Chapter 9
Glacial Cirques in the Romanian Carpathians and Their Climatic Implications

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Abstract This section summarizes a morphometric analysis of glacial cirques from the Romanian Carpathians, further inferring climatic information from spatial patterns of morphometric traits. Results derived from the detailed statistical analysis of a comprehensive database of glacial cirques are presented briefly. The distribution of cirques by altitude, aspect, size, classification (cirque grade), and geology is presented and related to controlling factors. New contributions concerning the palaeoglaciation level during Late Pleistocene in the Romanian Carpathians, and the direction of prevailing winds during glaciation are provided. Statistical distributions of cirque size and shape are outlined and illustrated. A comprehensive data base of all glacial cirques in the Romanian Carpathians is now available to guide or substantiate further comparative or/and interdisciplinary studies. It is also possible to rank the mountain ranges by the degree of glacial modification.

Keywords Glacial cirques · Controlling factors · Morphometric analysis · Romanian carpathians

Carpathian Glaciation: Background

The Carpathians are a young, mid-latitude mountain system. In Romania they are between 45° and 48° North, sheltered from Atlantic maritime influences but a long way from the arid interior of Asia. Romania has a remarkable variety of mountain ranges that rise high enough to have supported glaciers in the last extensive glaciation and probably in several previous glaciations. Erosive glaciers persisted long enough to erode cirques and troughs at many valley heads. Glaciated ranges

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currently have over 1400 mm of precipitation per year, and less than 1800 h of sunshine (Mîndrescu et al. 2010).

Although the tectonics of the Romanian Carpathians are complex and varied, many mountain ranges reach altitudes between 1800 and 2500 m and three just exceed 2500 m. This has been sufficient to produce cirque and valley glaciers during the colder periods of the Late Quaternary, but not to produce extensive ice caps. Urdea et al. (2011) estimated Equilibrium Line Altitudes (ELAs) of former glaciers for 17 regions of minor glaciation as between 1497 and 1719 m, averaging 1610 m. These low values reflect conditions at maximum glaciation (lowest ELA) and can be related to the altitudes of the lowest cirque floors, not the average.

The early work of Urdea (2004) on degrees of weathering, and of Reuther et al. (2007) and Urdea and Reuther (2009) on cosmogenic exposure ages in the Transylvanian Alps (Southern Carpathians) has recently been revised by Ruszkiczay-Rüdiger et al. (2015). It now seems that glaciation in Romania was in phase with that elsewhere in Europe: there were at least two major glaciations in the Late Quaternary, including the Last Glacial Maximum (Würmian: Marine Isotope Stage 2). Furthermore, it has increasingly become evident that some cirques in three of the ranges with valley glaciers (Retezat, Făgăraş and Rodna) sheltered small glaciers in the Late Glacial Younger Dryas stage (Gheorghiu et al. 2015).

Distribution of Cirques

All summits rising above 2000 m altitude supported glaciers. Valley glaciers were produced in the highest mountains: Făgăraş (reaching 2544 m), Retezat (2509 m) and Parâng (2518 m), and in the Rodna Mountains of northern Romania (2303 m). Retezat and Făgăraş, respectively, have 238 and 116 km^2 above 1800 m; all other ranges have less than 75 km^2. Each valley glacier had its source in a cluster of cirques. Numerous cirques cluster around the plateaux of the Bucegi (2505 m), Iezer (2470 m) and Godeanu Mountains (2291 m). Cirques are found in all the major ranges of the Transylvanian Alps (TA). Many other ranges, not quite so high, produced isolated cirques: the Maramureş ranges, Tibleş, Călimani, Leaota, Cindrel, Lotru, Latoriţei, Căpăţânii, Şureanu, Ţarcu, Muntele Mic, and Bihor, each reaching between 1800 and 2250 m. A single (but well-developed) cirque is found on Malaia (1662 m) in the Siriu Mountains of the 'Carpathian Bend'.

It is estimated that altogether at least 631 cirques formed, 547 in the Transylvanian Alps, 81 in northern Romania (we include 14 on the Ukrainian side of the border ridge as it is best to cover all slopes of a mountain) and three in Bihor Mountains (Apuseni) in the west (Fig. 9.1). Recognition of a landform inevitably involves a subjective element, and there may be some revision of these numbers, but Ardelean et al. (2013) show that convergence is achieved for cirques once a precise operational definition is applied. Urdea et al. (2011) tabulated numerous further small glaciers (mainly niche glaciers and 'ice aprons') which do not appear

