Age of Pre-late-Wisconsin Glacial-Estuarine Sedimentation, Bristol Bay, Alaska

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INTRODUCTION

In central Beringia, the region centered around Bering Strait (Fig. 1), glaciers of pre-late-Wisconsin age were several times more extensive than those of late-Wisconsin age (see Hamilton, 1994, for a recent review). On Seward Peninsula and in the western Brooks Range of northwestern Alaska, the most recent of these extensive advances, during which glaciers reached the coast and locally deposited glacial-marine sediment, apparently dates to the middle Pleistocene (Huston et al., 1990; Kaufman et al., 1991). Similarly, in the Bristol Bay region of southwestern Alaska (Fig. 1), glaciers of pre-late-Wisconsin age advanced to the coast more than 50 km beyond late-Wisconsin limits. The ages of the pre-late-Wisconsin advances in southwestern Alaska, however, have remained tenuous.

The association of glacial deposits with marine sediments in Bristol Bay area affords an opportunity to integrate the glacial and sea-level history of southwestern Alaska into the developing chronostratigraphic framework of similar events in northwestern Alaska and eastern Siberia (e.g., Kaufman and Brigham-Grette, 1993; Brigham-Grette and Hopkins, 1994). The geochronological data presented in this study will allow the stratigraphic record in Bristol Bay (e.g., Lea et al., 1991) to be compared and linked to paleoclimate records from other terrestrial and marine investigations. This comparison will provide insights into the linkages between ocean and terrestrial processes, and the fluctuating climatic boundary conditions that modulate them.

Here we present a variety of geochronological data suggesting that extensive pre-late-Wisconsin glaciers entered Bristol Bay after the last interglaciation (oxygen-isotope substage 5e). This age is considerably younger, by 300,000–400,000 yr, than...
the most-recent advance of glaciers to the coast in northwestern Alaska. Our new geochronological data further confirm stratigraphic and paleogeographic evidence for contemporaneous advance of pre-late-Wisconsin glaciers from independent northwestern and southeastern source areas into Bristol Bay.

**Lithostratigraphy**

Wave-cut bluffs around the shores of Bristol Bay provide outstanding exposures of sediments that have accumulated in diverse depositional environments during the Pleistocene Epoch. The exposures are typically 20–40 m high and are nearly continuous for tens of kilometers. Their lithostratigraphy has been documented around the shores of Nushagak Bay (Fig. 2) where the Nushagak Formation forms the base of a regionally consistent stratigraphic sequence (Lea, 1989; Lea et al., 1991) (Fig. 3). The Nushagak Formation includes glacial and glacial-estuarine deposits derived from glaciers that flowed southeastward from the Ahklun/Wood River Mountains, entering a macrotidal estuary similar to the present bay (Lea, 1990). It also contains current-reeformed pumice and volcanic glass whose major-element chemistry does not match any other known tephra in the region, including the Old Crow tephra (P. Lea and D. Kaufman, unpublished data).

Similar glacial and estuarine sedimentary facies are exposed around the shores of Kvichak Bay to the southeast. These deposits are associated with glaciers that flowed northwestward over the Alaska Peninsula as far as Etolin Point (Muller, 1952; Detterman, 1986) (Fig. 2). At a number of sites around Kvichak Bay, two glacigenic units are separated by a lag horizon or nonglacial beach deposits. A detailed account of the stratigraphy and sedimentary environments represented by these deposits will be reported elsewhere. Here we informally assign the upper glacial-estuarine unit to the Halfmoon Bay drift of Muller (1952) and note that, like the Nushagak Formation, it records extensive advance of glaciers into a macrotidal estuary when relative sea level stood some 10–15 m higher than present (cf. Lea, 1989, 1990). The pre-late-Wisconsin Nushagak Formation of Nushagak Bay and Halfmoon Bay drift of Kvichak Bay are the foci of this study.

Around eastern Bristol Bay, pre-late-Wisconsin drift is overlain by a consistent lithostratigraphic sequence of nonglacial eolian and lacustrine units, the Flounder Flat and Etolin com-
plexes of late Pleistocene age, and the Igushik Formation of late Wisconsin age (Lea et al., 1991) (Fig. 3). The regional consistency of the overlying stratigraphic sequence, together with similar depositional and paleogeographic settings, suggests correlation of the Nushagak Formation and the Halfmoon Bay drift (Lea, 1989)—a hypothesis further tested by the geochronological data presented here.

GEOCHRONOLOGY

Radiocarbon

Previously published radiocarbon ages (Lea et al., 1991) of organic silt and peat from the overlying Etolin complex demonstrate that the glacial-estuarine sediment of the Nushagak Formation and Halfmoon Bay drift is older than about 38,000 yr (Table 1). Detrital wood found in drift near Johnston Hill (Riehle and Detterman, 1993) (Fig. 2, site 2) and paired molluscan valves recovered from deformed proglacial gravel at Etolin Point (site 4) and from a glacial diamicton at Second Point (southwestern end of Halfmoon Bay, site 1), also are beyond the range of radiocarbon dating. Because these age estimates are for material deformed or reworked by the advancing ice, however, they are maximum-limiting ages and cannot be used to constrain the age of the advance.

Stratigraphic and Paleoecological Evidence

Pollen and beetle fossils. Lea et al. (1991) reported pollen and beetle data from organic silt and peat of the Flounder Flat and Etolin complexes where they overlie the Nushagak Formation and correlative Halfmoon Bay drift. These paleoecological data indicate cooler-than-modern climates in all sampled organic silt and peat beds. In particular, Pleistocene pollen spectra lack alder (Alnus), despite its abundance in modern and Holocene pollen samples. Because we have not found evidence for climates as warm as present in nonglacial deposits overlying the drift, we infer that the drift postdates the last interglacial maximum.

