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^{36}Cl DATING OF THE CLASSIC PLEISTOCENE GLACIAL RECORD IN THE NORTHEASTERN CASCADE RANGE, WASHINGTON

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ABSTRACT. Surface-exposure ages of granodioritic and gneissic boulders on seven successive moraines record the Late Pleistocene history of a major glacier system in the northeastern Cascade Range of Washington. The youngest moraines are boulder-rich and sharp-crested, but successively older moraines have lower boulder frequencies and are more degraded. Seventy-six ^{36}Cl dates for the moraines cluster in groups having mean ages (± 1σ) of 12,500 ± 500, 13,300 ± 800, 16,100 ± 1100, 19,100 ± 3000, 70,900 ± 1500, 93,100 ± 2600, and 105,400 ± 2200 years; a still-older, highly weathered and eroded moraine is undated, but likely is at least 165,000 years old. The moraine ages and relative extent of the Icicle Creek glacier correspond closely to the ages and relative amplitude of July insolation minima at 47.5° N latitude. They also are in accord with ages for glaciations in the European Alps that were inferred by Milutin Milankovitch and colleagues in the 1920s based on calculations of summer insolation. Evidence that the greatest Late Pleistocene glacier advance occurred at the onset of the last glaciation (during marine isotope substage 5d) is consistent with a cooling climate and major glacier advances at that time elsewhere in North America and the Eurasian Arctic, with a dramatic increase in global ice volume, and with the shifting track of the jet stream over northwestern United States.

INTRODUCTION

Temperate mountain glaciers and their deposits are important sources of Quaternary paleoenvironmental information, but determining the chronology of most glaciated alpine regions has been a continuing challenge because datable materials in or associated with glacial deposits (organic matter, tephra, lavas) are often sparse or lacking. Chronologies of Pleistocene alpine glaciation in the American West, based largely on relative-age criteria, generally have been regarded as approximate or provisional.

Within the past decade and a half, surface-exposure dating has been applied to alpine glacial sequences in the western United States (for example, Phillips and others, 1990; Gosse and others, 1995; Licciardi and others, 2001). Ages of exposed moraine boulders and associated bedrock surfaces can now be obtained routinely using one or more cosmogenic isotopes (^{3}He, ^{10}Be, ^{26}Al, ^{36}Cl) and are providing new details and insights about the chronology and dynamics of Pleistocene glaciers.

The upper Wenatchee River drainage basin on the east flank of the North Cascade Range (fig. 1) has been the focus of several glacial-geologic studies. A sequence of alpine moraines near the junction of the Wenatchee River and Icicle Creek provides evidence of multiple advances of a large east-flowing Cascade glacier system. Until recently, the only age control for these moraines and for those in most other Cascade valleys was relative-age measurements using a variety of weathering criteria (Porter, 1976), and minimum limiting ages for some latest Pleistocene moraines based on late- and postglacial tephra layers (Porter, 1969, 1978; Crandell and Miller, 1974). Tentative ages were assigned to the moraines based on inferred correlation with the standard Midwestern North American ice-sheet succession (Sibrava and others, 1986) and with marine oxygen-isotope stages (Martinson and others, 1987). Inherent in these correlations was the tacit assumption that times of greatest alpine-glacier advance correlated

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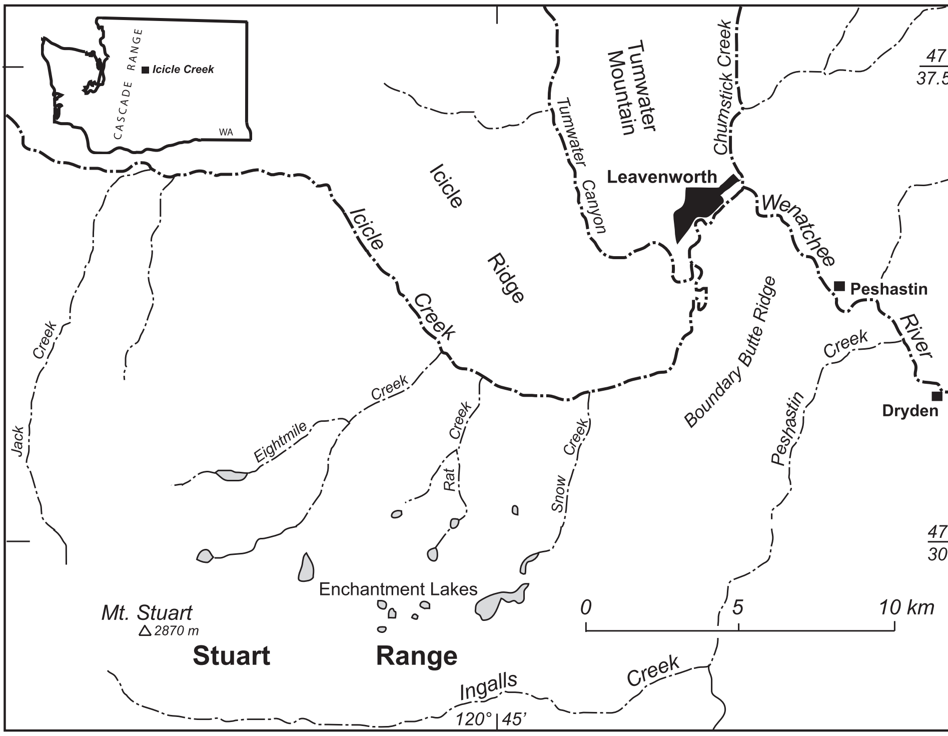


Fig. 1. Map of southern part of the northeastern Cascade Range showing location of Icicle Creek and other geographic features mentioned in the text.

with times of maximum global ice volume inferred from the marine oxygen-isotope record. Because ice-sheet maxima presumably coincided with the culminations of glacial isotope stages (MIS stages 2, 4, 6. . .), mountain glaciers also were thought to have reached maxima at these times. It also was generally assumed that the relative magnitude of the mountain glacier advances matched that of the ice-volume maxima.

We undertook a restudy of the glacial history of the Icicle Creek glacier system with the objectives of obtaining a cosmogenic-isotope chronology of the moraine sequence, comparing this chronology with that of the adjacent Cordilleran Ice Sheet, and assessing its relationship to changing Pleistocene climate. It involved additional detailed mapping, resulting in further elaboration of the glacial record, and sampling moraines for dating by the ^{36}Cl method. Seventy-six dates provide a chronology for the Late Pleistocene glacial succession and indicate that some previous assumptions regarding correlations with the global ice-volume record likely are in error. Whereas the new chronology shows that the alpine advances generally occurred at times of ice-sheet advance, the relative magnitudes of alpine and ice-sheet advances were not comparable.

EARLIER STUDIES

Nearly seventy years ago, Page (1939) assigned the glacial deposits of the Icicle Creek and adjacent drainages to three successively less-extensive glaciations, naming them after Peshastin, Leavenworth, and Mount Stuart (fig. 1; table 1). He described poorly exposed Peshastin drift as intensely weathered till and outwash gravel in which granodiorite boulders up to a meter in diameter are weathered to their core. He

TABLE 1
Evolution of Icicle Creek glacial nomenclature

Page (1939)	Porter (1969)	Waitt (1977)	This study	Abbreviations
Stuart	Leavenworth IV	Leavenworth V	Rat Creek I and II	RCI, RCII
Leavenworth	Leavenworth I-III	Leavenworth I-IV	Leavenworth I and II	LI, LII
Not recognized	*Not recognized*	*Not recognized*	Mountain Home	MH
Not recognized	*Not recognized*	*Not recognized*	Pre-Mountain Home	pMH
Peshastin	Chumstick	Mountain Home	Peshastin	P
Not recognized	Peshastin	Boundary Butte	Boundary Butte	BB

mapped relatively unweathered Leavenworth drift forming a conspicuous lateral moraine traceable for 5 km along the western flank of Boundary Butte Ridge (fig. 1) and noted its resemblance to “a railroad embankment of gigantic proportions.” During his “Stuart glaciation,” glaciers built conspicuous end moraines in Icicle Creek valley and its southern tributaries. One at the mouth of Rat Creek he described as a “perfect horseshoe” moraine and noted that it closely resembles Leavenworth deposits downvalley.

Porter (1969) subsequently reported relative-age data for the Leavenworth and two older drifts (Chumstick and Peshastin), subdivided the Leavenworth stage into four substages, with the Rat Creek moraine of Page’s “Stuart glaciation” representing the youngest (late-glacial) Leavenworth advance.

Waitt (1977) proposed additional changes to the nomenclature, redefining the Leavenworth Drift to include five subunits (I-V), the youngest of which was equivalent to Page’s Rat Creek moraines. He further proposed that Page’s Peshastin drift be renamed Mountain Home Drift, and that the oldest (included by Page in his Peshastin drift) be renamed Boundary Butte Drift.

REVISED MORAINE SEQUENCE

Our study has led to further refinement and revision of the Icicle Creek moraine sequence. We retain Waitt’s designation Boundary Butte for the highest, oldest lateral moraine and also retain the name Peshastin for the prominent moraine downslope from it. We have identified a previously unrecognized lateral moraine between the outermost Leavenworth lateral moraine and the Peshastin moraine, and have traced it discontinuously for 5 km along the western slope of Boundary Butte Ridge. For most of its length, the moraine lies above and nearly parallels Mountain Home Road, and we now use the name Mountain Home for this post-Peshastin, pre-Leavenworth moraine and the glacier advance during which it was built.

Two short lateral moraine segments lie outside the Mountain Home moraine at the northern end of Boundary Butte Ridge. Both have subdued crests and few surface boulders. We think that the outer of these may be of Peshastin age, as discussed below. The inner we designate the pre-Mountain Home moraine.

We recognize only two Leavenworth moraine systems, Leavenworth I (older) and Leavenworth II. The bouldery lateral moraines parallel one another along the west slope of Boundary Butte Ridge, then descend steeply at the north end of the ridge toward two corresponding end moraines on the valley floor. The inner moraine passes obliquely through Leavenworth, where it has been extensively modified by human activity. The outer is crossed by the Wenatchee River immediately south of its junction with Chumstick Creek, and is best preserved south of the river.

We also have mapped two nested moraines at the mouth of Rat Creek (Stuart moraines of Page, 1939, and Leavenworth V moraines of Waitt, 1977) and named them Rat Creek I (older) and Rat Creek II. Similar paired moraines occur in other tributary valleys of Icicle Creek but these have not yet been studied in detail or dated.

PREVIOUS AGE ESTIMATES

Page (1939) speculated that the Leavenworth deposits undoubtedly were "equivalent to all or to part of the Wisconsin stage." Porter (1969) inferred that the Leavenworth drift was of late Wisconsin age, the intermediate drift was of early Wisconsin age, and Peshastin drift was of pre-Wisconsin age. Waitt (1977) subsequently estimated that the Leavenworth moraines are approximately 11,500 to 18,000 years old, the Mountain Home Drift (Peshastin drift of this report) is about 130,000 to 140,000 years old, and Boundary Butte Drift is about 700,000 to 850,000 years old.

Waitt and others (1982) described evidence of a possible early Holocene glacier advance in the Enchantment Lakes area at the crest of the Stuart Range, which forms the southern headwaters of the Icicle Creek drainage (fig. 1). They noted that Glacier Peak tephra layer G (Porter, 1978) can be traced to the outer edge of cirque moraines that lie far above the Rat Creek moraines. This implies that the Rat Creek advance must be older than 11,100 to 11,300 ^{14}C years, the likely age of the tephra (Foit and others, 1993). They concluded that the Rat Creek advance might be "as old as 13,000 yr B.P., if not a little older."

ICICLE CREEK GLACIER

During the greatest Leavenworth advance, the Icicle Creek glacier flowed as far as 46 km from cirques along the Cascade crest (fig. 2). The glacier system was strongly asymmetrical. A dozen steep tributary ice streams, 2- to 4-km long, flowed from an ice cap on the crest of Icicle Ridge (1980−2130 m altitude). An equal number of larger southern tributary glaciers (3−13 km long) flowed from cirques (2135−2865 m) along the crest of the Stuart Range. During the Mountain Home and Peshastin advances the glacier probably terminated about 1 and 5 km, respectively, beyond the Leavenworth terminal moraine. During the latter advance the glacier overflowed (toward the east) almost the entire northern end of Boundary Butte Ridge. The average surface gradient of the main ice stream was about 24 m/km; that of the longest southern tributaries was 120 m/km. Owing to the strong climatic gradient across the Cascades, the equilibrium line rose eastward across the glacier and its tributaries at about 12 m/km (fig. 2). The ice is estimated to have been 380 m thick near the equilibrium line in the main valley.

COLLECTION AND ANALYSIS OF SAMPLES FOR ^{36}Cl SURFACE EXPOSURE DATING

The ^{36}Cl dating method was used in this study because the isotope production rates were calculated using calibration samples from the adjacent Puget Lowland at the same latitude and they were collected along an altitudinal gradient (sea level to 1600 m) that encompasses the altitude range of the Icicle Creek moraines (Swanson and Caffee, 2001).

Boulders and smaller clasts comprising the moraines of the Icicle Creek glacier are predominantly granodiorite. Many of the granodiorite rock samples we collected have a high chloride content that produces ^{36}Cl age versus erosion-rate profiles that are relatively insensitive to the range of boulder-weathering rates inferred for the study area (see below).

Samples were collected from boulders on the crests and upper slopes of moraines and from glacially abraded bedrock. They were chipped off the top surface of the largest moraine boulders (typically ≥2 m, but as much as 14 m) that appeared to have remained undisturbed since deposition. Samples (generally 1−3 cm thick) were

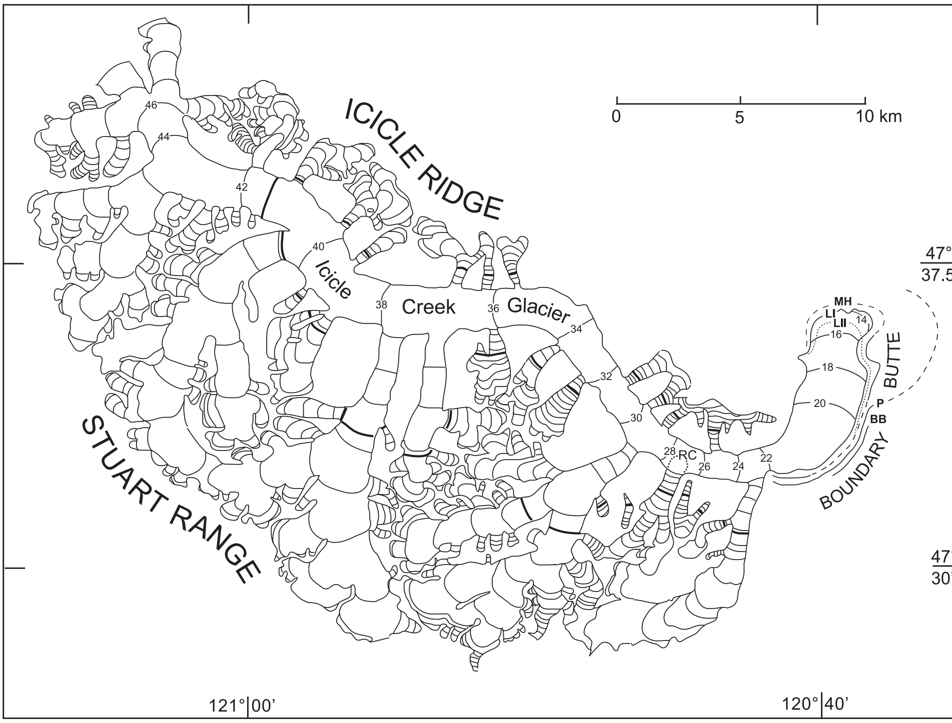


Fig. 2. Topographic reconstruction of Icicle Creek glacier (contour interval 200 feet = 61 m) at the time of the maximum Leavenworth I advance. The equilibrium line (bold line) crossed the surface of the main glacier at about 4200 feet (1280 m), but because of its eastward-rising gradient, its altitude on tributary ice streams lay at successively higher altitudes downvalley. Crests of major moraines in the lower reaches of the valley include Boundary Butte (BB), Peshastin (P), Mountain Home (MH), and Leavenworth I and II (LI and LII). The type Rat Creek moraines (RC) lie at the mouth of Rat Creek, the second major southern tributary.

obtained, using a sledgehammer and mason's chisel, from relatively flat surfaces (dip angles <15°) to minimize potential corrections related to the effect of surface geometry on the incident cosmic ray flux. Topographic shielding of this flux was estimated using an inclinometer, measured at 90° intervals around the horizon. Shielding corrections for topography are generally less than 2 to 5 percent for all of the measured samples and are incorporated into age calculations (Appendix).

