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Radiocarbon Age Constraints on Rates of Advance and Retreat of the Puget Lobe of the Cordilleran Ice Sheet during the Last Glaciation

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Calibrated radiocarbon dates of organic matter below and above till of the last (Fraser) glaciation provide limiting ages that constrain the chronology and duration of the last advance–retreat cycle of the Puget Lobe in the central and southeastern Puget Lowland. Seven dates for wood near the top of a thick proglacial delta have a weighted mean age of 17,420 ± 90 cal yr B.P., which is the closest limiting age for arrival of the glacier near the latitude of Seattle. A time–distance curve constructed along a flowline extending south from southwestern British Columbia to the central Puget Lowland implies an average glacier advance rate of ca. 135 m/yr. The glacier terminus reached its southernmost limit ca. 16,950 yr ago and likely remained there for ca. 100 yr. In the vicinity of Seattle, where the glacier reached a maximum thickness of 1000 m, ice covered the landscape for ca. 1020 yr. Postglacial dates constraining the timing of ice retreat in the central lowland are as old as 16,420 cal yr B.P. and show that the terminus had retreated to the northern limit of the lowland within three to four centuries after the glacial maximum. The average rate of retreat was about twice the rate of advance and was enhanced by rapid calving recession along flowline sectors where the glacier front crossed deep proglacial lakes.

INTRODUCTION

During the last glaciation, the margin of the Cordilleran Ice Sheet expanded southward from the Coast Mountains and Fraser Lowland of southwestern British Columbia into northwestern Washington. As it reached the Olympic Mountains, the glacier divided into two lobes; one moved west through the Strait of Juan de Fuca and across the now-submerged continental shelf (the Juan de Fuca Lobe), while a second (the Puget Lobe) flowed south of 48° N latitude into the Puget Lowland between the Olympic Mountains and the Cascade Range (Fig. 1).

The chronology of the Puget Lobe's advance and retreat during the Vashon Stade of the Fraser Glaciation (Armstrong *et al.,* 1965) was previously based on a suite of conventional radiocarbon ages of terrestrial and marine fossils sampled at localities scattered throughout the lowland (e.g., Yount *et al.,* 1980; Easterbrook, 1992). These ages have been used to infer the duration of ice sheet occupancy at specific locations (e.g., Seattle), as well as average advance and retreat rates of the terminus. Booth (1986a), for example, estimated an advance rate of 50 to >200 m/yr using limiting radiocarbon dates and assuming an advance rate half that of the retreat rate. Thorson (1989) suggested that overall advance and retreat rates likely exceeded 150 and 300 m/yr, respectively, and Anundsen *et al.* (1994) estimated the average retreat rate of the glacier terminus to be 250–275 m/yr. Each of these estimates was based on limiting uncalibrated radiocarbon ages.

New radiocarbon dates for wood samples that predate the arrival of the ice sheet at the latitude of Seattle, together with previously dated preglacial and postglacial terrestrial organic samples from sites in the central lowland, permit more precise estimates to be made of the time when the glacier reached its maximum limit, the interval during which the glacier overlay Seattle and other lowland sites, and average rates of advance and retreat along the approximate midline of the Puget Lobe.

RADIOCARBON DATES

Although numerous radiocarbon dates have been obtained for shells collected from widespread late-glacial glacialmarine deposits in the northernmost Puget Lowland and adjacent Fraser Lowland, many of these dates are unsatisfactory for determining rates of ice recession because (1) postdepositional diagenetic alteration of a shell may result in an anomalously young age, and (2) the isotopic composition of late-glacial meltwater and marine water in the Puget Lowland is unknown, and so the most appropriate marine reservoir correction for shells of late-glacial age in the Puget Sound area is uncertain. For these reasons, in this study we have elected to use only dates of terrestrial plant samples (e.g., gyttja, peat, wood), which avoid both problems.

Dates below Vashon Till

Wood samples previously collected from beneath the Vashon Till Member of the Fraser Drift at sites in Seattle date to 15,100 ± 300 and 15,000 ± 400 ^{14}C yr B.P. (W-1305 and

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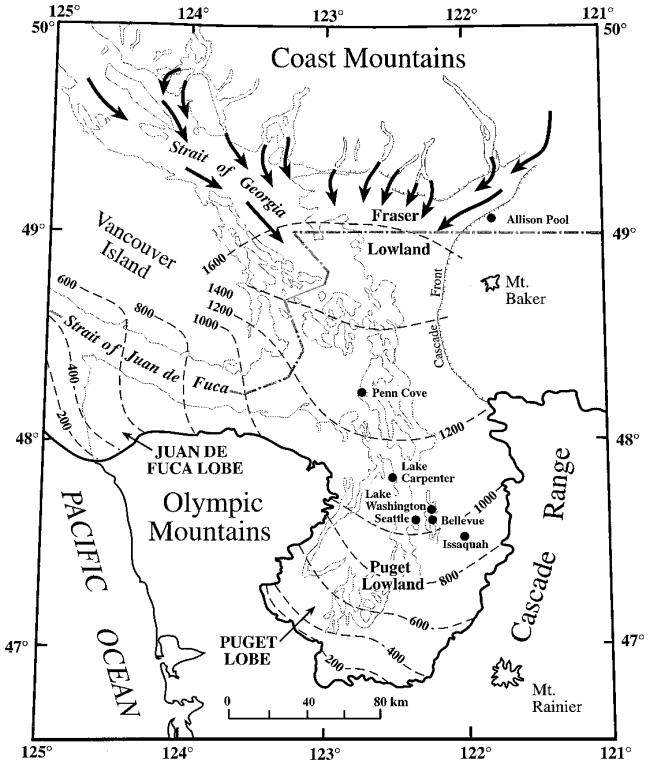

FIG. 1. Map of northwestern Washington and southwestern British Columbia showing the extent of the Cordilleran Ice Sheet during the maximum advance of the last (Fraser) glaciation. Contours (m) on the Puget Lobe are based on Thorson (1980, Fig. 4); other contours are inferred from ice-flow-directional indicators and upper ice limits in adjacent mountains. Bold arrows indicate inferred flow direction of ice moving southeast along the Strait of Georgia and issuing from fjord valleys in the Coast Mountains of British Columbia. Black dots are radiocarbon sample localities and sites mentioned in the text.

