Effects of glaciation on the clinometry and hypsometry of the Romanian Carpathians

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Abstract—**SRTM1 DEMs for many mountain ranges in Romania were processed to provide slope gradient distributions for each 50 m band of altitude. The effects of cirques are seen in an increase in standard deviation of gradient, and a spread in all percentiles, especially an increase in the 95th, at relevant altitudes. Otherwise, variations in median gradient with altitude differ between ranges, and do not show the general increase found in the Alps below cirque floor altitudes by [15], [9] and [16].**

I. INTRODUCTION

The effects of glaciation on mountains such as those in Romania are well established, and specific geomorphometry has been applied to measure resulting landforms such as cirques [1, 2]. This also permits analysis of the altitudinal and azimuthal distribution of cirques as glacier sources [3, 4]. Efforts have been made to reduce the subjectivity of cirque definition [5] but undeniable subjectivity remains and the results of different workers cannot be regarded as comparable [6, 7].

General geomorphometry [8] provides a more objective way of expressing the effects of glaciation, or indeed of any other geomorphological agent, and thus permits precise comparisons between regions studied by different researchers so long as the same data set and techniques are used. Here our aim is to use a combination of clinometry and hypsometry to demonstrate the morphological effects of mountain glaciation. We use the near-global SRTM 1data to estimate slope gradient distributions at different altitudes [9] in the Romanian Carpathians (Fig. 1).

It is hypothesized that glacial erosion produced low-gradient cirque floors around former snowlines (ELAs) in the last 470 ka [3] in the Romanian Carpathians. During the LGM, moraines formed at 900-1300 m ([10] and references therein). ELA was at 1700 m in the Southern Carpathians and at 1250 m in the Eastern Carpathians [10, 11, 12, 13]. Some uncertainty in determination of former snowlines is caused by the possible presence of icecaps on some plateaux [14] The effects of glacial erosion were complicated by temporal variations in snowline (of the order of 1000 m in the Late Quaternary) and may be masked by other processes (tectonic and fluvial).

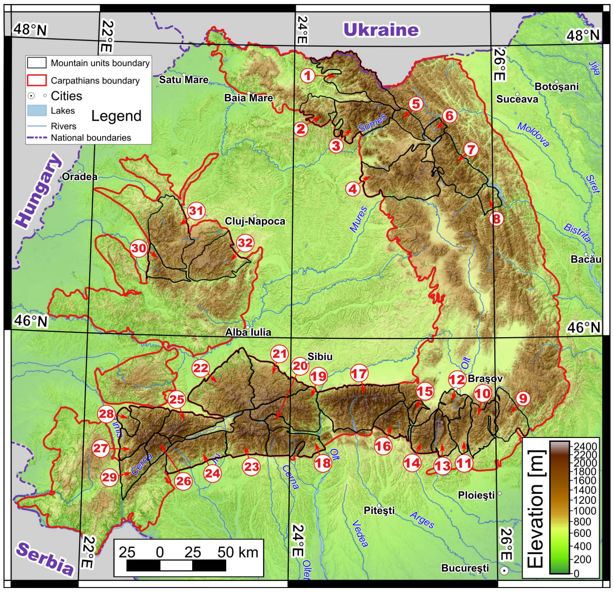

Figure 1. Location of the chosen mountain ranges in Romania.

II. DATA AND METHODS

The SRTM DEM was used as the source for elevation range and slope computation. The Arc-Second SRTM1 Global void-filled version (https://lta.cr.usgs.gov/SRTM1Arc) was imported, mosaicked and reprojected in the Stereo 70 national Romanian projection (EPSG:3844) in SAGA GIS, to give a grid with 30 m mesh. Analyses were performed for all mountain ranges with summits reaching above 1800 m: 20 with glacial cirques and 12 'unglaciated' ranges, whose summits are generally a little lower. If the latter ever held small glaciers, their erosional impact has been negligible. Ranges are outlined on Fig. 1 and identified in section II.

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All data concerning cirques are from the work of [1] and [3]. To avoid small numbers of cirques, those authors grouped the 20 glaciated ranges into 12 regions, but here the 20 ranges are analyzed separately. As the outlines on Fig.1 show, ranges have been defined broadly, including their foothills. Slope gradients are measured, however, only above 550 m.

Slope gradient was computed in SAGA using a 3x3 pixel square kernel, i.e. 90x90 m. Slope versus elevation distribution plots were created in R stat using the methodology of [15] and especially [9]. Note that this produces rather different results to the drainage-based methods of [16]. For each 50 m band of altitude the gradient distribution was plotted, and summarised both by percentile measures (median, quartiles etc.) and moment-based measures (mean, standard deviation and skewness).

