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Late Pleistocene Cosmogenic ^{36}Cl Glacial Chronology of the Southwestern Ahklun Mountains, Alaska

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Thirty-two cosmogenic ^{36}Cl surface exposure ages constrain the timing of two late Pleistocene glacial advances in the western Ahklun Mountains, southwestern Alaska. Boulders were sampled from one early Wisconsin (*sensu lato*) and six late Wisconsin moraines deposited by ice-cap outlet glaciers and local alpine glaciers. Four moraine boulders deposited during an extensive early Wisconsin ice-cap outlet glacier advance have a mean surface exposure age of 60,300 ± 3200 yr. A moraine deposited by an ice-cap outlet glacier during the restricted late Wisconsin advance has a mean surface exposure age of 19,600 ± 1400 yr. Five moraines deposited by late Wisconsin alpine glaciers have mean ages that range between 30,000 and 17,000 yr. The ^{36}Cl ages are consistent with limiting ^{14}C and thermoluminescence ages from related deposits and indicate that Ahklun Mountains glaciers reached their most extensive position of the last glaciation early during the late Pleistocene, in contrast to the deep-sea isotopic record of global ice volume.[1]

Key Words: **glacial chronology; Alaska; ^{36}Cl; cosmogenic analysis.**

INTRODUCTION

During the last glaciation, the Ahklun Mountains were the largest glaciated mountain range in southwestern Alaska outside of the Cordilleran Ice Sheet (Fig. 1). Recent research in the Ahklun Mountains has focused on reconstructing Pleistocene paleoenvironmental conditions using proxy records in coastal bluff exposures and lacustrine sediment cores and using the glacial-geologic record to delimit past glacier extent. This work has revealed a terrestrial record of multiple Pleistocene glacier fluctuations and interglacial sea-level high stands (e.g., Axford, 2000; Briner and Kaufman, 2000; Kaufman *et al.*, 2001a, 2001b; Manley *et al.*, 2001). However, the glacial history of the late Pleistocene is only loosely constrained by a few numerical ages.

Absolute chronologies of Pleistocene glaciation in the Ahklun Mountains, and throughout Alaska, are poorly constrained mainly because organic productivity in subarctic landscapes is low and material for radiocarbon dating is sparse and because in many instances the ages of glacial deposits exceed the limit of radiocarbon dating (Hamilton, 1994). In this study, we used cosmogenic ^{36}Cl to determine surface exposure ages for moraine boulders associated with two late Pleistocene glacial advances in the southwestern part of the range. The cosmogenic ^{36}Cl chronology reported in detail here is updated from Briner (1998), from which the age assignments in Briner and Kaufman (2000) were made. The material in this paper builds on the glacial-geologic work presented in detail in Briner and Kaufman (2000) and complements existing radiocarbon (Manley *et al.*, 2001) and thermoluminescence data (Kaufman *et al.*, 2001b).

GLACIAL GEOLOGY

The high, central peaks of the Ahklun Mountains hosted late Pleistocene ice caps, from which outlet lobes expanded radially down major river valleys (Manley *et al.*, 2001). Small cirque and valley glaciers expanded from isolated massifs scattered across the range. In the southwestern Ahklun Mountains, Briner and Kaufman (2000) differentiated two late Pleistocene glacier advances as the Arolik Lake and Klak Creek glaciations

[1] Supplementary data for this article (Appendix 1) are available on IDEAL (http://www.idealibrary.com).

