ROCK GLACIERS

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ROCK GLACIERS OF CENTRAL BROOKS RANGE, ALASKA, U.S.A.

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INTRODUCTION

Distribution and activity of rock glaciers, central Brooks Range, Alaska

Rock glaciers, common in the central Brooks Range, encompass small lobate forms perched along valley walls and larger tongue-shaped deposits that emanate from cirques. Reconnaissance studies have been undertaken in two areas, the Atigun Pass region spanning the Continental Divide in the east-central Brooks Range, and the upper Kurupa River region, 230 km to the west (Fig. 6.1). In both areas, rock glaciers are best developed below resistant ridges of massive to thick-bedded sedimentary rocks interbedded with and underlain by thin-bedded pelitic rocks. The combination of lithologies may control rates of debris production in the source area and/or the degree of insulation of the debris cover.

Lobate rock glaciers (White 1976) form at the base of talus cones and, with few exceptions, are broader than long downslope. In this region they often occur beneath truncated bedrock spurs where a minimum of fluvial activity occurs. Lobate rock glaciers that occur side by side along valley walls can superficially resemble the remnants of lateral moraines. Surface pits excavated to 150 cm in the Atigun Pass region reveal interstitial ice.

Rock glaciers that are described as tongue-shaped (Wahrhaftig and Cox 1959; White 1976) are longer than broad except where overridden by other deposits. In the central Brooks Range they extend up to 3.5 km from associated cirque headwalls and have transverse and longitudinal ridges that cannot be attributed to active ice margins or typical morainal deposition. These ridges show no organized pattern of age distribution along or between individual crests.

Active rock glaciers have sharp-crested, cascading front slopes, and many show sharp, defined surface features indicating recent movement. Inactive forms have rounded crest and stable fronts with a mature lichen cover, and are no longer fed by active talus.

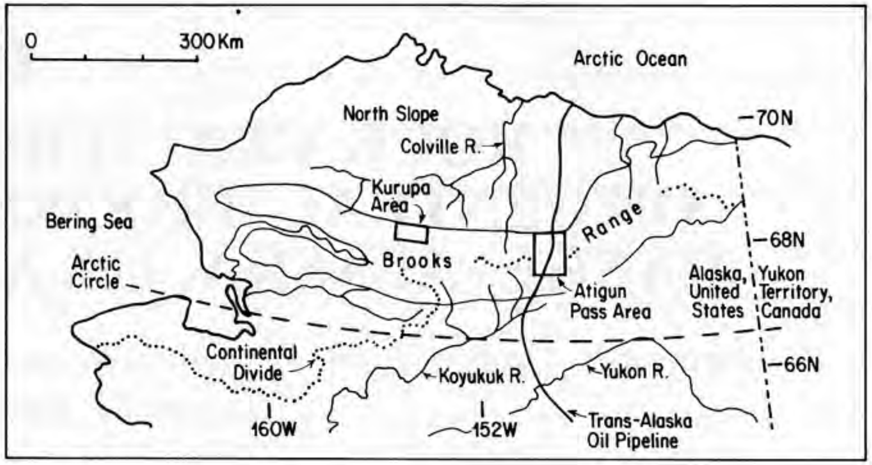


Figure 6.1 Location of rock glacier study areas.

All but a few of the tongue-shaped rock glaciers examined in the central Brooks Range appear to have once had, or now reveal, glacial ice cores. Most of these also have glacier ice exposed at their heads. Field relations suggest that the headward glacier ice continues downslope through a transition zone to the ice core of the rock glacier. The transition zone is recognized by the occurrence of partially stable, looped ridges that show a distinct age pattern. These ridges mark periods of reactivation of ice at the cirque headwall and are true end moraines. The areal proportion of a rock-glacier tongue to its transition zone and exposed headward glacier varies considerably, but subequal areas are common. The larger of the cirque glaciers, which were very active during late Holocene time, are commonly associated with proportionally smaller than average rock-glacier tongues that extend downslope and beyond their transition-zone moraine systems.

DISTRIBUTION

Seventy-five percent of active lobate rock glaciers in the central Brooks Range, and almost all of the active tongue-shaped forms, occur on the north side of an east-west trending Continental Divide. This divide separates the North Slope/Arctic Ocean drainages from those of interior Alaska (Fig. 6.1). All rock glaciers occur within the zone of continuous permafrost (Ferrians 1965); mean annual temperature at 1,500 m approaches -14° C and annual precipitation ranges from 400 to 700 mm, about half of which is snow.

Lobate rock glaciers in the field areas that we have examined occur over a altitudinal range of 900 through 2,000 m (Fig. 6.2). In contrast, tongue-shaped rock glaciers occur only between 1,100 and 1,800 m elevation with the active ones confined to the upper 500 m. The distribution of these tongue-shaped rock glaciers is strongly controlled by the occurrence of cirques and Holocene glaciers. Mean elevations of cirque glaciers associated with rock glacier tongues are ~100 m lower than

