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Climatic implications of cirque distribution in the Romanian Carpathians: palaeowind directions during glacial periods

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ABSTRACT: The many glacial cirques in the mountains of Romania indicate the distribution of former glacier sources, related to former climates as well as to topography. In the Transylvanian Alps (Southern Carpathians) cirque floors rise eastward at $0.714\,\mathrm{m\,km^{-1}}$, and cirque aspects tend ENE, confirming the importance of winds from some westerly direction. There is a contrast between two neighbouring ranges: the Făgăraş, where the favoured aspect of cirques is ENE, and the Iezer, where the tendency is stronger and to NNE. This can be explained by the Iezer Mountains being sheltered by the Făgăraş, which implies precipitation-bearing winds from north of west at times of mountain glaciation. Palaeoglaciation levels also suggest winds from north of west, which is consistent with aeolian evidence from Pleistocene dunes, yardangs and loess features in the plains of Hungary and south-western Romania. In northern Romania (including Ukrainian Maramureş) the influence of west winds was important, but sufficient only to give a northeastward tendency in cirque aspects. This gave stronger asymmetry than in the Transylvanian Alps, as the northward (solar radiation incidence) tendency in these marginally glaciated mountains was less diluted by wind effects. Cirque floors in northern Romania are lower also in northeast-facing cirques. In general, cirque aspects result from several factors and the mean tendency is not downwind, but is displaced from poleward by wind and by minor effects. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: cirques; palaeowinds; Romania; Carpathians; glaciation.

Introduction

Glacial cirques have long been used as evidence of former climates (e.g. Porter, 1977, and references in Evans, 2008). Earlier work in the Carpathians (e.g. de Martonne, 1900; Pawłowski, 1936) was based on rather poor maps, but since 1989 air photos and former military maps have become available, together with modern surveys. Hence a resurvey of cirques in Romania by Mîndrescu (2006) permits more accurate measurement of cirque form and altitude, and provides a comprehensive inventory: cirques have been defined, delimited and measured in ways consistent with those applied by Evans and Cox (1995) in Britain and by Evans (1994) in British Columbia. Our aim in this paper is to use this new information on the altitude, aspect and spatial distribution of cirques across the whole of Romania to make several inferences concerning glacial palaeoclimates in the Late Pleistocene. In particular, we discuss the implications of both regional and local variations for palaeowind directions and precipitation patterns.

The mountain glaciation of Romania in the Late Pleistocene was extensive, and remarkable for the dominance of cirque development. A number of glacial troughs were developed, but only three glaciers were longer than 10 km (Urdea, 2004), and these pre-dated the Last Glacial Maximum (LGM). The style of glaciation was thus marginal, more like that of individual Appennine, Balkan or Iberian ranges than that of the Alps or Pyrenees (in contradiction to Velcea, 1973). The glacial cirques and troughs provide evidence of former cirque and valley glaciers and thus of climate during a number of glacial maxima, as their erosion is believed to require tens or hundreds of thousands of years. The altitudes of cirque floors and of the palaeoglaciation level, and the aspects (azimuths, downslope directions) of cirques, may be strongly affected by former wind directions, as well as by temperature and solar radiation conditions (Evans, 1977; Mîndrescu, 2004).

Study area

At 45–48° N latitude, the Romanian Carpathians (Fig. 1) occupy a central position within the temperate climate zone. They

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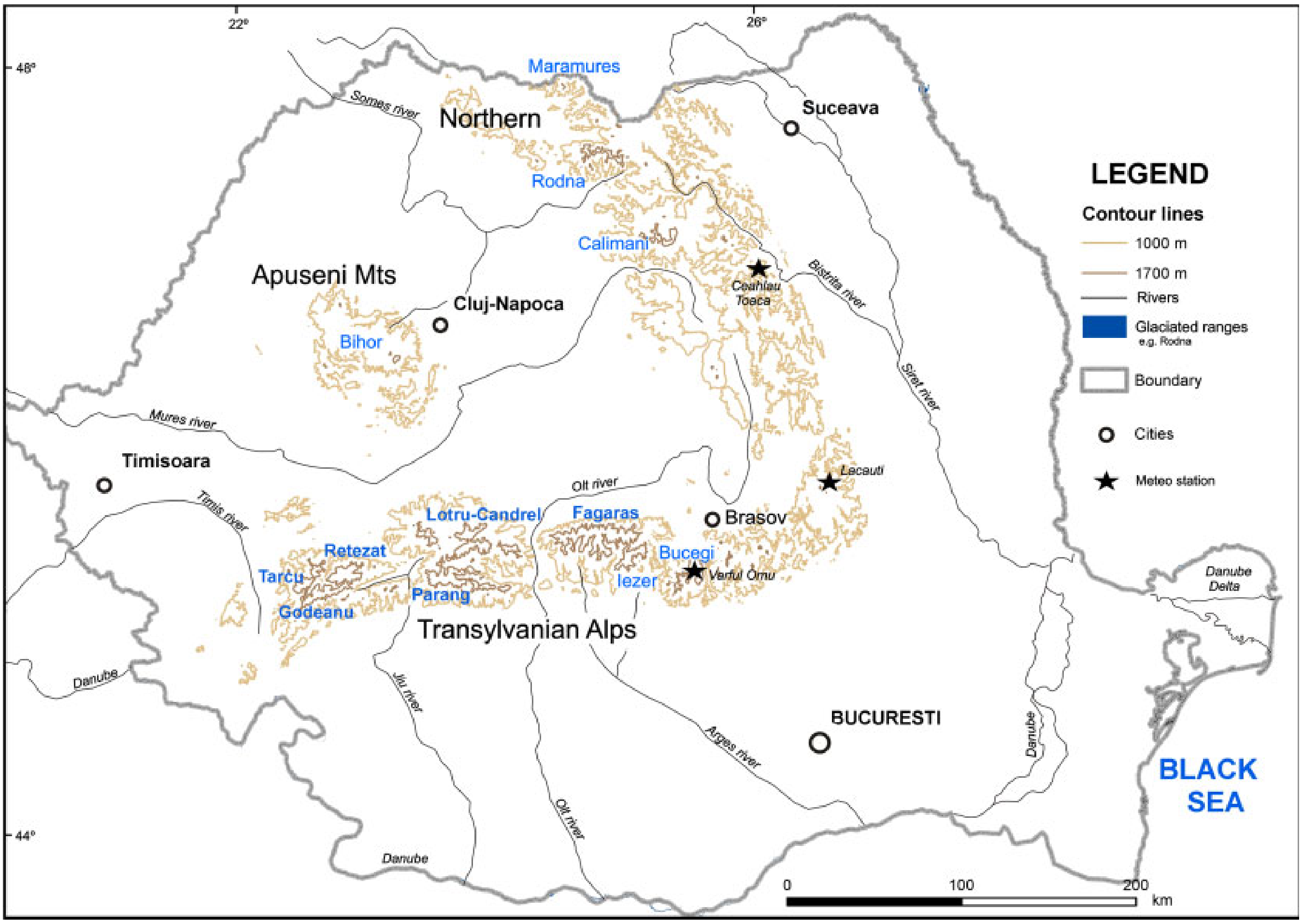

Figure 1 Romania, showing high ground, with names (in blue, online) of the main mountain ranges with cirques, as used here for the 12 range groups (e.g. in Fig. 7). This figure is available in colour online at www.interscience.wiley.com/journal/jqs

provide evidence of Quaternary climates in an important transitional region between cool temperate and Mediterranean climates. They are also placed between the oceanic climates of western Europe and the arid regions of interior Asia. It is believed that the oceanic climates are most responsive to climate change in the North Atlantic, and Central Asia is the least responsive. For climatic studies, the Carpathians are thus a key region that would have recorded changes in patterns of atmospheric circulation and their consequences for precipitation gradients.

Romania contains many mountain ranges with summit altitudes between 1800 and 2544 m, high enough to support small glaciers during glacial periods of the Late Pleistocene, but not to support any present-day glaciers. The numerous former glaciers developed a large number of cirques: we recognise 631 glacial cirques in Romania and the adjacent Ukrainian Maramureş, as the range straddles the international border (Fig. 2). Most cirques are eroded into schists, granites, or gneisses, which permitted fairly uniform cirque erosion. Structural influences were stronger on the massive conglomerates of the Bucegi Range. Glaciation was heaviest and most azimuthally symmetrical in the Transylvanian Alps (Southern Carpathians), with 547 cirques in all. This applies especially to the Făgăraş Mountains because of their high altitude and the length of the main ridge (above 2000 m altitude), and to the Retezat Mountains because they receive more precipitation than ranges farther east. Taking the area above 1800 m as that most exposed to glaciation, the Făgăraş with 238 km^2 and the Retezat with 116 km^2 are well ahead of the other ranges, which each have less than 75 km^2. The second centre of glaciation was in the north (the Rodna, Maramureş and Călimani Ranges), where regionally lower temperatures compensated for lower altitudes and 81 cirques formed. Finally, the Bihor Range of the Apuseni Mountains, a lower massif sometimes termed the Western Carpathians in Romania, was just high enough to support glaciers producing three cirques.

