Environments and soils of holocene moraines and rock glaciers, central Brooks Range, Alaska

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1 ABSTRACT

Field measurements and multivariate analyses of over 50 cirque glaciers confirm that Neoglacial moraines without ice cores occur in cirques with low input of headwall debris and extensive direct-radiant energy during the ablation season. Most moraines are cored with glacial ice, having formed in environments with either minimal solar energy and variable input of supraglacial debris or high inputs of both debris and solar energy. Neoglacial transition zones upslope of rock glacier tongues are equivalent to glacier-cored moraines but are ~100 m lower in altitude. A few form where as little as 1% direct radiation is received and vertical headwall exposures exceed 400 m.

Cirque-glacier deposits in granites were more extensively glacier cored than those studied in sedimentary terrain. Their cirque environments differ respectively in solar energy received (65 ± 20% versus 85 ± 10%), potential debris supply as measured by height of bedrock in cirque cliffs (245 ± 135 m versus 130 ± 90 m), and ELA depression during Neoglacial maxima (130 ± 60 m in contrast with 70 ± 35 m).

Soil development helps differentiate these Holocene deposits in sedimentary terrain. Thin organic horizons and oxidation to depths of 15 cm occurs in <400 years on Neoglacial moraines. On moraines lichenometrically dated ~2000 B.P. the organic horizons reach 3 cm thicknesses, A horizons extend to depths of 10 cm and oxidized C horizons to 20 to >50 cm. Rock glacier tongues, downslope of Neoglacial transition zones, had upper surfaces stabilized by early Holocene time based on relative-dating criteria including soil pH values of 4.8-6.4. These are intermediate between values of 7.5-8.0 for freshly deposited till and 4.7-5.4 for late Pleistocene moraines downvalley.

2 INTRODUCTION

Cirque glaciers across the central Brooks Range have similar dimensions and orientations, yet varying environments in sedimentary and granitic terrains promote formation of different types of glacial deposits. The objectives of this study are to physically differentiate and explain the setting of alpine glacial deposits by 1) completing an environmental and morphological analysis of Neoglacial deposits, and 2) developing a preliminary chronosequence of soil development on moraines and rock glaciers. Both objectives complement our on-going glacial chronologic studies (Calkin & Ellis 1980). This paper also considers the validity of combining chronologies found on various landforms to delineate glacial and climatic variations through time in this most northerly mountain mass of western North America.

The Brooks Range is an east-west trending mountain system lying above the Arctic Circle which has been repeatedly glaciated since at least early Pleistocene time (Fig. 1; Hamilton 1977). Most valleys in the central Brooks Range were free of Pleistocene ice by the beginning of Holocene time (Hamilton & Porter 1975). Three field areas within the central Brooks Range were studied. The Atigun Pass area was chosen for the main portion of the work because of easy access to a large number of glaciers located along the trans-Alaska oil pipeline corridor (Fig. 2; Ellis & Calkin 1979). The centrally-located Anaktuvuk

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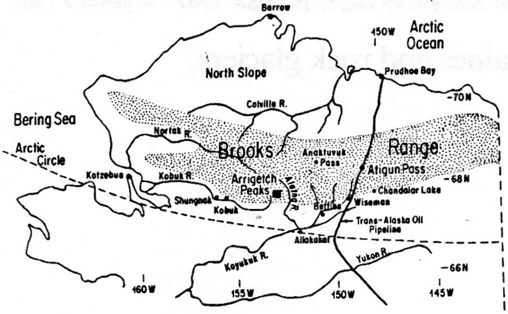


Figure 1. Location map of the central Brooks Range, northern Alaska. Cirque glaciers and their deposits near Atigun Pass, Anaktuvuk Pass, and the Arrigetch Peaks form the basis of this study.

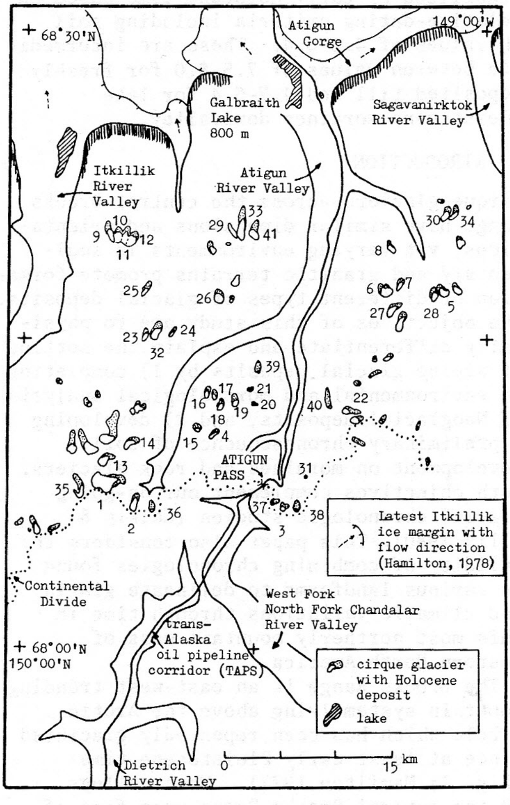


Figure 2. Location map of the Atigun Pass area, east-central Brooks Range. Forty-one cirque glaciers and their deposits were mapped in the field with 1-12 identified as non ice-cored moraines (M), 13-34 as ice-cored (Mg) and glacier-cored moraines (MG), and 35-41 as glacier-cored rock glaciers with Neoglacial transition zones (TRGC) upslope of early Holocene rock glacier tongues.

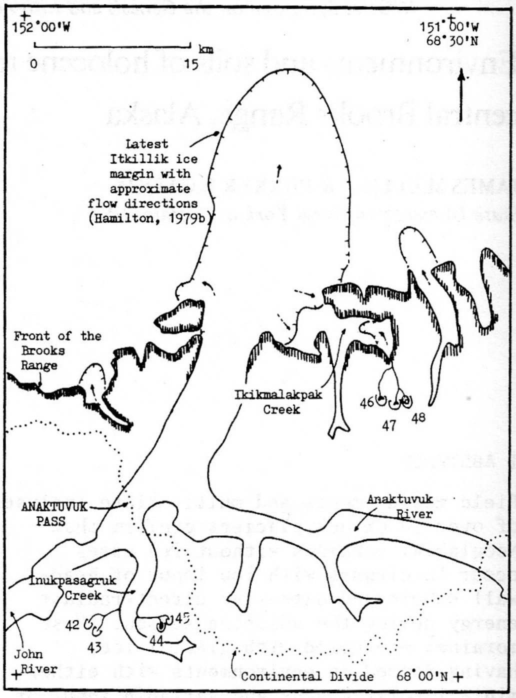


Figure 3. Location map of the Anaktuvuk Pass area, central Brooks Range. Cirques 42-47 were empty and of late Pleistocene age or had rock glaciers without exposed glacier cores. A glacier-cored moraine (MG) was mapped in cirque no. 48 and used in this study.

Pass is significant because of previous reconnaissance work undertaken on deposits of cirque glaciers (Fig. 3; Detterman et al. 1958; Porter 1966). Glaciers in the Arrigetch Peaks (Fig. 4), the third area studied, are of special interest because of their different climatic and lithologic setting (Hamilton 1965; Ellis et al. 1981).