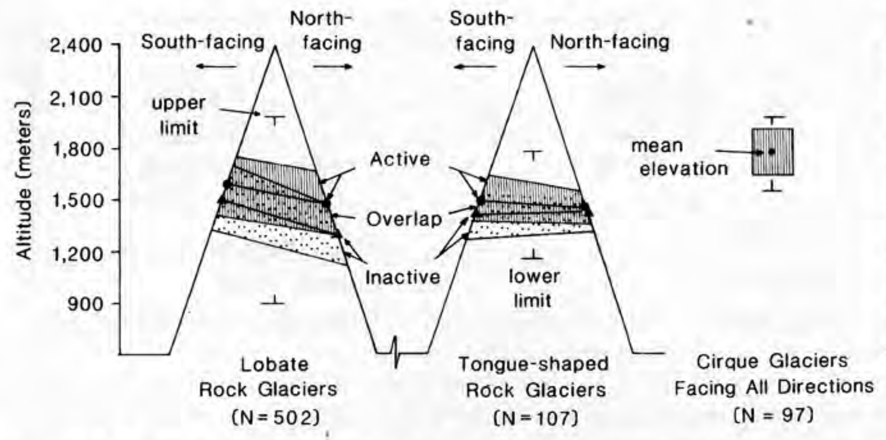


Figure 6.2 Comparison of altitudinal distribution of south- and north-facing rock glaciers and all existing glaciers. Rock glaciers facing 090° and 270° azimuths were not included. The 67 percent zone of occurrence about the mean is shown for active and inactive rock glaciers and for glaciers. Adapted from Ellis and Calkin (1979).

those without rock glaciers. Rock glaciers that may have developed in association with cirque glaciers at higher elevations were presumably obliterated by late Holocene glacier advance.

The distribution of cirques and Holocene glaciers reflects regional temperature patterns, the southernly moisture sources of the Pacific Ocean, and the occurrence of glaciers where heat transfer is minimized (Ellis and Calkin 1979; Ellis 1984). Central Brooks Range glaciers currently respond most to changes in summer temperature (Calkin, Ellis, and Haworth 1985). The lower limit of glacier-cored rock glaciers at ~1,100 m corresponds today to mean thaw-period temperature of ~4° to 5°C.

Mean altitudes of north- and south-facing rock glaciers are similar (Fig. 6.2). Active tongue-shaped forms that face south occur on the average only 50 m higher than those facing north, and these active tongues are only 50 m higher than inactive ones. However, lobate rock glaciers that face south occur 150 m higher than those that face north. Also, active lobate rock glaciers occur 150 m higher than inactive ones.

In addition, the mean altitude of tongue-shaped and lobate rock glaciers is similar both south and north of the Continental Divide near Atigun Pass. The lower limit for active tongue-shaped deposits, however, does rise northward from 1,300 m south of the Divide to 1,450 m north of the Divide. Mean altitudes of all cirque glaciers also rise from south to north across the range, because of the depletion of moisture derived predominantly from the south.

Orientations of active tongue-shaped rock glaciers average 029° azimuth east of north and are markedly asymmetric compared to the orientations of other rock glaciers (Fig. 6.3). The preferred orientation is similar to that of the cirque glaciers that have a very strong orientation to the north-northeast. This orientation minimizes solar radiation and sensible heat received at the ice surface. Inactive tongue-shaped rock glaciers have a weaker preferred orientation.

Lobate rock glaciers display little preferred orientation, whether active or inactive.

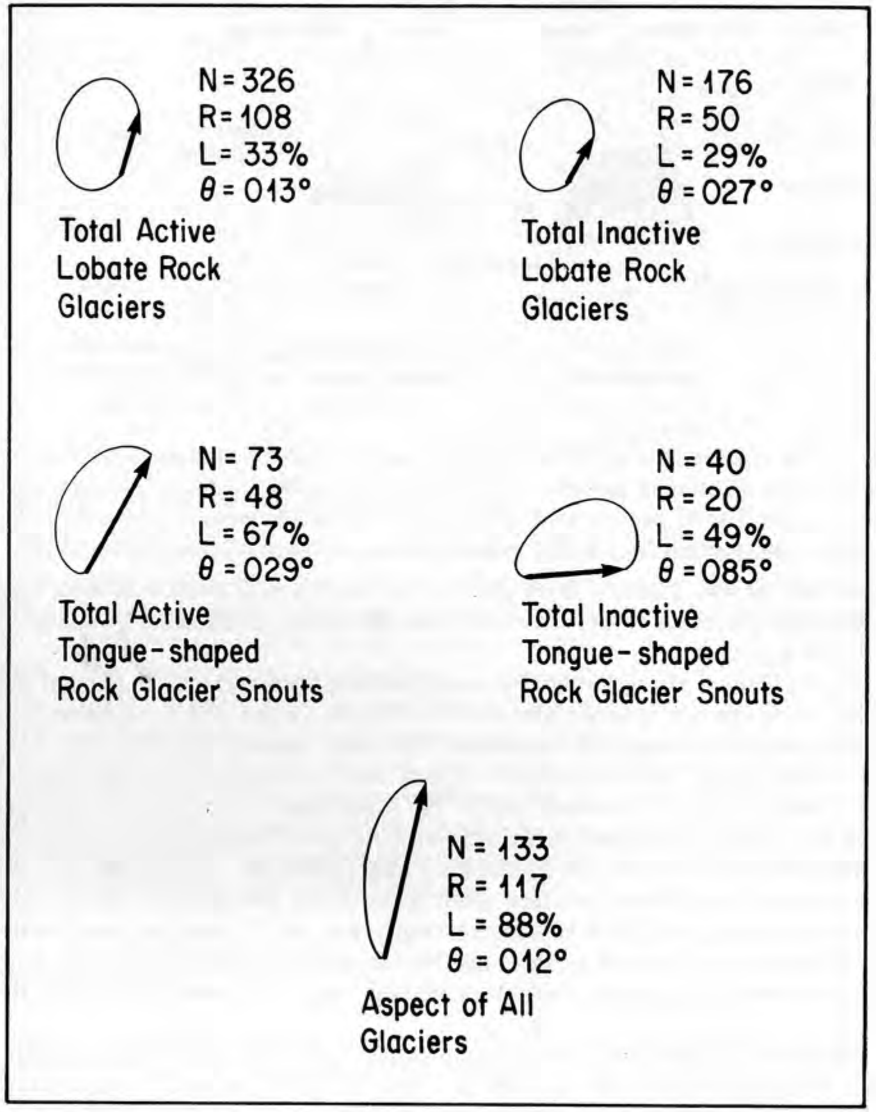


Figure 6.3 Graphical summary of orientation data for lobate and tongue-shaped rock glaciers and glaciers in the Atigun Pass area. N=number of measured forms; R=length of mean vectors (shown by thickened line); L=R/N, degree of asymmetry; O=mean orientation. Method after Evans (1977). Data after Ellis and Calkin (1979).