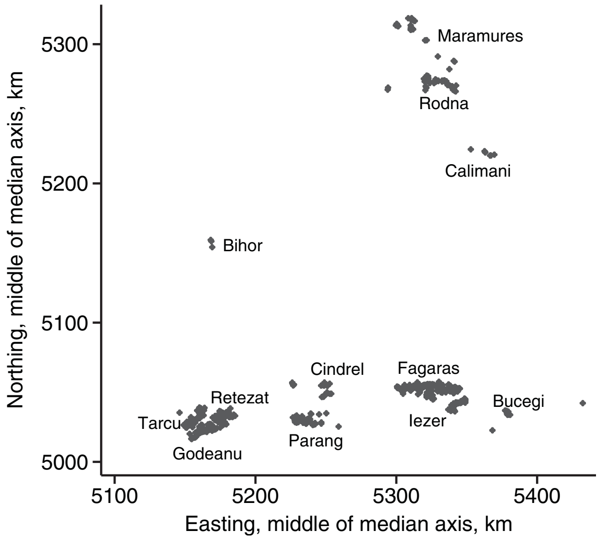

Figure 2 Spatial distribution of glacial cirques of Romania, with names of the main ranges

Neotectonics

Geologically, the mountains of Romania are young: they were folded and exhumed in the Cretaceous and Cenozoic Alpine Orogeny. Structures of the ‘inner’ ranges, which contain most of the cirques, are essentially Palaeogene, while the outer fold-thrust belt (mainly East Carpathian) is Miocene, with collision tectonics culminating 13–11 Ma ago. Sanders *et al.* (2002, Fig. 5) estimated erosion (denudation) of between 3 and 6 km throughout the mountains in the last 15 Ma: of this, about a quarter is Pliocene and Quaternary (last 5 Ma). The present topography is still younger, with kilometres of uplift at the beginning of the Quaternary in the southeastern Carpathians, and with deformation continuing at present (van der Hoeven *et al.*, 2005). Continuing uplift is in part an isostatic response to denudation, and in part a compressional folding of the Carpathian region.

The recency of uplift makes it desirable to consider the chronology of uplift before relating cirque or palaeoglacier altitudes to climate. Reuther *et al.* (2007, p. 153) suggest that altitudes may have been insufficient for glaciation in the early Quaternary. However, this depends on the balance between uplift and denudation: Sanders *et al.* (2002, p. 130) estimate that the *average* altitude of the Carpathians reached over 2000 m, before declining in the Pliocene and Quaternary. Early Pleistocene moraines would have been completely eroded; there were probably more glaciations than the three with surviving moraines in the Retezat. These three were dated as Late Pleistocene by Reuther *et al.* (2007) and probably relate to Marine Isotopic Stage (MIS) 4, MIS 2 and the Younger Dryas. We surmise that cirques could develop in the last 360 ka, with probable glaciation in MIS 2, 4, 6, 8 and 10. In the Pindus Mountains of northern Greece (600 km SSW of Retezat), Hughes *et al.* (2006) dated the most extensive glaciation as MIS 12, and Hughes *et al.* (2007) established that some well-developed limestone cirques have not been reoccupied by ice since MIS 12. Thus it is likely that many Romanian cirques were occupied in MIS 12, extending the time span to 470 ka, but differences in tectonism and climate may be important. These time spans are sufficient also for cirque forms to be obliterated if previous glacier occupation is not renewed.

Neotectonic uplift rates of up to 3 mm a^{-1} are confirmed by recent GPS measurements, with an uplift of 2.82 ± 1.06 mm a^{-1} between 1997 and 2004 at Fundata, between the Iezer and Bucegi Mountains (van der Hoeven *et al.*, 2005). It is, however, unlikely that such rates continue steadily throughout the time spans of cirque development. Necea *et al.* (2005) show that, in the southeastern Carpathians (Bend Carpathians), Quaternary uplift has been episodic. Superimposed on ‘a general pattern of decreasing uplift rates from Early to Late Pleistocene’ (Necea *et al.*, 2005, p. 153) were two periods of increased uplift on the eastern fringe of the Carpathians in the Vrancea area: 750 m in the late Early Pleistocene and 250 m in the late Middle to Late Pleistocene. The 250 m terrace of the River Putna suggests Middle Pleistocene uplift of at least 0.4 mm a^{-1}, while the 40 m terrace, dated at 200 ka, implies uplift of 0.2 mm a^{-1}.

The latter rate would mean 94 m uplift in 470 ka, whereas 1 mm a^{-1} would be 470 m and imply delayed initiation of cirque formation. The glaciated areas of northern Romania and the Southern Carpathians are less seismic than the Vrancea/Carpathian Bend area, and were uplifted mainly around 12 Ma rather than 4 Ma, but the pattern of Late Pleistocene uplift is not yet known in sufficient spatial and temporal detail. If uplift was rapid and differential between ranges such as Făgăraş, Parâng and Retezat, some climatic conclusions drawn below would need modification. However, it is unlikely that the glaciated ranges have been as tectonically active in the Pliocene and Quaternary as the southeastern Carpathians (Leever *et al.*, 2006). It is also possible that the late Quaternary deceleration of uplift applies more widely in the Romanian Carpathians.

Modern climate

Five stations on ridges above 1700 m, and two sheltered high stations, give indications of the present-day mountain climates, which are wetter and colder than temperate climates and fall into subnival, alpine and subalpine geoecological zones (Urdea and Sarbovan, 1995). The *Atlas of Romania* (Republicii Socialiste România, 1979) provides a series of useful maps, using altitude for interpolation. The wettest areas in Romania, with a mean annual precipitation of over 1400 mm in the mid 20th century, provide a good approximation of the ranges affected by glaciation. They have more than 600 mm in both the warm and the cold halves of the year. The easterly ranges of the Eastern Carpathians are relatively dry in the cold season, whereas in the warm season precipitation is more evenly spread across Romania’s mountains. In glaciated areas, precipitation now occurs on more than 170 days a year, and snow lies on the ground for more than 150 days (200 days in the core areas of ranges in the Transylvanian Alps). Even in the shadiest locations, snow patches do not now survive the heat of August.

A further characteristic of the glaciated areas is less than 1800 h of sunshine a year, with less than 1250 h in the warm season and less than 700 h in the cold. Cloud cover averages over 65% (over 70% in core areas). Over 135 days are completely overcast and fewer than 35 days have clear sky. Global radiation is less than 146 W m^{-2}, with <106 W m^{-2} in the warm season and <43 W m^{-2} in the cold. There are fewer than 90 frost-free days. The annual temperature range is less than 19°C, from below -8°C in January to below 10°C in July. Mean annual temperature (1979–1999) was $+0.1$°C at Bâlea Lac (2038 m altitude) in the Făgăraş Mountains (Voiculescu, 2002); for 1896–1975 it was 0.0°C at Ţarcu (2180 m) further west in the Transylvanian Alps, -2.5°C at Vârful Omu (2504 m) in the Bucegi Mountains and 1.4°C at Vlădeasa (1836 m) in the Apuseni Mountains, Western Romania. Mean annual precipitation was around 1200 mm for all four stations.

Winds at high stations come dominantly from the west (Fig. 3). This effect is strongest at Ceahlău (46.6° N in the Eastern Carpathians), where winds blow from the west 55% of the time (1971–1995: calms are 17%) and at Lăcăuţi (45.8° N: from W and WNW 50%). At Vârful Omu (45.3° N: 2001–2007) west winds blew 18% of the time, with a further 20% from WNW and WSW, and 21% from NW and SW, giving 59% balanced around W. These three exposed stations show the dominance of west winds, with the spread around W increasing southward. Ţarcu in the Parâng range shows a different pattern, with 26% from N and 13% from S. Bâlea Lac shows winds from N (14%) and SE (13%), while Iezer Pietrosu (1785 m in the Rodna Mountains, northern Romania) shows winds from ENE and SW: these bimodal distributions arise because these two stations are sheltered in cirques and thus less exposed to regional winds.

Methods and data

Cirques are hollows formed at glacier sources in mountains, with gently sloping floors partly enclosed by steep, arcuate

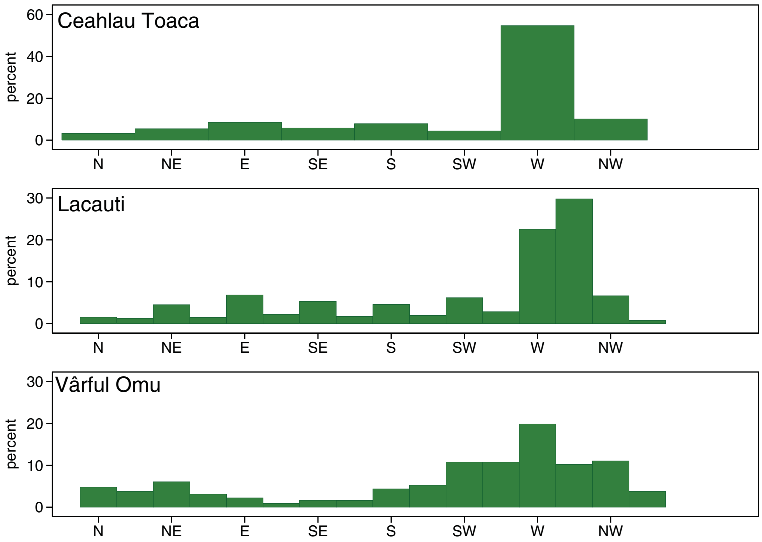

Figure 3 Modern wind directions at Ceahlău (1971–1995: 1890 m, Eastern Carpathians), Lăcăuţi (2001–2007: 1776 m, Carpathian Bend) and Vârful Omu (2001–2007: 2504 m, Bucegi). Frequencies are weighted by mean monthly speeds, where available (i.e. for Lăcăuţi and Vârful Omu). This figure is available in colour online at www.interscience.wiley.com/journal/jqs