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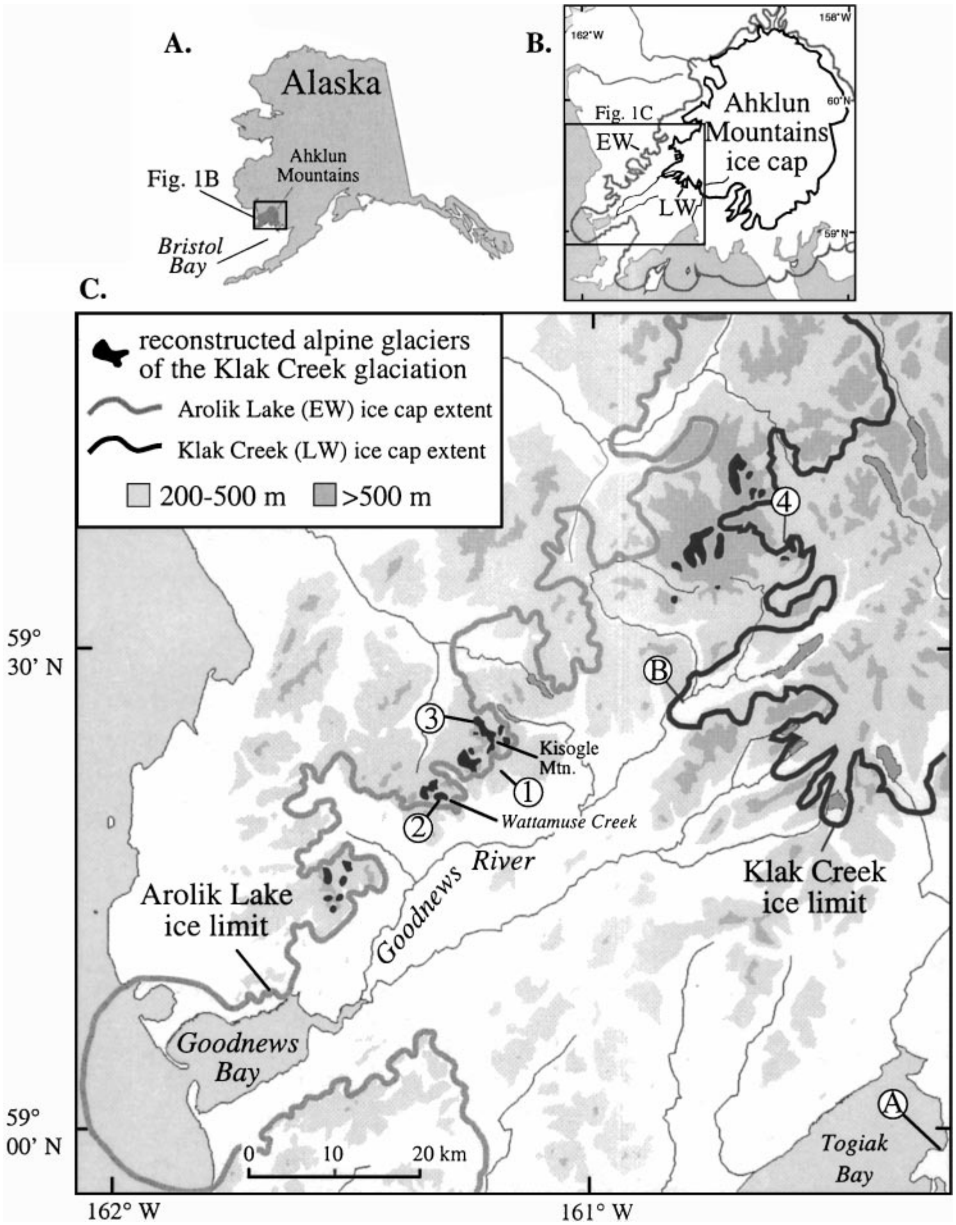

FIG. 1. (A) The location of the Ahklun Mountains, southwestern Alaska. (B) Extent of the Ahklun Mountains ice cap during the early and late Wisconsin (EW and LW, respectively; compiled from Axford (2000), Briner and Kaufman (2000), and Manley *et al.*, (2001)). (C) Southwestern Ahklun Mountains showing early (Arolik Lake) and late (Klak Creek) Wisconsin ice-cap limits and reconstructed late Wisconsin alpine glaciers from Briner and Kaufman (2000). The ice-cap limits depict the maximum extent of the ice-cap outlet glaciers and do not delimit nunataks. Numbers refer to ^{36}Cl dating localities and letters refer to independently dated sites discussed in text.

and assigned them to the early (*sensu lato*) and late Wisconsin stades, respectively, based on relative weathering data and earlier versions of the cosmogenic data reported here. Well-preserved glacial landforms (moraines, outwash terraces, and proglacial lake shorelines and deltas) allowed Briner and Kaufman (2000) to precisely delimit the extent of the Arolik Lake and Klak Creek glaciations.

During the Arolik Lake (early Wisconsin) glaciation, an outlet glacier extended down the Goodnews River valley to Goodnews Bay (Fig. 1; Briner and Kaufman, 2000; Manley *et al*., 2001). Distributary lobes from the Goodnews River outlet glacier flowed northwestward into unglaciated tributary river valleys, where moraines were deposited ~10–25 km from the Goodnews River. Massifs flanking the large valleys in the western Ahklun Mountains supported small alpine glaciers that were mostly confluent with ice-cap outlet glaciers during the early Wisconsin (Briner and Kaufman, 2000).

