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Pleistocene glacial history of the southern Ahklun Mountains, southwestern Alaska: Soil-development, morphometric, and radiocarbon constraints

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Abstract

Four new AMS ^{14}C ages, glacial mapping, and measurements of soil development, loess thickness, and moraine morphology constrain the age and extent of at least three Quaternary advances by outlet lobes of an ice cap over the Ahklun Mountains of southwestern Alaska. The relative-age data are from 107 sites correlated to 25 ice-marginal positions in the Kanektok, Goodnews, Togiak, and Kulukak River valleys and along the southeastern flank of the range. Radiocarbon ages provide minimum ages for six — and a maximum age for one — of the former ice margins. Soil and morphometric parameters subdivide the ice limits into three relative-age groups. One to three pre-Wisconsin advances, probably middle Pleistocene in age, are represented by drift with relatively thick B horizons (60 ± 5 cm, with Bt horizons), thick loess caps (80 ± 12 cm), and broad moraines (135 ± 134 m) with gentle side slopes ($7 \pm 5°$). An extensive early Wisconsin (sensu lato, s.l.) advance, > 39.9 ka, and three associated stillstands or readvances are characterized by intermediate soil and morphometric parameters (Bw and weak Bt horizons with thicknesses of 40 ± 11 cm; loess thicknesses of 69 ± 46 cm; crest widths of 38 ± 13 m; and slope angles of $14 \pm 4°$). The maximum late Wisconsin advance, > 16.9 ka, and two readvances or stillstands are associated with thin (20 ± 5 cm), weakly to moderately developed Bw horizons, thin loess caps (28 ± 8 cm), narrow crest widths (28 ± 9 m), and steep slope angles ($18 \pm 3°$). The data confirm that early-Wisconsin glaciers in southeast Beringia were much more extensive than late Wisconsin glaciers, which were apparently limited by availability of moisture.

1. Introduction

Within the North American Arctic, Alaska occupies a strategic paleoenvironmental position because large areas of the state escaped late Wisconsin glaciation and thus preserve a record of older events (Fig. 1; e.g., Hopkins, 1982; Hamilton et al., 1986). Glacial records extending to the early or middle Pleistocene have been developed for parts of central and northern Alaska (Hamilton, 1994), providing a framework for assessing paleoclimate controls on glaciation. For example, glaciation in many areas appears to have been strongly modulated by changes in eustatic sea level and sea-ice conditions, which affect moisture availability as well as the intensity and trajectory of storm tracks (e.g., Barry, 1982). Furthermore, evidence is emerging for synoptic-scale variability in climate forcing associated with individual glacial events. Glaciers in northwestern Alaska (Seward Peninsula and western Brooks Range) during the penultimate glaciation were an order-of-magnitude less extensive than during earlier glaciations (Kaufman and Hopkins, 1986; Hamilton, 1986). In contrast, advances elsewhere (eastern Bristol Bay and St. Lawrence Island) during the penultimate glaciation reached close to, or beyond, older limits (Lea, 1990a; Heiser et al., 1992; Kaufman et al., 1996; Brigham-Grette et al., 2001). Documenting such variability in time as well as space will expand the chronostratigraphic framework of glacier response across Beringia, and will enable us to test among models of regional climate variability.

Unlike other major ranges of formerly glaciated Alaska, the Ahklun Mountains (Fig. 1) have received little study (Porter, 1967; Lea, 1989). Previous reconstructions based on limited field data have differed

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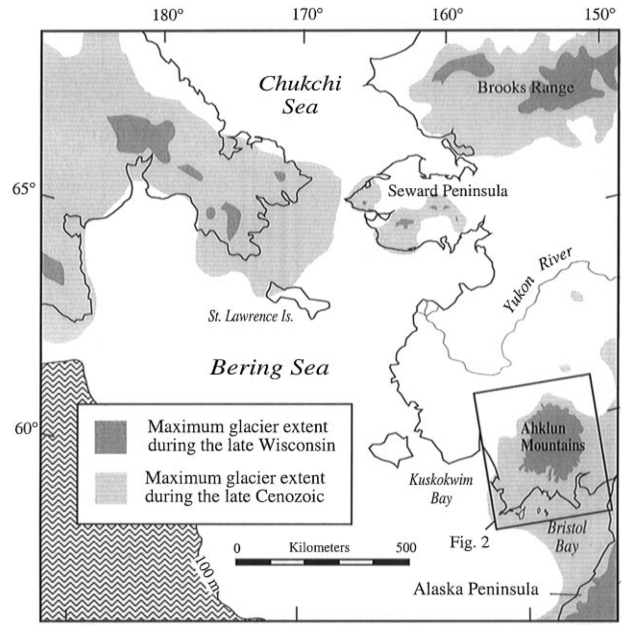

Fig. 1. Central Beringia, showing late-Wisconsin and late-Cenozoic glacier limits, and location of the Ahklun Mountains. Also shown is the approximate extent of the Bering Sea (defined by the 100 m isobath) during the late Wisconsin. Glacier limits are modified from Hamilton et al. (1986).

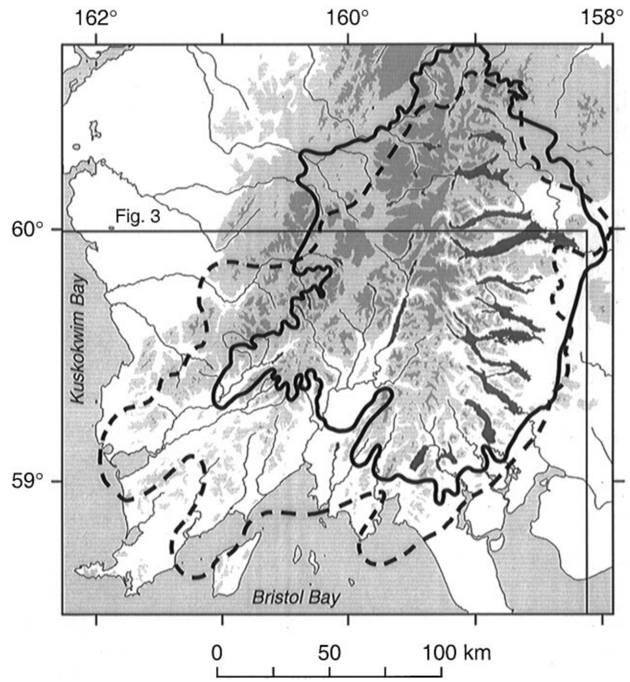

Fig. 2. Contrasting reconstructions of the Ahklun Mountains ice cap. The solid line depicts the Late Pleistocene limit portrayed on the statewide compilation of Coulter et al. (1965). The dashed line is from a reconnaissance, small-scale compilation of late Wisconsin ice extent by Hamilton (1994). Light shading depicts elevations of 200–600 m, medium shading indicates those from 600 to 1600 m, and dark shading highlights large lakes. Map location shown in Fig. 1.

greatly (Fig. 2), depicting late Wisconsin ice margins sheltered within range fronts (Coulter et al., 1965) or extended across lowlands to the present-day coast (e.g., Hamilton et al., 1986; Hamilton, 1994). These reconstructions imply significant discrepancies in glacier volume and climatic forcing for the late Wisconsin, as well as for earlier glacial periods. The Ahklun Mountains are well situated to experience shifts from transitional maritime climate to continental conditions as the Bering Sea retreated $\geqslant 500$ km to the southwest during the late Wisconsin (Fig. 1). Furthermore, the area bisects a gradient in modern climate and past glacier response that extends from the Alaska Peninsula and eastern Bristol Bay (e.g., Lea et al., 1991; Kaufman et al., 1996; Stilwell and Kaufman, 1996) to Seward Peninsula (Kaufman and Hopkins, 1986).

This paper expands on available evidence for determining the timing and extent of Pleistocene advances by an ice cap centered over the Ahklun Mountains. Our reconstructions are based on radiocarbon dating, relative-age criteria, field mapping, stratigraphic relations, and aerial-photographic interpretation. The relative-age data consist of B-horizon thickness and development, loess thickness, moraine slope angles, and crest widths. Our focus is on four major outlet lobes extending southward and westward from the central mass of the ice cap, and on piedmont lobes that coalesced at the southeastern edge of the ice cap. The study area encompasses the Ahklun Mountains and surrounding coastal lowlands south of 60°N and west of 158°W. The data indicate that the ice cap expanded at least three times, and perhaps as many as 10 times, during the Pleistocene. Variation in the extent of these advances implies that paleoclimatic forcing varied with each glacial event. In particular, our data indicate that the late Wisconsin glaciation was much more restricted than indicated by previous reconstructions, apparently limited by a cold, but dry, climate.

2. Regional setting and previous studies

The Ahklun Mountains (Fig. 2) form the highest range in Alaska west of the Alaska Range. The range reaches its highest elevations in the north where summits exceed 1500 m asl and are capped by modern-day glaciers. Repeated glaciations during the Pleistocene have excavated an extensive network of valley troughs, most of which are controlled by structure within the underlying bedrock (weakly metamorphosed Mesozoic sedimentary and volcanic rocks; Hoare and Coonrad, 1961a, b). The southern and western flanks are dissected by broad, fault-bounded valleys, forming a diffuse mountain front of rolling uplands merging unevenly with a fringing coastal lowland. The eastern margin is fronted by several large, deep "fiord lakes". Our studies are concentrated along the coastlines of northwestern Bristol Bay and southeastern