Major-element analyses of rock samples were determined by X-ray fluorescence (XRF) spectrometry, with an analytical uncertainty of <2 percent and a detection limit of 0.01 percent. Boron and gadolinium (elements with large cross-sectional areas for neutrons) concentrations were measured by prompt gamma emission spectrometry, with an analytical uncertainty of <2 percent and a detection limit of 0.5 ppm. Uranium and thorium contents were determined by neutron activation, with an analytical uncertainty of <2 percent and a detection limit of 0.5 ppm. Chemical analyses were performed by XRAL Laboratories (Don Mills, Ontario, Canada). Total chlorine content was determined by combination ion-selective electrode. At least five replicates of each sample were measured to attain an analytical uncertainty of <5 percent. In cases of low chloride concentrations (<15 ppm), as many as 25 replicates of each sample were run to attain an uncertainty of <5 percent.

^{36}CL is produced in exposed terrestrial rocks mainly by cosmic-ray-induced spallation reactions of K and Ca isotopes and by neutron activation of ^{35}Cl. Muon capture by K and Ca isotopes becomes progressively more important in producing ^{36}Cl at low altitude and with increasing depth below the Earth's surface. Noncosmogenic, radiogenically produced ^{36}Cl is generally in secular equilibrium and can be subtracted from the total AMS-measured ^{36}Cl to determine the cosmogenic component. The remaining cosmogenic component can then be used to calculate surface exposure ages using equations presented by Liu and others (1994).

A wet-chemical technique, modified from the procedure outlined by Zreda and others (1991), was used to extract Cl from silicate rock. Samples were analyzed for ^{36}Cl by a tandem Van de Graaf accelerator at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory. Analytical uncertainties (1 σ) of the AMS measurements are typically 2 to 5 percent.

In calculating ^{36}Cl ages, we used the production rates of Swanson and Caffee (2001; Swanson, 2005), which were calibrated using the ^{14}C-dated deglaciation history of the northern Puget Lowland, Washington. Their calibration sites lie at a geomagnetic latitude similar to that of Icicle Creek and require little latitudinal scaling (table 2). Furthermore, because secular variation in the cosmic ray flux does not vary significantly above 50° N latitude (Lal, 1991), the derived production rates are applicable, with minor scaling, to surfaces that are both younger and older than the surface from which they were originally calibrated. R. C. Finkel and T. W. Swanson (unpublished data) have calculated ^{10}Be ages for several of the Puget Lowland calibration sites, and their calculated ^{10}Be ages are consistent with calculated ^{36}Cl ages based on the Swanson and Caffee (2001) production rates.

We used production rates for calcium and potassium reactions of 87 $\pm$ 7 atoms ^{36}Cl/g Ca/year and 228 $\pm$ 23 atoms ^{36}Cl/g K/year, respectively. The calculated ground-level secondary neutron production rate in air, P_f (0), inferred from thermal neutron absorption by ^{35}Cl, is 762 $\pm$ 28 neutrons/g air/year for samples with low water content (1−2 wt. %). Production due to muon capture by ^{40}Ca was estimated using a value of ~5.0 $\pm$ 1.0 atoms/g Ca/year that was derived empirically by Stone and others (1998). These production rates were scaled to the altitude and latitude of the study area using polynomials reported by Lal (1991). Due to variability in paleointensity of the magnetic field over the integrated exposure history of a given sample, the production rates used to calculate ^{36}Cl ages have been scaled with respect to the effective geomagnetic latitudes (table 2; Appendix) in the manner described by Nishizumi and others (1989) and Clark and others (1995). Age calculations were made using a boulder erosion rate of 2 mm/1000 years, midway between the inferred range of boulder weathering scenarios of 1 to 3 mm/1000 years (see below). Ages were calculated using a ^{36}Cl exposure program (CHLOE) described by Phillips and Plummer (1996). Data used to calculate the ^{36}Cl ages are given in the Appendix.

A scaling effect due to snow cover was included in the age calculation. In moist, maritime mountain ranges like the Cascades, long-lasting seasonal snow can reduce substantially the magnitude of the cosmic ray flux reaching the land surface. At Mount Rainier, where record annual snowfalls of up to 30 m have been recorded, Holocene moraine boulders typically remain snow-covered for 6 to 8 months of the year. Apostle (2000, Apostle, ms 2004) sampled lahar boulders at 1735 to 1790 m altitude on the southern slope of the volcano that have been exposed for the last 5000 to 5600 years (Vallance and Scott, 1997) and reported that the boulders have ^{36}Cl exposure ages half that old, presumably the result of a thick and persistent snow cover during Neoglaciation (most of the last 5000 years).

The Pleistocene Icicle Creek moraines lie in the rain shadow of the eastern Cascades. Annual snowfall at Leavenworth for AD 1948 to 2001 averaged 243 cm and winter (DJF) snow depth averaged 17 cm (http://www.mthome.com/weather.html). Snow-free conditions last from April to November. Snow cover at moraine sampling

TABLE 2

Example of effects of secular variation in paleomagnetic field intensity and boulder weathering rate on ^{36}Cl ages of Peshastin samples

Sample ID[a]	Altitude (m)	Sample Thickness (cm)	Shielding Factor	^{36}Cl/Cl ± 1 sigma (10^{-15} atoms)	^{36}Cl Exposure Age (1000 years)						
					Present Latitute (47.5° N)	Effective Latitude[b,c] (50.3°)	Weathering Rate (mm/1000 years)				
							0	1.1	2.2	3.3	4.4
PESH 1-2	741	1	0.96	707 ± 23	113.4	110	157.5	110.0	104.3	109.9	114.5
PESH 1-3	732	1	0.96	1009 ± 17	112.0	108.6	141.0	108.6	104.3	110.5	115.1
PESH 1-4	738	1	0.93	756 ± 13	100.4	97.5	127.3	97.5	91.9	93.8	96.1
PESH 1-5	741	1	0.94	1009 ± 15	112.8	109.5	147.5	109.5	103.8	108.3	112.3
PESH 1-6	732	2	0.96	725 ± 14	116.1	112.6	156.8	112.6	106.8	112.3	117.0
PESH 1-7	701	2	0.97	678 ± 10	108.7	105.5	143.7	105.5	99.8	103.8	107.0
PESH 1-8	777	2	0.97	789 ± 15	108.1	105.3	144.0	105.3	99.0	101.8	104.9
PESH 1-9	768	2	0.96	871 ± 14	114.4	110.9	147.0	110.9	106.1	112.1	115.9
PESH 1-10	768	2	0.97	791 ± 12	108.2	105	144.1	105.0	98.5	101.0	103.8
PESH 1-11	768	1	0.97	668 ± 11	104.7	101.7	143.2	101.7	97.3	98.7	101.8

sites can be estimated using modern data from Mountain Home Lodge (altitude 613 m) above Leavenworth based on a 20 percent water equivalency. The estimate includes uncertainty due to longer and shorter durations of seasonal snow at somewhat higher and lower altitudes, respectively, than at the Mountain Home site. Reduced precipitation during cold, dry glacial times (Whitlock and Bartlein, 1997) may have led to only a thin seasonal snow cover on moraines, but lower melt-season temperatures probably reduced ablation of the snow pack. Despite such uncertainties, corrections for estimated snow cover at our sampling sites are generally in the range of 3 to 5 percent.

GEOLOGIC CONSTRAINTS ON MORAINE BOULDER AGES

If all boulders on a moraine were freshly quarried, remained unweathered and geomorphically stable since deposition, and lacked a prior history of exposure to cosmic radiation, their isotopic ages should cluster in a tight group. However, outliers in age populations show that this is not always the case, for generally a few boulder ages lie statistically outside the primary age cluster. Such boulders can appear to be too old or too young depending on their source and exposure history prior to and following a glacier advance (fig. 3). In this study we consider a moraine boulder sample to be an outlier in a sample population if it lies beyond one standard deviation of the population mean. The exposure age of a moraine was obtained by calculating the mean age of all samples lying within one standard deviation of the mean age of the primary population cluster. However, the true age of the moraine is more likely represented by the age of the oldest boulder that is not a statistical outlier (Putkonen and Swanson, 2003). We assume that moraine ages obtained by the ^{36}Cl dating of exposed boulders represent minimum ages for moraine abandonment and stabilization.

Boulder Sources and Transport Paths

Large moraine boulders are overwhelmingly composed of coarse-grained granodiorite of the Mt. Stuart pluton. Metamorphic lithologies of the Chiwaukum Schist that form Icicle Ridge are a minor component of the right-lateral moraines but are present in the terminal moraines near Leavenworth and at Rat Creek. The likely origins of the granitic boulders include (1) glacially plucked bedrock along the floor and margins of Icicle Creek valley and its southern tributary valleys, (2) rockfalls from steep valley walls onto the glacier surface, (3) incorporation of loose boulders from alluvium, colluvium, and rockfall deposits on valley floors, and (4) reworking of older glacial deposits, including terminal and lateral moraines (fig. 4).

Prior Exposure History

Moraines typically contain a mix of boulders with and without a prior history of exposure to cosmic rays. The former usually appear as outliers in a population of boulder ages (fig. 3). If averaged with the primary population, these outliers may generate a mean age that is older than the age of moraine stabilization. The outermost end moraine of any glaciation likely contains the largest component of such older outliers. Reworked boulders can have various exposure histories, and may not form a distinct older age cluster.

Many of the exposed large boulders on the Icicle Creek lateral moraines are subangular to subrounded and probably represent fresh to variously weathered rockfall debris that fell onto the glacier surface from adjacent valley walls. In the glacier's accumulation area, such rockfall debris would have been incorporated in the glacier and transported subglacially and englacially toward the terminus (fig. 4). Debris falling onto the glacier's ablation area would have traveled mainly supraglacially toward the ice margin and been deposited as a primary component of end moraines.

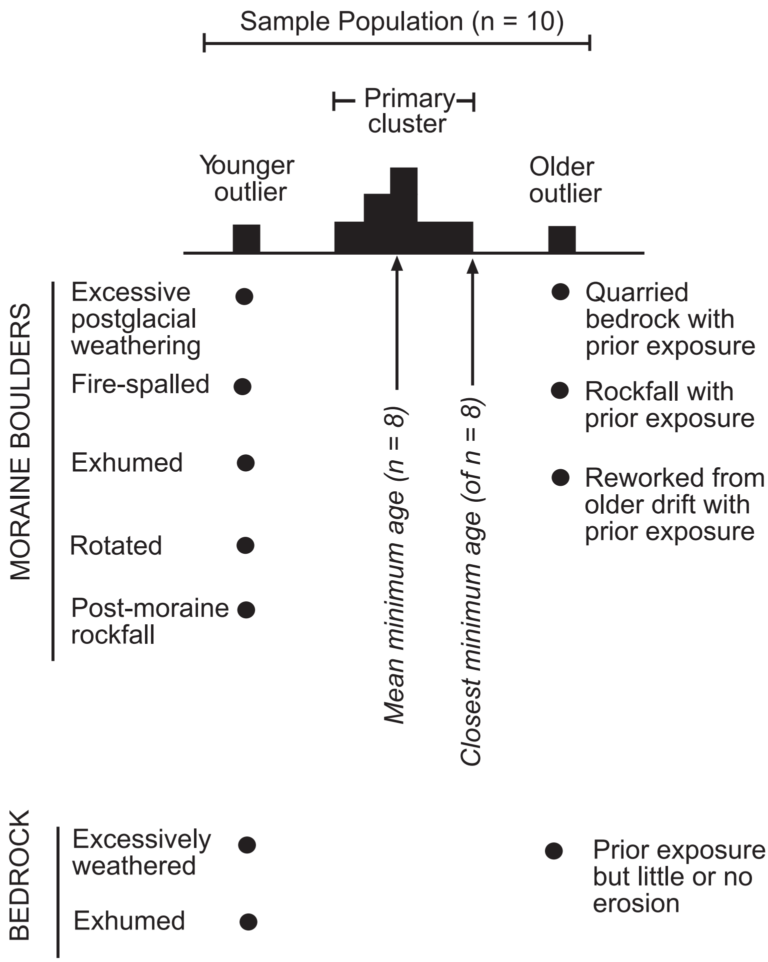


Fig. 3. Possible factors explaining the presence of older and younger outliers in a hypothetical population of ten granitic moraine boulders and bedrock samples (see text).

Rockfalls reaching a glacier surface will include boulders with and without prior exposure histories (fig. 4). If one assumes that one side of an equidimensional (cubic) joint-bounded boulder had a long prior exposure history, then there is a 16 percent chance (1 in 6) that the boulder, if deposited on a moraine crest, will lie with the formerly exposed side upright (the side sampled for cosmogenic-isotope dating). For glaciers subject to frequent rockfalls, a small percentage of boulders with a prior exposure history can introduce anomalously old ages into the sample population.

Boulders plucked from deeply eroded (>2 m) valley-floor bedrock likely have had little or no prior exposure, but those quarried from little-eroded surfaces may retain inherited cosmogenic isotopes (fig. 4; Briner and Swanson, 1998) and appear anomalously old. As in the case of rockfall boulders, only one side of a large (>2 m) cubic boulder plucked from bedrock is likely to have been exposed to cosmic radiation. All sides of smaller boulders (<1 m) may retain some degree of prior exposure.

Because many old moraines contain boulders with some prior exposure history, it is necessary to sample at least seven boulders on a moraine to identify these anomalous

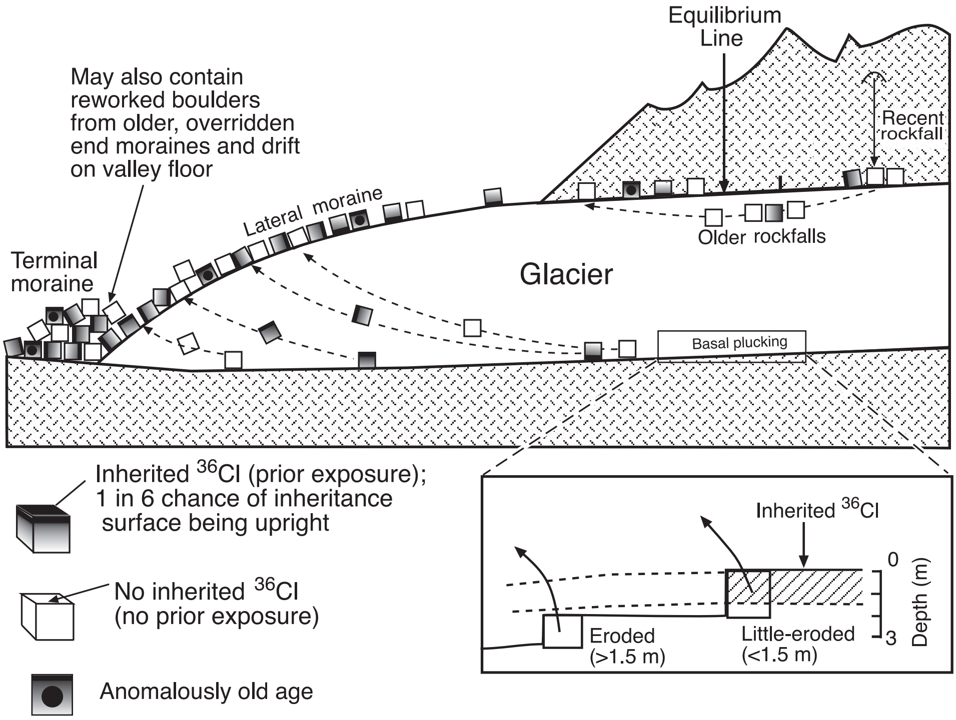


Fig. 4. Potential sources of boulders in Icicle Creek moraines

components (Putkonen and Swanson, 2003). In this study we sampled seven or more boulders on most moraines, and commonly ten or more. With sample populations of this size, outliers were identified more confidently and excluded when calculating a moraine's likely depositional age.

Moraine Degradation and Boulder Exhumation

As a moraine crest erodes and matrix is removed, exposed boulders may rotate, shift, or roll. The top (sampled) surface will then have received less cosmic radiation than will the top of a stable boulder and may appear as a young outlier in an age population. A postglacial rockfall boulder deposited on a moraine would also have an anomalously young age, unless its upper surface had a history of prior exposure.

When a boulder-rich lateral moraine is deposited, its distal slope typically attains the angle of repose of the sediment, but the proximal slope may be much steeper. Degradation of the moraine crest begins as the glacier withdraws, and rain, meltwater, and mass-wasting processes begin to erode the matrix. An oversteepened proximal slope will erode back until it stabilizes at a lower angle, in the process shifting the crest in the distal direction. The crest is lowered and flattens as sediment is transferred downslope (Porter, 1969), and originally buried boulders without prior exposure emerge progressively at the surface (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003). Previously largely sheltered from cosmic radiation, these emerging boulders will have younger exposure ages than surface boulders that have been continuously exposed since moraine deposition, assuming the production pathway is largely spallogenic.

Fig. 5. Excavation in Peshastin moraine near locality P-11 showing extensive granular disintegration of 2-m granite boulders in the weathering zone.