Interglacial shoreline. No last-interglacial (Pelukian) shoreline is cut onto the drift, despite its nearly continuous presence around the shores of western and northern Alaska (Brigham-Grette and Hopkins, 1995). Apparently, the Pelukian shoreline has either been buried by younger sediment or eroded by an ice advance subsequent to substage 5e.

Old Crow tephra. The Old Crow tephra forms a stratigraphic marker horizon distributed widely throughout Alaska and Yukon Territory (Westgate et al., 1983). Although previous age estimates of the tephra have varied considerably, a generally accepted isothermal-plateau fission-track date of
140,000 ± 10,000 yr (Westgate et al., 1990), together with its stratigraphic position below deposits that record warmer-than-modern climates (Hamilton and Brigham-Grette, 1991), suggests that it was erupted prior to the last interglacial maximum. Geochemical affinities (Westgate et al., 1985) and grain-size data (Waythomas et al., 1993) indicate that the source of Old Crow tephra is probably one of several Pleistocene calderas on the Alaska Peninsula (Miller and Smith, 1987). Given its likely source and widespread distribution throughout Alaska, we argue that a relatively thick and coarse layer of Old Crow tephra should have been deposited in the Bristol Bay region. For comparison, the Holitna lowland, located 250 km north of Bristol Bay, contains a 35-cm-thick layer of Old Crow tephra with a modal grain size of 3.5 phi (very fine sand; Waythomas et al., 1993). Tephra layers observed within Pleistocene nonglacial sediments in this region, however, are thin and discontinuous and have mineral contents, shard morphologies, or stratigraphic positions distinct from Old Crow tephra. The simplest explanation for the lack of Old Crow tephra, despite intensive search along tens of kilometers of excellent exposure, is that the eruption predates the extensive glacial advances that formed the Nushagak Formation and Halfmoon Bay drift.

**Amino Acid Epimerization**

The utility of amino acids as a geochronological tool for Quaternary biominerals is now well established (see the review of principles and applications by Wehmiller, 1993). Proteins and their constituent amino acids bound within the carbonate matrix of fossil molluscan shells are degraded to a degree commensurate with their age and temperature history. For geochronological purposes, the most reliable of the complex network of reactions comprising protein diagenesis is the racemization reaction (or epimerization, in the case of the amino acid isoleucine). This reaction involves the inversion of amino acids from their protein L-configuration to their nonprotein D-configuration. The ratio of the amino acid D-alloisoleucine to its diasteriomer L-isoleucine (aIle/Ile) measures the extent of epimerization in the amino acid isoleucine and has been used previously for geochronological purposes in the Arctic and elsewhere.
Methods. Samples were processed by conventional methods at the Amino Acid Geochronology Laboratory, Utah State University. They were cleaned by rotary grinding to remove the outer shell layer, then by acid leaching in dilute HCl to remove 20–30% by weight, followed by vigorous rinsing in purified H2O and drying under laminar flow. Samples were dissolved in 7 N HCl using a ratio of 0.2 ml mg⁻¹ shell and hydrolyzed by sealing under N2 and heating for 22 hr at 110°C, then dried under a stream of N2 at 100°C, rehydrated, and loaded onto a high-performance liquid chromatograph (HPLC). The HPLC employs step-wise addition of sodium-citrate buffers of increasing pH and post-column derivitization by o-phthalaldehyde with electronic integration of fluorescence.

Results and discussion. We found fossil molluscs at three sites, all associated with drift derived from the Alaska Peninsula, Halfmoon Bay (Second Point), Etolin Point, and South Naknek beach (Fig. 2, sites 1, 4, and 6, respectively). Shells from Etolin Point and Halfmoon Bay were analyzed for radiocarbon and yielded nonfinite ages (Table 1).

At South Naknek beach, lithologically similar glaciogenic diamictons are separated by an unconformity that extends several kilometers laterally and is associated with a stony marine-lag horizon at 5.4 m altitude. We correlate the diamicton units above this lag with Halfmoon Bay drift and ascribe the lag surface to an interval of high relative sea level that predates the last advance of pre-late-Wisconsin glaciers to the coast. Alle/Ile in paired valves of *Portlandia arctica* from this lag average 0.052 ± 0.003, slightly higher than in *Mya truncata* (0.041 ± 0.007) from littoral deposits of the last interglacial (Pelukian) marine transgression at its type locality near Nome (Fig. 1; Table 2) (Kaufman, 1992).

Because the rate of epimerization is taxon-dependant, we attempted to determine the relative reaction rate in *Portlandia* and *Mya* using high-temperature laboratory experiments. Experience indicates that the relative intergeneric difference in reaction rates measured at high temperature parallels differences in reaction rates measured at room temperature.

### TABLE 1
New and Previously Published Radiocarbon Ages for Material Reworked Into or Overlying Pre-late-Wisconsin Drift from Northeastern Bristol Bay

<table>
<thead>
<tr>
<th>Site number (Fig. 2)</th>
<th>Age (yr)</th>
<th>Laboratory number</th>
<th>Material</th>
<th>Context</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>141,200 invites AA-11088</td>
<td>Mollusc</td>
<td>Base of glaciigenic diamicton</td>
<td>This report</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>40,000 invites I-13468</td>
<td>Detrital wood</td>
<td>Estuarine silt and sand</td>
<td>Riehle and Detterman, 1993</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>38,000 invites W-3577</td>
<td>Peat</td>
<td>Etiol complex</td>
<td>Galloway, 1995b</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>36,400 invites GX-10381</td>
<td>Mollusc</td>
<td>Deformed proglacial gravel</td>
<td>This report</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>35,600 ± 1500 invites W-3576</td>
<td>Peaty silt</td>
<td>Etiol complex</td>
<td>Galloway, 1995b</td>
<td></td>
</tr>
</tbody>
</table>

a Considered nonfinite.

b Collected by W. L. Coonrad in 1974.

c Collected by D. M. Hopkins in 1972.

