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MORPHOMETRIC ANALYSIS OF PLEISTOCENE GLACIAL DEPOSITS IN THE KIGLUAIK MOUNTAINS, NORTHWESTERN ALASKA, U.S.A.

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ABSTRACT
Since the earliest studies of alpine glacial geology, descriptive evaluation of moraine morphology has remained an important relative-age criterion. However, the development of moraine morphology as a quantitative relative-dating tool has lagged considerably behind other techniques. Morphometric and other relative-age data were collected on early- to late-Pleistocene end moraines located in the Kigluaik Mountains of Seward Peninsula, Alaska. Slope-frequency, Fourier, and linear regression analyses of topographic profiles measured along and normal to moraine axial-crests were used to generate nine indices of surface irregularity. Discriminant analysis indicates that average slope, calculated from the slope-frequency distribution, is the best single distinguishing criterion, and that even a few simple field measurements of morphometry provide a viable basis for subdividing and correlating moraines. Morphometric and other relative-age data constrain the timing of glaciations in the Kigluaik Mountains, and suggest that successively older advances are separated by intervals of increasing duration. In addition, morphometric study of moraines can offer insights into processes controlling landscape degradation.

INTRODUCTION
The concept that landforms evolve toward reduced topographic roughness formed the basis for early theories of geomorphic evolution (Davis, 1899). Geomorphic processes, driven by water and gravity, tend to reduce surface relief and smooth the landscape. Early glacial-geologic studies relied heavily on the concept of geomorphic evolution (e.g., Chamberlin, 1878; Blackwelder, 1931). Morphology was central in assessing the relative ages of moraines and providing a basis for subdividing and correlating glacial deposits. Even today, few reports on alpine-glacial deposits lack a descriptive account of moraine morphology. Especially in reconnaissance studies, and those that rely on aerial-photo interpretation, the visual evaluation of moraine topographic irregularity remains an important relative-age criterion.

Oddly, however, the development of moraine morphology as a quantitative relative-age tool has lagged considerably behind other techniques. Ruhe (1950) was the first to advocate the use of quantitative analysis of topography as a means of differentiating glacial drifts. But since the publication of his note, only minor efforts have been made to quantify the morphology of glacial deposits (e.g.,...
Meierding, 1977 Werner, 1982; Ten Brink and Way-thomas, 1985; Colman and Pierce, 1986; Hamilton, 1986). In general, these efforts have proven inadequate for differentiating Quaternary deposits that other criteria demonstrate are of disparate age. Morphologic indices are commonly considered subordinate to better-proven criteria, including rock weathering and soil development (Burke and Birkeland, 1979).

The best attempts at quantifying moraine morphology thus far include measures of widths of moraine crests and angles of flanking slopes. The methods employed in gathering these data vary widely and invariably focus on simply the average or maximum values of these parameters as assessed from a few sample sites. Alternative measures, including those that describe overall topographic irregularity, for example, may provide more sensitive age criteria.

The purpose of this study is to consider more seriously the use of morphometry as a relative-age tool and its applications to understanding landscape evolution. In addition, morphometric data, in conjunction with other relative-age indicators, are applied to constrain the ages of glacier advances in the Kigluaik Mountains, Alaska.

Glacial deposits of the Kigluaik Mountains generally are well-suited to morphometric study. Previous studies provide a basic stratigraphic framework, including broad radiometric age control, for the Quaternary deposits (Hopkins, 1953, 1967; Hopkins et al., 1983; Kaufman and Hopkins, 1985, 1986; Kaufman, 1986; Kaufman et al., 1988). The use of morphometry as a relative-age indicator has particular merit in the Kigluaik Mountains where intermingling and diverse lithologies impose difficulties in applying relative-age techniques based on rock-weathering and soil-forming processes. In addition, the moraines in this subarctic environment lie beyond treeline; consequently, they are well exposed and easily traversed.