Granular Disintegration of Moraine Boulders

The coarse-grained granodiorite of the bouldery moraines along Icicle Creek and Boundary Butte Ridge tends to weather mainly by granular disintegration, promoted by oxidation of mafic minerals. On the Peshastin moraines, apparently little-weathered surface boulders contrast with small buried boulders ($\leq$ 0.5 m diameter) in the weathering zone (1−3 m depth) that are entirely weathered to grus. Large subsurface boulders in old moraines typically have a rind of grus tens of cm thick surrounding a hard, little-weathered core (fig. 5). Large buried granitic boulders (1−2 m diameter where exposed in section) in the weathering zone of the Boundary Butte drift are completely weathered to grus. These observations imply that rates of decomposition and granular disintegration in the weathering zone exceed those at the surface, probably because greater subsurface moisture promotes more-intense chemical–weathering reactions.

The long-term weathering of surface moraine boulders is illustrated by surface boulder frequencies (SBF; the number of boulders within a given area along a moraine crest) on successively older moraines (Porter, 1969). SBF is locally quite variable on the Rat Creek and Leavenworth moraines because some very large boulders ($\geq$8 m diameter) are present. Sectors with individual boulders covering more than 25 m^2 therefore were avoided. Leavenworth moraines have an average SBF of 90−100/100 m^2, the Mountain Home (previously informally called 'Chumstick') of 20/100 m^2, and the Peshastin moraine of <1/100 m^2. Surface boulders on the Boundary Butte moraine are so rarely encountered that they do not provide a meaningful SBF value.

Spalling of Boulders

An additional important mechanism of surface boulder weathering is spalling during major fires. The lower Wenatchee River basin is subject to frequent natural

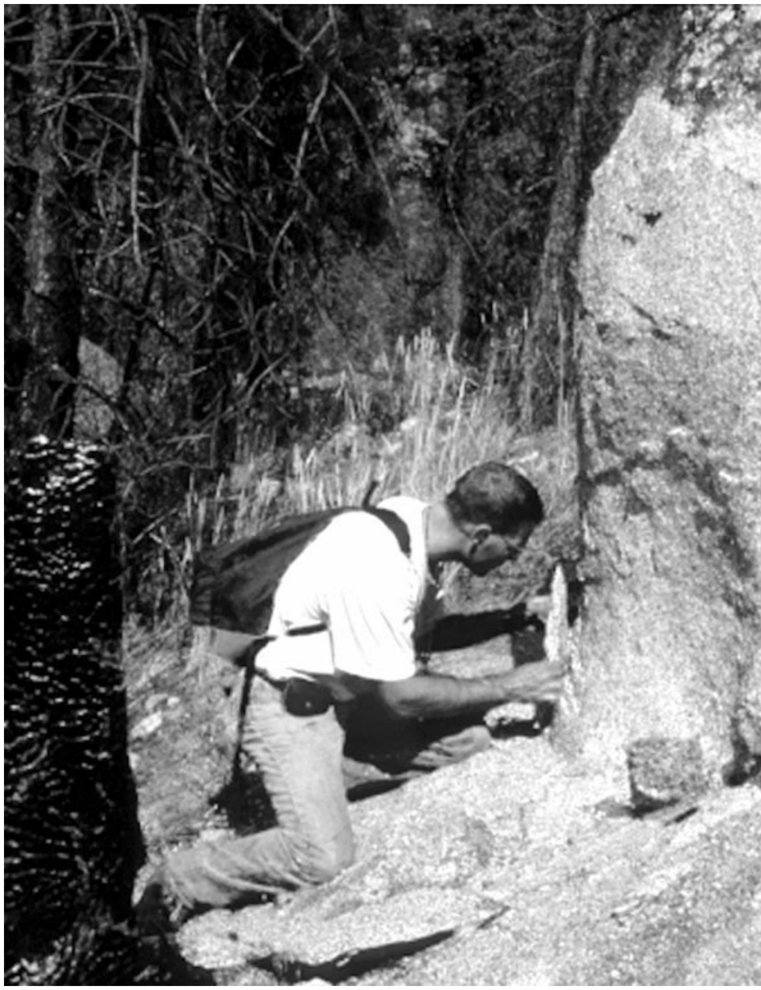


Fig. 6. Large granodiorite boulder (2 m tall) near crest of LI lateral moraine showing spalling around sides resulting from intense 1993 forest fire in Icicle Creek drainage. Lichen-covered top of boulder (upper right) is little modified. Carbonized tree (left) shows proximity of boulder to intense heat.

fires, for it lies in a zone of low mean annual precipitation (64 cm/year at Leavenworth) and high maximum summer temperatures (29°C). It supports a mixed conifer-hardwood forest dominated by Ponderosa pine.

A large fire during 1993 swept across a sector of the Icicle Creek lateral moraines, burning the forest and its understory and producing a noticeable affect on high-standing boulders. Those close to burning trees spalled on the side facing the most intense heat (fig. 6). However, little or no fresh spalling was detected on the top surfaces of large boulders (standing >2 m high) in the fire zone. Possibly this was because the flammable low understory vegetation generated the highest temperatures near the boulders. These observations suggest that the primary effect of fires on some large exposed granitic moraine boulders near Icicle Creek is the reduction of their lateral dimensions; the top surfaces, where samples are taken for cosmogenic dating, may be less affected. Nevertheless, during major fires all exposed boulder surfaces may be subjected to spall-producing heat.

In assessing the role of fire in boulder weathering, the long-term fire history must be considered. We have no independent measure of this but assume that fire frequency was greatest under warm, dry interglacial and interstadial conditions. During the late Quaternary, the frequency of large fires may have been highest during the driest parts of the last interglaciation (about 125,000 to 117,000 years ago) and the early to middle Holocene (about 13,000 to 4000 years ago) when climates were warmer and drier than today in the eastern Cascades (Whitlock and Bartlein, 1997, table 2; Whitlock and others, 2003). Paleoecological information from the Pacific Northwest for 6000 cal years B.P. indicates that higher-than-present summer temperatures, heightened drought, and drier soils and fuels, were all factors contributing to fire frequencies higher than present (Whitlock and others, 2003). Thus, spalling events related to an increase in major fires may be broadly episodic and linked to long-term climate trends.

Degradation of Rock Surfaces and Long-Term Weathering Rates

An important parameter in the ^{36}Cl age calculation is the estimated long-term weathering rate of boulder and bedrock surfaces sampled for isotopic analysis. Such an estimate is based on observed weathering features on surfaces whose age is known or can be approximated. Glacially abraded granitic surfaces were sampled at several places on the main valley floor (about 490−500 m altitude) to obtain limiting ^{36}Cl ages for deglaciation. Glacial grooves are reasonably common on these surfaces, but striations (1−2 mm deep) and glacial polish are rarely observed, implying that most were eradicated by postglacial weathering. Rock surfaces downvalley from the Rat Creek moraines potentially have been exposed to weathering for about 15,000 years following deglaciation, suggesting that small-scale erosional features (up to several mm deep) tend to be obliterated over this time interval (a weathering rate of ≥0.15 mm/1000 years). Page (1939) and William A. Long (personal communication, 1980) reported polished and striated rock surfaces in the high southern tributary valleys of Icicle Creek, which likely were deglaciated not long after deposition of the inner Rat Creek moraine (about 13,000 years ago), and probably before about 11,500 years ago. Waitt and others (1982) reported scoured and striated quartz-diorite rock surfaces in the Enchantment Lakes area (2300 m; fig. 1) beyond Neoglacial moraines, but they also noted granular disintegration of granitic rocks that produced weathering pits as deep as 10 cm, weathered joints, and pedestals. This degree of weathering may well be related to lithology, for an estimated 20 percent of the local bedrock contains easily weathered mafic minerals.

An average long-term weathering rate as high as 4−5-mm/1000 years is unlikely in the case of continuously exposed granodiorite boulders on the Icicle Creek moraines. Such a rate would mean that moraine crests about 100,000 years old would be nearly devoid of boulders because 1 m or more of their diameter would be lost to weathering. Nevertheless, a rate this high may apply in the subsurface weathering zone, where halos of grus are ≥30 cm thick around granitic boulders of Peshastin age and ≥50 cm thick around subsurface Boundary Butte boulders. A rate of 3 mm/1000 years, which would reduce the diameter of a Leavenworth-age surface boulder by about 12 cm over 20,000 years, is probably an upper limit. Accordingly, we estimate that long-term average weathering rates of granitic rock surfaces in this area that have not been subjected to spalling fall between about 1 and 3 mm/1000 years (fig. 7). High rates might apply to boulders in the weathering profile, especially during times of moist, warm climate. A rate of ≤1 mm/1000 years may have characterized stadial intervals of the late Pleistocene when cooler and drier conditions prevailed. For age calculations we have used an intermediate value of 2 mm/1000 years, which is consistent with our SBF measurements.

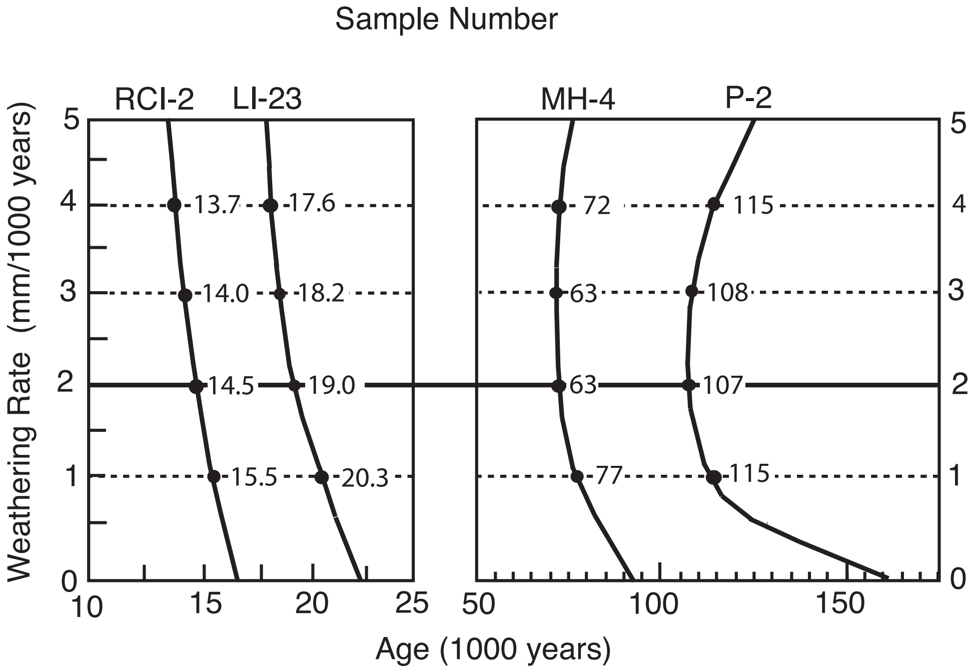


Fig. 7. Influence of weathering rate on ^{36}Cl age of moraine boulders. Inferred range of weathering rates (1–3 mm/1000 years) for Icicle Creek moraines are delimited by dashed lines at these values; intermediate value, (solid line) is used for age calculation. Possible ages for samples from Rat Creek (RC1–2), Leavenworth (L1–23), Mountain Home (MH–4), and Peshastin (P–2) within this range limit are shown where curves intersect the weathering-rate values. Because our samples have a high Cl content thermal neutron activation of ^{35}Cl is the dominant production pathway. Unlike the spallogenic production pathways, ^{36}Cl produced by thermal neutron activation initially increases with depth and then decreases exponentially below a depth of 18 cm (Liu and others, 1994). As a consequence, boulder ages are insensitive to erosion rate between values of 1 and 4 mm/1000 years, especially in the case of older moraines. With higher weathering rates (≥5 mm/1000 years) degradation of weathered rock exposes new rock that extends below the depth of the ^{36}Cl production "pulse," and calculated ages begin to rise.

Icicle Creek moraines and their ^{36}Cl ages

Because the pre-Rat Creek lateral moraines were deposited by Icicle Creek glaciers having the same general flow path during each glaciation and transported sediment from the same sources. The initial lithology and geometry of the successive moraines probably were similar. However, the Rat Creek glacier terminated upvalley from sedimentary rocks of the Swauk Formation that underlie all the older lateral moraines on Boundary Butte Ridge, and its moraines are composed largely of granodioritic and gneissic detritus.

Rat Creek Moraines

Two bouldery moraine loops cross lower Rat Creek (fig. 8) near its junction with Icicle Creek at 550 m altitude. Granitic boulders on their crests reach diameters of 8 m or more (fig. 9B). The outer moraine (Rat Creek I = RCI) has been truncated by Icicle Creek, but the inner moraine (Rat Creek II = RCII) is a continuous bouldery ridge that merges with the RCI left- and right-lateral moraines. The lateral moraines are traceable to about 600 m altitude at the northeast end of the steep bedrock canyon of Rat Creek. Similar moraines lie in comparable geographic positions in the other southern tributary valleys of Icicle Creek (for example, Eightmile Creek; fig. 1). Mazama tephra crops out behind the RCII moraine near the margin of a broad

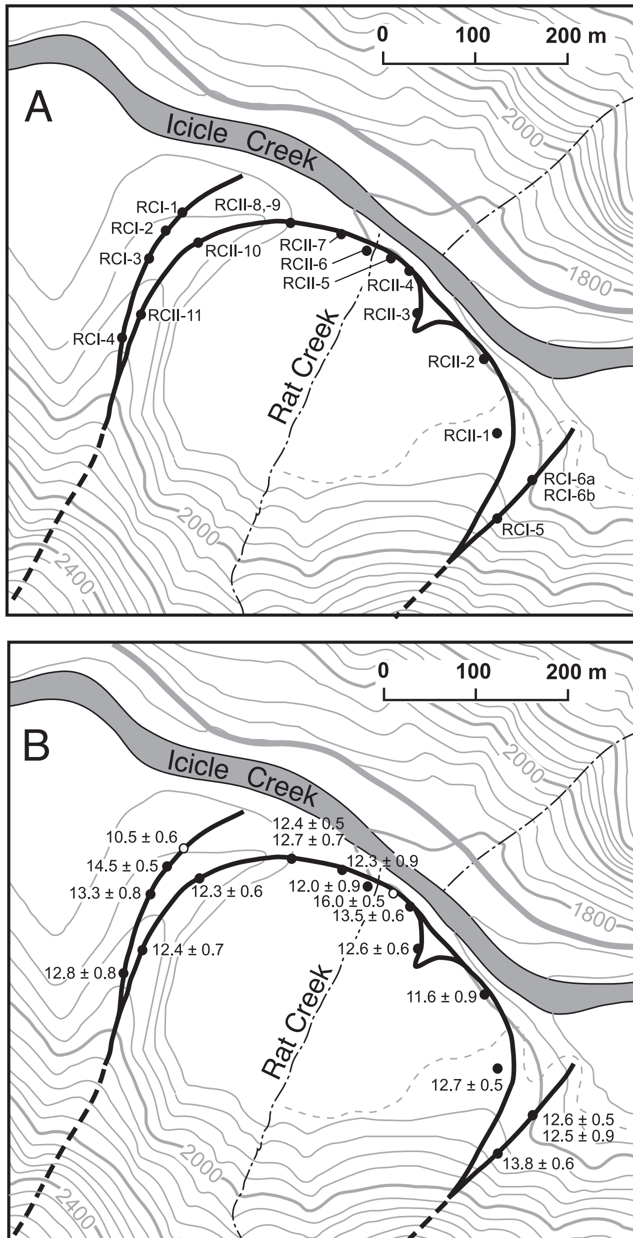


Fig. 8. Maps of Rat Creek moraines (outer moraine = RCI, inner = RCII). (A) Localities where moraine boulders were sampled. (B) ^{36}Cl ages (1000 years) of sampled boulders.

depression filled with postglacial alluvium; its age of about 6800 ^{14}C years was the only minimum limiting age for the moraines prior to the present study.

Seven samples for ^{36}Cl dating were obtained from the RCI moraine and eleven from the RCII moraine (fig. 8; Appendix). Ages ($\pm$ 1σ AMS uncertainty) for the RCI boulders range from 10,500 $\pm$ 600 to 14,500 $\pm$ 500 years and average 13,300 $\pm$ 800

A

B

C

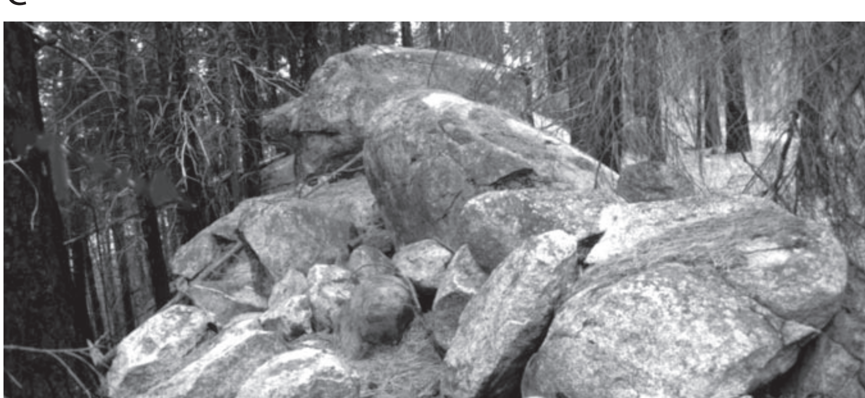


Fig. 9. Boulders on lateral moraine crests showing relative frequency of granitic boulders and relative degree of moraine degradation. (A) Little Ice Age right-lateral moraine of Nisqually Glacier, Mt. Rainier, showing oversteepened proximal slope to right (60−70°) and distal slope to left (at angle of repose, about 34°); (B) Rat Creek II: the boulder is 6 m tall and 14 m long; (C) View along crest of Leavenworth I lateral moraine. View is to northwest from Boundary Butte.

