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CIRQUES AS GLACIER LOCATIONS

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ABSTRACT

A comparison between the 319 cirques that contain glaciers and a sample of 240 empty cirques in the Rocky Mountains shows that in the present climatic situation, landforms are strong factors in determining the locations of glaciers. An optimum glacier location is a large cirque facing northeast, with a planimetric shape of width greater than length, high steep walls, a pass located to the windward, and a peak to the southwest. Glaciers survive in the present climatic conditions because of a geomorphic feedback system, whereby glaciers are protected by cirque forms that owe their morphology to glacial processes.

INTRODUCTION

During the Pleistocene period, huge valley and plateau glaciers covered large portions of the American Rocky Mountains, but as climate changed, glaciers receded and in most cases vanished. Of the thousands of cirques that mark the alpine landscape from the United States/Canadian border to New Mexico, only 319 contain glacial ice. Table 1 provides a brief glacier census of the Rocky Mountains south of the border as determined by interpretation of aerial photography and ground checks—only ranges with glaciers are listed. These cirques generally have geomorphic and microclimatic characteristics that permit the maintenance of glaciers (characteristics that are lacking in neighboring empty cirques), and although geomorphologists have long recognized the cirque as a landform produced by glacial erosion, few have examined the role of cirques in the preservation of glaciers during periods of adverse climatic conditions. This paper is an attempt to identify the significant characteristics of the geomorphology of cirques which help to preserve glaciers, and to specify the exact differences between glacierized and empty cirques.

The term *cirque* was first applied by Charpentier (1823) to semicircular basins in alpine areas, but several decades passed before they were recognized as products of glacial activity. The activities of cirque glaciers in developing cirque morphology have been explored (Lewis, 1938) but, with one notable exception, the protective role of cirques in preserving glaciers during mild climatic periods such as the present has not been examined closely. The geomorphology

TABLE 1
Glacier census

Mountain unit	Number of glaciers	Glacierized area (km^2)
Cabinet	2	0.505
Livingstone	41	10.577
Lewis	70	17.757
Flathead	2	0.674
Swan	6	0.612
Mission	6	1.012
Crazy[a]	4	0.400
Beartooth	71	10.891
Big Horn	9	0.974
Absaroka[a]	9	0.720
Teton	12	1.657
Wind River	64	31.578
Front Range	23	1.495
Total	319	78.852

[a]Areas of poor map and photo coverage.

near the glacier has an important influence on radiation receipt and thus on the mass balance of the glacier (Andrews and Dugdale, 1971; Williams *et al.,* 1972; Wendler and Ishikawa, 1974), so that the cirque, originally a form produced by the process of glaciation, has become a form that *controls* the glacial process.

The process of cirque glaciation may be considered a series of cyclic events. As climate in a given alpine area becomes more glacial, snow patches enlarge preexisting depressions by nivation (Matthes, 1900; Hobbs, 1911; Lewis, 1938), they become areas of long-term snow retention, and if accumulation exceeds ablation for a period of time, small glaciers gradually develop within geomorphic constraints (Davies, 1969). As the glaciers grow, they erode their beds, altering the original shape of the nivation hollows to form cirques (McCabe, 1939; McCall, 1960); if the climate is extremely favorable for glacier formation, ice may flow out of the cirques and down the valleys. At this point, valley glaciers are actively changing the geomorphic environment (Cotton, 1947), landforms exert little control over the glacier systems except in very broad terms, and the glacier equilibrium line lies outside the cirque.

As climate changes and becomes more mild, the glaciers recede into the cirques and in some cases may disappear completely. Now landforms exert a strong influence on the glacier systems because the only glaciers to survive will be those in very favorable geomorphic circumstances—protected from the warming effects of insolation by their aspect and by high walls, and nourished with snow that avalanches from steep slopes or blows into the cirques from plateau surfaces upwind. Surviving glaciers have equilibrium lines confined within the host cirque. As climate changes again to conditions more favorable for glaciation, strong geomorphic control of glacial systems wanes, and the ice again advances, repeating the cycle.

The study of Rocky Mountain glaciers reported here examines one small slice of time in the cycle—the present, when landform exerts strong control over glacial systems. The theories expressed here concern themselves with the geographic nature of the connection between landforms and glaciers in an attempt to identify which parts of the geomorphic system play a role in the connection.

CIRQUE CONTROL OF GLACIERS

A comparison between the shapes of glaciers and the shapes of the cirques they occupy reveals the degree of control exerted on the glacial systems by geomorphology. Planimetric shape can be expressed both for cirques and for glaciers by the ratio of length to width (Figure 1). High length/width ratio values indicate long, narrow shapes, while low values indicate short, wide forms. If a glacier is not strongly controlled by the cirque, it forms a tongue of ice flowing down the valley and displays a high ratio. On the other hand, if the glacier is controlled by its sur-

