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NATURE AND DISTRIBUTION OF GLACIERS, NEOGLACIAL MORAINES, AND ROCK GLACIERS, EAST-CENTRAL BROOKS RANGE, ALASKA

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ABSTRACT

The east-central Brooks Range was just high enough to support cirque glacierization during the middle to late Holocene; presently glaciers are shrinking. The 133 glaciers in the field area are all above 1500 m altitude, and those fronted by stable moraines occur on a trend surface rising from 1600 m south of the Continental Divide to 2000 m, 25 km farther to the north. Glaciers that extend into unstable ice-cored rock glacier deposits occur on a parallel trend 100 m below. Both trend surfaces reflect depletion of moisture derived predominantly from southerly sources. Ice masses associated with both stable and unstable deposits have similar orientations significantly concentrated (asymmetric) about 012°, strongly minimizing exposure to insolation. This contrasts markedly with the symmetric orientation of Pleistocene glaciers. The transition from existing glaciers through tongue-shaped to lobate rock glaciers is characterized by increasingly symmetric orientations and expanding altitudinal and areal distributions. For example, lobate rock glaciers are weakly asymmetric indicating decreased climatic sensitivity and increased screening by surrounding terrain relative to the other forms.

INTRODUCTION

The cirques and high mountain slopes of the Brooks Range, Alaska, in common with many other alpine glacial areas, display an assemblage of cirque glaciers with their associated moraines as well as prominent tongue- and lobate-shaped rock glaciers. Richmond (1962) in the La Sal Mountains of Utah and Madole (1972) in the Front Range of Colorado applied the stratigraphic facies concept to these features, with Madole emphasizing their transitional nature and gradational altitudinal distribution. The purpose of this study is to describe and analyze the spatial as well as directional characteristics of these surficial forms in an arctic/alpine environment. Analysis of their distribution patterns is an important initial step toward deciphering the glacial and climatic histories of this region, as well as the present glacial and periglacial regime. This study should also provide the basis for prediction of probable responses of ice masses and slope deposits to future regional and world-wide climatic changes. The research is part of an overall study of the past and present hydrologic regimes in the east-central Brooks Range.

The study area includes 4000 km^2 centered around Atigun Pass where the Trans-Alaska Pipeline System (TAPS) and haul road cross the east-west trending Continental Divide

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(Figure 1). At least 133 exposed glaciers lie within this rugged glaciated area where relief ranges between 1000 and 1200 m with peaks rising 2300 m. The area is underlain by a section of marine and nonmarine sedimentary rocks of Late Devonian through Permian age which are deformed by deep-seated thrust faults and large, steeply dipping folds overturned toward the north (Gates and Gyrc, 1963; Brosgé et al., 1979). The Divide and higher peaks in the region immediately to the north are composed of resistant Kanayut Formation conglomerates and sandstones. Less resistant, phyllitic Hunt Fork Shale dominates south of the Divide. The northernmost portion of the central Brooks Range is made up of a thick sequence of crystalline limestone of the Lisburne Formation.

The Continental Divide appears to correlate with a transition zone between the continental climate of Alaska's interior and the North Slope's arctic regime (Berg et al., 1978). The field area is within the zone of continuous permafrost (Ferrians, 1965; Péwé, 1975) and is both above and north of the spruce treeline. U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) temperature reports along the TAPS corridor indicate the mean annual temperature of Atigun Pass at 1440 m altitude (a.s.l.) is about −12°C with a freezing-index of 4800 degree days and thawing-index of only about 400 degree days. This is 5°C lower than that recorded on the southern flank of the range, reflecting the decrease in temperature with increase in latitude and elevation (Berg et al.,

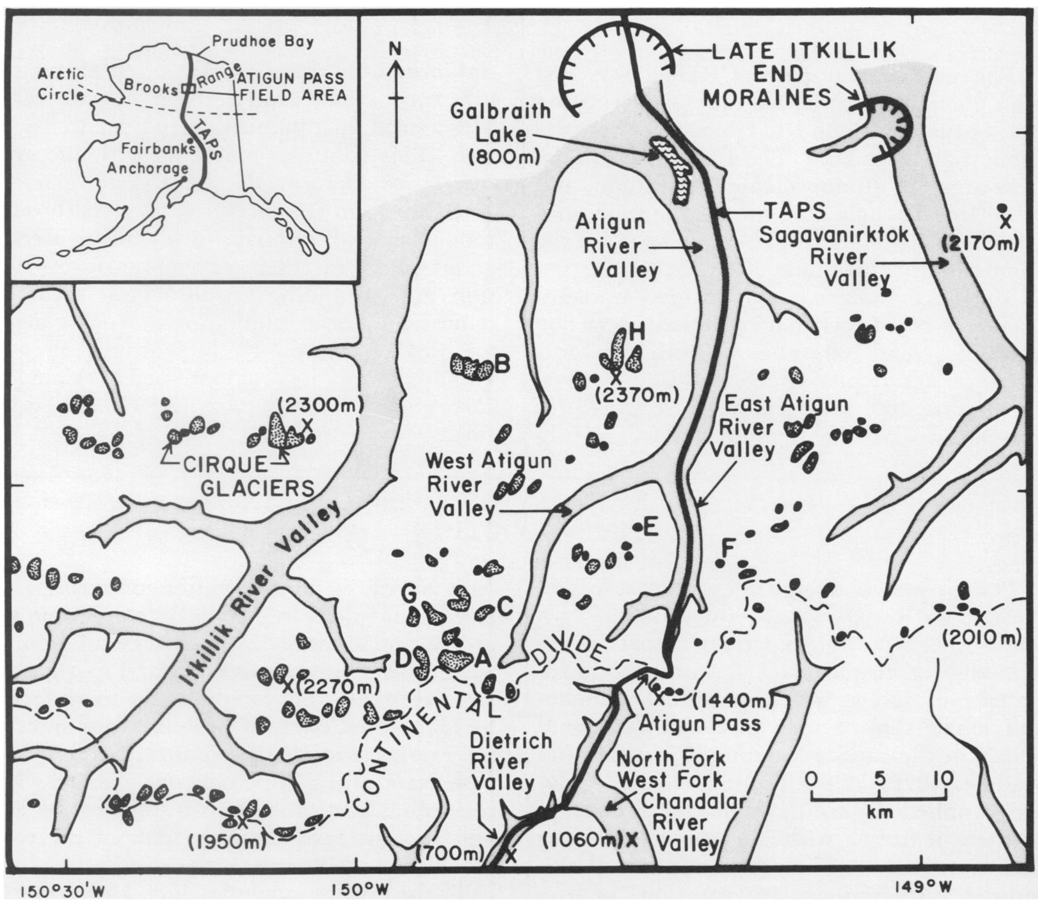

FIGURE 1. Atigun Pass field area showing present glaciers with major river valleys. Letters a-h refer to glaciers shown on Figure 4. Area west of Itkillik River studied with 1:63,360 USGS topographic sheets only for glacier aspect and mean elevation.

1978). Precipitation also decreases with latitude across the Brooks Range (Péwé, 1975). Extrapolation of CRREL data, glacier snowpit studies (Ellis and Calkin, 1978), and records from Anaktuvuk Pass 94 km to the west (Porter, 1966) suggest that annual precipitation approximates 40 g cm^{-2} (~50% snow) at Atigun Pass. Temperatures above freezing are attained in May through September, but low insolation during the rest of the year permits temperatures to reach below -45°C during the winter.