III. Results

The effects of cirque glaciation on gradient are seen mainly in rising p95 (95th. percentile) and upper quartile at altitudes of cirque headwalls; and falling lower quartile at altitudes of cirque floors. The altitudes used were independently measured from maps by [3]. p05 (5th. percentile) is usually zero at cirque floor altitudes, but also at many lower altitudes. As cirques provide additional high gradients (headwalls, >0.58 or 30°) and low gradients (floors, <0.36 or 20°), they increase measures of dispersion: standard deviations, inter-quartile ranges, and p05-95 ranges. Usually the highest couple of 50 m bands have a very small number of observations and their capricious statistics should not be emphasized. Altitudes ending in 25 or 75 m refer to mid-points of the 50 m classes; those ending in 00 or 50 m, to class boundaries or to the two adjacent classes.

Starting with the 'most glaciated' mountain ranges, Retezat (range 25 on Fig.1) provides the clearest glacial signal. Above 1800 m, both standard deviation (SD) and inter-quartile range (IQR) of gradient increase (Fig. 2), coinciding with the 1760 – 2500 m range of cirque altitudes. (Using the 05 and 95 percentiles, 90% of the 84 cirque floors are between 1760 and 2190 m: headwalls, from maximum floor altitude to maximum crest altitude, are 1850-2500 m). The falling lower quartile from 1800 to 2100 m reflects the floors. Headwalls produce a rising upper quartile, and p95 increases from 0.82 at 1775 m to 1.25 at 2375 m (Fig. 3). Median gradient increases only above 2100 m, i.e. above most cirque floors. In the Făgăraș Mountains (range 17), the 206 cirque floors are 1830-2230 m, and both SD and IQR increase above 1900 m. The lower quartile falls from 1875 to 2175 m. p95 increases from 1.07 at 1875 m to 1.22 at 2300 m, as headwalls are 1900-2510 m. Upper quartiles and medians increase only from 2200 to 2350 m.

In northern Romania, the 45 cirque floors in the Rodna Mountains (3) are lower, mainly between 1520 and 1910 m. Floors are reflected only weakly, in the lower quartile falling from 1700 to 1800 m. Headwalls (1620-2280 m) are more evident, in an increasing p95 from 1650 to 2275 m, where it reaches 1.2. Both SD and IQR rise from 1700 to 2300 m. Median gradient rises from 1800 to 2200 m. A fourth range heavily impacted by glaciation is Parâng (23), with 51 cirques. Again walls are more evident than floors, with p95 increasing from 0.85 at 1775 m to 1.13 at 2275 m: the upper quartile rises similarly, and median increases from 1950 to 2300 m. SD and IQR increase from 1850 to 2350 m (2450 for SD).

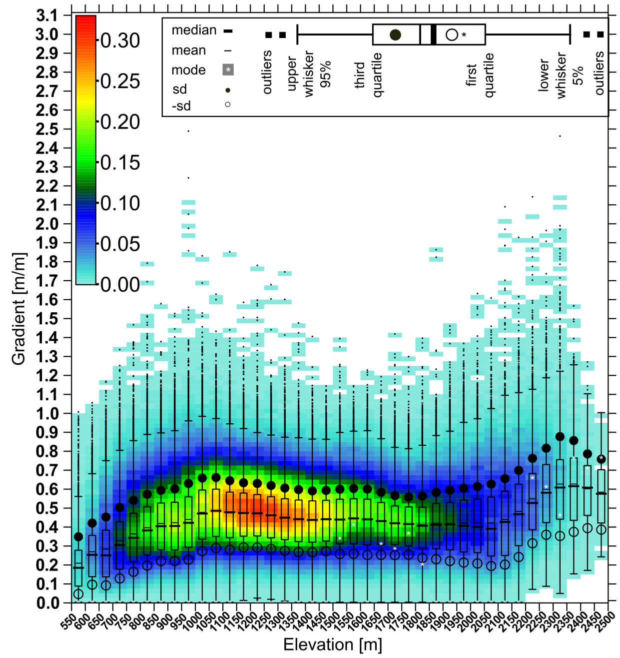

Figure 2. Combined boxplots and density distributions per 50 m class of altitude and 0.025 class of gradient, for Retezat Mountains, SW Carpathians.

The Godeanu Mountains (26) have 69 cirques, but are noteworthy for an extensive summit surface above 2050 m producing steep falls in p95 and upper quartile. SD increases from 1850 to 2200 m (and IQR 1925-2200 m), showing the effect of cirques. Similarly the Țarcu Mountains (27; with 58 cirques) have a well-developed summit plateau. This causes all percentiles to fall from 2050 m upward: but from 1750 to 2050 m p95 increases and the lower quartile falls, reflecting floors at 1630-1980 m and headwalls at 1700-2180 m. Overall, the gradient plot is fairly flat, but SD and IQR do increase from 1850 to 2100 m.