Their occurrence does not appear to be controlled by exposure to direct solar radiation. Lobate forms are found over a wider range of altitudes and orientations than tongue-shaped ones, presumably reflecting the occurrence of ice as interstitial masses rather than as segregated cores.

Tongue-shaped rock glaciers, showing exposed glacier ice at the headwall, occur in cirques with an average headwall height of 250 ± 140 m; cirques bearing glaciers without rock-glacier tongues occur beneath headwalls of 110 ± 60 m height (Ellis and Calkin 1983). The formation of a rock glacier evidently is favored in cirques with higher headwalls that supply more debris. In addition, rock glaciers beneath these higher headwalls receive an average of 8 percent less direct solar radiation than moraines at cirque glacier margins.

MORPHOLOGY AND SURFACE FEATURES

Lobate rock glaciers in the central Brooks Range extend 15 to 200 m beyond headward talus cones and are 15 to 70 m in thickness at their front slopes. A good correlation exists between length and thickness; a ratio of 3:2 is most common (Fig. 6.4A). This figure also suggests that length/thickness ratios are similar for both active and inactive forms.

A group of 25 lobate rock glaciers display upper surfaces that slope gently at 2° to 5°; these grade upslope to talus and are truncated toward the toe by avalanche slopes of 30° to 40° (Lamb 1984). Many inactive and even some active forms, however, have top surfaces sloping back toward the headwall forming meltwater-filled depressions (Fig. 6.5).

Tongue-shaped rock glaciers that we have examined extend beyond transition zones from less than 100 m to at least 1,200 m (Fig. 6.6). Many may have had a longer exposed length before disturbance by Holocene glacier expansions. Thicknesses of 50 to 100 m are common. In contrast to lobate rock glaciers, tongue-shaped forms here may lose considerable thickness as they become inactive.

The upper surface of the rock glaciers consists of angular boulder debris with a poorly sorted sandy or shaley matrix, reflecting the composition of conglomerates, sandstones, and phyllites. The covering debris layer on tongue-shaped rock glaciers is 80 to 200 cm in thickness. Near-surface debris bands and elongate bubbles in the exposed ice core of at least two rock glaciers are similar to that in cirque glacier ice (Fig. 6.7).

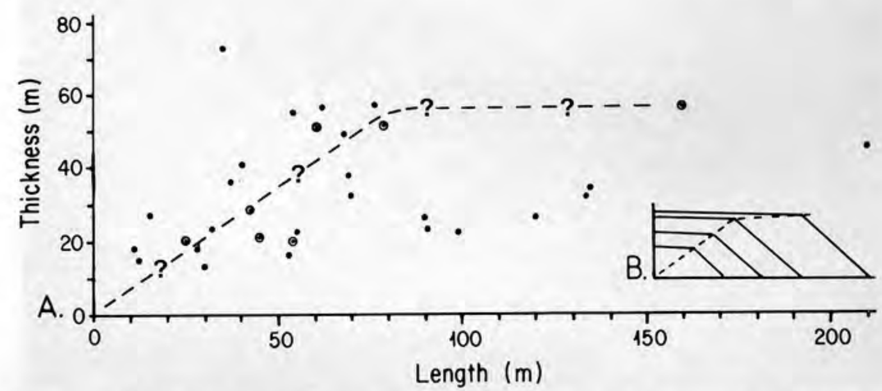


Figure 6.4 A) Thickness versus length of a group of lobate rock glaciers from the Kurupa and Atigun Pass areas. Circled data points represent active forms. B) Inferred morphological development of lobate rock glaciers.

Figure 6.5 View east of lobate rock glacier in the Atigun Pass area with an active front. Note reverse top slope, ponded water in spoon-shaped depression, and light surface tone resulting from a minimal lichen cover. View east shows a sharp active front and snow-covered, talus debris source.

Figure 6.6 View south of tongue-shaped rock glacier at 1,420 m in the Atigun Pass area. Transition zone and rock glacier tongue extend 750 m downslope from exposed glacier.

Tongue-shaped rock glaciers in the central Brooks Range exhibit many of the surface features associated with ice-cored deposits described elsewhere (Wahrhaftig and Cox 1959; Vernon and Hughes 1966; White 1976), including longitudinal and transverse ridges, meandering furrows, and surface pits. Patterned ground is well developed where debris cover is thin, especially near the rock-glacier terminus. The longitudinal ridges are rounded in cross section and often can be traced directly to talus cones. Furrows that separate them are V-shaped and generally free of vegetation. Five to ten meters of total relief is not uncommon. The longitudinal ridges occur in some places where extensional flow might be expected in the ice core because of slope steepening or where longitudinal differences in flow rates may occur.

Transverse ridges for the most part are difficult to trace laterally, but lineations of multiple ridges, troughs, and boulder lines may form distinct patterns on aerial

Figure 6.7 Exposed ice core at avalanche crest of Jaeger rock glacier (see Fig. 6.9 for location). Thin debris cover cascades over exposure.

