis

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ABSTRACT

A complete inventory of the 631 glacial cirques in Romania (and adjacent Ukraine) shows that they are scale-specific and develop allometrically, extending in length more rapidly than they deepen: shape changes with size. Horizontal dimensions are around 700 m, vertical around 300 m. On each quantitative measure they form a single, unimodal population with limited variation in size (on a logarithmic scale). Cirque axial gradients (15–33°) are appropriate to occupation by rotationally-flowing glaciers. Lake basins are more common (26%) on granitic rocks, compared with 10.6% of all cirques. Geology also affects vertical dimensions and gradients. The relation between subjective (five grades) and objective measures of cirque development is shown by an r^2 of 62% when Grade is predicted from maximum gradient, minimum gradient, and plan closure. Cirques larger in horizontal dimensions have better grades.

Cirque floors cover around 28% of cirque map area. Larger cirques, and nested inner and outer cirques, are common in ranges that rose well above the snowline, and are associated with more extensive, more symmetrical glaciation and more cols. In size and shape Romanian cirques are similar to those in England and Wales. They are similar in some respects to those in part of the British Columbia Coast Mountains, except for smaller vertical dimensions. They may have developed only in the last few glaciations: mountain ranges can be ranked by degree of glacial modification and symmetry of glaciations. The 'buzzsaw hypothesis' is applicable only in the cores of the higher ranges: elsewhere, summit surfaces that are essentially preglacial survive.

1. Introduction

1.1. Aims and objectives

Despite a long history of investigation, the origin of mountain cirques remains contested, with Turnbull and Davies (2006) suggesting a general origin from deep-seated rock avalanches rather than glacial erosion. Erosion of cirques at the head of mountain glaciers remains difficult to explain, but Evans (2006a) summarised the conventional view that rotational flow in steep glaciers (Lewis, 1960) compensates for low ice discharge and velocity, and glacial quarrying at the base of the headwall is aided by water pressure fluctuations (Hooke, 1991). While glacial cirques have long been studied for the evidence they provide on former glaciation (reviewed in Evans, 2008), relatively few have been studied quantitatively. Andrews and Dugdale (1971) provided the first thorough statistical analysis of cirque morphometry, measuring many attributes, and Evans and Cox (1974) provided an operational definition of cirques that was agreed among a group of British geomorphologists. Evans (2006b, 2010) has made or compiled complete inventories of several regions on a comparable basis, and here we aim to provide a similar survey and analysis of the large number of cirques in Romania.

These data permit us to test a number of hypotheses:

- is there a clearly defined (unimodal) cirque size?
- does this vary spatially, and with altitude, aspect, relief, local position and geology? What is the relative importance of these variables?
- does cirque shape and degree of development vary with these controls?
- how strongly do cirque shape and development variables correlate with each other?
- does cirque shape vary with cirque size?
- do Romanian cirques cover a range of variation similar to those elsewhere?

Finally, can these variations be assembled in a model of cirque development? The inventory of 631 cirques also permits comparison with similarly defined cirque data sets and (in future) with rock avalanche scar data. Questions of Romanian cirque distribution in relation to palaeoclimate are discussed elsewhere (Mîndrescu et al., 2010).

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1.2. Study area

Romania has no present-day glaciers or permanent snow patches; the latest snow patches are found within cirques in the Rodna (Buhăiescu Mare) and Maramureş (Pop Ivan, Ukraine) Mountains, but none of them survive until August. All of the many separate mountain ranges rising above 2000 m altitude, however, supported glaciers in the Late Pleistocene (Table 1), whereas only one mountain below 1600 m did so. There were numerous valley glaciers (one in Retezat was 18 km long: Urdea, 2004), but most were cirque glaciers. A large number of glacial cirques were eroded, mainly in crystalline rocks (see below): we recognize 631 glacial cirques, 617 in Romania and 14 on the Ukrainian side of the border ridge in Maramureş. These are distributed over 20 mountain ranges: Urdea et al. (2011) map small (possibly short-lived) glaciers in further ranges, but these did not erode glacial cirques.

In modern Romania precipitation comes largely from the west, and thus the western part of the Transylvanian Alps (the Retezat, Godeanu and Ţarcu Mountains), and the Bihor or Apuseni Mountains in western Transylvania (Fig. 1), receive more rain and snow than the eastern mountains. From regional cirque distributions and local cirque aspects it appears that a similar situation applied during Late Pleistocene glacial phases, with the main moisture-bearing winds coming from north of west (Urdea and Reuther, 2009; Mîndrescu et al., 2010). Thus glaciation was most extensive in the higher and wetter mountain ranges, and these developed the greatest numbers of cirques. First come the Făgăraş Mountains with 206 cirques: they have 238 km^2 above 1800 m and the altitude of the highest summit is 2544 m. Second, the Retezat (Fig. 2a) reaches 2509 m and has 84 cirques. It is followed by the Godeanu (2291 m, 69 cirques) and the Ţarcu (2192 m, 58 cirques) (Fig. 2a), whose western location compensates for lower altitude. The Parâng (2518 m; 51 cirques) and the Iezer (2470 m; 38 cirques), despite their altitudes, are relatively small ranges and sheltered from winds from north of west. Although the Bucegi Mountains reach 2505 m, the high area is restricted and only 11 cirques formed. Three summits in the Bihor Mountains, exposed to winds from west and northwest, support cirques on leeward slopes despite their low altitudes (1848, 1658 and 1530 m). This strongly suggests that, as today, snowfall during glacial periods must have been greater in the Bihor Mountains and the westernmost Transylvanian Alps than at similar altitudes elsewhere in Romania.