ASSUMPTIONS

A major assumption in the use of morphometry as a relative-age indicator is that moraines are deposited with similar initial form. However, many studies have shown that a drift sheet of uniform age can include forms with a wide array of surface irregularities and relief (e.g., Gravenor and Kupsch, 1959; Mickelson et al., 1983). This is true for landforms sculptured at the glacier bed as well as debris deposited along the ice margin as lateral and terminal moraines. The history of glacier fluctuations can impose significant variability on the initial form. In many cases, primary morphology is controlled by the underlying terrain. Drift texture, as influenced by lithology, transport distance, and the relative proportion of till to stratified drift, also imposes great influence (Flint, 1971). Perhaps the single most important variable regulating the degree of primary microlrelief, especially at high latitude sites, is the presence of buried ice. Ice-cored moraines characteristically display greater surface irregularity than moraines composed solely of till. The effects of buried ice may be long-lived, for morphologic freshness is continuously restored as the ice slowly decays.

In addition to initial morphologic differences, the rate at which contemporaneous moraines are modified by postdepositional erosion may also vary. Stream incision and tectonic uplift can regulate erosion rates. Sediment texture and lithology, slope orientation, and regional climate are other variables controlling not only the rate of erosion but also the type of process responsible for morphologic degradation. In turn, the process governing the downslope transport of material dictates the form of the erosional feature. In general, the rate of downslope transport of material is directly proportional to surface gradient; but certain processes operate at a rate dependent on other factors, including slope length (Carson and Kirkby, 1972; Young, 1972).

Clearly, a multitude of variables control both the initial form and subsequent modification of moraines. Nevertheless, those who study glacial deposits consistently find that moraine morphology, particularly in a qualitative sense, is highly dependent on relative age. Older deposits invariably are more subdued. Pierce (1979), for example, states that a major age criterion is the visual evaluation of moraine topography. Empirically, then, on a time scale of tens to hundreds of thousands of years, the length of time a moraine is subjected to weathering and erosion is apparently the dominant variable controlling its surface morphology.

METHODS OF MORPHOMETRIC ANALYSIS

To assess quantitatively the topographic roughness of moraines in and around the Kigluaik Mountains, two types of profiles were measured on 24 moraines: one along the axial crest and the other normal to it along the moraine distal and proximal slopes (Figure 1). For consistency, all data were collected on end moraines where surface irregularities were greatest.

Axial-Crest Profiles

Axial-crest profiles were surveyed by pacing distances between conspicuous breaks in slope and measuring the angle of the intervening slope segment using a clinometer. Measurements of slope angle are probably accurate to within a degree and distances to within 10%. Lengths of profiles ranged from 170 to 470 m and averaged 250 m.
The typical length of a measured slope segment was 6 to 10 m. This method, based on a subjective choice of breaks in slope, gives an accurate record of axial-crest profile form (Young, 1972: 146). The procedure is also rapid, allowing a large segment of the moraine to be sampled, thereby reducing the ambiguity inherent in sampling-site selection.

Three types of analyses were performed on the axial-crest profiles from which five measures of topographic roughness were derived. The measures describe different attributes of terrain roughness including slope steepness, relief, and topographic irregularity. They provide a procedure that alleviates the subjectivity that frequently plagues morphologic assessments for even the most complicated forms.

**Slope Frequency Analysis**

Each profile was subdivided into 1-m-long slope segments. The angle of each segment was then tabulated to construct a slope-frequency distribution from which the following statistics were calculated:

- **Mean slope angle.** This measure averages the steepness of small (1 m) slope segments comprising the profile, and provides an objective value for mean slope.
- **Standard deviation of slope angles.** As a measure of scatter about the mean, this statistic is a crude indicator of topographic irregularity.
- **Maximum slope angle.** This is the angle of the steepest slope segment measured along the profile.

**Linear Regression Analysis**

**Standard deviation of residuals.** This measure is indicative of the amount of relief along a profile. It was determined by first calculating a least-squares regression through the profile coordinates, then calculating the standard deviation of the residuals every 1 m along the profile.