During the less extensive Klak Creek (late Wisconsin) glaciation, an ice-cap outlet glacier deposited moraines ~80 km upvalley from the early Wisconsin ice-cap outlet glacier moraines at Goodnews Bay (Fig. 1). Unlike during the Arolik Lake glaciation, alpine glaciers terminated independently from the ice cap during the late Wisconsin (Fig. 1). Terminal moraines deposited during the Klak Creek glaciation typically lie 5–10 km downvalley from cirque headwalls. In many valleys, end moraines were also deposited 0.5–2 km from cirque headwalls, suggesting that a standstill during retreat or a readvance occurred during a late phase of the Klak Creek glaciation (Briner and Kaufman, 2000).

^{36}Cl METHODS

Samples were collected for ^{36}Cl dating from the top surface of 32 moraine boulders deposited by both ice-cap outlet and alpine glaciers. Boulders on Arolik Lake moraines are rare and were only found at one site; however, Klak Creek ice-cap outlet glacier and alpine glacier moraines commonly contain boulders. Three to six samples were collected on each moraine from granodiorite and meta-basalt boulders with exposed diameters of 0.5–4 m. Samples (less than 5 cm and typically 3 cm thick) of the boulder's uppermost surface were collected from relatively flat rock surfaces ($<10^\circ$) to minimize potential correction and errors related to surface-geometry effects on the incident cosmic ray flux. Topographic shielding of cosmic rays was determined at each sample site and incorporated into each age calculation.

To extract Cl from silicate rock in a form suitable for accelerator mass spectrometry (AMS) measurement, we used a whole-rock wet chemical technique modified from a procedure outlined by Zreda *et al.* (1991) and reported in Swanson and Caffee (in press). Samples were processed in the Cosmogenic Isotope Lab at the University of Washington and were analyzed for ^{36}Cl by AMS at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory. Major elemental analyses of ground rock samples were determined by X-ray fluorescence (XRF) with an analytical uncertainty of $<2\%$ and a detection limit of 0.01%. Analyses for B and Gd were measured on selected samples by prompt gamma emission spectrometry, and U and Th contents were determined on selected samples by neutron activation. The Cl_{total} content was determined using a combination ion-selective electrode; at least three replicates of each sample were measured to attain low analytical uncertainty.

^{36}Cl ages were calculated using the computer spreadsheet program CHLOE (Chlorine-36 exposure; Phillips and Plummer, 1996). The spreadsheet program was modified to incorporate the production rates for ^{36}Cl reported by Swanson and Caffee (in press). We used Swanson and Caffee's (in press) production rates because they were calibrated at relatively high geomagnetic latitude (48°N), and because the geomagnetic field intensity changes only a few percent above 48°N (Lal, 1991), the production rates need not be scaled greatly from the calibration area to the sample localities in this study (~59°N). Furthermore, because secular variation in the cosmic ray flux is insignificant at high latitudes (Lal, 1991), Swanson and Caffee's (in press) production rates are applicable to surfaces younger and older than the surface for which they were calibrated.

The largest analytical uncertainties of the ages are the precision of the AMS ^{36}Cl/Cl measurement and the measurement of Cl_{total}. The AMS uncertainty ranges from 2 to 10%, and the uncertainty of Cl_{total} ranges from 2 to 18% but is typically $<5\%$. The age errors reported in this study incorporate only the AMS analytical uncertainty. The uncertainty in the Cl_{total} concentration commonly results in age errors that are ~25–30% of the age error due to AMS uncertainty. Mean moraine ages (the mean of all boulder ages per moraine) are reported as the weighted mean with one standard deviation error (see Table 1).

The surfaces of boulders in the southwestern Ahklun Mountains have likely eroded since they were deposited. Striae are typically absent from these moraine boulders; however, where present, sculpted bedrock still retains grooves. Although bedrock erosion rates have not been calculated in Alaska, a recent study utilizing cosmogenic isotopes in Arctic Canada provided a maximum nonglacial erosion rate of 1.1 mm $(10^3\ \text{yr})^{-1}$ (Bierman *et al.*, 1999). To assess the sensitivity of our ^{36}Cl ages to erosion, we calculated the ages with boulder erosion rates of zero and 1.1 mm $(10^3\ \text{yr})^{-1}$. We are not suggesting that the nonglacial erosion rate in the Ahklun Mountains is necessarily 1.1 mm $(10^3\ \text{yr})^{-1}$ but use this value to demonstrate how the ^{36}Cl ages can be affected by boulder surface erosion.

