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Late Pleistocene Glaciation of the Southwestern Ahklun Mountains, Alaska

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Glacial deposits in the southwestern Ahklun Mountains, southwestern Alaska, record two major glacier advances during the late Pleistocene. The Arolik Lake and Klak Creek glaciations took place during the early and late Wisconsin, respectively. During the Arolik Lake glaciation, outlet glaciers emanated from an ice cap centered over the central portion of the Ahklun Mountains and expanded beyond the present coast. During the Klak Creek glaciation, ice-cap outlet glaciers terminated ~60 km upvalley from Arolik Lake moraines. The area also supported numerous alpine glaciers that expanded from small massifs. During both episodes of glaciation, these alpine glaciers apparently reached their maximum positions sometime after the retreat of the ice-cap outlet glaciers. Equilibrium-line altitudes for reconstructed alpine glaciers of the Klak Creek glaciation average ~390 ± 100 m elevation in the western Ahklun Mountains, which is at most 500 m, and possibly only 200 m, below the estimated modern equilibrium-line altitude. The maximum late Pleistocene advance in the southwestern Ahklun Mountains occurred during the early Wisconsin, similar to advances elsewhere in western Alaska, but in contrast to the isotopic signal in the deep-sea record of global ice volume. The restricted extent of Klak Creek glaciers might reflect the increased distance to the Bering Sea resulting from eustatic sea-level regression and decreased evaporation resulting from lower sea-surface temperatures and increased sea-ice extent.

INTRODUCTION

The hallmark of Beringia (the broad region that spans from northeastern Siberia to the Yukon) during the Pleistocene was the vastness of its unglaciated area. Outside of the Cordilleran Ice Sheet, which developed over much of southern Alaska, glaciers of the last glacial maximum were largely restricted to the highest massifs (e.g., Hamilton, 1994). Unlike the ice sheets that developed over middle latitudes of the Northern Hemisphere, glaciers in Beringia did not impose a major control on the regional ice-age climate. The limited glacier ice that expanded from the mountainous regions, on the other hand, does provide insights into aspects of the paleoclimate of Beringia, including the distribution of moisture sources and the extent and timing of stadial-scale climatic fluctuations.

The Ahklun Mountains of southwestern Alaska (Fig. 1) are the highest range in western Alaska and encompass one of the few major glaciated regions in Alaska outside of the Cordilleran Ice Sheet. Although the stratigraphic record of pre-late Wisconsin glaciations exposed in coastal bluffs around northern Bristol Bay has been the topic of recent study (e.g., Kaufman *et al.*, 1996, in press), less has been published on the late Pleistocene glacial record inland. This study focuses on the southwestern sector of the Ahklun Mountains, an area that has received little prior research. We chose this area because it contains evidence for fluctuations of two distinct glacial systems: (1) outlet glaciers of an ice cap that developed over the central part of the range and (2) alpine glaciers that advanced from several localized massifs. Differences in the timing of maximum ice positions reached by these two independent glacier systems provide clues to the paleoclimate controls on glaciation in the region. The geometries of the former valley glaciers are also more easily reconstructed than those of outlet glaciers that are fed by an ice cap. Well-preserved ice-marginal features provide the basis for reconstructing the ice thickness, surface slope, and equilibrium-line altitude of paleoglaciers. These data provide information on the direction of atmospheric

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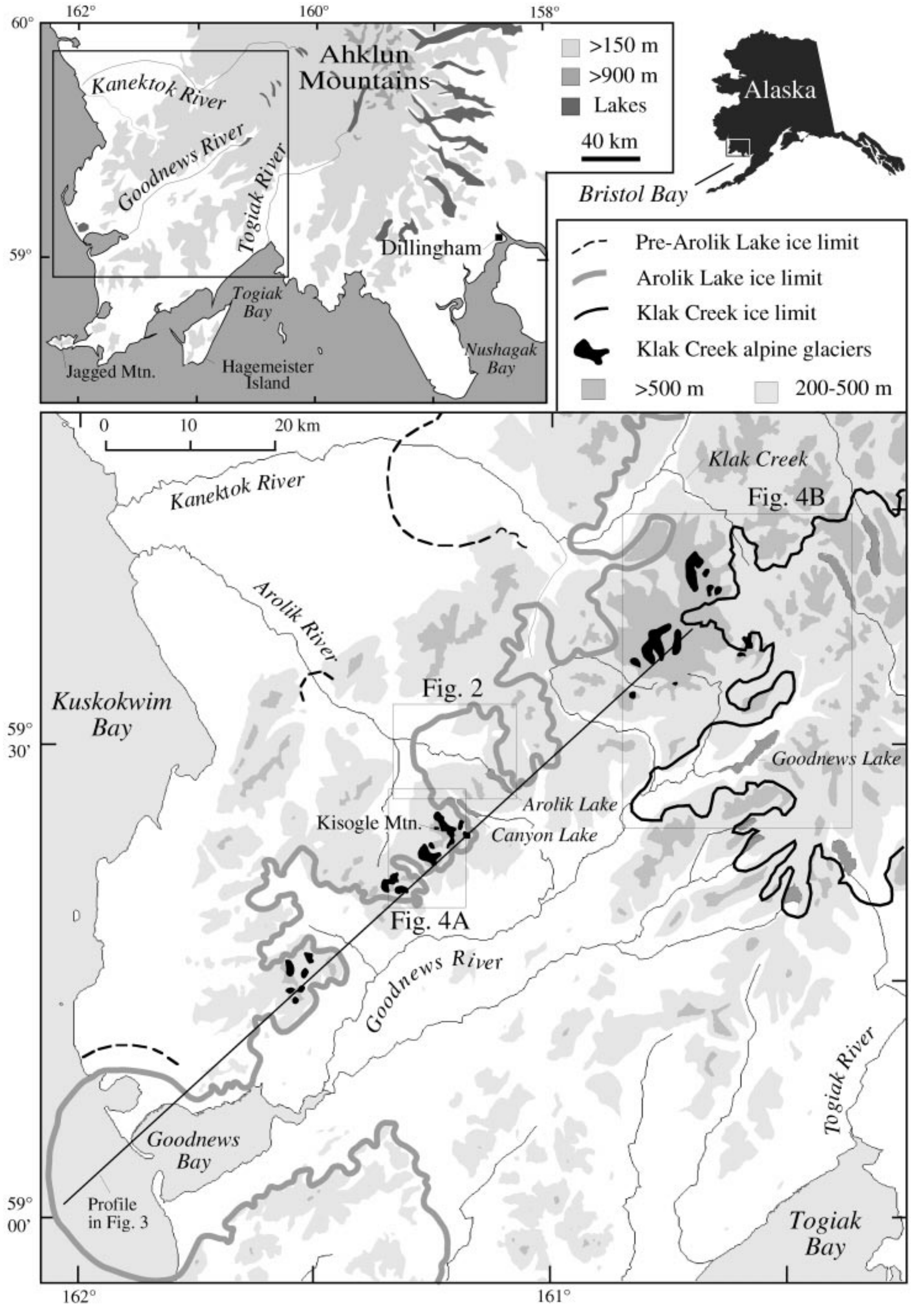