### TABLE 2
Amino Acid (Isoleucine) Epimerization Ratios from Pre-late-Wisconsin Deposits, Northeastern Bristol Bay

<table>
<thead>
<tr>
<th>Site number (Fig. 2)</th>
<th>Laboratory number</th>
<th>Genus</th>
<th>Species</th>
<th>Mean</th>
<th>1σ</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1003-1006 invites Portlandia</td>
<td>arctica</td>
<td>0.028</td>
<td>0.005</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 1043 invites Hiatella</td>
<td>arctica</td>
<td>0.027</td>
<td>0.001</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 AAL-6516 invites Hiatella</td>
<td>arctica</td>
<td>0.027</td>
<td>0.001</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 1383 invites Portlandia</td>
<td>arctica</td>
<td>0.052</td>
<td>0.003</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nome AAL-6 invites Mya</td>
<td>truncata</td>
<td>0.041</td>
<td>0.007</td>
<td>16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Mean and standard deviation of “N” shells (intershell variation); alle/Ile values for the Inter-Laboratory Comparison Standards ILC-A, ILC-B, and ILC-C analyzed at the Utah Amino Acid Laboratory (UAL) during the course of this study were 0.159 ± 0.002, 0.551 ± 0.004, and 1.154 ± 0.001, respectively; these are well within the range measured for the same samples by other laboratories (Wehmiller, 1984).

b Sample analyzed at Institute of Arctic and Alpine Research, University of Colorado.

c Multiple samples from the type locality of the Pelukian transgression, reported by Kaufman (1992).
ences in alle/lle measured in coeval fossils of the same genera (D.S. Kaufman, unpublished data). Furthermore, heating experiments at different temperatures yield the same differences between reaction rates, despite rate constants that differ by more than an order of magnitude. These data suggest that long-term diagenetic processes are reasonably well simulated in a short time interval at high temperature (e.g., Miller, 1985).

Modern specimens of *Myla* and *Portlandia* were heated simultaneously at approximately 142° and 110°C for various lengths of time in a temperature-controlled oven. The results show no significant difference \( p < 0.1; n = 8 \) between the rates of epimerization in *Portlandia* and *Myla* at both temperatures for alle/lle < 0.1 (Fig. 4). We therefore conclude that significant differences between alle/lle ratios of *Portlandia* shells in Bristol Bay and *Myla* shells from Pelukian deposits at Nome primarily reflect differences in age or temperature history.

Because air temperature, and consequently the rate of epimerization, is higher at Bristol Bay than at Nome (present mean annual temperature (MAT) is 1°C at King Salmon compared to −4°C at Nome), the small difference in amino acid ratios (0.01) is compatible with the correlation of the marine-lag horizon at South Naknek beach with the Pelukian transgression ca. 125,000 yr. The alternative, that the South Naknek shells are significantly older than the Pelukian transgression, is unlikely because it would require the average late-Quaternary temperature at Nome to be nearly as high or higher than at Bristol Bay, despite >5° difference in latitude. Furthermore, for the south Naknek shells to date as old as the penultimate high-sea-level interval (oxygen-isotope stage 7) would require significantly higher alle/lle ratios. The alternative, that the South Naknek shells are significantly younger than 125,000 yr, is also unlikely given the reasonable assumption that late-Pleistocene temperatures lowered following the peak warmth of the last interglaciation in substage 5e. Paradoxically, the lower average postdepositional temperature would require an older age to explain their extent of epimerization. Although the amino acid data alone do not rule out the possibility that the South Naknek shells are somewhat older or younger than the Pelukian transgression, we prefer the reasonable first-order conclusion that the two are correlative, despite any reasonable difference in reaction rates between the two genera.

We found molluscan shells in Halfmoon Bay drift at two sites on Kvichak Peninsula. Ice-thrust, proglacial-estuarine sand, and gravel contained articulated shells of *Hiatella arctica* at Etolin Point. At Second Point, articulated *Portlandia arctica* were collected from the base of a glaciogenic diamicton that overlies deformed proglacial estuarine sand and mud. Because the shells are found in sediment deformed or reworked by the advancing ice, their ages are strictly interpreted as maximum limiting ages for the advance. Sediment-flow diamictons interstratified within the estuarine sediments, however, indicate that deposition of Halfmoon Bay drift occurred during an interval of high relative sea level (cf. Lea, 1990). We favor the hypothesis that the shells in the glacial-estuarine drift date closely to the time of this advance, rather than the exhumation and reworking of articulated shells from an older glacial-estuarine event. In any case, the shells provide a maximum age for the Halfmoon Bay drift.

Shells of *Hiatella arctica* from Etolin Point yielded a mean alle/lle ratio of 0.027 ± 0.001 (Table 2). *Portlandia arctica* from Second Point yielded an indistinguishable alle/lle ratio of 0.028 ± 0.005. Although the rate of epimerization depends to some degree on the fossil genus, the reaction rate in *Portlandia* is approximately the same as in *Hiatella*; both are ranked by Miller and Brigham-Grette (1989) as epimerizing at a moderate rate and with high reliability for geochronological purposes. The indistinguishable alle/lle ratios measured in the shells therefore indicate that the drift at Second Point is correlative with drift at Etolin Point, near the western limit of Halfmoon Bay drift (Fig. 2).

Alle/lle ratios in the shells from Second Point and Etolin Point are about half those of the South Naknek beach shells, and two-thirds those of *Myla* from Pelukian deposits at Nome. Given the assumptions outlined above of comparable intergeneric epimerization rates and late-Quaternary temperatures in Bristol Bay no higher than late-Quaternary temperatures at Nome, these relationships indicate that these shells were incorporated into Halfmoon Bay drift sometime after the peak of the last interglaciation. Halfmoon Bay drift thus represents an extensive advance of pre-late-Wisconsin ice into Bristol Bay during a period of high relative sea level after the peak of the last interglaciation (<125,000 yr B.P.).