The boulders have also been covered periodically by snow, which has likely affected their apparent exposure age. The large distance and elevation difference between the study area and the nearest climate station prevents a reliable estimate of snow-cover history. However, by modeling exposure ages with an assigned snow cover (6 months per year of snow cover up to 3 m deep and a snow density of 0.2 g cm^{-3}) we assess of the effects of snow cover on apparent exposure ages.

Uncertainty associated with the geomorphic history of boulders is potentially important but difficult to quantify. We have endeavored to minimize this problem through careful and highly selective sampling practices targeting large boulders on crested or hummocky moraines. Because these landforms tend to degrade rapidly, boulders are exhumed continuously as slopes degrade around them (Hallet and Putkonen, 1994; Zreda *et al.*, 1994). Sampling the largest boulder is preferable because it is less likely to have been previously covered by till or would be the first to be exposed to the cosmic flux in a degrading moraine. Large boulders are also less susceptible to shielding by winter snow or former loess cover. While we can minimize potential geomorphic uncertainty by sampling the largest boulders, there is often no way of knowing in the field which boulders have been exhumed or have rolled.

Inheritance of ^{36}Cl from prior exposure introduces another potential source of uncertainty in age estimates. If a boulder surface was exposed to the cosmic ray flux prior to glaciation, then it may contain inherited ^{36}Cl and yield an apparent age that predates its deposition. Moraine boulders likely have complex exposure histories, and it is possible that they contain varying

TABLE 1
Late Pleistocene ^{36}Cl Ages from the Western Ahklun Mountains[a]