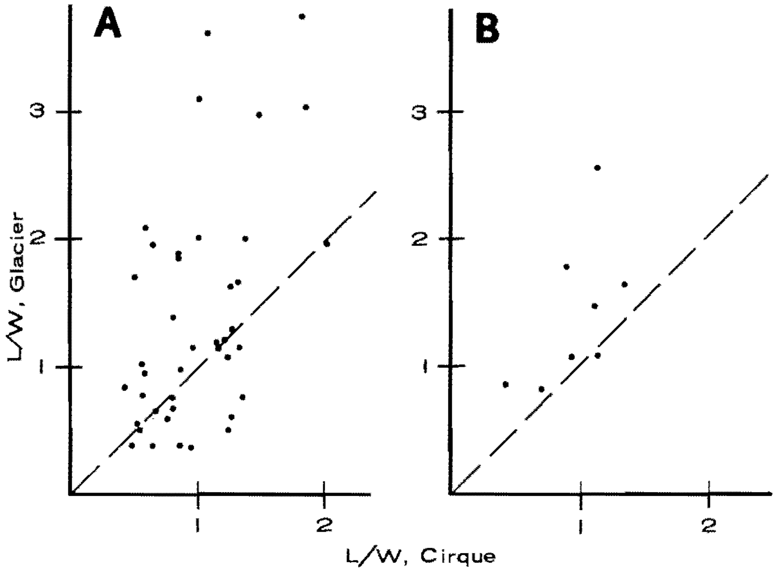

FIGURE 1. Scatter diagrams showing length/width ratios for cirques vs. those for glaciers from two sample mountain ranges, A, Livingstone Range; B, Big Horn Range. Plotted lines represent one to one correspondence.

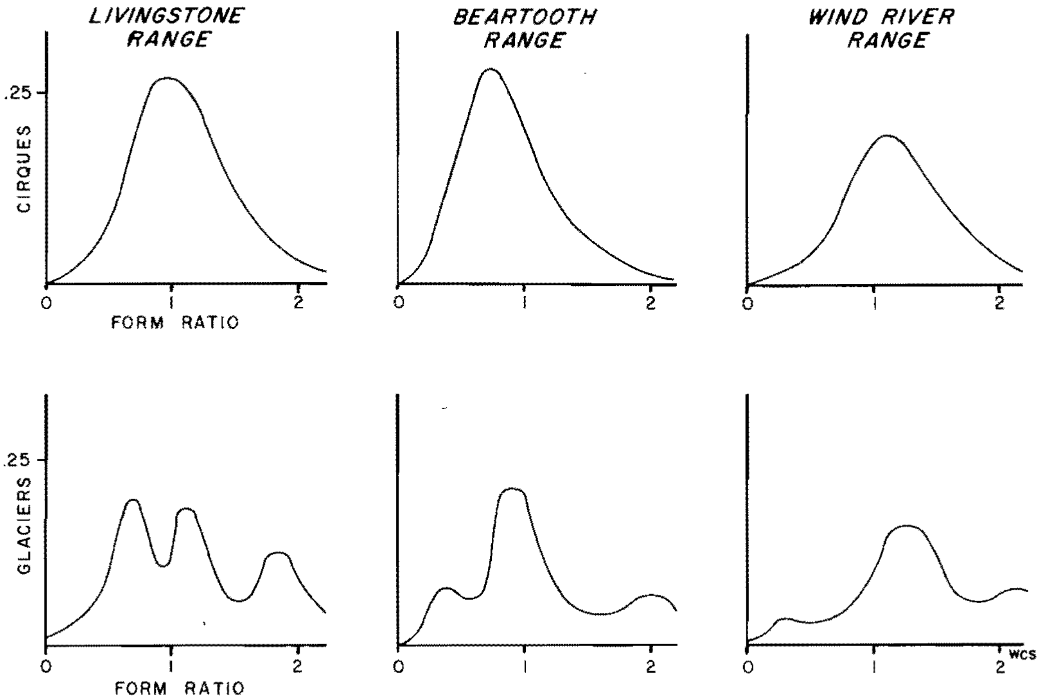

FIGURE 2. Frequency distributions for form ratios of cirques and glaciers in three ranges of the Rocky Mountains. Form ratio = length/width; original class intervals were 0.1.

rounding basin, the body of ice will approximate the ratio of its host cirque. Thus, in any one range, a comparison of the frequency distributions of form ratios shows two examples of glacier-form control by cirque morphology, though in each case there are examples where long, relatively narrow glaciers occupy gullies within the host cirque, resulting in great differences between glacier shape and cirque shape.

Data from the Livingstone, Beartooth, and Wind River ranges were used to assess cirque control of glaciers, because these ranges possess the large numbers of glaciers required for the construction of frequency distributions. Regression analysis, with form ratio (cirque) as the independent variable and form ratio (glacier) as the dependent variable, is not admissible because the data on glacier shapes do not meet the assumptions of normality or homoscedasticity. The frequency distributions (Figure 2) show that, although form ratios for cirques produce normal distributions, ratios for glaciers are trimodal, with one mode at a value less than the mean, one mode near the mean, and a third mode at a value greater than the mean. The central mode represents the form ratios of glaciers that are controlled by their cirques, with cirques and glaciers producing almost identical values. The mode above the mean corresponds to glaciers that flow out of their cirques or that are confined to long, narrow fracture zones eroded into slot-shaped beds. The mode below the mean corresponds to glaciers that are short and wide, shapes dictated by the circular shapes of the cirques in combination with protecting shadows that are effective in only portions of the bowls. In Figure 2, the largest modes in the frequency distributions for form ratios of glaciers correspond to the single modes of the frequency distributions of form ratios for cirques, except for the Livingstone Range where the lowest and central modes are nearly equal. In all cases, the highest mode, representing glaciers uncontrolled by their host cirques, contains the fewest numbers.