Assessing the extent to which shells in Halfmoon Bay drift are younger than Pelukian shells at Nome or shells at South Naknek beach is difficult because the rate of epimerization is strongly dependent on temperature history, and the Quaternary thermal history of the Bristol Bay lowland is not sufficiently well constrained. Nonetheless, we can make reasonable assumptions about the direction of past temperature change (e.g., the average late-Pleistocene temperature was lower than pre-
sent mean annual temperature, MAT) and use these to obtain reasonable age limits. Because the average postdepositional temperature of the post-last-interglacial shells must have been lower than for the shells that experienced the warmth of the last interglaciation, the age of the younger shells is not as young as is suggested by a linear comparison of their alle/Ile ratios to those in the Pelukian shells alone. The higher the ambient temperature of the interval separating their ages, the less the estimated age difference.

To estimate the numerical age of the Halfmoon Bay and Etolin Point shells based on their alle/Ile ratios, we assume a reasonable postdepositional temperature and apply this to an empirically derived equation that relates alle/Ile to time and temperature. For alle/Ile ratios less than ~0.3, this relation is approximated using a reversible first-order kinetic model; the expression was developed by Miller (1985) for the molluscan genus Mya and, based on laboratory heating experiments (Fig. 4), is appropriate for *Portlandia*,

$$EDT = \frac{6141}{16.45 - \log \left\{ \frac{(1 + \text{alle/Ile})}{(1 - 0.77\text{alle/Ile})} \right\} -0.0194/1.77t}$$

where EDT is the effective diagenetic temperature (the weighted mean temperature that represents the kinetic effect of all temperature fluctuations experienced by the sample) in K, and $t$ is time in yr.

To estimate the age of the younger shells, we rewrite Eq. (1) in terms of $t$ and evaluate two models of temperature versus time to calculate EDTs (Fig. 5). In the first model, we assume that the temperature history experienced by the (Pelukian) shells at South Naknek beach is not significantly different than for the younger shells. The EDT calculated for fossil *Portlandia* (= rate in Mya) from the South Naknek beach ($t = 125,000$ yr; alle/Ile = 0.052) is $-5.4^\circ C$. This is about $6^\circ C$ lower than the present MAT, which is a reasonable EDT for the late Quaternary. Applying this EDT and a mean alle/Ile in *Portlandia* from Second Point (0.028) to Eq. (1) yields an age estimate of about 55,000 yr. This is a minimum age estimate because the EDT of the last interglacial shells at South Naknek beach must have been higher than for the younger shells at Second Point, which did not experience the peak warmth of the last interglaciation.

To obtain a more reasonable estimate of the EDT for the younger shells, we subdivide the postdepositional temperature history of the South Naknek beach shells into two periods: (1) an interglacial interval (oxygen-isotope substage 5e) lasting 10,000 yr, during which the lag horizon at South Naknek beach was submerged by high-eustatic sea level; and (2) a late-Quaternary interval following the interglacial interval and lasting 115,000 yr. For the interglacial interval, we specify an EDT of $+4^\circ C$, approximately the same as the current mean annual bottomwater temperature in Bristol Bay (Levitus, 1982). For the late-Quaternary interval, we calculate the EDT required to maintain the overall EDT of the 125,000-yr shells at $-5.4^\circ C$, as calculated above, and, at the same time, account for the warmth of the last interglaciation. Using this model, we estimate an EDT of about $-8.2^\circ C$ for the last 115,000 yr. Applying this EDT and the alle/Ile ratio measured in the younger shells (0.028) to the age equation of Miller (1985) yields an age estimate of about 90,000 yr for the Second Point shells. Although more reasonable than the minimum estimate, the uncertainty in this age is broad, about ±20,000 yr based on the reproducibility of alle/Ile in the Second Point shells alone. The actual uncertainty is probably greater, although other errors associated with estimated temperatures and durations used in the model may cancel.

**Optical and Thermoluminescence Dating**

Luminescence geochronology is based on the time-dependent dosimetric properties of quartz and feldspar minerals. The technique has been used previously to determine ages of up to 100,000 yr and older for sediments that received sufficient solar radiation prior to deposition (e.g., Berger, 1988; Forman, 1989). Usually, exposure of sediment to sunlight for at least 8 hr eliminates most of the stored luminescence signal from mineral grains. Exposure of these minerals to ionizing radiation from the decay of naturally occurring radioisotopes in sediments results in the trapping of electrons that accumulate during burial, after the sediment is shielded from further light exposure. Excitation of sediments by heat or light releases the stored electrons as luminescence emissions. The intensity of the luminescence can be used as a measure of sample age by dividing the laboratory-determined paleodose (equivalent dose,
Luminescence dating, especially of glaciogenic waterlain sediment, can be problematic because of the potential for insufficient solar resetting prior to deposition. Waterlain sediment often receives limited light exposure during deposition because of the light-filtering effects of water and turbidity (Jerlov, 1976). Thus, waterlain sediment may have a higher residual luminescence level than subaerial deposits that have received extensive light exposure. Traditional thermoluminescence (TL) techniques, such as the total-bleach and the regeneration techniques, assume full solar resetting of the TL signal, and can yield overestimates in the age of waterlain sediments. The partial-bleach procedure has been used to evaluate incomplete solar resetting of waterlain sediment and, in some situations, has yielded apparently accurate TL age estimates (e.g., Berger et al., 1984; Forman et al., 1987; Berger and Hanson, 1992; Berger and Eyles, 1994). On the other hand, the inherited TL signal found in some waterlain sediments can undermine the accuracy of the technique (e.g., Forman and Ennis, 1992). The recent advent of optical dating, including infrared stimulated luminescence (IRSL) (Aitken and Xie, 1992; Lang, 1994), provides a more sensitive tool for discriminating inherited from postdepositional luminescence emissions, ultimately providing a better geochronometer for waterlain sediment (Huntley et al., 1985; Smith et al., 1986; Hütt et al., 1988).