Sample	^{36}Cl Age (10^3 yr)$^{-1}$[b]										
	Zero erosion	1.1 mm (10^3 yr)$^{-1}$ erosion	Snow cover[c]	Snow and erosion	^{36}Cl/Cl (10^{-15})	Cl (ppm)	CaO (wt%)	K_2O (wt%)	Latitude (N)	Longitude (W)	Altitude (m)
Goodnews River valley (Site 1, Fig. 1) *Early Wisconsin ice-cap outlet moraine*											
Olympic Creek-1	57.9 ± 1.8	48.7 ± 1.5	61.8 ± 1.9	51.7 ± 1.6	217 ± 6.6	551.5	6.91	2.41	59°22′44″	161°12′08″	328
Olympic Creek-2	62.3 ± 1.7	51.5 ± 1.4	69.0 ± 1.9	56.3 ± 1.5	216 ± 5.8	630.5	7.36	2.09	59°22′42″	161°12′06″	312
Olympic Creek-3	57.5 ± 1.6	48.5 ± 1.4	61.5 ± 1.7	51.4 ± 1.4	206 ± 5.8	561.5	7.14	2.50	59°22′48″	161°11′50″	274
Olympic Creek-4	63.9 ± 2.3	52.5 ± 1.9	68.3 ± 2.5	55.7 ± 2.0	222 ± 8.1	676.5	6.61	2.49	59°22′52″	161°12′08″	312
Weighted Mean	**60.3 ± 3.2**	**50.2 ± 2.0**	**65.1 ± 4.1**	**53.8 ± 2.6**							
Wattamuse Creek valley (Site 2, Fig. 1) *Late Wisconsin terminal moraine*											
Wattamuse T-1	26.7 ± 0.9	24.1 ± 0.8	30.5 ± 1.0	27.2 ± 0.9	97.1 ± 3.2	785	5.10	3.96	59°20′56″	161°17′56″	274
Wattamuse T-2	*20.4 ± 0.9*	*19.0 ± 0.8*	*21.8 ± 0.9*	*20.2 ± 0.9*	84.8 ± 3.6	550	5.09	4.06	59°20′56″	161°17′52″	274
Wattamuse T-3	*57.7 ± 4.4*	*48.3 ± 3.7*	*66.2 ± 5.1*	*54.5 ± 4.2*	183 ± 14	673	7.36	2.06	59°21′00″	161°18′00″	274
Wattamuse T-4	30.3 ± 2.5	27.3 ± 2.3	34.6 ± 2.9	30.8 ± 2.6	115 ± 9.6	620	4.73	4.05	59°21′06″	161°18′10″	276
Wattamuse T-5	39.1 ± 2.0	34.6 ± 1.7	44.8 ± 2.2	39.1 ± 2.0	150 ± 7.5	564	4.30	4.14	59°21′06″	161°18′08″	278
Wattamuse T-6	30.3 ± 2.3	27.5 ± 2.1	33.5 ± 2.5	30.2 ± 2.3	134 ± 10	481	4.68	3.95	59°21′02″	161°18′04″	276
Weighted Mean	**30.4 ± 5.3**	**27.3 ± 4.4**	**34.7 ± 6.2**	**30.7 ± 5.1**							
Late Wisconsin recessional moraine											
Wattamuse R-1	25.9 ± 0.8	23.9 ± 0.7	28.6 ± 0.8	26.2 ± 0.8	123 ± 3.6	440	3.52	4.69	59°20′46″	161°19′04″	351
Wattamuse R-2	26.4 ± 1.6	24.2 ± 1.5	31.3 ± 1.9	28.4 ± 1.8	126 ± 7.8	432	3.38	4.55	59°20′46″	161°19′04″	351
Wattamuse R-3	*47.0 ± 1.3*	*41.7 ± 1.1*	*54.0 ± 1.4*	*47.7 ± 1.3*	220 ± 5.9	372	3.81	4.27	59°21′48″	161°19′00″	351
Weighted Mean	**26.0 ± 0.4**	**24.0 ± 0.2**	**29.1 ± 1.9**	**26.6 ± 1.6**							
Kisogle Mountain region (Site 3, Fig. 1) *Late Wisconsin terminal moraine*											
Kisogle-1	17.9 ± 1.4	16.6 ± 1.5	19.0 ± 1.5	17.7 ± 1.4	64.3 ± 5.1	476	11.90	0.80	59°26′42″	161°13′34″	244
Kisogle-2	17.1 ± 1.5	16.2 ± 3.1	20.2 ± 1.8	18.9 ± 1.7	80.2 ± 7.1	200	5.21	1.67	59°26′40″	161°13′30″	251
Kisogle-3	*3.1 ± 0.6*	*3.1 ± 0.3*	*3.3 ± 0.6*	*3.3 ± 0.6*	63.2 ± 12.0	17	6.23	0.26	59°26′38″	161°13′54″	244
Kisogle-4	18.6 ± 1.8	17.3 ± 1.4	21.3 ± 2.1	19.6 ± 1.9	78.5 ± 7.6	566	6.11	2.88	59°26′56″	161°14′10′	206
Kisogle-5	16.6 ± 1.3	15.6 ± 1.2	19.6 ± 1.5	18.2 ± 1.4	61.2 ± 4.8	395	10.90	0.75	59°26′44″	161°14′26″	236
Weighted Mean	**17.5 ± 0.9**	**16.4 ± 0.7**	**19.9 ± 1.0**	**15.8 ± 0.8**							
Late Wisconsin recessional moraine											
Cloud Lake-1	17.2 ± 1.1	15.8 ± 1.0	20.3 ± 1.3	18.5 ± 1.2	76.3 ± 5.0	318	4.87	1.08	59°25′22″	161°11′52″	358
Cloud Lake-2	*24.0 ± 1.3*	*21.4 ± 1.1*	*28.4 ± 1.5*	*24.9 ± 1.3*	92.8 ± 4.9	548	3.17	2.11	59°25′22″	161°11′52″	358
Cloud Lake-3	18.1 ± 1.4	16.5 ± 1.3	20.7 ± 1.6	18.6 ± 1.5	64.9 ± 5.1	546	5.44	0.65	59°25′22″	161°11′52″	358
Cloud Lake-4	15.0 ± 1.2	14.3 ± 1.2	17.1 ± 1.4	16.1 ± 1.3	84.2 ± 6.9	144	6.45	0.44	59°25′14″	161°11′54″	343
Cloud Lake-5	16.0 ± 1.2	14.7 ± 1.1	18.9 ± 1.4	17.1 ± 1.2	66.2 ± 4.8	365	2.20	1.33	59°25′08″	161°11′40″	358
Weighted Mean	**16.7 ± 1.4**	**15.5 ± 1.0**	**19.5 ± 1.6**	**17.8 ± 1.2**							
Klak Creek region (Site 4, Fig. 1) *Late Wisconsin terminal moraine*											
Chilly Valley-1	*26.7 ± 1.0*	*24.9 ± 0.9*	*28.5 ± 1.1*	*26.4 ± 1.0*	153.8 ± 4.6	129	4.91	0.64	59°36′20″	160°35′22″	457
Chilly Valley-2	19.5 ± 1.0	18.7 ± 0.9	21.4 ± 1.1	20.5 ± 1.0	125.6 ± 4.7	134	4.93	1.41	59°36′20″	160°35′08″	488
Chilly Valley-3	*6.2 ± 0.2*	*6.2 ± 0.2*	*7.1 ± 0.2*	*7.1 ± 0.2*	195.0 ± 9.7	24	6.20	2.44	59°36′30″	160°34′56″	411
Chilly Valley-4	16.8 ± 0.6	16.5 ± 0.6	17.9 ± 0.6	17.5 ± 0.6	161.2 ± 5.1	69	4.76	1.70	59°36′30″	160°34′46″	396
Weighted Mean	**17.8 ± 1.9**	**17.3 ± 1.6**	**19.2 ± 2.5**	**18.6 ± 2.1**							
Late Wisconsin ice-cap outlet moraine											
Gusty Lakes-1	19.3 ± 0.4	19.4 ± 0.4	22.8 ± 0.5	23.0 ± 0.5	707.0 ± 16.0	21	2.21	3.69	59°36′42″	160°35′58″	396
Gusty Lakes-2	20.2 ± 0.6	20.3 ± 0.6	23.9 ± 0.7	23.9 ± 0.7	565.0 ± 16.0	19	1.42	2.71	59°36′42″	160°35′58″	396
Gusty Lakes-3	17.6 ± 0.5	17.5 ± 0.5	20.0 ± 0.5	19.9 ± 0.5	363.5 ± 9.4	37	2.43	3.52	59°36′34″	160°35′54″	396
Gusty Lakes-4	20.7 ± 0.4	20.8 ± 0.4	23.6 ± 0.5	23.7 ± 0.5	593.3 ± 12.0	15	1.50	3.52	59°36′20″	160°36′00″	396
Gusty Lakes-5	*9.4 ± 0.6*	*9.5 ± 0.6*	*10.7 ± 0.7*	*10.8 ± 0.7*	429.8 ± 27.0	19	1.25	3.97	59°36′30″	160°36′18″	373
Weighted Mean	**19.6 ± 1.4**	**19.6 ± 1.5**	**22.7 ± 1.8**	**22.7 ± 1.9**							