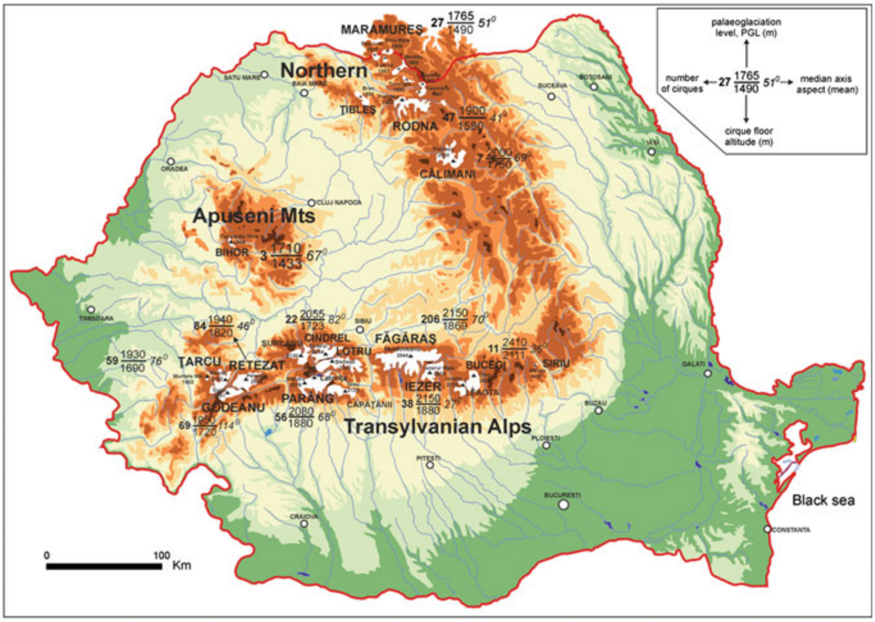

Fig. 9.1 Distribution of the glacial cirques in the Romanian Carpathians (clockwise ordering): Maramureş (*27*), Rodna and Ţibleş (*47*), Călimani (*7*), Siriu (*1*), Bucegi (*11*), Leaota (*1*), Iezer (*38*), Făgăraş (*206*), Lotru and Cindrel and Şureanu (*22*), Parâng and Latoriţa and Căpăţânii (*56*), Retezat (*84*), Godeanu (*69*), Ţarcu and Muntele Mic (*59*) and Bihor (*3*)

to have developed cirques, probably because they were too short-lived. These had Equilibrium Line Altitudes as low as 1544 m.

The distance between the northernmost Carpathian cirque, Dezeskul Grun (Northern Maramureş Mts) and the southernmost, Groapa Olanului Mare (Godeanu Mts) is 302 km, whereas the longitudinal span of the cirque population is 286 km between La Blid (Muntele Mic) and Malaia (Siriu Mts). Carpathian cirques are located in 14 major drainage basins and distributed as follows: Olt (153), Strei (151), Argeş (110), Tisa (48), Jiu (39), Timiş (30), Cerna (28), Dâmboviţa (28), Bistriţa (22), Someş (8), Ialomiţa (8), Arieş (3), Prut (2) and Buzău (1). While cirques are found in 19 Carpathian massifs, 87 % of the cirque population pertains to just 7 mountain groups: Rodna, Iezer, Făgăraş, Parâng, Retezat, Godeanu, and Ţarcu. Of these, Făgăraş and Retezat Mts hold the highest density of cirques, and these alone contain 46 % of the 631 cirques. It may therefore be concluded that cirque glaciers formed especially in the highest massifs, as well as the westernmost mountain areas.

The general eastward layout of main ridges resulted in an uneven distribution of cirques on the two slopes/mountainsides, i.e. northern and southern: 57 versus 42 %. At this broad scale, it would appear that Carpathian cirques exhibit only moderate glacial asymmetry; however, this varies regionally with Northern

Romania (NR: Northern Romanian Carpathians) having 83 % of cirques formed on northern slopes and just 16 % on southern slopes. Conversely, the cirque population of the Transylvanian Alps is overall rather evenly spread on the two mountain sides (northern—52.5 %, southern—47.5 %), albeit distributions vary significantly depending on the massif.

Ranges Apparently Lacking Cirques

One peculiar aspect of glaciation in the Romanian Carpathians regards the small number, or absence, of cirques in mountain areas similar in altitude, morphology, or position with clearly glaciated ranges. How can this be explained? Such instances are frequent, particularly in the Eastern Carpathians (EC), but are not absent from the Transylvanian Alps (e.g. Piatra Craiului, Căpăţânii, Şureanu/Vârful lui Pătru, Vâlcan Mts), either. In the EC (e.g. Suhard, Bistriței, Ceahlău Mts) this situation can be explained partly by local structural or topographic conditions, but largely by the triad of controls forming the so-called *ice cube* (Mîndrescu 2006): latitude, altitude and distance eastward (from the western edge of the EC mountain chain, and thus from oceanic climatic influences). As expected, in the Eastern Carpathians cirques are clustered in the northern part of the range (NR) which is also the highest. Continentality increases eastward in the EC, so that susceptibility to glaciation also decreases eastward. Coincidentally, the peak elevation line is located in the western extremity of the EC range, acting as a major orographic barrier and effectively reducing the precipitation and susceptibility to glaciation eastward. Thus, eastward location combined with altitude can best explain the absence of active cirque glaciers from major ranges such as Suhard, Giumalău, Bistriţei, Ceahlău and Baiu Mts, as well as the scarcity of cirques in Siriu and Leaota Mts.

Two additional controls, both related to the geological structure, had lasting effects on the forms of glaciation, mainly in the Eastern Carpathians: suspended synclines and Neogene volcanic and subvolcanic bodies. Two ranges rising above 1900 m a.s.l. consist of suspended synclines, i.e. Ceahlău, Ciucaş (EC) and Piatra Craiului (TA); in these cases, the high gradients typical for syncline flanks likely prevented the formation of cirque glaciers. Furthermore, the occurrence of young volcanic structures (as in Ţibleş, Călimani or Gurghiu Mts) or subvolcanic bodies (Toroiaga in Maramureş Mts) also interfered with the formation or full development of cirque glaciers due to steep slopes and the lack of preexisting topography with hollows facilitating ice accumulation.