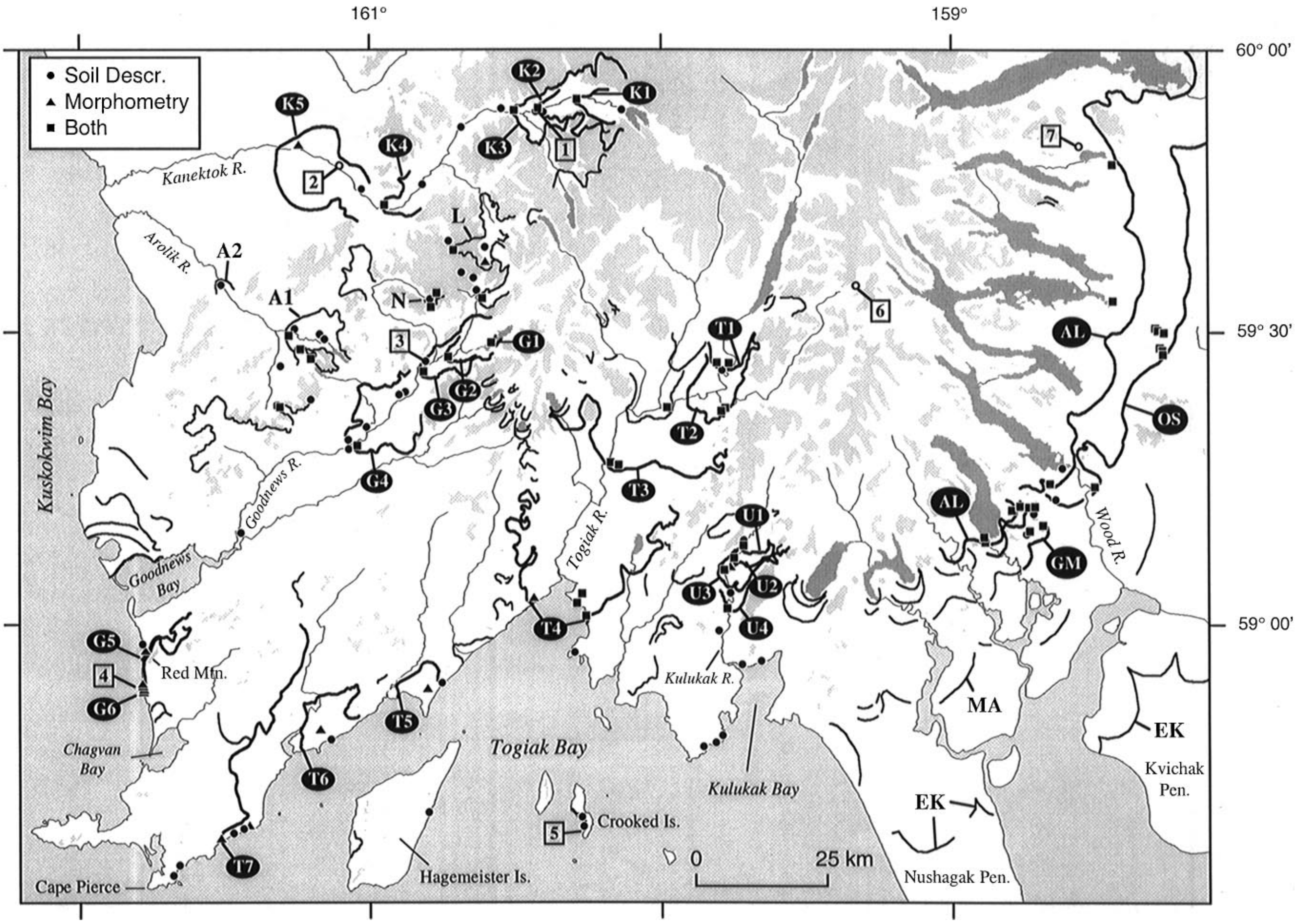

Fig. 3. The southern Ahklun Mountains, showing: major ice-marginal positions investigated in this study (bold lines, labeled with circled numbers and letters; AL = Aleknagik; OS = Okstukuk; GM = Gnarled Mountain; MA = Manokotak; EK = Ekuk); other ice-marginal positions (medium-thick lines); soil-description and morphometric sites (legend, upper left); and radiocarbon-dated localities (open squares). Light shading depicts elevations of 400–1500 m. Map location shown in Fig. 2.

Kuskokwim Bay, within the Kanektok, Goodnews, Togiak, and Kulukak River valleys, and along the southeastern range front (Fig. 3). Quaternary deposits blanket valley floors and coastal lowlands, and are commonly exposed in river and coastal bluffs.

An early statewide compilation identified glacial limits in the Ahklun Mountains based on aerial-photographic interpretation and compilation from published bedrock maps (Hoare and Coonrad, 1961a, b). Coulter et al. (1965) depicted an area covered by glacier ice during the late Pleistocene as an oval centered over the range with outlet lobes extending partway down major valleys (Fig. 2). Coulter et al. (1965) inferred that advances during the middle to late Pleistocene and early to middle Pleistocene were much more extensive, reaching beyond the modern coast south and southwest of the Kulukak, Togiak, and Goodnews River valleys (see Fig. 3).

A field-based investigation subsequently concluded that late Wisconsin ice reached the modern Kuskokwim Bay coast southwest of Goodnews Bay. Porter (1967) distinguished four ages of drift based on preservation of constructional morphology, degree of soil and clast weathering, and five ^{14}C ages. One of these, on basal peat in a kettle fill over the youngest drift sheet, is 8.9 ka BP (Table 1), and was interpreted as a closely limiting minimum age. Thus, based on a limited area of study southwest of Goodnews Bay, Porter (1967) concluded that an outlet lobe occupying the Goodnews River valley was much more extensive than previously implied for the late Wisconsin by Coulter et al. (1965).

Subsequent statewide compilations have slightly modified the middle to late Pleistocene glacier limit of Coulter et al. (1965) and have incorporated Porter's (1967) interpretation that late Wisconsin ice was extensive. For example, Péwé (1975) and Hamilton (1994) depict late Wisconsin ice extending partly beyond the present-day limits of Togiak and Goodnews Bays (Fig. 2). Differences among the reconstructions amount to 40–90 km of glacier extent.

Recent studies on the southeastern flank of the Ahklun Mountains identified tentative late-Wisconsin limits, and constrained the age of a much more extensive early

Table 1
Radiocarbon dates from the southern Ahklun Mountains region

Site[a]	Laboratory number	Radiocarbon age (^{14}C yr BP)	Material	Significance	Ref.[b]
	Upper Kanektok River valley				
1	AA-23083	5045 ± 55	Plant macrofossils	Min. age for K1	3
	Lower Kanektok River valley				
2	AA-23085	> 41,500	Plant macrofossils	Min. age for K5	3
	Upper Goodnews River valley				
3	AA-23082	16,890 ± 120	Plant macrofossils	Min. age for G3; max. age for G2	3
	Kuskokwim Bay, south of Platinum				
4	UW-56	8910 ± 110	Peat	Min. age for G6	1
4	I-426	11,500 ± 250	Peat	Min. age for G6	1
4	UW-71	12,110 ± 130	Peat	Min. age for G6	1
4	UW-70	12,840 ± 170	Peat	Min. age for G6	1
4	UW-57	> 45,000	Peat	Min. age for G6	1
	Crooked Island, Togiak Bay				
5	AA-23089	39,860 ± 1200	Plant macrofossils	Min. age for T7	3
	Ongivinuk Lake Core				
6	Beta-64692	18,450 ± 80	Bulk organic matter	Min. age for Aleknagik moraine	2
	Grandfather Lake Core				
7	Beta-59071	12,870 ± 210	Bulk organic matter	Min. age for Aleknagik moraine	2

[a]See Fig. 3.
[b]References: (1) Porter (1967); (2) Hu et al. (1995); (3) this study.

Wisconsin (sensu lato, s.l., used here to include (sub)stages 5d through 4) advance. Lea (1989) identified five glacial limits, two of which lie close to the range front and are correlated with the late Wisconsin based on reconnaissance photo and map interpretation (Aleknagik and Okstukuk limits; Fig. 3; see also Thompson et al., 1994). The third and fourth in the sequence, the Gnarled Mountain and Manokotak limits, were interpreted as early Wisconsin stillstand or readvance positions. Radiocarbon, luminescence, and amino-acid racemization evidence indicate that advance to the Ekuk limit occurred ca. 90–75 ka (Kaufman et al., 1996). These studies indicate that glaciation of the southeastern Ahklun Mountains during marine oxygen isotope stage 2 was much less extensive than during late stage 5 and/or stage 4.

3. Ice-marginal positions

Ice-marginal positions marked by lateral and end moraines were compiled from aerial photographs, field study, published geologic maps (which show belts of hummocky drift; Hoare and Coonrad, 1961a, b), and Coulter et al. (1965). Not included in this study are tens of valley glaciers that were separate from the ice cap during the late Wisconsin (Manley et al., 1997, 1998; Briner et al., 1998; Briner, 1998). Moraines vary from simple, individual, push-type ridges to composite ridges and belts of hummocky stagnation drift. Regardless, an ice limit was mapped at the distal edge of each moraine or morainal belt. The position of each ice limit is thus approximate in detail, but is sufficiently resolved for the scale of this study.

Four to seven major ice-marginal positions were mapped within each of the Kanektok, Goodnews, Togiak, and Kulukak River valleys (Fig. 3). These are referred to hereafter by alphanumeric codes (e.g., K1, G3, T2, U4, etc.); letters indicate valleys (K = Kanektok, G = Goodnews, T = Togiak, and U = Kulukak River valleys), and numbers encode position within each down-valley sequence of ice limits (Fig. 3). Each relative-age site (see below) is attributed to an ice-marginal position based on direct association or geomorphic correlation. Many of the sites are directly located on moraines. Others are on outwash terraces that grade up-valley to unequivocal ice-marginal positions. In other cases, outwash-terrace remnants are identified as proglacial or recessional, and correlated with ice margins based on height above river level. A few sites are on drift sheets associated with retreat from down-valley ice limits. Eight sites southwest of the Togiak River and south of the Kulukak River are located down-flow of identifiable moraines, and are associated with older, extensive advance(s) into Togiak Bay (Fig. 3).

Based on our field observations of morphology and stratigraphy, the outer two limits in the Goodnews River sequence are slightly modified from mapping by Porter (1967). We place ice-marginal position G5 at the southern limit of morainal ridges northwest of Red Mountain (Fig. 3), where Porter (1967) mapped recessional moraines of the Unaluk glaciation. Ice-marginal position G6 coincides with a prominent, albeit subdued, moraine that intersects the coast between two radiocarbon localities (UW-57 and UW-71; cf. Porter, 1967). This moraine lies ca. 1 km north of the maximum extent of drift of the Chagvan glaciation as mapped by Porter (1967).

Four major ice-marginal positions were also identified from intermontane valleys and low divides north of the Goodnews River (cf. Briner et al., 1998; Briner, 1998). Several sites are associated with a tri-lobate margin extending in part down the Klak Creek valley ("L" on Fig. 3). This margin can be traced to the third moraine in the Goodnews River valley (G3) by assuming a continuous ice-surface slope across a 14 km gap between lateral moraines. Higher in elevation, and down-flow of the G3 limit lies a small moraine ("N" on Fig. 3), which was deposited by a narrow outlet glacier moving westward into the upper Nimgun Creek valley. We assume that this moraine and associated sites correlate with moraine G4. Several sites in the upper Arolik River valley correspond with a lobate ice margin ("A1" on Fig. 3) that can be traced southwestward for >30 km and is apparently correlative with the next older moraine in the Goodnews River valley, moraine G5. Finally, an ice limit across the middle Arolik River ("A2" on Fig. 3) was identified from the down-valley limit of ice-contact drift exposed in outcrops. This limit delineates an extensive advance that we associate with ice limit G6. In this way, we have incorporated data from sites north of the Goodnews River valley into relative-age assessment of correlative G3 through G6 moraines.

Ice-marginal positions on the eastern flank of the Ahklun Mountains are marked by nearly continuous bands of hummocky drift (Fig. 3). Ice limits southwest of the Wood River are taken from Lea (1989, p. 81; cf. Hamilton, 1994). Our relative-age data are from the youngest three margins: the Aleknagik, Okstukuk, and Gnarled Mountain moraines. The inner two margins can be traced for tens of kilometers to the north, where other relative-age sites are located.