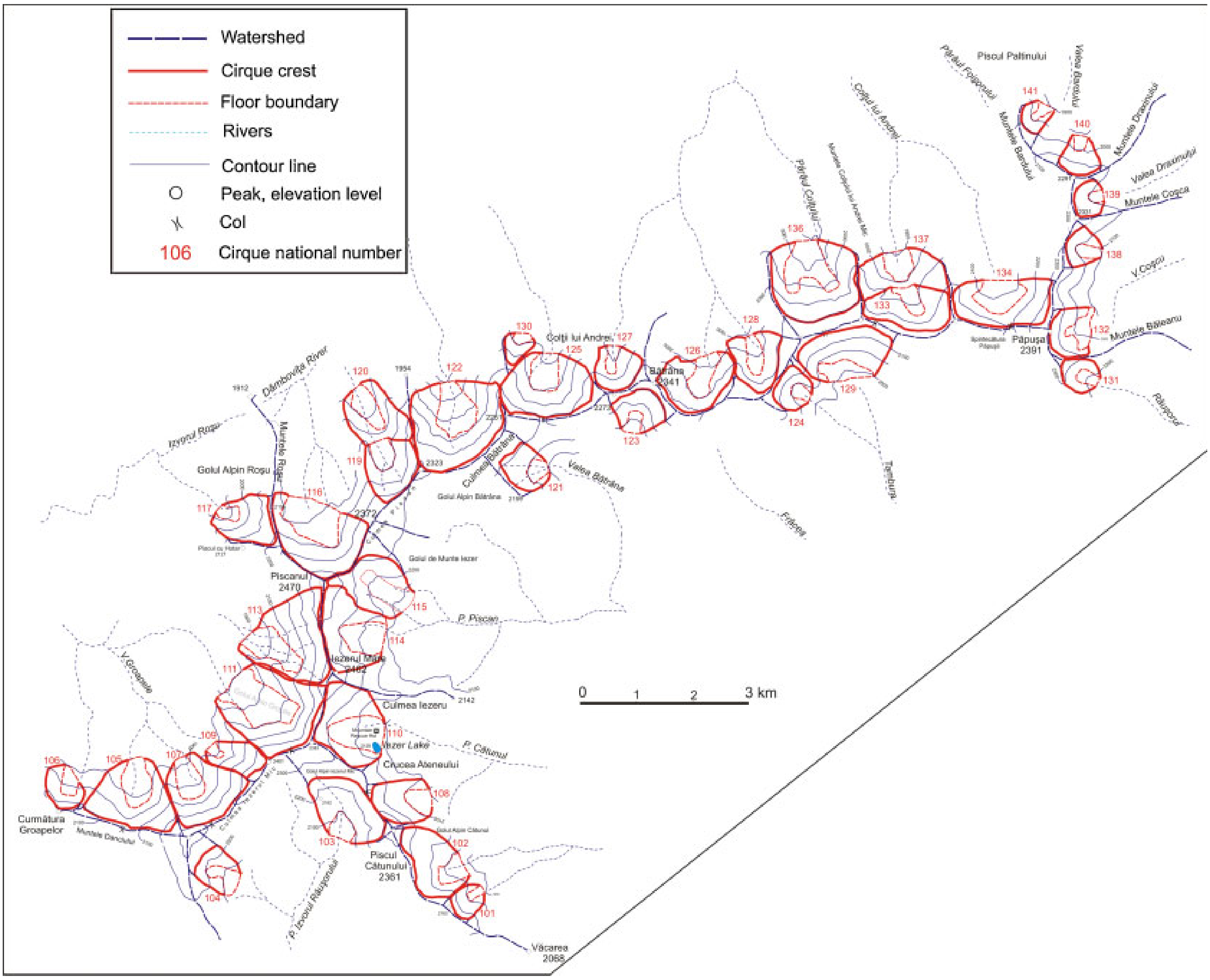

Figure 4 Cirque definition map of Iezer Mountains, after Mîndrescu (2006). The cirques are eroded in micaschist and micaceous paragneiss. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

slopes (headwalls). At least part of the floor should be gentler than 20° and some of the headwall should be steeper than the main angles of talus (31–36°). Cirques were identified here from air photos, maps and previous literature including the *Atlas of Romania* (which incorporated maps by Niculescu, 1965, and by Iancu). Fieldwork was undertaken in each of the ranges, including visits to most of the cirques: this permitted checking landforms where the quality of maps was limited by generalisation or by cliff drawing interrupting contours.

Using digitised 1:10 000 maps with 5 m contour interval for Maramureş and Călimani, and digitised 1:25 000 maps with a 10 m contour interval for other ranges, an inventory of 658 likely cirques was initially identified and measured. Cirques and their floors were outlined on-screen, and summary maps produced for each range (e.g. Fig. 4). Further checks were made and 27 marginal cirques, with maximum wall gradients below 36° or minimum floor gradients above 20°, were dropped. Analyses in this paper thus deal with 631 cirques. The increase compared with some previous authors is because we have included all features matching the accepted definition, subdivided the cirque complexes at some valley heads, and recognised both 'inner' and 'outer' or 'lower' cirques where there are two or more distinct floors. For example, in the Iezer Mountains, our 38 cirques cover a distribution similar to the 40 mapped by Nedelcu (1967). In the Făgăraş, the *Atlas of Romania* (Plate III-2, based on Nedelcu's work) shows 177 source cirques; Pişota's somewhat different map (1971, figure 37) shows 171, but does not cover the six easternmost. Our 206 include 25 'outer' cirques, so the difference in source cirques is slight. Iancu's (1963, figure 3) 48 cirques in the Parâng massif compare with our 51 in distribution as well as in number. In the Godeanu Mountains, Niculescu (1965) mapped 59 source cirques, which are very close to our 69 that include 10 outer cirques (below source cirques). In the Ţarcu Mountains, Niculescu (1990) mapped 37 cirques, but their mean aspect is very similar to ours (below) based on 59 cirques including five outer cirques. Note that previous maps indicate simply headwall crests, whereas ours (Fig. 4) complete the delimitation so that unambiguous morphometric measures can be made.

Nevertheless, some scepticism remains concerning the number of cirques recognised here (Urdea, personal communication), for example the 84 in the Retezat (including Little Retezat). However, we read maps in Pişota (1971) and the Atlas (Plate III-2) as showing approximately 61 source cirques. We