W1227, respectively; Table 1). However, new dates from two sites east and southeast of Seattle provide the closest limiting ages for the ice advance.

A date of 14,890 ± 70 ^{14}C yr B.P. has been obtained for detrital spruce wood collected near the top of outwash directly beneath thick Vashon till at an excavation in Bellevue (Kathy Troost, personal communication, 1998; Table 1). This date is indistinguishable at one standard deviation from the two Seattle samples collected at the same latitude, but it has a smaller standard error than these two dates, making it the most important of the three for close age control.

A recently excavated section in a large borrow pit near Issaquah, Washington (Fig. 1), exposed wood embedded in the topset beds of a thick proglacial delta that is capped by several meters of stony Vashon till (Fig. 2). Both the proglacial delta and an adjacent delta deposited during glacier recession lie at the downstream end of a meltwater channel that discharged water into an ice-dammed lake during glacier advance and also during recession (Glacial Lake Sammamish; Bretz, 1913; Curran, 1965). Seven samples of the outer wood of tree trunks and branches (provisionally identified as *Picea sitchensis;* A. A. Breitsprecher, personal communication, 1992) excavated from fluvial sediments lie within 10 m of the overlying till. Six AMS dates and one conventional ^{14}C date range from 14,600 ± 100 to 14,480 ± 70 ^{14}C yr B.P. (Table 1), the youngest ages yet obtained beneath Vashon till in the central Puget Lowland. The seven dates are statistically identical (95% confidence interval), and their weighted mean age is 14,546 ± 28 ^{14}C yr B.P.

Postglacial Dates

Six limiting dates for glacier recession come from five sites in the northern and central Puget Lowland. Two samples of freshwater gyttja from near the base of a sediment core taken from Lake Carpenter near Kingston, Washington (Fig. 1), date to 13,600 ± 280 and 13,700 ± 150 ^{14}C yr B.P. [QL-4065 (12.00–12.03 m depth) and QL-4067 (12.39–12.41 m depth), respectively; Anundsen *et al.,* 1994; Table 1]. Although a slightly older date was obtained for marine shells somewhat lower in the core (12.61–12.65 m), we do not include it because of the uncertainty of the marine reservoir correction at this site.

Three dates have been obtained from the Lake Washington basin near Seattle. Rigg and Gould (1957) reported a date of 13,650 ± 550 ^{14}C yr (L-346A) for basal limnic peat in a core from Lake Washington; shells (undated) were noted ca. 3.4 m below the peat in bluish marine clays. Because of its large standard deviation and the availability of more closely limiting dates, this date was ignored in our study. Basal gyttja in a sediment core from northern Lake Washington has an age of 13,430 ± 200 ^{14}C yr B.P. (QL-1517; Leopold *et al.,* 1982). A date of 13,610 ± 80 ^{14}C yr B.P. (QL-1891) has been obtained for basal gyttja in a core from Mercer Slough, a site adjacent to Lake Washington at the southwestern edge of Bellevue (Table 1; E. B. Leopold, personal communication, 1998).

ICE-FLOW PATTERN AND SELECTED FLOWLINES

We have calculated the rate of advance and retreat of the Puget Lobe using calibrated radiocarbon ages (Stuiver and Reimer, 1993) and the inferred flow pattern of the glacier as it expanded to its maximum size and then retreated. In this analysis, we use flowlines for the Puget Lobe reconstructed by Thorson (1980) from ice-flow-directional indicators. We assume that the glacier terminus during the advance was oriented essentially normal to these flowlines. However, during glacier recession, calving retreat likely produced pronounced embayments where the terminus crossed linear proglacial lakes that were up to several hundred meters deep (see below).

In Figure 3, four flowlines are shown that extend to the full-glacial limit from sites where limiting radiocarbon ages have been obtained. The flowline from Lake Carpenter to the ice limit is 112 km long, whereas that from Seattle is 63 km, that from Lake Washington is 43 km, and that from the

TABLE 1
Selected Radiocarbon Dates Related to the Last Advance–Retreat Cycle of the Puget Lobe