**Fourier Analysis**

This procedure allows the essential topographic elements to be expressed as a sum of sinusoidal undulations of different sizes (see Davis, 1973, for an introduction to Fourier analysis). A fast Fourier transform program was used to generate an amplitude spectrum for each axial-crest profile. The amplitude spectrum displays the variation of amplitude of each Fourier harmonic with its spatial frequency (on a logarithmically scaled amplitude versus frequency plot). For this analysis, profiles were divided into 1-m intervals and only those topographic features with wavelength between 4 and 20 m were included.

**Slope of amplitude spectrum.** The “ roughest” topographic profiles are those with diverse spectral composition in which high-frequency features are present at high amplitudes and the slope of the amplitude spectrum is low. Weathering and mass-wasting are expected to result in a preferential attenuation of high-frequency topographic irregularities. Therefore, more subdued terrains are represented by greater negative slopes of the amplitude spectrum.

**Cross Profiles**

Cross profiles were measured by pacing consecutive distances that span one eye-height (165 cm) of vertical relief. Locations of all slope breaks were recorded to construct the final profile form. A survey staff was implanted at the crest for enhanced detail of the uppermost 1.5 m of relief. A rangefinder was used occasionally to measure lengths of long spans on straight slopes. In most cases, profiles were extended a short distance beyond major slope breaks at the base of moraines. These inflections usually mark the junction with the head of an outwash plain, or older moraine beyond the distal flank, and ground moraine behind the proximal slope.

Four measures of topographic roughness were derived from the cross profiles:

1. **Crest width** was measured in the field as the paced distance between two points on opposite flanking slopes perpendicular to the trend of the axial crest and one eye-height below it. This procedure provides a quick and reproducible measure.

2. **Distal slope angle at 20 m** was measured in the field as the angle of a straight line connecting the moraine crest with a point 20 m along the distal slope. A survey staff at the crest was sighted on to locate eye level. This simple field measure is arbitrary but was included to assess its suitability as a proxy for a more rigorously determined mean slope angle.

3. **Mean slope angle** was calculated from the slope-frequency distribution of all 1-m-long segments comprising both the proximal and distal slopes of the cross profile.

4. **Maximum slope angle** is the angle of the steepest slope segment encountered along the profile.

**GLACIAL- GEOLOGIC SETTING**

The Kigluaik Mountains are a rugged, ice-sculptured massif that rise above the surrounding rolling uplands of the southwestern Seward Peninsula (Figure 2). Situated approximately 50 km north of Nome on the northern
coast of the Bering Sea, the range forms a narrow belt 20 km wide trending approximately east-west for about 75 km and embracing the highest summits on the Seward Peninsula. Mount Osborn, the highest at 1437 m, is located along the axis of a broad, fault-bounded antiform composed of Precambrian and lower Paleozoic granulite-facies metaigneous and metasedimentary rocks (Till, 1983). A cirque cut deeply into the northern shoulder of Mount Osborn supports the largest (<1 km²) of three small glaciers remaining on the Seward Peninsula.

The Kigluaik Mountains, along with three other small mountain masses on the Seward Peninsula, possess a record of former glaciers that were much more extensive than today. Of the four mountain ranges, none is as accessible nor preserves as completely the glacial sequence found in and near the Kigluaik Mountains. Here, the effects of repeated glaciation are conspicuously manifested in deep U-shaped valleys, well-developed moraines, numerous cirques, and an abundance of erratic boulders. The valleys draining the southern flank preserve an especially extensive glacial record that spans some two million years and includes at least six, and possibly as many as eight, episodes of glacier expansion (Hopkins, 1953, 1967; Kaufman and Hopkins, 1986). During the earliest episodes, ice originating in the Kigluaik Mountains occupied major valley systems and advanced south beyond the present coastline at Nome (Figure 2). The four most recent major glacier advances affected an area nearly an order of magnitude less extensive.