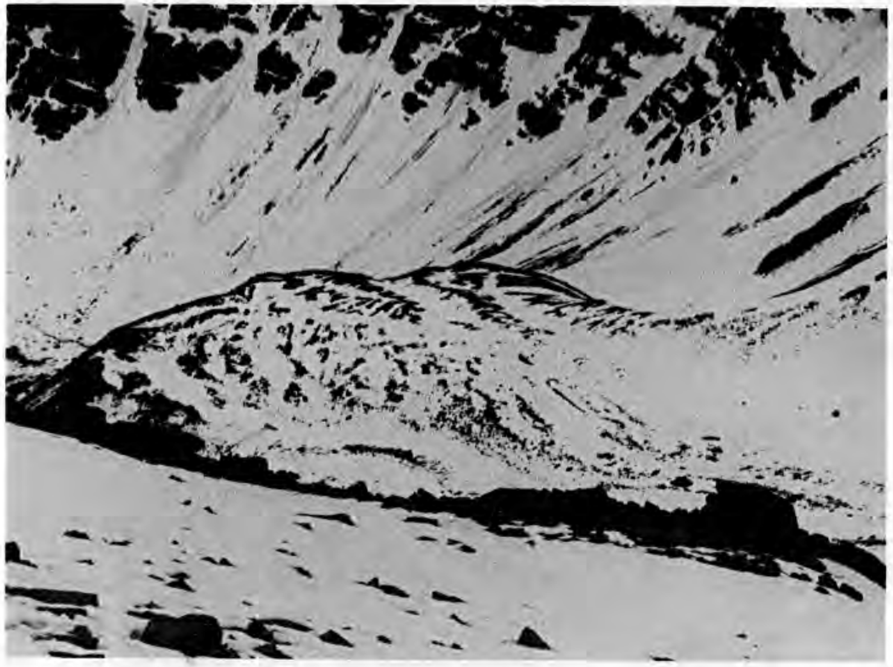


Figure 6.8 View of an east-facing, active rock glacier at 1620 m in the Kurupa area. Near-vertical view displays well-developed, but discontinuous, transverse ridges.

photography (Fig. 6.8). They commonly occur on a finer scale than longitudinal ridges; some are only 1 to 2 m in relief and are spaced 3 to 4 m apart. These ridges do not show distinct differences in weathering characteristics or lichenometric age as do morainal ridges of the transition zone. Moreover, they may be formed on rock glaciers undergoing compression or shearing within the ice core.

REQUIREMENTS FOR ACTIVITY

Active lobate rock glaciers in the Atigun Pass area of the east-central Brooks Range all have thicknesses greater than 50 m (Bruen 1980). Stable surface areas of these large rock glaciers provide a minimum lichenometric age of ~2,000 years. A sufficient thickness, however, is not the only requirement for activity; lobate forms whose rock and ice matrices reach thicknesses of 70 m or greater are still inactive when they occur at low elevations. In contrast, in the more westerly Kurupa area, active lobate rock glaciers occur that have attained thicknesses of only 20 to 30 m. Cascading talus covers a large part of these small rock glaciers, and stable parts of their surfaces have lichenometric ages dating from the last few centuries. In the Kurupa area, inactive forms have an average thickness of 40 m and also show a better-developed tundra mat and older lichenometric age.

Data points representing active lobate forms from both areas are circled in Figure 6.4A. If the assumption is made that the lichenometric age of the surface does represent the age of the landform, then a line drawn through the circled points (i.e., active rock glacier; Fig. 6.4A) could represent average morphological development of lobate rock glaciers through time. This concept represented schematically in Figure 6.4B, suggests that a roughly linear increase in thickness and length occurs until a thickness of ~55 m and a length of ~80m have been attained. At this stage of development length may increase proportionally faster than thickness (e.g., Olyphant 1983).

A multivariate statistical study was made of insolation, altitude, and debris supply for 50 rock glaciers in the east-central Brooks Range to test their relationship with rock glacier activity (Ellis 1982). The mean orientation of active and inactive rock glaciers varies from north-east to east, but correlation between direct solar radiation and rock-glacier activity is very poor. Activity could also not be related to rock-glacier altitude. In the west-central Brooks Range study area, however, active forms received an average of 15 percent less direct radiation than inactive ones (Lamb 1984).

Although climatic limits apply to the initial formation of lobate rock glaciers, once formed, they appear to be climatically insensitive. Activity, poorly related to radiation and altitude, may depend most on continuous and ample debris supply.

SURFACE MOVEMENT

Detection of surface movement of two glacier-cored, tongue-shaped rock glaciers (called here Jaeger and Pika) near Atigun Pass is based on theodolite surveys made in 1978, 1982, and 1983 (Figs. 6.9, 6.10). Both rock glaciers originate in cirques at ~1,590 m near the Continental Divide. Small exposed glaciers are present at the head of each rock glacier. Snouts of the rock glaciers lie 440 to 490 m downslope and 50 to 100 m below these remnant ice masses of Jaeger and Pika, respectively. Both display similar soil development, surface weathering, and minimum lichenometric ages of 4,000 to 5,000 years BP. Maximum diameters of the *Rhizocarpon geographicum* lichen generally increase toward the toe but not in a regular pattern.