4. Soil profile development

4.1. Methods

Soil profiles were described at 107 sites (Fig. 3) in till, ice-contact stratified drift, outwash, and in overlying loess. Profiles were described from natural exposures or from pits into terrace surfaces or broad moraine crests. Features described with depth include horizonation, structure, parent material lithology and genesis, and clay films, if present (as per Soil Survey Staff, 1975; Birkeland, 1984). Rather than describing a small number of profiles in detail, our approach has been to describe as many profiles as possible over a large area. Most of the profiles (83 of 107) are from unforested sites. The remainder are from boreal forest on the southeastern flank of the range. All are from well-drained sites, typically on sandy parent materials. In such settings, B-horizon thickness and progressive development of Bw and Bt horizons are indicators of relative age (e.g., Birkeland, 1984). B-horizon thickness was calculated from Bw and Bt horizons plus half the thickness of A/B, AB, B/A, BA, B/C, and BC horizons.

4.2. Results

Soil profiles include a variety of weakly to moderately developed Bw and Bt horizons (Figs. 4–6, Table 2). B-horizon thicknesses range from 3 cm to 96 cm, averaging 31 ± 18 cm. B horizons exhibit varying degrees of reddening and weak to moderate structure, due to variable oxidation and clay illuviation. Tephra beds form prominent thin (<5 cm) layers in many profiles, typically over buried horizons, and may form a significant portion of parent materials where homogenized with loess. Surface and buried O and A horizons are variably thick. Cryoturbation is sometimes apparent from wavy, irregular, or broken boundaries between horizons, but is not pervasive. None of the horizons are gleyed.

B horizons generally increase in thickness with distance down-valley in each of the Kanektok, Goodnews, Togiak, and Kulukak River valleys (Fig. 4), and along the southeastern flank of the range. The average coefficient of variation for 23 ice margins with two or more correlative sites each is 31% (standard deviation $\times$ 100/mean). A few of the surface and buried soils appear to have been stripped (eroded) compared to profiles on correlative landforms. For example, a soil on hummocky drift associated with ice-marginal position T7 (lower solid circle, Fig. 4C, at 140 km) displays a weak Bw horizon only 15 cm thick. In contrast, a Bw horizon on a correlative thrust ridge 2 km away is 75 cm thick (upper solid circle, Fig. 4C). Anomalously low values for positions G4, G5, T4, and beyond U4 might also reflect truncation by subaerial erosion. Nonetheless, average B-horizon thickness provides a useful measure of relative age for ice-marginal positions with three or more described soils. Profiles on moraines do not appear more likely to be stripped than profiles on other landforms.

Based on B-horizon thickness and degree of soil development, our sites fall broadly into two relative-age groups (Figs. 4–6; Table 2). Profiles typical of the inner three moraines and associated drift in the Kanektok, Goodnews, Togiak, and Kulukak River valleys (ice margins K1-K3, G1-G3, T1-T3, and U1-U3) consist of O/A/thin Bw/C horizons (Figs. 5 and 6). B horizons average 20–25 cm in thickness per valley, and structure is massive or weakly developed. Bt horizons were not found within this relative-age group. Profiles on outer moraines and drift surfaces (ice margins K4-K5, G4-G5, T4-T7,

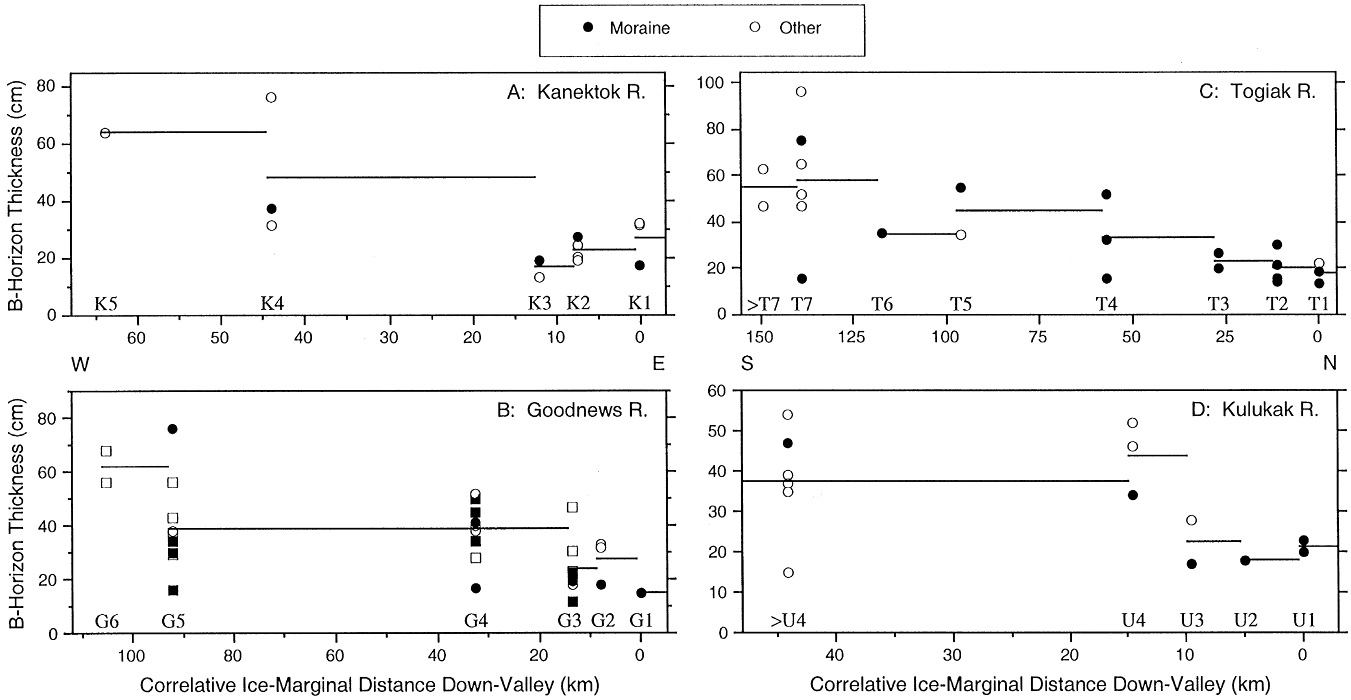

Fig. 4. Comparison of B-horizon thickness for soil-description sites in four valleys. Symbols are plotted according to down-valley distance of correlative ice margins (in km from the innermost ice margin). Solid circles show data for sites on moraines. Open circles show data for sites on outwash terraces or till sheets. Squares show corresponding data for sites between the Goodnews and Kanektok Rivers, correlated to ice margins in the Goodnews River valley. Horizontal lines depict averages for, and extend to the right of, each ice limit. The data are summarized in Table 2.

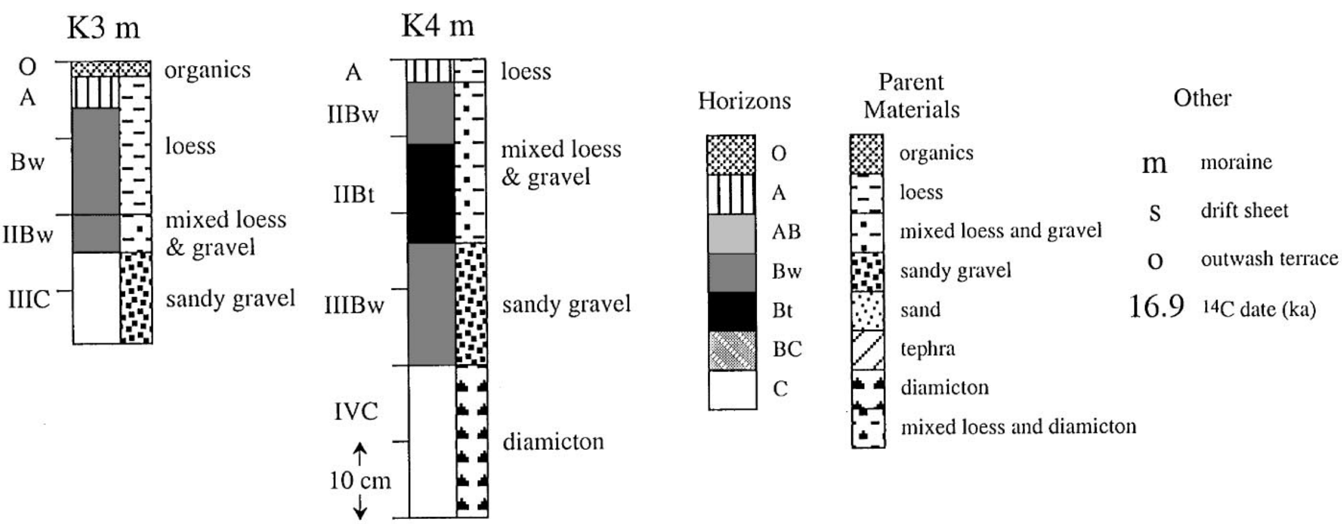

Fig. 5. Representative soil profiles for the two youngest relative-age groups, and symbols used to portray soil horizons and parent materials. For example, the B horizon on the third moraine of the Kanektok River valley (K3) is a weakly developed Bw horizon. The B horizon on the fourth moraine in this valley (K4) is a moderately developed Bt horizon. Each profile is labeled with a morphostratigraphic code keyed to a correlative ice-marginal position, followed by a lower-case letter indicating the type of landform at each site.