Some of the basic questions considered within the objectives of this study are as follows:

a) Which environmental factors best discriminate between different types of glacier deposits?

b) Are there physical differences between cirque-glacier deposits in the three study areas which may cause significant differences in chronologies?

c) Which soil properties are consistent with lichenometry and other dating techniques as age indicators in sedimentary terrain?

Preliminary studies of cirque- and glacier-distribution patterns have been undertaken by the U.S. Geological Survey (1978) for the Brooks Range (scale 1:250,

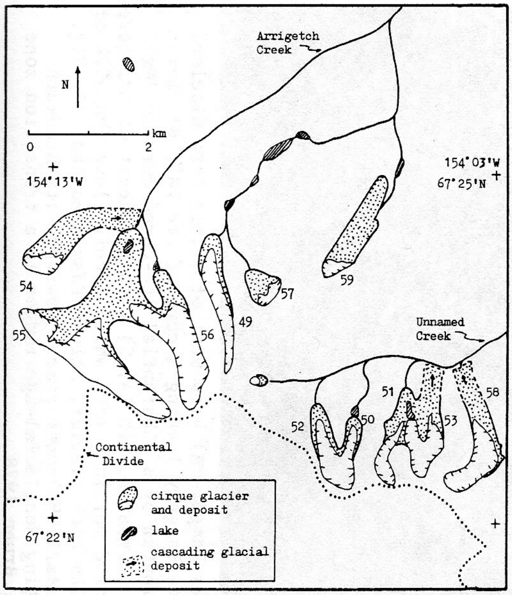


Figure 4. Location map of the granitic Arrigetch Peaks, west-central Brooks Range. Moraines without cores of ice (M, 49-51), moraines cored with glacier ice (MG, 52-58), and a glacier-cored rock glacier with an upslope Neoglacial transition zone (TRGC, 59) were mapped.

000) and by Porter (1966) in the Anaktuvuk Pass area. In addition, more detailed studies of glaciers and their downslope deposits have been done for the Atigun Pass area (Ellis & Calkin 1979) and the Arrigetch Peaks (Ellis et al. 1981). However, to our knowledge no environmental or soil analysis has been done on cirque glacier moraines and rock glaciers in the valley heads of the central Brooks Range.

Four types of cirque glacier deposits are found in the central Brooks Range (Fig. 5A-D). Three out of four cirque glaciers examined are associated with moraines which are cored with ice (Mg, Fig. 5B). In some cases glacial ice is exposed beneath a thin cover of debris (MG, Fig. 5C). The remaining cirque glacier moraines either have formed without ice cores (M, Fig. 5A) or are situated as glacier-cored transition zones (TRGC, Fig. 5D) upslope of rock glacier tongues. The crescentic ridges of transition zones are of Neoglacial age in the central Brooks Range (Ellis 1982). In contrast, the rock glacier tongues are of early Holocene age and show evidence of en mass downvalley movement.

3 GEOGRAPHICAL SETTING AND CLIMATE

The three study areas (Figs. 2-4) are above the boreal spruce tree line and within the zone of continuous alpine permafrost (Ferrians 1965). Vegetation above tree line, at 600 to 700 m altitude, consists of shrubby tundra with alder and dwarf birches which gives way to a mixed, herbaceous-dwarf tundra vegetation at higher altitudes (Brown 1980: 36). Bouldery, cirque glacier moraines are unvegetated when located near receding ice margins; however, lichens, algae, mosses, and grasses can cover these deposits and rock glaciers to varying degrees.

The cirque glaciers are defined as subpolar because firn is saturated with water during the ablation season. In addition, internal ice temperatures were measured as about -1°C in an upper cirque of a glacier farther east in the Brooks Range (Orvig & Mason 1963). The glaciers are cold because meltwater streams meander on their surfaces (and do not descend to the bed) (Paterson 1969: 178).

3.1 Atigun Pass area

Most of the higher peaks and glacierized cirques in this region are composed of siliceous conglomerates and sandstones or quartzites of the resistant Devonian Kanayut Conglomerate (Brosgé et al. 1979). These peaks rise to altitudes of 2300 m. The northernmost portion of this region is made of a thick sequence of the crystalline Lisburne Limestone. Less resistant, phyllitic Hunt Fork Shale dominates immediately south of the Continental Divide (Fig. 2). At least 130 cirque glaciers lie within this region; 97% of these occur north of the Divide where the severe arctic climate of the North Slope dominates.

Climatic data collected along the trans-Alaska oil pipeline system (TAPS) since 1975 (Brown 1980) indicate temperatures above freezing from May through September in the Pass area, but low insolation during the rest of the year allows temperatures to reach -45°C. The mean annual temperature at Atigun Pass (1440 m) is estimated about -14°C. Glacier snow pits (Bruen 1980) and TAPS data suggest annual precipitation at Atigun Pass ranges between 400 and 700 mm of which about 50% is snow.

3.2 Anaktuvuk Pass area

Anaktuvuk Pass is at an altitude of only 650 m (Fig. 3); there are fewer glacierized cirques here than around the higher Atigun Pass area. Field work was undertaken in cirques supported by the Kanayut Conglomerate. Climatic data are meager, but Porter (1966) estimated that the mean an-