Prior to our study, glacial and geomorphic field work at the valley heads in the study area had largely been confined to general engineering mapping along the TAPS corridor (Ferrians, 1971; Kachadoorian, 1971), more detailed but yet unpublished slope hazard and surficial stratigraphic studies by the Alyeska Pipeline Company, and surficial geologic mapping (scale 1:250,000) by the U. S. Geological Survey (Hamilton, 1978a, 1978b). However, preliminary studies of the type we discuss have been undertaken by Porter (1966) in the Anaktuvuk Pass area. Porter showed that the mean glacier-elevation trend surface rises northward and attributed this to orographic control on the movement of precipitation-producing, moist air masses originating to the south and west. However, considerably more information can be extracted from cirque glacier altitudinal distribution if the deposits immediately downslope are also analyzed.

Data were gathered during field studies over more than 500 km^2 during the summers of 1977 and 1978. This area was extended to include 3200 km^2 by analysis of U. S. Geological Survey 1:80,000 aerial photographs (Series GS-VCIK, Aug. 1970) complemented by Chandalar Lake and Philip Smith Mountains 1:63,360 topographic quadrangle sheets. Glacier aspect and mean elevations were recorded over an additional 800 km^2 from the topographic sheets only (Figure 1). This overall study area of 4000 km^2 overlaps Porter's (1966, Figure 20a) glacier elevation survey on its western boundary. Field work also included some critical areas in the Anaktuvuk Pass area. To our knowledge, distribution analysis of the type presented here has not been published for any portion of the Brooks Range.

PAST GLACIERIZATION OF THE CENTRAL BROOKS RANGE

The extent of Quaternary glaciers in Alaska has been summarized by Coulter et al. (1965) and Péwé (1975), and details of the central Brooks Range late Cenozoic glaciation and stratigraphy were reviewed more recently by Hamilton and Porter (1975) and Hamilton (1977). The earliest continuous and well-defined drift system in the central Brooks Range extended well beyond the mountain front during early to middle Pleistocene to positions approximately 100 km north and 150 km south of the Continental Divide (Detterman, 1953). The last major Pleistocene event, the Itkillik Glaciation (Detterman, 1953) reached just beyond the mountain front (Detterman et al., 1958; Hamilton and Porter, 1975). Itkillik I moraines represent a maximum ice advance that occurred at least 17,000 and possibly >53,000 ^{14}C years ago (Hamilton, 1979, pers. comm.). The northern terminus of the last and least intense Itkillik event, termed late Itkillik (see Hamilton, 1978a), is represented in Atigun Valley by an arcuate end moraine 45 km north of Atigun Pass near Galbraith Lake (Figure 1). Hamilton (1972) notes that this glacial phase may have taken place about 12,000 ^{14}C years ago, and that much of the upper Sagavanirktok Valley east of Atigun Valley became ice free about 11,800 ^{14}C years ago. Snowline has risen on the order of 600 m from the time of maximum Itkillik advances (Hamilton and Porter, 1975).

Relatively undissected and unvegetated glacial deposits at thresholds of cirques have been referred to the Fan Mountain Glaciation (Detterman et al., 1958). In the cirques near Anaktuvuk Pass, Porter (1964, 1966) recognized two distinct end moraines: one within the cirques designated Fan Mountain II and an outer set, Fan Mountain I, lying within 3 km of the threshold. These are considered to be post-Hypsithermal (Neoglacial) in age (Porter and Denton, 1967) and represent periods of Holocene cooling. However, this climatic change was considerably less marked than that attributed to the Pleistocene. The snowline must have been several hundred meters higher in the Neoglacial, and cirques occupied by glaciers considerably more asymmetric in their distribution than during the Pleistocene as shown by Figure 2.

Our ongoing study of Holocene glacial and periglacial activity in the central Brooks Range utilizes lichenometry (Beschel, 1961; Webber and Andrews, 1973) and related dating methods on the surfaces of moraines and rock glaciers. This work suggests that many of the moraines correlated with the Fan Mountain Glaciation, including type deposits of Porter (1964, 1966) in the Anaktuvuk Pass area, are rock glaciers and/or moraines dating from late Pleistocene to early Holocene time. Furthermore, the Holocene chronology of glacier expansions and retreats is much more complicated than previously envisioned. The oldest Neoglacial moraine yet found has *Rhizocarpon geographicum* s.l. lichen with maximum diameters indicative of cirque glacier expansion more than 3500 years ago (Calkin and Ellis, 1978; Ellis, 1978). At least five expansions are recorded with a major event ending within the last 400 years. In contrast, lobate and tongue-shaped rock glaciers can have upper surfaces near the snouts with maximum lichen diameters indicative of surface stability since early to mid Holocene time. The surficial geology and exceptional lichen diameters immediately downvalley of cirques with Neoglacial deposits suggest a lack of glacier expansion beyond late Holocene limits since retreat of Late Wisconsin valley glaciers.

Under the present climate, the cirque glaciers of the area are wasting away. Temperatures to 6°C during July and August 1977 caused melting and total loss of the previous budget year's snow accumulation ($\sim$25 g cm^{-2}), and an additional loss of 1 to 2 m of ice from a sample of three cirque glacier surfaces studied near Atigun Pass (Ellis and Calkin, 1978). Porter (1966) noted the snowline at Anaktuvuk Pass to be at about 2070 m, well above the shrinking cirque glaciers. This is contrary to the situation suggested by Péwé (1975, Figure 11) in which the modern snowline was depicted as lying across many of the glaciers in the central Brooks Range.

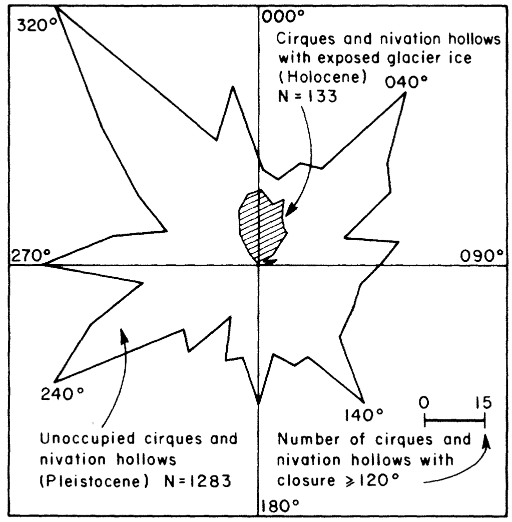

FIGURE 2. Orientation of cirques and nivation hollows in the field area. Basins with glacier ice are labeled as Holocene, those without ice are assumed to have been actively cut only during Pleistocene glaciations.

DESCRIPTION AND DEFINITION OF FEATURES

CIRQUE GLACIERS

The glaciers have a mean length of 750 m, ranging in exposed length from less than 100 m to 2500 m. Areas range up to 2 km^2 (see also U. S. Geological Survey, 1978, unpublished). The mean relief of the cirque glaciers is 220 m, which gives an average glacier surface slope of 17° (Figure 3, Table 1).