U4- > U4) have thicker B horizons, averaging 41–52 cm per valley, and often display O/A/thin Bt/thick Bw/C horizonation. Structure varies from massive to moderately developed. Bt horizons, present in 23 of the 50 profiles in this group, have clay films described as very few to common, thin films on ped faces and as coats on grains. In general, the Bt horizons, where present, are weakly developed, without strong reddening. The break in development between the inner and outer moraines and drift is clear for the Togiak River valley, and is stepwise and sharp for the Kanektok, Goodnews, and Kulukak River valleys (Figs. 4 and 6). Strong Bt development at two sites beyond the T7 limit suggests that associated drift is significantly older than moraines

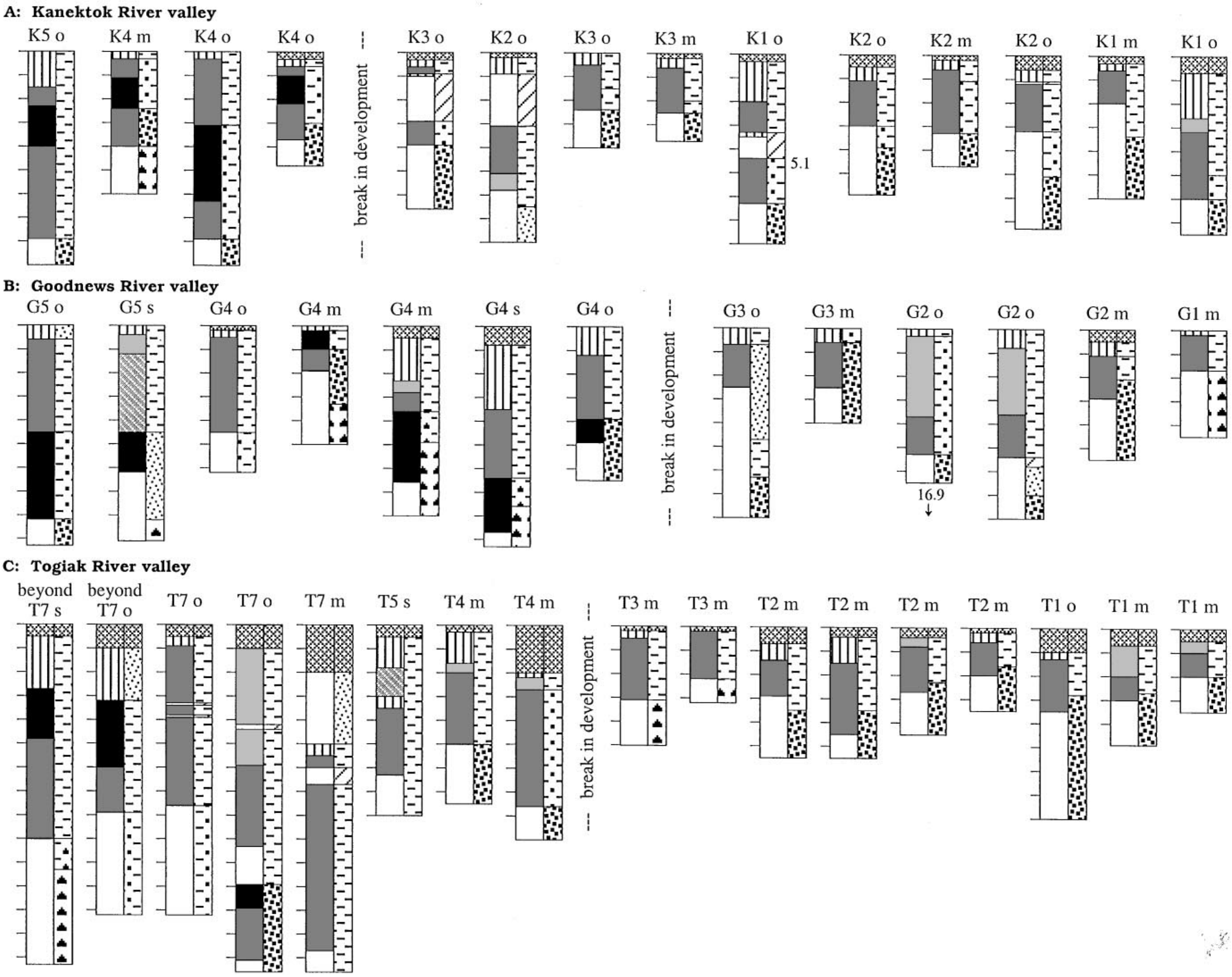

Fig. 6. Summary of soil profiles and near-surface stratigraphy for sites along the Kanektok and Goodnews Rivers and selected sites along the Togiak River. See Fig. 5 for explanation of symbols and patterns and Fig. 3 for locations. Profiles increase in development downstream of the third moraine in each valley. Down-valley is to the left.

T4-T7. An increase in average B-horizon thickness suggests that ice limit G6 is significantly older than limits G4 and G5.

Along the east side of the range, weakly to moderately developed Bw horizons are generally thin (15 ± 12 cm). The three ice-marginal positions appear to separate into two relative-age groups, based on B-horizon thickness: the youngest, Aleknagik limit (9 ± 5 cm), and the older two, Okstukuk and Gnarled Mountain limits (18 ± 7 cm, and 18 ± 20 cm, respectively; Table 2).

5. Loess thickness

5.1. Methods

We also measured loess thickness at 84 of the 107 soil-description sites to assess the potential of this parameter for discriminating the relative age of glacial events. Loess was easily recognized as a massive, well-sorted silt or very fine sandy silt. We hypothesize that cumulative loess thickness should increase with age as stable landscape surfaces are exposed to dust loading during successive glacial events. However, loess thickness might vary also with distance from source and as a function of local reworking or vegetation cover (as it affects eolian suspension settling; Lea, 1990b). Calculations include half the thickness of mixed loess and gravel horizons, or mixed loess and diamicton horizons, in cases where pedogenic mixing has homogenized these parent materials. Loess thickness was not measured for soil sites along the eastern front of the Ahklun Mountains.

5.2. Results

Loess tends to increase in thickness with distance down-valley (Figs. 6 and 7; Table 2). The eolian mantle averages 51 ± 44 cm, and is as thick as 140–240 cm at

Table 2
Summary of relative age data for the southern Ahklun Mountains region[a]

Ice Margin[b]	Inferred age[c]	B-Hor. thickness (cm)	Loess thickness(cm)	n^d	Slope angle (°)	Crest width (m)	n^e
K1	LW	27 ± 8	41 ± 7	3	22	27	1
K2	LW	23 ± 4	32 ± 9	4	19	23	1
K3	LW	17 ± 3	18 ± 5	3	15	21	1
K4	EW	48 ± 24	28 ± 23	3	13	36	1
K5	pre-W	64	79	1	3	229	1
G1	LW	15	17	1	17	27	1
G2	LW	28 ± 8	31 ± 22	3	19	17	1
G3	LW	25 ± 11	33 ± 16	7	19 ± 1	19 ± 6	4
G4	EW	39 ± 11	36 ± 20	10	15 ± 5	19 ± 2	3
G5	EW	39 ± 17	45 ± 26	10	11 ± 2	43 ± 15	5
G6	pre-W	62 ± 8	68 ± 16	2	10 ± 3	40 ± 8	4
T1	LW	18 ± 5	18 ± 3	3	20 ± 1	28 ± 3	2
T2	LW	20 ± 7	23 ± 8	4	19 ± 2	27 ± 1	3
T3	LW	23 ± 4	25 ± 6	2	12 ± 1	40 ± 18	2
T4	EW	33 ± 19	35 ± 10	3	15 ± 3	40 ± 10	4
T5	EW	45 ± 15	140 ± 16	2	19	38	1
T6	EW	35	34	1	18	23	1
T7	EW	58 ± 28	115 ± 83	6	17 ± 1	45 ± 5	2
beyond T7	pre-W	55 ± 11	92 ± 16	2			
U1	LW	22 ± 2	39 ± 22	2	16	28	1
U2	LW	18	31	1	20	52	1
U3	LW	23 ± 8	34 ± 19	2	21 ± 2	22 ± 2	2
U4	EW	44 ± 9	60 ± 22	3	11	36	1
beyond U4	EW	38 ± 13	132 ± 38	6			
Aleknagik	LW	9 ± 5		7	19 ± 2	34 ± 28	6
Okstukuk	LW	18 ± 7		9	17 ± 5	30 ± 11	10
Gnarled Mtn.	EW	18 ± 20		7	8 ± 2	62 ± 23	5
LW		20 ± 5	28 ± 8	14	18 ± 3	28 ± 19	14
EW		40 ± 11	69 ± 46	10	14 ± 4	38 ± 13	9
pre-W		60 ± 5	80 ± 12	3	7 ± 5	135 ± 134	2

[a]Values are means ± 1 SD of site observations for each ice margin, and grand means ± 1 SD of ice-marginal averages for each age group.
[b]Results are compiled by correlation to major ice-marginal positions in four drainage systems and along the east side of the range. At bottom, data are averaged for the three major relative-age groups identified in this study (LW = Late Wisconsin; EW = Early Wisconsin (*s.l.*); pre-W = pre-Wisconsin).
[c]Ages inferred from comparison of relative-age data and ^{14}C dates. See Note [b].
[d]Number of sites per ice margin, or number of ice margins per age group, with measurement of B-horizon thickness and loess thickness.
[e]Number of sites per ice margin, or number of ice margins per age group, with measurement of moraine morphometry.

five sites in outer Kulukak and Togiak Bays. The average coefficient of variation for 23 ice margins with two or more correlative sites each is 40%. In the Kanektok River valley, ice limits K1-K4 exhibit similar loess thickness (18–41 cm). A loess cap measuring 79 cm suggests that K5 is significantly older. In the Goodnews River valley, loess thickens with distance down-valley, but no distinct groups are evident. In the Togiak River valley, loess thicknesses for limits T1 through T4 appear to cluster (18–35 cm). With the exception of an anomalously low value for T6 (based on a single observation of 34 cm), down-valley limits form another relative-age group (92–140 cm). In the Kulukak River valley, sites beyond U4 display an average loess thickness of 132 cm, significantly greater than the averages for moraines U1 through U4 (31–60 cm).

At many sites, at least two cycles of loess deposition and soil formation are apparent in composite soil profiles. For example, a site correlative with ice-margin T5 ("T5 s" on Fig. 6), exhibits a B/C horizon in loess over a buried A horizon, which overlies a thick Bwb horizon in loess below. Another example is site "G5 o", where a weakly developed Bw in loess abruptly overlies a moderately developed Bt in loess; the contrast in development between horizons, the superposition of Bw over Bt, and the sharp contact between them suggest that this profile consists of welded soils, and that the Bt horizon is a paleosol. Similarly, Btb horizons are recognized at sites "G4 s", "K4 o", and "K4 m", among others. A third, common stratigraphic relationship is exemplified by one of two sites labeled "K1 o", where a Bw in loess overlies a thin Ab and an unaltered tephra, which in turn overlie a buried Bw developed partly in loess. Other sites where tephra overlie paleosols include "K3 o", "T7 m", and "T7 o". The composite profiles, and the evidence for multiple intervals of loess deposition, are concentrated