Transverse profiles across the snout of each rock glacier were surveyed by theodolite from bedrock control stations (Fig. 6.11). Fixed-line profiles were used to record vertical movement. Horizontal movement was measured by surveys to a fixed point on the central lobe and to the crestline of each rock glacier. The fixed traverses on the tongue of both rock glaciers exhibit a great deal of vertical fluctuation. Along the traverse, the surface of Jaeger rock glacier displayed a net subsidence of 0.06 to 1.22 m $\pm$ 0.05 m during the 1978 to 1983 period, with a mean lowering of 0.11m yr^{-1}. The snout traverse of Pika rock glacier showed 0.06 to 0.94 m $\pm$ 0.05 m lowering during the same period, with a mean rate of 0.10 m yr^{-1}. These preliminary rates are similar to those reported by Haeberli, King, and Flotron (1979) in the Swiss Alps and slower than surface lowering measured in Antarctica by Hassinger and Mayewski (1983). Most lowering occurred on high points of lobes rather than on steep flanks. A traverse of Jaeger in 1982 revealed areas on two lobes where

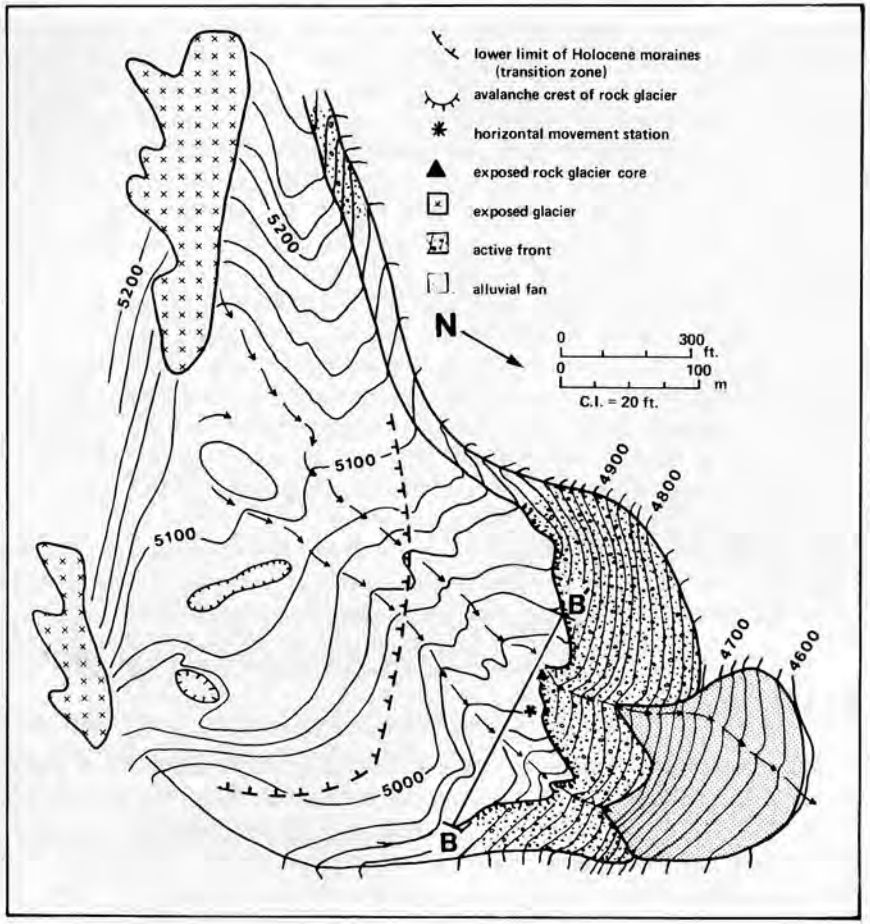


Figure 6.9 Topographic map of Jaeger rock glacier with a transition zone of late Holocene moraines and small exposed headward glacier. Position of traverse and cross section (Fig. 6.11B) is marked B - B'.

the surface appeared to rise by 0.3 to 0.6m ± 0.05 m. Net thinning of Jaeger and Pika rock glaciers may represent the melting rate of the ice core, thinning because of net increases in velocity, or combinations of these effects. Areas of thickening recorded in the 1982 survey may result from horizontal movement bringing a thicker zone of rock glacier into the line of traverse.

Preliminary horizontal flow rates determined by fixed point survey (see Figs. 6.9 and 6.10 for locations) indicate that the central lobe of Jaeger rock glacier moves on the order of 0.40 m yr^{-1} and that of Pika rock glacier at about 0.10 m yr^{-1}. Neither of these rates, however, may be representative of long-term rates. Taken together with rock glacier lengths, these movement rates result in extremely dissimilar ages. Despite the similarity of other age indicators, the five year movement study yields an age of only 1,100 years for Jaeger rock glacier while it suggests an age of about 5,000 years for Pika rock glacier. These movement rates are within the lower range

of movement reported for a rock glacier surface from southern Alaska, the U.S. and Canadian Rockies, and the Swiss Alps. Generally movement rates range between 0.1 and 1.0 m yr^{-1} (Wahrhaftig and Cox 1959; Whalley 1974; Osborn 1975; Barsch 1977).

Comparision of the horizontal position of avalanche crests for Jaeger and Pika rock glaciers indicates that both rock glacier snouts are advancing at lobe centers on the order of 0.1 to 0.4 m yr^{-1}. Other areas of the crest appear to be stationary.

This is remarkable surveying! - change detected between 1978 and 1983. (J. Ellis)

ROCK GLACIER AGE

The major technique used to date Holocene surfaces in the central Brooks Range has been lichenometry. A growth curve for *R. geographicum* was developed for this region by Calkin and Ellis (1980). The growth curve is well controlled to 1,300 years in the Atigun Pass area, and has been extended to the middle Holocene based on data from areas of similar climate. Because of the instability of active rock glacier surfaces, the influx of talus to lobate forms, and perhaps episodic snow cover of some duration, lichenometric dates on rock glaciers can provide only minimum ages of formation. In some cases they probably give the age of only the latest full activity. We have attempted to augment lichenometric methods by comparing the soil development and boulder weathering on rock glacier surfaces with those of moraines whose age is better known, either by lichenometry or direct radiocarbon dating.