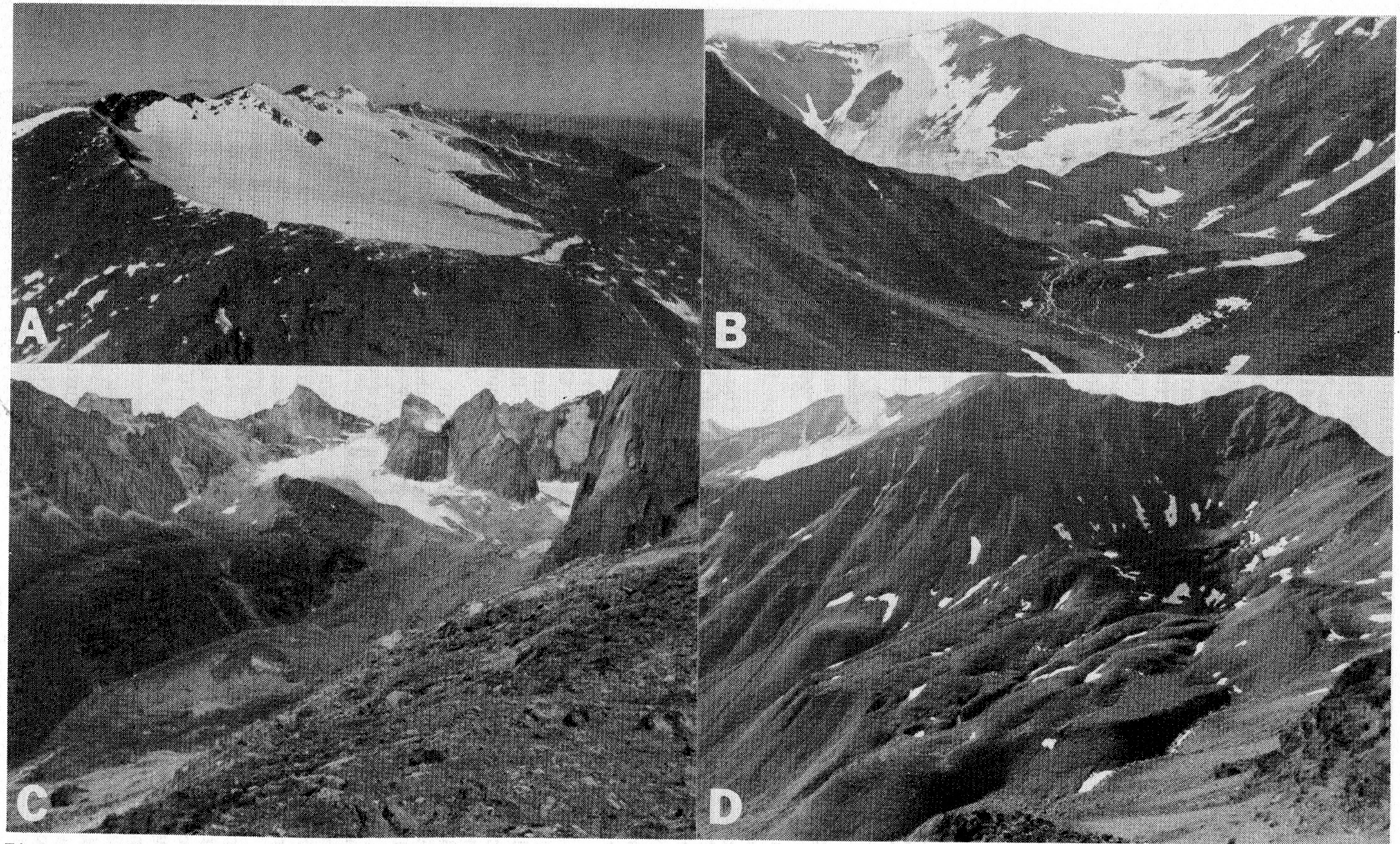


Figure 5. Types of cirque glacier deposits found in the central Brooks Range: A) View west of Triple East Glacier, Atigun Pass area (no. 12, Fig. 2) which leads downslope into a moraine largely lacking a core of ice (M); B) View south of Cisco Glacier, Atigun Pass area (no. 26, Fig. 2) which is fronted by a substantial ice-cored moraine (Mg). Note marked increase in height of bedrock exposed in cirque cliffs as compared with 5A; C) View southeast of Arrigetch glaciers (nos. 55, 56, Fig. 4). These lead downslope into glacier-cored moraines (MG) which receive less than 55% of the potential direct radiation energy on 24 July; D) View south of Pika Rock Glacier, Atigun Pass area (no. 37, Fig. 2) which has an upper surface that largely dates to stabilization by early Holocene time. However, its headward glacier core has reacted to Holocene climatic deteriorations, depositing Neoglacial-age ridges in a transition zone (TRGC) upslope of the undisturbed rock glacier tongue. Photo by M.P. Bruen 1978.

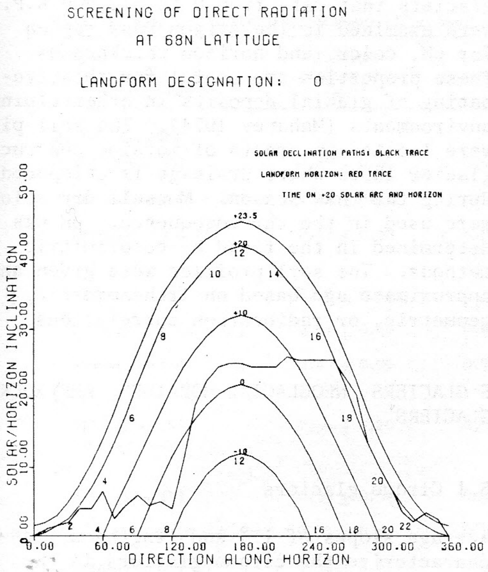


Figure 6. Topographic horizon of Grizzly Glacier (no. 3, Fig. 2) superimposed on paths of the sun at lat. 68°N for different solar declinations (-10° ≅ 24 February or 20 October, 0° ≅ 21 March or 23 September, ±10° ≅ 16 April or 28 August, +20° ≅ 21 May or 24 July, +23.5° ≅ 21 June). In this study the +20° declination was used for terrain screening calculations as it represents a typical part of the ablation season. The hours of the day are plotted in two-hour increments along the trace of the +20° solar path. Sunrise(s) and sunset(s) are determined by following the horizon trace from left to right. When the horizon crosses and goes inside the solar path it means the sun has just appeared above the horizon ("sunrise"). When the horizon trace crosses and goes outside the sun path the sun is blocked from view ("sunset"). In this example, the sun initially appears at 1.6 hrs of the 24 hr day and radiation is received at the moraine until 16.9 hrs when the sun is blocked. The sun reappears at 18.9 hrs and shines on the deposit until 22.2 hrs into the day. Sunshine duration totals 18.6 hours on 24 July; this converts to 93% of the potential energy available to a horizontal, unscreened surface at this latitude.

nual temperature and annual precipitation at the pass was about -10°C and 300 mm. Only one cirque was mapped with an exposed headward glacier (no. 48, Fig. 3); the data for the deposit was combined with the 41 ice masses mapped at Atigun Pass (Fig. 2).

3.3 The Arrigetch Peaks

The Arrigetch Peaks occupy an area of about 110 km^2 on the south flank of the west-central Brooks Range (Fig. 4) and consist of granitic orthogneiss of Cretaceous age (Nelson & Grybeck 1980). The area is characterized by nearly vertical slopes. These protrude as much as 1000 m above the more erodible limestone, shale, and schist of the surrounding terrain, forming peaks to altitudes of 2150 m.

The moisture regime of the Arrigetch area appears to be transitional between the wetter maritime conditions of the western Alaskan coast and the relatively dry continental climate of interior Alaska (Ellis et al. 1981). Coastal storms commonly invade from the west via the broad Noatak and Kobuk valleys (Fig. 1). The sparse climatic data and widespread cover of Trentepholia iolithus algae on the granitic moraines (Ellis et al. 1981) suggest the Arrigetch Peaks is slightly warmer and wetter than the more easterly Atigun Pass area.

4 METHODS

Altitudes were taken from 1:63,360 and 1:250,000 topographic sheets which display contour lines at 100 ft (30 m) and 200 ft (60 m) intervals, respectively. Over 50 cirque glaciers and their deposits were analyzed in the field for area, altitude, aspect, topographic horizon, receipt of direct radiation energy, and potential supraglacial-debris supply as measured by height of bedrock exposed above the glacier in surrounding cirque cliffs. All were planimetrically reconstructed to their previous shape during Neoglacial maxima based on surficial geologic and lichenometric mapping (Ellis 1982). Equilibrium-line altitudes (ELA's) for Neoglacial maxima were determined with an assumed accumulation area to ablation area ratio of 2:1 or a ratio of accumulation area to total glacier area (AAR) of 0.67. ELA depression values were calculated from present mean glacier altitudes to the ELA's reconstructed for Neoglacial maxima.

The shadowing effect of surrounding cirque cliffs and mountainous terrain on the different types of glacial deposits was analyzed in the field by plotting the horizon at 015° increments (24 horizon inclinations per survey site) with a Brunton compass attached vertically to a tripod. Each landform's horizon was superimposed upon the sun's 24 hour path at +20° declination (~24 July) to determine times of sun appearance and disappearance (Fig. 6). This

Table 1. Variables used in multivariate analysis of glacial landforms.