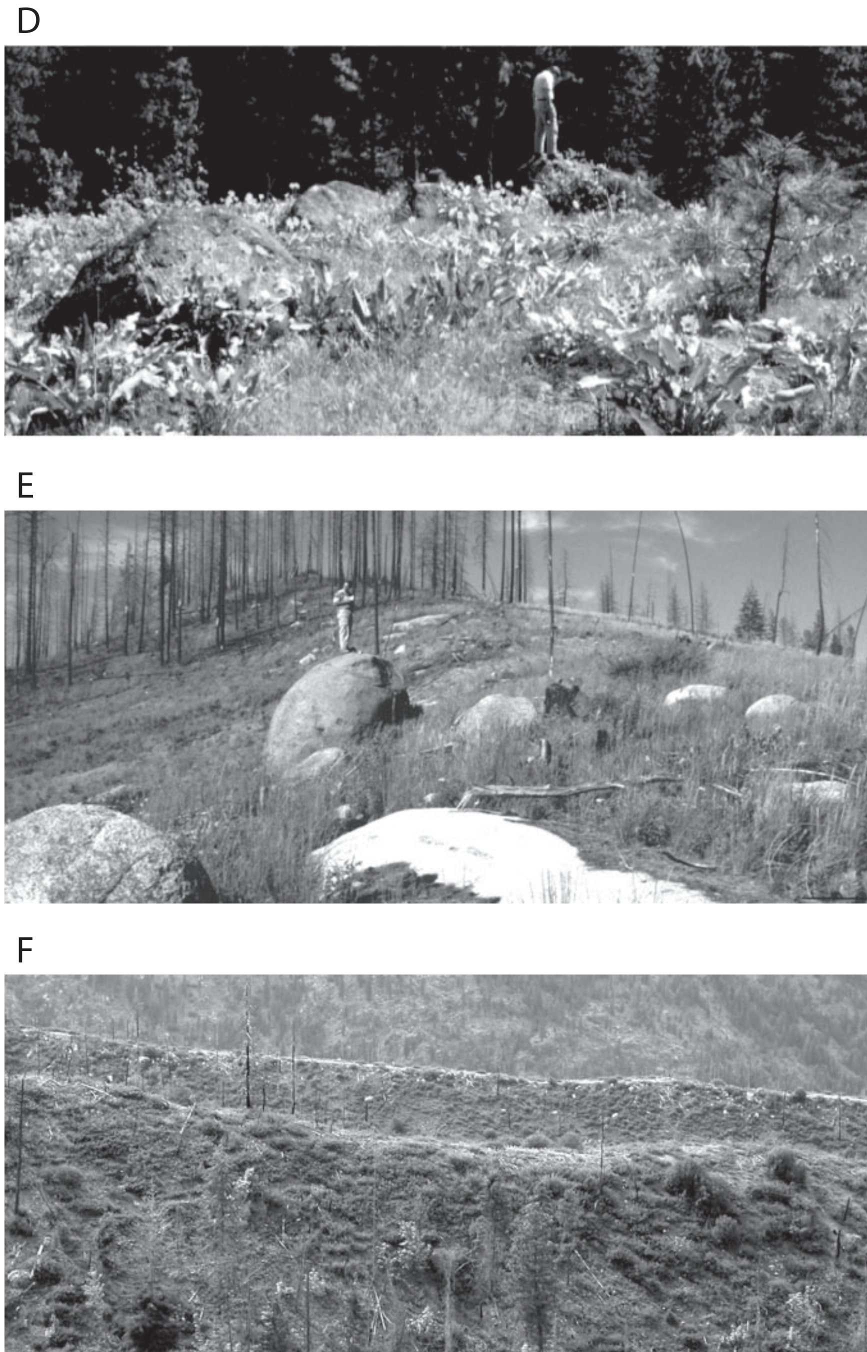


Fig. 9. (D) Boulders on crest of Mountain Home moraine; (E) Scattered boulders (0.5–2 m tall) on Peshastin moraine; (F) Boulders (1–2 m tall) visible on distal flank and crest of Peshastin moraine (more distant, lower) and absent on Boundary Butte moraine (closer, higher). View is to northwest from Boundary Butte.

years, excluding one outlier (RCI-1: 10,500 ± 600 years). Ages for the RCII boulders range from 11,600 ± 900 to 16,000 ± 500 years. Excluding one outlier (16,000 ± 500 yr), their ages average age 12,500 ± 500 years. If the assumed weathering rate (2 mm/1000 years) is reduced to 1 mm/1000 years, the mean age for the moraines increases by 500 to 700 years. Regardless of which weathering rate is adopted, the mean ages of the two moraines differ by less than 1000 years. The tight clustering of ^{36}Cl ages for each of the Rat Creek moraines likely is due to their small size, high boulder frequency, and minimal degradation since deposition. It implies that their average ages approximate the actual ages of moraine stabilization, which is consistent with model results of Putkonen and Swanson (2003).

We obtained three samples (pRC−1, pRC−2, pRC−3) from glacially scoured granitic bedrock and one (pRC−4) from a free-standing boulder on the floor of Icicle Creek valley about 700 m east-southeast of the Rat Creek moraines. The bedrock dates (18,600 ± 1100 and 15,900 ± 600 years) were included in the LII age distribution, for this rock surface was progressively deglaciated following deposition of the LII moraine. The oldest bedrock age (22,400 ± 1000 years) falls within the range of LI boulder ages and points to limited post-LI erosion at this site. The boulder has an age of 13,600 ± 600 years, similar to that of the RCI moraine boulders.

Leavenworth Moraines

Ice limits during the Leavenworth advances are defined by two terminal moraines (LI and LII) in the town of Leavenworth and by corresponding lateral moraines on the west slope of Boundary Butte Ridge (figs. 9C, 10, and 11). The Wenatchee River crosses the bouldery LI terminal moraine about 650 m north of U. S. Highway 2. West of the river the ice limit reaches the crest of a high bedrock hill north of Cascade High School. The glacial limit was not identifiable beyond a lower bedrock hill just west of the high hill; probably it lies beneath a broad, gently sloping alluvial fan built by ephemeral streams that drain the southeast slope of Tumwater Mountain. The LII terminal moraine crosses the Wenatchee River about 200 m north of the highway bridge. In Leavenworth it forms a broad low ridge and a band of scattered large granodiorite boulders that arcs toward the mouth of Tumwater Canyon 2 km to the southwest (fig. 12A).

The LI and LII ice limits rise steeply up the northwest end of Boundary Butte Ridge where they coincide with bouldery lateral moraines (figs. 10, 11, and 12B). Mountain Home Road parallels the LII moraine for about 400 m before turning east to pass across the LI moraine, which it follows southward for 5 km to where the two moraines merge. The LI/LII moraine then continues south for another kilometer. Both moraine crests are capped by concentrations of free-standing and partly buried granitic boulders, many greater than 4 m in diameter and some exceeding 10 m. Road cuts show that the moraine matrix is a poorly compacted diamicton of pebbly sand and silt.

About 2 km south of the north end of Boundary Butte Ridge the LI moraine swings slightly east and is bordered by several small bouldery moraines. Their position and geometry indicate that they predate the main LI ridge. Their similarity in boulder weathering to that of the LI moraine and their low height suggest that the moraines represent minor fluctuations of the LI ice margin on a scale similar to minor fluctuations of alpine glaciers during the Little Ice Age.

Lateral moraines apparently are absent along the lower eastern slope of Icicle Ridge. In contrast to the gentle west slope of Boundary Butte Ridge, the opposite valley wall rises steeply, affording little chance for postglacial preservation of boulder-rich ice-marginal sediments. Furthermore, the far-larger source areas of granitic boulders in the southern tributaries of Icicle Creek compared to those entering from the north means that sediment supply may have been much less to the glacier's left-lateral margin.

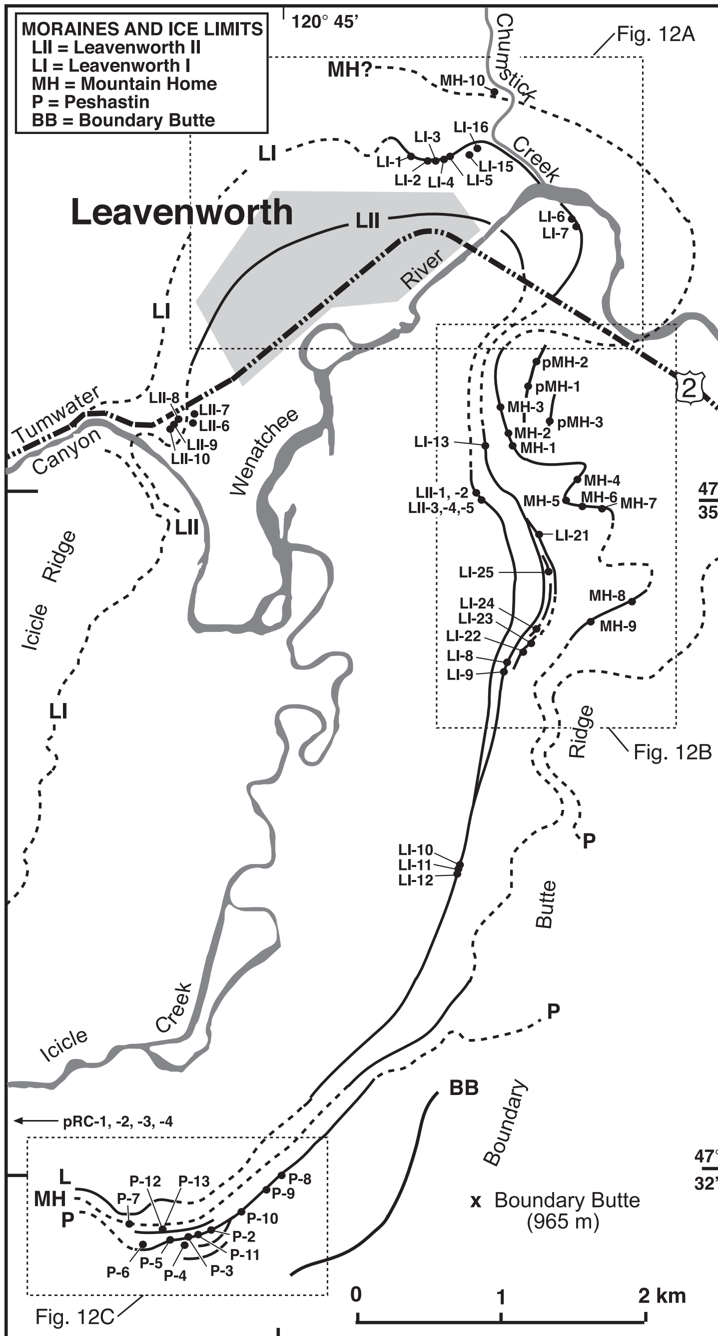


Fig. 10. Map of lower valley of Icicle Creek near its junction with the Wenatchee River showing moraines of Icicle Creek glacier and sites where moraine boulders and bedrock surfaces were sampled.

Exposure ages of four boulders on the LI terminal moraine (LI−6, LI−7, LI−15, LI−16) (figs. 10 and 12A) and seven boulders on the LI lateral moraine (LI−8 through LI–13 and LI–21 through LI–25 (figs. 10 and 12B) range from 11,700 ± 800 to

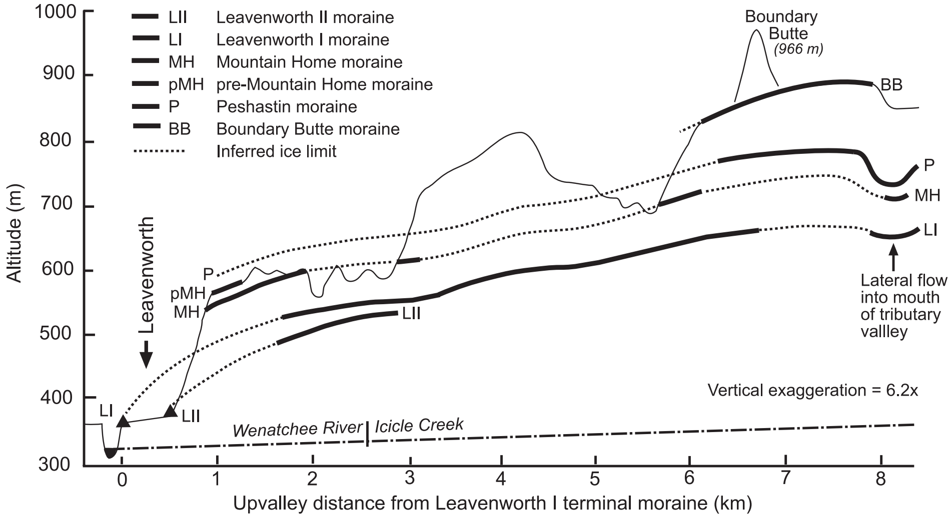


Fig. 11. Transect along Boundary Butte Ridge in lower Icicle Creek-Wenatchee River valley showing positions of right-lateral moraine crests (bold lines; dotted where inferred) of Icicle Creek glacier. Triangles are LI and LII terminal moraines.

45,100 ± 1300 years and average 19,100 ± 3000 years (excluding four outliers: 45,100 ± 1300, 14,200 ± 1300, 13,100 ± 600, and 11,700 ± 600 years; LI−9, LI−17, LI−11, and LI–19, respectively. Five boulders along the crest and lower slope of the steep bedrock hill at the northern edge of Leavenworth (L1-1, LI-2, LI-3, LI-4, and LI–5) have ages ranging from 13,100 ± 700 to 16,800 ± 700 years (figs. 10 and 12A). Excluding the youngest date, which we regard as an outlier, these boulders near the limit of the LI advance have ages more consistent with the LII advance. However, they lie well beyond and higher than the mapped LII ice limit. The anomalously young ages are inferred to result from exhumation and (or) reorientation of boulders along the southern side of the hillcrest when the Wenatchee River, occupying a large meltwater channel along its southern base during the LII advance, undercut and steepened the adjacent slope, thereby resetting the exposure age of the exhumed boulders. We consequently have grouped these samples with the LII samples in calculating the age of the LII ice limit.

Five ages for boulders of the LII lateral moraine (LII−1 through LII–5; figs. 10 and 12A) range from 12,600 ± 800 to 21,200 ± 600 years. Three outliers in this group have ages of 12,600 ± 600, 13,100 ± 700, and 21,200 ± 600 years (LII−3, LII−2, and LII−4, respectively). The youngest two possibly are the result of boulder reorientation, whereas the oldest is likely a reworked LI boulder. When combined with the exhumed boulders (LI−1 through LI–5) north of Leavenworth (fig. 12A) the average age for LII moraine stabilization is 16,100 ± 1100 years.

Five samples were obtained from bedrock and erratic boulders on a rock knob near the mouth of Tumwater Canyon (LII−6 through LII−10; fig. 10). They lie close to the LII limit where it descends toward the canyon mouth. LII−6 and LII−7 were mapped at the limit. Samples LII−8, LII−9, and LII−10 were collected just above the LII limit, and are included in the sample average for the LI advance. One (LII−9) has an LI age (19,000 ± 2400 years) and one is considered a young outlier (11,700 ± 800 years).