Only the four youngest of these glacial episodes, ranging in age from early to late Pleistocene, are considered in this study. Glacial features of these ages were first described in reconnaissance studies by Brooks (1901: 43) and Moffitt (1913: 52). Subsequent investigations focused on both the youngest and oldest portions of the glacial sequence. Glacial deposits of late Pliocene and early Pleistocene age have been studied extensively on the southern coastal plain where Hopkins (1967, 1972, 1973) and Hopkins et al. (1960) documented the stratigraphic relationships between the oldest drift sheets and several interglacial transgressive marine units. A study largely focused on Wisconsin and sparse Holocene deposits concentrated at the core of the Kigluaik Mountains is in progress (Calkin et al., 1986, 1987). This report is part of that
TABLE 1

Major characteristics of the latest four Pleistocene glaciations in the Kigluaik Mountains
(from Kaufman and Hopkins, 1986)

<table>
<thead>
<tr>
<th>Glaciation</th>
<th>Minimum age(^a)</th>
<th>Regional ELA depression(^b)</th>
<th>Extent of glaciers</th>
<th>General character of deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Osborn</td>
<td>11,530 ± 450</td>
<td>70 m during late phase; 180 m during maximum extent</td>
<td>Typically 3 km long, confined to tributary valleys during maximum; 1 km long during late phase</td>
<td>Sharply defined moraines; slightly affected by periglacial processes; bouldery surfaces; associated with tarns and steep-walled cirques</td>
</tr>
<tr>
<td>Salmon Lake</td>
<td>&gt;40,000</td>
<td>270 m</td>
<td>Typically 16 km long; filled major trunk valleys; formed lobate termini beyond mountains</td>
<td>Well-preserved morphology; significantly affected by periglacial processes; thin loess cover</td>
</tr>
<tr>
<td>Stewart River</td>
<td>&gt;40,000</td>
<td>Slightly greater than during Salmon Lake glaciation</td>
<td>Advanced about 5 km beyond Salmon Lake ice limit; recognized only in southern valleys</td>
<td>Smooth terrain punctuated by gravelly ridges; well-developed patterned ground; thin loess cover</td>
</tr>
<tr>
<td>Nome River</td>
<td>810,000 ± 80,000</td>
<td>Estimates are speculative due to uncertainty in altitude of source area</td>
<td>More than 50 km long; advanced beyond present coast; northern limit not clearly defined</td>
<td>Highly subdued topography; deeply buried by loess; supports a well-developed drainage network</td>
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</table>

\(^a\)Yr BP.
\(^b\)Minimum equilibrium-line altitude (ELA) depression assuming that modern ELA, estimated from three glaciers residing in well protected cirques, lies at 660 m asl.

research but also incorporates older deposits found beyond the Kigluaik Mountains. The four ice advances considered in this study have been designated, from oldest to youngest, the Nome River, Stewart River, Salmon Lake, and Mount Osborn glaciations (Hopkins, 1953; Kaufman and Hopkins, 1986). Table 1 lists the major characteristics of each glaciation.

RESULTS

Moraines were initially assigned stratigraphic ages based on visual assessment of post-depositional modification. The criteria used include a qualitative assessment of moraine morphologic “freshness,” surface-boulder and subsurface weathering, and degree of modification by periglacial processes, as well as the geometric positions of end moraines. Once the moraines were classified, the quantitative data were used to evaluate this initial classification and to assess the relative length of time separating deposition of the tills. The relative-age data also serve as an objective means for characterizing moraine groups.

TOPOGRAPHIC PROFILES

Qualitatively, representative axial-crest profiles of Mount Osborn and Salmon Lake age appear similar, whereas the profiles of older moraines are more easily differentiated (Figure 3). Figure 4 shows representative cross profiles for moraines of different ages. Steep slopes approaching the crest of moraines are distinctive in the three younger moraine groups. They record topographic spines that traverse morainal ridges. These features are typically armored by pebbly gravel that enables steep slopes to endure even on the older moraines.

Morphometric relative-age data derived from slope-frequency, linear-regression, and Fourier analyses of the axial-crest profiles (Figure 5), and cross profiles (Figure 6) overlap considerably, and additional measurements are needed to improve their reliability. Only two sets of measurements are available for the Nome River deposits. However, these are characteristic of its subdued relief that varies imperceptibly across the study area.