These distributions indicate that, under present climatic conditions, glacial systems are strongly controlled by the cirques that surround them. Climate naturally plays a strong role as well but the comparisons of cirque and glacier forms demonstrate the powerful influence that geomorphology exerts in the present state of

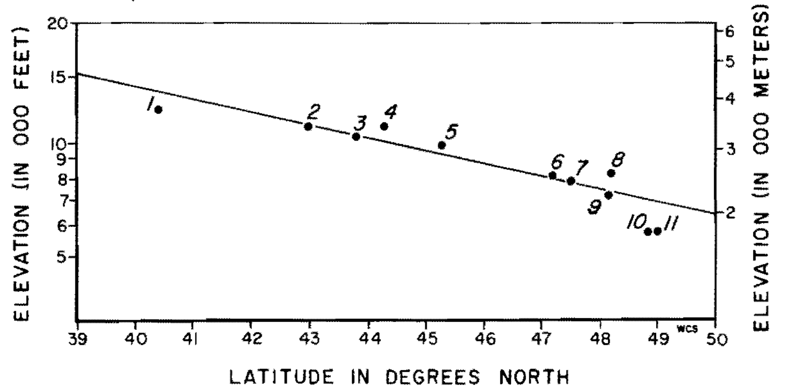

FIGURE 3. Critical elevations in the Rocky Mountains south of United States/Canada border. Regression line is defined by $E_c = e^{(12.6014 - 0.772L)}$, where E_c = critical elevation, e = base of natural logarithm system, L = latitude. Mountain ranges are identified by number: (1) Front Range; (2) Wind River Range; (3) Teton Range; (4) Big Horn Mountains; (5) Beartooth Range; (6) Mission Range; (7) Swan Range; (8) Flathead Range; (9) Cabinet Range; (10) Lewis Range; (11) Livingstone Range.

the glacial cycle. Shape demonstrates the general role of control by cirques, but we must turn to cirque environment (surrounding landforms), aspect and morphology for an explanation of why glaciers occupy some locations and not others.

THE CIRQUE ENVIRONMENT

The four major factors to be analyzed concerning the geomorphic environment of cirques are altitude, forms on the cirque rim, nearby plateau surfaces, and cirque aspect.

ALTITUDE

The lowest equilibrium line altitude (ELA) in each mountain range provides an important limiting value, because above the ELA, climatic conditions are suitable for the maintenance of glaciers with exact glacial locations determined by geomorphology. The ELA for the lowest glacier in each range was approximated by the contour dividing accumulation from ablation areas such that accumulation areas were twice the size of the ablation areas (Miller *et al.*, 1975), which in most cases corresponded to the mean altitude of the glacier. This average value was used based on analyses by Porter (1970) rather than specific measurements of actual ELA values, which fluctuate considerably from one year to the next. Figure 3 shows that latitude explains 84% of the variation in lowest ELA values, which has a log-normal distribution. Residuals are largely the products of continentality (Beartooth and Big Horn ranges) or of domination by cold air masses (Lewis and Livingstone ranges). Above the lowest ELA, glaciers are distributed in the vertical dimension in proportion to the amount of available landscape; they do not become more numerous with increasing altitude.

THE CIRQUE RIM AND SURROUNDING LANDFORMS

A cirque is normally thought of as an armchair-shaped bowl (Flint, 1971), or as a single landform with well-defined landform characteristics (Embleton and King, 1968; Andrews and Dugdale, 1971; Evans and Cox, 1974), but in the Rocky Mountains, cirque rims include secondary landforms, especially passes and peaks. Derbyshire (1968) recognized that surrounding landforms influence glacier formation, and field experience in the Front Range, Beartooth Range, and Glacier National Park indicates that the arrangement of landforms along the cirque rim has a substantial effect on whether or not the cirque contains a glacier. A pass upwind, or on the western edge of the cirque, funnels snow-bearing winds into the cirque, increasing snow accumulation. Drifting snow is channeled into the cirque by the windward pass. A peak on the southern edge casts afternoon shadows into the cirque, protecting snow and ice from ablation under direct sunlight in the warmest part of the day. Peaks and passes are defined for analytic purposes as topographic highs or lows that have relief of 100 m with 2.5 km^2.

TABLE 2

Near-cirque landforms[a]

Cirque status	No pass upwind	Pass upwind, no peak to south	Pass upwind, peak to south	Total
Glacierized	24	6	40	70
Empty	47	8	17	72
Total	71	14	57	142

[a]Chi-square test statistic equal 216.8, significant at 0.001.