FIG. 1. Southern Ahklun Mountains, southwestern Alaska, showing locations mentioned in text, along with the ice limits of the Arolik Lake (early Wisconsin) and Klak Creek (late Wisconsin) glaciations. These limits depict the maximum extent of the ice-cap outlet glaciers and do not include nunataks and unglaciated uplands.

moisture flux across the region. In addition, this study presents the glacial–geologic context for other geochronological and paleoenvironmental research in the field area. The area contains one of the few zones of glaciated crystalline bedrock in the Ahklun Mountains. These resistant lithologies provided suitable samples for cosmogenic–isotope geochronology (Briner, 1998). The area also encompasses several deep lakes that lie beyond the limit of late Wisconsin glaciers. Sediment cores obtained from these lakes are the focus of ongoing research.

Prior to this project, few researchers had worked in the southwestern Ahklun Mountains. Hoare and Coonrad (1961) delimited the extent of glacial drift on their reconnaissance geologic map of the Goodnews Bay 1:250,000-scale quadrangle. This information was later incorporated into a state-wide map of glacial deposits by Coulter *et al.* (1965). Their map shows the limit of late Wisconsin glacier ice ~60 km upvalley from the coast in the Goodnews River valley (Fig. 1). The most recent state-wide compilation of glacial limits (Hamilton, 1994), on the other hand, shows the late Wisconsin ice limit at the coast. The more extensive ice limit was based on minimum ^{14}C ages obtained by Porter (1967) from the Goodnews Bay area. About 300 km east of Goodnews Bay, in the Nushagak Bay area (Fig. 1), Kaufman *et al.* (1996) dated glacial–estuarine sediments exposed ~80 km beyond the late Wisconsin limit of ice that originated in the southeastern Ahklun Mountains. They determined that these sediments are 90,000 to 75,000 yr old on the basis of amino acid and thermoluminescence analyses, indicating an extensive ice advance prior to the late Wisconsin but younger than the last interglaciation. Most recently, Manley *et al.* (in press) summarized the glacial geologic history of the southern part of the Ahklun Mountains. They determined the regional extent of several major outlet glaciers of the Ahklun Mountains ice cap during the Pleistocene.

For this study, we focus on the late Pleistocene glacial history of two principal massifs (Kisogle Mountain and the massif northwest of Goodnews Lake; Fig. 1) in the southwestern Ahklun Mountains. We present detailed glacial–geologic mapping of an area influenced by both alpine and ice-cap glaciation during the multiple advances of the Pleistocene. This study expands on previous work by Manley *et al.* (in press), who compiled relative-age data and mapped ice margins of the ice-cap glacier system over a broad region of the southern Ahklun Mountains.

Glacial–geologic features were mapped in the field and on aerial photographs. Moraines and other ice-marginal features are easily discernible on aerial photographs and on the ground in this open tundra landscape. We subdivided and correlated drift units based on morphostratigraphic position and relative-weathering criteria. Soil B-horizon development, loess thickness, and moraine morphology were measured on moraines throughout the field area.

GLACIAL GEOLOGY

The Ahklun Mountains trend about 250 km northeast to southwest and are flanked by the Kuskokwim Bay and Bristol Bay lowlands on the west and east, respectively (Fig. 1). The range reaches its highest altitudes in the north where summits exceed 1500 m and are capped by modern glaciers. The high, steep eastern front of the Ahklun Mountains is dissected by a series of elongate east–west-trending, fjord-like glacial lakes dammed by terminal moraines. These glacially overdeepened troughs were carved during repeated Pleistocene advances of outlet glaciers emanating from an ice cap over the highest part of the range. In contrast, the western range front is more diffuse, with broad valleys and rolling hills and scattered high, rugged massifs. The broad, fault-bounded valleys of the southwestern Ahklun Mountains (Kanektok, Arolik, and Goodnews river valleys) contained the expansive outlet glaciers of the ice cap. These low-lying outlet glaciers extended onto flat lowlands far beyond the mountain front where they deposited broad belts of hummocky drift that lack continuous outer moraine ridges and are associated with extensive glacial fluvial terraces that span valley floors. These outlet glaciers expanded well into otherwise unglaciated terrain where they dammed tributary fluvial systems along their margins, forming an extensive network of proglacial lakes.

The scattered massifs that punctuate the uplands between the large troughs supported relatively small alpine glaciers. These glaciers carved deep cirques during repeated Pleistocene advances. Some of the alpine glaciers were confluent with outlet glaciers from the main ice cap; others were perched above outlet glaciers, terminating independently from the ice-cap system. Where alpine ice terminated above the outlet glaciers, it deposited laterally continuous, single-crested terminal moraines. Hummocky drift and several recessional moraines record the stagnation and upvalley retreat of the alpine glaciers.

Pre-late Pleistocene Advance

Evidence for the oldest glaciation in the western Ahklun Mountains is found at and beyond the range front in all three major river valleys that drain the southwestern Ahklun Mountains (Fig. 1). In the Arolik River valley, pre-Wisconsin drift is exposed in the subsurface at several places along the river where it is buried by >1 m of loess and other nonglacial deposits (Briner, 1998). The drift was deposited by a distributary glacier that originated in the Goodnews River valley, crossed a topographic divide, and combined with local ice from the surrounding mountains. The maximum downvalley extent of this drift along the Arolik River is ~45 km northwest of the Goodnews River and 15 km beyond the maximum late Pleistocene ice limit (see below). In the Goodnews River valley, pre-late Pleistocene ice advanced beyond the present coast line and deposited moraines north and south of Goodnews Bay (Porter, 1967; Manley *et al.*, in press). In the Kanektok River valley, pre-late Pleistocene drift comprises exceptionally broad and subdued (slope angles of 3–5°) moraines buried by a thick loess blanket beyond the range front (Manley *et al.*, in press). The old drift units in the three main valleys might correlate with one another or might record multiple advances of pre-late Pleistocene glaciers. Evidence for multiple middle Pleistocene advances was recently reported on Hagemeister Island, where glacier ice repeatedly advanced from the Togiak River valley onto the continental shelf (Fig. 1; Kaufman *et al.*, in press).