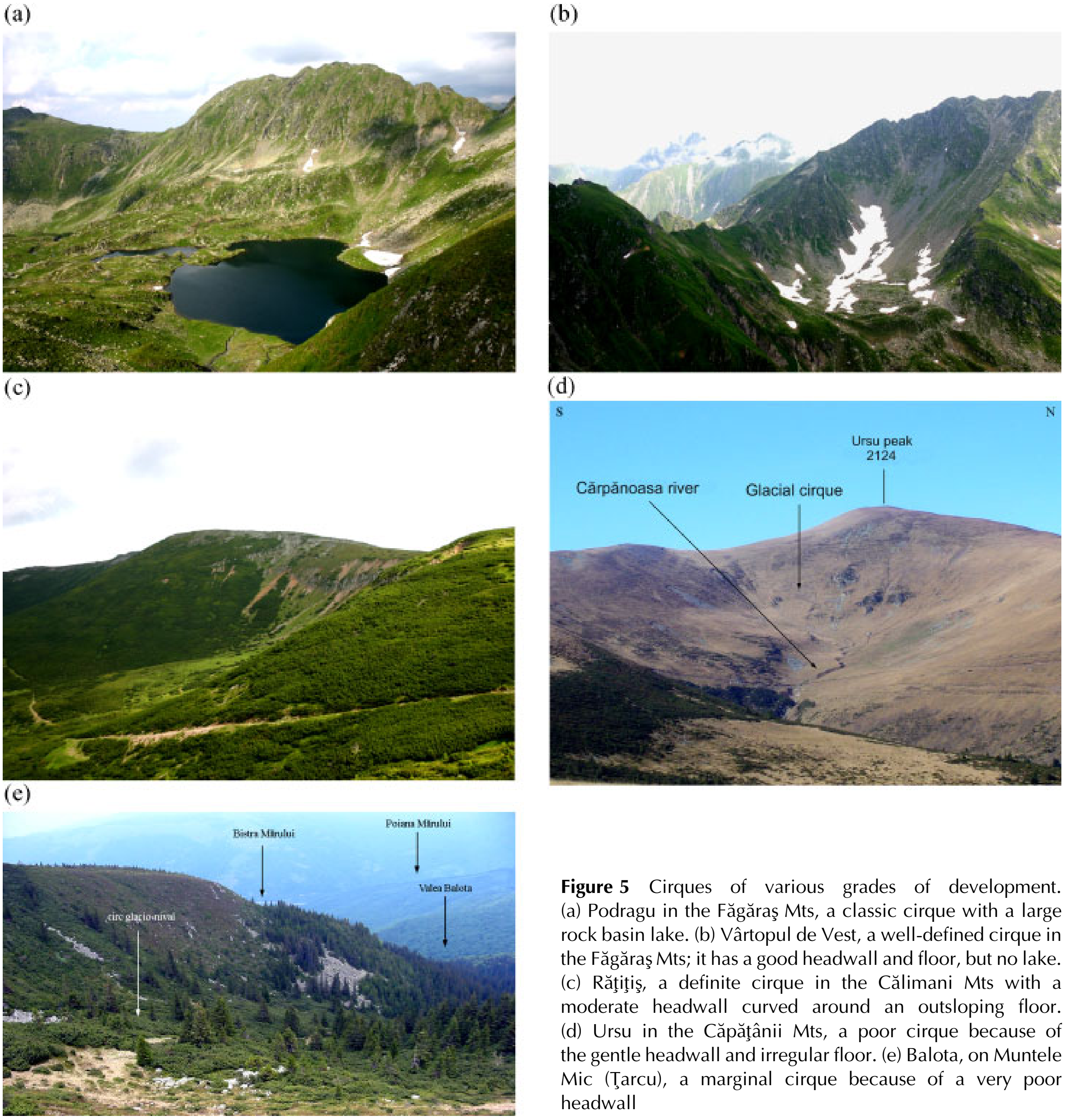

Figure 5 Cirques of various grades of development. (a) Podragu in the Făgăraş Mts, a classic cirque with a large rock basin lake. (b) Vârtopul de Vest, a well-defined cirque in the Făgăraş Mts; it has a good headwall and floor, but no lake. (c) Răţiţiş, a definite cirque in the Călimani Mts with a moderate headwall curved around an outsloping floor. (d) Ursu in the Căpăţânii Mts, a poor cirque because of the gentle headwall and irregular floor. (e) Balota, on Muntele Mic (Ţarcu), a marginal cirque because of a very poor headwall

recognise also 20 lower or outer cirques, so the difference is slight. The spatial coverage is very similar, the differences being on the peripheries. We maintain that, given our efforts to separate cirques in cirque complexes and to recognise the simplest concavities, the number of cirques is reasonable and all have served as glacier sources. Moreover, we have maintained consistency between the different mountain ranges.

On average, Romanian cirques are 654 m long, 718 m wide, and have headwalls 209 m high. Cirques have been assigned to five qualitative grades (Fig. 5), which permits analyses with or without marginal or poor cirques. Using the Evans and Cox (1995) grading scheme, 62 cirques are classic, 216 well defined, 253 definite, 73 poor and 27 marginal. 87% of the cirques (89% of the classic cirques) are in seven ranges with over 35 cirques each: Rodna (Sârcu, 1978), Iezer (Fig. 4), Făgăraş (Fig. 6), Parâng, Retezat, Godeanu and Ţarcu. A full set of outlines and median axes are recorded on contour maps in Mîndrescu (2006).

The procedures of Evans and Cox (1995) and Evans (2006b) were applied, and several further variables were measured. A few variables were defined a little differently: in particular, *wall aspect* was measured as the aspect of the highest part of the headwall, i.e. along the line for which wall height was measured. This is the part of the headwall which provided the best shade and shelter against wind.

The cirque threshold separates the floor from the slope or valley below. The *median axis* is defined as a line from the middle of the threshold (usually near the lowest point of the cirque) to the headwall crest, dividing the cirque map area into two equal halves, to left and to right: it is thus central to the cirque. The *(median) axis aspect* is measured in an outward direction from headwall to threshold. Both cirque aspects are measured as azimuths, 0–360°, outward and downward from the headwall toward the valley. They are local variables, distinct from (although correlated with) cirque position within a range. Thus our interpretations relate cirque aspect to the local effects of wind-drifting snow to lee slopes (Mitchell, 1996) rather than to the regional effects of increased precipitation on windward slopes of large ranges. The latter is considered in the regional trends of cirque altitudes.

As in the previous work, *altitude* was estimated for six points (Fig. 7); the lowest, the modal (most frequent) on the floor, the highest on the floor, the crest altitude at the median axis, the maximum crest altitude, and the maximum altitude above (draining into the cirque). The division between cirque floor and headwall is drawn at a 26° gradient. *Palaeoglaciation level* is defined here as the crest altitude required to support a cirque; it is interpolated between crests which have no cirques and nearby ones that do, with some consideration of cirque grade.

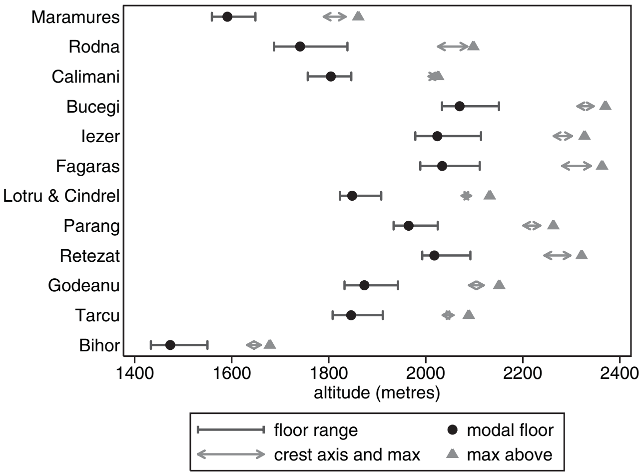

Figure 7 Mean values of floor and crest altitudes, and maximum altitude above, for cirques in the 12 mountain range groups in Romania. Floor altitudes are lowest (per cirque), highest and modal (most representative); crest altitudes are maximum, and at the median axis. Range groups are ordered from north, to southeast (Bucegi), to west

For statistical analysis, the techniques used were linear least-squares regression, vector analysis of aspect and circular (Fourier) regression for the relation of altitude to aspect (Cox, 2006). These are summarised where used below. 'Statistical significance' here implies significance at the 0.05 level. Where error bands (±) are cited, they define 95% confidence intervals.

Results

Cirque altitudes

Cirques are found in 19 mountain ranges (Table 1), but for statistical analyses those with few cirques are grouped with neighbours in the 12 range groups shown in Figs 1 and 2 and Table 2. (Bihor is too far from other ranges with cirques to be

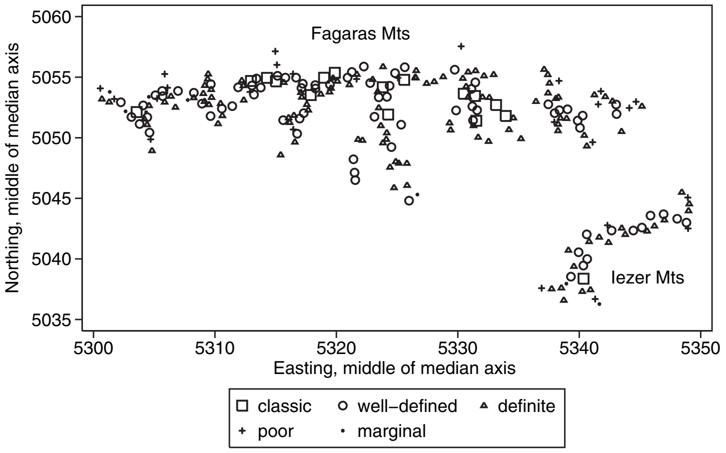

Figure 6 Cirque distribution and grades in the Făgăraş and Iezer Mountains, Transylvanian Alps, Romania, using the fivefold grading scheme of Evans and Cox (1995)

Table 1 Altitudes (m) of mountains with and without glacial cirques, and the inferred palaeoglaciation level (PGL). Mountain ranges are ordered from north, south to Ciucaş, and then to the west, ending with Bihor/Vladeasa

Range	Lowest with	Highest without	Interpolated PGL
Maramureş	1713, 1775	1763, 1811	1765
Tibleş	1839	1829	1830
Rodna W	1787, 1792	1931, 2034	1900?
Rodna E	1930, 1945	1856, 2002	1900
Călimani	1897, 1958	2031, 2050	2000
Bistriţei	—	1758, 1859	>1850
Ceahlau	—	1907, 1900	>1900
Buzău–Vrancei	—	1785, 1777	>1780
Ciucaş–Siriu	1662	1883, 1954	1800?
Baiu	—	1900, 1923	>1920
Bucegi	2404, 2421	2401, 2481	2410
Iezer	2170, 2163	2093, 2142	2150
Făgăraş E	2130, 2132	2044, 2084	2100
Făgăraş C	2157, 2170	2172, 2258	2170
Făgăraş W	1750, 2193	2129, 2162	2170?
Cindrel	2047, 2129	2007, 2035	2040
Lotru	1992, 2070	2080, 2171	2070
Latoriţei	2049, 2053	1978, 2038	2040
Căpăţânii	2125	1954, 2108	2120
Parâng	2061, 2084	2074, 2184	2080
Şureanu	2000, 2056	2009, 2130	2050
Vâlcan	—	1946, 1868	>1940
Retezat	1943, 1977	1852, 2180	1940
Godeanu	1872, 1891	2000, 2030	1950
Ţarcu	1860, 1910	1924, 1995	1930
Muntele Mic	1801	1675	1800
Vladeasa	—	1826, 1836	>1830
Bihor	1530, 1658	1597, 1774	1710

grouped with any.) Further analyses were performed on six major regions. For the whole cirque dataset, average modal floor altitude is 1938 m and average maximum crest altitude is 2217 m. Most cirques (82%) have thresholds between 1650 and 2110 m altitude and 83% are on mountains 2000–2470 m high. 86% of lakes in cirques are between 1800 and 2200 m altitude.

For the whole of Romania, cirque floor modal altitudes rise to the east and south:

$$\mathit{floor\ altitude} = 4494 + 0.931\ \mathit{east} - 1.471\ \mathit{north} \quad R^2 = 42\%$$

where *east* = grid easting in km and *north* = grid northing in km (Romanian UTM grid).