Variable	Explanation
NSUN	Direct radiation energy received (%)
NELA	Altitude of the ELA during Neoglacial maxima (m)
NHEAD	Height of bedrock exposed in cirque cliffs (potential supraglacial debris supply, m)
NLAT	Latitude of glacial landform (°)
NDROP	Amount of ELA depression as measured from present mean glacier altitude to altitude attained during Neoglacial maxima (m)
NAREA	Area involved during Neoglacial maxima (km^2)

solar path (List 1951) was chosen to best characterize the glacial ablation period.

Superimposing the landform's horizon upon the sun's path, as it would be on 24 July, establishes the duration of direct radiation received at each site (Fig. 6). The amount of direct radiation energy received at each landform during these times of sun appearance was then calculated (Ellis 1982), and the sum compared to that measured at lat. 68°N on unscreened horizontal surfaces under clear skies (Kondratyev 1973: 304-305). This measured amount (~590 cal cm^{-2} day^{-1}) is treated as the potential unscreened energy and assigned a value of 100%. The comparison of the actual amount of energy received to this potential energy provides a measure of the reduction in direct solar energy due to screening by surrounding terrain. Albedo of the moraines was considered constant. A similar study on one valley glacier has been carried out in the northeastern Brooks Range with a theodolite (Wendler & Ishikawa 1974).

Increasing slope inclination in a more northerly aspect also reduces solar insolation (Ellis et al. 1981, Table 2). The effects of aspect, slope, and terrain screening were combined to provide a measure of the total receipt of direct radiation energy at each cirque glacier deposit during a typical part of the ablation season.

Morphological and environmental variables (Table 1) were analyzed in order to detect those that were most capable of distinguishing between the different types of cirque glacier moraines (Fig. 5A-D). The results of linear discriminant analysis (Klecka 1975) on 43 sedimentary and 11 granitic moraines are presented in this paper. The technique indicates the relative contribution of each variable (Table 1) to discriminate between the previously defined groups of glacial deposits (M, Mg/MG, TRGG) and between moraines in sedimentary and granitic terrains.

Twenty-three soils on moraines and rock glaciers that date from 0 to ~12,500 B.P. were examined in the Atigun Pass region for pH, color, and horizon thicknesses. These properties are useful for relative-dating of glacial deposits in other alpine environments (Mahaney 1974). The soil pits were located on crests of moraine and rock glacier lobes where drainage is unimpeded during the thaw season. Munsell dry colors were used in the chronosequence. pH was determined in the field by colorimetric methods. The soil profiles were given an approximate age based on lichenometric, geometric, or radiocarbon correlations.

5 GLACIERS, NEOGLACIAL MORAINES, AND ROCK GLACIERS

5.1 Cirque glaciers

Average slopes of 17° and lengths of 740 m characterize the cirque glaciers in the Atigun Pass area (Ellis & Calkin 1979); average slopes of 16° and lengths of 1280 m were measured for 11 glaciers in the granitic Arrigetch Peaks (Ellis et al. 1981). The Atigun and Anaktuvuk glaciers average ~1800 m in mean altitude and are all above 1500 m while those in the west-central Arrigetch have mean altitudes about 300 m lower. Glaciers across the central Brooks Range are very strongly oriented north-northeast to minimize insolation, demonstrating marginal conditions and highly significant climatic control on glacierization during Holocene time. Relatively debris-free areas of glaciers average ~0.4 to 0.5 km^2; however, they range from 0.1 to over 2.0 km^2 (Table 2). Cirque glaciers averaged only ~0.65 km^2 in area during Neoglacial maxima.

5.2 Moraines without cores of ice

Moraines which lack substantial ice cores (M) have subtle relief and are the most stable type of cirque glacier deposit (Fig. 5A). Those in sedimentary terrain receive ~94% of the potential direct radiation energy on 24 July while those in the granitic Arrigetch gain only ~85% (Table 3). In both terrains these deposits have low topographic horizons (minimal shading) and little bedrock exposed in cirque cliffs (Table 2) as compared with ice- or glacier-cored moraines.

Table 2. Area and altitudinal summary of present and Neoglacial maxima cirque glaciers.

Type lithology no. examined	Present glacier area (km^2)	Neoglacial maxima area (km^2)	Exposed headwall (m)	Neoglacial maxima ELA (m)	ELA depression (m)
M, Mg, MG, TRGC					
All (n = 53)	0.45 ± 0.40	0.64 ± 0.64	153 ± 109	-	82 ± 49
Sedimentary (n = 42)	0.44 ± 0.37	0.58 ± 0.42	129 ± 89	1730 ± 85	70 ± 35
Granitic (n = 11)	0.49 ± 0.50	0.87 ± 0.83	246 ± 134	1340 ± 30	128 ± 62
M					
All (n = 15)	0.58 ± 0.44	0.79 ± 0.54	72 ± 55	-	78 ± 43
Sedimentary (n = 12)	0.61 ± 0.49	0.82 ± 0.60	58 ± 49	1795 ± 90	57 ± 24
Granitic (n = 3)	0.45 ± 0.08	0.71 ± 0.23	100 - 180	1295 - 1375	148 ± 47
Mg					
All (n = 18) -Sedimentary-	0.36 ± 0.20	0.53 ± 0.26	148 ± 70	1740 ± 50	79 ± 35
MG					
All (n = 12)	0.55 ± 0.54	0.91 ± 0.86	190 ± 122	-	119 ± 57
Sedimentary (n = 5)	0.52 ± 0.49	0.77 ± 0.67	100 ± 0	1715 ± 50	97 ± 54
Granitic (n = 7)	0.55 ± 0.61	1.00 ± 1.00	247 ± 125	1345 ± 30	135 ± 58
TRGC					
All (n = 8)	0.28 ± 0.36	0.49 ± 0.43	250 ± 139	1640 ± 80	40 ± 40
M, Mg, MG					
All (n = 45)	0.48 ± 0.40	0.72 ± 0.57	137 ± 95	-	89 ± 48
Sedimentary (n = 35)	0.47 ± 0.37	0.59 ± 0.42	112 ± 70	-	75 ± 35
Granitic (n = 10)	0.53 ± 0.50	0.92 ± 0.84	226 ± 122	1345 ± 30	139 ± 53

5.3 Ice-cored moraines

Ice-cored moraines (Mg) lack a visible ice core, yet have marked relief and sharp-crested fronts in the downvalley direction (Fig. 5B; Østrem 1971). They can grade into zones without ice cores along continuous ridges. Ice-cored moraines were only mapped in the Atigun Pass area (Fig. 2); in the other two field areas glacier cores were clearly exposed beneath the till. Considerable overlap in planimetry and terrain screening values (Tables 2, 3) between these moraines and those visually-cored with glaciers (MG, Fig. 5C) substantiates grouping them together in subsequent statistical analyses. Therefore, all ice cores are considered to be made of glacier ice.

5.4 Glacier-cored moraines

Cirque glacier deposits in the granitic Arrigetch Peaks are more extensively cored with glacier ice than those studied in sedimentary terrain. Glacier-cored moraines (Mg/MG) in sedimentary terrain acquire ~83% of the potential solar energy. In contrast, eight measured in granite receive only ~61% of the potential energy (Table 3). The potential debris supply available to glacier-cored moraines is greater in the deeper cirques of the Arrigetch where 245 ± 125 m of bedrock is exposed in cirque cliffs as compared with 140 ± 65 m for similar deposits in sedimentary terrain.