Like TL, the optical-dating clock is reset by exposure of sediment to sunlight prior to deposition. The fundamental difference between these two methods is that optical dating uses light to liberate the time-stored luminescence emissions, whereas TL is measured by heating the sample. TL analysis releases photons within a mineral that are derived from both light-sensitive and light-insensitive electron traps. Even after exposing sediment to sunlight for >8 hr, for example, a small but measurable TL signal remains. In contrast, optical dating uses light of a particular wavelength to release rapidly only the light-sensitive electrons from the mineral lattice. Astonishingly, the decrease in the optically stimulated luminescence signal after exposure to sunlight for as little as 20 sec is the same as the reduction in the TL signal after a 20-hr light exposure (Godfrey-Smith et al., 1988), attesting to the promise of optical techniques for dating sediments that might have received brief (<4 hr) and wavelength-restricted light exposure.

**TABLE 3**

<table>
<thead>
<tr>
<th>Laboratory number (OTL)</th>
<th>481</th>
<th>482</th>
<th>526</th>
<th>527</th>
<th>541</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ count (ks/cm$^2$)*</td>
<td>0.31 ± 0.02</td>
<td>0.37 ± 0.02</td>
<td>0.24 ± 0.01</td>
<td>0.35 ± 0.02</td>
<td>0.36 ± 0.02</td>
</tr>
<tr>
<td>Th (ppm)</td>
<td>3.5 ± 0.5</td>
<td>4.1 ± 0.6</td>
<td>2.4 ± 0.5</td>
<td>2.9 ± 0.5</td>
<td>3.8 ± 0.6</td>
</tr>
<tr>
<td>U (ppm)</td>
<td>1.5 ± 0.2</td>
<td>1.8 ± 0.2</td>
<td>1.3 ± 0.1</td>
<td>1.9 ± 0.2</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>Unsealed/sealedb</td>
<td>0.98</td>
<td>0.99</td>
<td>0.97</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td>$K$O (%)c</td>
<td>1.53 ± 0.02</td>
<td>1.87 ± 0.02</td>
<td>1.36 ± 0.02</td>
<td>1.83 ± 0.02</td>
<td>1.87 ± 0.02</td>
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<tr>
<td>Moisture content (%)d</td>
<td>30 ± 10</td>
<td>25 ± 5</td>
<td>25 ± 5</td>
<td>25 ± 5</td>
<td>25 ± 5</td>
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<tr>
<td>OSL $\alpha$ valuee</td>
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<td>0.05 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td>0.07 ± 0.01</td>
<td>0.06 ± 0.01</td>
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<tr>
<td>TL $\alpha$ valuef</td>
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<td>0.03 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td>0.02 ± 0.01</td>
<td>0.05 ± 0.02</td>
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<tr>
<td>OSL dose rate (Gy/ka)g</td>
<td>1.92 ± 0.13</td>
<td>2.36 ± 0.16</td>
<td>1.68 ± 0.11</td>
<td>2.38 ± 0.16</td>
<td>2.35 ± 0.16</td>
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<tr>
<td>TL dose rate (Gy/ka)g</td>
<td>1.79 ± 0.11</td>
<td>2.20 ± 0.15</td>
<td>1.60 ± 0.11</td>
<td>2.12 ± 0.15</td>
<td>2.30 ± 0.16</td>
</tr>
</tbody>
</table>

* Thick-source alpha-count rate; U and Th concentration calculated from alpha count rate, assuming secular equilibrium (e.g., Huntley and Wintle, 1981).

b Ratio of bulk alpha count rate under unsealed and sealed counting conditions; a ratio of >0.95 indicates little or no radon loss (Huntley and Wintle, 1981; Jensen and Prescott, 1983).

c Percent K determined by flame photometry at the Radiogenic Isotope Laboratory, Department of Geological Sciences, The Ohio State University.

d A higher moisture content was estimated for the Holocene tide-flat sediment (OTL-481) than for the emerged late-Pleistocene bluff sediment; the estimated uncertainties associated with these values is conservative and believed to encompass the reasonable range of moisture contents for this class of sediment.

f Measured alpha efficiency factor as defined by Aitken and Bowman (1975).

g Dose-rate value includes a contribution from cosmic radiation of 0.14 ± 0.01 Gy/10$^3$ yr.
ing, each sample was tested for anomalous fading by storing irradiated (100–450 Gy) material for at least 32 days and comparing to the TL signal of an aliquot that was analyzed <1 hr after irradiation (Table 3). The anomalous fading tests reveal no significant instability in the TL emissions of the preheated sample.

The rate of TL ingrowth was evaluated by applying additive beta doses to the natural TL signal by a series of irradiations with a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ source. The highest radiation dose added to the natural TL signal was at least six times the calculated ED, which is sufficient for accurate extrapolation (Fig. 6). The natural and additive-dose data were fitted by a saturating exponential function (cf. Huntley et al., 1988; J. Pierson, unpublished data) over the range of temperatures, usually between 250° and 350°C, that encompasses at least 90% of the measured TL signal and exhibits a plateau in ED values. This refined computational procedure used to calculate the ED is somewhat different than that used for the preliminary ages reported by Kaufman et al. (1994), resulting in ages about 20% younger.

**IRSL methods.** Optical stimulation of sediments was accomplished using infrared emissions (880 ± 80 nm) from a ring of 30 diodes (Spooner et al., 1990) with an estimated energy delivery of 17 mW cm$^{-2}$. The output from the diode array at the sample position was calibrated by measuring the current induced in a silicon photodiode (Telefunken BPW-34) connected to a resistive circuit. We examined the resultant blue (Schott BG-39; <5% transmission below 360 nm) emissions from the sediments. The background count rate for measuring blue emissions was low (80 counts sec$^{-1}$), with a signal-to-noise ratio of >20. Samples were excited for 90 sec, and the resulting IRSL signal was recorded in 1-sec increments.