In the northern major region, with 81 cirques:

$$\mathit{floor\ altitude} = 5946 + 1.313\ \mathit{east} - 2.129\ \mathit{north} \quad R^2 = 34\%$$

Recalculating without the term for easting (which is insignificant, at $P = 0.05$), cirque floors rise southward at 2.87 m km^{-1}, over a north–south distance of 99 km within the area with cirques. Floor altitudes average 1591 m in Maramureş, 1749 m in the Rodna Mountains, and 1804 m in the Călimani (Fig. 7).

In the Transylvanian Alps, with 547 cirques:

$$\mathit{floor\ altitude} = -4076 + 0.650\ \mathit{east} + 0.523\ \mathit{north} \quad R^2 = 14\%$$

Recalculating without the term for northing (which is insignificant), cirque floors rise eastward at 0.714 m km^{-1}, over a 286 km distance. Cirque floors in the Făgăraş average 2034 m altitude; those farther west average 1925 m.

Trends were calculated also for different cirque aspects in the Transylvanian Alps. These were consistent, but the eastward rise of cirque floors was less (0.365 m km^{-1}) for the north-facing quadrant than for others. Trends for smaller divisions, i.e. within ranges, tend to be statistically insignificant. Thus it is best to regard the overall southeastward rise of cirque floors in Romania as the resultant of two components: an eastward rise of 204 m along the Transylvanian Alps, related to diminishing precipitation; and a southward rise of 283 m in northern Romania, due partly to rising temperatures but also to diminishing precipitation.

Cirques are thus lowest in the north and west of Romania. Maramureş has floor altitudes more than 200 m lower than the western ranges of the Transylvanian Alps, and the three cirques in the Bihor Mountains are lower still, due to their position on the west side of northern Romania. Considering means for 12 range groups, Fig. 7 shows floor altitudes rising southward from

Table 2 Vector statistics and significance tests for wall and axis aspect, by range group

Group	Obs	Wall aspect (highest part)						**Median axis aspect**			
		Mean	Strength	95%	Limits	Rayleigh	Kuiper	**Mean**	**Strength**	**95%**	**Limits**
		°	%	°	°	probabilities		°	%	°	°
Maramureş	27	44.3	62.7	21.5	67.1	0.000	0.000	**50.7**	**76.6**	**36.1**	**65.3**
Rodna	47	34.5	44.2	8.7	60.2	0.000	0.000	**41.1**	**54.7**	**21.0**	**61.3**
Călimani	7	15.5	73.7	334.8	56.1	0.016	0.014	**8.7**	**69.1**	**320.8**	**56.6**
Bucegi	13	4.2	9.8	—	—	0.887	0.844	**36.3**	**24.3**	—	—
Iezer	38	26.7	39.9	355.2	58.1	0.002	0.007	**26.7**	**38.3**	**348.4**	**65.0**
Făgăraş	206	59.4	18.6	28.7	90.1	0.001	0.005	**70.3**	**21.5**	**43.8**	**96.9**
Lotru–Cindrel	22	67.8	42.5	19.4	116.2	0.017	0.016	**82.3**	**37.0**	**21.6**	**143.0**
Parâng	56	72.1	43.8	47.4	96.7	0.000	0.000	**68.2**	**45.3**	**45.4**	**90.9**
Retezat	84	60.1	20.8	15.2	105.1	0.026	0.063	**46.4**	**22.9**	**359.6**	**93.1**
Godeanu	69	105.8	33.1	76.1	135.5	0.000	0.003	**114.1**	**30.5**	**81.0**	**147.2**
Ţarcu	59	69.7	42.4	44.8	94.6	0.000	0.000	**76.5**	**45.9**	**53.9**	**99.2**
Bihor	3	77.8	72.4	—	—	0.223	0.253	**66.8**	**71.4**	—	—
Total	*631*	*60.2*	*29.1*	*49.5*	*70.9*	*0.000*	*0.000*	***63.0***	***31.4***	***52.7***	***73.3***

95% confidence limits on the vector mean are given as northwest-most followed by southeast-most. The Rayleigh significance test gives the probability of results at least as extreme as those obtained, if the population is azimuthally uniform, tested against the alternative of one favoured mode. The Kuiper test is against any deviation from uniformity. Note that results for axis aspect (right, bold) are close to those for wall aspect, falling into two clear sets: more northward (the first five) and more eastward (the last seven). Obs, number of observations (cirques).
To form 'range groups', Rodna includes Ţibleş (2 cirques) and Suhard; Bucegi includes Siriu (1) and Leaota (1); Lotru–Cindrel includes Şureanu (4) as well as Lotru (10) and Cindrel (8); Parâng includes Latoriţei (4) and Căpăţânii (1); Ţarcu includes Muntele Mic (1).

Maramureş to Bucegi, and generally falling westward through the Transylvanian Alps from Bucegi to Ţarcu. There are also contrasts between ranges on the north side of the Transylvanian Alps and those on the south side: cirques in Lotru and Cindrel (including Şureanu) are over 100 m lower than those further south, in Parâng. Floors in Retezat are higher than in neighbouring ranges, but here we should note the correlation between floor altitudes and crest and mountain altitudes. The large numbers of high summits in Retezat and Făgăraş produce more high floors, giving higher standard deviations of modal floor altitude. If instead we take the 5 percentile (from lowest) of floor altitude, Retezat has a value of 1760 m, transitional between 1640 for Godeanu (to the west) and 1820 for Parâng (to the east). Moreover, Făgăraş at 1830 m is lower than Iezer at 1870 m. This is suggestive of a moisture source from north of west.

In more detail, Fig. 8 shows the statistical distribution of individual values of floor and maximum crest altitudes, for major regions. These are intermediate between Gaussian (giving a transposed sigmoidal plot) and rectangular (giving a linear plot as in ‘Northern’). There are two low outliers, which are discussed below. Iezer-Bucegi and Făgăraş are similar, Parâng–Lotru–Cindrel cirques are considerably lower, Retezat-Godeanu has lower cirques at the low end and northern region cirques are considerably lower. The difference between floor and crest altitudes is a measure of vertical cirque dimension, greatest for Făgăraş. For comparison, Urdea (2004) gives the lowest Pleistocene snowlines, as around 1550 m in the Rodna Mountains and 1670 m in the Transylvanian Alps. These are rather low, at the 10 and 3 percentiles of cirque floor altitudes respectively.

Pişota (1971, table 5) provided an inventory of ‘glacial lakes’ in the Southern Carpathians; essentially these are cirque lakes. Lake median altitudes rise from 1860 m in the west (Ţarcu and Godeanu, with 32 lakes), through 2090 m in Retezat (56 lakes) and 1979 m in Parâng (28), to 2170 m in Făgăraş (29 lakes). This eastward rise of 310 m is rather greater than the rise in cirque floors. Also the three lakes in Şureanu have a median attitude of 1780 m, which is considerably lower than 1975 m for the four farther east in Cindrel as well as the 28 farther south in Parâng: this suggests a moisture source from northwest.

Palaeoglaciation level

So far the focus has been on the presence of cirques. The absence of cirques, however, provides further useful information, often neglected in studies of cirque floor altitude trends. The presence of cirques implies geomorphologically effective glaciers lasting for some time. Their absence does not exclude the possibility of glaciers, but it is found that in high-relief areas only a few glaciers have sources outside cirques. The concept of glaciation level (Østrem *et al.*, 1981) or glaciation threshold (Porter, 1977) relates to the altitude required for a mountain or ridge crest to support a glacier, which is some 250 m above the equilibrium line altitude (ELA) in southern British Columbia. Evans (1990) applied this concept to glacial cirques and thus former glaciation, establishing a *palaeoglaciation level* (PGL) which is based on the negative as well as the positive evidence. Table 1 applies this to the mountain ranges of Romania. It gives only the two highest crests (usually summits) without cirques, and the two lowest with. The PGL is not an average of these but is interpolated on the basis of these and further crests, and the surrounding topography. (Ideally, all four altitudes should be similar.) This procedure requires judgement, and it is difficult to evaluate error margins, but results are expected to be within 100 m of true values. By averaging out topographic variations, PGL gives a better representation of former regional climatic conditions than do ELAs based on reconstructions of individual glaciers. The former plateau glaciers tabulated by Urdea (2004) are mainly on surfaces above PGL and their inclusion would not modify the values given here.

The results essentially support the spatial patterns shown by cirque floors. The lowest levels, below 1800 m, are in the north and west: Maramureş and Bihor. Immediately northeast of Bihor, there are no cirques on the Vlădeasa Mountains (1836 m). In northern Romania, the PGL rises southward from Maramureş through Rodna to Călimani. It rises eastward from 1830 m in the small Tibleş range to 1900 m in the Rodna. In the Eastern Carpathians south of Călimani a series of summits between 1750 and 1907 m failed to support glaciers generating cirques.

In the Transylvanian Alps, PGL rises eastward along with cirque floor altitudes (Table 1). This clearly contradicts Pawłowski’s (1936) denial of an E–W trend in former snowline. As latitude varies little, this rise is due mainly to declining precipitation at times of cirque formation. In the far west, 1801 m (Muntele Mic) is just sufficient to support a poor cirque. The next three ranges – Ţarcu, Godeanu and Retezat, each with many cirques – have very similar levels of 1930–1950 m. But there are no cirques in the Vâlcan Mountains, despite summits of 1946 and 1868 m: they are sheltered from the west and, especially, the northwest, by the three previous ranges.