Of the 133 mapped glaciers, 102 were evaluated for type of associated deposit by aerial photo interpretation and 17 of these were examined in the field. Some representative glaciers and their deposits are shown in Figure 4. Fifty-five of these glaciers extend downslope into either ice-cored or ice-cemented moraines; 23 into ice-cored looping rock glacier ridges on older, rock glacier deposits; and 19 into ice-cored rock glaciers. The remaining 5 glaciers have no terminal deposits.

MORAINES

In the Atigun Pass area no evidence of Neoglacial drift (morainal *or* rock glacier deposit) has been found without its associated glacier or exposed headward ice core. Similarly, Hamilton (1979, written communication) notes, "I have found Fan Mountain (Neogla-

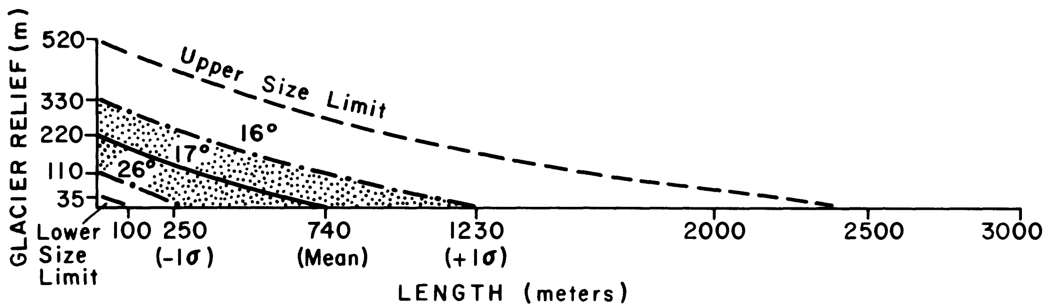

FIGURE 3. Generalized profile of 133 cirque glaciers in the field area showing mean altitude and length with 67% zone of occurrence (± 1 standard deviation [σ]), upper and lower size limits, and slope of glacier surface. See also Table 1.

TABLE 1
Profile dimensions for glaciers with moraines or with rock glacier deposits

		Glacier length		Glacier relief	
Glacier with deposit type	No. of glaciers	Mean (m)	Standard deviation (m)	Mean (m)	Standard deviation (m)
Glaciers with moraines	55	860	460	240	100
Glaciers with ice-cored rock glaciers and transition zone	22	830	540	200	100
Glaciers with ice-cored rock glaciers and no transition zone	19	560	600	180	130
All glaciers	133	740	490	220	110

cial) moraines without glaciers. These cases are fairly rare, and much more commonly the moraines are associated with small ice remnants too small to be shown at 1:250,000 scale." (Hamilton's maps [1978a, 1978b, and in preparation] incorporate the areas around Atigun and Anaktuvuk passes.)

Ice-cored moraines are ridges that contain either buried glacier ice (Goldthwait, 1951), or snowbank ice (Østrem, 1964, 1974). In this environment, the ice cores may persist for thousands of years (Østrem, 1974). Ice-cored moraines are distinguished from rock glaciers in the field by the appearance of their terminal and lateral ridges which show no indication of downvalley movement (Østrem, 1974). Lichenometric work demonstrates the stability of ice-cored and ice-cemented moraines formed in this area during the last 3000 to 4000 years (Calkin and Ellis, 1978; Ellis, 1978), and help to support Barsch's suggestion (1971) that glacier fluctuations are recorded by individual morainal ridges around the glacier snouts.

Photo recognition of ice-cored moraine deposits was based on characteristics observed during our field work, discussed by Østrem (1971) and Whalley (1974), and illustrated in Figures 4a-c. Ice-cored rock glaciers occur where substantial cliffs rise above the glacier, but ice-cored moraines typically form where headwall and sidewalls are low. In addition, ice-cored moraines commonly occur on relatively horizontal to gently sloping terrain that minimizes the potential for postdepositional movement (see Østrem, 1971, Figure 2). Very few glaciers with ice-cored moraines are heavily covered with debris in their ablation areas (Whalley, 1974), and a significant depression is often present between the relatively clean, retreating glacier snout and the morainal ridges. Stable moraines, especially those appearing to be only ice-cemented, tend to occur in more open areas where shading by

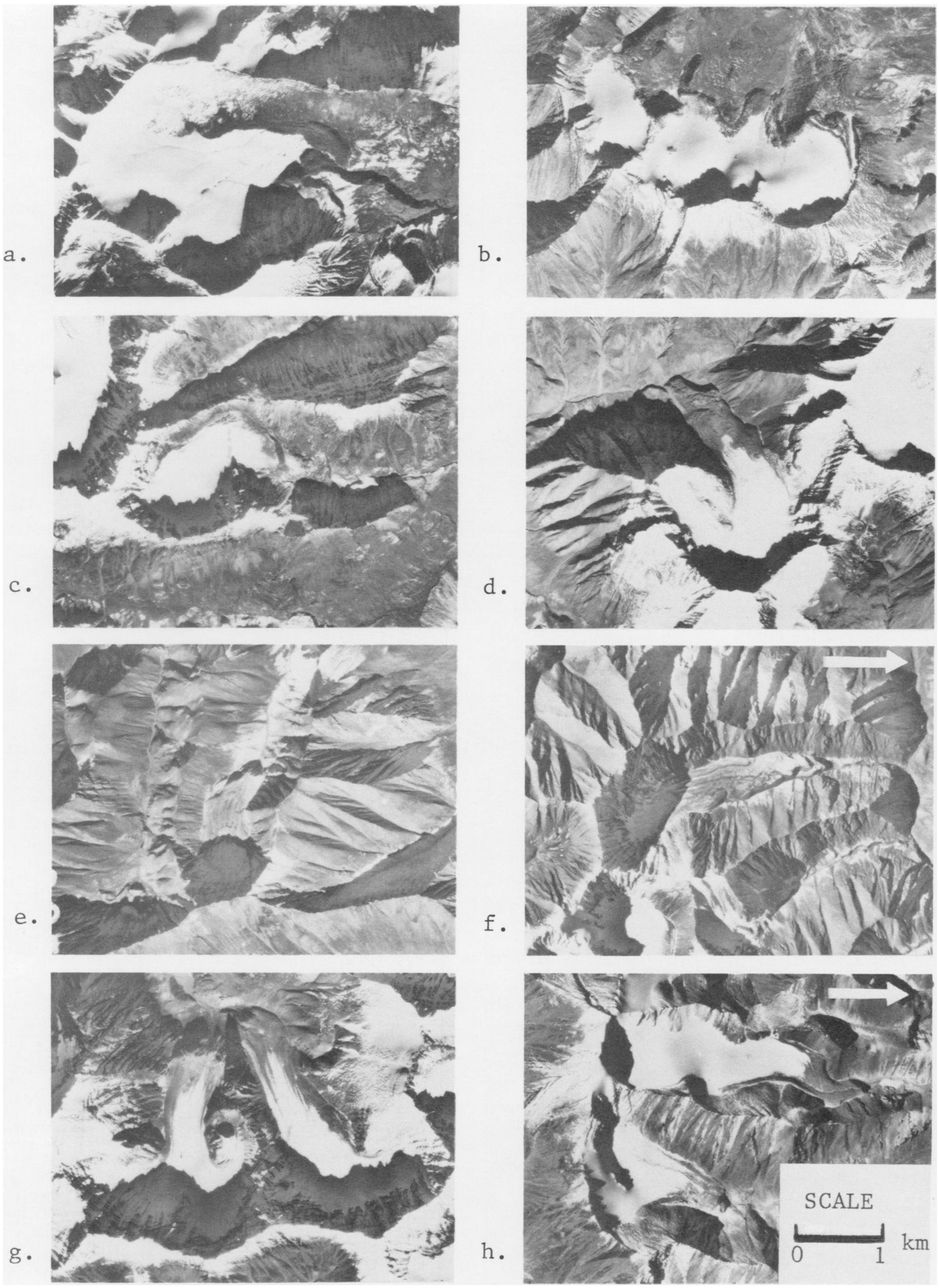
a.
b.
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FIGURE 4. (Facing.) Examples of cirque glaciers from the field area with Neoglacial moraine and rock glacier deposits immediately downslope. North is to the top of the page except where indicated by arrow on f and h. From USGS 1:80,000 GS-VCIK series. Locations of glaciers shown by letters a-h on Figure 1.