The ^{36}Cl age distributions for the LII and LI moraines show greater scatter than those for the Rat Creek moraines. Much of this scatter is best explained by postglacial

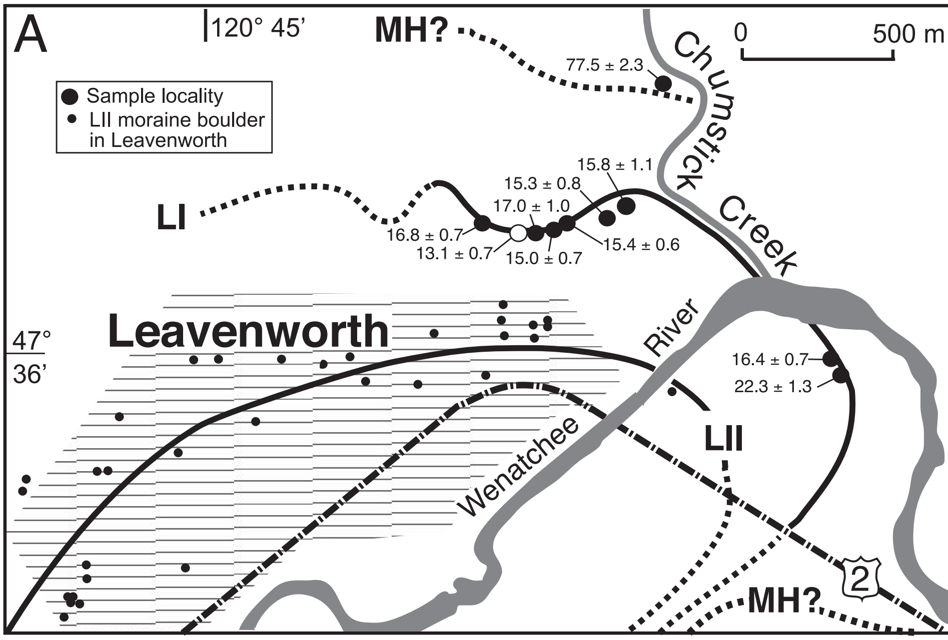


Fig. 12. Maps showing moraines of Icicle Creek glacier and ages of sampled boulders. Ages shown are in thousands of ^{36}Cl years. Open circles identify statistical outliers. (A) Leavenworth I and II terminal moraines in and near Leavenworth, and possible Mountain Home moraine remnant. Large granitic boulders within the city limits of Leavenworth, shown by small dots, form an arc that trends southwest toward the mouth of Tumwater Canyon (fig. 10). Inferred ice limits shown by dashed lines.

degradation, rotation, and exhumation of boulders on the large Leavenworth lateral moraines. Putkonen and Swanson's (2003) model predicts increased age scatter for large moraines like those of the Leavenworth advances, and it predicts that only one of five boulder ages exceed 90 percent of the actual moraine age, with a 95 percent probability. Thus, the stabilization ages of the LII and LI moraines may be closer to the oldest boulder ages, excluding outliers, within their respective sample groups (17,000 ± 1000 and 24,700 ± 1100 years, respectively) than to their calculated composite averages (table 3).

Mountain Home Moraine

The Mountain Home lateral moraine is best preserved along the northern end of Boundary Butte Ridge, about 1 km southeast of Leavenworth (figs. 10 and 12B). It parallels Mountain Home Road for 2 km and rises upvalley from about 535 to 550 m altitude (fig. 11). Through the lower 1 km of this reach, the moraine crest lies along the west side of the main bedrock ridge. Farther south the glacier overtopped the ridge crest to form lobes that terminated at altitudes of about 520 to 575 m in the upper reaches of three small, unnamed valleys (figs. 11 and 12B). A segment of the moraine is preserved on the slope of Boundary Butte Ridge 1.2 km north-northwest of Boundary Butte, but elsewhere the Mountain Home ice limit is only inferred.

A subdued elongate north-northwest-trending ridge about 1 km north of Leavenworth and 500 m beyond the LI moraine may be a remnant of the Mountain Home terminal moraine (figs. 10 and 12A). At the entrance to the canyon of Icicle Creek, the Mountain Home limit probably coincides with a change in slope along the first southern interfluve spur at about 730 m.

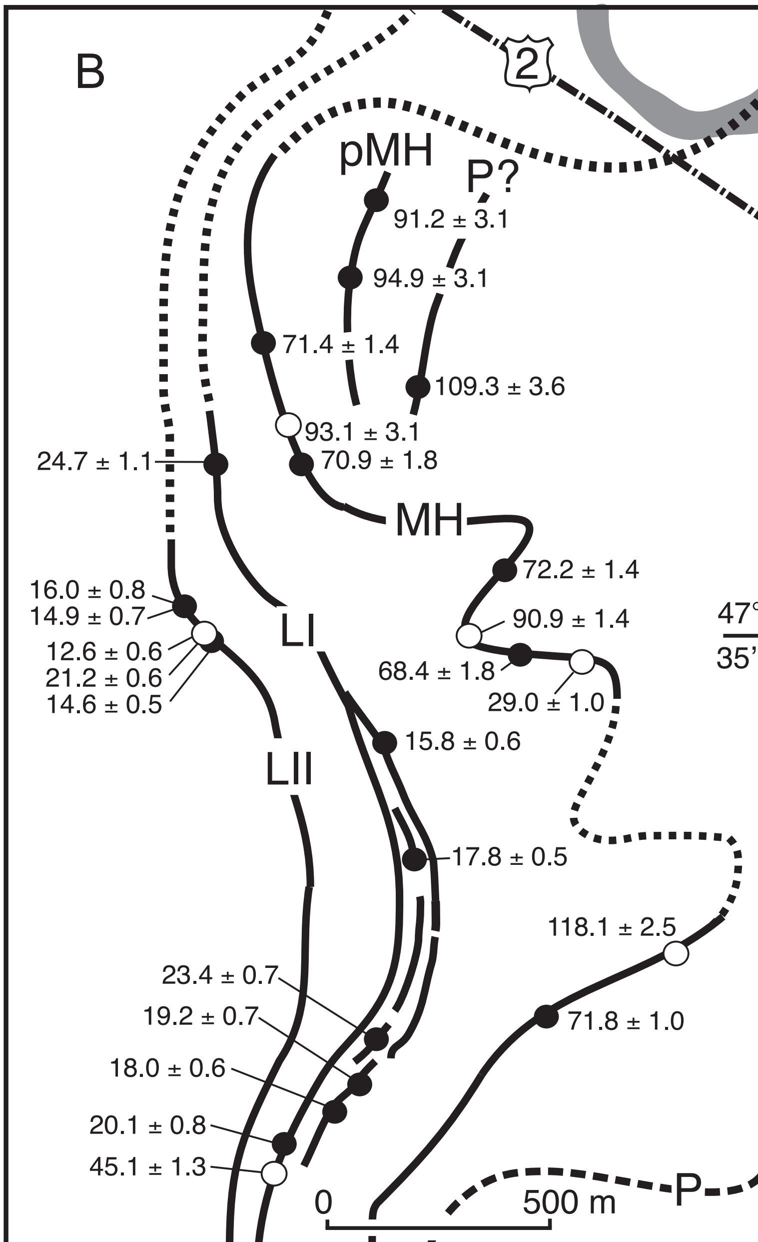


Fig. 12. (B) Lateral moraines along the crest and northwestern slope of Boundary Butte ridge. Inferred ice limits shown by dashed lines.

The crest of the lateral moraine is more subdued and less bouldery than the Leavenworth lateral moraines (fig. 9D). Sandy gravelly drift exposed in a 2−m excavation on the proximal slope near the moraine crest is weathered light-yellowish brown. Most small (<10 cm) granitic stones in the soil profile are weathered to grus. Erratic boulders along the crest have diameters of 1 to 3 m.

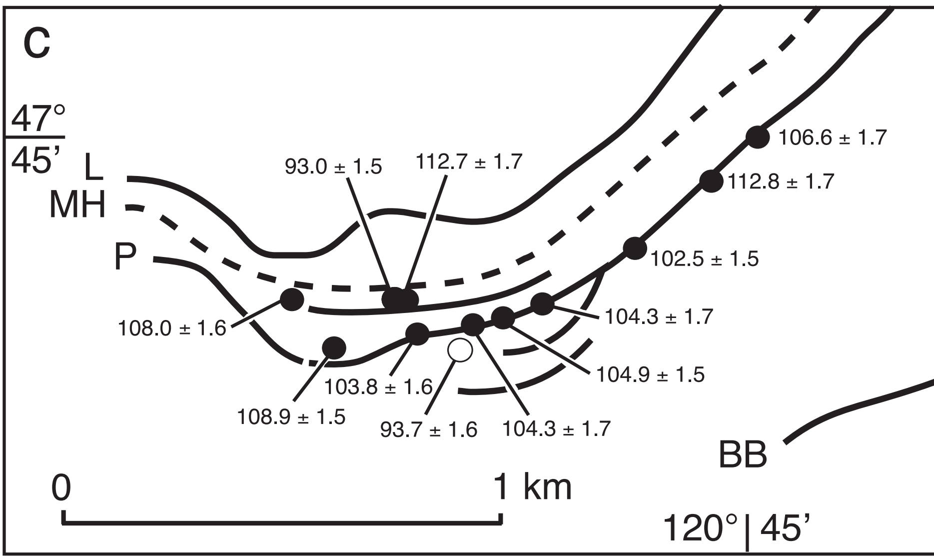


Fig. 12. (C) Sampled Peshastin (P) surface boulders nears the southern end of the main Peshastin moraine and on small moraines near the southwestern end of Boundary Butte Ridge that cross the mouth of a high tributary valley. Dashed line shows inferred Mountain Home ice limit.

Of ten boulders sampled along the crest of the Mountain Home moraine, we regard one as a young outlier (29,000 ± 1000 years; MH-7) and three as old outliers (90,900 ± 1400, 93,100 ± 3100, and 118,100 ± 2500 years); MH-5, MH-2, MH-8, respectively). The remaining five dates range from 68,400 ± 1800 to 72,200 ± 1400 years and average 70,900 ± 1500 years. A boulder near the east end of the moraine remnant north of Leavenworth (fig. 12A) is older (77,500 ± 2300 years; MH-10) than the main cluster of MH boulder ages on Boundary Butte Ridge; its relationship to the MH lateral moraine is uncertain.

Pre-Mountain Home, Post-Peshastin Moraine

Two subdued moraine segments, each about 500 m long, were mapped at the north end of Boundary Butte Ridge (figs. 10 and 12B). The inner is 200 to 300 m east of the crest of the Mountain Home moraine and the outer lies 250 to 400 m beyond it.

Table 3

Mean Age of Boulder Population and Age of Oldest Boulder

Moraine	Population Mean[a]	Oldest Date
Rat Creek II	12,500 ± 500 (n=9)	13,500 ± 600
Rat Creek I	13,300 ± 800 (n=6)	14,500 ± 500
Leavenworth II	16,100 ± 1100 (n=11)	17,000 ± 1000
Leavenworth I	19,100 ± 3000 (n=17)	24,700 ± 1100
Mountain Home	71,900 ± 1500 (n=5)	72,200 ± 1400
pre-Mountain Home	93,100 ± 2600 (n=3)	94,900 ± 3100
Peshastin	105,400 ± 2200 (n=8)	112,800 ± 1700

[a]Excludes outliers

Both are broad-crested and have scattered surface boulders. Neither has previously been described or mapped. Each is traceable to the abrupt steep bedrock slope that descends to the floor of the Wenatchee valley. Their downslope trajectory is obscure; probably each ice limit swings eastward to reach the main valley floor northeast of Boundary Butte Ridge.

Two boulders on the inner moraine have ages of 91,200 ± 3100 and 94,900 ± 3100 years (pMH-2, and pMH-1; average = 93,100 ± 2600 years) and may date a glacier advance between the Mountain Home and Peshastin advances. Two outliers of similar age in the Mountain Home moraine (93,100 ± 3100 and 90,900 ± 1400 years) may be reworked from this drift. The 109,300 ± 3600-year age of a boulder on the outer moraine (pMH-3) falls within the range of Peshastin boulder ages and suggests either that this is a Peshastin lateral moraine segment or that a post-Peshastin advance reworked and deposited a Peshastin-age boulder.

Peshastin Moraines

Page (1939) based his Peshastin stage on weathered drift along the Wenatchee River valley near Peshastin (fig. 1) and inferred that a prominent lateral moraine beyond the Leavenworth moraines on Boundary Butte Ridge was correlative with it. Apparently included in his mapped Peshastin "till" was Mountain Home drift at the northern end of Boundary Butte Ridge and the two small moraine segments east of it. He also mapped Peshastin till in a broad zone on the northeastern slope of Boundary Butte Ridge and north of the Wenatchee River, but we have been unable to confirm this mapping. No unequivocal exposures of Peshastin drift were found in this zone, now mostly covered by orchards. Like Page, we have been unable to identify a Peshastin terminal moraine on the valley floor. Nevertheless, exposures of coarse weathered outwash gravel and the gradient of the Peshastin lateral moraine are consistent with his suggestion that the glacier probably terminated between Peshastin and Dryden (fig. 1).

The prominent Peshastin lateral moraine has a single linear crest traceable for 2 km along the southwestern slope of Boundary Butte Ridge (figs. 9E, 9F, 10, and 11). Weathered granitic boulders up to several meters in diameter are scattered along its flattened crest, the surface of which is modified by an unimproved forest road. The moraine descends northeastward from about 780 to 750 m (15 m/km), and its distal slope rises 13 to 25 m above the adjacent gentle western slope of Boundary Butte Ridge. Farther north, the glacier overtopped the ridge and flowed into the Peshastin Creek drainage (figs. 1, 10, and 11).

At its southwest end, the Peshastin moraine divides into three subdued ridges that cross the lower end of a high, shallow unnamed tributary valley (figs. 10 and 12C). The innermost and intermediate ridges appear to merge with the crest of the main lateral moraine, but the outer ridge emerges from beneath the intermediate ridge.

Granitic boulders exposed in weathering profiles of the inner and intermediate Peshastin moraines where they are crossed by Mountain Home Road are strongly weathered (fig. 5). Boulders of more-resistant lithologies (basalt, quartzite) show only modest weathering, and are not easily broken with a hammer blow.

Scarce surface boulders and a flattened cross profile of the lateral moraine point to postdepositional weathering, degradation, and progressive exhumation of originally buried boulders. To assess degradation, we measured five profiles across the moraine crest and obtained average off-crest slope angles for the proximal and distal flanks (32−34° and 15−30°, respectively; fig. 13). We assume that the cross profiles of all moraines on Boundary Butte Ridge were similar at the time of deposition and approximated those of recent moraines, for example lateral moraines of Nisqually Glacier on Mt. Rainier (fig. 9A), and that subsequent degradation has modified the steepness and width of the crestal region. Extrapolating the present distal and proximal slope angles to their point of intersection above the moraine crest provides

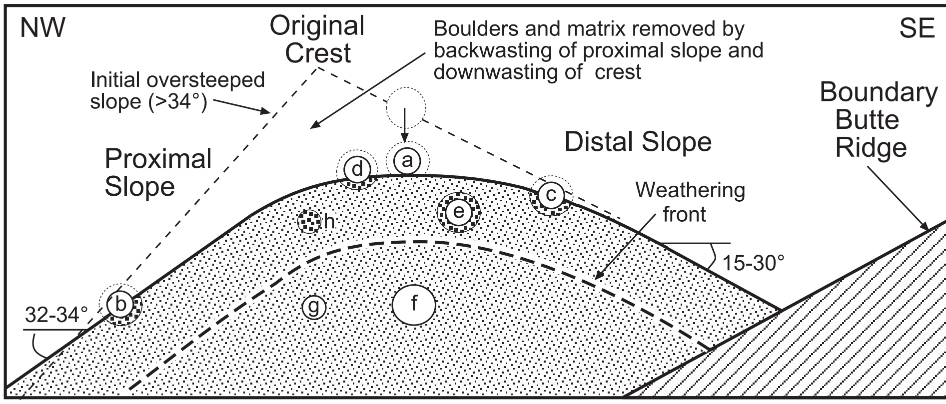


Fig. 13. Diagrammatic profile (not to scale) across Peshastin lateral moraine showing effects of erosion on exposure history of boulders. The initial profile is assumed to have been asymmetric, and similar to many recent bouldery Cascade moraines (fig. 9A). Rapid raveling back of the oversteepened proximal face shifts the crest progressively toward the distal side of the moraine until it achieves the angle of repose (32–34°), leading to exhumation of buried boulders. Erosion of matrix and small clasts then results in lowering and flattening of the crest. Projection of measured distal and proximal slopes suggests that the crest of the Peshastin moraine at time of moraine formation was at least 2.7 m higher than now. Boulders a, b, and c, each originally 2 m in diameter and with their tops continuously exposed since deposition, would be reduced in size due to surface weathering during the past 100,000 years. Boulder a has moved downward as the crest has lowered. Buried portions of boulders b, c, and d have a rind of grus surrounding a solid, less-weathered core. Boulder d, originally buried within the moraine and now exhumed, has a shorter exposure history than boulders b and c. Boulder e has entered the weathering zone as the crest lowered and has a halo of grus surrounding its solid core. Boulders f and g lie beneath the weathering zone and remain relatively unweathered. Boulder h, within the weathering profile and only 1 m in diameter, is weathered to the core. Boulders that remained continuously at the surface, or below the weathering profile, would likely be less weathered than those that spent a lengthy time in the weathering zone during moraine degradation. The effects of fire have not been considered, but likely played a role in diminution of surface boulders, especially during interglacial and interstadial intervals.

an approximate minimum height for the initial crest. For the main Peshastin lateral moraine, this reconstructed crest height lies 2.1 to 3.2 m above the present degraded crest. For the five profiles, the average postdepositional lowering of the crest is at least 2.7 m. Large boulders (≥2 m diameter) buried close to the surface would have been exposed relatively early as the loose matrix was eroded away.

Twelve boulders were sampled on the Peshastin moraines. Three samples were obtained along the main lateral moraine crest (P-8 through P-10) and five from the equivalent main crest in the high tributary valley (P−2, P−3, P−5, P−6, P−11). Four others are young (P−4, P−12) and old (P−9, P−13) outliers. No suitable boulders were found along the small outermost moraine, the crest of which has been bulldozed.