A statistical test of landform assemblages in Glacier National Park substantiates the field observations on which the foregoing comments are based. A matrix with rows for glacier-bearing cirques and empty cirques, and columns denoting no pass upwind, pass upwind without a southerly peak, and pass with peak was constructed for the Livingstone and Lewis ranges of Montana. A chi-square test of cell frequencies shows that cirques with glaciers have, significantly more often than empty cirques, a pass upwind and a shielding peak (Table 2). The confidence level of 0.001 indicates that any theory concerning cirques as glacier locations must take into account surrounding landforms.

PLATEAU SURFACES

Plateau surfaces (areas greater than 0.5 km^2 with less than 50 m relief) might be expected to act as temporary storage areas from which fallen snow may be blown into nearby cirques (Martinelli, 1965, 1973, discussed drifting snow on alpine plateau surfaces). Winter field observations in the Southern Rocky Mountains and chi-square tests for glacierized and empty cirques with and without plateau surfaces upwind suggest that the process does not normally occur here because snow does not collect on the plateau surfaces. Even during heavy snowstorms, these surfaces are bare, although most of the rest of the alpine terrain may be deeply covered. Only major surface irregularities are associated with snow deposition on plateaus, surfaces which appear to be of little importance in determining glacier locations.

CIRQUE ASPECT

Previous studies in other regions have demonstrated a strong preferential aspect for cirques, which is to northeast in the Northern Hemisphere (Gilbert, 1904; Lewis, 1938; King and Gage, 1961). Although more cirques in the Rocky Mountains face this quadrant than any other, numerous cirques may be found facing any quadrant. The situation differs from that of Labrador, Britain, and parts of Scandinavia, where preferential orientation is strongly developed (Andrews, 1965; Temple, 1965; Groom, 1958). Figure 4 shows the aspects of 240 randomly selected cirques, 30 from each of eight mountain ranges in the Rocky Mountain chain. Aspect was measured as degrees east of true north with the long axis of the cirque as an indicator. Cirques were selected as follows: (1) map quadrangles covering the mountain unit under study were assigned sequential numbers, (2) a random number was drawn to select a quadrangle, (3) random coordinates were drawn to identify a point in the quadrangle, (4) the landform closest to that point meeting the definition of cirque was sampled (Evans and Cox, 1974), and (5) the procedure was repeated beginning with the second step.

The geologic structure of any given mountain range has some influence on cirque aspect, as shown by Unwin (1973) for areas in Wales. The crest line of the Lewis Range trends northwest-southeast, so that most cirques of the range are oriented away from the crest line, and in opposing directions.

Figure 4 also shows glacier aspects and gradients on Schmidt nets for the same eight ranges considered previously. All the ranges show a similar point dispersion for glacier distribution: a few glaciers with a variety of gradients (some very steep) in the northwest to north sector, a majority of glaciers in the north to east sector with a variety of gradients, and a diminishing number of glaciers south of east with increasingly gentle gradients. This arrangement seems to be a response to insolation. Insolation does not strongly affect northwest- to east-facing glaciers, but those facing south of east must have gentle gradients in order to minimize the effect of exposure: steeply sloping glaciers would absorb great amounts of energy (Sellers, 1965; Geiger, 1966). Prevailing winter winds from the west or northwest combined with shade effects reinforce the insolation effect.

Maximum gradients decrease in a regular linear fashion as successive aspects are considered clockwise from west, a relationship that may be described by

$$g_m = A - Ba \qquad (1)$$

where g_m = maximum glacier gradient, a = aspect measured as degrees clockwise from west, and A and B are constants. West aspect is a convenient starting place because no glaciers in the Rocky Mountains face west, and because in all ranges maximum gradients are greatest for glaciers facing the northwest. Table 3 shows the results of least-squares solutions for equation (1) for each of the mountain ranges in Figure 4, revealing some regional variation in the parameters of the function. Except for the Lewis and Front ranges, the function provided a reliable model of the relationship between aspect and minimum gradient. In the Beartooth and Big Horn ranges, maximum glacier gradients are especially sensitive to aspect (as indicated by relatively large values for the coefficient B), apparently as a reflection of marginal glacial conditions associated with continental locations. The other mountain ranges have functions with remarkably similar coefficients.

CIRQUE MORPHOLOGY

Cirque morphology and its role in determining the suitability of a cirque for glacial occupancy may be analyzed from four perspectives: size, length/width ratio, length/height ratio, and profile.

Cirque Size

Cirque size is the most important factor in determining whether or not the cirque is glacierized. Cirque width, taken as the maximum distance from rim to rim, and cirque height, taken