Photo	Explanation
a	Buffalo Glacier with ice-cemented ridges up to 700 m from snout.
b	Triple Glacier with ice-cemented morainal ridges on gently-sloping bedrock (see also Holmes and Lewis, 1965, Figure 10, and Reed, 1968, Figure 22 for another example in the Brooks Range).
c	Snow Bunting Glacier fronted by ice-cored moraine. Note steep front 200 m from snout. Immediately downslope is inactive rock glacier derived from early Holocene (?) landslide.
d	Rock glacier complex with ice-cored transitional zone (cresentic ridges) upslope of an older rock glacier surface.
e	Parka Squirrel Glacier. Ice-cored transitional zone (cresentic and transitional ridges) upslope of an older rock glacier surface.
f	Mosquito Glacier. Ice-cored rock glacier with poorly-expressed transitional zone leading into older rock glacier surface (see also Porter, 1966, Plate 21 for another example in the Brooks Range).
g	Ice-cored rock glacier deposits with thick supraglacial debris and longitudinal ridges (see also Detterman et al., 1958, Figure 10 for another example in the Brooks Range).
h	Wolverine Glacier (east cirque) leads into thin rock glacier deposit which is upslope of older rock glacier surfaces. Twin Glacier (west cirque) is longest in field area. Downslope deposit is a thin (<2 m) ice-cored rock glacier. Anomalous deposit form and clean glacier surface would probably lead to aerial photo interpretation as moraine, but field work confirms instability. Ice core extends to the snout of the rock glacier deposit.

surrounding mountain terrain is minimized. Field measurements, similar to those done by Wendler and Ishikawa (1974) in the northeastern Brooks Range, are being carried out to determine the role of direct solar radiation in the localization of morainal deposits. An additional guide to the occurrence of stable moraines is their location close to retreating glacier snouts. Most Neoglacial morainal complexes in the east-central Brooks Range are within 400 m of the glaciers that generated them, and none is more than 800 m distant.

Field work suggests that our previous photo interpretation efforts that did not include all of the above criteria have overestimated the number of stable morainal deposits. The number of glacial deposits interpreted as stable moraines from aerial photographs should also be regarded as a probable maximum, as field work will reveal a few cases where movement is occurring.

TONGUE-SHAPED ROCK GLACIERS

Tongue-shaped rock glaciers were identified by criteria set forth by Wahrhaftig and Cox (1959), Vernon and Hughes (1966), and White (1976). We have used an arbitrary minimum length of 500 m due to aerial photo resolution limitations, except where field evidence was available. A rock glacier was recorded as "inactive" if there was a dark tonal quality on the photo indicating mature lichen growth over the upper surface and front, and/or rounded frontal lobes with no sharp break in slope at the snout (Wahrhaftig and Cox, 1959). Active, partially active or reactivated rock glaciers were classed together as *active*. Active rock glaciers with exposed glacier ice cores (ice-cored) were differentiated from those with no visible ice core.

Active, tongue-shaped rock glaciers can be subdivided into ice-cored and transitional ice-cored varieties. The first type has an ice core covered with supraglacial debris that extends directly into clearly unstable deposits characterized by an extensive series of longitudinal debris ridges (Figures 4g and h). There tends to be only a slight depression between the rock glacier debris cover and ablating, exposed ice core. In one example (Figure 4h), field mapping has verified the existence of a glacier ice core under the entire 900 m length of a rock glacier deposit less than 2 m thick. More typical are active rock glacier tongues in which exposed ice cores are associated with longitudinal debris ridges, and meandering furrows with supraglacial streams. Such active forms have apparently overridden older rock glacier surfaces. This type of rock glacier is classified simply as an *ice-cored rock glacier.*

The second type of active, ice-cored rock glacier tongue is characterized by partially stable, looping ridges immediately downslope of the exposed ice glacier (Figures 4d-f). The ridges override or abut downslope against an older, rock glacier deposit. This type of rock glacier is classified as *transitional ice-cored rock glacier* after Foster and Holmes (1965) who described a similar morphology in the Alaska Range. The cresentic ridges may be comparable to the modern glacial moraines depicted by Wahrhaftig and Cox (1959, Figure 12) that occur between glaciers and rock glacier tongues farther downslope. These ridges have previously been interpreted as either ice-cored moraines or rock glacier deposits (Østrem, 1971; Barsch, 1971), but here are classified as ice-cored rock glacier deposits because of their instability and evidence for downslope movement.

Lichenometric mapping of the transitional ice-cored rock glacier deposits indicates that they are potentially more stable than the longitudinal ridges on ice-cored rock glaciers. However, since both types are more unstable than the true moraines, they are grouped together. Active rock glacier tongues with exposed ice cores attain overall lengths of 2500 m; however, lengths of 1000 m including a transitional zone of about 400 m are more common.

Lobate Rock Glaciers

The characteristics of lobate rock glaciers as defined in this study are summarized by White (1976). They are broader than long downslope, and develop below taluses along valley walls including cirque walls. During aerial photo mapping in cirques, an arbitrary length boundary of 500 m was imposed to differentiate lobate from tongue-shaped rock glaciers. A width boundary of 800 m was used to subdivide lobate rock glaciers lining valley walls (see Wahrhaftig and Cox, 1959).

Some protalus ramparts or lobes (Richmond, 1962; Blagbrough and Breed, 1967) formed by accumulation of debris at the base of snowbanks may have been included in the lobate rock glacier category, although none was recognized in the field. A very small number of tongue-shaped rock glaciers less than 500 m in length also may be included in the lobate classification.

METHODS

Altitudes for exposed glaciers were taken at their mean height, and for lobate and tongue-shaped rock glaciers at the snout crest. The topographic sheets are contoured at 100-ft (30-m) intervals without field checking; elevation accuracy is estimated to average this interval. Aspects (orientation) of glaciers and associated cirque headwalls were measured according to the method of Evans (1977). All orientations, including the short axes of lobate rock glaciers, were recorded to the nearest 10°.

The orientation distributions of the various classes of landforms and glaciers were analyzed and compared to each other by plotting the aspects in cumulative vector form (Evans, 1977). This method of vector statistics was introduced by Evans (1969) for cirque aspect analysis. It derives the vector resultant (mean aspect) by vector summation rather than the conventional rose diagram. This method gives the general trend of a distribution, strength of the mean aspect, and allows comparison numerically with other distributions.