Late Pleistocene Advances

A sequence of at least four moraines deposited by outlet glaciers is found within each of the major valleys of the southwestern Ahklun Mountains. In contrast to the pre-late Pleistocene drift, deposits ascribed to the late Pleistocene retain hummocky moraine morphology. Manley *et al.* (in press) subdivided these moraines into two distinct age classes on the basis of relative-weathering data. Alpine glacier moraines in the southwestern Ahklun Mountains can also be subdivided into two broad groups based on morphostratigraphic position. Within the field area, moraines of the older age group are characterized by slope angles that average 11 ± 3° (grand mean; $n = 6$ moraines; data listed in Appendix 1 (available as supplementary data), summarized in Table 1). Fourteen soil profiles described from the older drift have B horizons that average 39 ± 14 cm thick; 10 of these exhibited structural (Bt horizon) development. Loess capping the older drift averages 42 ± 27 cm thick. In contrast, terminal moraines belonging to the younger age group are typically steeper (18 ± 3°; $n = 26$); have soils with thin B horizons (26 ± 13 cm; $n = 19$) that lack structure (Bw horizon); and are capped by thin sheets of loess (27 ± 14 cm; $n = 19$). The difference in mean values of the relative-weathering indices suggests that the two moraine groups probably record separate advances of at least stadial scale. We herein refer to the older glacial period as the Arolik Lake glaciation and the younger as the Klak Creek glaciation.

Arolik Lake glaciation. During the Arolik Lake glaciation, most of the western Ahklun Mountains were glaciated by a combination of alpine glaciers that originated in a few of the highest massifs and by lower elevation outlet glaciers that drained the central Ahklun Mountains ice cap and flowed radially down major river valleys (Fig. 1). The outlet glaciers deposited broad belts of kettled, hummocky drift that span valley floors and form ridges ~4–20 m high and constructed extensive outwash terraces. The terminal moraine that arcs across the east fork of the Arolik River (Fig. 1) is herein designated the reference locality (59° 35′ N, 161° 10′ W) for drift of the Arolik Lake glaciation. This moraine is clearly defined by its abundant kettle lakes (Fig. 2). It is characterized by slope angles that range from 10 to 14° ($n = 9$ individual measurements) and is mantled by loess 48 ± 37 cm thick ($n = 5$). Boulders are absent on the moraine surface. Test pits and natural exposures show soil profiles with structurally developed B horizons 38 ± 12 cm thick ($n = 5$).

The Goodnews River valley contained the principal outlet glacier for the southwestern Ahklun Mountains during the Arolik Lake glaciation. The glacier extended ~150 km southwestward from its source in the central part of the range to Goodnews Bay (Fig. 1) and, in places, was fed by local sources of confluent alpine ice. Elsewhere along its northwestern margin, the glacier splayed into tributary valleys. These distributary lobes of the Goodnews River valley trunk glacier flowed northwestward at nearly right angles to the axis of the Goodnews River valley. In several valleys, they overtopped preglacial topographic divides and spilled into valleys draining into Kuskokwim Bay where they deposited hummocky drift as much as ~25 km northwest of the Goodnews River. The moraines are bouldery where the ice scoured through mountain passes or along valley walls.

The upper elevation of ice in distributary troughs is clearly marked by lateral moraines and ice-marginal drainages. This evidence allows us to reconstruct the ice profile of the Goodnews River valley outlet glacier (Fig. 3). The outlet glacier had an average thickness of 250–300 m and a surface gradient of 4.1 m km^{-1}. Using conventional calculations for the shear stress at the bed of a reconstructed glacier (Paterson, 1981), we estimate a value of 10 kPa, which is lower than expected for valley glaciers. The large extent of this outlet glacier with such a low surface gradient might reflect a deformable bed over unconsolidated valley-fill deposits.

The Arolik Lake moraine was formed by one of several major distributary lobes of the Goodnews River valley. It flowed through the narrow (~0.5 km wide) trough which now confines Arolik Lake, then spread out as an ~8-km-wide piedmont lobe over the broad, upper Arolik River valley. Canyon Lake (Fig. 1), situated in the adjacent valley to the southwest, also lies in a glacially eroded trough. The distributary lobe that flowed through the Canyon Lake trough deposited a moraine similar to, but ~25% the areal extent of, the Arolik Lake moraine. The Canyon Lake moraine slightly onlaps the Arolik Lake moraine (Fig. 2), indicating that the glacier that deposited the Canyon Lake moraine reached its maximum position sometime following the retreat of the glacier in the Arolik Lake valley.

The somewhat later maximum advance of the Canyon Lake lobe may have been caused by either glaciologic factors related to the geometry of the distributary lobes or different source area contributions. Arolik and Canyon Lake valleys contained ice from the same distributary glacier from the Goodnews River valley. This distributary overtopped a topographic divide and then bifurcated to feed both Canyon and Arolik Lake valleys. Because the Canyon Lake valley is slightly higher in elevation than the Arolik Lake valley, it is difficult to attribute the later advance of the Canyon Lake distributary following the retreat of an upglacier distributary to glaciologic factors. Instead, we attribute the asynchronous maximum positions to the contribution of alpine ice that formed locally over the Kisogle Mountain massif to the Canyon Lake glacier late during the Arolik Lake glaciation. Similarly, a small glacier that emanated from the unnamed valley on the southwest side of Canyon Lake (Fig. 4A) appears to have descended to the floor of the Canyon Lake trough, reaching its maximum position and depositing a terminal moraine following the retreat of the ice-cap outlet glacier.