Altitude

Cirque floor altitudes range between 1330 and 2360 m, and average 1938 m (median 1960 m). They are lower in Northern Romanian Carpathians and in Bihor: the 81 cirques in the north, in Maramureş, Ţibleş, Rodna, and Călimani have floor modal altitudes averaging 1696 m, while the three cirques in Bihor (central western Romania) average 1473 m. The 1030 m range in altitudes reflects firstly climatic and secondly topographic differences between mountain ranges. Floor altitudes vary considerably within each range, due to local topographic conditions and the variation in snowline (ELA) as climate varied during the Late Pleistocene. Altogether, in the majority of cirques from the Romanian Carpathians the floor altitudes range from 1800 to 2000 m (which is rated as the most intensely glaciated level).

In the Transylvanian Alps from Ţarcu to Bucegi, there are 546 cirques with a mean floor altitude of 1978 m: the range is from 1470 to 2360 m. There is broad variation within each range, but in general they are higher to the east, rising at 0.755 m/km, over 235 km (Fig. 9.2). Temperature differences being small, this trend is attributed to a reduction in precipitation, implying that snow was brought by winds from the west. The trend is greatest for south and east facing cirques (1.075 and 1.004 m/km, respectively, by 90° quadrant); it is only 0.360 and 0.395 m/km for north- and for west-facing cirques. Cirque floors in Lotru, Cindrel, and Șureanu) are over 100 m lower than those farther south in Parâng, sheltered from northwest winds. Variations of floor altitude with aspect are significant only when this eastward trend is allowed for. Averages are 1966 m for the North quadrant, 1979 m for the East, 1973 m for the South and 2010 m for the West.

In Northern Romania cirques formed mainly near the western edge of the EC mountain chain on crystalline and volcanic rocks, where ranges exceed at least 1800 m a.s.l., particularly in the northern sector. For example, the northernmost cirques in the Romanian Carpathians, known as the Mica Mare group, occur just below summits with altitudes between 1820 and 1713 m. Cirque floor altitudes in

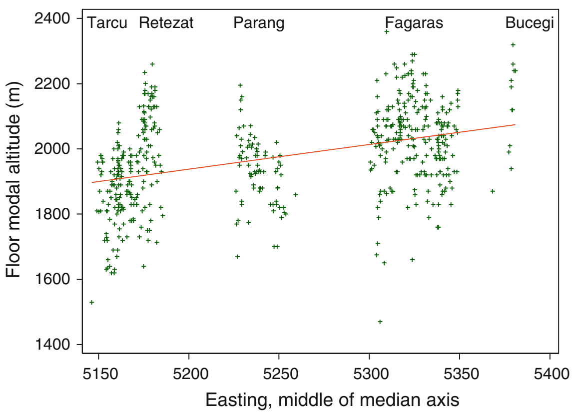

Fig. 9.2 Cirque floor altitudes in the Transylvanian Alps, from Ţarcu to Bucegi

Northern Romania decrease with latitude (northward), and increase eastward, such that the floors are higher in the ranges on the Moldavian side.

The highest Carpathian cirques are in the Transylvanian Alps (Southern Carpathians), with an average floor altitude 280 m higher than in Northern Romanian cirques. In 70 % of South Carpathian cirques the floor altitude ranges between 1800 and 2100 m. While cirque glaciers could fully develop wherever the peak altitude was at least 1900 m, the average altitude of summits which support cirques in the Transylvanian Alps is 2275 m; some of the floor altitudes compare with altitudes of the highest peaks in Rodna Mts. Furthermore, floor altitudes span over 800 m, significantly larger compared to Northern Romania. Cirque floor altitudes in the Transylvanian Alps were determined mainly by summit altitudes and the longitudinal position of mountain ranges within this sector of the Carpathians; the highest cirques are found in the '2500 elevation group' (i.e. massifs rising above 2500 m a.s.l.) or in the easternmost ranges, farthest removed from oceanic climate influences.

The overall southeastward rise of cirque floors in Romania should be regarded 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 (Mîndrescu et al. 2010).

Aspect and Wind

The tendency to face north (poleward: solar radiation and shade effect) is combined with an eastward tendency (mainly because of snow drifted to leeward slopes by wind) which is strongest in the Transylvanian Alps, where it increases westward (Fig. 9.3). The mean axial aspect is 063° overall, but 042° for northern Romania and 069° for the Southern Carpathians. A mean of 093° for Godeanu–Ţarcu implies formative wind from north of west, as does the greater wind effect in Făgăraş than in Iezer, which lies southeast of Făgăraş (Mîndrescu et al. 2010), plus the cirques in Parâng being lower than those to its north. Retezat and Făgăraş are the most dissected ranges, with the sharpest ridges; this is because of their more symmetrical glaciation (lower vector strengths), related to higher summit altitudes. Although Parâng is also high, extensive summit plateaux have been preserved there and in Lotru and Cindrel, permitting a greater wind-drifting effect.