The IRSL properties were examined on the same fine-
grained polyminerlal fraction analyzed for TL. Similar additive
beta-dose, normalization, and ED-computational procedures
used in TL analysis (e.g., Forman et al., 1994) were also em-
ployed to determine IRSL ages. One difference between TL
and IRSL procedures is the shorter and higher-temperature
preheat, at 160°C for 5 hr, for IRSL analysis (cf. Aitken and
Xie, 1992). Measurement of the IRSL signal was also delayed
at least 1 day after preheating. Tests for anomalous fading of
the laboratory-induced and preheated IRSL signal, after >32
days storage, revealed insignificant (<7%) reduction in signal,
indicating stability of the laboratory and natural infrared emis-
sions.

Results and discussion. To test the applicability of lumi-
nescence-dating techniques to intertidal deposits of Bristol
Bay, we collected mud from modern (OTL-481) and radiocar-
bon-dated Holocene (OTL-526) tidal flats at Squaw Creek,
near Dillingham (Fig. 2, site 7; Table 4). Silty mud from 2–5
cm below the active mud-flat surface yielded TL ages ranging
from 4400 ± 500 to 6000 ± 500 yr, depending on the light-
exposure and bleaching technique used to determine the ED. In
contrast, IRSL analysis of the same sample yielded an age
estimate of 700 ± 300 yr which is reasonable for sediment from
2–5 cm below the tide-flat surface.

weekly lithified sediment collected from deeper (4.6 m be-
low high tide) in the mud flat yielded TL age estimates of
15,000 ± 2,000 and 7,000 ± 1,000 yr for the 8-hr UV and 16-hr
sunlight exposures, respectively, whereas the IRSL analysis
yielded an age of 5000 ± 1000 yr (Table 4). Wood from the
same level was dated by the conventional 14C technique at

TABLE 4
Thermoluminescence and Optically Stimulated Luminescence Data and Age Estimates for Samples from
Northeastern Bristol Bay

<table>
<thead>
<tr>
<th>Site number (Fig. 2)</th>
<th>Laboratory number (OTL)</th>
<th>Equivalent dose method</th>
<th>Light exposure</th>
<th>Temp (°C) or time</th>
<th>Equivalent dose (Gy)</th>
<th>Age estimate (10^3 yr)</th>
<th>Anomalous fading ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 481</td>
<td>TL-total bleach 16 hr sun 270–350</td>
<td>16 hr sun 270–350</td>
<td>8.51 ± 0.46</td>
<td>4.4 ± 0.5</td>
<td>0.98 ± 0.02</td>
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</tr>
<tr>
<td>7 526</td>
<td>TL-total bleach 8 hr UV 270–350</td>
<td>8 hr UV 270–350</td>
<td>11.47 ± 0.48</td>
<td>6.0 ± 0.5</td>
<td>0.99 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 482</td>
<td>TL partial bleach 1 hr sun 270–350</td>
<td>1 hr sun 270–350</td>
<td>9.47 ± 0.41</td>
<td>4.9 ± 0.5</td>
<td>0.96 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS L infrared</td>
<td>1 hr sun 3–59 sec 1.21 ± 0.48</td>
<td>1.21 ± 0.48</td>
<td>0.7 ± 0.3</td>
<td>0.95 ± 0.02</td>
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</tr>
<tr>
<td>8 541</td>
<td>TL-total bleach 8 hr UV 270–350</td>
<td>8 hr UV 270–350</td>
<td>9.47 ± 0.41</td>
<td>4.9 ± 0.5</td>
<td>0.96 ± 0.02</td>
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<td></td>
</tr>
<tr>
<td>TL-total bleach 16 hr sun 270–350</td>
<td>16 hr sun 270–350</td>
<td>10.20 ± 0.41</td>
<td>3.6 ± 0.3</td>
<td>0.94 ± 0.02</td>
<td></td>
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</tr>
<tr>
<td>OSL infrared</td>
<td>3 hr sun 3–59 sec 7.60 ± 0.41</td>
<td>7.60 ± 0.41</td>
<td>3 ± 0.3</td>
<td>1.00 ± 0.02</td>
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</tr>
<tr>
<td>8 541</td>
<td>TL-total bleach 8 hr UV 270–350</td>
<td>8 hr UV 270–350</td>
<td>8.57 ± 0.41</td>
<td>4.6 ± 0.4</td>
<td>0.96 ± 0.02</td>
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</tr>
<tr>
<td>TL-total bleach 16 hr sun 270–350</td>
<td>16 hr sun 270–350</td>
<td>11.37 ± 0.41</td>
<td>6.3 ± 0.4</td>
<td>0.98 ± 0.02</td>
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</tr>
<tr>
<td>OSL-infrared</td>
<td>3 hr sun 3–59 sec 13.90 ± 0.41</td>
<td>13.90 ± 0.41</td>
<td>7 ± 0.4</td>
<td>1.00 ± 0.02</td>
<td></td>
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<tr>
<td>8 541</td>
<td>TL-total bleach 8 hr UV 270–350</td>
<td>8 hr UV 270–350</td>
<td>203.50 ± 0.41</td>
<td>101 ± 6</td>
<td>0.98 ± 0.02</td>
<td></td>
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</tr>
<tr>
<td>OSL-infrared</td>
<td>3 hr sun 3–59 sec 184.10 ± 0.41</td>
<td>184.10 ± 0.41</td>
<td>82 ± 6</td>
<td>0.99 ± 0.02</td>
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<tr>
<td>8 541</td>
<td>TL-total bleach 8 hr UV 270–350</td>
<td>8 hr UV 270–350</td>
<td>240.10 ± 0.41</td>
<td>101 ± 8</td>
<td>0.98 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSL-infrared</td>
<td>3 hr sun 3–59 sec 202.80 ± 0.41</td>
<td>202.80 ± 0.41</td>
<td>86 ± 8</td>
<td>0.97 ± 0.02</td>
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</tr>
<tr>
<td>8 541</td>
<td>TL-total bleach 8 hr UV 270–350</td>
<td>8 hr UV 270–350</td>
<td>197.30 ± 0.41</td>
<td>80 ± 6</td>
<td>0.93 ± 0.03</td>
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</tr>
</tbody>
</table>