Klak Creek glaciation. During the youngest late Pleistocene glaciation, herein named the Klak Creek glaciation, ice-cap outlet glaciers and alpine valley glaciers readvanced down all valleys that were previously glaciated during the Arolik Lake glaciation. The outlet glacier in the main stem of the Goodnews River valley terminated ~60 km upvalley from the

TABLE 1
Summary of Relative-Age Data[a]

Age group	B-Horizon thickness (cm)		Loess thickness (cm)		Slope angle (°)	
	Average ± σ	n^b	Average ± σ	n^b	Average ± σ	n^c
Arolik Lake	39 ± 14[d]	14	42 ± 27	14	11 ± 3	6
Klak Creek	26 ± 13	19	27 ± 14	19	18 ± 3	26

[a] Summarized from Appendix 1.
[b] Number of soils described.
[c] Number of moraines studied; multiple measurements were averaged for each moraine.
[d] Ten soils exhibit structural (Bt) development.

terminus of the former glacier that extended to Goodnews Bay during the Arolik Lake glaciation (Fig. 1). The location of the terminal moraine formed during the Klak Creek glaciation agrees with the inferred late Wisconsin ice limits mapped by Coulter *et al.* (1965), but is considerably more restricted than the extent of late Wisconsin ice depicted in subsequent statewide compilations (cf., Hamilton, 1994). The reference locality for drift of the Klak Creek glaciation is in the Klak Creek valley (Fig. 4B; 59° 43′ N, 160° 35′ W), where an outlet glacier from the central Ahklun Mountains ice cap deposited a prominent terminal moraine. The moraine is traceable 15 km to the southwest to the headwaters of Nukluk Creek (Fig. 4B), where the hummocky, lobate moraine has slopes that range from 10 to 30° (n = 11 individual measurements). A river bank cut through the moraine exposes a soil with a 22-cm-thick B horizon and 32 cm of loess over the drift.

During the Klak Creek glaciation, the upper Goodnews River valley and its tributaries were occupied by a complicated network of glacier ice with source areas both in the central Ahklun Mountains and in local centers of alpine glaciation.

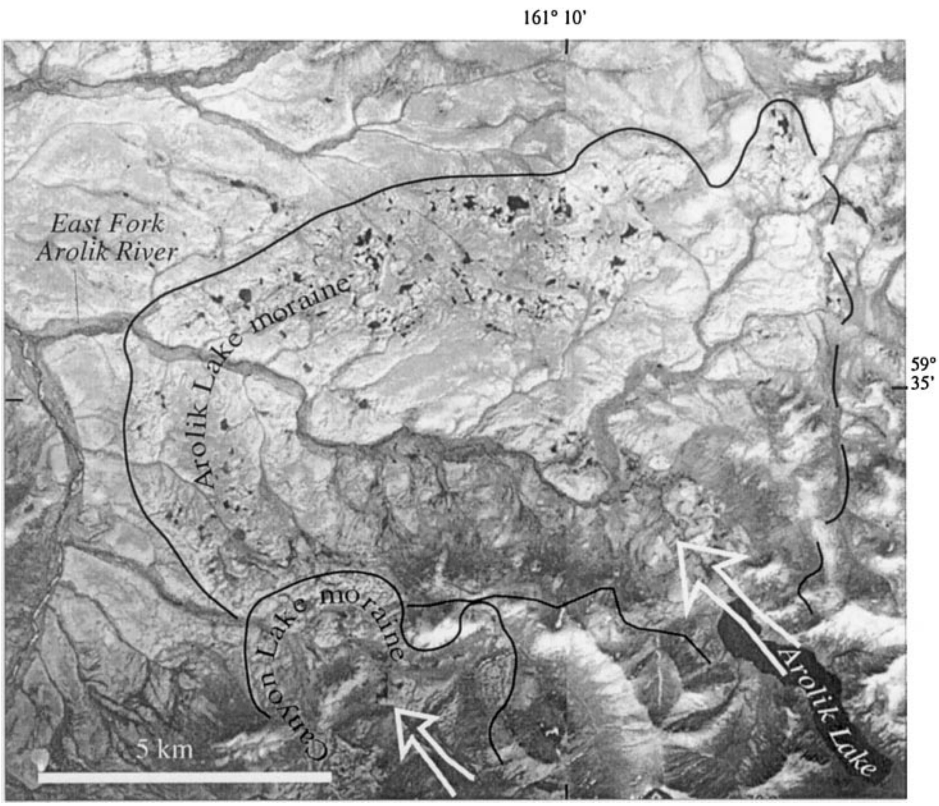

FIG. 2. Aerial photograph of upper Arolik River area showing the type locality for drift of the Arolik Lake glaciation. The moraine is highlighted by abundant kettle lakes. Also shown is the Canyon Lake moraine, which was deposited by distributary ice from the Goodnews River valley as well as from local alpine ice from Kisogle Mountain. Arrows indicate ice-flow direction. Location shown in Figure 1.

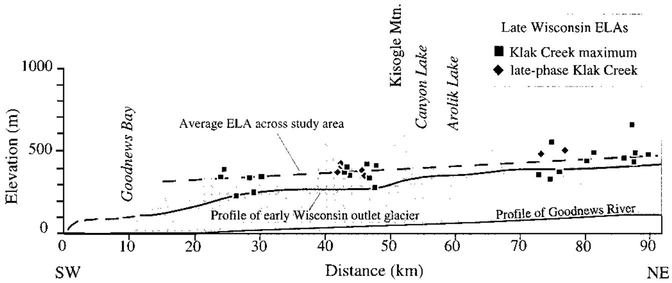

FIG. 3. Topographic profile of the mountains that border the northwest side of the Goodnews River valley from Goodnews Lake to Goodnews Bay. The bold line is a reconstructed profile of the ice-cap outlet glacier that flowed down the Goodnews River valley during the Arolik Lake glaciation. The ice thickness is known where it spilled into tributary valleys northwest of the Goodnews River and formed lateral moraines or trimlines. Late Wisconsin equilibrium-line altitudes reconstructed from alpine glaciers that expanded from massifs bordering the Goodnews River valley are also shown. The dashed line depicts a linear regression of late Wisconsin ELAs projected onto the profile. Profile location is shown in Figure 1.

The relative contribution from local valley glaciers increased northeastward, up the Goodnews River valley. The moraines in the Klak Creek region were deposited by one of the largest outlet glaciers draining the western sector of the ice complex in the upper Goodnews River valley region (Fig. 4B).

The largest outflow of glacier ice in the field area extended southwestward down the main stem of the Goodnews River valley. It encroached into otherwise unglaciated terrain where it impounded rivers of tributary valleys. A clear example is the proglacial lake that formed in the Awayak Creek valley (Fig. 4B). Locally prominent shorelines delimit a lake up to 140 m deep with a surface area of ~19 km^2. A voluminous kame delta was built into the lake where the Awayak Creek distributary glacier terminated in the proglacial lake.