Laboratory number	Age ± 1σ (^{14}C yr B.P.)	Age (cal yr B.P.)[a]	Sample material	Sample locality	Geographic coordinates	Reference
		Post-Vashon till samples (Washington)				
QL-1517	13,430 ± 200	16,349 (16,068) 15,771	Organic clay	Lake Washington	47°34.9′, 122°11.2′	Leopold *et al.* (1982)
QL-4065	13,600 ± 280	16,659 (16,294) 15,904	Freshwater gyttja	Lake Carpenter	47°48.3′, 122°31.3′	Anundsen *et al.* (1994)
QL-4067	13,700 ± 150	16,631 (16,422) 16,207	Freshwater gyttja	Lake Carpenter	47°48.3′, 122°31.3′	Anundsen *et al.* (1994)
QL-1891	13,610 ± 80	16,446 (16,307) 16,167	Bog peat	Mercer Slough	47°34.8′, 122°10.7′	E. B. Leopold, personal communication, (1998)
		Sub-Vashon till samples (Washington)				
CAMS-23160	14,450 ± 90	17,446 (17,313) 17,182	Detrital wood	Issaquah delta	47°32.6′, 122°01.5′	This report
CAMS-23170	14,620 ± 100	17,643 (17,503) 17,365	Detrital wood	Issaquah delta	47°32.6′, 122°01.5′	This report
CAMS-23171	14,580 ± 70	17,573 (17,459) 17,346	Detrital wood	Issaquah delta	47°32.6′, 122°01.5′	this report
CAMS-23175	14,600 ± 90	17,611 (17,481) 17,352	Detrital wood	Issaquah delta	47°32.6′, 122°01.5′	This report
CAMS-23176	14,480 ± 70	17,463 (17,347) 17,233	Detrital wood	Issaqah delta	47°32.6′, 122°01.5′	This report
CAMS-23177	14,550 ± 70	17,541 (17,426) 17,312	Detrital wood	Issaquah delta	47°32.6′, 122°01.5′	This report
QL-4620	14,560 ± 60	17,544 (17,437) 17,331	Detrital wood	Issaquah delta	47°32.6′, 122°01.5′	This report
W-1227	15,000 ± 400	18,327 (17,916) 17,474	Detrital wood	Seattle	47°38.0′, 122°19.0′	Mullineaux *et al.* (1965)
W-1305	15,100 ± 300	18,330 (18,020) 17,692	Detrital wood	Seattle	47°37.5′, 122°19.5′	Mullineaux *et al.* (1965)
Beta-112019	14,890 ± 70	17,915 (17,799) 17,687	Detrital wood	Bellevue	47°37.0′, 122°11.5′	K. Troost, personal communication, (1998)
		Sub-Vashon till samples (British Columbia)				
GSC-4355	16,000 ± 180	19,086 (18,876) 18,685	Spruce wood	Allison Pool	49°05.1′, 121°48.2′	Clague *et al.* (1988)
GSC-4363	16,100 ± 150	19,168 (18,975) 18,802	Spruce wood	Allison Pool	49°05.1′, 121°48.2′	Clague *et al.* (1988)

[a] Obtained using CALIB 3.0.3c program (Stuiver and Reimer, 1993). Value in parentheses is cal age. Values outside the parentheses are maximum and minimum age ranges obtained from intercepts.

Issaquah delta is 23 km; the potential measurement error for flowline lengths is estimated to be ±2 km.

GLACIER ADVANCE

During the Vashon Stade, the Cordilleran Ice Sheet advanced south from British Columbia and reached the northern limit of the Puget Lowland about 18,000 cal yr ago (Fig. 4). As it entered the lowland, the terminus likely was grounded and advancing across a landscape standing ca. 120–150 m above river floodplains that were graded to a marine embayment in the outer Strait of Juan de Fuca. At that time, the landscape supported an open mesic subalpine forest (Barnosky, 1981). As the advancing glacier blocked northward-flowing streams, major valleys were dammed, forming proglacial lakes. Dropstones in the lacustrine Lawton Clay Member of the Vashon Drift (Mullineaux *et al.,* 1965) that would provide evidence of a calving terminus have not been reported. Therefore, we infer that the terminus was grounded and separated from proglacial lakes by morainal shoals or prograding deltas. Outwash deposited beyond the advancing glacier formed the Esperance Sand Member of the Vashon Drift (Mullineaux *et al.,* 1965), which filled topographic depressions in the landscape (Booth, 1994).

Just prior to overriding the sites of Seattle and Bellevue, the terminus of the Puget Lobe lay north of the bold dashed line labeled 17,530 cal yr in Figure 3a. By ca. 17,420 cal yr ago the advancing margin lay immediately north of Issaquah, having earlier impounded a proglacial lake to the level at which the proglacial delta topset beds are graded. The dated detrital wood from the topset strata may have been deposited only a few decades before the glacier overrode the delta.

Advancing along the trends of the three easternmost flowlines, the glacier terminus reached the front of the Cascade Range successively later from northeast to southwest. At the range front it piled up against steep interfluves and flowed into the lower reaches of valleys, producing a digitate margin (e.g., Thorson, 1980; Booth, 1986b). The mean altitude of the ice margin declined from ca. 790 m at the termination of the Issaquah flowline to 610 and 500 m, respectively, at the southern ends of the Lake Washington and Seattle flowlines (Fig. 3b). At the end of the Lake Carpenter flowline the glacier terminated in relatively gentle terrain near the southern limit of the lowland at an altitude of ca. 150 m.

To obtain estimates of advance and retreat rates for the Puget Lobe, the Lake Carpenter flowline was selected as the