Between the Jiu and Olt Rivers (between Petroşani and Sibiu), PGL is between 2040 and 2080 m except in the southeast,

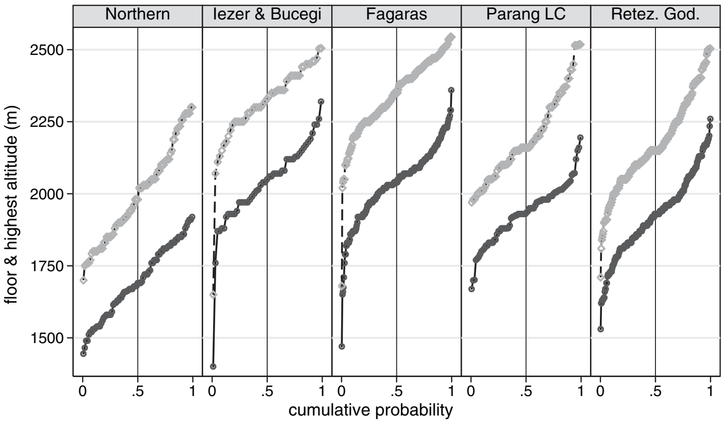

Figure 8 Quantile plots (Cox, 2005) showing the cumulative distributions of modal floor altitude (dark) and maximum crest altitude (pale) for five major regions (not Bihor, as it has only three cirques). Medians can be read off from intersections with the 0.5 line

where it is 2120 m in the Căpăţânii Mountains (east of Parâng). On the north side, PGL is 2050 m in Şureanu and 2040 m in Cindrel. East of the Olt, the level is around 2170 m in most of the Făgăraş, except for Mezuna de Nord, a poor valley-side cirque on a 1750 m northern ridge. (Its floor gives the low outlier in Figs 8 and 12.) The Iezer Mountains have a more precisely defined PGL of 2150 m.

East of the Dâmboviţa River, there is a sudden rise to over 2400 m in Bucegi, where the massive conglomerates give strong structural effects (and it is believed there was a plateau glacier: Velcea, 1973). The next range, east of Sinaia, is Baiu (1923 m), with no cirques. Immediately to the east an anomaly is encountered in the Siriu Mountains, where Muntele Mălaia (1662 m) has a well-defined valley-head cirque with a good floor (this gives the low outlier for 'Iezer-Bucegi' in Fig. 8): cirques are lacking not only on its 1657 m neighbour but also on nearby Mount Ciucaş (1954 m). This area is exposed to the southeast, and is also the most tectonically active part of Romania. Overall, however, the PGL results support the hypothesis of winds from north of west bringing precipitation: paired comparisons between Muntele Mic and Vâlcan, Şureanu and Căpăţânii, and Făgăraş and Bucegi can be regarded as NW windward–SE leeward couplings. Ranges with many summits rising hundreds of metres above PGL, such as the Făgăraş and Retezat, were able to support more varied cirques, including south-facing cirques (see below) and multi-level, cirque-within-cirque features. Higher mountains are more likely to have complexes of inner cirques, tributary to outer cirques with lower floors. While 'maximum altitude above' averages 2242 m for all 631 cirques, it is 2192 m for valley-side cirques, 2226 m for valley-head cirques and 2326 m for outer cirques. This explains the concentration of the 73 outer cirques in Făgăraş (25), Retezat (15), Godeanu (10), Parâng (7), Rodna (6) and Ţarcu (5).

Cirque aspects

Vector statistics (Fisher, 1993) are widely used for directional data (e.g. Evans, 1969, 1977); Curray (1956) gave a readable summary with geological applications. Where directions are plotted as unit vectors end-to-end, or the sine and cosine components are summed and used to define a net direction, the direction of the resultant vector is termed the *vector mean*. It is the best measure of central tendency on the circle, i.e. of directional data such as wind or cirque aspect. The degree of concentration of directions around this mean is measured by the *vector strength* or 'mean resultant length', the length of the resultant vector divided by the total length of vectors: here this ratio is expressed as a percentage. 100% means all directions are identical; 0% means opposing directions cancel out and there is no resultant, no net directional tendency.

Cirque aspects reflect the aspects of former glacier sources, which relate to topographic context, solar radiation and shade, wind (drifting snow, but also causing more melt on more exposed slopes), and morning–afternoon differences (the diurnal march of temperature and cloudiness) (Evans, 1977). For a large dataset from a range with ridges at various orientations, the climatic controls are considered dominant over topographic ones.

Range-by-range analysis of both (head)wall and (median) axis aspect distributions (Table 2) showed a contrast between the Eastern Carpathians (together with Iezer-Bucegi), and the rest of the Transylvanian Alps from the Făgăraş to Ţarcu. The 81 cirques in northern Romania have vector mean directions of 036° ± 16° (wall aspect) and 042° ± 13° (axis aspect) (Fig. 9), with vector strengths of 52% and 62% respectively. The 499 cirques from Făgăraş west to Ţarcu (the *southwestern* division) have means of 072° ± 13° and 075° ± 13° respectively. Moreover, the latter have a broader spread of aspects, with vector strengths of only 27% or 28%. Iezer and Bucegi have favoured cirque aspects more similar to those of northern Romania than to the rest of the Transylvanian Alps. Their combined vector mean is 025° ± 36° (wall) and 034° ± 33° (axis) and strength is 32% (wall) and 37% (axis). They show much less eastward tendency than the southwestern division (and the three in the Bihor Mountains of western Transylvania).

Could there be a topographic explanation for this? Mountain ridges are linear features, and this influences cirque aspect especially when small numbers of cirques are considered. Ranges such as the Retezat have ridges in all orientations, but the Godeanu main ridge is SW–NE and the Rodna is E–W. This may shift the mean cirque aspects, but probably by no more than 20° from the climatically favoured aspect. The Făgăraş main ridge trends E–W, but several long subsidiary ridges trend N–S, giving ample opportunity for east- (or west-)facing cirques to develop. The main ridge of Iezer is 18.9 km long and has a mean orientation of 060° ↔ 240°, favouring cirques facing 330° or 150°. Three cirque-bearing subsidiary ridges have a total length of 16.6 km and a 179° ↔ 359° mean orientation, favouring cirques facing east or west. Axis aspects are bimodal, with 15 Iezer cirques around 350° and 10 around 100°, suggesting a strong influence of ridge orientation, although the vector mean aspect is 027°. Wall aspects are unimodal around a mean which also is 027°. The 19 cirques on the northern slope of Iezer face a little west of north, while the eight cirques on the southern slope face southeast on average. But the 11 cirques on eastern and western slopes have wall aspects displaced some 20° northward of their axis aspects. This shows how climatic factors redirect glacial erosion to give steeper headwalls on favoured aspects, while axis aspects are more influenced by topographic trends.

Like the Godeanu and Ţarcu, and unlike the Făgăraş, the Iezer and Bucegi have extensive flat or rounded summit areas suitable for wind drifting of snow. It is concluded that west and northwest winds were stronger in the southwestern division than in Iezer-Bucegi and northern Romania. The Iezer (and Bucegi) Mountains (Fig. 10) are downwind of the Făgăraş and

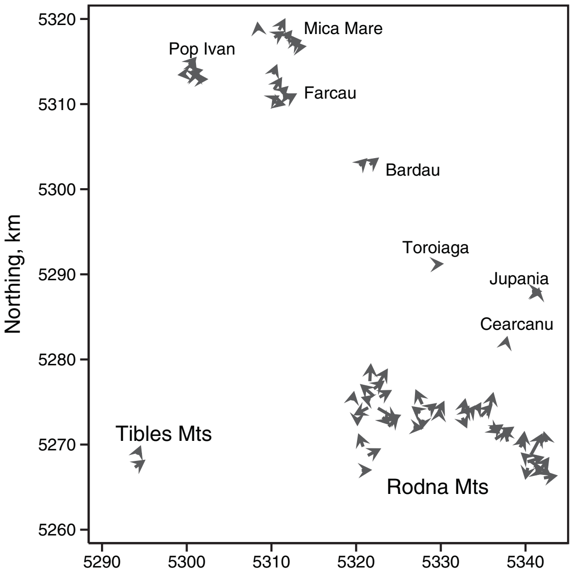

Figure 9 Median axis aspects of cirques in the Rodna and Maramureş Mountains, northern Romania. Arrow length is proportional to cirque size

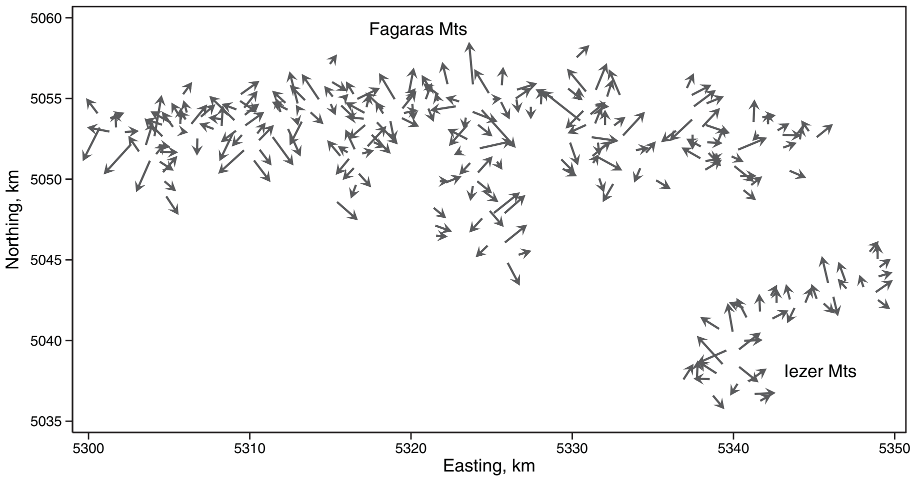

Figure 10 Median axis aspects of cirques in the Făgăraş and Iezer Mountains, Transylvanian Alps. Arrow length is proportional to cirque size

more sheltered from winds from the west and the northwest, so they fit the northern Romanian pattern.