Maximum diameters of *R. geographicum*, ranging up to 300 or 400 mm, have been recorded on inactive lobate rock glaciers in the Kurupa area (Fig. 6.1). This is well beyond the maximum diameter found to date on Holocene moraines in the Brooks Range and is within the range of the largest diameters recorded on stable bedrock in the region. We infer that some lobate rock glaciers formed soon after late Pleistocene valley deglaciation which occurred about 12,000 years BP (Hamilton and Porter 1975).

Most lobate and tongue-shaped rock glaciers support *R. geographicum* populations characterized by maximum diameters of less than 100 mm, which would suggest ages of less than 3,000 years. Other surface characteristics, however, indicate that this does not represent the true age of most of the rock glaciers. For example, crustose lichens commonly cover 50 to 70 percent of boulder surfaces on rock glaciers, while less than 40 percent coverage is common on late Holocene moraines (Ellis 1982). In addition, soil development on rock glaciers in the central Brooks Range suggests that they are intermediate in age between Holocene moraines and the youngest Pleistocene moraines (Fig. 6.12). As soils develop in these deposits, A horizons thicken, a color B (Bw) horizon develops, chromas become stronger and soil pH values decrease (Ellis and Calkin 1983).

Studies of boulder weathering also place the age of rock glacier surfaces intermediate between those of late Holocene and Pleistocene moraines. A summary based on 20 sandstone and conglomerate boulders at each of 40 sites is presented in Table 6.1. Larger surface pits, greater relief on conglomerate pebbles, and a more frequent occurrence of weathering rinds and split boulders distinguish these surfaces on rock glaciers from those of late Holocene cirque glacier moraines. Anomalously

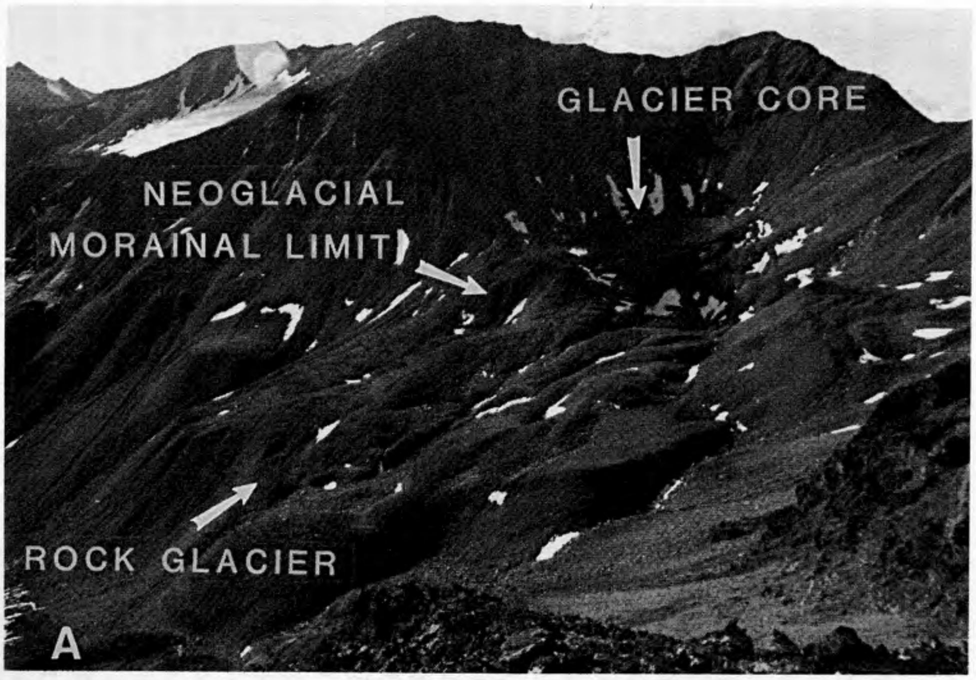
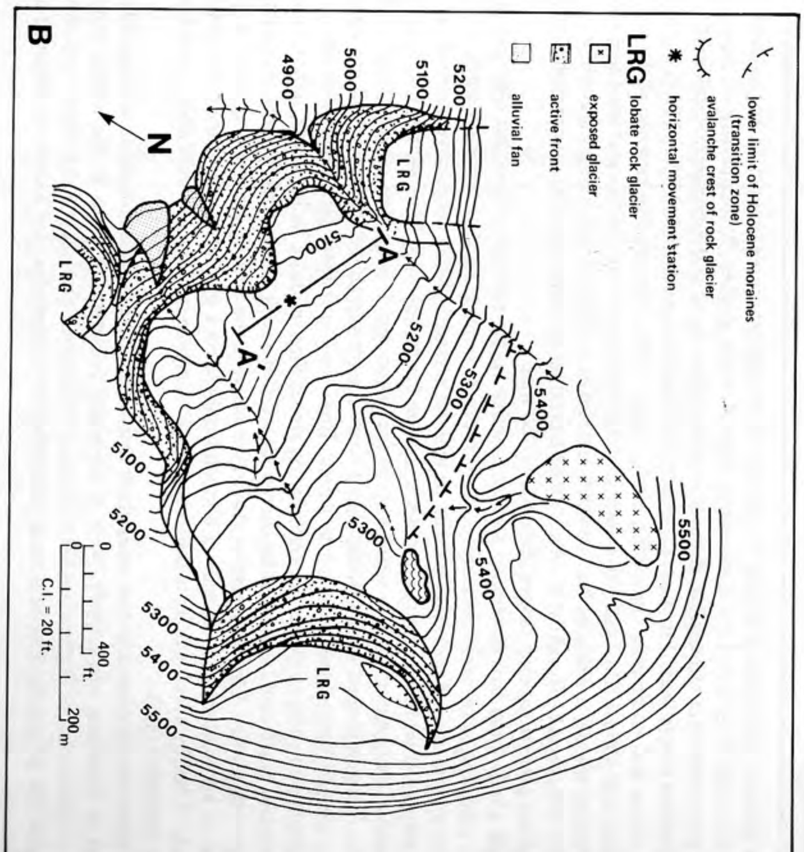