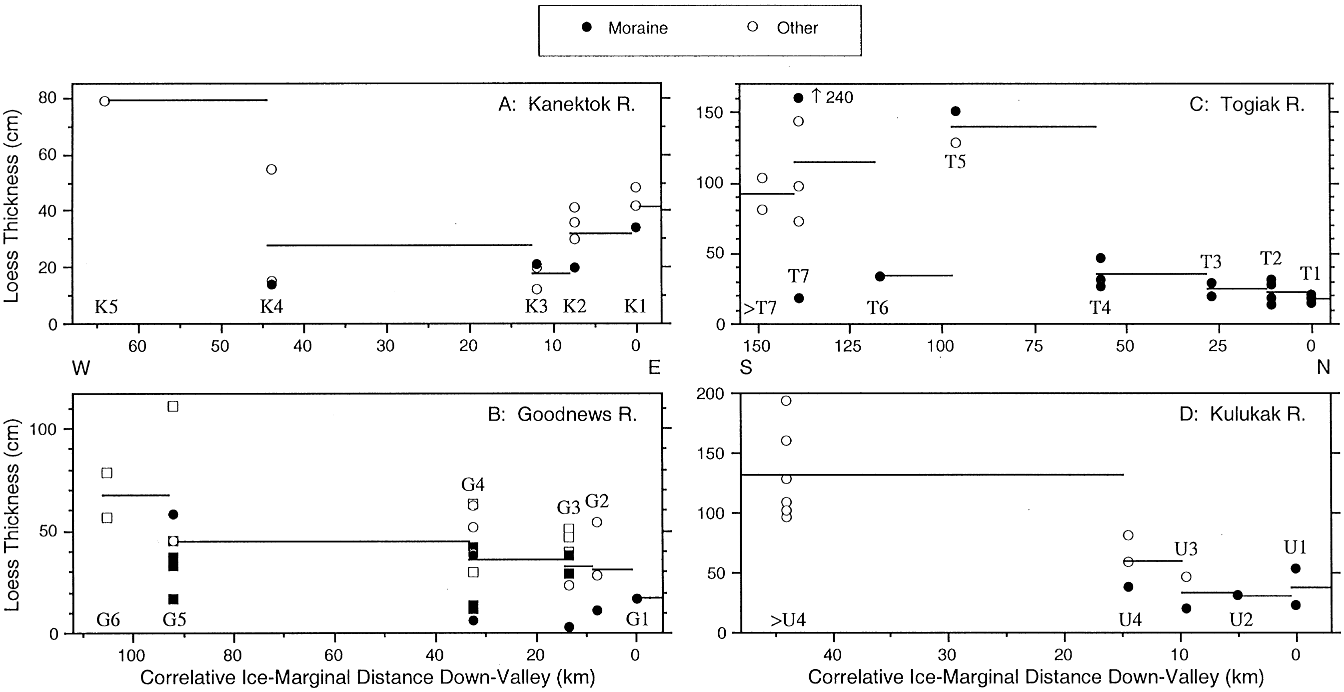

Fig. 7. Comparison of loess thickness with correlative ice-marginal distance down-valley. See Fig. 4 for explanation of symbols. Data summarized in Table 2.

on older surfaces associated with the outer two or three ice margins in each valley.

6. Moraine morphometry

6.1. Methods

Moraine-crest widths and flanking-slope angles were measured at 64 sites following the methods of Kaufman and Calkin (1988). For each site, data were collected at two to eight positions separated by distances > ca. 100 m. The majority of the sites (43 of 64) are in open, unforested areas. The remainder are in boreal forest on the south-eastern flank of the range. One to as many as 10 sites were established per ice-marginal position (Fig. 3; Table 2). Our procedure is similar to that followed elsewhere in Alaska, including the Kigluaik Mountains (Kaufman and Calkin, 1988; Peck et al., 1990), the Brooks Range (Hamilton, 1986), and the Alaska Peninsula (Stilwell and Kaufman, 1996). We hypothesize that with time after deglaciation, slope-degradation processes will tend to reduce flanking slope angles while increasing crest widths.

As with these other studies, interpretation of moraine morphometry is dependent on several assumptions. First, slope angles are assumed to have been similar among moraines shortly after deposition. At the scale of a morainal belt, this apparently was not always the case, as surface expression and "roughness" can vary over distances of hundreds of meters or kilometers across hummocky drift. To minimize this effect, we concentrated on areas within moraine belts that exhibited the steepest slopes and most "hummocky" appearance, where multiple constructional processes initially would have created slopes close to the angle of repose (e.g., melting of buried ice, thrust ridge formation, and ice-contact, gravity-driven deposition of supraglacial debris). In such settings, time-dependent slope-degradation processes following deglaciation are the primary factor controlling morphology.

Other assumptions appear to be valid. Morainal sediments consist of unconsolidated sandy gravel or sandy, gravelly diamicton, which would have similar mechanical attributes following deglaciation — a factor that affects rates and processes of slope degradation. Slope angles are not strongly a function of slope height (cf. Pierce and Colman, 1986; mean $r^2 = 0.23$; regression-equation slopes are not significantly different from 0.00 for 19 of the 24 ice margins with sufficient observations, F-test, $\alpha = 0.05$). Similarly, crest widths are independent of slope height (mean $r^2 = 0.29$; regressions are not significant for 18 of the 21 ice margins with sufficient observations, F-test, $\alpha = 0.05$). Finally, ice-proximal slope angles are not significantly different from ice-distal slope angles (T-test, $\alpha = 0.05$, $p = 0.93$).

6.2. Results

Slope angles tend to decrease with distance down-valley (Fig. 8; Table 2). For example, in the Kanektok River valley, moraines K1, K2, K3, K4, and K5 have

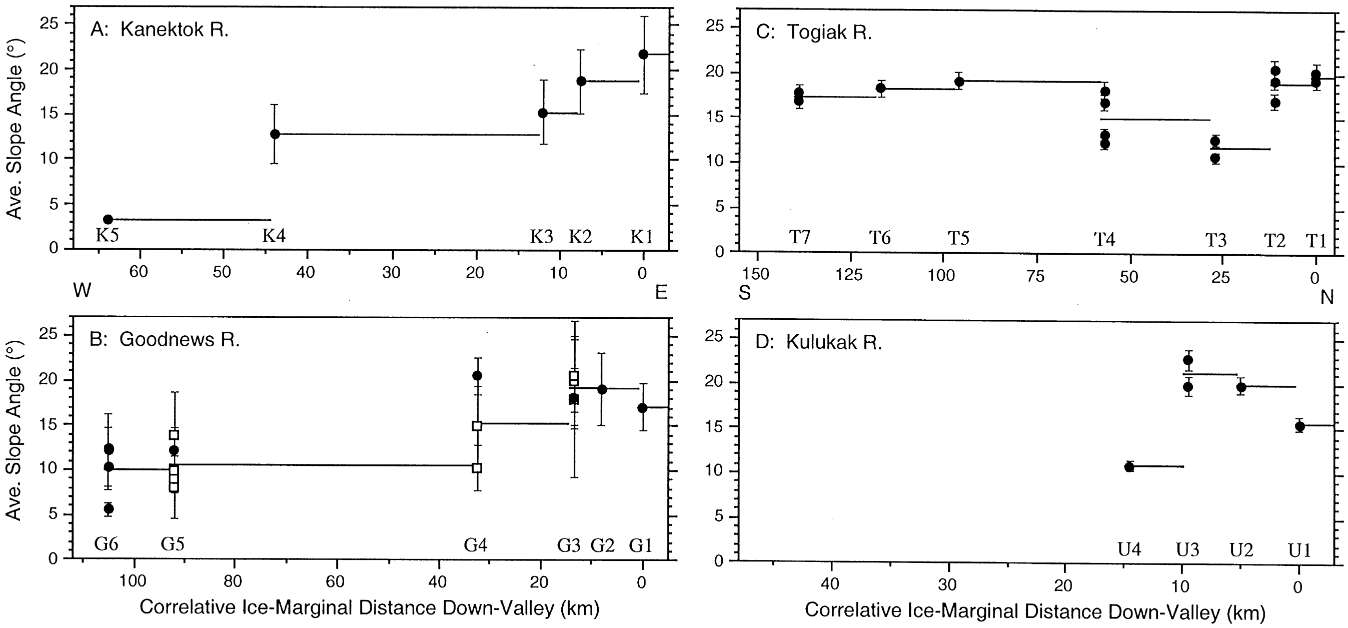

Fig. 8. Comparison of average moraine side-slope angles with correlative ice-marginal distance down-valley. Solid circles show data for sites along the Kanektok, Goodnews, Togiak, and Kulukak River valleys. Open squares depict results for sites between the Goodnews and Kanektok Rivers, correlated to moraines in the Goodnews River valley. Error bars are ± 1 SD for observations correlated to the same ice margin. Data in Table 2.

average slope angles of 22, 19, 15, 13, and 3°, respectively. The extremely low slope for K5 is a conspicuous outlier. The other moraines in this sequence follow the expected relationship of decreasing average slope angles with distance down-valley, but no subdivision in relative age is readily apparent. In the Goodnews River valley, slope angles suggest that the inner three moraines (17–19°) or four moraines (15–19°) are not significantly different in relative age, and that moraines G5 and G6 (10–11°) are appreciably older. Average slope angles for moraines in the Togiak River sequence show no trend for decreasing slope angles with distance down-valley. Averages as high as 17–19° for moraines T5 through T7 are comparable to averages of 20 and 19° for moraines T1 and T2. In this case, flanking slope angles do not differentiate relative age. In the Kulukak River valley, an average of 11° for moraine U4 implies that it is significantly older than the inner three moraines, which have averages of 16–21°.

Slope angles for moraines on the east side of the Ahklun Mountains separate ice-marginal positions into two relative-age groups. The Aleknagik and Okstukuk moraines have average slope angles of 19 and 17°, suggesting that they are significantly younger than the Gnarled Mountain limit, which has an average of 8°.

The crest-width data (Table 2) appear less helpful for assessing relative age. No significant trends are apparent for the Togiak and Kulukak River valley sequences. However, data from the other two river valleys follow the expected relationship of increasing crest width with distance down-valley, and support the relative-age differences indicated by the slope-angle data. For example, the inner three moraines in the Kanektok River valley cluster together (with crest widths of 21–27 m). The fourth moraine exhibits an intermediate value (36 m). A crest width of 229 m for the fifth moraine implies a much older age, in agreement with very gentle slopes. In the Goodnews River valley, crest widths suggest that the inner four moraines (17–27 m) form a relative-age group, and that moraines G5 and G6 (40–43 m) are significantly older.

Crest-width data from the east side of the Ahklun Mountains separates the three ice limits into two groups. The Aleknagik and Okstukuk moraines share relatively low averages of 30–34 m, whereas the Gnarled Mountain limit is characterized by an average crest width of 62 m.

7. Radiocarbon ages

Among 11 radiocarbon determinations from the region that constrain the timing of glacial events, four are AMS ^{14}C dates reported here for the first time (Table 1). The ^{14}C dates (age estimates, cf. Colman et al., 1987) provide minimum ages for underlying drift. One of the dates additionally provides a maximum age for overlying outwash, and another constrains the timing of postglacial loess deposition and B horizon development.

Three ^{14}C dates determine a pre-late Wisconsin age for associated ice limits. At site 2 on the lower Kanektok River, 5 km upstream from moraine K5 (Fig. 3), an AMS ^{14}C date of $> 41{,}500$ ^{14}C yr BP was obtained on macrofossils from peat overlying outwash gravel. The outwash is apparently recessional in origin; thus, the date is

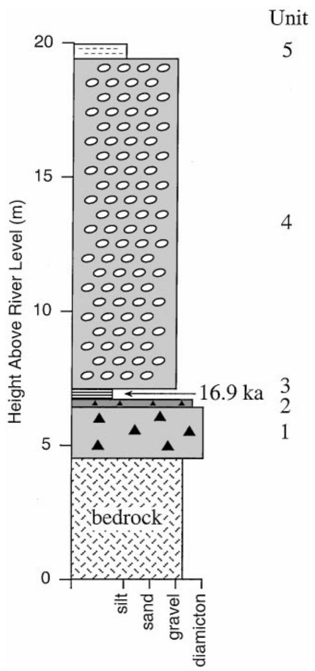

Fig. 9. ^{14}C dated stratigraphic section at site 3, Fig. 3. See text for explanation.

a minimum age for ice-marginal position K5, and revises the age for this limit, which was depicted on a statewide compilation as late-Wisconsin in age (Hamilton, 1994). At site 5 on Crooked Island (Fig. 3), an AMS ^{14}C date of 39 860 $\pm$ 1200 ^{14}C yr BP was determined on macrofossils in peat overlying drift associated with a nearby thrust ridge, which we correlate with ice margin T7. The result, near the limit of radiocarbon dating, is interpreted as a minimum age for the peat, and establishes a pre-late-Wisconsin age for T7. At site 4 south of Goodnews Bay (Fig. 3), a conventional ^{14}C date of >45.0 ka was reported by Porter (1967) for peat at the base of a kettle fill, which overlies till we have traced 0.5 km southward to glacier limit G6.