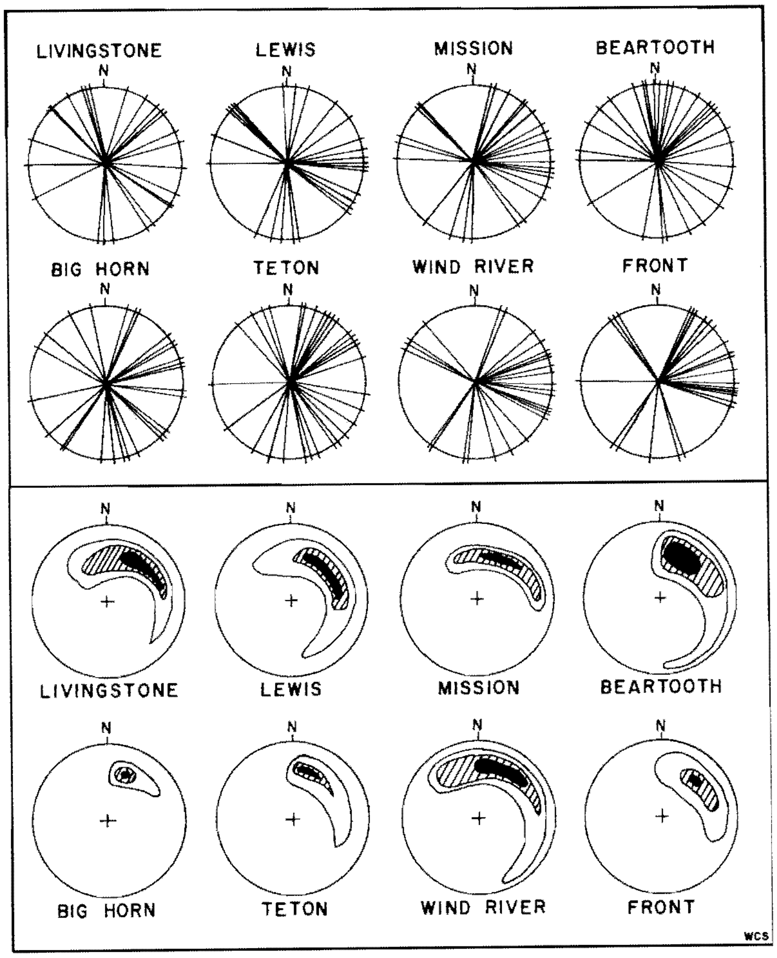

Figure 4. Above: orientations of 30 randomly selected cirques from each of eight mountain ranges in the Rocky Mountains. Below: gradients and orientations of all glaciers from the same eight ranges plotted on the southern hemisphere of Schmidt Net Diagrams. Density of vector impact points shown by shading.

TABLE 3

Regression analysis for maximum gradient vs. aspect

Range	A	B	r	Sign.[a]
Livingstone	47.6885	−0.0943	−0.8388	0.01
Lewis	16.8682	+0.0786	+0.1177	NS
Mission	58.8658	−0.1877	−0.9295	0.01
Beartooth	103.1696	−0.3363	−0.9584	0.01
Teton	54.4840	−0.1197	−0.6815	0.01
Big Horn	76.0951	−0.3935	−0.8355	0.01
Wind River	50.2557	−0.1337	−0.9407	0.01
Front Range	39.4980	−0.1062	−0.4012	NS

[a]Sign. = level of significance; N.S. = not significant.

TABLE 4

Cirque widths[a]

	Glacierized cirques			Empty cirques			Analysis of variance		
Mountain unit	N_1	$\overline{X}_1$	σ_1	N_2	$\overline{X}_2$	σ_2	df	t	Sign.
Livingstone Range	41	1280	597	30	958	304	70	3.628	0.0005
Lewis Range	70	1459	466	30	1103	415	98	3.162	0.005
Mission Range	6	848	165	30	689	398	34	1.394	0.1
Beartooth Range	71	1012	418	30	869	370	99	1.691	0.05
Big Horn Range	9	880	241	30	725	198	37	1.671	0.1
Teton Range	12	833	276	30	917	322	40	0.824	0.25
Wind River Range	64	809	350	30	471	153	92	6.479	0.0005
Front Range	23	743	252	30	693	264	51	0.712	0.25

[a]N = number of observations; $\overline{X}$ = sample mean in m; σ = standard deviation in m; df = degrees of freedom; t = Student's t, a test statistic; Sign. = level of significance, one-tailed test.

as the vertical distance from the floor of the cirque to the top of the headwall, are the most important parameters of size: wide cirques were previously occupied by large glaciers most likely to leave remnant ice bodies, and high walls protect fallen snow and ice from solar insolation.

Measurements of cirque width and height have been made for each glacier-bearing cirque in eight mountain ranges and, for comparison, of 30 randomly selected cirques without glaciers from each of the same ranges. The comparison of measurements between the 295 glacierized and 240 empty cirques was performed on a range-by-range basis, in order to minimize variation resulting from geology, climate, and relief. Mean cirque widths range from 300 m (1500 feet) to 1600 m (4800 feet), with glacierized cirques averaging about 160 m (480 feet) larger than empty cirques in the same mountain range. Analyses of variance show that, in six of the eight ranges, glacierized cirques are larger than empty cirques, and that in four of these six ranges the difference is significant at the 0.05 level or better (Table 4). The difference is significant in the Big Horn Range at the 0.10 level, and in the Mission Range (with only six glaciers) the sample size was too small to produce meaningful conclusions. The Teton Range exhibits a very small difference, because the suitability of cirques in that range as glacier locations is strongly determined by surrounding landforms and aspect: rapid uplift, intensive glacial erosion, and extremely steep energy gradients make the Teton Range a special case of cirque width (and of most other cirque variables).