a TL measurements were made with a Corning 5/58 and HA-3 filters in front of the photomultiplier tube; samples were preheated to 124°C for 48 hr prior to analysis; OSL-infrared (IRSL) measurements were made with BG-39 filter in front of the photomultiplier tube; IRSL samples were preheated to 160°C for 5 hr prior to analysis.

b Hours of light exposure to define residual level; “sun” is natural sunlight in Columbus, Ohio; “UV” is light exposure from 275 W General Electric sunlamp.

c Hours of light exposure to define residual level; “sun” is natural sunlight in Columbus, Ohio; “UV” is light exposure from 275 W General Electric sunlamp.

d Errors for individual equivalent dose (ED) determinations, at a particular temperature or light exposure time, are determined using a nonlinear least-squares routine, based upon the Levenberg–Marquardt method (Marquardt, 1963; Press et al., 1986, pp. 521–528), in which inverse-variance weighted data are modeled by a saturating-exponential function (Huntley et al., 1988; J. Pierson, unpublished data). Errors are generated for each ED calculation in a variance–covariance matrix. The resultant uncertainties in ED reflect dispersion in the data and random errors from modeling the data by a saturating exponential function. The mean ED and associated error are evaluated from a range of individual ED determinations for a broad temperature range (e.g., 200–400°C) or time-since-light-exposure (e.g., 2–90 sec). Statistical analyses (t-test; Devore, 1987, pp. 487–492) of over 50 separate data sets indicate nondependence of TL-generated ED values with temperature. A similar nondependence is also identified between light exposure time and ED values determined by optical dating (J. Pierson, unpublished data). ED values determined by TL for a range of temperatures or by optical dating for light exposure times are evaluated as one statistical population. Thus, standard statistical data-weighting procedures are utilized to calculate an average ED and associated errors (Bevington, 1969, pp. 69–71, 119–131).

e Samples were tested for anomalous fading by storing irradiated (100 to 450 Gy) samples for at least 32 days and comparing the luminescence signal to an aliquot measured <1 hr after irradiation; anomalous fading ratio between 1.00 and 0.90 indicate little or no fading, within analytical resolution.

f Residual level equivalent to 3+ hr light exposure; signal within background level.
3430 ± 65 ¹⁴C yr B.P. (GX-20481). Correcting this age to calendar years (Stuiver and Reimer, 1993) yields a 2σ age range of 3480–3870 cal yr B.P., which overlaps at 2σ with the IRSL age estimate.

These results indicate that the TL signal of sediment from the intertidal mud-flat environment was not completely reset by solar radiation, but contains an inherited TL signal equivalent to approximately 5000–15,000 yr. The ages estimated using dose rates determined by exposing samples to a UV-dominated laboratory light, a common treatment for TL dating of loess, clearly results in age overestimates. Exposure to 16 hr of sunlight results in less-pronounced age overestimates, with inherited ages within analytical resolution. We therefore consider the TL age estimates derived from the 8-hr UV procedure to be overestimates of the true depositional age. Similar overestimates in TL age from total- and partial-bleach analyses have been documented for other waterlain sediments (Forman and Ennis, 1992).

Nevertheless, the TL results indicate that the intertidal sediments were exposed to at least several hours of sunlight prior to deposition, which is more than adequate exposure for optical dating. The IRSL emissions for the modern and Holocene sediments are near the background level, with an inherited signal equivalent to <1000 yr. Exposure of the modern and upper-Holocene estuarine mud to 1–3 hr of unshielded sunlight reduced the IRSL signal to a low definable level, within the background signal. These analyses demonstrate the rapidity with which the infrared luminescence signal declines upon exposure to unfiltered light. Assuming similar depositional environments for the modern, Holocene, and upper-Pleistocene estuarine mud, we suggest that the IRSL ages provide accurate chronologic control.

Intertidal sediment from pre-late-Wisconsin drift was dated at two sites within the Nushagak Formation (Table 4), (1) Squaw Creek (Fig. 2, site 7, collected 1 m altitude from laminated silt and mud containing beds of glaciogenic sediment-flow diamicton) and (2) Ekuk (site 8, collected 17 m altitude from laminated silt and silty fine sand at section EK2 shown in Lea, 1990), and from one site within Halfmoon Bay drift, Second Point (site 1, collected 5 m altitude from laminated silt and silty fine sand below deformed tidal sand and glaciogenic diamicton). The 16-hr-sunlight-treated TL ages overlap at 1σ at all three sites and average 81,000 ± 7000 yr. Given the potential for incomplete solar resetting for these deposits, we consider this estimate a maximum-limiting age. The IRSL ages also overlap at 1σ at all three sites; they average 77,000 ± 6000 yr, which we consider a closer estimate of the true age of the deposit.