5.5 Neoglacial transition zones of glacier cored rock glaciers

Eight Neoglacial transition zones (TRGC) were mapped; they average 250 ± 140 m of bedrock exposed in cirque cliffs. Terrain screening measurements demonstrate mean horizons of ~20° and average receipts of direct radiation about 73%. However, a few transition zone moraines form where as little as 1% solar energy is received and/or vertical headwall exposures exceed 400 m. In the east-central Brooks Range, glaciers fronted by transition zones (TRGC) that have partially overridden downslope rock glacier tongues are ~100 m lower in altitude than those glaciers fronted by only morainal loops (M, Mg, and MG; Ellis

Table 3. Terrain screening and exposure of glacial landforms.

Type of deposit lithology no. of sites	Site altitude (m)	Duration (hr)	Potential energy blocked (%)	Exposure gain or loss (%)	Total direct energy received (%)	Mean horizon (°)	Maximum horizon (°)
M							
All (n = 17)	1623 ± 201	17.1 ± 3.1	-6.6 ± 5.9	-1.3 ± 1.6	92.1 ± 6.2	13.5 ± 4.4	26.4 ± 5.6
Sedimentary (n = 14)	1687 ± 126	17.9 ± 2.9	-4.8 ± 4.5	-1.4 ± 1.7	93.8 ± 5.2	12.0 ± 3.2	24.2 ± 3.1
Granitic (n = 3)	1267 ± 29	13.8 ± 1.4	-14.8 ± 4.1	-0.7 ± 0.6	84.5 ± 4.6	20.3 ± 1.7	36.7 ± 0.8
Mg							
All (n = 20) -Sedimentary-	1675 ± 66	12.6 ± 2.2	-15.3 ± 7.2	-2.5 ± 2.2	82.3 ± 7.7	18.2 ± 2.4	30.7 ± 3.4
MG							
All (n = 17)	1429 ± 215	11.4 ± 3.5	-24.1 ± 15.1	-2.4 ± 1.8	73.5 ± 15.6	20.5 ± 5.2	36.1 ± 10.2
Sedimentary (n = 9)	1608 ± 77	13.9 ± 2.2	-12.8 ± 6.1	-2.3 ± 1.7	84.9 ± 6.2	16.4 ± 3.3	28.0 ± 5.1
Granitic (n = 8)	1227 ± 106	9.5 ± 2.2	-36.7 ± 11.4	-2.5 ± 2.1	60.8 ± 12.6	25.2 ± 1.5	45.2 ± 5.5
TRGC							
All (n = 16)	1490 ± 174	10.6 ± 3.8	-25.5 ± 25.4	-1.9 ± 1.8	72.6 ± 24.9	20.4 ± 4.9	33.4 ± 7.1
Sedimentary (n = 14)	1541 ± 100	11.4 ± 3.0	-19.2 ± 16.3	-2.1 ± 1.9	78.8 ± 16.1	19.1 ± 2.9	31.5 ± 4.8
Granitic (n = 2)	1000 - 1270	8.4 - 1.5	-41.6 - -99	-1 to 0	57.4 to 1	23.7 - 34.5	44.0 - 50.5

& Calkin 1979).

5.6 Reconstructed ELA's

ELA's reconstructed for Neoglacial maxima with AAR = 0.67 average 1755 ± 55 m for cirque glaciers fronted by morainal deposits (M, Mg, MG) and 1640 ± 80 m for those leading into rock glacier transition zones (TRGC) in the Atigun Pass area. Moraines without cores of ice (M) have the highest, steady-state ELA's averaging 1795 ± 90 m. These east-central ELA's are significantly higher than those found in the Arrigetch Peaks where ELA's for glacier-cored moraines averaged 1345 ± 30 m.

The lowering of ELA from the mean altitude of present glaciers fronted by moraines (excluding transition zone deposits) was 75 ± 35 m in the Atigun/Anaktuvuk region and 140 ± 55 m in the more westerly Arrigetch. For glaciers fronted by the transition zone moraines, an ELA lowering of only ~40 m occurred during Neoglacial maxima (Table 2).

6 DISCRIMINATION OF NEOGLACIAL DEPOSITS

A trend of decreasing solar energy received (92% to 73%) and increasing head- and sidewall horizons (13° to 20°) generally characterizes the gradation (Fig. 7) from non ice-cored moraines (M) through glacier-cored moraines (MG). However, measurements on Neoglacial transition zones (TRGC) of rock glaciers are scattered in a plot of radiation versus horizon (Fig. 7). A more continuous transition from M through MG to TRGC is revealed when receipt of direct radiation energy is plotted against estimated height of bedrock in cirque cliffs (Fig. 8). This figure also demonstrates that moraines without ice cores (M) are formed in sedimentary terrain where potential debris is less than 150 m high in cirque cliffs and greater than 83% of the potential solar energy is received. The marked environmental contrast between the cirques of the Arrigetch moraines and those in sedimentary terrain is well shown in Figure 8.

Moraines without ice cores, glacier-cored moraines and transition zones were distinguished with linear discriminant analysis using four of six environmental and morphological variables (Table 1). Analysis 1 (Fig. 9) utilized latitude (LAT), Neoglacial maxima ELA (NELA), direct radiation energy received (NSUN), and potential debris supply (NHEAD). It indicates the importance of the Neoglacial maxima ELA in controlling the type of moraine deposited. The higher this steady-state ELA the more likely moraines without ice cores (M) will be deposited. The

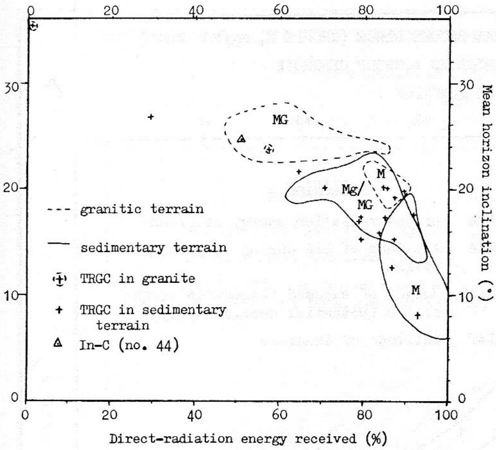


Figure 7. Plot of horizon inclination versus percent of direct radiation energy received for moraines without cores of ice (M), moraines cored with glacier ice (Mg/MG), and glacier-cored rock glaciers with transition zones (TRGC). The deposits are distinguished according to lithology in the central Brooks Range: sedimentary terrain of Atigun and Anaktuvuk and granitic terrain of the Arrigetch Peaks.