The retreat of glaciers from their maximum positions was not steady. Two or more end moraines were deposited by outlet glaciers upvalley from terminal limits in at least four of the major valleys in the western and southern Ahklun Mountains, including the Goodnews River valley (see Manley *et al.*, in press, for a regional overview). In the Goodnews River valley, prominent end moraines are located ~5 and ~12 km upvalley from the terminal moraine; the younger moraine impounds Goodnews Lake (Fig. 4B). Another prominent end moraine is found ~15 km upvalley from the Klak Creek terminal moraine where it impounds Nagugun Lake. Each end moraine is associated with glacial–fluvial deposits that form well-preserved inset terraces flanking the Goodnews River.

In addition to the major ice-cap outlet lobes in the lower elevations of the broad river valleys, several scattered massifs supported local alpine glaciers during the Klak Creek glaciation. In most places, the alpine glaciers did not extend to elevations low enough to merge with the outlet-glacier ice. One of the clearest examples of alpine glaciation took place in the Kisogle Mountain area (Fig. 4A). The largest glacier deposited a single-crested, laterally continuous terminal moraine ~6 km north of cirque headwalls in the Kisogle Mountain valley. Eight other valleys in the Kisogle Mountain area contain terminal moraines ascribed to the Klak Creek glaciation. The retreat of valley glaciers from their terminal positions was interrupted by stillstands and possible readvances that deposited a complicated series of end moraines. In most valleys, a zone of hummocky drift, with individual hummocks up to 20 m high, is nested behind the terminal ridge. Farther upvalley, in the highest cirques, clearly defined, single-crested end moraines impound tarns 0.5–2.0 km from the cirque headwalls (Figs. 4A and 5). We ascribe these moraines to a "late phase" of the Klak Creek glaciation.

Although we consider the advance of alpine glaciers to be broadly correlative with the advance of the ice-cap outlet glaciers during the Klak Creek glaciation, in two locations studied in the field, drift of the ice-cap and the alpine glacier systems are juxtaposed, providing morphostratigraphic relations needed to assess the slight difference in the timing of their respective maximum advances. In the upper Klak Creek valley, a lobe of the outlet glacier splayed southward into the headwaters of Awayak Creek. Here, it deposited the Gusty Lakes moraine, which is overlapped by a moraine of an alpine glacier that emanated from Chilly Valley (informal names, inset on Fig. 4B). Assuming that the Chilly Valley moraine marks the maximum extent of the alpine glacier, then the superpositional relationship demonstrates that the valley glacier reached its maximum position sometime after the retreat of the Klak Creek outlet glacier from its maximum position. Similarly, a distributary lobe that splayed into the Nukluk Creek valley deposited an outwash head that was subsequently cut and filled by younger outwash that grades to a moraine deposited by alpine glaciers in the headwaters of Nukluk Creek (Fig. 4B). Because the outwash head of the alpine glacier is inset into the outwash head of the outlet glacier, we infer that the alpine glacier reached its maximum position during retreat of the outlet glacier.

GEOCHRONOLOGY

A few key radiocarbon and thermoluminescence ages, along with two (mean) cosmogenic ^{36}Cl ages, provide geochronological control on the late Pleistocene glaciations in the southwestern Ahklun Mountains. The ages, together with the regional compilation of ice limits (Manley *et al.*, in press), allow the glacial geology of the southwestern Ahklun Mountains reported in this study to be placed in the context of the glacial history of the Ahklun Mountains as a whole. Here we summarize geochronological data that are reported in detail elsewhere (Manley *et al.*, in press; Kaufman *et al.*, 1996, in press; Briner, 1998).

The oldest late Pleistocene drift is exposed in bluffs at Togiak Bay (Fig. 1). The drift lies ~30 km downvalley from the late Wisconsin limit in the Togiak River valley and ~40 km inside of the maximum late Pleistocene ice limit that we