Figure 6.10 A) View southeast from Continental Divide toward Pika rock glacier (photography by M.P. Bruen). B) Topographic map of Pika rock glacier, transition zone, and overriding lobate rock glaciers. Position of traverse and cross section (Fig. 6.11A) is marked A - A'.



high pitting and pebble relief on the two middle Holocene moraines that were examined make comparisons with rock glaciers difficult. The large difference in some boulder weathering characteristics between these middle Holocene moraines and rock glaciers may be the result of surface movement of the rock glaciers. In addition, stones on rock glaciers and late Pleistocene moraines may have had surfaces that have undergone exfoliation, creating fresh boulder faces.

Table 6.1 Comparison of boulder weathering for moraines and rock glaciers of the central Brooks Range.

Rock glaciers in the central Brooks Range can be divided into three groups: 1) tongue-shaped deposits cored by glacier ice and extending beyond cirque glaciers, 2) tongue-shaped deposits also associated with cirques but without proven glacier cores and commonly dominated by longitudinal ridges, and 3) smaller, ice-cemented lobate masses extending 15 to 150 m beyond talus cones and commonly coalescing along valley walls. Seventy-five percent of the rock glaciers, and almost all of the active forms, occur on the north side of the east-west trending continental divide at altitudes between 900 and 2,000 m. These rock glaciers are within the zone of continuous permafrost in which mean annual temperature at 1,500 m approaches -10° C and annual precipitation ranges from 400 to 700 mm.

Rock glaciers are best developed and most active below resistant ridges that also include large percentages of easily weathered, platy rocks to provide insulation for subsurface ice. Active tongue-shaped rock glaciers with or without exposed glacier cores have a strong N to NE orientation which minimizes insolation. Lobate forms, however, have aspects that face all directions, demonstrating less sensitivity to insolation and a lower ice content relative to debris. Tongue-shaped rock glaciers occur over a narrower altitudinal range and are more geographically restricted than lobate forms. Both tongue-shaped and lobate deposits are preserved 50 to 100 m higher on south-facing slopes than on those facing north, although no correlation was found between solar energy received at a rock glacier and the present activity of the rock glacier. Little correlation also exists between the activity state and a) bedrock, b) slope, c) orientation, or d) latitude or altitude for those rock glaciers north of the Continental Divide. Whether a rock glacier is active appears to depend most upon the availability of debris from headward cliffs.

Detailed measurements in two areas show active and inactive lobate deposits average 50 to 25 m in thickness respectively, with a minimum thickness of 40 m in the active cases. Large, spoon-shaped depressions between many lobate rock glaciers and their headward cliffs suggest the presence of deteriorating subsurface ice; interstitial ice has been observed in surface pits.

Most tongue-shaped rock glaciers grade upslope to transition zones marked by Neoglacial moraines. Below the transition zone they exhibit various transverse lineations that result from flow within the glacier core and may have little relation to short-term climatic changes. Longitudinal ridges may also be present where talus is supplied over the long term at rates matching rock-glacier flow. Exposures of the glacier core show oriented debris bands and elongate bubbles, characteristic of glacier flow.

Tongue-shaped and lobate rock glaciers were initiated by increased mass-wasting following late Pleistocene deglaciation. Although most tongue-shaped forms were preserved through the Hypsithermal, only those extending to lower elevations avoided complete incorporation by late Holocene glacial advances. Significant soil development and boulder weathering, along with extensive lichen growth, characterize surfaces of rock glaciers. Surveys document present surface movement on the order of only a few centimeters per year or slower, which contributes to the preservation of surface features.

Table 6.1 Comparison of boulder weathering for moraines and rock glaciers of the central Brooks Range.

Parameter	Late Holocene Moraines (n=14)† ~60-1,400 yr BP††	Mid-Holocene Moraines (n=2)† ~3,500-7,000 yr BP†††	Rock Glaciers†† (n=3)	Latest Pleistocene Moraines (n=11)† ~11,500-12,500 yr BP
mean maximum rounding (mm)	2.8	11	3.1	19
mean maximum pitting (mm)	2.4	22	5.2	7.6
percent of boulders with rinds	29	55	55	52
mean rind thickness (mm)	0.7	1.1	0.9	0.9
mean pebble relief (mm)	0.4	3.9	0.8	1.0
percent split boulders	10	25	30	24

† Two groups of 20 boulders measured at most sites
†† Includes two tongue-shaped and one lobate form
††† Dates from lichenometric mapping (Ellis and Calkin 1984; Haworth, unpub.)