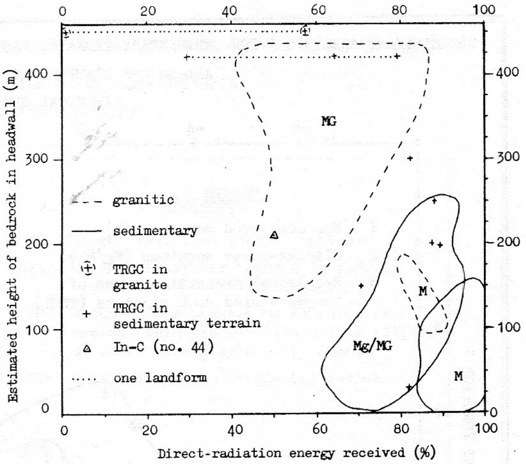


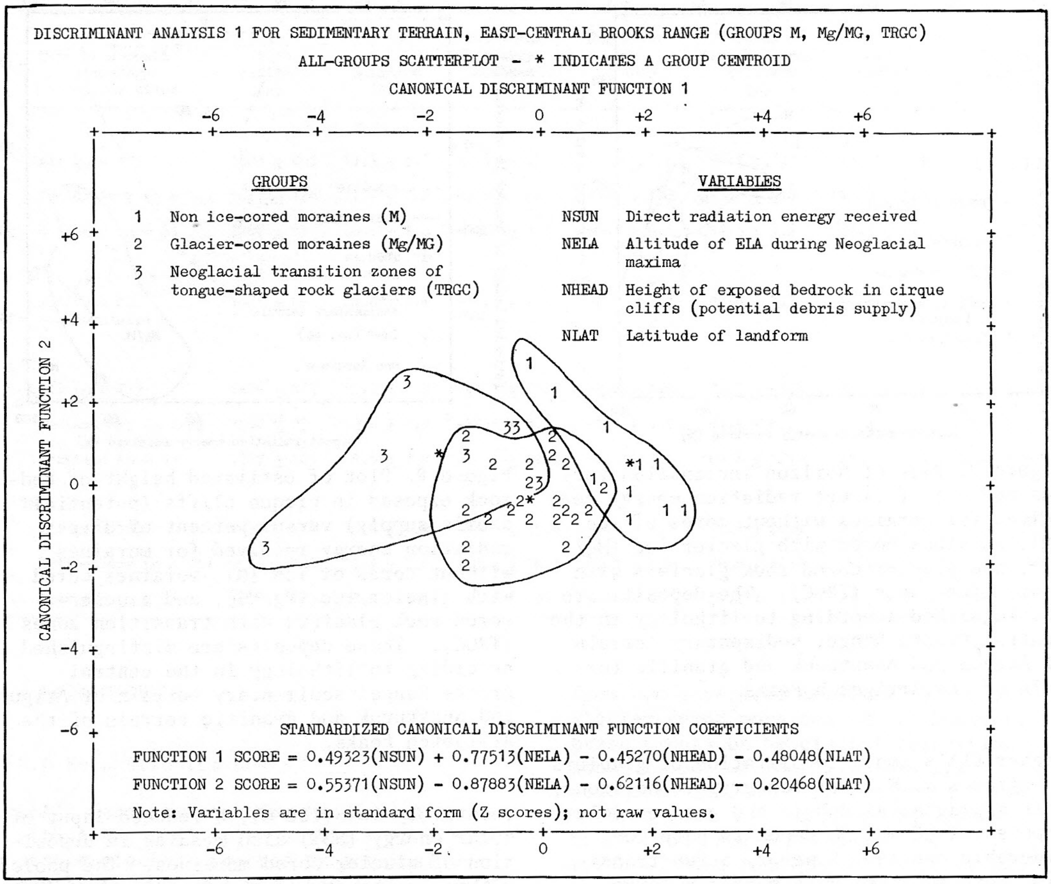
Figure 8. Plot of estimated height of bedrock exposed in cirque cliffs (potential debris supply) versus percent of direct radiation energy received for moraines without cores of ice (M), moraines cored with glacier ice (Mg/MG), and glacier-cored rock glaciers with transition zones (TRGC). These deposits are distinguished according to lithology in the central Brooks Range: sedimentary terrain of Atigun and Anaktuvuk and granitic terrain of the Arrigetch Peaks.

higher ELA's imply localization of glaciers in cirques with lower topographic horizons, less supraglacial debris and greater solar inputs. TRGC and MG deposits have considerable overlap; however, a few transition zone moraines have markedly lower solar inputs and Neoglacial ELA's, and higher potential debris supply.

Analysis 2 (Fig. 10) used amount of ELA lowering (NDROP) and area involved during Neoglacial maxima (NAREA) in place of the geographically-dependent NELA and NLAT, which were used in Analysis 1 (Fig. 9). This second analysis clearly discriminates non ice-cored moraines from the glacier-cored varieties. In addition, there is extensive intermixing of glacier-cored moraines and those of transition zones suggesting more similarities than differences.

Potential debris supply (NHEAD) is the most important environmental factor in determining the type of deposit formed; the less bedrock exposed in cirque cliffs the more likely a moraine without an ice core will be formed. A moraine deposited in an environment with a high receipt of solar energy (92%), which favors formation of non ice-cored moraines, will possess a substantial glacier core if a high debris input (~250 m) from cirque walls is available. In those glacierized cirques of the Arrigetch Peaks where input of debris is relatively low (150 m), a reduced input of solar energy (53%) also results in deposition of glacier-cored moraines. The pooled within-groups correlation matrix showed little correlation (-0.04, -0.02) of these two environmental factors when discriminating the three moraine groups (M, Mg/MG, TRGC) in the same lithologic setting (Ellis 1982). The correlation coefficients in Figure 10 indicate minimal depressions of ELA during Neoglacial maxima favor TRGC and, for reasons unknown, moraines without cores of ice.

A third discriminant analysis (Fig. 11) was applied between the 43 sedimentary and 11 granitic cirque deposits. The variables are non-geographical and the same as used in the second analysis (NSUN, NHEAD, NDROP, NAREA). The amount of ELA depression from present mean glacier altitude is by far the most important discriminant between the two terrains. Of secondary importance are the marked differences in solar energy received and potential debris supply, both of which may be explained by granitic terrain supporting deeper cirques than sedimentary bedrock. This discriminant analysis indicates a slight negative correlation (-0.38) between the two factors, energy received and



GROUPS

1 Non ice-cored moraines (M)
2 Glacier-cored moraines (Mg/MG)
3 Neoglacial transition zones of tongue-shaped rock glaciers (TRGC)

VARIABLES

NSUN	Direct radiation energy received
NELA	Altitude of ELA during Neoglacial maxima
NHEAD	Height of exposed bedrock in cirque cliffs (potential debris supply)
NLAT	Latitude of landform

STANDARDIZED CANONICAL DISCRIMINANT FUNCTION COEFFICIENTS

FUNCTION 1 SCORE = 0.49323(NSUN) + 0.77513(NELA) - 0.45270(NHEAD) - 0.48048(NLAT)

FUNCTION 2 SCORE = 0.55371(NSUN) - 0.87883(NELA) - 0.62116(NHEAD) - 0.20468(NLAT)

Note: Variables are in standard form (Z scores); not raw values.

Figure 9. Scatterplot of Linear Discriminant Analysis 1 for glacial deposits in sedimentary terrain with morainal groups (M, Mg/MG, TRGC), variables, and standardized coefficients for discriminant variables shown. These coefficients indicate the relative contribution of each variable to the function. The closer the coefficient is to ± 1.0, the larger the relative contribution of the variable to discriminating between the groups. Here the ELA for Neoglacial maxima (NELA), a geographically-dependent variable, is the most important discriminant.

height of bedrock exposed in cirque cliffs.

7 SOILS OF MORAINES AND ROCK GLACIERS

Soil development in the sedimentary terrain of the Atigun Pass area helps differentiate moraines and rock glaciers. Tills sampled at the contact of receding glaciers or from unweathered zones at depth far beyond the ice margin yielded pH soil values from 7.5-8.0 and color chromas of ~2 (Fig. 12). Thin organic horizons of ~1 cm thickness and oxidation depths to 15 cm develop in less than 400 lichenometric years. On moraines lichenometrically dated at ~2000 B.P., organic horizons reach 3 cm thicknesses, A horizons extend to depths of 10 cm with pH values of ~6.2, and oxidized C horizons occur from 20 to >50 cm. Thicker A horizons, development of a B horizon, chromas of ~3, and soil pH values of 4.8-6.4 help distinguish early Holocene rock glacier tongues from moraines located upslope in Neoglacial transition zones.