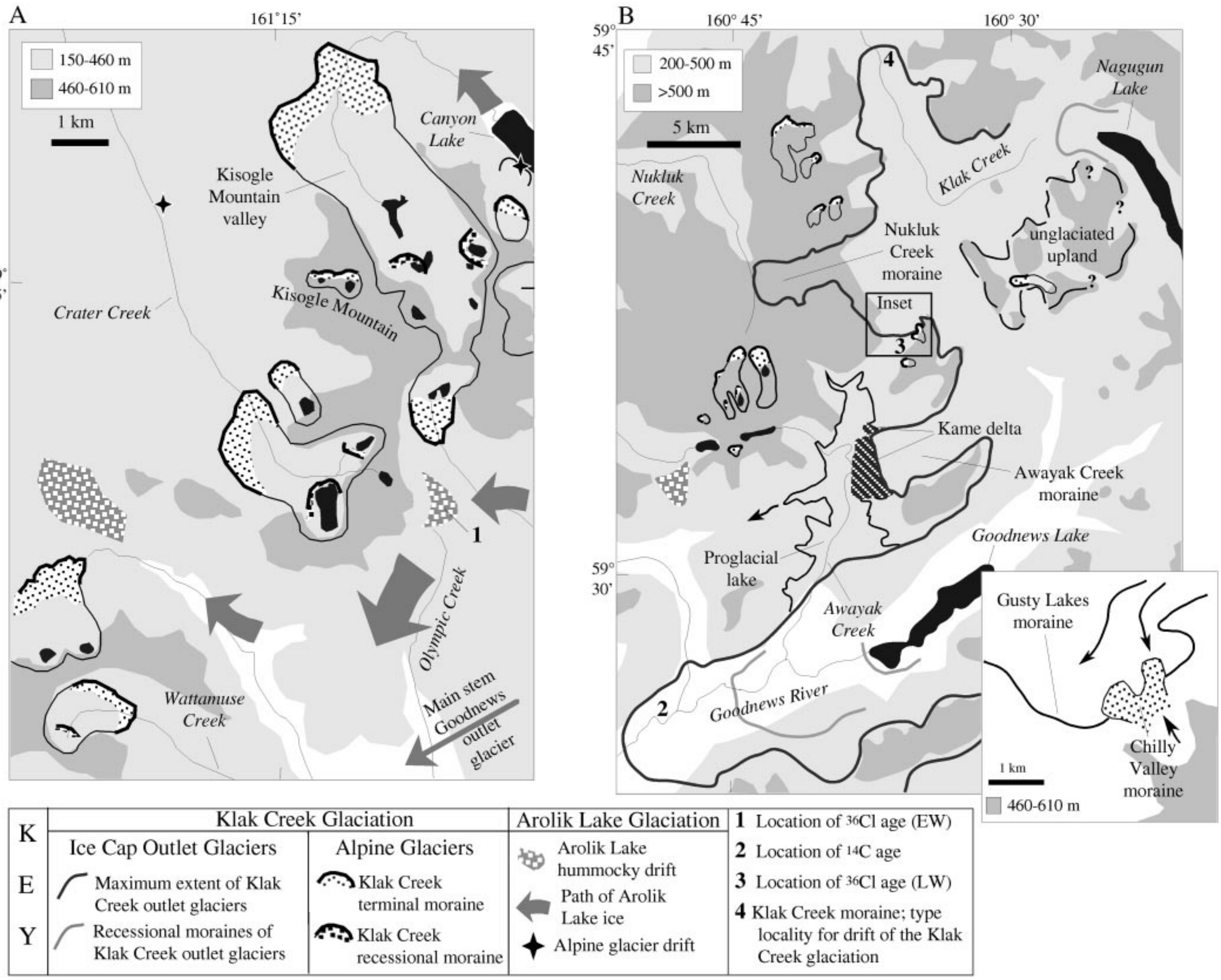

FIG. 4. Extents of Klak Creek (late Wisconsin) glaciers in two locations of detailed field study. (A) The Kisogle Mountain region. Solid bold lines represent terminal ridge crests; patterned areas up valley indicate hummocky drift. The ice-cap outlet glaciers did not extend into this area during the Klak Creek glaciation. Arrows depict ice flow of the northern margin of the Goodnews River valley ice-cap outlet glacier during the Arolik Lake glaciation. (B) The Klak Creek/upper Goodnews River region. The inset map shows detail of the superposed alpine glacier moraine (Chilly Valley) and ice-cap outlet glacier moraine (Gusty Lakes). A mean age of 18,900 ± 1400 ^{36}Cl yr (Briner, 1998) for the Gusty Lakes moraine overlaps with a ^{14}C age of 20,200–19,700 cal yr B.P. (Manley *et al.,* in press), from along the Goodnews River. Map areas shown in Figure 1.

correlate with the Arolik Lake glaciation based on morphostratigraphic position. The drift is underlain by a 2-m-thick basalt flow, which, in turn, is underlain by tephra-rich stratified silt and sand. Three thermoluminescence (TL) age estimates on sediment baked by the basalt flow at two localities date the lava emplacement and provide a mean maximum age for the overlying drift of 70,000 ± 10,000 yr (Kaufman *et al.,* in press). The maximum age of the Togiak Bay drift can be compared with a mean surface-exposure age of 53,600 ± 2000 ^{36}Cl yr obtained by Briner (1998) on boulders from Arolik Lake drift deposited by the outlet glacier in the Goodnews River valley (Table 2). The ^{36}Cl age is consistent with the maximum-limiting TL age on drift of the Arolik Lake glaciation. Together with nonfinite ^{14}C ages of organic matter overlying the drift across the southern Ahklun Mountains (Manley *et al.,* in press), these ages firmly place the Arolik Lake glaciation within the early Wisconsin, correlative with marine oxygen-isotope stage 4. An ice advance during marine oxygen-isotope stage 4 is slightly younger, but overlaps with, the 90,000–75,000 yr age obtained for glacial–estuarine sediments in the Nushagak Bay region (Kaufman *et al.*, 1996). The drift in the Nushagak Bay region may be either correlative with or slightly older than the Arolik Lake glaciation.

The age of the Klak Creek glaciation is constrained by ^{14}C and surface-exposure ages (Table 2). The most closely limiting ^{14}C age is for plant macrofossils in glacial–lacustrine mud from

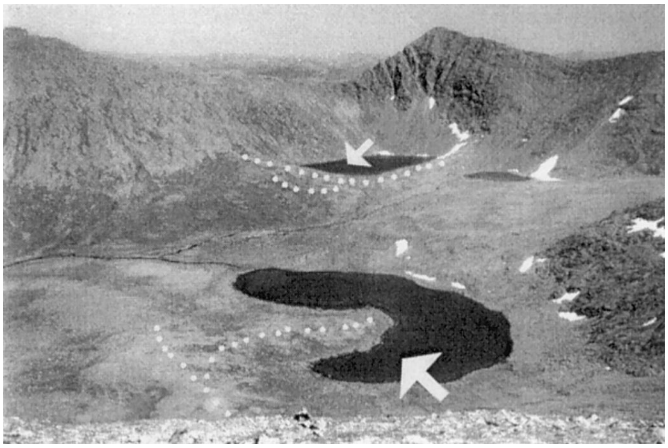

FIG. 5. Latest Pleistocene (late-phase Klak Creek) moraines in the upper part of the Kisogle Mountain valley (white dotted lines; Fig. 4A), southwestern Ahklun Mountains. View is to the east. White arrows show ice-flow direction.

an outcrop on the Goodnews River ~2 km upvalley from the terminal moraine (Fig. 4B; Manley *et al.*, in press). The age indicates that the Goodnews River valley glacier had retreated from its maximum limit by 16,890 ± 120 ^{14}C yr B.P. (AA-23082, 20,200–19,700 cal yr B.P.; Stuiver and Reimer, 1993). The ^{14}C age can be compared with ^{36}Cl ages from the Gusty Lakes moraine located ~25 km to the north and traceable to the Goodnews River valley moraine (Fig. 4B). The mean exposure age of 18,900 ± 1400 ^{36}Cl yr (Briner, 1998) overlaps with the ~20,000 yr B.P. calibrated ^{14}C age from the Goodnews River valley. The ^{36}Cl and ^{14}C ages thus converge on the same age for the maximum position of the ice-cap outlet glaciers during the Klak Creek glaciation. They indicate that this late Wisconsin advance in the western Ahklun Mountains was correlative with marine oxygen-isotope stage 2.

EQUILIBRIUM-LINE ALTITUDES

The well-preserved ice-marginal features and well-defined source areas for alpine glaciers enabled us to reconstruct former glacier geometries accurately. From these reconstructions, we estimated the paleoequilibrium-line altitudes (ELAs) for 34 alpine glaciers that formed in massifs scattered throughout the southwestern Ahklun Mountains during the Klak Creek glaciation. Unlike the Klak Creek glaciation, alpine glaciers of the Arolik Lake glaciation were mostly confluent with ice-cap outlet glaciers. Their ELAs could only be estimated within broad limits and only for three glaciers. ELA estimates were derived using both the toe-to-headwall ratio (THAR) and the accumulation area ratio (AAR) techniques. Meierding (1982) compared these methods of calculating ELAs in the Rocky Mountains of Colorado and was most confident in results using an AAR of 0.65 and a THAR of 0.4, which gave similar ELA estimates. More recently, Torsnes *et al.* (1993) compared methods and found that an AAR of 0.60 ± 0.05 provided the most reliable estimate for modern and Little Ice Age glaciers in western Norway. In this study, we chose to use an AAR of 0.60 and a THAR of 0.4. These values yielded similar ELAs (Appendix 2, available as supplementary data).