The Iezer Mountains (16) have 38 cirques, with headwalls at 1950-2450 m: p95 increases from 1950 m to 2225 m, reaching 1.07. SD and IQR increase from 1925 to 2200 m. The 27 cirques in Maramureș (1) are unusually distributed, on seven separate mountains. The lower quartile falls from 1475 to 1675 m, due to

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the cirque floors at 1465-1690 m. p95 (from 0.80 to 1.06), IQR and SD all increase from 1475 m to 1825 m, reflecting headwalls at 1550-1920 m as well as floors. This provides a clear 'glacial' signal.

The Cindrel Mountains (21) have extensive summit plateaux. The 8 cirques are evident mainly in the increasing SD and IQR from minima at 1825 m, up to 2200 m. The adjacent Lotru Mountains (19) have 10 cirques, with floors are 1700-1960 m, and headwalls 1750-2200 m. After falling to 1875 m, SD and IQR increase to 2150 m, as does p95. Above that the summit plateau dominates.

Călimani (4), with 7 relatively poor cirques on young volcanic rocks, shows low variability of gradients with altitude. Headwalls (1790-2100 m) are poorly represented, with p95 increasing only from 1675 to 1825 m. The gentle decline in lower quartile from 1725 to 1975 m shows some effect of cirque floors (1760-1850 m). The increase of SD and IQR from 1675 to 1875 m is a clearer effect of the cirques. In Șureanu (22), headwalls give a high p95 at 1750-1950 m. The lower quartile is low at 1550-1800 m, reflecting the floors. Above 2000 m, as in neighbouring Cindrel and Lotru, the plateau gives decreasing high percentiles.

Bihor (30) has the lowest cirques: the three floors are at 1330, 1440 and 1660 m, and headwalls are 1450-1840 m. Gradients show only a hint of cirque floors, from the lower quartile fall from 1325 to 1575 m, and of headwalls in the p95 increase from 1625 to 1725 m: a very weak glacial signal. SD and IQR increase from 1675 to 1775 m. Ţibleş (2) has only 2 cirques: p95 is high at 1550-1800 m, reflecting headwalls. The lower quartile falls from 1375 to 1600 m, and so is low at floor altitudes. Four ranges with only one cirque show a generally convex-up plot, with little impact from the cirque floor. The effect of cirque headwall is visible in a small upturn of mean and percentile gradients at the appropriate (high) altitude: 1500-1650 m for Siriu (9), 1500-1710 m for Muntele Mic (28), 1810-2130 for Leaota (14) and 1840-2101 m for Căpăţânii (18). The single cirque floor has little impact on the plots.

To summarise, after due allowance for summit plateaux, in almost all ranges with more than two cirques increases in SD and IQR show the altitudes at which cirques are present: exceptions are Șureanu (22), with a headwall and weak floor signal, and Bucegi (13) and Latoriţa (20), with no discernible signal. The complex gradient pattern in Bucegi relates to structure, with conglomerate scarps and a rolling high plateau. The increased IQR is strongly reflected in p95, less so in the upper quartile: the headwall signal is clear in 14 ranges. The effects of headwalls are thus clearer than those of floors, as the latter have relatively small areas (averaging 28% of cirque area, with SD 10%). However, there is a definite fall in the lower quartile of gradient at relevant altitudes in six ranges, and weaker indications in five others. The clearest signals – or 'glacial signatures' in the gradient distributions – are provided by Retezat, Făgăraş, Ţarcu, Maramureş and Rodna.

TABLE I. STATISTICS FOR CIRQUE MODAL FLOOR ALTITUDE IN ROMANIA, FOR 21 MOUNTAIN RANGES.

Mountain rang	*mean*	*sd*	*p5*	*p25*	*p50*	*p75*	*p95*	*n*
Maramureş	1591	72	1465	1540	1580	1662	1690	27
Ţibleş	1565	21	1550	1550	1565	1580	1580	2
Rodna	1749	115	1520	1670	1770	1840	1910	45
Călimani	1804	33	1760	1770	1810	1830	1850	7
Siriu	1400	.	1400	1400	1400	1400	1400	1
Bucegi	2149	124	1940	2010	2190	2240	2320	11
Leaota	1870	.	1870	1870	1870	1870	1870	1
Iezer	2024	97	1870	1970	2040	2080	2170	38
Făgăraş	2034	131	1830	1960	2040	2115	2230	206
Căpăţânii	1860	.	1860	1860	1860	1860	1860	1
Lotru	1844	78	1700	1800	1835	1881	1960	10
Cindrel	1893	103	1701	1825	1925	1960	2020	8
Latoriţei	1850	29	1820	1825	1850	1875	1880	4
Parâng	1976	84	1830	1930	1980	2015	2150	51
Şureanu	1773	82	1670	1720	1775	1825	1870	4
Retezat	2018	134	1760	1930	2050	2130	2190	84
Godeanu	1874	110	1640	1810	1890	1960	2010	69
Ţarcu	1851	98	1630	1810	1860	1930	1980	58
Muntele Mic	1530	.	1530	1530	1530	1530	1530	1
Bihor	1473	169	1330	1330	1430	1660	1660	3
Total	***1938***	***173***	***1622***	***1830***	***1960***	***2065***	***2190***	***631***