The group mean values (triangles) of all deposits trend toward decreasing topographic roughness with increasing age. Although rigorous statistical procedures were not strictly followed, an analysis of variance was carried out to assess the discernibility of moraine groups. The results indicate that, for all but the measure derived from Fourier analysis, the Nome River moraines are distinct, and at least two of the other moraine groups are distinguished by significantly different mean values \((p = 0.05)\).

Apparently, for Fourier analysis, shorter spacing between profile survey stations is required to define more accurately the spectral composition of topographic profiles. Measurements taken at regular intervals of 1 m or less would provide a more suitable data set. Fourier analysis has been used successfully as a quantified expression.
of larger-scale terrain microrelief (Stone and Dugundji, 1965) and holds promise for study of smaller-scale features. Unlike measurements derived from slope frequency analysis, spatial pattern of surface undulations is integral to Fourier analysis. This procedure can therefore differentiate terrains that have identical slope-frequency distributions. However, the time devoted to a detailed survey of a small portion of the moraine may be more usefully spent acquiring survey data over a larger area. By sampling a large area, the effects of local variations in sediment texture or moraine form become less significant.

A discriminant analysis program (SPSS/PC+ DSCRIMINANT; Marija, 1986) was employed to assess the statistical significance of the moraine groupings (Davis, 1973). For this procedure, the relative-age data work in concert to generate discriminant functions that maximize between-group differences relative to within-group variances of a predetermined grouping. The functions provide a basis for grouping that minimizes misclassification, allowing the percentage of "correctly" classified moraines to be calculated and used as an indicator of the predetermined grouping's success (Dowdeswell and Morris, 1983). The discriminant analysis was also used to identify the morphometric variables that best distinguish between the moraine groups.

Results of the discriminant analysis show that morphometric data alone provide a viable basis for classification of moraines. The results also indicate that mean slope angle of axial profiles is the best single morphometric criterion by which to differentiate moraines. However, only four simple field measurements of morphometry are needed to produce an equally good classification; these are maximum slope along and normal to the axial crest, crest width, and angle of the upper 20 m segment of the distal slope (a proxy for mean slope angle derived from slope frequency analysis, $r = 0.89$).

Slope-frequency distributions for each moraine within a group were pooled to generate cumulative frequency curves (Figure 7). They illustrate distinctive slope frequency characteristics that substantiate differences in the morphometric character of moraine groups.

**Other Relative-Age Data**

In addition to the morphometric relative-age data, a wide variety of surface-boulder and subsurface weather-

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**FIGURE 3.** Representative axial-crest topographic profiles from moraines of different ages (youngest at top). Refer to Figure 2 for location of relative-dating sites.

**FIGURE 4.** Representative cross profiles from moraines of different ages (youngest at top). Refer to Figure 2 for location of relative-dating sites.
features were measured at each of the 24 moraine stations. Of the 12 weathering parameters, only a few aid in distinguishing among moraine groups (Table 2). The percentage of fractured surface-boulders, their roughness, maximum diameter, grain relief, and freshness, as well as subsurface stone-weathering index, show no clear trend with age. Calculation of univariate F-ratios indicates that the group means for these criteria are indistinguishable \( (p = 0.05) \). Somewhat better relationships are displayed by measures of weathering-pit depths that unexpectedly seem to decrease with increasing surface age, and by oxidation depth that apparently increases with age. The most useful parameters are surface-boulder frequency, boulder angularity, and boulder protuberance (Figure 8). Group means derived from these parameters are statistically different \( (p = 0.05) \) and show trends toward decreasing values with increasing age.

The techniques used in this study to assess weathering characteristics of surface boulders and subsurface sediments closely follow other studies conducted in the western United States (e.g., Birkeland et al., 1979). The methods are typically applied in regions of spatially and mineralogically uniform lithologies. The intricately foliated and lithologically diverse rocks comprising the Kigluaik Mountains are poorly suited to most traditionally applied boulder weathering criteria. Lithology is an important variable that must be minimized if variations in relative-age data are to be considered time dependent (Burke and Birkeland, 1979). The mineral composition and texture of a boulder not only control the rate at which it weathers, but also determine its capacity to exhibit particular weathering features. A major shortcoming of the surface-boulder and subsurface weathering data reported here is that they were collected on moraines composed of a variety of lithologic types and relative abundances.