Of all the variables tested, cirque height gives the most consistent and convincing results (Table 5). Mean cirque height ranged from 220 m (660 feet) to 600 m (1800 feet) with glacierized cirques averaging as much as 300 m (900 feet) higher than empty cirques nearby. In every range except one, cirque headwalls were significantly higher in glacierized cirques than in empty ones. In five of the seven ranges the level of significance is 0.005, and in the other two 0.05. The Beartooth Range displays a similar though statistically nonsignificant relationship.

These results, remarkably consistent from one range to another, considering the diverse geologies and degrees of glacial dissection of the ranges, indicate that cirque width and particularly cirque height are important factors in determining glacier locations: the wider and deeper the cirque, the more likely it is to contain a glacier.

Planimetric Shape

The planimetric shapes of cirques may be described quantitatively by the length/width ratio. Width is defined as before, while length is measured as the horizontal distance from the center of the lip or sill to the farthest point on the cirque rim. This shape parameter has been used extensively in geomorphology for stream channels (Lane, 1937), for glacial valleys (Graf, 1970), and for cirques (Andrews and Dugdale, 1971). Cirques with a high length/width ratio are long and narrow, while those with a low ratio are short and wide. A ratio of unity indicates an equidimensional cirque.

There is no common significant trend in the length/width ratio among the eight mountain ranges except for the Teton Mountains and the Lewis Range; the total of 535 glacierized or empty cirques displays an almost constant planimetric shape throughout, with the length/width ratio very close to one, indicating that, despite varying degrees of glacial dissection and characteristics of geology, cirques tend toward a common shape of approximately equal length and width (Table 6).

Two ranges display significant differences in planimetric shape between glacierized and empty cirques. In the Lewis Range, cirques with glaciers have smaller length/width ratios than those without glaciers, indicating that, in this mountain unit, short, wide cirques are more favorable for glacier formation than are long, narrow cirques, probably because in this area of high precipitation, the former type traps more windborne snow than does the latter. The Teton

TABLE 5

Cirque heights[a]

	Glacierized cirques			Empty cirques			Analysis of variance		
Mountain unit	N_1	$\overline{X}_1$	σ_1	N_2	$\overline{X}_2$	σ_2	df	t	Sign.
Livingstone Range	41	574	194	30	200	78	69	14.103	0.0005
Lewis Range	70	532	238	30	240	107	98	6.267	0.0005
Mission Range	6	398	95	30	286	125	34	2.308	0.025
Beartooth Range	71	343	128	30	321	108	99	0.843	0.25
Big Horn Range	9	486	144	30	236	98	37	4.632	0.0005
Teton Range	12	428	190	30	262	112	40	2.758	0.005
Wind River Range	64	326	122	30	227	106	92	3.987	0.0005
Front Range	23	276	98	30	229	98	51	1.681	0.05

[a]N = number of observations; $\overline{X}$ = sample mean in m; σ = standard deviation in m; df = degrees of freedom; t = Student's t, a test statistic; Sign. = level of significance, one-tailed test.

TABLE 6

Cirque length/width ratios[a]

	Glacierized cirques			Empty cirques			Analysis of variance		
Mountain unit	N_1	$\overline{X}_1$	σ_1	N_2	$\overline{X}_2$	σ_2	df	t	Sign.
Livingstone Range	41	0.958	0.408	30	1.026	0.440	69	0.774	0.25
Lewis Range	70	0.701	0.355	30	1.034	0.430	98	3.505	0.0005
Mission Range	6	0.978	0.661	30	1.019	0.368	34	0.135	NS
Beartooth Range	71	0.894	0.398	30	0.806	0.400	99	0.103	NS
Big Horn Range	9	0.939	0.309	30	1.084	0.371	37	1.160	0.25
Teton Range	12	1.078	0.378	30	0.771	0.552	40	2.046	0.025
Wind River Range	64	1.328	0.568	30	1.243	0.459	92	0.772	0.25
Front Range	23	0.904	0.319	30	1.015	0.477	51	1.057	0.25

[a]N = number of observations; $\overline{X}$ = sample mean; σ = standard deviation; df = degress of freedom; t = Student's t, a test statistic; Sign. = level of significance, one tailed test. (NS = not significant.)

Mountains, with glaciers occupying long, narrow cirques, again present a special case. In this range, long, narrow cirques tend to be deep, with high surrounding walls. Although two other ranges show similar but nonsignificant trends, the difference between cirque samples is extremely small. In general, it could be that short, wide cirques favor glaciers, but the evidence so far is statistically inconclusive.

Gradient

Another shape parameter, length/height (both as defined previously), expresses the shape of the cirque in vertical section. Manley (1959) claimed that a well-developed cirque exhibits a length/height ratio of 2.8 to 3.2, and Embleton and King (1968) demonstrated this for cirques of widely varying sizes. Andrews (1965) found ratios of 2.1 to be common in Labrador, but Embleton and King (1968) suggested that the cirques there are not fully developed. A high ratio indicates a long, shallow cirque, while a low ratio reflects a short cirque with high walls.