Soils on Pleistocene valley drift dated at ~12,500 B.P. (Hamilton 1979a) are more uniformily well developed than those on rock glaciers. They have pH values ranging from 4.7-5.4. In northern Atigun Valley (Fig. 2), these late Pleistocene

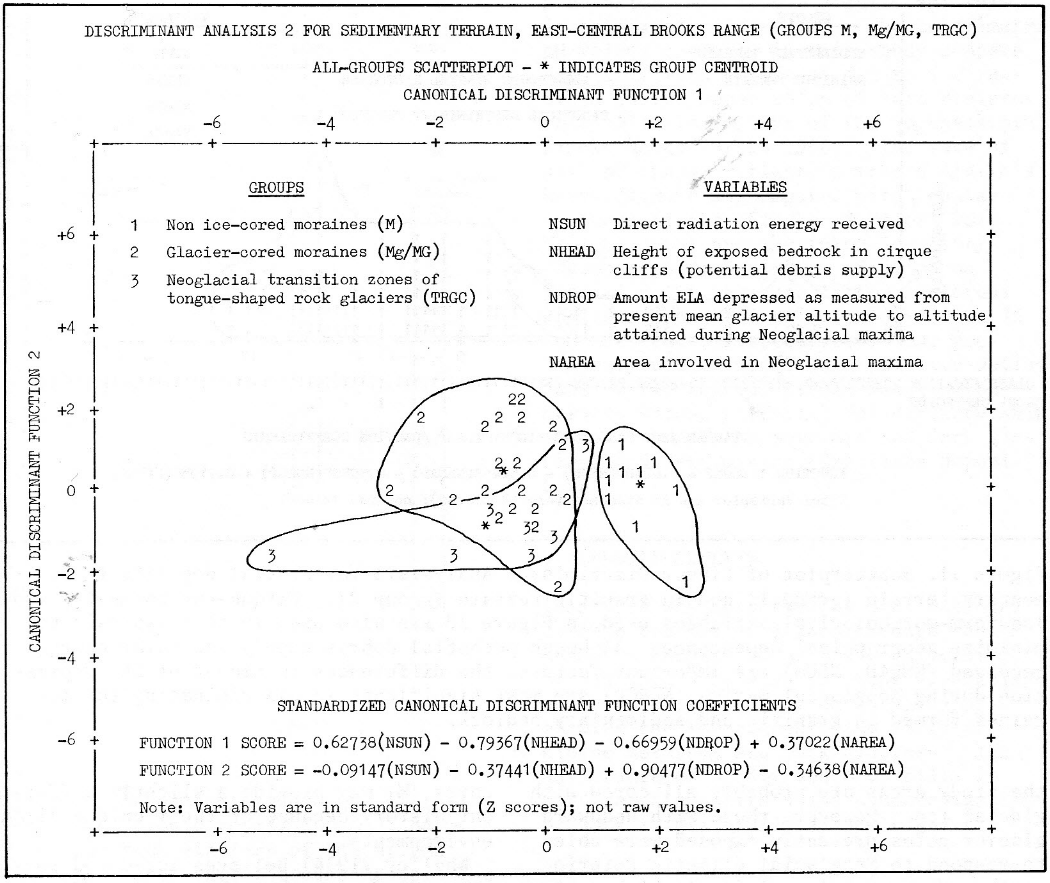


Figure 10. Scatterplot of Linear Discriminant Analysis 2 for glacial deposits in sedimentary terrain with morainal groups, variables that should be relatively independent of geographic location, and standardized coefficients given (see Fig. 9). Potential supraglacial debris supply (NHEAD) is the most important variable discriminating the morainal groups.

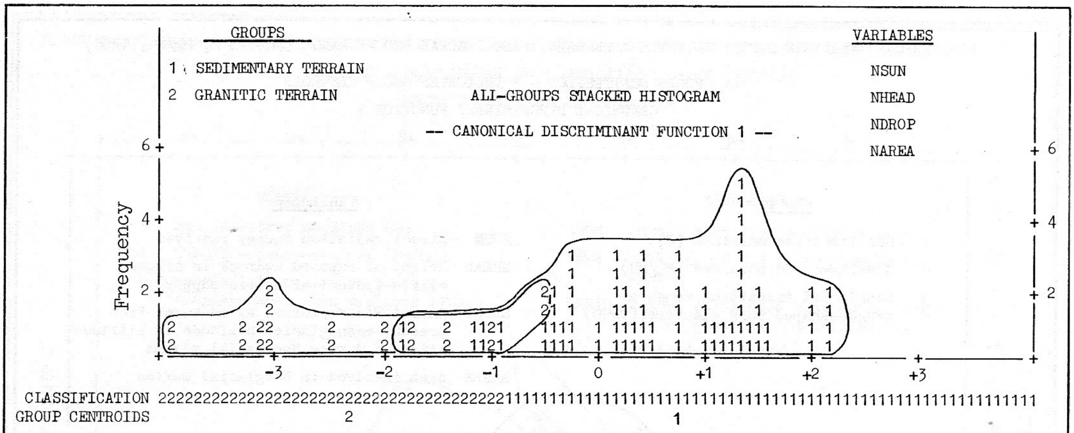
moraines typically have organic horizons to 7 cm depth, A horizons from 20 to 25 cm thicknesses, and color B horizons with chromas to 4. On the south side of the Continental Divide two soil pits on valley moraines had pH values from 5.0 to 5.4 in the upper solum; color chromas here were also ~4. More caliche build-up was observed to the south than to the north of the Continental Divide. Calcareous loess derived from extensive exposures of limestone along the south flank of the east-central Brooks Range may cause this calcium carbonate build-up.

8 DISCUSSION

Moraines without cores of ice occur in relatively unique cirque environments which are characterized by minimal heights of bedrock exposed in cirque cliffs, extensive receipt of direct radiation energy, and low topographic horizons. The higher the cirque, the higher the probability that the glacier will form non ice-cored moraines.

Moraines cored with ice form in cirques with variable inputs of solar energy and debris; however, increased supraglacial debris is the most important environmental factor promoting preservation of glacier cores. The widespread occurrence of glacier-cored moraines and rock glaciers emphasizes the major contribution supraglacial debris has in deposition of alpine tills of the central Brooks Range.

Active, tongue-shaped rock glaciers in



STANDARDIZED CANONICAL DISCRIMINANT FUNCTION COEFFICIENTS

FUNCTION 1 SCORE = 0.62388(NSUN) - 0.52452(NHEAD) - 0.90888(NDROP) + 0.11588(NAREA)

Note: Variables are in standard form (Z scores); not raw values.

Figure 11. Scatterplot of Linear Discriminant Analysis 3 for glacial deposits in sedimentary terrain (group 1) and in granitic terrain (group 2). Cirque-environmental and landform-morphological variables used in Figure 10 are also used in this analysis to minimize geographical dependence. Although potential debris supply and solar energy received (NHEAD, NSUN) are important factors, the differences in amount of ELA depression during Neoglacial maxima (NDROP) are most significant in discriminating the moraines formed in granitic and sedimentary bedrock.

the study areas are probably all cored with glacial ice. However, those with headward glacier cores presently exposed were able to respond to Neoglacial climatic deteriorations due to their relatively higher altitudes. This has resulted in deposition of glacier-cored morainal ridges within Neoglacial transition zones (TRGC). These zones have not completely overrun their downslope, early Holocene rock glacier tongues (Fig. 5D).