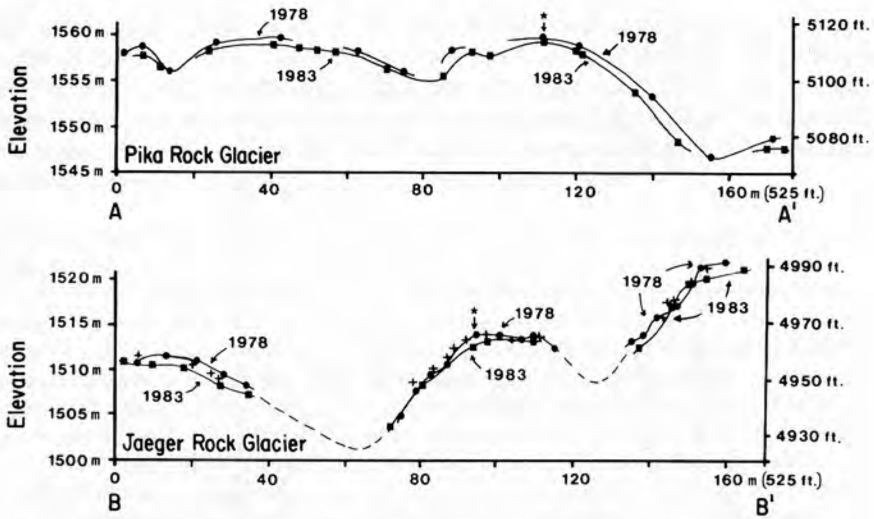


Figure 6.11 A) Surface displacement along fixed traverses of Pika rock glacier, and B) Jaeger rock glacier. Elevations were measured by theodolite shots on stadia held at points indicated. Horizontal movement was measured at positions marked with asterisk.

We suggest that some of the lobate rock glaciers formed soon after late Pleistocene deglaciation and have retained their characteristic profile through any early to middle Holocene warm intervals that may have occurred. In a few cases, lobate forms are overriding tongue-shaped rock glaciers (e.g., Fig. 6.10).

The maximum age of tongue-shaped rock glaciers is not well characterized by lichen diameters. The occurrence of moraines as old as 2,500 years BP within transition zones above rock glacier tongues yields at least a minimum age for the rock glacier. A few rock glacier tongues, such as Jaeger and Pika, provide minimum lichenometric ages approaching the middle Holocene. Rates of modern surface movement give conflicting evidence of age; however, the relative warmth of the twentieth century, and especially of the 1970s and 1980s may affect movement rates. Tongue-shaped rock glaciers, like many lobate forms, may have been initiated in latest Pleistocene or early Holocene time; if this is the case, they are the only evidence of glacier development at this time (Ellis and Calkin 1984). Our evidence also does not preclude middle Holocene formation of some rock glacier tongues and even some lobate forms, perhaps coincident with the expansion of cirque glaciers in the middle Holocene.

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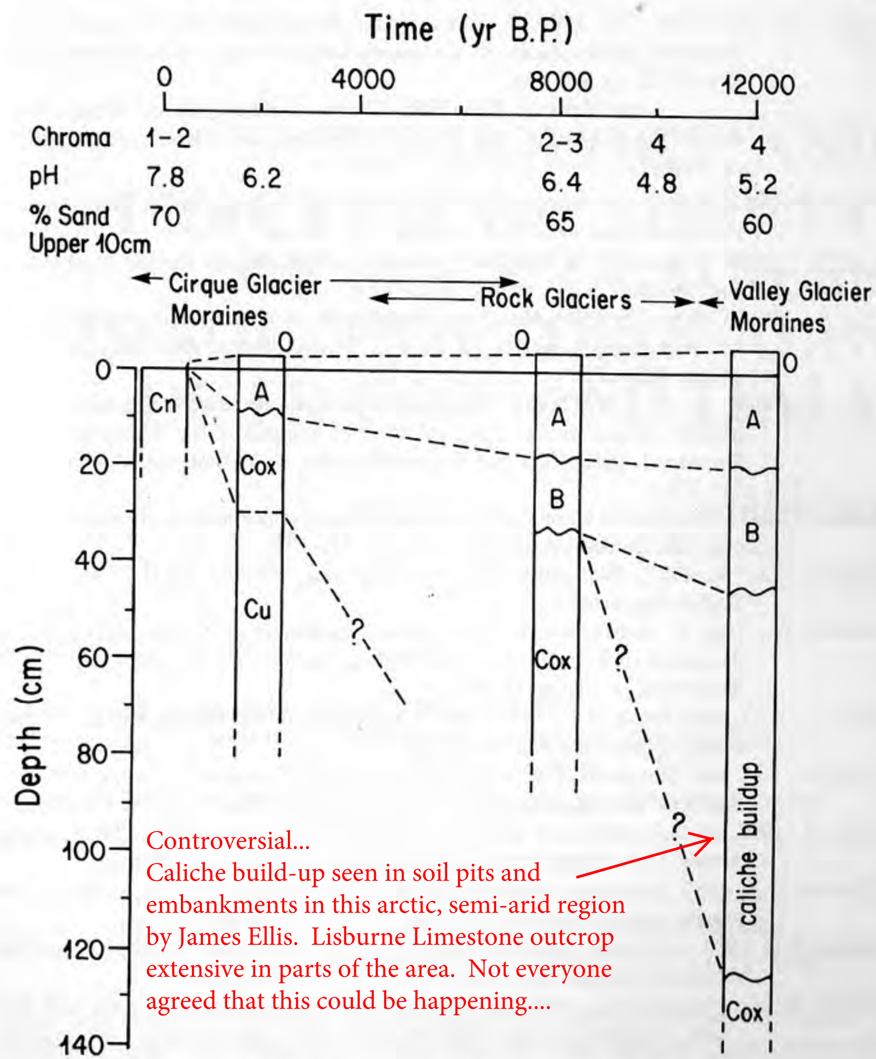

Figure 6.12 Generalized schematic of soil development from 0 to 12,000 year BP on moraines and rock glaciers of the Atigun Pass area. An oxidized C horizon is designated Cox and a seemingly unweathered C horizon by Cn. Caliche build-up apparently depends on influx of calcareous loess. Adapted from Ellis and Calkin (1983).

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