Cirque *type* was classified as: valley-side, valley-head with threshold, valley-head without threshold, inner or outer. Cirque aspect statistics do not seem to vary with this classification, but in the Transylvanian Alps classic cirques and cirques with lakes have more northward tendencies. Thus aspect varies with *grade* but not with qualitative type.

Aspect statistics do vary with altitude. In the Făgăraş Mountains, the 141 cirques on mountains above 2300 m have no significant aspect tendency ($P=0.05$ on Rayleigh's test); their vector strength is only 10%. The 65 on lower mountains have a strength of 39% and a mean aspect of 049° ± 24°. This is consistent with higher mountains supporting glaciers on all aspects, while lower ones can support glaciers only on the most favoured aspects (Pawłowski, 1936; Evans, 1977, p. 169). Further validation comes from cirque altitudes taken in 45°classes of aspect. The mean of each altitude variable is between 149 and 198 m lower for NE-facing cirques than for SW-facing, and there is a steady variation with aspect between these extremes. In particular, the altitude of mountains above SW-facing cirques averages 192 m higher than those above NE-facing cirques (excluding the three low cirques in Bihor). The lowest mountain with a SW-facing cirque is 2102 m, but the lowest with a NE-facing cirque is 352 m lower and the lowest with N-facing is 389 m lower.

For the 12 mountain range groups (Table 2), Bihor and Bucegi have too few cirques for their asymmetry to be significant – although their mean directions are consistent with their neighbours. One summit in Bucegi, Vârful Omu at 2507 m, is much higher than the rest and thus has cirques on all aspects. Unimodal asymmetry (a single favoured aspect) is most significant for Maramureş, Rodna, Parâng, Godeanu and Ţarcu. Vector strengths are greatest for Maramureş, Călimani and Bihor, all with small numbers of cirques, followed by Rodna, Parâng, Lotru–Cindrel and Ţarcu, which have strengths of 42–44% for wall aspect and 37–55% for axis aspect. Considering *axis aspect* in 45° octants, Făgăraş has 61% of Romania's SW-facing cirques, Godeanu has 27% of the S-facing and Retezat has 21% of the SE-facing. This is consistent with these ranges rising higher above snowline and ELA, which permitted glacier formation on less-favoured slopes. Thus Făgăraş has the most dispersed axis aspects and the lowest (21.5%) vector strength, followed by Retezat with 22.9% (Fig. 11).

Except for Bucegi which has only 13 cirques, Făgăraş also has the most dispersed *wall aspects* and the lowest (18%) vector strength, followed by Retezat with 21% (Table 2). Vector means for axis aspect are between 14.5°clockwise and 13.7°

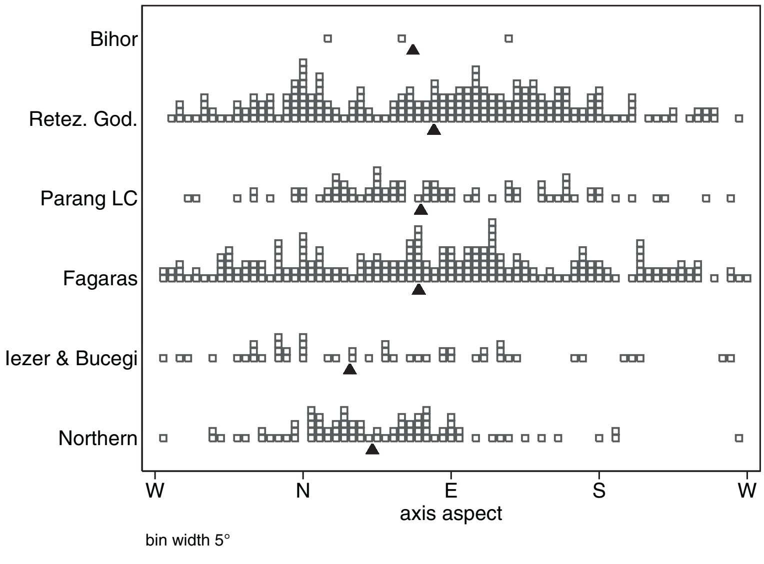

Figure 11 Axis aspects of cirques in six major regions of Romania. Each square represents one cirque; the solid triangles give the vector mean aspects

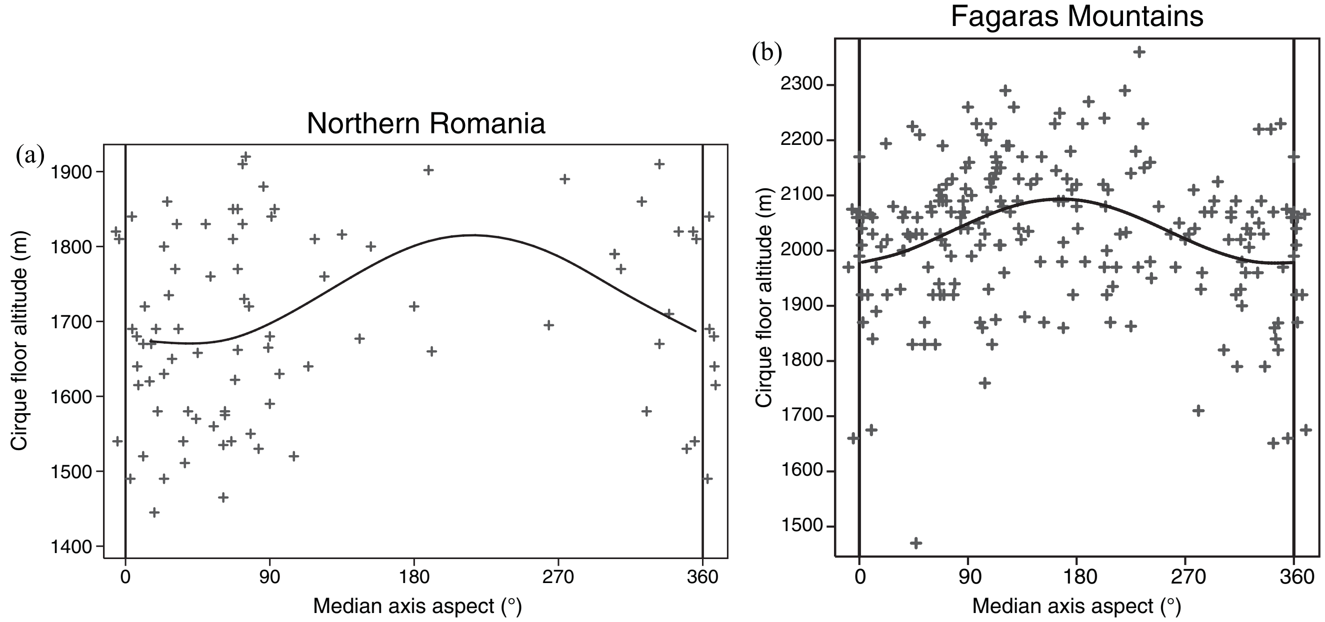

Figure 12 Plots of cirque floor altitude against median axis aspect. The fitted lines are regressions of altitude on sine and cosine of aspect (Evans and Cox, 2005). In northern Romania, cirques facing 037° are lowest, 117 m lower than those facing 217°. Făgăraş cirques facing 346° are lowest: 113 m lower than those facing 166°. Because the plots are unfolded cylinders, a small overlap is given at each 'end' of the x-axis, beyond the vertical lines

anticlockwise of wall aspect means; vector strengths are within 14% of each other. Results for the two aspect variables for the whole country, however, are much closer (differences of 3° and 2.3%: Table 2, last row). If aspects are assigned to eight 45° octants, all octant means of axis aspect are displaced toward the overall vector mean (ENE); this is consistent with a unimodal model, in which frequency declines away from the mean. Means of wall aspects corresponding to each octant of axis aspect (except for NE) are displaced toward ENE, usually even further. This is consistent with glacier mass balance steering aspect towards the most favoured direction, by glacial erosion undercutting the headwall more vigorously: we expect wall aspect to be closer to the climatically favoured direction, than site (axis) aspect.

If an aspect favoured in terms of cirque numbers (as shown by vector means) is due to glacier balance variations having produced a lower ELA, we expect that aspect to have cirque floors at lower altitudes (Evans, 2006b). In northern Romania (mainly Rodna and Maramureş), the NE tendency of cirque numbers shown in Fig. 11 is indeed supported by lower floors in cirques facing NE (Fig. 12). In the Făgăraş Mountains, however, those facing NNW are lower, whereas the vector mean is ENE. In Retezat-Godeanu, floor altitude has no significant variation with aspect. Local variations in cirque floor altitude provide support for the vector analysis results mainly in terms of N–S contrasts related to solar insolation and shading, but not more generally.