55 % of Carpathian cirques face north, northeast, and east. Of the 8 aspect classes, east-facing cirques are the most numerous (130); 68 % of cirques have aspects between 0° and 180° (eastward components), and just 32 % have aspects from 180° to 360° (westward). Moreover, northward cirques are more frequent (59 %) compared to southward ones (41 %). Based on these ratios, an eastward tendency of Carpathian cirques appears to be prevalent, especially for the Southern Carpathians (TA), despite the northward and southward orientation of the main

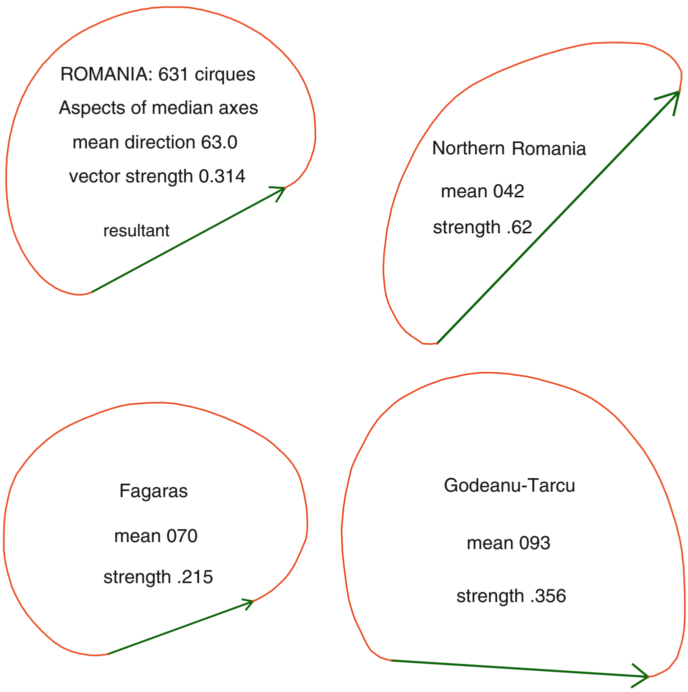

Fig. 9.3 Mean axial aspect of cirques in the Romanian Carpathians (*upper-left*), Northern Romania (*upper-right*), Făgăraş Mts (*bottom left*) and Godeanu–Ţarcu Mts (*bottom-right*)

slopes of glaciated ranges. The two main tendencies in terms of aspect, eastward and northward, are more balanced in northern Romania (NR).

Selective glacial asymmetry is derived from the analysis of well-defined cirque populations in terms of location and degree of development. Main crest asymmetry is the most relevant type we encountered and is applicable solely to glacial cirques tangent to the main crests. The most outstanding main crest asymmetry documented in the Romanian Carpathians is in the Făgăraş range which hosts the largest cirque population in Carpathian arc (206). The total mountain area measured above the 1500 m a.s.l. contour line is 649 km^2, of which the northern slope accounts for just 188.5 km^2 (29.5 %) and the southern slope for 451.5 km^2 (70.5 %). A measure of asymmetry computed from the number of cirques located on the two slopes is the north/south ratio, yielding 0.75 for Făgăraş (88 cirques on north slope/118 cirques on south slope: inverse asymmetry). However, when solely cirques tangent to the main crest are considered, the asymmetry is 1.36 (68 on north slope/50 cirques on south slope: normal asymmetry). Thus, the main crest asymmetry is normal and suggests that glaciation was more intense on the northern slope of Făgăraş Mts (Mîndrescu 2009).

The eastward tendency is strongest for the highest Romanian Carpathian cirques (104 with floors above 2100 m a.s.l., with a vector mean direction of 115°).

The 414 cirques with floors between 1800 and 2100 m (inclusive) have a vector mean direction of 055°. The lowest cirques (112 with floors below 1800 m a.s.l.) typically have NE aspects (mean 053°). This impacted on cirque size; thus, north-, northeast- and southeast-facing cirques are the largest and best-developed among Carpathian cirques. Thus, while the lee effect acted as the main control in western and/or higher altitude ranges, the shade effect was determinant in northern and lower mountains.

The northward and eastward tendencies are only slightly evident in cirque floor altitudes. In northern Romania, cirques facing 037° have floors 117 m lower than those of opposite aspects; and in the Făgăraş, those facing 346° are 113 m lower than opposite. Elsewhere, however, there is less variation with aspect.

The palaeo-ELA estimates tabulated by Urdea et al. (2011) show remarkably little variation between north-facing and south-facing glaciers, with the latter usually less than 100 m higher. Kuhlemann et al. (2013) corrected their palaeo-ELA estimates for 17 valleys in the central Făgăraş Mountains to give values between 1631 and 1900 m. The lower values are for southward aspects, which they attributed to moisture brought by winds from the southwest. This contradicts the cirque evidence mentioned above, as well as the trend of aeolian features in the Pannonian and Oltenian plains. An alternative explanation is that that plateau remnants on the north–south ridges between the south-flowing Făgăraş glaciers provided further sources of wind-blown snow, even from northwest winds, and that increased accumulation there (see also Mîndrescu 2004).

Size

Romanian cirques are comparable in size to those elsewhere (Barr and Spagnolo 2015; Evans and Cox 2015), and generally intermediate between those measured in Britain and in British Columbia. Width, length and height range are centred around median values of 596, 650 and 260 m respectively (Fig. 9.4), and mean values are rather higher. Distributions are skewed, with small cirques more frequent than large ones: thus Mîndrescu and Evans (2014) provided analyses on logarithmic scales. Cirques around the highest mountains are somewhat larger than lower or isolated cirques. Size varies over one (decimal) order of magnitude, with length and width always between 180 and 2230 m, and height range between 115 and 870 m (Fig. 9.4). Cirque areas vary between 4 and 377 ha, averaging 44 but with a median of 32 ha.