The mean aspect can be determined by either graphical or trigonometrical methods (Evans, 1969, 1977). In this study, aspects are grouped in intervals of 10°, length (K) is proportional to the number of landforms/glaciers facing that aspect (α), and the mean aspect (θ) is given by

$$\theta = \tan\left(\frac{\Sigma\, K \sin \alpha}{\Sigma\, K \cos \alpha}\right) \qquad (1)$$

The length of the vector resultant (R) is obtained from

$$R = [(\Sigma K \sin \alpha)^2 + (\Sigma K \cos \alpha)^2]^{1/2} \qquad (2)$$

The degree of concentration of aspects (strength L) along this vector resultant is obtained by dividing the length of the resultant (R) by the total length of the individual vectors (N). The vector strength (L) may be defined as the degree of asymmetry for the distribution, e.g., the asymmetry tends to be high if the range of aspects about the mean is low. Degree of asymmetry is expressed in the following terms (Evans, 1977):

Vector Strength (L)	Degrees of Asymmetry
80-100%	extremely asymmetric
60-80%	strongly asymmetric
40-60%	markedly asymmetric
20-40%	weakly asymmetric
<20%	symmetric

DISTRIBUTION RESULTS

GLACIER ICE AND ITS DEPOSITS

Seventy percent of the glacierized cirques in the field are localized in the resistant Kanayut Formation conglomerate and 97% of exposed glacier ice is north of the Continental Divide. This pattern of cirque glacierization dominates 100 km east and west of Atigun Pass. It correlates with the occurrence and overall greater elevation of tough Kanayut conglomerates north of the Divide.

Glacier ice has a mean aspect of 012° with an extremely asymmetric strength of 88% (Table 2, Figure 5). There is a strong relationship between mean glacier aspect and associated cirque headwall aspect as might be expected (Evans, 1977). The cirques that are presently occupied by glacier ice have an extremely asymmetric strength of 85% about a mean vector of 008°. This is compared in Figure 2 with the unoccupied cirques and nivation hollows of Pleistocene age, which have a mean vector strength of only 13% about 318°. The glaciers are therefore slightly more asymmetric than the cirques that contain them with both facing northward, minimizing insolation. It appears that cirque aspect may be interpreted essentially in relation to climate via glacier balance (Evans, 1977). The exceptional tendency of the existing glaciers to have aspects that minimize insolation is further enhanced by the steepness of glacier slopes which average nearly 20° (Figure 3). This typical northerly slope reduces direct solar radiation by 5% during the summer ablation season (L. Williams, 1979, pers. comm.).

Two hundred kilometers northeast of Atigun Pass in the eastern Brooks Range, Wendler (1969) showed that northern slopes are more glacierized (66%) than south-facing slopes (15%). Evans (1977) reports this area as having 188 glaciers with a vector mean of 008° and a strength of 59%. The reduced vector strength of Wendler's area relative to that around Atigun Pass is partly due to the higher mountain elevations there (with peaks to 2760 m), greater degree of glacierization, and the different method used to gather aspect data (Wendler, 1969).

Altitude will differentiate between those glaciers depositing moraines and those forming ice-cored rock glaciers (Table 3), while aspect will not (Figure 5). Glaciers fronted by morainal ridges have a mean altitude of 1820 ± 90 m with upper and lower boundaries at 2000 and 1600 m, respectively. Glaciers leading into unstable, ice-cored rock glacier deposits have a mean altitude of 1700 ± 90 m with boundaries at 1900 and 1500 m (Figure 6). These contrasting distributions define two parallel trend surfaces each 200 m thick (Figure 7). The surfaces were constructed using glacier mean elevations which were computed along the lithologically controlled, east-west-trending cirque glacier clusters that occur between the major, north-sloping valleys of the Itkillik, Atigun, and Sagavanirktok rivers. The mean elevations of the two glacier classes consistently differ by 100 m in these clusters, except in the southern part of the field area. Figure 8 shows the two trend surfaces extended to incorporate Anaktuvuk Pass and the Mt. Doonerak areas. Exposed glacier ice has not been found in the field below 1500 m altitude. The same lower limit occurs in the eastern Brooks Range (Wendler, 1969) and is shown by Péwé (1975) on his small scale survey map covering the whole Brooks Range.

The trend surfaces were extrapolated westward into the Anaktuvuk Pass area based on field mapping of 7 cirques using lichenometric dating techniques (see Figure 8). Exposed glaciers were found in only two of these cirques and they extended into ice-cored rock glacier deposits of Neoglacial age. These two exposed ice cores were mapped at 1600 m in the cirques at the head of the east fork of Itikmalakpak Creek. The other cirques had no exposed glacier ice or Neoglacial drift, so thus delineate minimum altitudes for the lower trend surface. However, partially active rock glaciers of late Pleistocene to early Holocene age were mapped at or below four of the five cirques including the western cirque of Mt. Ahgook and the two cirques east of Mt. Kollu-