Table 1
Romanian mountain ranges (20 glaciated): highest summits in each range (in metres), ordered from north to south, then to west; and modern works on glaciated ranges. * indicates monographs. Note that figures from different sources sometimes vary by a few metres.

Range name	Summit height (m)	Reference
Maramureş	1956	Sîrcu (1963)
Ţibleş	1853	Mac et al. (1990)
Rodna	2303	Sîrcu (1978)*
Călimani	2100	Naum (1970); Kern et al. (2006)
Siriu (Mălaia)	1662	Orghidan (1932); Naum (1957)
Bucegi	2505	Micalevich-Velcea (1961)*
Leaota	2133	Sultana (1976)*, Murătoreanu (2009)*
Iezer	2470	Nedelcu (1967), Szepesi (2007)*
Făgăraş	2544	Florea (1998)*
Cindrel	2244	Niculescu (1969)
Lotru	2242	Ancuţa (2005)
Latoriţei	2055	Călin (1987)
Căpăţânii	2130	de Martonne (1907)
Parâng	2518	Iancu (1970)*, Marinescu (2008)
Şureanu	2130	Trufaş (1962), Niculescu (1969)
Retezat	2509	Urdea (2000)*
Godeanu	2291	Niculescu (1965)*
Ţarcu	2192	Niculescu (1990), Gruia (1998)
Muntele Mic	1802	Niculescu (1990)
Bihor/Apuseni	1848	Berindei (1971)

With 547 cirques, the Transylvanian Alps (the South Carpathians) were clearly the main centre of glaciation in Romania. In the north of Romania, regionally lower temperatures compensated for lower altitudes, giving a second centre of glaciation with 81 cirques. Most of these (45) are in the Rodna Mountain Range (summits up to 2303 m), but 27 are on separate mountains with summits of 1713–1957 m altitude in Maramureş, and seven are in the Călimani Mountains (1989 and 2100 m). South of these, a large section of the relatively dry Eastern Carpathians with summits up to 1907 m lacks glacial cirques. This includes the 'Carpathian Bend' or Buzau area, with the greatest modern and Quaternary seismicity: absence of cirques other than one on Siriu argues against generality of the earthquake/rock avalanche origin proposed by Turnbull and Davies (2006). Altogether, 20 mountain ranges in Romania, named in Fig. 1, have one or more glacial cirques.

For most statistical analyses it is necessary to merge those ranges with few cirques with adjacent ranges, giving 12 range groups (regions). Thus Ţibleş (2 cirques) is assigned to Rodna region, Ciucaş-Siriu and Leaota (1 each) to Bucegi, Căpăţânii (1) and Latoriţa (4) to Parâng, and Muntele Mic (1) to Ţarcu, while Lotru (10), Cindrel (8) and Şureanu (4) are combined as Lotru–Cindrel region (Fig. 2b).

1.3. Previous work

The study of glaciation in the Romanian mountains was started by Tietze (1878) and its history is summarized in Urdea and Reuther (2009), but only a small proportion of the literature deals quantitatively with glacial cirques. The pioneer was de Martonne (1900) who, faced with poor quality maps, personally surveyed two Parâng cirques in detail. He later covered the whole eastern part of the Parâng, plus the Soarbele cirque in the Godeanu Mountains (Fig. 2 of de Martonne, 1906: an impressively accurate map).

De Martonne (1900) measured the maximum, minimum and mean floor altitudes for 16 cirques, plus their floor areas, mean floor gradients, aspect, and number and minimum altitude of lakes. All the cirques contained roches moutonnées, and three had clear striations. In much of the Carpathians, however, weak rocks such as flysch and schist preserve few striations, and weathering of coarse-grained granites and gneisses produces rough surfaces, eliminating most striations (de Martonne, 1901). De Martonne (1901, 1907) noted the influence of geological structure, distinguished large cirques from small hanging cirques, and produced a compromise between 'glacialist' and 'antiglacialist' interpretations. Further cirque mapping was performed by Szilády (1907) for the Rodna Mountains.

Sawicki (1912) suggested former snowlines, and Pawłowski (1936) mapped snowlines throughout the Carpathians. Under the 1947–1989 communist regime, many regional geomorphology monographs were published, often containing morphological maps of mountains with cirques. Table 1 lists these (marked *), and/or the most recent research papers. Published classifications of cirques included Niculescu's (1965, 1969, 1990) fourfold division into simple, elongated and complex cirques, and 'complexes of [adjacent] cirques'. He attributed steps within cirques and glacial troughs to geological factors: others have related them to preglacial features. Sîrcu (1964) discussed the limited glaciations of most of the Eastern Carpathians.

During recent decades Romanian glacial geomorphology regained contact with the Western literature, and quantitative evaluation of glacial features using geomorphometric methods was introduced. The application of absolute dating methods began to establish a chronology of multiple glaciations and readvances, with initial results in the Retezat (Reuther et al., 2004, 2007; Urdea et al., 2011) and Rodna (Gheorghiu, 2012; László et al., 2013) Mountains. These have demonstrated that some cirques were last occupied in the Younger Dryas. New glacial features continue to be discovered (Mîndrescu, 2002, 2009a; Urdea et al., 2011), demonstrating that glaciation was more widespread than previously considered.