As shown in Table 7, the 535 cirques measured in the Rocky Mountains demonstrate a high degree of systematic variability in the length/height ratio, but the mean values (which vary from 1.7 to 5.07 with most values from 2.5 to 3.3) for each range fall within the limits suggested by Manley (1959). These values show that cirques develop toward an optimum vertical shape, despite wide variation in climatic, geomorphic, and geologic environments. The total population of cirques consists of two different subpopulations: glacier-bearing cirques and empty cirques. In every mountain range tested, the length/height ratio is smaller (usually by a factor of 0.9) for glacierized cirques than for empty cirques, indicating that the former, with their high walls and short lengths, are the most favorable glacier locations. Certainly, at least some of the variation in length/height ratios and its resulting influence on the presence or absence of glaciers are the result of variations in cirque height as described earlier. Steep walls add snow by avalanching and cast large protecting shadows, while the deep cirque with short length forms an effective trap for snow. The length/height ratio is second in importance only to cirque height; it should be included in any theory of glacier location.

Cirque Profile

The importance of the vertical morphology of cirques in controlling glacial systems is illustrated by their height and by their length/height ratio, but these parameters do not describe the forms of the cirque walls. Mathematical formulas have been successfully used to simulate slopes in general (Scheidegger, 1970) and glacial valleys in particular (Svensson, 1959; Haynes, 1968; Graf, 1970; Doornkamp and King, 1971), but they have not been used previously to analyze cirque walls. Cirque morphology has been analyzed in general terms by Harker (1901), Cowper-Reed (1906), Hoppe (1959), and Linton (1959). Fourier analysis (Horton *et al.*, 1962) and polynomial equations (Doornkamp and King, 1971) are useful for some slopes, but the cirque form does not lend itself well to definition in terms of waves. Because the profile begins with a very flat slope just behind the lip of the cirque and becomes progressively steeper, an exponential form,

$$Y = e^{(a + b X)}, \qquad (2)$$

where Y = vertical distance, X = horizontal distance, A and B are constants, and e = base of the natural logarithm system, seems appropriate.

Table 7

Cirque length/height ratios[a]

	Glacierized cirques			Empty cirques			Analysis of variance		
Mountain unit	N_1	$\overline{X}_1$	σ_1	N_2	$\overline{X}_2$	σ_2	df	t	Sign.
Livingstone Range	41	2.025	0.899	30	4.753	0.585	69	8.800	0.0005
Lewis Range	70	1.882	0.687	30	5.082	2.831	98	5.936	0.0005
Mission Range	6	2.079	0.457	30	2.873	1.134	34	0.270	0.4
Beartooth Range	71	2.558	1.040	30	2.606	1.101	99	0.208	NS
Big Horn Range	9	1.708	0.444	30	3.440	1.224	37	6.298	0.005
Teton Range	12	2.250	0.950	30	3.290	1.590	40	2.600	0.01
Wind River Range	64	3.199	1.533	30	3.217	2.203	92	0.039	NS
Front Range	23	2.406	0.558	30	3.353	1.700	51	2.796	0.005

[a]N = number of observations; $\overline{X}$ = sample mean; σ = standard deviation; df = degrees of freedom; t = Student's t, a test statistic; Sign. = level of significance, one-tailed test. (NS = not significant.)

It results in a curve that becomes progressively steeper, as the cirque wall does, but the real profile has a much sharper break betweeen cirque floor and headwall than would be indicated by the exponential model. Battey (1960) noted that joint patterns influence cirque morphology, a circumstance which may explain the steep and straight characteristics of headwalls if erosion proceeds along lines of weakness. The distinctive influence of geologic structure on cirque morphology has been conclusively demonstrated by several workers (Thompson, 1950; Haynes, 1968; Unwin, 1973). The combined profile of the straight, steep slope of the headwall, the circular segment at the foot of the headwall, and the shallow floor leading to the lip, can be most effectively modelled by a power function:

$$Y = a\ X^b. \quad (3)$$

This form has been used in the past to model glacial valley walls, where the exponent b ranges from 1.5 to 2.0, indicating a parabola (Svensson, 1959; Graf, 1970). Increasing values of b indicate steepening headwalls and increasingly sharp breaks in slope at their bases (Figure 5).

The power function may also be expressed in linear form as

$$\log_e Y = (\log_e a) + b\ (\log_e X), \quad (4)$$

where b may be calculated by least squares. Ten pairs of X and Y values were obtained for the present study from each of the 535 test cirques discussed above, and a regression was calculated for each cirque using equation (3). The mean correlation coefficient was +0.995, indicating that the power function is an excellent model of the cirque profile from headwall to lip. The exponent values (b) range from 2.0 (parabola) to 3.0 (cubic parabola), indicating that the walls are more sharply curved than those in glacial valleys, an apparent result of intensified erosion at the slope base by the circular motion of cirque glaciers (McCall, 1960).