[a] See Appendix 1 for additional geochemical data (available as supplementary data).
[b] Italicized ages are excluded from weighted mean calculations; mean ages are weighted by the inverse of the coefficient of variation (CV) squared, where CV = the error divided by the age for each sample. Error (one standard deviation) includes accelerator mass spectrometry analytical precision only.
[c] Snow cover calculations are based on 8 months of snow reaching up to 3 m in thickness with a density of 0.2 g cm^{-3}.

amounts of inherited ^{36}Cl, undetectable during field sampling. This effect is expected to produce scatter among samples collected from a particular surface, rather than simply increase the overall apparent exposure age.

^{36}Cl CHRONOLOGY

To determine the ^{36}Cl exposure age of the Arolik Lake glaciation, four moraine boulders were sampled ~3 km downvalley from the late Wisconsin alpine glacier limit north of the Goodnews River (Site 1; Fig. 1). Samples were collected from the tops of 2- to 4-m-high boulders that lie on a flat, well-drained surface, far from steep valley walls. The boulders were transported to their present location by an alpine glacier originating in the headwaters of Kisogle Mountain (Fig. 1) and confluent with the Goodnews River valley outlet glacier near the sample locality (Briner and Kaufman, 2000). Although the boulders were not collected directly from the early Wisconsin terminal moraine at Goodnews Bay, their high, lateral location indicates that the ^{36}Cl ages closely constrain the timing of deglaciation. Their mean ^{36}Cl age is 60,300 ± 3200 yr (ages reported as the zero erosion weighted mean; Table 1 [see Appendix 1 for a complete list of geochemical data, available as supplementary data], Fig. 2).

Six moraines deposited during the Klak Creek glaciation were dated from three locations. A terminal moraine in Wattamuse Creek valley (Site 2, Fig. 1) lies 1.5 km downvalley from its cirque headwall. A smaller end moraine lies ~1.0 km upvalley from the terminal moraine. Five 0.5- to 1.5-m-high boulders from the terminal moraine yield a mean age of 30,400 ± 5300 yr (Wattamuse T samples; Table 1; Fig. 2). Two ~1.5-m-high boulders from the upvalley end moraine yield a mean age of 26,000 ± 400 yr (Wattamuse R samples; Table 1; Fig. 2). The mean moraine ages do not include statistical outliers (defined as having an age that is $>2\sigma$ from the mean of the others; shown as italicized ages on Table 1 and as open squares in Fig. 2). These outliers may have anomalously young ages because of postdepositional tilting or rolling or anomalously old ages because of attributed to inherited ^{36}Cl from prior exposure.