Porter (1967) reported four other conventional ^{14}C dates from this area (site 4). A date of 8.9 ka was determined on basal peat overlying till 1.0 km north of the G6 limit. We reinterpret the date strictly as a minimum limiting age, rather than as a closely limiting age (Porter, 1967), and suspect that a hiatus of significant duration exists at the base of the peat. Three dates of 11.5, 12.1, and 12.8 ka were obtained on peats in kettle fills 0.5–0.9 km south of the G6 limit, overlying commonly stratified sandy gravel that we interpret as proglacial outwash. These four dates provide distant minimum ages for ice limit G6, and are superseded by the minimum age of >45.0 ka described above for the same drift.

A new AMS ^{14}C date from the upper Goodnews River from glaciolacustrine sediment constrains the ages of moraines G3 and G2. At site 3 (Figs. 3 and 9), a river cutbank exposes five Quaternary units overlying bedrock. Unit 1, at the base, is a gray, sandy, compact diamicton — a basal till associated with advance to limit G3. Above this lies a 20-cm-thick bed of tan silty clay with 5–10% pebbles (Unit 2), a diamicton we interpret as ice-proximal glaciolacustrine sediment deposited in an ice-contact lake dammed by moraine G3. This is overlain by Unit 3, 15 cm of tan, rhythmically laminated, fining-upward, silty clay with common interlaminae of fine to medium sand — glaciolacustrine sediment deposited in a more distal setting within the glacial lake. Woody plant macrofossils from this unit yielded a ^{14}C date of 16 890 $\pm$ 120 ^{14}C yr BP (Table 1). Sandy cobble gravel above (Unit 4) is outwash forming a terrace that can be traced to moraine G2, 4 km up-valley. The terrace formed after the moraine dam failed and the glacial lake drained. Capping the sequence is a thin bed of massive silt — loess, Unit 5 — and an associated soil profile (one of two labeled "G2 o" on Fig. 6).

The date of 16.9 ka limits the age of three depositional events. First, the date provides a minimum age for the underlying till associated with moraine G3. Second, the date constrains the time when plant macrofossils and glacigenic sediments were delivered to the lake, as the margin of an outlet lobe lay a short distance up the Goodnews River valley (at or near the lake margin), after retreat from the G3 limit. These relations suggest that the date is a closely limiting minimum age for moraine G3. Third, the date provides a maximum age for deposition of the overlying outwash and moraine G2.

A middle Holocene age was obtained from the upper part of a stratigraphic section on the upper Kanektok River (site 1, Fig. 3). Small plant macrofossils from a thin peat bed directly under a prominent tephra yielded a date of 5045 $\pm$ 55 ^{14}C yr BP (Table 1; one of two profiles labeled "K1 o" on Fig. 6). The date provides a minimum age, though not a closely limiting one, for underlying outwash forming a terrace correlative with moraine K1. The date determines a mid- to late- Holocene age for 32 cm of overlying loess, indicating that loess deposition in the region continued after retreat of late Wisconsin glaciers. Similarly, the date indicates that development in the loess of a weak, 13-cm-thick Bw horizon required at most five millennia to form.

Radiocarbon dates reported by Hu et al. (1995) for two lake cores from the study area provide minimum ages for underlying drift. A basal, conventional ^{14}C date on bulk organic matter from Grandfather Lake is 12.9 ka (Table 1; site 7, Fig. 3), providing a minimum age for the Aleknagik moraine, which lies 5 km down glacier-flow lines. A basal AMS ^{14}C date on bulk organic matter from Ongivinuk Lake is 18.5 ka (Table 1; site 6, Fig. 3). This date would similarly provide a minimum age for the Aleknagik moraine. The relationship of this date to ice limits in the Togiak River valley is unclear. However, Hu et al. (1995) express that the dates from this core are suspect — at least 1000 yr too old, if not several millennia too old, based on convincing correlation of pollen assemblages to those in the Ongivinuk Lake core and to well dated pollen records elsewhere in Alaska. Thus, we reject the basal date from the Ongivinuk Lake core (as did Hu et al., 1995), and accept the basal date from the Grandfather Lake core as a minimum age for formation of the Aleknagik moraine.

8. Age assessment

Comparison of the relative-age data and radiocarbon dates allow us to subdivide the ice-marginal positions of the Ahklun Mountains ice cap into three age groups (Fig. 10). The relative-age parameters (Table 2) vary to the extent that they are able to differentiate and subdivide age groups. With increasing ability to do so, these parameters are: crest width, slope angle, loess thickness, and soil development (horizonation, thickness, and structure). Radiocarbon dates help to constrain the timing of glacial events in four of the five down-valley moraine sequences (Table 1). Our chronologic resolution is limited, but permits correlation among valleys, across Alaska, and with global records of ice volume (the marine oxygen-isotope record). The three age groups pertain to: (1) the pre-Wisconsin period (stage 6 or older; middle or early Pleistocene); (2) an early Wisconsin glaciation (*s.l.*, (sub)stages 5d through 4; cf. Kaufman et al., 2001); and (3) the late Wisconsin glaciation (stage 2, Last Glacial Maximum).

8.1. Pre-Wisconsin ice limits

The oldest age group identified in the Ahklun Mountains region is represented by ice margins K5 and G6, and by drift beyond T7 (Figs. 3 and 10, and Fig. 11; Table 2). Moderately developed Bt horizons and B-horizon thicknesses of 60 ± 5 cm suggest that these ice margins are significantly older than those of the next younger age group (see below). Slope angles ($7 \pm 5°$) and crest widths (135 ± 134 m) are consistent with broad ranges of values reported for early- and middle-Pleistocene moraines elsewhere in Alaska (Hamilton, 1994). Substantial

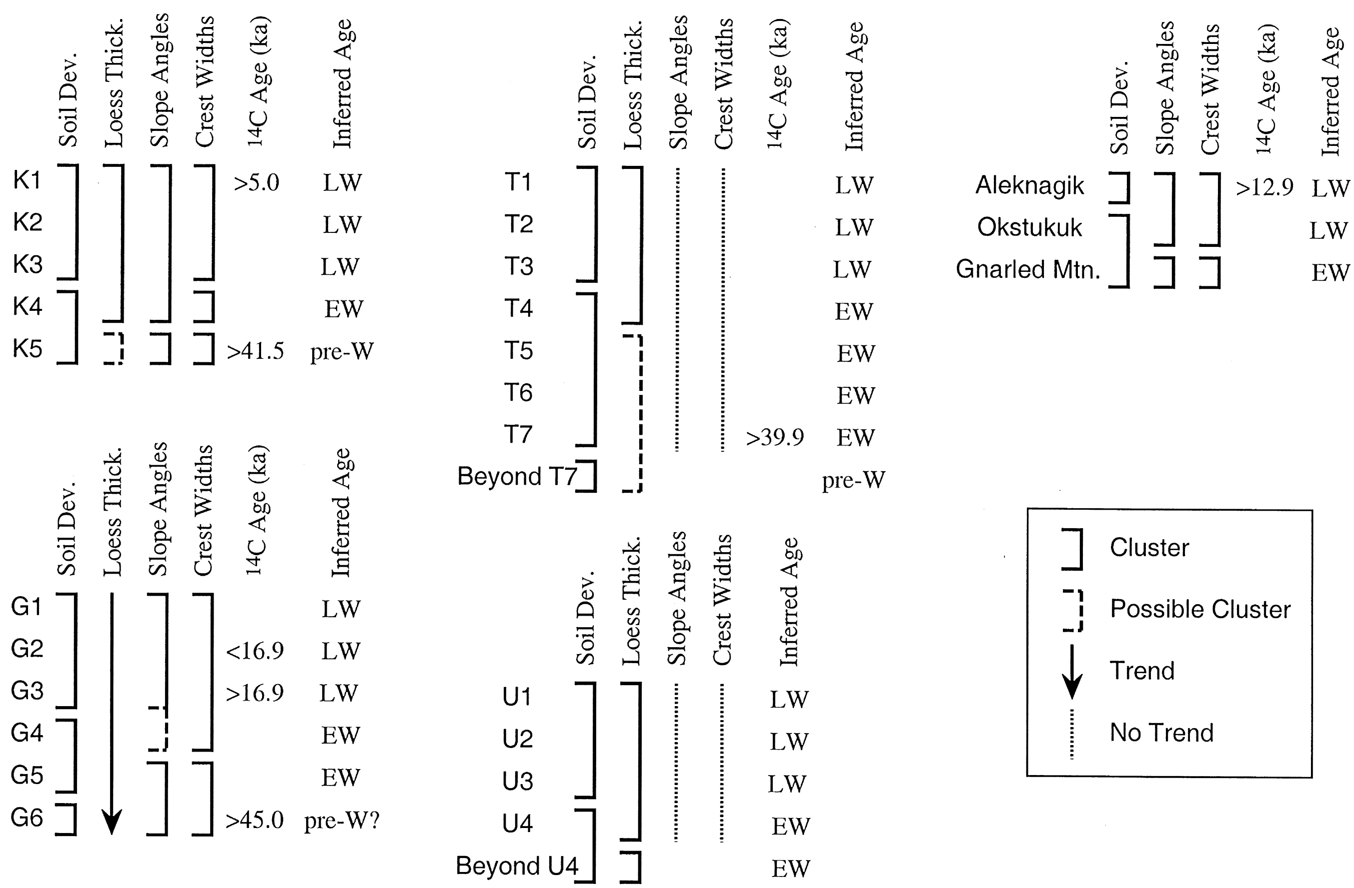

Fig. 10. Schematic summary of relative-age data and radiocarbon age estimates for the Kanektok, Goodnews, Togiak, and Kulukak River valleys, and the eastern flank of the Ahklun Mountains. The soil and morphometric data were evaluated for clustering with respect to age, and were compared with ^{14}C constraints to infer ages for three relative-age groups (pre-W = pre-Wisconsin; EW = Early Wisconsin (*s.l.*); LW = Late Wisconsin).