Based on the ratio of horizontal axes (W/L), a large number of cirques from Romanian Carpathians (47 %) rank as circular (W/L = 0.80–1.20) (i.e. developed evenly along the two horizontal axes), of which 12 % are nearly perfectly balanced. Of the remainder, 37 % rank as broad cirques (W/L > 1.20), whereas just 16 % are long cirques (W/L < 0.80) (i.e. developed more along the median axis). In just 4 cirques the length is twice as great as the width, whereas in another 16 this ratio is reversed (width = 2 × length); in 98 instances the width is 1.5 the size of the length

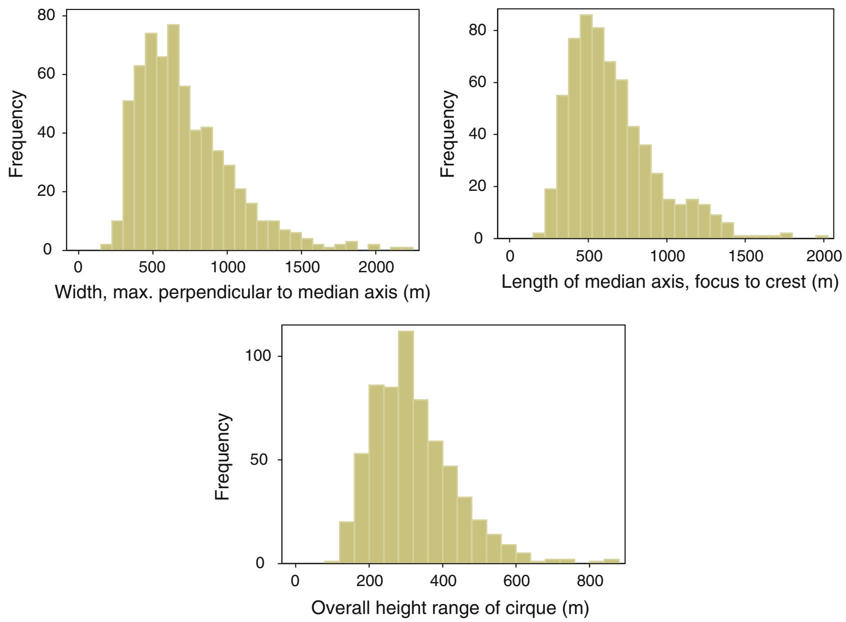

Fig. 9.4 Romanian cirque sizes: length, width and height

(broad cirques), while in 41 the ratio is inverse (length = 1.5 × width; trough cirques). The greater occurrence of broad cirques compared to trough cirques indicates a typical pattern of development for Carpathian cirques by lateral-regressive glacial erosion in the rock mass. Moreover, morphometric values help distinguish between glacial cirques and non-glacial (fluvial) valley heads.

Headwall height values are an additional criterion for cirque classification, according to which in many cirques (47 %) headwall height is in the average (100–199 m) range, defining the typical headwall for Carpathian cirques, whereas only 4 % (26 cirques) have low headwalls (under 100 m). 35 % have tall headwalls (200–300 m inclusive), and a distinctive type includes cirques with very tall headwalls exceeding 300 m in height, accounting for 14 % of all cirques. Six of these have headwalls over 500 m high, none of which are classic cirques; some may possibly be glacial trough-heads instead of actual cirques. The morphometric range of the headwall points toward a minimum value (threshold) of headwall height, below which gradients become inadequate for cirque glaciers to be erosive. This equals 60 m in Northern Romania, 70 m in the Transylvanian Alps and 80 m in Bihor Mts.

As regards the variation of cirque size with aspect, differences exist between north facing and south-facing slopes, with the latter being comparatively smaller in general. However, in terms of area ratios, south-facing cirques have floors better calibrated (adjusted) to overall cirque dimension, which could arise from the nature of less rigid, southern glaciers: the increased intensity of insolation 'fuelling' south-facing glaciers resulted in 'warmer', more dynamic bodies of ice. Albeit not as productive as north-facing glaciers in terms of cirque area enlargement, they were more effective in shaping floors than headwalls.

By region, the largest cirques are in Rodna: median length 742 m, width 729 m and amplitude 310 m. It is followed by Făgăraş in vertical dimensions, but by Bucegi in horizontal: in fact, median width (734 m) is slightly greater for Bucegi although means are much greater for Rodna (816 cf. 727 m for length and 868 cf. 780 m for width). With both smaller and larger cirques than Bucegi, Rodna has much higher standard deviations. Maramureş and Călimani have the smallest cirques in width and length, but Bihor and Ţarcu have the smallest in vertical dimensions (Mîndrescu and Evans 2014).

Shape

Cirque shape was most often described when defining glacial cirques as 'hollow spaces' of various sizes, enclosed on three sides and open downstream. In fact, the shape of the cirque is given by headwall curvature around the floor. The plan closure of the cirque best defines both the shape and the erosion process exerted by cirque glaciers. Depending on their degree of maturity, they increasingly eroded into the mountain, becoming enclosed. Unlike other evidence of glacial erosion, cirque plan closure was the least altered following deglaciation.