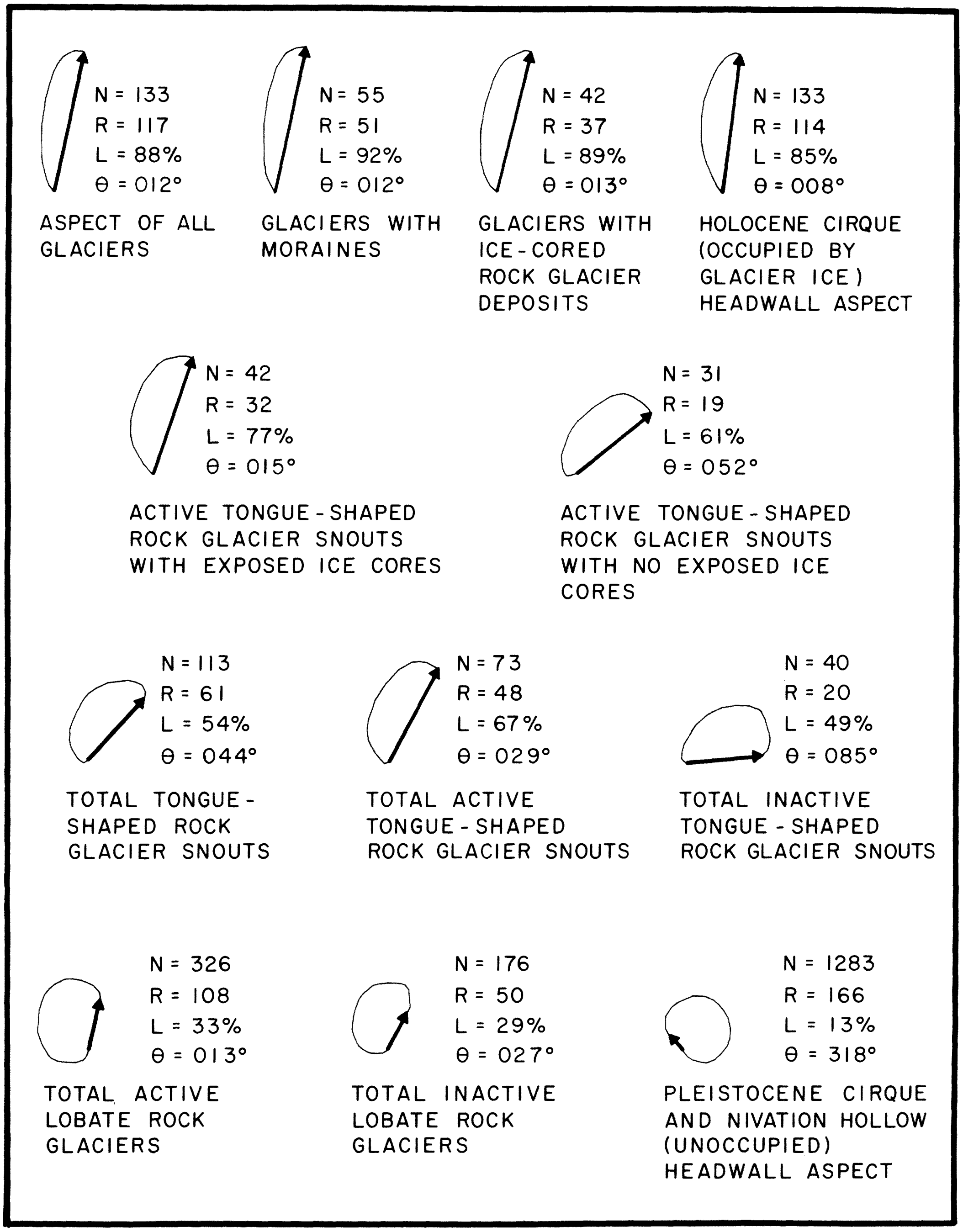

FIGURE 5. Graphical summary of aspect distribution data. See also Table 2. Note absolute scale varies so that strength of mean vectors (L) are of equal lengths if $L = 100\%$. L is shown by the thickened arrows, and equals R/N.

TABLE 2

Summary of aspect distribution data[a]

Landform	No.	Class	Location relative to Continental Divide	Aspect (degrees)	Strength (*L*) (%)
Lobate rock glaciers	76	Inactive	S	058	44
	100	Inactive	N	344	20
	84	Active	S	032	24
	242	Active	N	009	38
	176	Inactive	N and S	027	29
	326	Active	N and S	013	33
	502	Inactive and active	N and S	019	32
Tongue-shaped rock glaciers	20	Inactive	S	088	48
	20	Inactive	N	077	50
	9	Active	S	107	80
	64	Active	N	020	73
	40	Inactive	N and S	085	49
	73	Active	N and S	029	67
	113	Inactive and active	N and S	044	54
	42	Active and ice-cored	N and S	015	77
	31	Active and (?) ice-cored	N and S	052	61
Glaciers	55	Moraine deposit	N and S	012	92
	42	Ice-cored rock glacier deposit	N and S	013	89
	133	All	N and S	012	88
Cirques with glaciers	133	All	N and S	008	85
Unoccupied cirques and nivation hollows	1283	All	N and S	318	13

[a]See also Figure 5.

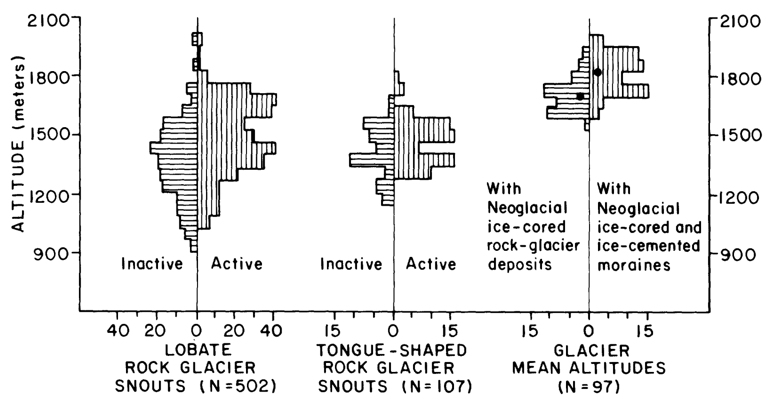

FIGURE 6. Summary of altitudinal distribution for glaciers and rock glaciers. Sixty-seven percent zone of occurrence for both active and inactive states shown. See also Table 3.

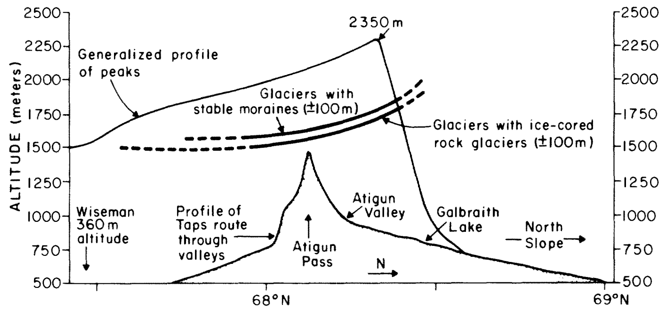

FIGURE 7. North-south profile through Atigun Pass with upper trend surface representing glaciers with ice-cored and ice-cemented moraines, and lower trend surface for glaciers with ice-cored rock glacier deposits. Each surface represents a zone 100 m above and below.

TABLE 3
Summary of altitudinal distribution data[a]

Landform	No.	Class	Location relative to Continental Divide	Quadrants slope faces	Mean elevation (m)	Standard deviation (m)
Lobate rock glaciers[b]	24	Inactive	S	S	1430	20
	23	Inactive	N	S	1570	180
	45	Inactive	S	N	1350	130
	66	Inactive	N	N	1250	190
	27	Active	S	S	1620	90
	45	Active	N	S	1550	200
	50	Active	S	N	1510	150
	168	Active	N	N	1460	210
	47	Inactive	N and S	S	1500	180
	111	Inactive	N and S	N	1290	180
	72	Active	N and S	S	1580	170
	218	Active	N and S	N	1480	190
Tongue-shaped rock glaciers[b]	7	Inactive	S	S	1360	100
	8	Inactive	N	S	1480	160
	9	Inactive	S	N	1370	110
	12	Inactive	N	N	1490	120
	5	Active	S	S	1450	120
	4	Active	N	S	1560	160
	3	Active	S	N	1460	10
	59	Active	N	N	1450	110
	15	Inactive	N and S	S	1420	140
	21	Inactive	N and S	N	1430	120
	9	Active	N and S	S	1500	140
	62	Active	N and S	N	1450	100
	39	Active and ice-cored	N and S	N and S	1440	120
	32	Active and no exposed ice core	N and S	N and S	1480	90
Glaciers	55	Moraine deposit	N and S	—	1820	90
	42	Ice-cored rock-glacier deposit	N and S	—	1700	90

[a]See Figures 7, 8, and 9.
[b]Those rock glaciers facing 090 and 270° are not included in the analysis.