Eight of the twelve resulting exposure ages are tightly grouped, range from 102,500 ± 1500 to 108,900 ± 1700 years, and average 105,400 ± 2200 years. Boulder P-4 (93,700 ± 1600) is a young outlier. Two older dates (112,700 ± 1700 and 112,800 ± 1700 years; P−13 and P−9, respectively) are outliers, for they fall just outside the 1σ range of the primary age cluster. If they were included in the cluster, the mean age would increase from 105,400 ± 2200 to 106,900 ± 3700 years.

The innermost of the Peshastin moraines shown in figure 12C may either be of late Peshastin or pre-Mountain Home age. Although we have mapped this moraine as Peshastin, one date (P−12: 93,000 ± 1500 years) is consistent with a pre-Mountain home age, while the two older dates (P−7 and P13: 108,000 ± 1600 and 112,700 ± 1700 years) fall in the range of Peshastin dates.

Boundary Butte Moraine

The Boundary Butte moraine lies about 85 m below and 500 m northwest of the top of Boundary Butte (965 m) (figs. 9F and 10). Its broad crest stands 70 to 100 m higher than the adjacent Peshastin lateral moraine and descends northeast from about 875 m to 730 m over a distance of 2 km (fig. 11). Adjacent to Boundary Butte the crest is broad, nearly flat, and has very few surface boulders (commonly only 20−30 cm of a boulder is exposed). Granodiorite boulders as much as 2 m in diameter exposed in a shallow road cut near the southwest end of the ridge are completely weathered to grus.

The effects of boulder weathering and moraine degradation have led to the complete disappearance of all but a few small granitic boulders on the crest of the Boundary Butte moraine. Some likely originated as much-larger boulders that were weathered and exhumed as the moraine degraded. Surface-exposure ages for such old moraines underestimate the moraine age. Our trial dating of several small, likely exhumed boulders on the Boundary Butte moraine produced anomalously young ages.

ASSESSMENT OF MORAINE AGES

Of the 76 samples we dated, 10 are younger outliers and 10 are older (fig. 14). Among the Leavenworth outliers twice as many are younger than are older, which may reflect postglacial reorientation of boulders on unstable boulder-rich moraine crests. Among Mountain Home ages, older outliers are more plentiful; all probably were reworked from the pre-Mountain Home and Peshastin drifts.

Degraded Leavenworth and Rat Creek moraine crests often consist of loose piles of large boulders with little or no exposed matrix. These bouldery crests appear relatively stable, but they could become unstable during a large earthquake. The northern Cascade Range is seismically active. Over thousands of years, occasional large earthquakes may have caused moraine boulders to tumble or shift position, thereby resetting the cosmogenic clock as fresh or less-impacted surfaces became exposed to the full effect of cosmic radiation.

Significant lowering and flattening of moraine crests and exhumation of buried boulders mainly affect the Mountain Home, Peshastin, and Boundary Butte moraines. The mean age of Peshastin boulders (105,400 ± 2200 years) probably underestimates the depositional age of the moraine by at least several thousand years. The oldest boulder dates, excluding outliers, are 112,800 ± 1700 and 112,700 ± 1700 years (table 3), which probably are closer to the time of moraine stabilization.

Because of long-term weathering and erosion, any pre-Boundary Butte glacial deposits are likely to lack surface granitic boulders, although small clasts of more-resistant lithologies may still appear at the surface. Using our inferred range of average long-term weathering rate (1 to 3 mm/1000 years), a 1-m boulder would be reduced to grus in 500,000 to 165,000 years, respectively. At a rate of 5 mm/1000 years, complete weathering of the boulder would take 100,000 years. The scarcity of boulders on the Boundary Butte moraine (SBF $<1/100$ m^2) and grusified boulders at least 2 m in diameter in the weathering zone lead us to conclude that the moraine is unlikely to be less than about 165,000 years old nor more than 500,000 years (see below). This moraine is the only mapped drift in the Icicle Creek sequence to be subjected to weathering over at least two interglacial intervals (last and Holocene interglaciations) during which a higher-than-average rate of boulder weathering may have prevailed.

In an early review of this paper, a referee expressed concern regarding the ^{36}Cl production rates used in this study and suggested that ^{10}Be dates be determined for several of the sampled boulders to compare with the ages obtained using the production rates of Swanson and Caffee (2001). Accordingly, ^{10}Be ages were determined for two Peshastin boulders (P−4: 113,300 ± 10,800 years; P−7: 118,800 ± 11,900 years)

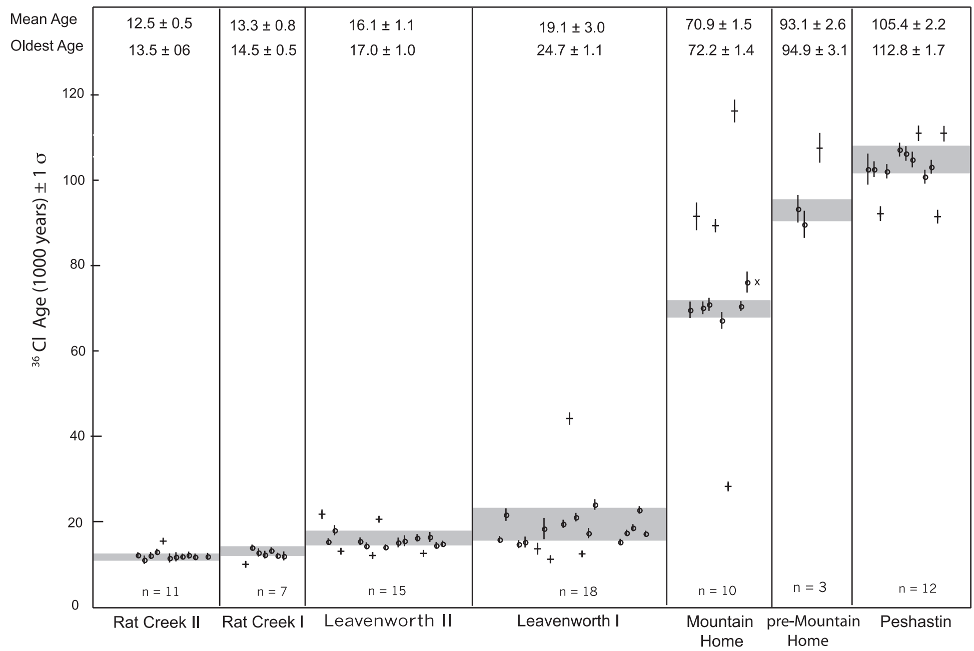


Fig. 14. ^{36}Cl ages $\pm$ 1 σ (AMS uncertainty) of moraine boulders and bedrock sampled in the Icicle Creek drainage. Statistical outliers are shown as crosses and were defined according to established protocol discussed in the text. The length of the vertical line through each data point corresponds to the magnitude of the AMS uncertainty. Mean moraine age $\pm$ 1 σ of each sample population is shown at the top of the chart and as a shaded area on the plot. Statistical outliers were excluded in calculating mean values. Also shown is oldest date in each population. The MH date with an 'x' beside it is MH-10, the significance of which is not clear. See text for discussion.

and for one Mountain Home boulder (M−6: 65,600 $\pm$ 6200 years). These calculated ^{10}Be ages are consistent, within 1-sigma error ranges, with the corresponding mean and oldest ^{36}Cl ages reported in table 3 and the Appendix.

COMPARISON OF CASCADE GLACIER CHRONOLOGY WITH MARINE δ^{18}O, ICE-SHEET, AND DEGLACIAL VARIATIONS, AND WITH INSOLATION TRENDS

Based on our ^{36}Cl chronology, Late Pleistocene fluctuations of the Icicle Creek glacier can be compared with global ice-volume changes based on marine oxygen isotopes, with advances of the nearby Cordilleran Ice Sheet, with the late-glacial Younger Dryas event, and with insolation trends that may have controlled both climate and the timing of mountain glacier expansions in the Pacific Northwest and the European Alps.

Correlation with Marine Oxygen-Isotope Stages

At the outset of our work, we anticipated that dates for Leavenworth moraines would fall within marine isotope stage (MIS) 2; our chronology bears this out (fig. 15). The primary cluster of Mountain Home ages falls in MIS 4. Although we had surmised that Peshastin drift likely was deposited during MIS 6, the tightly clustered ^{36}Cl dates indicate an MIS 5d age, about 20,000 years younger than the end of MIS 6. The dates from the pre-Mountain Home moraine, and three (reworked?) outliers in the Mountain Home drift (90,900, 93,000, and 93,100 years), suggest an advance during MIS 5b.

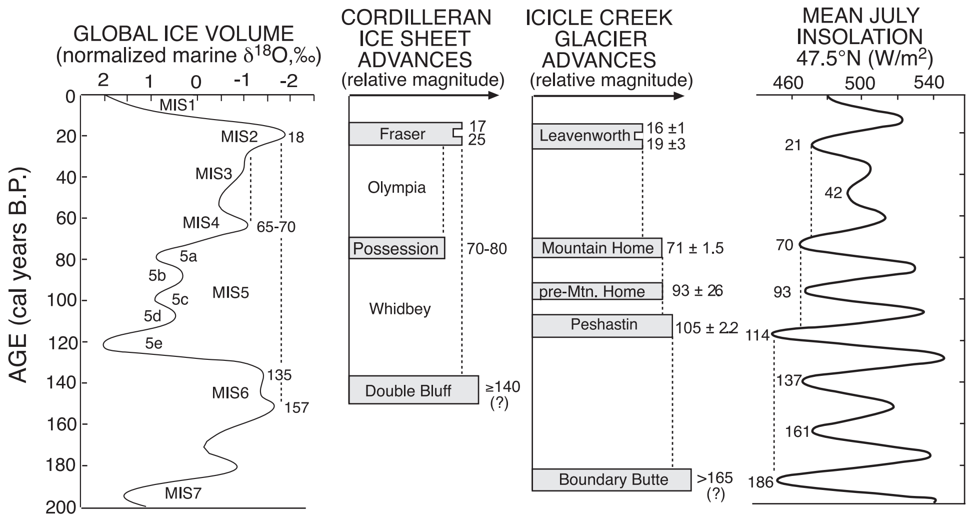


Fig. 15. Chronology and relative extent of Icicle Creek glacier advances compared with those of the Puget Lobe of the Cordilleran Ice Sheet. These records are compared with the curve of global ice volume, based on the standard marine oxygen-isotope record (Martinson and others, 1987), and with a curve of summer (July) insolation for the latitude of the Icicle Creek glacier (47.5° N; data from M. F. Loutre, personal communication, 2001). Whereas the relative magnitude of the ice sheet advances approximately match those of the last three glacial marine-isotope stages (MIS 2, 4, and 6), the relative magnitudes of the Icicle Creek glacier advances match those of prominent insolation minima (21,000, 70,000, 92,000, and 114,000 years ago) of the last 160,000 years.

Comparison with Cordilleran Ice Sheet Chronology

West of the Cascades, the chronology of all but the youngest advances of the Puget Lobe of the Cordilleran Ice Sheet is not well constrained. During the last (Fraser) glaciation, mountain glaciers coalesced and entered the Fraser Lowland of British Columbia about 21,000 ^{14}C years (25,000 cal years) ago (Coquitlam advance; Hicock and Armstrong, 1981; Booth and others, 2004). The Puget Lobe subsequently reached its maximum extent about 14,000 ^{14}C years ago (16,900 cal yr ago) (Vashon advance; Armstrong and others, 1965; Porter and Swanson, 1998) (fig. 15). The less-extensive Possession advance likely culminated between 80,000 and 70,000 yr ago (Porter, 2004; K. Troost, personal communication, 2006) during MIS 4. The Double Bluff advance pre-dated last-interglacial deposits of the Whidbey Formation and likely dates to MIS 6. Morainal deposits lying in a belt outside the Fraser drift limit in the southern lowland may correlate with Double Bluff drift (Porter, 2004).

In figure 15, the timing and relative down-glacier extent of the Puget Lobe and Icicle Creek glacier advances are compared with the marine oxygen-isotope stages. The Coquitlam and Vashon maxima of the Fraser glaciation are close in age to the Leavenworth I and II advances, respectively. The Possession advance may correlate with the Mountain Home advance. Although the Double Bluff advance may have been the greatest of the Puget Lobe, its likely MIS 6 age contrasts with the MIS 5d age of the Peshastin, suggesting that these major ice sheet and alpine events were asynchronous. Furthermore, the relative down-glacier extent of ice during successive advances was dissimilar (fig. 15). Whereas the Possession glacier apparently was less extensive than the Double Bluff and Fraser glaciers, the vertical separation of Icicle Creek lateral moraines suggests a diminishing ice volume and downvalley extent of successively younger alpine glaciers.

Correlation of Rat Creek Advances with European Younger Dryas

Kaufman and others (2004) have discussed whether the closely nested Rat Creek moraines were built during the late-glacial Younger Dryas interval (12,900−11,600 cal years B.P.). The mean ^{36}Cl age for the Rat Creek I moraine (13,300 ± 800 years) predates the Younger Dryas interval, although the 1-σ error range overlaps it. However, the oldest date of a Rat Creek I boulder is 14,500 ± 500 years, which predates the Younger Dryas. The mean Rat Creek II age (12,500 ± 500 years) falls within the range of Younger Dryas time. These ages are consistent with another dated sequence in the Cascades: the outer of two (Hyak-age) moraines at Snoqualmie Pass, south of Icicle Creek, has a mean ^{36}Cl age of 14,100 ± 500 years (pre-Younger Dryas), while the average age of the inner moraine (12,700 ± 800 years) lies within the Younger Dryas interval.

Comparison With Insolation Trends at 47.5° N Latitude

If the Icicle Creek record is compared with the long-term trends of July insolation at this latitude, a close relationship is seen between the timing of alpine-glacier maxima and insolation minima (fig. 15). Times of minimum July (summer) insolation (21,000−22,000, 70,000, 92,000−93,000, and 114,000−115,000 years ago; data from M. F. Loutre, personal communication, 2001) approximately match the mean and *oldest* ages of the Icicle Creek glacier maxima (19,100 ± 3000, *24,700 ± 1100*; 70,900 ± 1500, *72,200 ± 1400*; 93,100 ± 2600, *94,900 ± 3100*; and 105,400 ±2200, *112,800 ± 1700* years ago; table 3). Less-prominent insolation minima (for example, 43,000 years ago) are not represented by moraines, suggesting that glacier advances at such times may have been more restricted in extent than the Rat Creek advance. The relative extent of the major glacier advances, decreasing from Peshastin to Leavenworth, parallels the relative amplitude of insolation minima from 114,000 to 21,000 years ago (compare dashed lines in two right columns of fig. 15).

AGES OF THE BOUNDARY BUTTE AND POSSIBLE OLDER ADVANCES

Although the Boundary Butte advance has not been dated, if the relationship between insolation and glacier advances holds true prior to Peshastin time, the Boundary Butte may correlate with one of the three next-older significant insolation minima (186,000, 207,000, or 230,000 years) (fig. 16). The next-older minimum (608,000 years ago) of equal amplitude is an unlikely candidate because weathering over this long time interval would have destroyed boulders as large as 3.6 to 6 m in diameter (3 and 5 mm/1000 yr, respectively) (fig. 16) and resulted in much greater flattening of the Boundary Butte moraine crest than is observed. As many as 13 interglaciations since 608,000 years ago were comparable in intensity to MIS 1, and these were times when weathering rates likely were higher than average.

Seventeen smaller-amplitude insolation minima occurred between 608,000 and 230,000 years ago during which glaciers probably expanded into the Icicle Creek valley. Because most of these glaciers likely were confined to the middle and upper reaches of the valley, morainal evidence of their existence has been obliterated. However, each would have contributed to the long-term morphologic shaping of the glacial valley.