Paleomagnetic Inclination

Oriented samples of muddy intertidal sediment were collected from the Nushagak Formation for paleomagnetic analysis. We collected three samples from each of 12 stratigraphic levels, spaced at 25 cm, at an exposure that extended 3 m above sea level at Nelsonville (Fig. 2, site 9). Magnetic orientations...
were measured and alternative-field (AF) demagnetization was performed on a 2G cryogenic magnetometer at the Department of Geology and Planetary Sciences, University of Pittsburgh. The natural remanent magnetization (NRM) measured in all samples showed normal inclinations, which remained stable upon demagnetization up to 750 Oe. Paleomagnetic declinations and inclinations calculated for each sample by principal-components analysis on AF-demagnetized data (Wobus, 1995) cluster around the present geomagnetic field (Fig. 7).

Similar steep, normal paleomagnetic inclinations were obtained from nine samples collected from intertidal mud at Squaw Creek, where the luminescence-dating sample was collected, about 1.5 km north of the Nelsonville site. Apparently, the fluxgate-type magnetometer used by Kaufman et al. (1994) to analyze the same samples lacked sufficient sensitivity to measure accurately the low-intensity NRM signals in the sediment. These new analyses show that the orientation of the geomagnetic field at the time of deposition of at least part of the Nushagak Formation was similar to present, consistent with a late-Quaternary age.

Summary of Geochronologic Control

(1) The lack of detectable radiocarbon activity in organic silt and peat atop the Nushagak Formation and Halfmoon Bay drift demonstrates that these units are older than about 38,000 yr.

(2) The lack of interglacial indicators and Old Crow tephra (~140,000 yr) atop the drift suggests that the Nushagak Formation and Halfmoon Bay drift are younger than the last interglaciation.

(3) Amino acid (aIle/Ile) ratios in *Portlandia* from Halfmoon Bay drift (~0.03) are lower than in *Mya* from last-interglacial Pelukian deposits at Nome (~0.04), despite lower temperatures at Nome and apparently equivalent rates of epimerization in *Mya* and *Portlandia*, implying a younger age. The amino acid data combined with an EDT calculated for probable last-interglacial shells at South Naknek beach indicate an age older than about 55,000 yr. A more reasonable, lower EDT for the younger, post-last-interglacial shell yields an age of about 90,000 yr, with an uncertainty of at least 20,000 yr.

(4) Luminescence analyses, including IRSL and TL, of intertidal glacial-estuarine sediment collected from the opposite sides of Bristol Bay, suggest that glaciers advanced to the coast from two independent ice sources after 81,000 ± 7000 yr, and probably closer to 77,000 ± 6000 yr.

We are confident that the glacial-estuarine sediment of Nushagak and Kvichak bays is younger than the last interglaciation and older than the range of radiocarbon. The amino acid and luminescence data converge on an age between about 75,000 and 90,000 yr, late during oxygen-isotope stage 5. We recognize, however, that these geochronological techniques lack sufficient certainty to exclude the possibility that the glacial-estuarine sediment is as young as oxygen-isotope stage 4 or as old as substage 5d.

CONCLUSIONS

(1) Luminescence analyses of modern and radiocarbon-dated Holocene intertidal mud-flat deposits from Bristol Bay suggest that the sediment deposited in this environment has received sufficient sunlight exposure to produce intracrystalline electron traps. The sediment is well bleached with respect to its IRSL signal, indicating that this procedure should produce reliable ages for Pleistocene sediments deposited in similar environments.

(2) The essentially identical luminescent properties of Pleistocene intertidal mud collected from the glacial-estuarine Nushagak Formation near Dillingham and from Halfmoon Bay drift at Second Point confirm stratigraphic and paleogeographic inferences that these sediments were deposited synchronously. Apparently, glaciers advanced simultaneously into Bristol Bay from two independent source areas, the Ahklun/Wood River Mountains to the northwest and the Alaska Peninsula to the southeast.

(3) The results of amino acid analyses, together with reasonable assumptions about taxon-dependent reaction rates and past temperatures, indicates that the unconformity that extends for kilometers laterally and is associated with a stony marine-lag horizon at 5.4 m altitude at South Naknek beach may be correlative with the Pelukian transgression (substage 5e). This correlation provides maximum- and minimum-limiting ages on the overlying and underlying glaciogenic diamictons, respectively, suggesting that glaciers advanced to, or near, their maximum Pleistocene positions both prior to and subsequent to the last interglaciation.

(4) The equivalent aIle/Ile ratios measured in younger shells incorporated into the drift of an advancing late Pleistocene glacier at Etolin Point and Halfmoon Bay indicate that the deposits at these two sites, both near the outer limit of Alaska Peninsula-derived drift, are correlative.

(5) Alle/Ile ratios in these shells are significantly lower than ratios in *Mya* from Pelukian deposits at Nome, further confirming an extensive advance of pre-late-Wisconsin glaciers into Bristol Bay during a period of high relative sea level *after* isotope substage 5e. Using an EDT calculated from the aIle/Ile in South Naknek beach shells with a presumed age of 125,000 yr, along with an equation that describes the relation between temperature and the rate of epimerization (Miller, 1985), indicates that the shells are older than about 55,000 yr. Taking into account the warmth of the last interglaciation, the shells are probably closer to 90,000 yr, although the uncertainty in this age estimate is broad. The shells were subsequently incorporated into drift, probably shortly after this time.

(6) IRSL and TL analyses indicate an age of about 75,000–80,000 yr for the glacial-estuarine deposits. This age is consistent with other geochronological data that demonstrate a pre-late-Wisconsin and post-substage-5e age, including nonfinite radiocarbon dates, isoleucine epimerization ratios, the lack of interglacial indicators and Old Crow tephra (~140,000 yr).
atop the glacial-estuarine unit, and normal paleomagnetic inclinations.

(7) Although the geochronological evidence points to a late marine-oxygen-isotope-stage-5 age for the most recent major ice advance in southwestern Alaska, we cannot rule out the possibility that the advance took place as recently as stage 4 or as old as stage 5d. Nonetheless, this age is considerably younger, by 300,000 to 400,000 yr, than the most-recent major advance of glaciers to the coast in northwestern Alaska.

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