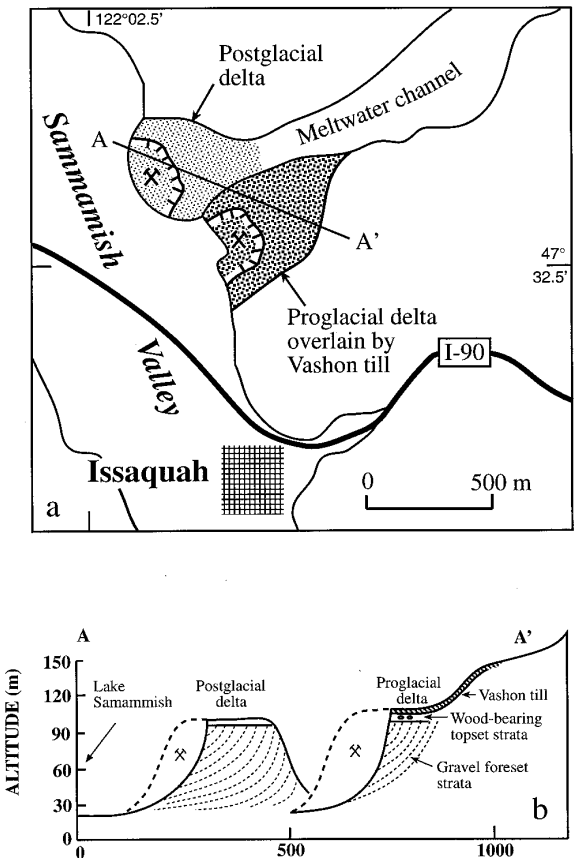

FIG. 2. Issaquah delta complex at the margin of Lake Sammamish valley. (a) Map showing the location of wood-bearing proglacial delta sediments adjacent to the postglacial delta, and the associated meltwater channel. (b) Section (A-A′) across the deltas illustrating the position of wood samples beneath Vashon till having ages ranging from 14,450 ± 90 to 14,620 ± 100 ^{14}C yr B.P.

primary transect because it lies near the middle of the glacier, extends to the southern terminus of the lobe, and passes through the site of the oldest of the postglacial dates. However, the youngest dates beneath Vashon till (at Seattle, Bellevue, and Issaquah) all lie east of this flowline. A line lying just north of Seattle and Bellevue and oriented normal to the four flowlines (labeled S-BM in Fig. 3) is inferred to mark the margin of the advancing glacier at the time it overrode the Seattle and Belleview sites. Carried westward, this line intersects the Lake Carpenter flowline ca. 23 km south of Lake Carpenter. A similar line (Issaquah ice margin (IM) in Fig. 3) marks the ice limit shortly before the Issaquah delta was overridden. When extended westward, this line intersects the Lake Carpenter flowline 10 km south of the Seattle–Bellevue line.

To obtain the average rate of advance of the glacier down the Puget Lowland, we extend the Lake Carpenter flowline into southern British Columbia, where the Allison Pool site in the Chilliwack valley east of Vancouver constitutes a critical control point (Clague *et al.*, 1988). At this site, two samples of spruce wood lying beneath Vashon till have ages of 16,180 ± 180 and 16,100 ± 150 yr B.P. (Table 1). The calibrated equivalents of these dates indicate that the advancing ice-sheet margin reached the latitude of this site sometime after ca. 18,925 cal yr B.P. (mean of the two calibrated dates). Although other radiocarbon dates for sub-Vashon till samples between Seattle and the Canadian border have been reported (e.g., Clague, 1980; Easterbrook, 1969, 1992; Minard, 1985), they

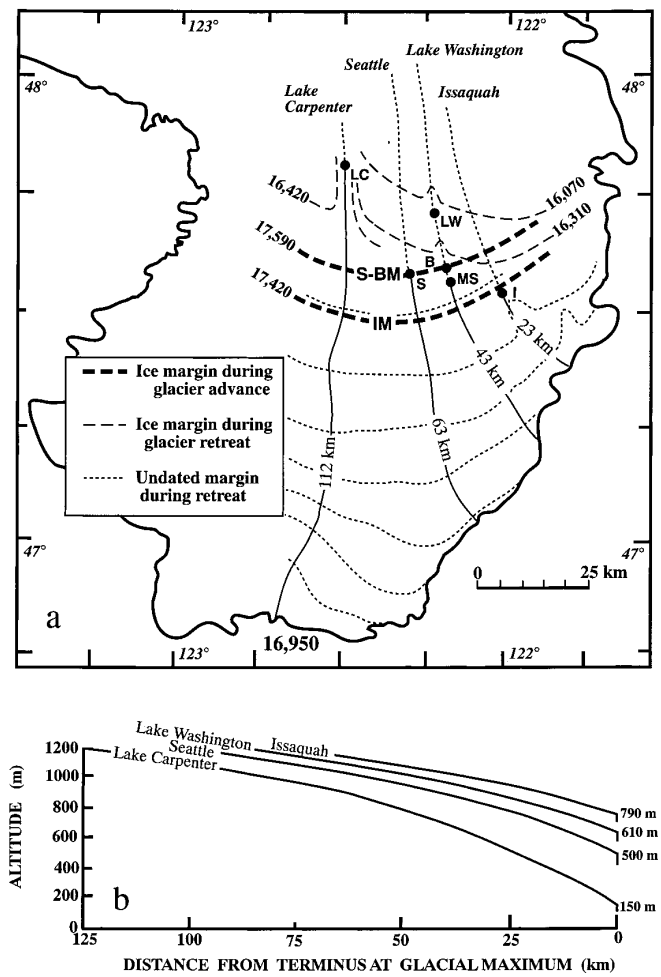

FIG. 3. Radiocarbon sample localities in the central and northern Puget Lowland and associated flowlines along which radiocarbon dates have been obtained. (a) Map showing radiocarbon sample localities (black dots: LC, Lake Carpenter; LW, Lake Washington; S, Seattle; B, Bellevue; MS, Mercer Slough; I, Issaquah) and flowlines passing through them, based on flowline reconstruction by Thorson (1980, Fig. 2). Length of flowlines (kilometers) is from sample localities to the glacial limit. Seattle–Bellevue ice margin (S-BM) and Issaquah ice margin (IM) mark approximate positions of the glacier terminus at 17,590 and 17,420 cal yr ago, respectively. Ages of ice margins during retreat are based on limiting ages from Lake Carpenter (16,420 cal yr), Mercer Slough (16,310 cal yr), and Lake Washington (16,070 cal yr). Inferred time that the glacier terminus reached the ice limit along the Lake Carpenter flowline is shown as large bold number near limit. (b) Profiles along flowlines shown in (a) and altitudes of terminus at the glacier limit. Abrupt termination of profiles marks position of glacier margin at the front of the Cascade Range.