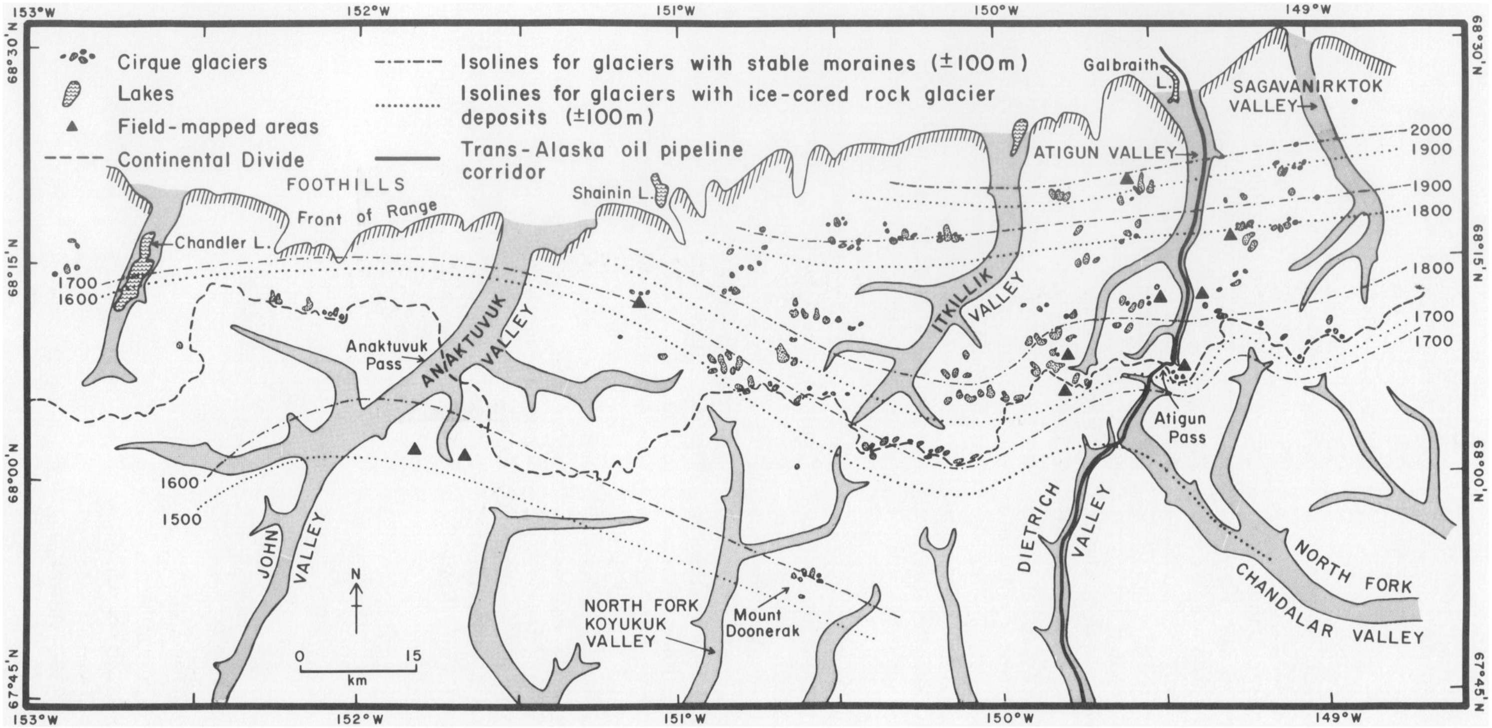

FIGURE 8. Trend surfaces for glaciers with moraines and glaciers with ice-cored rock glacier deposits in the central Brooks Range. Area west of 150°30′W based on field work and Porter (1966, Figure 20a).

tuk where Porter (1966, Figure 18 and Plates 13, 14) had mapped Fan Mountain drift.

The trend surfaces are well supported in the Atigun Pass area except at the pass itself and farther east along the Divide (Figure 8).

TONGUE-SHAPED ROCK GLACIERS

Eighty-three of the 113 tongue-shaped rock glaciers occur north of the Divide, and are concentrated in blocky-fracturing conglomerates and sandstones of the Kanayut Formation. Only 30% of the tongues south of the Divide are active with only 9% showing exposed ice cores. North of the Divide, 76% are active and 46% have exposed ice cores. Rock glaciers with exposed ice cores always have active snouts. Rock glacier altitudinal distribution is summarized in Figures 6 and 9, and Table 3. The following text rounds the elevations to the nearest 50 m, including the zone that contains 67% of the total sample.

Except for the relatively low elevations of inactive tongue-shaped rock glaciers south of the Divide (~ 1350 m), there is no significant difference in snout elevations north and south of the Divide. In addition, there is little altitudinal difference between south- and north-facing tongues. Active tongues occur within a belt 150 m thick, centered about 1500 m on south-facing slopes that descends to 1450 m on north-facing slopes. The lower limits of tongue-shaped rock glacier snouts are 1200 m for inactive forms and 1300 m for active forms, both located in the southern part of the field area. This lower limit rises northward to 1450 m at 68°25′N.

Active, tongue-shaped rock glaciers have a mean aspect of 029° with a strength of 67% (strongly asymmetric) (Figure 5 and Table 2). Tongues with exposed ice cores are somewhat more asymmetric than those that show no ice core. Inactive snouts have a mean aspect of 085° with a strength of only 49%.

LOBATE ROCK GLACIERS

Five hundred and two lobate rock glaciers and coalescing lobes were mapped. These are concentrated north of the Divide in the resistant Kanayut Formation, particularly under steep cliffs formed of this blocky fracturing rock. South of the Divide, lobate rock glaciers occur beneath cliffs where blocky conglomerates or sandstones crop out above steep slopes underlain by the phyllitic Hunt Fork formation.

Lobate rock glaciers occur in a zone 500 m thick that persists from 68°N latitude north to the foothills of the Brooks Range. However, only 50% of the lobate rock glaciers south of the Divide are active, while to the north, 70% are active. They tend to have slightly higher altitudes south of the Divide, although the difference is not statistically significant (Table 3). An apparent exception to this trend is shown by the inactive, south-facing class of lobate rock glaciers, because eight of these form an anomalously high (1600 to 2000 m) cluster on cliffs just north of the Divide. These face from 160 to 200°. Debris shortage or lack of protection from insolation may account for their present inactive state.

Active lobes tend to be 150 m higher than inactive ones (Figure 6 and Table 3). Both active and inactive forms tend to be 100 m higher on south-facing slopes than on north-facing ones (see Madole, 1972: 120). The active lobes facing south lie within a 350-m thick belt with a mean altitude of 1600 m,

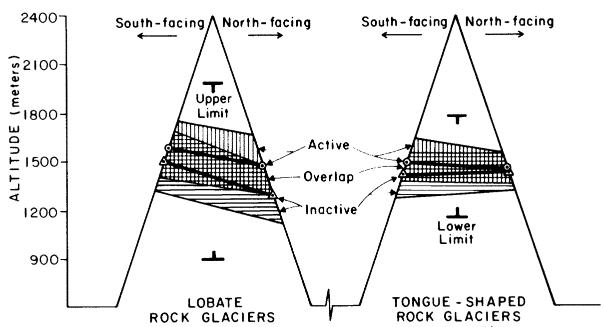

FIGURE 9. Comparison of altitudinal distribution of south-facing and north-facing rock glaciers. Those facing 090 and 270° were not included in analysis. The sixty-seven percent zone of occurrence about the mean is shown for both active and inactive states. See Table 3.

whereas those facing north form a 400-m thick zone having a mean altitude of 1500 m (Figure 9).

Weakly asymmetric aspects characterize lobate rock glaciers (Figure 5 and Table 2). No significant difference in aspect occurs north or south of the Divide. The active lobate forms show a mean aspect of 013° with a strength of only 33%. Inactive lobates are also weakly asymmetric.