In the Kisogle Mountain valley (Site 3, Fig. 1), the Klak Creek terminal moraine lies ~5 km downvalley from the cirque headwall region. Two end moraines lie ~3.5 km upvalley from the terminal moraine and ~0.5 km from their respective cirque headwalls. Four ^{36}Cl ages on boulders from the terminal moraine have a mean age of 17,500 ± 900 yr (Kisogle samples; Table 1; Fig. 2). Four boulders from one of the upvalley end moraines have a mean age of 16,700 ± 1400 yr (Cloud Lake samples; Table 1; Fig. 2) and constrain the age of the latest Pleistocene ice limit in the western Ahklun Mountains.

In a third location, moraine boulder samples were collected from ice-cap outlet and alpine glacier moraines in the Klak Creek region (Site 4, Fig. 1). In this area, we have obtained the only age for a moraine deposited during the Klak Creek glaciation by an ice-cap outlet glacier. Four boulders from the ice-cap outlet glacier moraine (informally named the Gusty Lakes moraine) have a mean age of 19,600 ± 1400 yr (Table 1; Fig. 2). Two boulders from the alpine glacier moraine (informally named the

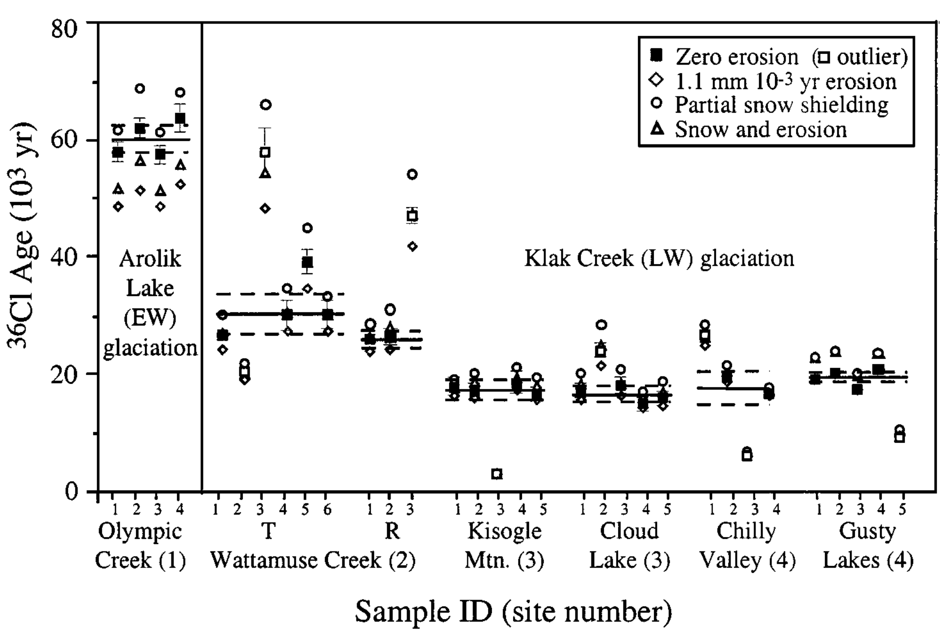

FIG. 2. ^{36}Cl ages from the western Ahklun Mountains (data shown in Table 1). The open squares represent ages that are $>2\sigma$ from the mean of the others for a given moraine and are thus excluded from the mean age calculations. Horizontal bars are weighted mean moraine ages (for the zero-erosion age estimates) with uncertainty (dashed lines). Numbers adjacent to labels on bottom axis are sample sites labeled in Figure 1.

Chilly Valley moraine) have a mean age of 17,800 ± 1900 yr (Table 1; Fig. 2).

INDEPENDENT AGES FROM THE AHKLUN MOUNTAINS

Thus far, age estimates for glacial events in the Ahklun Mountains have been based mainly on relative-age dating (e.g., moraine morphometry, soil development, and loess thickness; Manley *et al*., 2001). Several ^{14}C dates, tephrochronology, amino acid, and thermoluminescence data have also provided age constraints on Pleistocene glaciations across the range (e.g., Kaufman *et al*., 1996, 2001a, 2001b; Manley *et al*., 2001). Two numerical age estimates obtained on late Pleistocene drift in the southwestern Ahklun Mountains, along with ice limits mapped across the range (Axford, 2000; Briner and Kaufman, 2000; Manley *et al*., 2001), allow our work to be placed in the context of the glacial history of the Ahklun Mountains as a whole.

Thermoluminescence (TL) age estimates from a coastal bluff at Togiak Bay (Locality A, Fig. 1) provide a maximum age for early Wisconsin drift of 70,000 ± 10,000 yr (Kaufman *et al*., 2001b). The ice-cap outlet glacier limit at Olympic Creek (Site 1, Fig. 1) is correlated with the early Wisconsin limit ~40 km downvalley of the TL-dated sediment (Manley *et al*., 2001). Our age of 60,300 ± 3200 yr is younger than, but consistent with, the maximum-limiting TL age of 70,000 yr for the early Wisconsin drift.