**Figure 5.** Morphometric data derived from axial-crest topographic profiles. Dots represent individual measurements; triangles are group mean values. From youngest to oldest: MO = Mount Osborn; SL = Salmon Lake; SR = Stewart River; NR = Nome River.

**Figure 6.** Morphometric data derived from cross profiles. Dots represent individual measurements; triangles are group mean values. From youngest to oldest: MO = Mount Osborn; SL = Salmon Lake; SR = Stewart River; NR = Nome River.
Morphometric and other relative-age criteria can be used to assess the relative timing of the major glacier expansions recorded in the Kigluaik Mountains. The relative-age data clearly demonstrate that the oldest (Nome River) glacial deposits have experienced strikingly more postdepositional modification than drift of the subsequent advances. The difference in weathering characteristics between the Salmon Lake and Stewart River moraines is slightly greater than the difference between the Salmon Lake and Mount Osborn moraines. Hence, the relative-age data suggest that successively older advances are separated by intervals of increasing duration. However, because weathering rates probably decrease logarithmically with time (Colman, 1981), the age differences between glaciations are further amplified.

Broad radiometric age control combined with inferred correlations with the marine oxygen-isotope record (Shackleton and Opdyke, 1973) and dated glacial deposits in other parts of Alaska help constrain the absolute age of this relative chronology. The most discriminating relative-age data (seven morphometric and three rock-weathering parameters) were averaged and compared to the value obtained from Mount Osborn moraines (Figure 9). The result is plotted on a logarithmic scale to reflect weathering processes that operate at decreasing rates with time. If this model is correct, then, of the two alternative age assignments illustrated, the older ages seem to fit the data best (Figure 9B). However, because the precise rate at

![Figure 7](image-url)  
Figure 7. Pooled within-group cumulative slope-frequency distributions from (A) cross, and (B) axial-crest profiles.

![Figure 8](image-url)  
Figure 8. Surface-boulder and subsurface weathering relative-age data for the three most useful parameters. Boulders were examined on only one Nome River moraine where till was exposed through the otherwise continuous loess cover. Dots represent individual measurements; triangles are group mean values. From youngest to oldest: MO = Mount Osborn; SL = Salmon Lake; SR = Stewart River; NR = Nome River.

![Figure 9](image-url)  
Figure 9. Alternative age assignments for glacial deposits in the Kigluaik Mountains. Oxygen-isotope curve and stages are from Shackleton and Opdyke (1973). From youngest to oldest: MO = Mount Osborn; SL = Salmon Lake; SR = Stewart River; NR = Nome River.
which relative-age indices change with time is not known, both alternatives are thought to be equally possible. An additional uncertainty is imposed by lumping relative-age criteria that change at disparate rates.

For both alternatives, the Mount Osborn glaciation is considered to coincide with marine isotope stage 2. A minimum radiometric age for drift of the Mount Osborn glaciation (Kaufman et al., 1988; Table 1), its distribution, morphology, and weathering characteristics are all similar to Itkilk II drift in the Brooks Range which was deposited between about 25,000 and 11,000 yr BP (Porter et al., 1983; Hamilton, 1986). The Mount Osborn glaciation is probably of late Wisconsin age.

Relative-age data suggest that the very extensive ice advance of Nome River time is far older than the subsequent glacial episodes. At Nome, drift of the Nome River glaciation is overlain by fossiliferous marine sediments of the 120 ka Pelukian marine transgression (Hopkins, 1967). A closer confining age for the Nome River glaciation may be provided by a potassium-argon age of 810,000 ± 80,000 yr for a normally magnetized, basaltic lava flow that overran a moraine of probable Nome River age on the northwest flank of the Bendeleben Mountains (Kaufman and Hopkins, 1986). On this basis, the Nome River glaciation could correspond to any of the isotope minima predating 800 ka.