sd = standard deviation; *p* = percentile; *n* = number of cirques. Data as for [1].

Unglaciated ranges show a variety of trends. The increase of median gradient with altitude, which is common in the Alps (Robl et al., 2011) is found only in Baiului (11: Fig.3) and Ciucaş (10), and weakly in Suhard (5). Cernei (29) and Vlădeasa (31) show the opposite trend, a gentle decline with altitude, with steepest gradients below 1450 and 1550 m respectively. Muntele Mic (28) shows mainly decline, with steepest slopes below 1300 m. Ceahlău (8) shows a more complex plot: gradients are fairly steady below 1150 m, then rise to a maximum at 1525 m before falling back at high altitudes. Likewise Piatra Craiului (15) is steady below 1300, rising to a maximum at 1725 m before falling. Vâlcan (24) shows steady gradients, steepest below 1300 m: there is a minimum at 1525 m and a maximum at 1875 m. Bistriţa (7) is also steady, but with lower gradients below 700 m and above 1650 m. Giumalău (6) has mainly low gradients, oscillating with altitude. Thus the 'unglaciated' ranges have varied gradient: altitude relations, but all differ from the 'glacial' pattern.

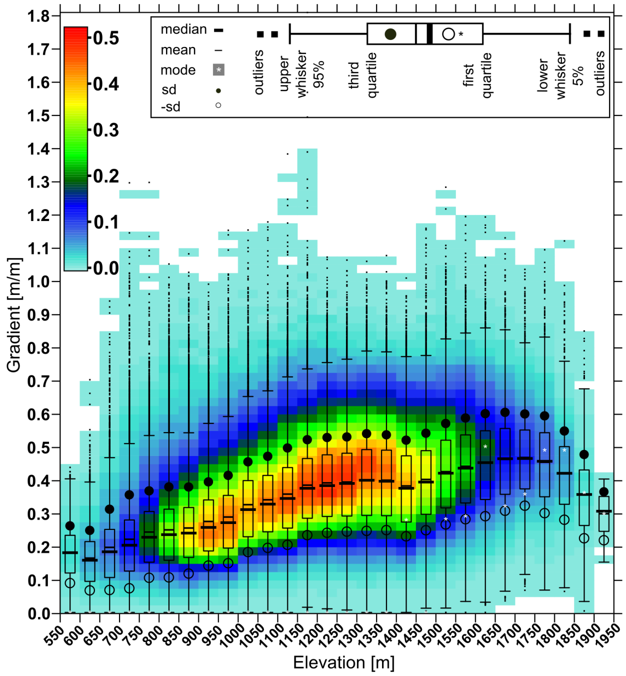

Figure 3. Combined boxplots and density distributions per 50 m class of altitude and 0.025 class of gradient, for Baiul Mountains, SE Carpathians.

IV. Discussion

Gradient frequency distributions for narrow altitude bands provide considerable detail on the form of slopes in mountain ranges. This combination – 'hypsoclinometry' – is much more informative than treating hypsometry and clinometry separately. Steep and gentle slopes have been produced by various processes, and the distributions are not easily summarized. Nevertheless, in the more heavily glaciated mountains there are clear indications of greater dispersion (SD, IQR) of gradients where cirques are present, and especially at the altitudes of headwalls, where there are more gradients above 0.58, and usually some above 1.0. At such altitudes, gradient distributions normally have low kurtosis, i.e. short tails and broad modes. Bimodality is not evident, as the contrast between steep headwalls and flat cirque floors is not sharp enough, and slopes outside cirques often have intermediate gradients. Reduced lower quartiles indicate increased frequencies of low gradients at the altitudes of cirque floors but this signature is generally weaker than the headwall signature. The 30 m grid used seems to provide sufficient resolution to reveal steep gradients, as numerous values above 1.0 and some above 2.0 are calculated. Further work will analyze more restricted areas around the cirques, and relate these graphs and statistics to maps of slope gradient.

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