Plant macrofossils provide a minimum-limiting radiocarbon age of 20,200–19,700 cal yr (Manley *et al*., 2001) for the late Wisconsin terminal moraine in the Goodnews River valley (Locality B, Fig. 1). This ^{14}C age overlaps with the mean ^{36}Cl age (19,600 ± 1400 yr) obtained from the Gusty Lakes moraine (Site 4, Fig. 1) located ~25 km to the north and traceable to the Goodnews River valley moraine. The consistency between the ^{36}Cl ages and independent ^{14}C and TL ages help to validate the use of Swanson and Caffee's (in press) production rates for age calculations in southwestern Alaska.

DISCUSSION AND CONCLUSIONS

Anomalous moraine boulder ages are likely a result of sampling relatively low-lying boulders that have been affected by moraine degradation in this high-latitude, alpine landscape. The mean moraine ages have large standard deviations, and ~25% of the boulders sampled were excluded from mean age calculations because they were anomalously young or old. Nonetheless, by sampling many boulders per moraine, we obtained ^{36}Cl ages that successfully distinguish moraine ages at stadial scales.

The Ahklun Mountains ^{36}Cl chronology indicates that an extensive early Wisconsin glacier advance was followed by a more restricted late Wisconsin advance. The age of 60,300 ± 3200 yr for the Arolik Lake glaciation provides strong evidence that, as it has been assigned elsewhere in Alaska (Hamilton, 1994), the major penultimate drift is late Pleistocene (early Wisconsin) rather

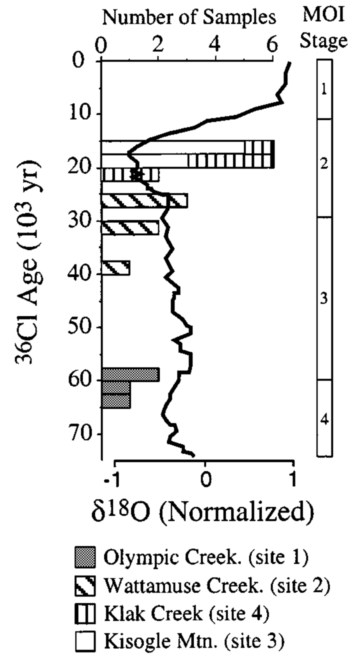

FIG. 3. Histogram of ^{36}Cl ages (with zero erosion), excluding statistical outliers. Site numbers adjacent to locations in key are shown in Figure 1. Numbers at right are marine oxygen isotope (MOI) stages ($\delta^{18}O$ curve from Martinson *et al*., 1987). Given the analytical and potential production rate uncertainties, the ^{36}Cl ages overlap with MOI stages 2 and 4. However, the restricted extent of the late Wisconsin (Klak Creek) glaciation with respect to the early Wisconsin (Arolik Lake) glaciation is out of phase with the marine oxygen isotope record of global ice volume.

than pre-last interglacial in age. The restricted nature of the Klak Creek glaciation relative to the Arolik Lake glaciation stands in contrast to the isotopic signal in the marine record of global ice volume (Martinson *et al*., 1987; Fig. 3). This contrast reveals the importance of local factors such as moisture availability in controlling the regional climate of southwestern Alaska (Briner and Kaufman, 2000). Sea level was ~125 m lower than present during the late Wisconsin (Fairbanks, 1989), and the coast of the Bering Sea regressed ~600 km to the southwest of the Ahklun Mountains. In addition, prolonged sea-ice cover in the Bering Sea during the late Wisconsin (Sancetta *et al*., 1984) would have further reduced the amount of moisture that reached the Ahklun Mountains.

The idea that glaciers around the world advanced at different times during the last glaciation and that the relative magnitudes of these advances are at odds with the global marine oxygen isotope record is becoming increasingly accepted (Gillespie and Molnar, 1995). At several sites across Beringia, researchers are finding more extensive glacial advances during the early Wisconsin than during the late Wisconsin (e.g., Hamilton, 1986; Kaufman and Hopkins, 1986; Gualtieri *et al*., 2000), indicating that much of Beringia was relatively arid during the late Wisconsin. Within the limits of available dating methods, it appears that the maximum late Wisconsin glacier advances across Beringia were broadly synchronous (e.g., Hamilton, 1994; Gualtieri, 2000).

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