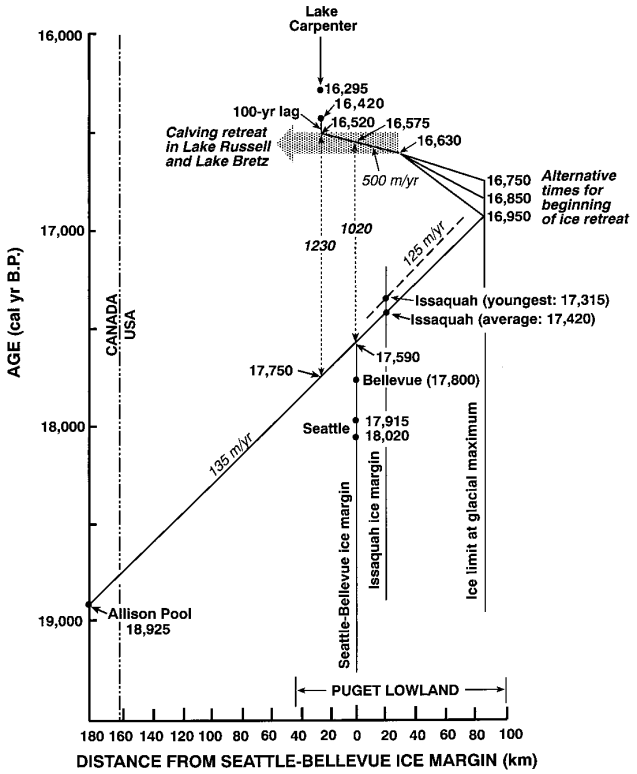

FIG. 4. Time–distance curve depicting advance and retreat of the Puget Lobe along the Lake Carpenter flowline. The average advance rate of 135 m/yr is based on the mean age of radiocarbon samples (cal yr B.P., rounded to nearest 5 yr) at Allison Pool and Issaquah; if youngest Issaquah date is used, the mean advance rate decreases to 125 m/yr. Assumptions regarding ice retreat include: (1) a 100-yr lag between deglaciation and initial organic sedimentation in Lake Carpenter; (2) an average calving retreat rate of 500 m/yr along Lake Russell and Lake Bretz in >300 m of water; and (3) the time that the terminus remained at the glacial limit (0, 100, or 200 yr) before retreating at a uniform rate to the point where calving retreat began. Based on the time–distance curve, the glacier covered the site of Lake Carpenter for 1230 yr and Seattle for 1020 yr.

all are sufficiently older than the Allison Pool dates that they can be rejected in this analysis.

If the youngest dates of sub-Vashon wood at the Allison Pool and Issaquah delta sites represent close limiting ages for the arrival of the glacier, then the ice margin traversed the ca. 200 km between these sites in about 1500 yr (18,925 to 17,420 cal yr B.P.) at an average rate of ca. 135 m/yr (Fig. 4); if the dates are not closely limiting, then the average rate of advance would be higher. This rate is extrapolated along the Lake Carpenter flowline beyond the Issaquah ice margin to the southernmost limit of the glacier to derive the time of the glacial maximum (16,950 cal yr B.P.; Fig. 4). An alternative rate of advance (125 m/yr) is obtained by using the youngest of the Issaquah radiocarbon dates (17,315 cal yr B.P.), rather than the average age, and results in arrival of the terminus at its maximum limit about 100 yr later than if the average age is used (Fig. 4).

GLACIER RETREAT

To construct the recessional part of the time–distance curve (Fig. 4) and calculate rates of ice retreat, we must make several assumptions regarding (1) the rate of retreat in proglacial lakes along the Lake Carpenter flowline, (2) the time lag at the Lake Carpenter site between deglaciation and revegetation, and (3) the length of time the glacier remained at its maximum limit.

Calving in Proglacial Lakes

We infer that calving bays developed along the margin of the Puget Lobe wherever the retreating terminus crossed a deep proglacial lake and that the calving retreat rates were greatest in the deepest, broadest lakes. Lake Russell (Bretz, 1910), which formed during an early phase of ice retreat, drained southward through the Black Lake spillway (Fig. 5) and occupied both the Puget Sound trough along the Lake Carpenter flowline and the Lake Washington basin. Lake Bretz (Thorson, 1989), a subsequent, lower phase of the same lake system, drained northward into the deglaciated Strait of Juan de Fuca via the Leland Creek spillway.

Reconstructed water depths along the Puget Sound trough are expressed as the difference between the present floor of the sound and the levels of Lake Russell and Lake Bretz, which have been isostatically tilted (Thorson, 1989). Water depths during calving recession were at least 280–320 m (Fig. 6). However, late-glacial and postglacial sediments beneath the floor of Puget Sound that locally are at least 200 m thick (M. L. Holmes, personal communication, 1998) suggest that water depths may have reached or exceeded 500 m along some sectors of the trough. Water depth is a critical factor in calving recession, for empirical studies of calving glaciers have shown that calving rate correlates closely with the depth of water at a calving terminus (Brown *et al.*, 1982; Funk and Röthlisberger, 1989).