To assess the plan shape of cirques from the Romanian Carpathians the plan closure was determined, according to which the cirque population was ranked in 6 shape classes: very open (below 90°), open (90°–130°), slightly open (130°–170°), troughs (170°–190°), slightly closed (190°–230°), and closed (above 230°). This variable illustrates the degree of downstream opening of glacial cirques. The vast majority of Carpathian cirques are open or slightly open (80 % are between 85° and 188°), whereas very open cirques are more numerous than troughs. Just 7 % are slightly closed and 2 % are closed. Considering the low percentage of cirques with lake basins (20 %), regarded as an indication of glacial maturity, it may be assumed that approximately 3/4 of the cirques were developing during the late stages of glaciation and just 1/4 had reached maturity, as suggested by their plan closure. Surely, cirque shape was influenced by several factors aside from the intensity of glaciation, which either accelerated or slowed their evolution, among which altitude, continental climate and geology (lithology and structure) are notable.

Plan closure averages 137°, and varies between 37° and 283° (Fig. 9.5). The analysis of plan closure revealed the existence of three types of cirques with different shapes: (i) cirques with values ranging from 92° to 122°, typical for glacial areas with few cirques (under 8, with the exception of Ţarcu); (ii) cirques between 125° and 143°, common for glacial areas from the extremities of Transylvanian Alps and Northern Carpathians; and (iii) cirques above 143° which are most frequent in massifs peaking above 2500 m a.s.l. or those with average cirque populations (Cindrel and Lotru).

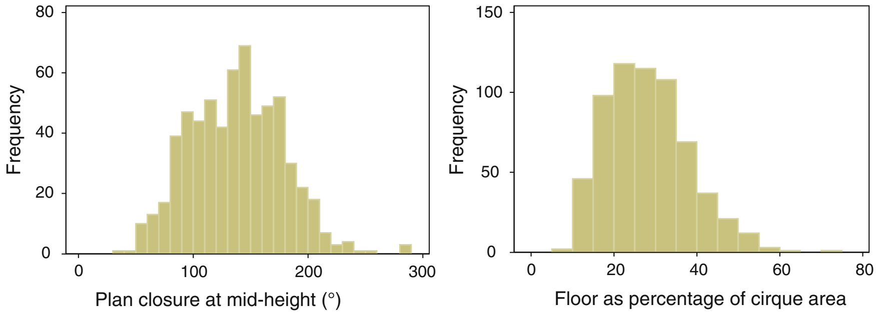

Fig. 9.5 Shape (plan closure) and floor area coverage of Romanian cirques

Plan closure varies with aspect, such that north-facing cirques from Retezat or Făgăraş have greater closure compared to opposing slopes. North, northeast, east and southeast-facing cirques typically have the most developed, mature shapes, consequent both on reduced insolation on north and northeast-facing slopes and on deflation of snow which favoured nival build up on east- and southeast-facing slopes. Lower insolation, in particular, favoured north-facing slopes (especially in inner sectors) of more massive mountain ranges (i.e. Făgăraş, Parâng, Retezat, Rodna), whereas deflation occurred mainly onto sheltered slopes of Maramureş, Godeanu, Ţarcu or southern Făgăraş.

Low floor gradients together with high headwall gradients define the degree of evolution of glacial cirques; thus the most advanced cirques, with gently sloping or even counter-slope floors and steep headwalls (profile closure above 50°) are those of Făgăraş, Retezat, Godeanu, Parâng, and Rodna, which are either high altitude mountain areas or the northern and western extremities of the Romanian Carpathians. Based on headwall height and gradient, cirques were ranked into several classes, of which deep cirques (with headwalls over 300 m high and gradients above 50°) are the most spectacular. In the Romanian Carpathians 11.4 % (75 cirques) rank as deep cirques; half of these are in the Făgăraş Mts (50 %), but they are present also in other major glacial areas such as Maramureş, Rodna, Iezer, Bucegi (1), Parâng, Retezat and Godeanu.

The minimum floor gradient in the Romanian Carpathians averages 8.4°, ranges between 0° and 20° and is bimodal, with 101 cirques having flat floors or lakes, recorded as 0°. Only 10 % of cirques have minima above 15.1°. In terms of maximum headwall gradient, values range from 36° to 75°, albeit 80 % are between 40° and 64°. Maximum gradient averages 51°. Cirques with low gradient headwalls (below 40°) indicate poor development and primitive cirque shape, and account for 10 % of all cirques (63). Conversely, headwall gradients exceeding 60° (in 122 cirques) indicate advanced, well-developed cirques on strong rocks and are typical for higher grade cirques.

The most important component of cirque shape is the overall gradient along the median axis, from crest to threshold. This averages 24°, and in 90 % of cirques it is between 15° and 33°, providing ideal conditions for rotational flow in a glacier that fills the cirque up to the centre of the crest. Cirques on higher mountains tend to have steeper headwalls and larger, flatter floors, and to bite more deeply into the mountains (to have greater closure in plan). Larger cirques tend to be better developed, with greater plan closure and maximum gradient, and lower minimum gradients. As cirques develop, they enlarge in length and width much more than in vertical dimensions.

Only 41 % of cirques have significant cols (depressions of more than 30 m in their crests). Multiple cols are found mainly in the Făgăraş, Retezat and Rodna mountains. In almost all cirques, floors cover between 10 and 55 % of the cirque map area (range 8–71 %: Fig. 7.5). A larger, flatter floor is indicative of better cirque development and greater glacial erosion.