Glaciers presently fronted only by morainal deposits (M, Mg, MG) are ~100 m higher than those glaciers leading downslope into transition zone moraines. In addition they averaged greater ELA depressions during Neoglacial maxima. These higher-altitude glaciers apparently obliterated or incorporated any previous early Holocene rock glacier lobes emanating from their cirques.

The most significant environmental factors favoring formation of transition zones and preservation of downslope rock glacier tongues are lower glacier altitudes and increased bedrock exposed in cirque cliffs. The overall physical similarity between glacier-cored deposits (Mg, MG, TRGC) enhances their combined use in a glacial chronology; however, moraines without ice cores (M) may provide a slightly different history because of their unique cirque environments.

Whalley (1974) believes ice-cored rock glaciers form rather than ice-cored moraines where there are substantial cliffs above the glacier and a plentiful supply of debris (see also Currey, 1969). Johnson (1980) proposes that debris supply is not a factor in glacier-cored, rock glacier placement; a small confined cirque is regarded as the optimum site. Our study supports the importance of supraglacial debris.

The environmental factor that most effectively distinguishes between moraines of the granitic Arrigetch and those of the more easterly Atigun and Anaktuvuk areas is the amount of ELA depression during Neoglacial maxima. Why the ELA lowering is greater in the west-central Brooks is uncertain; however, it may be related to 1) inconsistencies in determining ELA by the planimetric method or 2) the effects of increased annual precipitation, temperature, and cloudiness on glacier dynamics in the Arrigetch. Terrain screening and potential debris supply also discriminate between moraines in the deeper granitic cirques and those in sedimentary terrain

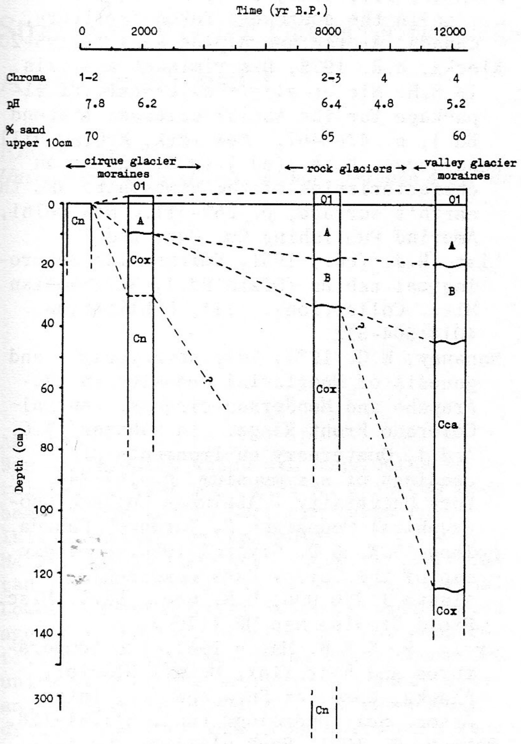


Figure 12. Generalized schematic of soil development from 0 to ~12,500 B.P. on moraines and rock glaciers of the Atigun Pass area, east-central Brooks Range. The parent material is till derived from sedimentary rocks. An oxidized C horizon is designated by "Cox" and a seemingly-unweathered C horizon by "Cn" (Birkeland 1974). B horizons are largely "color B's". Development of a calcium carbonate build-up apparently depends on influx of calcareous loess.

Because of their differing cirque environments, the timing of Neoglacial fluctuations may vary between the west- and east-central Brooks Range. The glacial history developed thus far for these regions (Ellis et al. 1981; Ellis 1982) is based largely on lichenometry; it may be too imprecise to detect such differences.

In the sedimentary terrain of the central Brooks Range, soil evolution on moraines and rock glaciers is typified by pH declining from 7.5-8.0 to 4.7-5.4, color chroma increasing from ~2 to ~4, and marked development of soil horizons over a ~12,500 year interval. Chelating agents, associated with the widespread lichen population, may have a significant role in this weathering trend. The colorimetric pH values measured in this study compare favorably with values of 4.5 to 5.0 recorded in the upper solum of late Pleistocene soils in valleys of the northeastern Brooks Range (Brown 1966). The rate of soil pH change reflects northern Alaska's harsh climate as compared with coastal southern Alaska (Crocker & Major 1955; Ugolini 1968) and the Yukon Territory (Jacobsen & Birks 1980). Soil pH on glacial drift in these latter two areas declines from ~8.0 to 5.0 and ~6.0 in 75 and 200 years, respectively. Our preliminary use of soils as a relative-dating tool in the central Brooks Range demonstrates strong potential for distinguishing surfaces on alpine moraines and rock glaciers and determining time since deposition.

9 ACKNOWLEDGEMENTS

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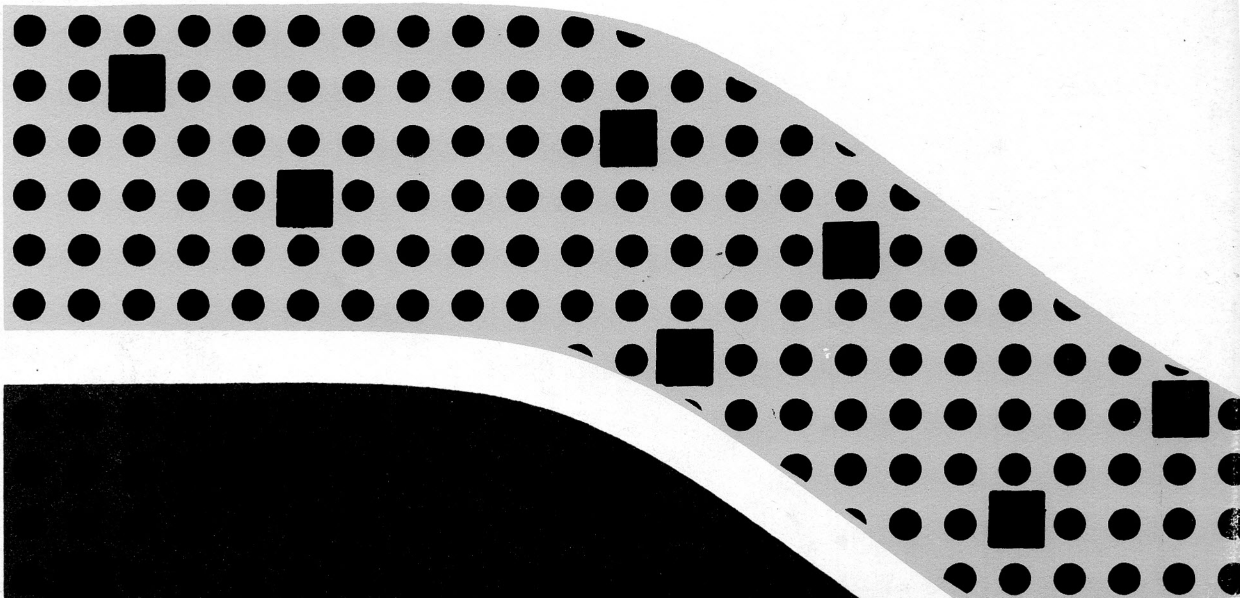

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