INSOLATION MINIMA AND ALPINE GLACIER MAXIMA

A correspondence between solar radiation minima and glacial maxima in the European Alps was proposed early in the last century (Imbrie and Imbrie, 1979, their figs. 24 and 26). Using astronomical curves calculated by Serbian mathematician Milutin Milankovitch (1920, 1941), Köppen and Wegener (1924) deduced that two phases of the penultimate (Riss) glaciation (PGl 1, PGl 2) and three phases of the last

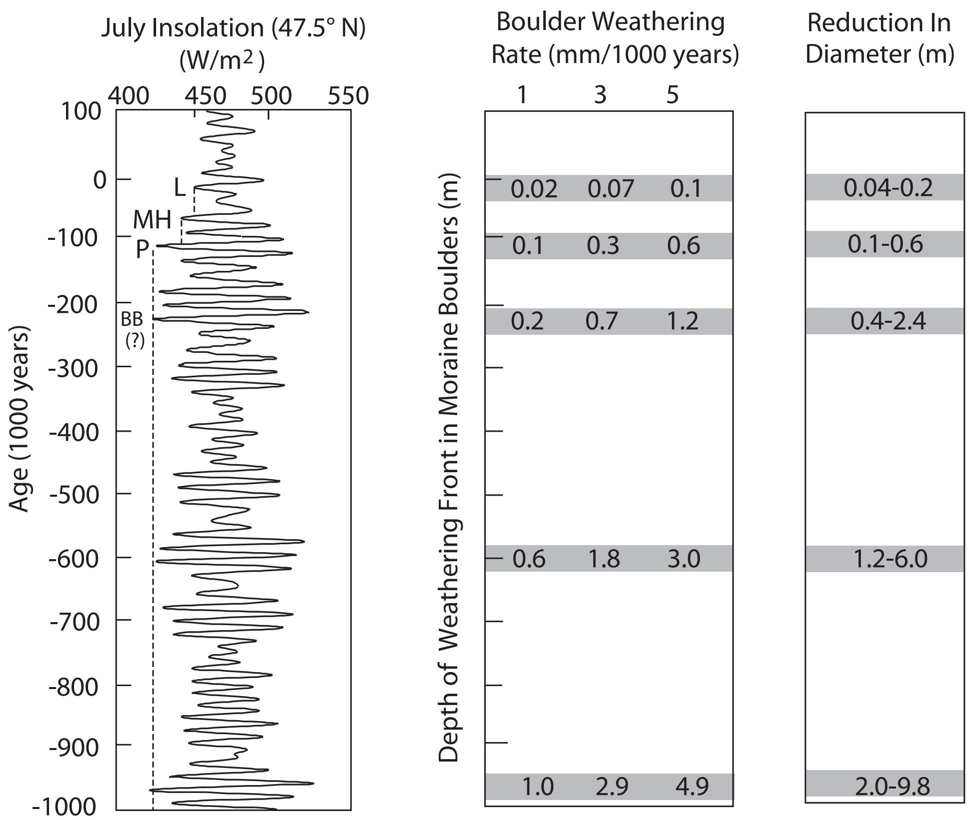
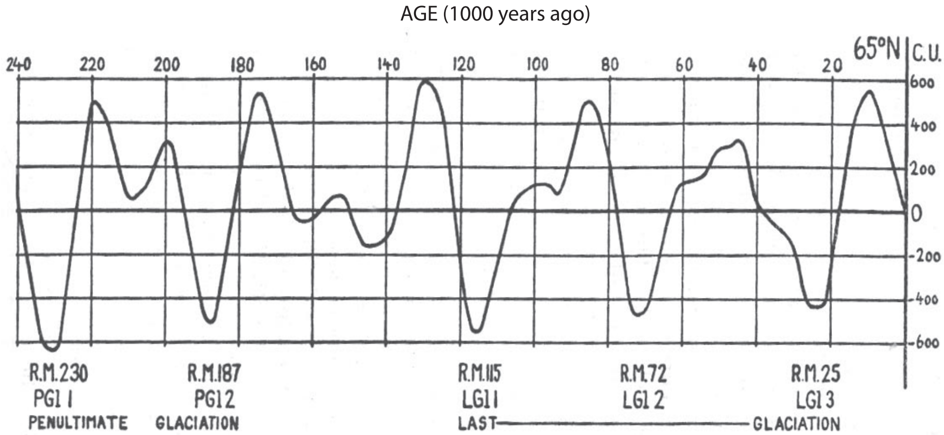


Fig. 16. Trends of July insolation during the past million years at Icicle Creek (47.5° N latitude) (data from M.-F. Loutre, personal communication, 2001). The last three prominent minima are correlated with the last three major late Pleistocene Cascade glacier advances (L, MH, and P). The Boundary Butte advance, if consistent with this pattern, may correlate with one of three strong minima at 187,000, 201,000, and 231,000 years ago. The next older minima of equal amplitude date to 608,000 and 968,000 years ago. Also shown are values for boulder weathering at these times when weathering rates of 1, 3, and 5 mm/1000 years are assumed (see text for discussion).

(Würm) glaciation (LGl 1, LGl 2, LGl 3) identified by Penck and Brückner (1909) were correlative with summer insolation minima for 65°N latitude at 230,000 (PGl 1), 187,000 (PGl 2), 115,000 (LGl 1), 72,000 (LGl 2), and 25,000 (LGl 3) years ago, respectively (updated version shown in Zeuner, 1958, his fig. 48) (fig. 17). They had no way of testing this inferred chronology, for it was proposed decades before the development of modern dating techniques that span the last several hundred thousand years.

The Icicle Creek glacial record supports this proposed Alpine chronology, for inferred ages of the youngest three Alpine minima closely match the ^{36}Cl mean and maximum ages for major advances of the Icicle Creek glacier (fig. 17), and thus are consistent with the Milankovitch astronomical chronology. Major glacier maxima in both mountain ranges, each lying at 47 to 48°N latitude, correlate well with calculated insolation minima at 25,000, 72,000, and 115,000 years ago. A minor insolation minimum at 65° N that dates about 92,000 years (fig. 17) is a prominent minimum at 47.5° latitude in the Cascades (fig. 15), where it appears to correlate with the pre-Mountain Home moraine (93,000 years).



Boundary Butte	Peshastin	Mountain Home	Leavenworth
(?)	105	71	19
	109	*72*	*25*

Fig. 17. Proposed correlation of Alpine glaciations (PGl 1, PGl 2, LGl I, LGl 2, and LGl 3) with summer insolation minima at 65° N latitude (in canonical units, C.U.), based on Milankovitch's (1920, 1941) calculations (from Zeuner, 1958, his fig. 48), compared with average ages (1000 years) and maximum ages (italics) of ^{36}Cl-dated moraines in the Cascade Range.

TIMING OF THE GREATEST LATE PLEISTOCENE GLACIER ADVANCE

The MIS 5d age of the Peshastin drift was not anticipated. Granitic boulders on the degraded Peshastin moraine are strongly weathered, suggesting that the moraine might predate the last interglaciation (MIS 5e). However, based on our ^{36}Cl chronology, the greatest Late Pleistocene alpine-glacier advance occurred at the onset of the last global glaciation (MIS 5d). This is consistent with Gillespie and Molnar's (1995) conclusion that the greatest Late Pleistocene alpine glacier advance predated the maximum expansion of the continental ice sheets during MIS 2.

Although at first glance, the MIS 5d age for the Peshastin moraine may seem anomalous, suggestive evidence elsewhere in the Northern Hemisphere also implies glacier expansion during MIS 5d. For example, Phillips and others (1990) reported ^{36}Cl ages of 79,000 to 119,000 years for eight granite boulders on the Mono Basin moraines of Bloody Canyon in the Sierra Nevada. When two outliers are excluded, the mean age is 103,000 years. They state that if the effects of mineral weathering and spalling are considered, the most likely age estimate for the moraines increases to 110,000 to 120,000 years. It nevertheless must be mentioned that this age assignment is controversial because of disagreement over stratigraphic relationships and uncertainty regarding cosmogenic-isotope production rates (A. R. Gillespie, *in* Kaufman and others, 2004).

Two groups of moraines (C and D) built by the Bull Lake glacier on the east side of the Wind River Range, Wyoming have yielded ^{36}Cl ages of 95,000 to 125,000 and 95,000 to 115,000 years, respectively (Chadwick and others, 1997; Phillips and others, 1997). The dates from each moraine have considerable scatter, which may partly be related to the small size of sampled boulders (1.5– <1 m), granular disintegration, and spalling. Analytical uncertainties range from 3500 to 36,000 years and average ±

15 percent. The youngest group (D) is 110,000 years old based on a combined ^{36}Cl and ^{10}Be age model and is provisionally correlated with MIS 5d.

A major episode of glaciation recorded in sediments of Lake Baikal in eastern Siberia occurred between 117,000 and 105,000 years ago (Karabanov and others, 1998). Glacial drift (Kormuzhikhantskaya moraine) within marine sediments in northwestern Siberia (62.5° N) is about 117,000 to 100,000 years old based on luminescence dating (Karabanov and others, 1998). A short but significant episode of glacier growth on Svalbard ('Glaciation C' at Kapp Ekholm) and in the Barents Sea occurred during MIS 5d (Mangerud and others, 1998).

A cold episode in North Atlantic marine cores represented by peaks in the percentage of polar foraminifera and ice-rafted detritus dates to about 107,000 to 103,000 years ago (McManus and others, 1994). Marine cores from the Pacific Ocean show a substantial decrease in sea-surface temperature between the MIS 5e maximum and the MIS 5d minimum. A rapid increase in global ice volume over this interval equaled half that of full-glacial (MIS 2) time (Lea, 2004, fig. 6B; Shackleton, 2000, fig. 4A).

The significant increase in global ice volume and local expansion of mountain glaciers occurred close to the time of the major insolation minimum that culminated 114,000 to 115,000 years ago. The resulting reduction in summer temperature and glacier ablation would have led to positive glacier mass balance and lowered ELAs, causing glaciers to expand.

The Pacific Northwest's strongly maritime climate is a significant factor in regional glacier mass balance, for Cascade glaciers are nourished by winter storms coming off the Pacific. Model simulations and pollen data suggest that during the last glacial maximum (MIS 2) winter (January) storm tracks shifted well south of their present positions, creating colder and drier conditions in the Pacific Northwest (Kutzbach and others, 1993; Thompson and others, 1993). Subsequent deglacial shrinkage of the Cordilleran Ice Sheet in western Canada allowed storm tracks to shift northward, bringing enhanced snowfall to southwestern British Columbia and to northwestern Washington as the Puget Lobe expanded to its full-glacial maximum about 17,000 years ago..

Geologic evidence from northwestern Europe, Svalbard, and the Barents Sea points to expansion of northern ice sheets in these areas during MIS 5d (Mangerud, 1991; Mangerud and others, 1998), but less than during MIS 2 and 4. In the Pacific Northwest, evidence of an MIS 5d ice-sheet advance has not yet been documented, but if an incipient ice sheet also began to form in southwestern Canada at that time, westerly Pacific storms may have passed mainly south of it across the Washington Cascades. As a result, winter snowfall might not have been reduced during the time that Peshastin-age glaciers reached their greatest size under summer-cool, winter-moist conditions.

ACKNOWLEDGMENTS

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Appendix

^{36}Cl ages and geographic, outcrop, and chemical data for Icicle Creek samples

Sample Number (Field)	Sample Number (Map)	Latitude °N	Eff. Latitude °N[a]	Longitude °W	Altitude m	Density[b] gm/cm^3	Thickness cm	Shielding All effects	^{36}Cl Age ± 1σ[c]	^{36}Cl/Cl	Na_2O wt. %	MgO wt. %	Al_2O_3 wt. %	SiO_2 wt. %	P_2O_5 wt. %	K_2O wt. %	CaO wt. %	TiO_2 wt. %	MnO wt. %	Fe_2O_3 wt. %	Cl ppm	B ppm	Sm ppm	Gd ppm	U ppm	Th ppm
RAT 2-1	RCII-1	47.55	47.9	120.76	555	2.7	1.0	0.92	12.7 ± 0.5	61	4.42	4.37	15.60	58.90	0.16	1.65	5.05	0.77	0.10	6.03	722	25.00	3.00	3.00	0.90	2.30
RAT 2-2	RCII-2	47.55	47.9	120.76	555	2.7	1.0	0.92	11.6 ± 0.9	59	3.76	4.09	15.60	61.00	0.08	1.58	5.43	0.62	0.08	5.41	917	27.00	0.50	0.50	2.20	1.40
RAT 2-3	RCII-3	47.55	47.9	120.76	555	2.7	1.0	0.92	12.6 ± 0.6	76	3.89	4.78	15.20	59.50	0.17	2.32	4.23	0.79	0.09	6.30	307	37.00	0.25	0.25	0.90	2.30
RAT 2-4	RCII-4	47.55	47.9	120.76	555	2.7	1.0	0.92	13.5 ± 0.6	58	5.64	3.68	15.50	55.30	0.07	1.27	5.13	0.58	0.08	5.11	754	56.00	3.00	3.00	1.30	2.90
RAT 2-5	RCII-5	47.55	47.9	120.76	555	2.7	1.0	0.92	**16.0 ± 0.5**	85	5.80	4.10	15.20	54.80	0.11	1.58	4.97	0.58	0.08	5.37	528	27.00	4.00	4.00	1.50	2.10
RAT 2-6	RCII-6	47.55	47.9	120.76	555	2.7	1.0	0.92	12.0 ± 0.9	57	3.61	5.31	15.10	59.60	0.07	1.23	5.31	0.80	0.10	6.37	636	35.00	2.00	2.00	1.50	1.60
RAT 2-7	RCII-7	47.55	47.9	120.76	555	2.7	2.0	0.92	12.3 ± 0.9	66	5.74	4.08	15.60	56.30	0.11	1.08	5.34	0.64	0.08	5.43	577	35.00	2.00	2.00	1.80	2.10
RAT 2-8A	RCII-8	47.55	47.9	120.76	555	2.7	2.0	0.92	12.4 ± 0.5	64	5.75	4.46	14.20	54.50	0.10	1.15	5.04	0.60	0.09	5.55	748	30.00	4.50	4.50	1.50	3.20
RAT 2-8B	RCII-9	47.55	47.9	120.76	555	2.7	2.0	0.92	12.7 ± 0.7	59	5.30	4.70	14.60	56.90	0.09	1.14	5.16	0.54	0.09	5.75	1067	30.00	3.00	3.00	1.00	2.10
RAT 2-9	RCII-10	47.55	47.9	120.76	562	2.7	2.0	0.92	12.3 ± 0.6	55	4.34	5.35	15.20	57.30	0.17	1.60	5.16	0.73	0.10	6.40	868	34.00	4.00	4.00	0.70	1.80
RAT 2-11	RCII-12	47.55	47.9	120.76	562	2.7	2.0	0.92	12.4 ± 0.7	61	4.83	4.27	15.40	59.20	0.16	1.43	5.21	0.57	0.10	5.27	672	23.00	6.00	6.00	0.90	1.90
RAT 1-1	RCI-1	47.55	47.4	120.76	573	2.7	1.0	0.92	**10.5 ± 0.6**	54	5.61	3.95	15.20	57.60	0.04	1.18	4.95	0.56	0.08	4.99	674	24.50	3.50	3.50	1.00	3.00
RAT 1-2	RCI-2	47.55	47.9	120.76	573	2.7	1.0	0.92	14.5 ± 0.5	87	4.97	3.61	15.00	58.10	0.09	1.29	5.06	0.60	0.10	5.50	330	24.50	3.50	3.50	1.40	3.00
RAT 1-3	RCI-3	47.55	47.9	120.76	573	2.7	1.0	0.92	13.3 ± 0.8	67	5.28	3.44	15.60	58.20	0.07	1.44	4.85	0.58	0.08	5.50	626	34.00	3.00	3.00	1.50	3.20
RAT 1-4	RCI-4	47.55	47.9	120.76	588	2.7	1.0	0.92	12.8 ± 0.8	64	3.72	4.68	15.00	60.00	0.11	1.23	5.24	0.66	0.09	5.69	592	32.00	4.00	4.00	1.30	2.90
RAT 1-5	RCI-5	47.55	47.9	120.76	558	2.7	1.0	0.92	13.8 ± 0.6	66	3.95	4.59	17.40	57.70	0.18	3.95	6.45	0.67	0.11	17.40	538	35.00	4.50	4.50	0.80	2.40
RAT 1-6A	RCI-6	47.55	47.9	120.76	549	2.7	1.0	0.92	12.6 ± 0.5	74	4.04	4.04	17.40	55.50	0.08	0.89	6.33	0.66	0.09	5.72	401	19.00	2.00	2.00	0.90	2.80
RAT 1-6B	RCI-7	47.55	47.9	120.76	549	2.7	1.0	0.92	12.5 ± 0.9	66	3.95	4.78	17.30	57.60	0.20	0.95	6.53	0.70	0.11	6.43	462	35.00	2.00	2.00	1.10	4.40
ICE 1-1(BR)	pRC-1	47.54	48.3	120.74	562	2.7	2.0	0.87	**22.4 ± 1.0**	107	4.74	7.17	14.70	54.30	0.06	0.65	6.45	0.69	0.13	7.93	574	21.00	3.00	3.00	0.25	1.30
ICE 1-2 (BR)	pRC-2	47.54	48.3	120.74	562	2.7	1.0	0.87	15.9 ± 0.6	83	4.67	6.86	14.90	51.60	0.04	0.39	6.82	0.67	0.13	7.67	279	20.50	3.50	3.50	0.25	0.25
ICE 1-3 (BR)	pRC-3	47.54	48.3	120.74	562	2.7	1.0	0.87	18.6 ± 1.1	128	4.24	7.17	14.70	54.30	0.06	0.07	6.45	0.69	0.15	8.93	157	8.00	0.25	0.25	1.10	2.80
ICE 1-4 (ER)	pRC-4	47.54	48.3	120.74	562	2.7	1.0	0.87	**13.6 ± 0.6**	62	4.96	5.78	14.60	54.10	0.15	0.90	5.72	0.79	0.12	7.86	497	27.00	3.00	3.00	1.20	1.00
LEAV 2-1	LII-1	47.58	49.3	120.65	494	2.7	1.0	0.94	16 ± 0.8	82	4.68	4.17	16.90	56.60	0.19	0.92	6.05	0.76	0.10	6.22	385	15.00	3.50	3.50	0.25	0.25
LEAV 2-2	LII-2	47.58	49.3	120.65	494	2.7	1.0	0.94	14.9 ± 0.7	68	4.79	4.10	16.90	58.80	0.29	1.26	5.24	0.68	0.08	6.04	673	30.00	4.00	4.00	1.50	2.00
LEAV 2-3	LII-3	47.58	49.3	120.65	488	2.7	1.0	0.94	**12.6 ± 0.6**	68	5.57	3.16	16.60	56.50	0.19	1.80	5.23	0.62	0.08	5.81	700	30.00	4.00	4.00	2.70	5.90
LEAV 2-4	LII-4	47.58	49.3	120.65	488	2.7	1.0	0.94	**21.2 ± 0.6**	141	4.77	3.83	15.10	60.60	0.15	1.74	4.45	0.63	0.07	5.22	228	31.00	4.00	4.00	2.70	5.90
LEAV 2-5	LII-5	47.58	49.3	120.65	488	2.7	1.0	0.94	14.6 ± 0.5	91	4.77	2.88	15.60	61.00	0.11	1.89	4.45	0.55	0.07	4.81	241	31.00	4.00	4.00	1.50	2.00
LTC-4 (BR)	LII-6	47.59	49.0	120.68	415	2.7	1.0	0.92	15.7 ± 1.0	75	3.40	5.80	15.40	58.20	0.19	1.45	5.88	0.70	0.10	6.66	436	40.00	3.00	3.00	1.70	3.80
LTC-5 (BR)	LII-7	47.59	49.0	120.68	421	2.7	1.0	0.92	16.1 ± 1.1	81	2.92	6.57	13.30	58.00	0.07	1.27	5.62	0.75	0.12	7.45	313	29.00	0.50	0.50	0.25	0.25
LEAV 1-1	LI-1	47.60	48.9	120.66	402	2.7	1.0	0.97	16.8 ± 0.7	108	4.58	2.42	14.90	64.10	0.07	1.81	4.03	0.45	0.06	4.03	163	30.00	5.00	5.00	0.25	2.70
LEAV 1-2	LI-2	47.60	49.3	120.66	402	2.7	1.0	0.97	**13.1 ± 0.7**	59	5.45	3.18	16.70	58.40	0.08	1.57	4.90	0.59	0.07	5.18	391	30.00	3.00	3.00	0.25	0.25
LEAV 1-3	LI-3	47.60	49.0	120.66	402	2.7	1.0	0.97	17 ± 1.0	78	5.04	4.16	17.30	55.30	0.17	0.96	6.27	0.73	0.10	6.55	476	26.00	3.00	3.00	0.80	2.30
LEAV 1-4	LI-4	47.60	49.0	120.66	402	2.7	1.0	0.97	15 ± 0.7	59	5.48	4.78	15.80	55.00	0.09	1.57	5.58	0.65	0.09	6.09	885	32.00	4.50	4.50	0.80	2.30
LEAV 1-5	LI-5	47.60	49.0	120.66	402	2.7	1.0	0.97	15.4 ± 0.6	75	4.97	2.66	14.70	62.80	0.08	1.91	4.07	0.61	0.06	4.63	424	40.00	2.00	2.00	1.70	3.20
LEAV 1A-1	LI-6	47.60	49.3	120.64	360	2.7	1.0	0.94	16.4 ± 0.7	73	4.44	5.55	15.40	57.60	0.17	0.94	5.76	0.72	0.10	6.88	432	27.00	5.00	5.00	1.30	2.80
LEAV 1A-2	LI-7	47.60	50.9	120.64	360	2.7	1.0	0.96	22.3 ± 1.3	108	5.48	3.81	17.10	55.50	0.19	0.94	5.82	0.68	0.10	6.05	316	27.00	5.50	5.50	1.10	2.30