In Glacier Bay, Alaska, where water depths during deglaciation following the Little Ice Age maximum reached 400–500 m, the calving retreat rate exceeded 500 m/yr (Brown *et al.*, 1982). Columbia Glacier in Prince William Sound, since entering its present recessional phase, has been calving back at an average rate of 600 m/yr along a fjord having dimensions similar to those of late-glacial Puget Sound (5–6 km wide, ca. 300 km deep) (Meier, 1994). Based on these and other modern analogues, we adopt a calving-retreat rate of 500 m/yr for the 55-km-long sector of the Puget Sound trough between the point where calving retreat began, north of the Steilacoom delta, and Lake Carpenter (Fig. 5). Selection of a calving retreat rate 100 m/yr faster or slower does not appreciably affect the following results.

The basal dates from Lake Carpenter indicate that the receding glacier margin had passed this site prior to ca. 16,420 cal yr ago (Fig. 4). We think it likely that this site was deglaciated earlier than other sites at this latitude because (1)

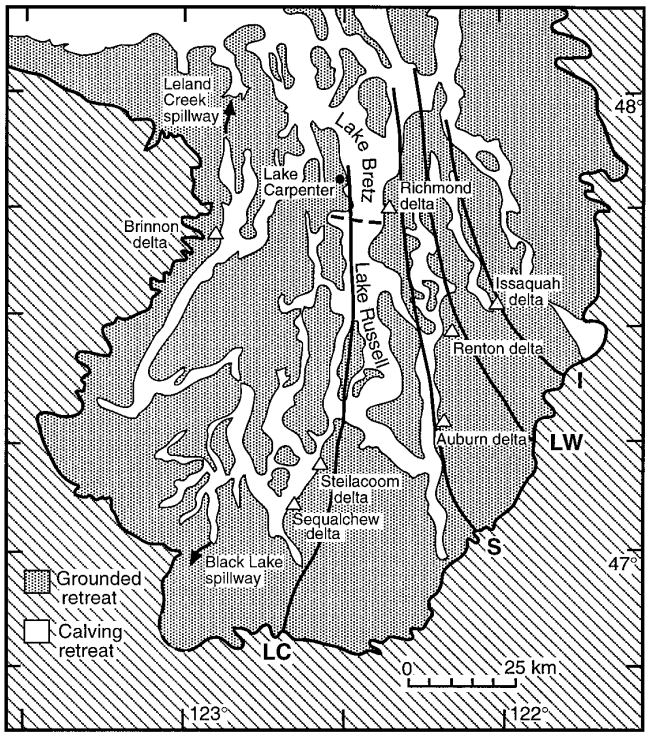

FIG. 5. Map of the Puget Lowland showing distribution of meltwater lakes during glacier recession (after Thorson, 1980, 1981, 1989) relative to four flowlines. In the shaded areas, the retreating glacier margin was grounded, whereas in the areas covered by meltwater lakes, calving retreat is inferred. The extent and depth of the lakes changed progressively as the ice front retreated northward, exposing lower outlets. During the early phases of ice retreat, Lake Russell occupied the Puget Sound trough and adjacent valleys and drained southward via the Black Lake spillway. When the Leland Creek spillway opened as the ice front retreated north of Seattle, the altitude of the lake surface lowered to form Lake Bretz (Thorson, 1989). Triangles show deltas used to reconstruct water-surface profiles (Fig. 6). The dashed line near Richmond delta shows the position of the terminus when the Leland Creek spillway opened and the level of Lake Russell fell to that of Lake Bretz.

the Lake Carpenter dates are as old as or older than the basal dates from Lake Washington and Mercer Slough, even though the latter sites lie farther south, and (2) the glacier would have retreated rapidly along the Lake Carpenter flowline in proglacial Lake Russell across a 6- to 8-km-wide front in water that generally exceeded a depth of 300 m (Fig. 6). The inferred history of ice retreat is consistent with the pattern of successive ice-margin positions reconstructed by Thorson (1980, Fig. 8), which imply rapid recession of the glacier terminus in the central Puget Lowland through the widest and deepest sectors of Lake Russell and Lake Bretz (Figs. 3, 5, and 6).

Revegetation at Lake Carpenter

The Lake Carpenter site was deglaciated prior to ca. 16,420 cal yr ago (the age of the basal gyttja in the lake), but how long did it take the site to be revegetated and organic sedimentation to commence in the lake? A possible analog is seen at Muir Inlet in Glacier Bay, Alaska, where Decker (in Goldthwait *et al.*, 1966) documented the rate of reforestation following glacier retreat. He noted that initial pioneer and alder–willow–thicket stages were followed within 50 yr of deglaciation by the appearance of scattered spruce, and that a spruce forest developed within an additional 25–40 yr. At Icy Bay, Alaska, terrain along the fjord system that was exposed by recent rapid calving recession became colonized with dense alder and scattered spruce seedlings within a decade of deglaciation (S. C. Porter, unpublished data). If colonization of pioneer vegetation in the Puget Lowland during late-glacial time kept pace with deglaciation, as it has more recently in Alaska, then revegetation and initial influx of organic matter to the Lake Carpenter and Lake Washington pollen sites may have lagged local deglaciation of these sites by no more than a century. In Figure 4, we assume that this lag interval was 100 yr; a longer lag time would require faster rates of ice retreat than we derive here.