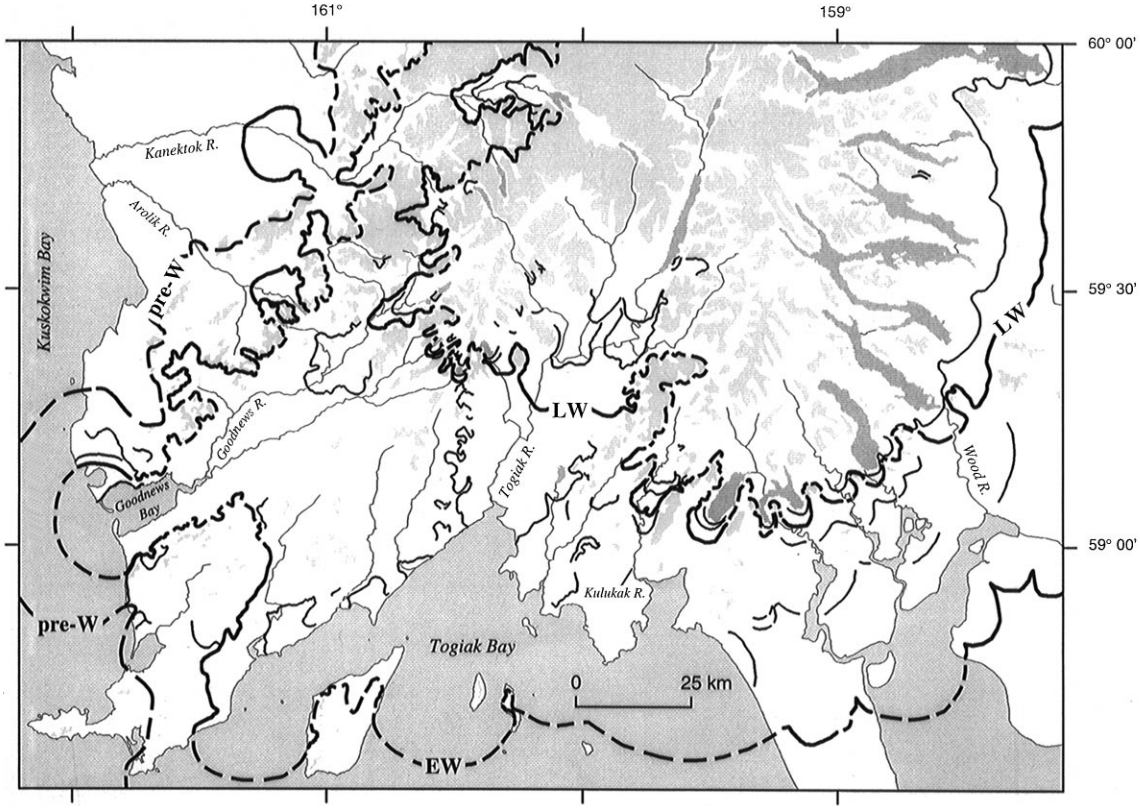

Fig. 11. The southern Ahklun Mountains, with maximum pre-Wisconsin (pre-W), early Wisconsin (EW), and late Wisconsin (LW) ice cap limits (bold lines; dashed where inferred) and other ice-marginal positions (thin lines). Placement of offshore limits is speculative. Nunataks and independent mountain glaciers are not shown. Light shading depicts elevations of 400–1500 m.

post-depositional modification of moraine K5 (with an average slope angle of 3°) suggests a middle-Pleistocene age, comparable to the 400 ka Nome River drift on Seward Peninsula (with slope angles of ca. 4°; Kaufman and Calkin, 1988; Kaufman et al., 1991). Limiting ages of >41.5 ka and >45.0 ka confirm a pre-late-Wisconsin age (Table 1). Morphologic evidence in southwestern Togiak Bay suggests a stage 6 or older age for drift beyond limit T7; four kilometers beyond this limit lies a low marine terrace inferred to be last interglacial in age (Kaufman et al., 2001). Moraines north of Goodnews Bay are evidence for pre-Wisconsin ice-marginal fluctuations. The outer moraine and two nested moraines may record three separate advances. Alternatively, they reflect one advance with two subsequent readvances or stillstands. Deposits comprising the oldest relative-age group are probably correlative with two to as many as five advances and/or readvances that reached the lower Togiak valley and Hagemeister Island during the interval ca. 500–250 ka, as documented by Kaufman et al. (2001) with age control on associated volcanic and glaciomarine deposits.

A portion of the field area seems to have escaped glaciation during the Quaternary. The maximum glacial limit appears to coincide with moraines K5, A2, the northernmost moraine north of Goodnews Bay, and possibly moraine G6 (Figs. 3 and 11). Lower reaches of the Kanektok and Arolik Rivers cross a featureless coastal lowland without exposed drift or morainal topography. Farther south, one or more pre-Wisconsin advances encompassed Chagvan Bay, but may have left a portion of the peninsula to the southwest untouched (Porter, 1967). Drift on southernmost Hagemeister Island (Kaufman et al., 2001) indicates that Togiak Bay was engulfed, as does the Nichols Hill drift on the Nushagak and Kvichak Peninsulas, south of the Ekuk limit (Lea, 1989). In sum, an ice cap over the Ahklun Mountains expanded during one or more early or middle Pleistocene advances into much of present-day Bristol Bay (cf. Coulter et al., 1965; Hamilton, 1994), but did not apparently reach the coastal lowland in the northwestern corner of the study area.

8.2. Early Wisconsin (s.l.) ice limits

The second relative-age group consists of nine ice-marginal positions (K4, G4-G5, T4-T7, U4, and the Gnarled Mountain limit; Figs. 3 and 10, and Fig. 11; Table 2). The presence of Bt horizons and moderately thick Bw horizons indicate that associated drift is significantly older than the younger, late Wisconsin age group (see below). B-horizon thicknesses of 40 ± 11 cm are comparable to maximum depths of oxidation of 30–120 cm for deposits elsewhere in Alaska attributed to the early Wisconsin (Hamilton, 1986, 1994). Other relative-age parameters are less definitive, but slope angles ($14 \pm 4^\circ$) and crest widths (38 ± 13 m) are comparable to ranges of 14–21° and 5–25 m for early Wisconsin moraines in the central Brooks Range and on Seward Peninsula (Hamilton, 1986, 1994). An early Wisconsin age (*s.l.*) for this group is based on a suite of dating methods applied to deposits within and adjacent to the field area (Kaufman et al., 1996, 2001). A minimum limiting ^{14}C date of 39.9 ka (Table 1) confirms a pre-late-Wisconsin age for drift on Crooked Island, which we correlate with ice limit T7. The Manokotak and Ekuk moraines, though not investigated specifically in this study, appear to fall in this age group (cf. Lea, 1989; Kaufman et al., 1996). Our data indicate that landforms associated with this age group experienced significant soil development, loess deposition, and moraine degradation prior to stage 2, during an interstadial period we ascribe to the middle Wisconsin (correlative with the Etolin Formation of Lea et al., 1991).

Within this group, one to as many as four ice margins are recognized for each down-valley sequence. The soil and morphometric data are not sufficiently resolved to recognize breaks in relative age within sequences. We cannot rule out the possibility of two to as many as four distinct advances by the ice cap outlet lobes during the early Wisconsin. However, we prefer a more conservative reconstruction of a single, "first-order" advance with subsequent stillstands and/or readvances. Similarly, our data are not sufficiently resolved to correlate moraines among down-valley sequences, with the exception of the outermost moraines in this age group. The maximum early Wisconsin limit appears to coincide with moraines K4, the second moraine north of Goodnews Bay, G5, and T7, crossing Togiak Bay to Crooked Island and extending eastward to the Ekuk limit on Nushagak Peninsula (Figs. 3 and 11; Lea, 1990a; Kaufman et al., 1996, 2001).

8.3. Late Wisconsin ice limits

The youngest relative-age group consists of fourteen ice-marginal positions (K1-K3, G1-G3, T1-T3, U1-U3, and the Aleknagik and Okstukuk limits; Figs. 3 and 10, and Fig. 11; Table 2). Bw horizons on correlative deposits are weakly to moderately developed and relatively thin (20 ± 5 cm), comparable to maximum depths of oxidation of ca. 30 cm for late Wisconsin drift elsewhere in Alaska (Hamilton, 1994; Stilwell and Kaufman, 1996). The soil profiles, described at 51 sites, lie up-valley of a clear to sharp increase in B-horizon thickness and development associated with the next older age group. Also, loess is thinner on average (28 ± 8 cm) than for the early Wisconsin (*s.l.*) age group (69 ± 46 cm). Morphometric parameters are less definitive, but average slope angles of $18 \pm 3^\circ$ and crest widths of 28 ± 9 m are consistent with broad ranges of 11–30° and 2–24 m for late Wisconsin moraines elsewhere in Alaska (Hamilton, 1994; Stilwell and Kaufman, 1996). A late Wisconsin age assessment is qualitatively supported by the fresh, little modified, hummocky surface expression of ice-marginal landforms. The outermost late Wisconsin moraine in the Goodnews River valley (G3) is older than 16.9 ka, and moraines G2 and G1 are younger than 16.9 ka (Table 1).

The maximum extent of the Ahklun Mountains ice cap during the late-Wisconsin is thus outlined by moraines K3, G3, T3, U3, and the Okstukuk moraine. The Aleknagik moraine and the inner two moraines in each of the Kanektok, Goodnews, Togiak, and Kulukak River valleys delineate stillstand or readvance positions. These are informally identified here as "late-stage" ice-marginal positions. Similarity in number and extent for each major valley suggests that moraines K1, G1, T1, and U1 are correlative, and that moraines K2, G2, T2, and U2 are correlative. Based on relative extent alone, the Aleknagik moraine appears to correlate with the latter group. However, the soil and morphometric data are not sufficient to identify breaks in relative age or to correlate among valleys.

The available data permit partial correlation with the late Wisconsin glacial history of the northern Alaska Peninsula. The minimum age of 16.9 ka for moraine G3 suggests that the maximum late Wisconsin limit of the Ahklun Mountains ice cap was reached during the early phase of the Brooks Lake glaciation, which falls in the range of 26–16 ka (Stilwell and Kaufman, 1996). This is consistent with the correlation of Lea (1989, p. 229) of the Okstukuk moraine — based on morphology, extent, and sequence position — with the outer of two moraines deposited during the early phase of the Brooks Lake glaciation. Deposition of the late-stage moraines was probably correlative with the late phase of the Brooks Lake glaciation, ca. 14–10 ka (Stilwell and Kaufman, 1996). Similarity in number and extent suggests correlation of the second moraine in each major valley with the Newhalen ice limit of Stilwell and Kaufman (1996), and the first moraine in each valley with the Iliuk ice limit. However, we lack sufficient radiocarbon control to test these hypotheses.