Regionally, cirques in Călimani are much poorer than elsewhere, with easily the worst plan and profile closure, Grade and maximum gradient, as well as the lowest relative floor area and number of cols and the highest minimum gradient. Bihor generally scores poorly and Maramureş, Iezer and Ţarcu also have poor scores. Maximum gradient is highest for Făgăraş, Retezat and Parâng, while minimum gradient is lowest for Retezat, Parâng and Lotru–Cindrel. The three latter have the highest overall Grade and all four together with Bucegi have the highest plan closures (mean 140°). Cols are most frequent in Rodna, Retezat and Făgăraş and floors are proportionately larger in Ţarcu and Retezat (Mîndrescu and Evans 2014).

Classification

Cirques may be graded into five classes of degree of development and clarity of definition and delimitation (Evans 2006). This reflects plan closure, maximum gradient, minimum gradient, roundness of headwall in plan, sharpness of crest and more subjective assessments such as presence of a clear down-valley limit (threshold) and simplicity of concavity in plan and profile. The first three of these are the more reliably quantifiable and, in combination, can provide a good estimate of cirque Grade, but the subjective assessment is also important. Of the 631 cirques, 62 are recognized as 'classic', 216 are 'well-defined', 249 'definite', 76 'poor' and 28 'marginal' (debatable): see illustrations in Mîndrescu et al. (2010). Larger and higher cirques are more likely to have a better Grade. Higher grade cirques tend to be larger in horizontal more than in vertical dimensions. The steady variation of size and shape variables with Grade is illustrated in Mîndrescu and Evans (2014).

The vast majority of Carpathian cirques rank as well-defined and definite (74 % of the total cirque population); the remaining 26 % are classic cirques (10 %) and poor or marginal (16 %). Figure 9.6 shows examples of each Grade. Based on this distribution the high intensity of cirque glaciation in the Romanian Carpathians may be inferred, as well as the short-life of glaciers during glaciation in the Romanian Carpathians.

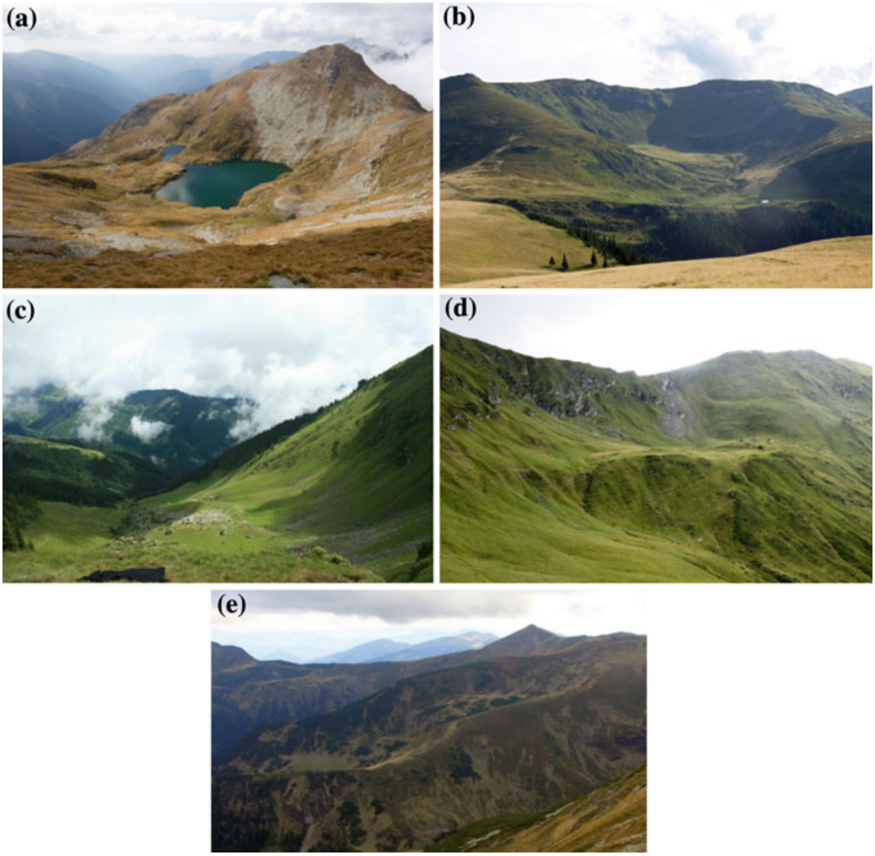

Fig. 9.6 Examples of cirque development in five grades. **a** Capra in the Făgăraş, a *classic* cirque with a large rock basin divided into two lakes. **b** Izvorul Cailor, a *well-defined* cirque in the Rodna Mts with a well-developed headwall and floor, but no lake. **c** Groapa Julii, a *definite* cirque in the Maramureş Mts with a moderate headwall curved around an outsloping floor. **d** Putredu Superior in the Rodna Mts, a *poor* cirque because of the gentle headwall and irregular floor. **e** Buhăiescu Mic in the Rodna Mts, a *marginal* cirque because of a very poor headwall and floor

Classic cirques are the best-developed and have all the features of ideal cirques, albeit most are lacking ample glacial basins such as Bucura or many in the High Tatras. These cirques have a longer history of glaciation (i.e. were glaciated during several glacial periods), therefore are more evolved and larger in size.