Appendix

(Continued)

Sample Number (Field)	Sample Number (Map)	Latitude °N	Eff. Latitude °N[a]	Longitude °W	Altitude m	Density[b] gm/cm³	Thickness cm	Shielding All effects	^{36}Cl Age ± 1σ[c]	^{36}Cl/Cl	Na_2O wt. %	MgO wt. %	Al_2O_3 wt. %	SiO_2 wt. %	P_2O_5 wt. %	K_2O wt. %	CaO wt. %	TiO_2 wt. %	MnO wt. %	Fe_2O_3 wt. %	Cl ppm	B ppm	Sm ppm	Gd ppm	U ppm	Th ppm
LEAV 1C-1	LI-15	47.61	49.3	120.66	366	2.7	1.0	0.95	15.3 ± 0.8	94	3.91	2.70	14.70	62.80	0.07	1.30	4.83	0.47	0.60	4.15	198	12.00	3.00	3.00	1.40	2.00
LEAV 1C-2	LI-16	47.61	49.5	120.66	366	2.7	1.0	0.95	15.8 ± 1.1	63	4.34	3.55	15.90	60.70	0.06	1.42	5.68	0.61	0.80	5.41	903	18.00	2.00	2.00	0.80	3.50
LTC-1 (BR)	LII-8	47.59	49	120.68	433	2.7	1.0	0.92	14.2 ± 1.3	71	3.78	3.60	14.70	63.00	0.06	1.44	5.20	0.50	0.07	4.69	420	35.00	3.00	3.00	1.30	3.20
LTC-2 (ER)	LII-9	47.59	49.0	120.68	433	2.7	1.0	0.92	19 ± 2.4	113	4.05	3.29	16.60	61.40	0.04	1.16	5.59	0.55	0.09	5.18	244	28.00	5.00	5.00	2.70	2.80
LTC-3 (ER)	LII-10	47.59	49.0	120.68	433	2.7	1.0	0.92	**11.7 ± 0.8**	69	3.61	6.36	15.20	55.10	0.22	0.64	7.44	0.78	0.12	7.47	490	17.00	3.50	3.50	4.50	1.40
LEAV 1B-1	LI-8	47.58	50.8	120.68	573	2.7	1.0	0.94	20.1 ± 0.8	116	4.71	4.09	17.20	57.30	0.23	0.98	6.03	0.87	0.08	5.29	406	25.00	4.00	4.00	1.10	1.20
LEAV 1B-2	LI-9	47.58	50.6	120.68	573	2.7	1.0	0.94	**45.1 ± 1.3**	334	4.82	2.64	15.80	62.40	0.15	1.42	4.64	0.49	0.07	4.38	192	25.00	4.00	4.00	1.30	2.80
LEAV 1B-3	LI-10	47.56	50.8	120.65	604	2.7	1.0	0.93	21.7 ± 0.9	123	3.74	4.66	15.70	59.70	0.18	1.64	5.84	0.65	0.08	5.81	679	25.00	3.00	3.00	2.80	3.40
LEAV 1B-4	LI-11	47.56	50.8	120.65	604	2.7	1.0	0.93	**13.1 ± 0.6**	110	3.91	2.79	14.90	63.70	0.06	1.13	5.17	0.47	0.07	4.37	173	17.00	3.00	3.00	2.80	4.20
LEAV 1B-5	LI-12	47.56	50.9	120.65	604	2.7	1.0	0.93	17.9 ± 1.1	106	4.08	3.58	16.30	61.20	0.04	0.75	5.99	0.60	0.09	5.50	258	27.00	5.50	5.50	0.25	0.25
LEAV 1B-6	LI-13	47.58	50.9	120.65	605	2.7	2.0	0.95	24.7 ± 1.1	182	4.51	2.62	16.90	63.30	0.12	1.31	5.26	0.47	0.06	4.00	255	22.00	3.00	3.00	0.50	4.90
PL 1-2	LI-21	47.58	49.5	120.65	524	2.7	1.0	0.93	15.8 ± 0.6	66	4.30	3.70	16.50	61.80	0.15	1.55	5.54	0.61	0.08	5.20	1080	32.00	3.00	3.00	0.25	3.10
PL 1-3	LI-22	47.58	49.5	120.65	549	2.7	1.0	0.92	18 ± 0.6	96	3.79	5.01	16.00	57.01	0.17	1.18	6.98	0.75	0.11	6.70	602	30.00	3.00	3.00	1.50	7.00
PL 1-4	LI-23	47.58	49.5	120.65	549	2.7	1.0	0.93	19.2 ± 0.7	93	3.71	5.91	15.80	56.30	0.18	1.81	6.47	0.63	0.12	7.35	601	24.00	4.00	4.00	0.25	0.25
PL 1-5	LI-24	47.58	50.8	120.65	546	2.7	1.0	0.93	23.4 ± 0.7	101	4.04	4.27	16.40	58.50	0.17	1.34	6.42	0.67	0.10	6.09	680	42.00	4.00	4.00	0.25	0.25
PL 1-6	LI-25	47.58	49.5	120.65	527	2.7	1.0	0.93	17.8 ± 0.5	153	4.17	2.75	15.90	63.20	0.09	1.93	4.58	0.56	0.07	4.25	135	19.00	3.00	3.00	0.25	0.25
MH 1-1	MH-1	47.59	50.6	120.65	585	2.7	2.0	0.96	70.9 ± 1.8	736	3.99	3.52	15.70	62.10	0.14	0.93	5.79	0.58	0.09	5.00	273	19.00	0.25	0.25	4.70	0.70
MH 1-2	MH-2	47.59	50.6	120.65	585	2.7	3.0	0.96	**93.1 ± 3.1**	868	3.88	2.70	14.60	65.00	0.06	2.13	4.48	0.49	0.06	3.88	230	8.00	2.00	2.00	1.30	6.60
MH 1-3	MH-3	47.59	50.6	120.65	585	2.7	1.0	0.96	71.4 ± 1.4	470	3.91	5.49	15.70	57.80	0.07	0.70	6.86	0.69	0.13	6.81	325	28.00	0.50	0.50	1.10	6.40
MH 1-4	MH-4	47.58	50.6	120.65	576	2.7	1.0	0.97	72.2 ± 1.4	650	4.16	2.51	15.60	64.40	0.09	1.72	4.80	0.49	0.06	3.71	174	18.00	0.20	0.20	1.30	3.00
MH 1-5	MH-5	47.58	50.6	120.65	573	2.7	2.0	0.96	**90.9 ± 1.4**	789	4.17	2.62	15.60	63.90	0.07	1.55	4.91	0.50	0.07	3.94	183	17.00	2.00	2.00	0.25	6.20
MH 1-6	MH-6	47.58	50.6	120.65	573	2.7	1.0	0.96	68.4 ± 1.8	421	4.09	3.31	15.90	62.50	0.06	0.86	6.04	0.65	0.09	4.83	370	32.00	0.50	0.50	0.25	0.25
MH 1-7	MH-7	47.58	50.6	120.65	549	2.7	1.0	0.95	**29 ± 1.0**	220	3.99	3.19	15.30	63.10	0.06	1.65	5.16	0.53	0.08	4.71	235	15.00	3.00	3.00	1.00	4.40
MH 1-8	MH-8	47.58	50.6	120.65	576	2.7	1.0	0.96	**118.1 ± 2.5**	732	2.58	9.71	13.00	55.30	0.37	0.47	6.34	0.67	0.16	9.98	360	11.00	2.00	2.00	0.25	0.25
MH 1-9	MH-9	47.58	50.6	120.65	597	2.7	2.5	0.97	71.8 ± 1.0	643	4.17	3.43	15.90	61.10	0.17	1.77	5.35	0.59	0.09	5.44	198	13.00	3.00	3.00	1.70	2.60
MH 1-1T	MH-10	47.61	50.6	120.66	378	2.7	2.0	0.97	77.5 ± 2.3	520	3.29	8.34	16.20	51.80	0.21	0.36	8.39	1.00	0.14	9.06	287	0.25	2.00	2.00	1.50	3.40
MH 2-1	pMH-1	47.59	50.6	120.65	561	2.7	1.0	0.96	94.9 ± 3.1	870	4.20	2.51	15.40	65.30	0.05	1.44	4.95	0.46	0.07	3.58	162	12.00	0.50	0.50	1.10	6.10
MH 2-2	pMH-2	47.59	50.6	120.65	561	2.7	1.0	0.96	91.2 ± 3.1	639	3.73	6.89	16.40	54.00	0.05	0.52	7.64	0.97	0.13	8.09	290	8.00	2.00	2.00	0.25	0.25
MH 2-3	pMH-3	47.59	50.6	120.65	588	2.7	2.0	0.96	109.3 ± 3.6	867	4.25	2.79	15.50	63.30	0.07	1.36	5.17	0.50	0.07	4.06	174	40.00	0.20	0.20	2.60	18.50

APPENDIX

(Continued)

Sample Number (Field)	Sample Number (Map)	Latitude °N	Eff. Latitude °N[a]	Longitude °W	Altitude m	Density[b] gm/cm^3	Thickness cm	Shielding All effects	^{36}Cl Age ± 1σ[c]	^{36}Cl/Cl	Na_2O wt. %	MgO wt. %	Al_2O_3 wt. %	SiO_2 wt. %	P_2O_5 wt. %	K_2O wt. %	CaO wt. %	TiO_2 wt. %	MnO wt. %	Fe_2O_3 wt. %	Cl ppm	B ppm	Sm ppm	Gd ppm	U ppm	Th ppm
PESH 1-2	P-2	47.54	50.3	120.68	741	2.7	1.0	0.96	104.3 ± 3.5	707	3.84	4.89	16.50	56.80	0.07	0.82	6.83	0.67	0.10	6.46	422	19.50	5.00	5.00	1.30	4.60
PESH 1-3	P-3	47.54	50.3	120.68	732	2.7	1.0	0.96	104.3 ± 1.7	1009	4.16	2.51	15.60	64.70	0.06	1.65	4.76	0.47	0.06	3.74	169	16.00	2.00	2.00	1.10	7.80
PESH 1-4	P-4	47.54	50.3	120.68	756	2.7	1.0	0.94	**93.7 ± 1.6**	756	4.04	2.88	15.30	63.90	0.50	1.80	4.90	0.50	0.08	4.55	300	17.00	3.00	3.00	1.80	18.60
PESH 1-5	P-5	47.54	50.3	120.68	741	2.7	1.0	0.94	103.8 ± 1.6	1009	4.01	2.65	15.60	64.50	0.13	2.04	4.43	0.52	0.07	4.03	208	11.00	0.05	0.05	0.25	0.25
PESH 1-6	P-6	47.54	50.3	120.68	732	2.7	2.0	0.96	108.9 ± 1.5	725	4.05	3.34	16.00	62.50	0.11	1.49	5.46	0.54	0.09	5.43	454	34.00	0.25	0.25	1.30	3.80
PESH 1-7	P-7	47.54	50.3	120.68	701	2.7	2.0	0.97	108.0 ± 1.6	678	3.98	3.93	15.80	61.70	0.11	1.53	5.75	0.63	0.09	5.50	430	28.00	3.00	3.00	0.60	4.10
PESH 1-8	P-8	47.54	50.3	120.67	777	2.7	2.0	0.97	106.6 ± 1.7	789	3.89	3.41	15.50	63.40	0.31	1.56	4.97	0.59	0.08	5.35	352	24.00	0.25	0.25	1.10	1.60
PESH 1-9	P-9	47.54	50.3	120.67	768	2.7	2.0	0.96	**112.8 ± 1.7**	871	4.18	3.54	15.90	63.20	0.07	1.06	5.37	0.58	0.08	4.97	236	20.00	0.25	4.00	0.25	3.20
PESH 1-10	P-10	47.54	50.3	120.67	768	2.7	2.0	0.97	102.5 ± 1.5	791	4.05	3.12	15.70	63.60	0.12	1.61	4.69	0.67	0.08	4.95	350	22.00	0.50	0.50	1.10	0.25
PESH 1-11	P-11	47.54	50.3	120.68	768	2.7	1.0	0.97	104.9 ± 1.5	668	3.85	5.42	16.30	57.70	0.19	0.93	6.81	0.69	0.11	6.77	415	23.00	3.00	3.00	0.25	2.50
PESH 2-1A	P-12	47.54	50.3	120.68	738	2.7	1.0	0.93	**93.0 ± 1.5**	763	4.24	3.30	16.00	62.60	0.09	1.14	5.42	0.61	0.08	5.01	266	12.00	2.00	2.00	0.25	3.30
PESH 2-1B	P-13	47.54	50.3	120.68	738	2.7	1.0	0.94	**112.7 ± 1.7**	807	4.23	3.25	16.10	62.50	0.08	1.12	5.40	0.58	0.02	5.03	576	12.00	2.00	2.00	1.00	1.00

[a]Calculated effective latitude is integrated over the exposure age of the respective sample
[b]Assumed rock density for granodiorite boulders is 2.7 gm/cm^3
[c]Ages are reported with 1σ AMS uncertainty; all cited ^{36}Cl ages are rounded to the nearest 100 years; values in bold type are outliers.

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