Overall, estimated ELAs for reconstructed glaciers of the Klak Creek glaciation average 390 ± 100 m in the field area and rise northeastward at ~2.5 m km^{-1} (Fig. 3). ELAs range from a low of 260 m elevation in the southwest part of the field area, near Goodnews Bay, to as high as 650 m for former glaciers ~100 km to the northeast, in the Klak Creek region (Appendix 2). Glaciers that formed on Jagged Mountain (Fig. 1), the southwesternmost glaciated massif, had ELAs as low as those near Goodnews Bay. During the late phase of the Klak Creek glaciation, when only a few glaciers were present in the highest cirques, average ELA had raised by ~30–50 m above the ELA associated with the fully extended glaciers in those valleys.

To compare these late Wisconsin ELA estimates to those of present conditions, we use the ELA values determined by Manley *et al.* (1997) for modern glaciers of the Ahklun Mountains. The closest extant glaciers are located ~125 km to the northeast of the field area; their ELAs average 900 m. Late Wisconsin ELAs in the southwestern Ahklun Mountains were therefore depressed by 640–250 m compared with modern ELAs. Because modern snowline rises to the northeast across the Ahklun Mountains (Manley *et al.*, 1997), however, this amount of ELA lowering is a maximum estimate. If we assume that the modern ELA gradient parallels the ELA gradient reconstructed for late Wisconsin glaciers, then the modern ELA in the western part of the range would be ~610 m. This is only ~220 m higher than the average ELA reconstructed for this area during the Klak Creek glaciation. We therefore conclude that the average full-glacial ELA in the field area lies, at most, ~500 m, and possibly only ~200 m, below the present ELA.

During the Arolik Lake (early Wisconsin) glaciation, almost all alpine glaciers in the southwestern Ahklun Mountains were confluent with ice-cap outlet glaciers, hampering attempts to reconstruct their ELAs. At three locations, however, we mapped deposits from alpine glaciers that expanded during the Arolik Lake glaciation and terminated independently from the ice-cap outlet glaciers. The first, located in the small tributary to Canyon Lake (Fig. 4A), is described above. At the other two

TABLE 2
Summary of Absolute-Age Data

Location (Fig. 4)	Age (yr B.P.)	Reference
1	53,600 ± 2000[a]	Briner (1998)
2	20,200 − 19,700[b]	Manley *et al.* (in press)
3	18,900 ± 1400[a]	Briner (1998)

[a] Mean ^{36}Cl age from four boulders on each moraine.
[b] Cal yr B.P.

sites (Jagged Mountain, Fig. 1, and Crater Creek, Fig. 4A), the lack of a well-defined terminal moraine prevents us from accurately delimiting the full downvalley extent of the glacier; the ELA estimates at these locations are only a maximum-limiting value. On the basis of these three points, the ELA during the Arolik Lake glaciation was below 175–320 m, or ~50–90 m lower than ELAs reconstructed for Klak Creek glaciers in those same areas.

DISCUSSION

The 100,000-yr buildup of the late Pleistocene continental ice sheets, which is well documented by marine oxygen-isotopes (e.g., Shackelton and Opdyke, 1973), is not mirrored in the glacial record of the Ahklun Mountains during the last glaciation. Instead, the maximum position of glacier ice was reached during the early part of the late Pleistocene (cf., Gillespie and Molnar, 1995). The maximum advance also occurred during the early part of the late Pleistocene in the Brooks and Alaska ranges and on the Seward and Alaska peninsulas (Hamilton, 1994). The contrast between restricted late Wisconsin ice extent versus extensive early Wisconsin ice extent lends insight into the importance of sea level and other boundary conditions on Beringian climate. We hypothesize, as did Hopkins (1982) and others, that during the Klak Creek (late Wisconsin) glaciation moist air masses penetrated infrequently into eastern Beringia.

The global aridity of the last glacial maximum (e.g., Broecker, 1997) was amplified in the Ahklun Mountains by paleogeographic changes associated with the regression of eustatic sea level. As sea level lowered by ~125 m during the late Wisconsin (Fairbanks, 1989), the coast of the Bering Sea regressed ~600 km southwest of the Ahklun Mountains, exposing a vast continental shelf and transforming the climate of the Ahklun Mountains from maritime to continental. The southwestward decline in regional late Wisconsin ELAs suggests that winter moisture penetrated the western Ahklun Mountains from the Bering Sea. If so, then lowering eustatic sea level would have increased the distance to the moisture supply. Sedimentological and diatom evidence indicates that sea-surface temperature was lowered and sea-ice cover was extensive and prolonged (possibly lasting throughout the year) in the Bering Sea during the late Wisconsin (Sancetta *et al.*, 1984), further reducing the evaporative flux to the Ahklun Mountain glaciers. In contrast, the lower ELAs of the Arolik Lake (early Wisconsin) glaciation might reflect greater moisture availability resulting from a warmer or more proximal marginal sea.

The idea that the Ahklun Mountains were drier than the rest of the globe during the late Wisconsin is supported by the magnitude of ELA lowering. Although the ELA lowering is consistent with values reported elsewhere in western Alaska (~300–600 m; Hamilton and Porter, 1975; Kaufman and Hopkins, 1986; Mann and Peteet, 1994; Stillwell and Kaufman, 1996), it is less than half of the average global ELA lowering of ~1 km (Broecker and Denton, 1990). Comparing Alaskan ELA lowering with global ELA lowering suggests that, during the late Wisconsin, either glacial-age cooling in Alaska was less or the region became unusually dry. On the basis of proxy paleoclimate evidence (e.g., Hopkins, 1982) and simulations of general circulation models (e.g., Bartlein *et al.*, 1998), however, temperature in eastern Beringia was apparently depressed by at least as much as the global average, suggesting that the relatively minor ELA depression in the Ahklun Mountains reflects a precipitation deficit (cf., Porter *et al.*, 1983).