<table>
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<th>Fracture (%)</th>
<th>Grain relief (mm)</th>
<th>Pit depth (mm)</th>
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<th>&gt;30 cm freq. (/100 m²)</th>
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aPercent boulders on which mineral grains stood in relief on >50% of their exposed surface.
bPercent boulders that exhibited one or more complete breaks.
cHeight of the most protuberant mineral grain.
dAverage of the three deepest weathering pits.
ePercent boulders that required many hammer blows to break, produced a ringing sound when struck, and displayed unoxidized interiors.
fTotal number of boulders encountered along a 2-m-wide strip along the moraine crest.
gNumber of boulders protruding >30 cm above the moraine surface.
hCalculated as a weighted mean by assigning values to each shape category as follows: very angular = 6; angular = 5; subangular = 4; subrounded = 3; rounded = 2; well-rounded = 1.
iDepth to base of subsurface oxidized zone.
jFifty stones (<8 cm in maximum diameter) collected from weathered zone in a test pit were classified based on the number of hammer blows required to break and the quality of sound when struck. “Weathering index” was calculated as a weighted mean by assigning values to each category as follows: rotten = 3; weathered = 2; fresh = 1.

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MORPHOLOGIC EVOLUTION OF MORAINES AND IMPLICATIONS FOR RELATIVE DATING

In addition to its application as a relative-age tool, morphometric study of moraines can offer insights into the processes controlling landscape degradation and, with proper age control, the rates at which they operate. The relative timing of glacier advances in the Kigluaik Mountains is established by the stratigraphic position of end moraines and is supported by evidence independent of the morphometric data, including surface-boulder and subsurface weathering. The relative-age data can therefore be used to chronicle moraine degradation through time.

Assuming that moraines are deposited with similar initial morphology and texture, and that the effects of slope orientation are neglected, the morphometric data demonstrate that surface roughness of moraines does indeed decrease with age. Although the integrated effect of geomorphic processes operating over tens of thousands of years is the overall reduction of surface relief and roughness, sharp features persist on many moraines of post-Nome River age. They suggest that a model of moraine degradation governed solely by a linear-diffusional process, in which the rate of downslope transport of material is directly proportional to surface gradient, is not entirely correct. An armor of lag gravel, nivation, or other periglacial processes contributes to the continued persistence, and perhaps enhancement, of sharp features.

Indeed, actively heaving boulders were common at the summit of mounds found frequently along moraine crests.

For most erosional processes, the rate of downslope movement of sediment is proportional to surface gradient and is independent of slope height. Theoretically, then, longer slopes retain steeper angles than shorter slopes having the same age and initial angle. This relation was documented empirically in studies of fault and terrace scarps (Bucknam and Anderson, 1979; Pierce and Colman, 1986) and is corroborated here by the correlation of mean slope angle (derived from the slope-frequency distribution) with slope height for moraine cross profiles. Figure 10 shows that average flanking slope angle steepens almost linearly with the log of moraine height and that this dependence becomes less important with age. Results of a t-test indicate that the slopes of these regression lines are distinct \( (p = 0.10) \). These data are analogous to those of Colman and Pierce (1986) who used measures of general maximum slope angle to demonstrate a similar relation for moraines in Idaho.

Because mean slopes angle from moraine cross profiles are correlated with moraine height, caution must be used when applying slope angle as a relative-age index. Higher moraines may appear younger than contemporaneous moraines with shorter slopes.

**Figure 10.** Relationship between mean slope angle (derived from slope-frequency distribution) and moraine height for cross profiles of three age groups \( (r = \text{correlation coefficient}; \text{open circles represent proximal slopes; solid circles are from distal slopes}) \).

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CONCLUSION

The aim of this study was to explore a variety of methods that may serve to refine moraine morphology as a relative-age tool. This preliminary effort produced positive results but should be supplemented with additional studies that assess the effects of such factors as slope orientation, sediment texture and lithology, and variations in initial form. In turn, these investigations should lead to an enhanced understanding of processes governing landscape evolution in glaciated terrains.

ACKNOWLEDGMENTS

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