The age assessments above also permit partial correlation with periglacial eolian deposits in the Bristol Bay Lowland southeast of the Ahklun Mountains. Broad outwash trains emanating from the Ahklun Mountains ice cap likely acted as source areas for the thick, widespread blanket of eolian silt and sand that forms the Igushik Formation (Lea, 1989, 1990b). Advance of outlet lobes to the maximum late Wisconsin limit appears to correlate with the lower part of the Igushik Formation. It remains unclear, however, whether the limit was reached prior to deposition of the Tunuing Silt Bed, which represents a slackening of glacially influenced, eolian deposition 22–17 ka (Lea, 1989, 1990b). The maximum age of 16.9 ka for moraine G2 suggests that outlet lobes reached

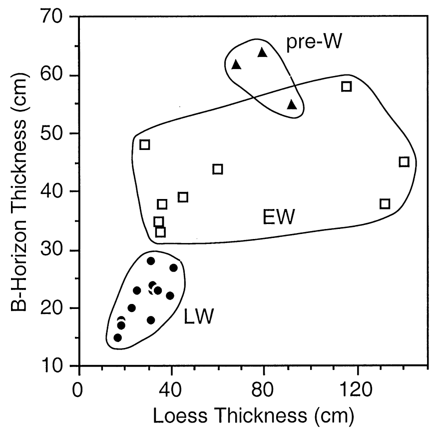

Fig. 12. Clustering of soil parameters for ice-marginal positions, with respect to B-horizon thickness, loess thickness, and inferred age (see Fig. 10).

the late stage positions during deposition of the thick upper part of the Igushik Formation, 17–13 ka (Lea, 1989, 1990b).

This study revises previous reconstructions of the late Wisconsin Ahklun Mountains ice cap. Our reconstruction largely agrees with that of Coulter et al. (1965) compare Figs. 2, 3 and 11). One exception is that Coulter et al. (1965) placed the late Wisconsin limit in the Goodnews River valley at moraine G4, rather than G3. Along the eastern flank of the Ahklun Mountains, our assessment of the late Wisconsin limit agrees with those of Lea (1989) and Hamilton (1994). However, on the southern and western flanks of the range our reconstruction differs substantially from that compiled by Hamilton (1994), which placed the late Wisconsin limit approximately with moraines K5, G6, T7, and beyond U4 (compare Figs. 2, 3 and 11). This depiction of an extensive late Wisconsin ice cap is mainly founded on the early work of Porter (1967), who placed the limit southwest of Goodnews Bay near moraine G6.

9. Soil development as an indicator of relative age

Given the age assessments above, the soil data can be summarized by age group (Fig. 12). For example, B-horizon thickness and loess thickness, averaged for each ice-marginal position, both increase with inferred age (as expected, given assumptions made for relative-age assessment). Fields defined by these variables are separate for the late Wisconsin and early Wisconsin age groups, suggesting that soil parameters resolve age differences on the order of 10^5 yr within the late Pleistocene. The field for the pre-Wisconsin age group overlaps slightly with the field for the early Wisconsin age group. Separation between groups is greater for B-horizon thickness than for loess thickness.

The increase in B-horizon thickness with increasing loess thickness may in part be due to parent material influences independent of age. Soil forming processes are accelerated with eolian dust influx and with the fine texture of loess, compared to other parent materials (e.g., Reheis, 1990). This influence can be addressed by testing for the significance of regressions between the two variables for deposits of similar age. For example, within the late Wisconsin age group, B-horizon thickness strongly increases with loess thickness, and the slope of the regression is significantly different from 0.00 ($r^2 = 0.34$; F-test, $\alpha = 0.5$). Similarly, within the early Wisconsin age group the relationship is significant ($r^2 = 0.15$; F-test, $\alpha = 0.5$). However, loess thickness itself can be an independent measure of relative age (see "Loess Thickness" section), and explains at most 35% of the variation in B-horizon thickness within relative age groups. Also, regressions between these variables are not statistically significant for each of the 14 ice-marginal positions with three or more correlative soil profiles (mean $r^2 = 0.43$; F-test, $\alpha = 0.5$). For these reasons, we believe that parent material is secondary to age as a soil forming factor for profiles investigated in this study, and that B-horizon thickness can be used to discriminate relative age.

To our knowledge, ours is one of very few studies that have described Bt horizons in Alaska. We have relied on a field-based definition, dependent on observation with hand lens of clay films (i.e., clay skins, cutans) as clay coatings on grains, on ped faces, or in pores, as bridges between grains, or as clay lamellae (Soil Survey Staff, 1975; Birkeland, 1984). The clay films thus imply accumulation of illuvial clay and translocation from overlying horizons. Unlike other areas of Alaska, the Ahklun Mountains region may be suited for Bt formation; it is warmer than the interior or North Slope, drier than to the southeast, and lacks the processes of podzolization associated with forested areas. Well-drained, pre- late Wisconsin landscapes in this region lie in the southern part of the zone of discontinuous permafrost, south of the limit of active ice-wedge formation. Thus, landscape surfaces appear to have escaped significant cryoturbation, and have been mostly stable for tens of thousands of years. However, without analyses of clay concentration, mineralogy, or micromorphology, we cannot determine whether the Bt horizons fulfill the more rigorous requirements for classification as argillic horizons (Soil Survey Staff, 1975).

Also, to our knowledge this is the first use of soil chronosequences with full horizon nomenclature to assess the relative age of Pleistocene glacial deposits in Alaska. Other glacial geologic studies have reported thickness or maximum depths of oxidation (see Hamilton, 1994; Stilwell and Kaufman, 1996). Chronosequences have also been described for other landforms (e.g., pingos; Walker et al., 1996) and for Holocene glacial sequences (e.g., Alexander and Burt, 1996). The results of this study suggest that morainal sequences elsewhere in Alaska might benefit from the chronosequence approach. The occurrence of Bt horizons, in particular, would help to identify pre–late-Wisconsin landforms. Horizonation in the soil profiles in the Ahklun Mountains region is not extremely well developed, and cryoturbation is a factor, but these limitations could be overcome with description of a large number of soils. Our data suggest also that further pedogenic analysis in the region — with complete soil descriptions and analysis of texture, mineral composition, and micromorphology — would be fruitful.

10. Summary and conclusions

Glacial mapping, relative age data, and radiocarbon age estimates provide new information on the extent and timing of at least three major advances by outlet lobes emanating from the southern half of an ice cap centered over the Ahklun Mountains (Fig. 11). Soil characteristics and morphometric parameters identify three relative age groups (Fig. 10). As many as seven other ice-marginal positions appear to have been occupied during readvances or stillstands. Available ^{14}C dates help to identify the maximum late Wisconsin limit of the ice cap, which was more restricted than previously reconstructed in statewide compilations. The new information helps to assess paleoclimatic controls on glaciation in southwestern Alaska (cf. Elias, 2001).

The data presented here indicate that during the early-to-middle Pleistocene, one to three extensive advances engulfed much of the southern Ahklun Mountains, surrounding lowlands, and a portion of present-day Bristol Bay. Outlet lobes extended 90 km to more than 180 km from the ice divide near the approximate center of the ice cap. These events may have been correlative with at least two, and possibly five, middle Pleistocene advances documented from coastal stratigraphic sequences in the southern part of the field area (Kaufman et al., 2001). Moraine morphometry at a few sites associated with the maximum Quaternary glacial limit suggests a middle-Pleistocene age for the maximum advance, perhaps correlative with an extensive advance on Seward Peninsula that deposited the Nome River drift ca. 400 ka (Kaufman et al., 1991).

During the early Wisconsin (*s.l.*, Kaufman et al., 1996, 2001), an advance of the ice cap produced outlet lobes that extended 80–160 km from the center of the ice cap, across the modern-day coasts of Goodnews and Togiak Bays. The maximum advance, as well as three recessional stillstands or readvances, deposited drift across broad, lower reaches of the major valleys, and commonly built moraines that have reorganized drainage patterns by forming new drainage divides. A minimum limiting ^{14}C age of 39.9 ka confirms a pre–late Wisconsin age for the outermost early Wisconsin limit. Development of Bw and Bt horizons, loess thickness, and to a limited extent morphometric parameters differentiate these deposits from the youngest relative-age group.

During the late Wisconsin, outlet glaciers were much more restricted, and were sheltered within the middle reaches of major valleys, extending only 50–80 km from the center of the mountain ice complex, with ice margins 10–80 km from the modern-day coasts of Kuskokwim and Togiak Bays. Bw horizons on late Wisconsin drift are thin and weakly to moderately developed; loess caps are thin; moraine side-slopes are commonly steep, and crest widths narrow. A ^{14}C date of 16.9 ka for glaciolacustrine sediment in the upper Goodnews River valley establishes a minimum age for the maximum advance of ice during stage 2. During the Last Glacial Maximum, the ice cap was less extensive than as depicted by Porter (1967) and Hamilton (1994), but was similar to the reconstruction of Coulter et al. (1965). The advance was broadly synchronous with the early phase of the Brooks Lake glaciation on the northern Alaska Peninsula to the east (Stilwell and Kaufman, 1996). Two readvances or stillstands occurred after 16.9 ka, during the late phase of the Brooks Lake glaciation.

Placed in a broader context, the results shed light on variations across Beringia in glacier extent and paleoclimatic forcing. Our data highlight that an early Wisconsin (*s.l.*) advance in southwestern Alaska was extensive, encompassing much of the area ever occupied by glacier ice during the Quaternary. This history is similar to that in eastern Bristol Bay, where early Wisconsin (*s.l.*) ice broadly extended across modern coasts. In contrast, early Wisconsin (*s.l.*) glaciers farther north were an order of magnitude less extensive than during the early or middle Pleistocene (Seward Peninsula and western Brooks Range; Kaufman and Hopkins, 1986; Hamilton, 1986). These comparisons imply regional asymmetry during the early Wisconsin in paleoclimatic forcing, perhaps tied to regional variations in moisture availability.

Late Wisconsin glaciers of southwest Alaska were strongly limited by available moisture and winter precipitation. Maximum extent of the Ahklun Mountains ice cap early during the Wisconsin glaciation, rather than during the Last Glacial Maximum, is evidence for glacier response out of phase with global ice volume and paleoclimate forcing of mid-latitude ice sheets (cf. Gillespie and Molnar, 1995). Our reconstruction of restricted extent for the Ahklun Mountains ice cap agrees with modest lowering of equilibrium-line altitudes (ELA's) for many small valley glaciers that fringed the ice cap. A preliminary estimate of 200–400 m of ELA lowering relative to present (Manley et al., 1997, 1998) — less than half the worldwide average for the Last Glacial Maximum — provides evidence for dry conditions. This situation was common throughout Beringia, as the Bering Sea regressed and exposed broad areas of continental shelf, forcing a shift to continental conditions (e.g., Barry, 1982;

Hopkins, 1982; Hamilton, 1994). Perennial or seasonal sea ice in the Bering Sea (Sancetta and Robinson, 1983; Sancetta et al., 1984) may have also limited moisture availability. The Ahklun Mountains and surrounding lowlands were well situated to experience such a shift from transitional maritime to continental climates.

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