Superpositional relations between drift of outlet glaciers that drained the central Ahklun Mountains and drift of local alpine glaciers demonstrate that alpine glaciers reached their maximum positions sometime following the retreat of outlet glaciers. This offset in relative age apparently occurred during both the Arolik Lake and the Klak Creek glaciations. The difference in the timing of glacier fluctuations might reflect nonclimatic glaciological factors. On the other hand, the later advance of alpine glaciers might have been linked to the retreat of the outlet glaciers as the ice cap over the central range lowered and allowed moist air from the Gulf of Alaska to augment the winter precipitation in the west. Alternatively, as sea-surface temperatures in the Bering Sea increased following the peak of the last glacial maximum, the additional evaporative flux may have differentially benefited the alpine glaciers in the southwestern Ahklun Mountains.

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REFERENCES

Bartlein, P. J., Anderson, K. H., Anderson, P. M., Edwards, M. E., Mock, C. J., Thompson, R. S., Webb, R. S., Webb, T., III, and Whitlock, C. (1998). Paleoclimate simulations for North America over the past 21,000 years: Features of the simulated climate and comparisons with paleoenvironmental data. *Quaternary Science Reviews* **17,** 549–585.

Briner, J. P. (1998). "Late Pleistocene glacial chronology of the western Ahklun Mountains, southwestern Alaska." Unpublished Master's Thesis, Utah State University.

Broecker, W. S. (1997). Mountain glaciers: Recorders of atmospheric water vapor content? *Global Biogeochemical Cycles* **11,** 589–596.

Broecker, W. S., and Denton, G. H. (1990). The role of ocean-atmosphere reorganizations in glacial cycles. *Quaternary Science Reviews* **9,** 305–343.

Coulter, H. W., Hopkins, D. M., Karlstrom, T. N. V., Péwé, T. L., Wahrhaftig, C., and Williams, J. R. (1965). Map showing glacial extents in Alaska. *U.S. Geological Survey Miscellaneous Geologic Investigations Map I-425.*

Fairbanks, R. D. (1989). A 17,000-year glacio-eustatic sea level record; Influence of glacial melting rates and the Younger Dryas event and deep ocean circulation. *Nature* **342,** 367–342.

Gillespie, A., and Molnar, P. (1995). Asynchronous maximum advances of mountain and continental glaciers. *Reviews of Geophysics* **33,** 311–364.

Hamilton, T. D. (1994). Late Cenozoic glaciation of Alaska. *In* "The Geology of Alaska" (G. Plafker and H. C. Berg, Eds.), The Geology of North America Vol. G-1, pp. 813–844. Geological Society of America, Boulder, CO.

Hamilton, T. D., and Porter, S. C. (1975). Itkillik glaciation in the Brooks Range, northern Alaska. *Quaternary Research* **5,** 471–497.

Hoare, J. M., and Coonrad, W. L. (1961). Geological map of the Goodnews Quadrangle, Alaska. *U.S. Geological Survey Miscellaneous Geologic Investigations Map I-339.*

Hopkins, D. M. (1982). Aspects of the paleogeography of Beringia during the late Pleistocene. *In* "Paleoecology of Beringia" (D. M. Hopkins, J. M. Matthews, Jr., C. E. Schweger, and S. B. Young, Eds.), pp. 3–28. Academic Press, New York.

Kaufman, D. S., Manley, W. F., Forman, S., and Layer, P. (In press). Pre-Late-Wisconsin glacial history, coastal Ahklun Mountains, southwestern Alaska—New amino acid, thermoluminescence, and $^{40}Ar/^{39}Ar$ results. *Quaternary Science Reviews.*

Kaufman, D. S., Forman, S. L., Lea, P. D., and Wobus, C. W. (1996). Age of pre-late-Wisconsin glacial-estuarine sedimentation, Bristol Bay, Alaska. *Quaternary Research* **45,** 59–72.

Kaufman, D. S., and Hopkins, D. M. (1986). Glacial history of the Seward Peninsula. *In* "Glaciation in Alaska, the Geologic Record" (T. D. Hamilton, K. M. Reed, and R. M. Thorson, Eds.), pp. 51–77. Alaska Geological Society, Anchorage, AK.

Manley, W. F., Kaufman, D. S., and Briner, J. P. (1997). GIS determination of late Wisconsin equilibrium line altitudes in the Ahklun Mountains of southwestern Alaska. *Geological Society of America Abstracts with Programs* **29,** 33.

Manley, W. F., Kaufman, D. S., and Briner, J. P. (In press). Late Quaternary glacier fluctuations in the southern Ahklun Mountains, southeast Beringia—soil development, morphometric, and radiocarbon constraints. *Quaternary Science Reviews.*

Mann, D. H., and Peteet, D. M. (1994). Extent and timing of the Last Glacial Maximum in southwestern Alaska. *Quaternary Research* **42,** 136–148.

Meierding, T. C. (1982). Late Pleistocene glacial equilibrium-line altitudes in the Colorado Front Range: A comparison of methods. *Quaternary Research* **18,** 289–310.

Paterson, W. S. B. (1981). "The Physics of Glaciers." Pergamon Press, Tarrytown, NY.

Porter, S. C. (1967). Glaciation of Chagvan Bay area, southwestern Alaska. *Arctic* **20,** 227–246.

Porter, S. C., Pierce, K. L., and Hamilton, T. D. (1983). Late Wisconsin mountain glaciation in the western United States. *In* "Late Quaternary Environments of the United States" (H. E. Wright, Jr., Ed.), pp. 71–111. Univ. of Minnesota Press, Minneapolis, MN.

Sancetta, C. A., Heusser, L., Labeyrie, L., Naidu, A. S., and Robinson, S. W. (1984). Wisconsin–Holocene paleoenvironment of the Bering Sea; Evidence from diatoms, pollen, oxygen isotopes and clay minerals. *Marine Geology* **62,** 55–68.

Shackelton, N. J., and Opdyke, N. D. (1973). Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. *Quaternary Research* **3,** 39–55.

Stillwell, K. B., and Kaufman, D. S. (1996). Late Wisconsin glacial history of the northern Alaska Peninsula, southwestern Alaska, U.S.A. *Arctic and Alpine Research* **28,** 475–487.

Stuiver, M., and Reimer, P. J. (1993). Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* **35,** 215–230.

Torsnes, I., Rye, N., and Nesje, A. (1993). Modern and Little Ice Age equilibrium-line altitudes on outlet valley glaciers from Jostedalsbreen, western Norway; An evaluation of different approaches to their calculation. *Arctic and Alpine Research* **25,** 106–116.