Duration of Ice at the Glacial Limit

By backward (southward) extrapolation from Lake Carpenter of the inferred average calving retreat rate (500 m/yr), the interval of calving retreat would have begun ca. 16,630 cal yr ago, or 320 yr after the glacier reached the termination of the Lake Carpenter flowline ca. 16,950 cal yr ago (Fig. 4). If the retreat began immediately (i.e., 16,950 cal yr B.P.), then the average retreat rate through the southernmost 60 km of the flowline to the 16,630-yr ice margin would have been ca. 185 m/yr. However, we infer that the terminus remained at or near its maximum limit for at least 100 yr (from 16,950 to 16,850 cal yr B.P.; Fig. 4). This inference is based not only on the large volume and extent of ice-contact stratified drift and outwash near the glacial limit, but also on the impressive size of ice-marginal meltwater channels in the terminal zone. The Puget Lobe had high rates of basal sliding and meltwater discharge (Booth, 1987), and high associated rates of fluvial erosion and deposition, but the extent and size of erosional and depositional features near the glacial limit imply that they formed over an interval of at least several decades, and probably longer. Assuming a 100-yr pause of the ice front at the end of the Lake Carpenter flowline, the minimum average rate of grounded recession from this limit is 275 m/yr (Table 2). If, instead, an interval of 200 yr is assumed, a grounded retreat rate of 500 m/yr is required (Fig. 4; Table 2), a rate equaling that we have used for an actively calving ice margin. Because the latter rate is unacceptably high, we conclude that the terminus likely remained at the ice limit no more than 150 yr, and most likely for about 100 yr.

Based on an assumed calving retreat rate of 500 m/yr, and assuming a 100-yr pause of the terminus at the glacial limit, the margin of the Puget Lobe retreated to Lake Carpenter (a distance of 112 km) in ca. 330 yr; assuming a 150-yr pause, this interval is reduced to 280 yr. The corresponding mean retreat rates (grounded + calving) between the glacial limit and

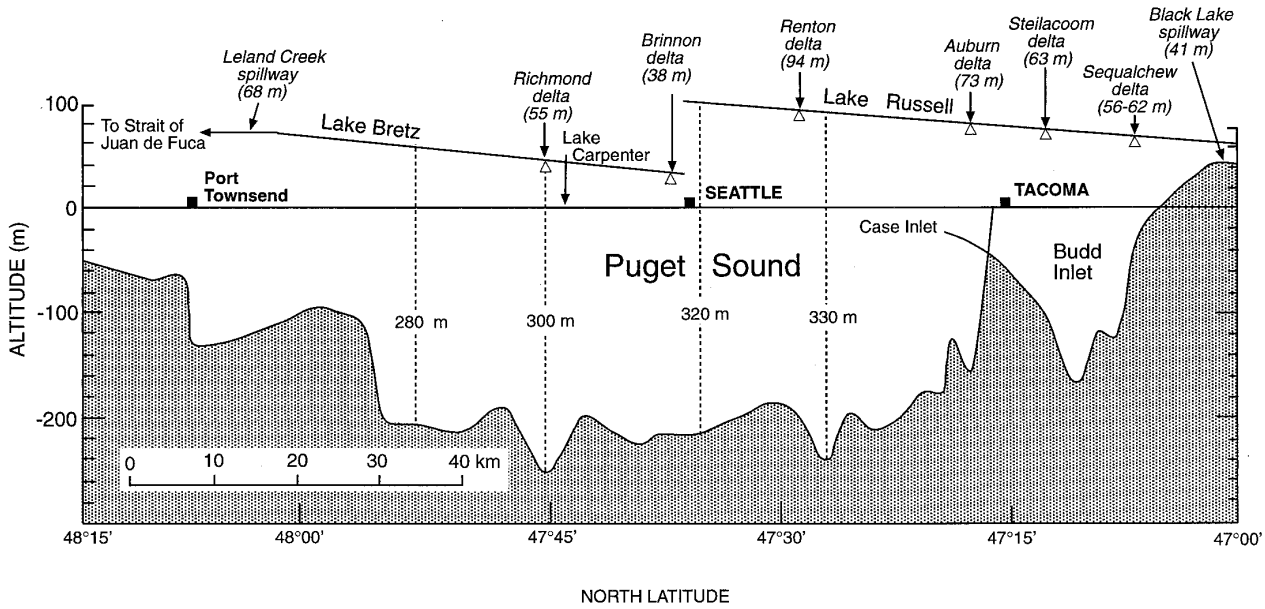

FIG. 6. Section along the Puget Sound trough showing the minimum depth of water during ice recession based on present submarine topography and the levels of Lake Russell and Lake Bretz obtained from the topset–foreset contact in late-glacial deltas (Thorson, 1981, 1989). The southward slope of former lake surfaces reflects postglacial isostatic rebound (Thorson, 1989).

Lake Carpenter assuming 100- and 150-yr pauses are 340 and 400 m/yr, respectively (Table 2).

LAKE WASHINGTON FLOWLINE

Of the other flowlines shown in Figure 3, both minimum and maximum constraining dates are available for only the Lake Washington flowline. However, as shown in Figure 4, the Bellevue limiting age may predate the passage of the glacier across the S-BM line by several hundred years. The minimum limiting date from Mercer Slough is equivalent to the younger of the two Lake Carpenter dates and older than the date from Lake Washington (Table 1). The apparent more rapid recession of the ice front to the Lake Carpenter site than to the Lake Washington site may reflect the importance of calving retreat along the former flowline in contrast to the largely grounded retreat along the latter flowline (Fig. 5). The ice front remained at the southern limit of the Lake Washington flowline substantially longer than at the end of the Lake Carpenter flowline because the former terminated farther north against the Cascade front. The glacier likely reached its limit there several hundred years earlier than it did along the Lake Carpenter flowline and began to retreat only after the thick ice piled against the Cascade front (Fig. 3b) had thinned to the level of the Puget Lowland.