Talus cones and lobate rock glaciers often occur side-by-side along valley walls. However, the lobate rock glaciers are localized directly beneath steep, truncated bedrock spurs where there is a minimum of fluvial activity in the debris source area. In contrast, talus cones lead upward to a fluvially enlarged channel or gully which has been eroded into the steep valley sidewall. The introduction of this relatively substantial fluvial activity in the debris source area appears to prevent talus cones from developing into lobate rock glaciers.

DISCUSSION

Aspects of Pleistocene cirques and nivation hollows (Figure 2) reflect the northeast-southwest and northwest-southeast fracture system mapped in the east-central Brooks Range (Ellis, 1978; Ellis and Calkin, 1978). This pattern contrasts strongly with that of presently glacierized cirques which demonstrate highly significant climatic control (minimization of direct solar radiation) with little structural influence. The difference supports the concept that the effect of aspect on glacierization is increased as snowline (and glaciation level) rises (Evans, 1977).

The rise in the mean elevation of present cirque glaciers from 1500 m south of the Divide to over 2000 m in the northern portion of the range supports observations by Porter (1966) that rising maritime air masses moving from the south and west dominate the altitudinal pattern of existing glaciers, rather than the horizontal temperature gradient that decreases toward the north. The glacier trend surface steepens markedly toward the north, and intercepts only the highest peaks in the range. The rise and steepening suggests that precipitation derived from the Arctic Ocean is negligible.

Moraine and ice-cored rock-glacier deposits associated with the cirque glaciers are favored by certain environmental conditions such as extent of headwalls and sidewalls, supply of supraglacial debris, slope of underlying terrain, and amount of shading by surrounding mountain terrain. Our analysis confirms that the higher the glacier, the more easily fulfilled are the environmental conditions for both the ice-cored and ice-cemented moraines. The two trend surfaces constructed outline the topoclimatic and debris supply differences between the two types of glacial deposits. Glaciers associated with ice-cored rock-glacier deposits exist at lower altitudes, because the higher ambient temperature there is compensated for by the increased debris cover and shading from insolation. The trend surfaces can be used to predict the type of deposit that will be associated with a particular cirque glacier in the central Brooks Range. We are directing our lichenometric dating program to those moraines associated with glaciers on the upper trend surface.

The mean occurrence of the Neoglacial drifts within 400 m of the exposed glacier snouts indicates that cirque glaciers attained lengths during mid to late Holocene time that were only 50% greater than those of present-day. Generalized glacier profiles (Figure 3) and preliminary area accumulation ratio studies (see Meier and Post, 1962; Porter, 1970) suggest the depression of equilibrium-line altitudes (ELA) that would accompany maximum Neoglacial expansion(s) are on the order of 100 m below existing glaciers' mean altitudes (Ellis, 1978). Figures 7 and 8 can be translated into first approximations of minimum Neoglacial ELAs by subtracting 100 m from each glacier trend surface.

Active tongue-shaped rock glaciers without exposed ice cores are so similar in their morphology and altitudinal distribution to those with visible glaciers, that it may be reasonable to suspect that both have glacier cores. Those without exposed ice cores have aspects that are less insolation-sensitive. This may occur because of their increased debris cover. Some structural control of aspect for all tongue-shaped rock glaciers appears to be demonstrated by moderate concentrations along the northeast and northwest fracture trend.

Lobate rock glaciers occur over a greater altitudinal and geographical range, and have a more variable aspect distribution than tongue-shaped ones. In addition, the localization of rock glaciers, particularly active ones, north of the Divide may show the unfavorable effects of the interior's continental climate. Field study suggests that many small tongue-shaped forms less than 200 m in length have developed from coalescing lobate rock glaciers in the manner postulated by Wahrhaftig and Cox (1959: 433). The distinctly lower altitudinal limit of the lobate assemblage may be partly related to their general development without insolation-sensitive glacier cores (ice cores). Also, many of the valley-sided lobate rock glaciers may have been initiated during times of lower temperatures and greater slope activity associated with late Pleistocene or early Holocene deglaciation. Their response to Neoglacial cooling is not clear, since both active and inactive lobate rock glaciers occur side-by-side in the lower altitudinal range (Figure 6). The weak tendency of lobate forms to face the insolation-minimum direction north-northeast may also reflect their lower ice content relative to debris, or the importance of protective shading by surrounding mountain terrain.

Active rock glaciers are concentrated north of the Continental Divide. This may reflect the influence of lower temperatures associated with the North Slope's climatic regime, which favors preservation of subsurface ice.

A substantial portion of the debris source area for rock glaciers is typically composed of siltstones, shales, and phyllites. The talus cones feeding rock glaciers are often made up of platey rock fragments from these less resistant rocks as typified by that shown in Figure 4f. Wahrhaftig and Cox's (1959) observation that rock glaciers are rare on platey or schistose rocks in the Alaska Range does not seem fully applicable in the central Brooks Range. The internal composition of rock glaciers as revealed by stream cuts and excavations in the field area typically show platey boulders, cobbles, and fragments aligned parallel to the upper surface in a medium sand matrix (Bruen, in preparation). The blocky boulders tend to be concentrated only on the upper surface and particularly at the snout.

In the Colorado Front Range, Madole (1972) described lobate rock glaciers as occurring within an altitudinally intermediate periglacial zone between the higher tongue-shaped rock glaciers and the lower talus deposits. Within the central Brooks Range, these three types of deposits overlap broadly.

SUMMARY

(1) Glaciers are clearly the most asymmetric and insolation-minimizing landform of the glacial-periglacial environment. The extremely asymmetric distribution in the east-central Brooks Range reflects marginal conditions for glacierization since the Pleistocene. During the maximum expansion(s) of the Neoglacial, equilibrium line altitudes were only on the order of 100 m below present mean glacier altitudes.

(2) Glaciers fronted by stable moraines rise northward from 1600 to 2000 m over an 80 km distance, while those associated with unstable ice-cored (tongue-shaped) rock glacier deposits parallel this trend but are 100 m lower. Lobate rock glaciers, generally thought to lack glacial ice cores, have similar mean altitudes but a greater overall vertical range of distribution than the tongue-shaped ones. The trend surfaces can be used to help predict the occurrence and activity of the major glacial and periglacial landforms. For example, the most distinct lichenometric record of Neoglacial fluctuations may be obtained from deposits associated with glaciers on the upper trend surface.

(3) Glaciers associated with stable Holocene moraines in the central Brooks Range have relatively low headwalls and sidewalls resulting in minimum shading, low supply of supraglacial debris and minimum surface debris. Their morainal complexes are less than 800 m long and are situated on gently sloping terrain.

(4) Ninety-seven percent of the glaciers and 74% of rock glaciers occur north of the Continental Divide, and are associated with the tough Devonian clastic rocks. These underlie the highest peaks which are concentrated at and north of the Divide. The more active rate of rock glaciers north than south of the Divide may be related to the lower tempera-

tures of the north slope's arctic climate.

(5) Both active and inactive lobate rock glaciers are less sensitive to insolation than are the tongue-shaped forms. The latter show increasing sensitivity proportional to their state of activity and content of ice. Numerical analysis of aspect may assist in the development of probable response models for rock glaciers as compared to the glaciologically monitored cirque glaciers.

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