As regards poor and marginal cirques, doubts have been expressed about their origin. Whereas they were most likely subjected to the action of ice in the shape of cirque glaciers (the most common glacier type in the Romanian Carpathians), in some instances cirque-like landforms may have resulted from other processes. The genetic processes which could best emulate the cirque shape are deep-seated rock slope failures, which can produce hollows (scars) resembling poor cirques (Turnbull and Davies 2006), although those in deglaciated ranges are commonly on trough-sides and only a few are likely to form cirques (Jarman 2006; Wilson and Jarman 2015).

The development of nested cirques is relatively common in the Romanian Carpathians, resulting from the succession of several glacial phases acting on a less than resilient yet structurally complex geological substrate. 73 large cirques contain one or more inner, higher cirques. These are found especially on the higher and more heavily glaciated mountains, rising 450 m above former Equilibrium Line Altitude: 63 of them are in five ranges: Făgăraş, Retezat, Godeanu, Parâng and Rodna.

Geology

According to the geological distribution, the most numerous cirques formed on gneiss and paragneiss (43.3 %), particularly those in Făgăraş and Godeanu ranges. This mapped lithology includes small extents of various other types of rocks, and ranks among the most mixed compared to the other mapped categories. The second largest group of cirques formed on granite (mainly in Retezat, Ţarcu and Parâng), followed by those on epimetamorphic schists (all cirques from Iezer, Jupania in Maramureş, Muntele Mic, and Bihor) and micaschists (Rodna and Parâng). Other cirques (albeit in small numbers) are on flysch and arkose (Maramureş and Godeanu), crystalline limestone (Făgăraş) and conglomerate (Bucegi, and Bardău cirques in Maramureş), diabase and diabase tuff (Maramureş and Godeanu) and andesite (Călimani, Ţibleş, and Toroiaga in Maramureş).

The higher mountains are on granite and gneiss and these have well-formed cirques, with a disproportionate number of large lakes, generally basins eroded into bedrock. Major lake basins are found in 11 % of cirques, but 26 % of granite cirques. The largest and best-developed cirques, however, are on mica-schist. The poorest and narrowest cirques are on andesite, which includes all those in the Călimani and Tibleş Ranges.

Geological structure (i.e. the disposition of strata) is another control of cirque development. Depending on the median axis of the cirque glacier and the main structural lines, two major tendencies are manifest in the development of cirques: either parallel or transverse to bedding. In the former case, cirque length increased significantly through headwall collapse leading to the formation of trough cirques with near horizontal floors which often lack evident cirque lips. Conversely, transverse cirques evolved more towards the sides of the headwall, thus increasing the plan closure.

Discussion: Origins

Turnbull and Davies (2006) suggested that many cirques formed by deep-seated rock slope failure, especially from earthquakes as these tend to produce failure on the upper part of a hillslope, whereas rainstorm-related failures tend to be lower on slopes. In Romania, earthquakes are most frequent around the Carpathian Bend, the southern end of the Eastern Carpathians. This, however, is a region with no cirques. Cirques are confined to higher mountains, and their strong correlation with evidence of glaciation (moraines, striations, facetted stones) supports the traditional interpretation, that they are formed by glacial erosion.

Cirques are formed by glaciers, not only cirque glaciers but also at the heads of valley glaciers with fairly steep surface gradients. The existence of cirques also encourages the formation and endurance of glaciers. Erosion of valley-head and valley-side concavities provides sheltered localities where wind-blown snow comes to rest, and shade that reduces melting from solar radiation. It is this positive feedback that makes cirques such distinctive landforms, and enduring evidence of the presence of erosional glaciers.

Conclusions

Cirque glaciation is characteristic of many mountain ranges in Romania. Some were just high enough to support small glaciers forming isolated cirques, but the highest ranges generated larger glaciers around whose sources many cirques developed. Cirques on higher mountains developed further, probably because the glaciers occupying them lasted longer. These cirques are larger, better developed and more complicated (more inner cirques nested within large outer cirques). They cover a broader range of aspects and are often back-to-back, producing sharp ridges with cols. Nearby, however, fragments of summit plateaux survive, showing that summits have not been lowered much by glaciation (i.e. by cirque development). Summit plateaux in the Godeanu, Țarcu, Parâng, Lotru and Cindrel Mountains have clearly not been lowered by glaciation.

The distribution of glaciers and thus of cirques was influenced by differential solar radiation and by wind. The effect of winds from the west was considerably greater in the Transylvanian Alps (Southern Carpathians) than in northern Romania. At least in the west (e.g. Godeanu Mountains), there is evidence of winds from north of west. The variation of cirque floor altitudes, over some 1000 m, suggests that higher and lower cirques may have developed in different climates, and it is possible that the direction of snow-bearing winds varied.

Romanian cirques are believed to have been eroded by glaciers in the last few glaciations of the Late Quaternary. Analysis and combination of seven measures of degree of glacial modification and cirque development, by region, led Mîndrescu and Evans (2014) to conclude that Retezat is easily the ‘most glaciated’, followed by Parâng and Făgăraş. Next come Bucegi, Rodna, Lotru–Cindrel and Godeanu. Glacial modification is much less in Maramureş, Iezer, Ţarcu and Bihor. Easily the least modified, with the poorest cirques, is Călimani.

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