Discussion: implication for former wind directions

In the Transylvanian Alps the eastward rise in cirque floor altitudes, and in palaeoglaciation level, clearly supports winds having been from the west. The absence of cirques from some mountains on the east side of the Eastern Carpathians, such as Suhard (1932 m), Giumalău (1857 m), Bistriţei-Budacu (1859 m) and Ceahlău (1907 m), all checked in the field, is also consistent with winds from a westerly quarter, given that lower western mountains such as Piatra Grăitoare (1658 m, in the Bihor Mountains) did support glacial cirques. Farther north in Maramureş, which is more exposed to the west, all mountains above 1811 m do have clear cirques.

The eastward tendency in cirque aspects in the Transylvanian Alps has been noted by previous workers such as Niculescu (1965). Our new finding is that winds from a westerly direction had more effect on cirque glacier balance in the western Transylvanian Alps and the Făgăraş Mountains than in the easterly ranges (Iezer and Bucegi) and in northern Romania. This is crucial for inferences of palaeowind direction during the LGM and earlier maxima of mountain glaciation.

The anticyclonic circulation around the Fennoscandian Ice Sheet was fairly shallow and seems to have had little effect in the Carpathian Mountains. It may, however, have contributed to the northward weakening of westerlies observed across Romania. Thus cirques in Slovakia (Luknis, 1968) do not show a strong eastward tendency. In the mountains of northern Romania during the LGM, winds from westerly directions were strong enough to displace cirque wall resultant vectors to 044° for Maramureş and 034° for Rodna. Axis aspects were 051° for Maramureş and 041° for Rodna. This is explained by an eastward tendency in snow drifting and hence in cirque aspect. However, shade effects were strong enough to displace wall aspect 6° northward from axis aspect. In the Transylvanian Alps, winds were relatively more important in displacing cirque aspects eastward.

Although cirques probably form over a series of glaciations, it is believed that most Romanian cirques were reoccupied by glaciers in the Late Würm, around the LGM. For example, in the Retezat Mountains, Reuther *et al.* (2004, 2007) dated a major valley glaciation ending 16.1 ± 1.6 ka; they regarded this as (slightly) post-dating the global LGM, during which the Carpathians may have been more arid. An earlier, somewhat more extensive glaciation could not be dated. They also dated a Younger Dryas advance, in which N-facing cirques in the Retezat were occupied by cirque glaciers (Urdea, 2000). Some cirques remained ice-free in the Younger Dryas; FIrcaş *et al.* (1999) cored down to a compacted clay in Tăul Zănoguţii, a glacial lake 0.55 m deep at 1890 m altitude in a SE-facing cirque in the Retezat, obtaining an oldest ^{14}C date of 11.1 ka

BP. The two previous glaciations were much more symmetrical as well as more extensive. Thus it is likely that most Romanian cirques were glacier-occupied just after the worldwide LGM, and probably on numerous earlier occasions. Urdea (2004) gives the snowline in the Transylvanian Alps as 2200 m in the Younger Dryas, 1840–2000 m in 'Würm III', 1800 m in 'Würm II' and 1670 m in an earlier glaciation.

Winds from south of west would not give the observed contrast between Iezer-Bucegi and Făgăraş: important snow-drifting LGM winds in the mountains must have come from the northwest quadrant. This is supported by lower PGLs in the northwestern ranges than in the southeastern, in three parts of the Transylvanian Alps. Differences in mean floor altitudes within the latter are less clear (Fig. 7) because higher cirques are found around higher summits. The N–S narrowness of the ranges, and the importance of topographic differences between the northern slopes and southern slopes of the Făgăraş, do not provide a good test for any southward (or northward) rising trend.

Niculescu (1965, pp. 35 and 228) found that, for the Godeanu Mountains, west and northwest winds were dominant in glacier formation – as they are today in snowpatch distribution. Northwest winds would be consistent with landforms in the Pannonian Plain, in central Hungary, where yardangs both in bedrock and in Late Pleistocene deposits demonstrate northwest winds (Ruszkiczay-Rüdiger *et al.*, 2007). These may have been persistent during cold, dry glacial phases. Also south of the Transylvanian Alps on the Oltenian Plain, major Pleistocene linear dunes trend WNW–ESE (Coteţ, 1957, p. 239).

Rózycki (1967) attributed linear loess ridges (gredas, analogous to Chinese liangs) to the effects of dominant winds during the Pleistocene. His figure 9 mapped these ridges from Poland to Bulgaria, giving a clear pattern of wind divergence around the Slovak Carpathians, with the northern branch blowing ESE across southern Poland and turning SSE across Moldavia and Dobrogea. The internal, Pannonian branch blew SE across central Hungary, crossed the Iron Gates Gorge and blew ESE across southwestern Romania and northwestern Bulgaria. Again, this is not unlike the present-day pattern of west and west-northwest winds (Fig. 3). Niculescu (1965, p. 227) concluded that the Carpathian mountain arc modified wind directions in the lower atmosphere in the Pleistocene as it does today. The Holocene dunes on the plains of Oltenia in southwestern Romania and the Alfold of southeastern Hungary were also formed by northwest winds. By contrast, dunes in a smaller area of northeastern Hungary and adjacent northwestern Romania resulted from north and northeast winds.

General: interpretation of mean glacier or cirque aspects

This discussion raises an important general conclusion. It is often inferred or implied, at least in popular works, that dominant winds came from the aspect opposite (180° from) mean cirque or palaeoglacier aspect. For example, the northeastward tendency in British cirque aspects is attributed to southwest winds at times of cirque formation. This is incorrect, as it implies that no factor other than wind influences aspect. As it is clear that N–S contrasts are near-universal in modern glacier populations (Evans and Cox, 2005), and morning–afternoon contrasts cause only a small displacement, usually to eastward, any wind effects are superimposed on these general effects. Thus if a wind from due west is equal in importance to N–S contrasts, in influencing azimuthal variation in glacier balance, we should expect eastward and northward tendencies to combine, giving a mean aspect near NE. Neglecting other factors, Table 3 shows, in the column 'West', the mean aspect expected from these two factors where the first column (x) shows the relative importance of a west wind. These were calculated simply as the arctangent of x, which gives the correct azimuth of the combined vector. Where the importance of this wind completely overwhelms N–S contrasts, mean aspect approaches 90°. Column 'Northwest' shows corresponding results, by further trigonometry, for a wind from the northwest, displacing aspect toward 135° as its importance increases.

Table 3 Aspect (columns 'West' and 'Northwest', in degrees east from north) resulting from combination of a wind effect with importance x times the northward effect of radiation and shade. Column 'West' is for a wind from due west, giving eastward tendency; column 'Northwest' is for a wind from the northwest, giving a southeastward (135°) tendency

x	West	Northwest
0.25	14	12
0.5	27	29
0.75	37	48
1.0	45	67
1.25	51	83
1.5	56	93
2.0	63	106
3.0	72	118
4.0	76	123
8.0	83	129
50.0	89	134

Thus the mean wall aspect of 72° for the southwestern division (499 cirques from the Făgăraş westward) could be produced by an infinite number of combinations of wind directions with relative importance of the two factors. If wind was from due west (on average, during times of cirque erosion), it would have been three times as important as solar radiation and shade. If it came from the northwest, wind would have had a little more effect than the latter: ×1.07. Given the evidence of cirque altitudes, a wind from somewhere between these directions is likely, probably closer to northwest than to west. This wind effect was much stronger than for glaciers today in the Alps, the Pyrenees or even Scandinavia (Evans, 2006a).

Similarly the 036° mean wall aspect for the 81 cirques in northern Romania could result from a west wind 73% as important as solar radiation and shade, or a northwest wind 60% as important. A northward reduction in wind effects seems reasonable, and the increased concentration of aspects (52%, compared with 27% for southwest) is due partly to this reduced interference by winds, and partly to fewer summits rising well above glaciation level. The more important wind and minor effects are, and the more their favoured aspect deviates from poleward, the lower the vector strength as more varied aspects are expected.

Conclusions

Cirques in Romania were probably formed over several glaciations and most were occupied around the LGM. Romanian glaciers around the LGM were short, but distributed over many different mountain ranges. Almost all issued from cirques or were confined to cirques. The spatial, altitudinal and aspect distributions of cirques indicate the influence of both solar radiation and wind in glacier mass balance. The regional effect of west winds is seen in the eastward rise of cirque floors and palaeoglaciation level, especially along the Transylvanian Alps. Mountains that rose higher above the snowline produced longer glaciers and more complex cirques: cirque-in-cirque forms are most common in the Făgăraş and Retezat Mountains (with 35 and 24, respectively, of the 98 'inner cirques'). They were also able to support glaciers on south- or west-facing slopes: of the 146 cirques with axes facing between 135° and 315°, 48% are in Făgăraş, 30% in Godeanu and 29% in Retezat.

Wind drifting of snow to eastern slopes had a stronger effect on cirque aspect in the Transylvanian Alps than in northern Romania. Within the former, its effects are greatest in western ranges such as the Godeanu Mountains, giving east-facing cirques. The big contrast in cirque aspects between the Făgăraş and the adjacent Iezer and Bucegi Mountains is explained by winds from north of west rather than south of west. Floor altitudes and especially palaeoglaciation levels also suggest precipitation-bearing winds from north of west. This evidence from high altitudes (1500–2500 m) is consistent with the evidence of aeolian forms at low altitudes and gives a picture of Romania being influenced by winds from WNW during glacial maxima. These winds may have been stronger in the Transylvanian Alps than in northern Romania, whereas modern winds are more consistently from the west in northern Romania.

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