In five of the eight ranges tested, the b value

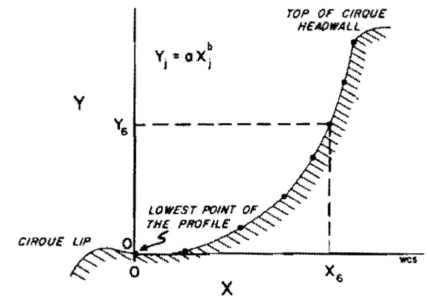

FIGURE 5. The conversion of the cirque profile into a power function, which describes the profile from its lowest point behind the lip to the top of the cirque headwall. The constants of the equation can be determined by standard regression techniques using paired X_i and Y_i values from points along the profile.

of the profile regression model is larger in glacierized cirques than in empty ones, and this relationship is significant in four of the five cases (Table 8). Steep walls contribute avalanched snow and protecting shadows, while the inflection in the curve of the profile, once created by glacial erosion, tends to perpetuate glacial systems by operating as a snow trap. In three other ranges an opposite trend appears, apparently because the profile effect is overridden by other factors. Again, the Teton Range falls outside the majority category. The major difference between ranges with b values higher for glacierized cirques than for empty ones is that ranges where cirque profile has an important effect on the location of glaciers are in areas of marginal glacial conditions. The Lewis, Beartooth, and Big Horn ranges are east of the main spine of the Rocky Mountains as indicated by the Continental Divide, and are remote from the moisture-bearing Pacific air masses. The Front Range is in a marginal location because of its southern location. Apparently in other ranges, more favorable glacial conditions and the effects of other variables of cirque morphology submerge the effect of cirque profile.

CONCLUSIONS

The forms of glaciers in the Rocky Mountains are controlled by the forms of host cirques, except in those few cases where ice flows out of the cirques or where the original glacier has wasted to a mere remnant. Glaciers that remain active under present climatic conditions do so because they occupy cirque locations that are especially suited to the capture and preservation of snow and ice.

Data presented in this paper (and summarized in Table 9) provide a foundation for a theory of glacier location which outlines an optimum glacier location that is most likely to contain a glacier. Although exceptions may be found to the general concept, it applies to a large majority of cases in the Rocky Mountains. The optimum glacier location is a northeast-facing cirque with a pass on the windward edge and a peak on the southern edge. On average, cirques with glaciers are wider and deeper than empty cirques, are

TABLE 8

Exponent values of power function models for cirque profiles

	Glacierized cirques			Empty cirques			Analysis of variance		
Mountain unit	N_1	$\overline{X}_1$	σ_1	N_2	$\overline{X}_2$	σ_2	df	t	Sign.
Livingstone Range	41	2.454	1.200	30	2.950	1.440	69	1.666	0.05
Lewis Range	70	3.260	1.910	30	2.158	2.015	98	2.267	0.01
Mission Range	6	2.289	0.743	30	2.653	1.011	34	1.000	0.25
Beartooth Range	71	2.318	1.154	30	1.999	0.713	99	2.285	0.005
Big Horn Range	9	3.403	1.541	30	2.460	0.960	37	1.553	0.1
Teton Range	12	1.744	0.512	30	2.446	1.522	40	2.333	0.025
Wind River Range	64	2.704	1.553	30	2.867	1.801	92	0.421	NS
Front Range	23	3.525	1.572	30	2.899	1.579	51	1.391	0.1

[a]N = number of observations; $\overline{X}$ = sample mean; σ = standard deviation; df = degrees of freedom; t = Student's t, a test statistic; Sign. = level of significance, one-tailed test. (NS = not significant.)

TABLE 9

Summary of analysis of variance tests comparing glacierized and empty cirques

Mountain unit	Width	Height	Length/width	Length/height	*b* value
Livingstone Range	L*	L*	S*	S*	S*
Lewis Range	L*	L*	S*	S*	L*
Mission Range	S*	L*	S	S	L
Beartooth Range	L*	L	L	S	L
Big Horn Range	L*	L*	S	S*	L*
Teton Range	S	L*	L*	S*	S*
Wind River Range	L*	L*	L	S	S
Front Range	L	L*	S	S*	L*

[a]L indicates that the mean value of the variable is larger for glacierized cirques than empty cirques; S indicates that the mean value of the variable is smaller for glacierized cirques than for empty cirques; * indicates that the difference of means is significant at the .011 level or better. See text for explanation of *b* value.

wider than they are long, have low length/height ratios, and, in marginal glacial climate areas, they have profiles with power functions with exponents (near 3.0) that are greater than those for nearby empty cirques.

The data also indicate that there is a marked regional variation in the size parameters describing cirque morphology. Generally, mean values for cirque width and depth are greater in the northern ranges of the Rocky Mountains, which may be contrasted with the shape parameters that seem to converge on common values throughout the entire region. For example, length/width ratios are very close to unity throughout the study area, and length/height ratios exhibit little variation from one range to the next. The mean values of cirque parameters in the Teton Range were frequently anomolous when compared with other ranges, perhaps as a result of their rapid uplift in recent times which produced steep gradients for the glaciers.

The existing glaciers in the Rocky Mountains are products of a geomorphic feedback process, wherein the cirque forms depend on glacial erosion while the existence of the glacier as a viable system is partially dependent on the development of cirque geomorphology.

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