DURATION OF GLACIER COVER

Knowing both the duration and changing thickness of the ice load at sites in the Puget Lowland is important for assessing

TABLE 2
Alternative Rates of Retreat of the Puget Lobe

Alternative dates for beginning of retreat from glacial limit (cal yr B.P.)	Duration of terminus at glacial limit (yr)	Mean retreat rate of grounded ice to latitude where calving commences[a] (m/yr)	Mean retreat rate (grounded + calving)[b] from glacial limit to Lake Carpenter[c] (m/yr)
16,750	200	500	485
16,800	150	350	400
16,850	100	275	340
16,900	50	220	295
16,950	0	190	265

[a] Calving commences at 16,630 cal yr B.P., 60 km north of glacial limit (Fig. 4).
[b] Assuming a calving retreat rate of 500 m/yr (see text).
[c] Retreating terminus reaches Lake Carpenter, 112 km north of glacial limit, at 16,520 cal yr B.P. (Fig. 4).

isostatic response of the crust to glaciation and deglaciation (Thorson, 1981). Using the time–distance curve for the Lake Carpenter flowline and the inferred regional pattern of glacier advance and retreat, intervals during which specific sites along the flowline were ice-covered can be derived. For example, at Lake Carpenter, the landscape was covered by ice for ca. 1230 yr. Along the Lake Washington flowline, at the latitude of Seattle and Bellevue, the duration of ice cover was ca. 950 yr (Fig. 4).

COMPARISON OF ADVANCE AND RETREAT RATES

Based on the available calibrated radiocarbon ages, and assuming that the terminus did not pause at the glacial limit, the mean retreat rate between the glacial limit and Lake Carpenter would be 265 km/yr (Table 2). Adding the inferred 100-yr pause at the glacial limit increases the mean rate to 340 m/yr (Table 2). This rate is ca. 2.5 times the mean advance rate of 135 m/yr between the Allison Pool and Issaquah sites and along the 85-km-long segment of the Lake Carpenter flowline between the glacial limit and the S-BM line. Within the constraints of the radiocarbon dates, a slower rate of advance or a longer pause of the terminus at the glacial limit would require higher mean rates of retreat (Fig. 7).

Few data are available from modern glaciers that can be compared directly with advance and retreat rates obtained for the Puget Lobe. Alaskan calving fjord glaciers are the largest comparable glaciers for which advance and retreat histories are known. During the last two advance/retreat cycles of the Icy Bay glacier system, each advance phase lasted ca. 300–500 yr, during which mean advance rates were ca. 110–120 m/yr; the retreat phases were only about 100–130 yr long and mean retreat rates were ca. 500–550 m/yr, giving an advance:retreat ratio of ca. 1:5 (Porter, 1989). For most large coastal Alaskan calving glaciers, measured advance rates are generally low (e.g., 32 m/yr for Hubbard Glacier, 22 m/yr for Harvard Glacier, 12 m/yr for Meares Glacier), whereas historic retreat rates are an order of magnitude or more higher [(e.g., 600 m/yr for Columbia Glacier (Meier, 1994), 350 m/yr for McCarty Glacier (Wiles and Calkin, 1993), and 400–600 m/yr for the Glacier Bay glacier system (Viens, 1995)].

These resulting advance:retreat ratios for modern glaciers contrast with the ratio we have derived for the Puget Lobe. However, the Alaskan fjord glaciers advance into deep marine water, and their rate of advance is partly determined by the extent to which frontal calving can be obviated by the construction of a morainal shoal at the terminus (Post, 1975; Viens, 1995). Unlike these fjord glaciers, the Puget Lobe (south of 48° N latitude) advanced rapidly across a nonmarine landscape and apparently did not calve into the relatively shallow lakes impounded beyond the terminus. Whereas Alaskan fjord glaciers tend to retreat rapidly backward in their deep fjords at rates averaging close to 500 m/yr, rapid calving

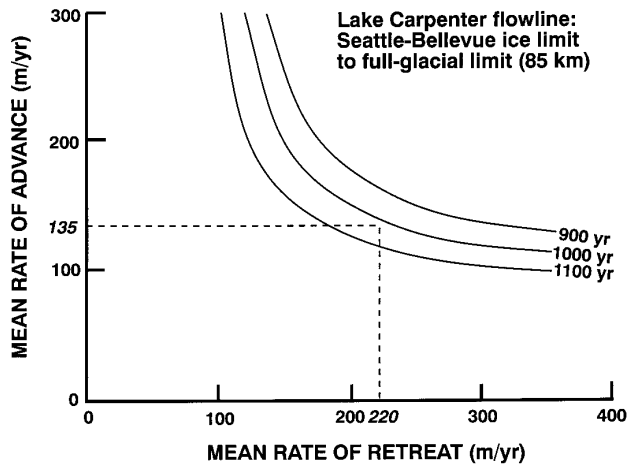

FIG. 7. Curves showing the possible range of mean advance and retreat rates along the Lake Carpenter flowline for ice-covered intervals of 900, 1000, and 1100 yr at the position of the S-BM line. For example, assuming an average advance rate of 135 m/yr, the average grounded retreat rate would be 220 m/yr if the glacier covered the S-BM line for 1020 yr and began to retreat immediately after reaching the glacial limit. A slower rate of advance or a longer time at the glacial limit would result in higher rates of retreat.

recession of the Puget Lobe was restricted to less than 25% of its retreating southern margin where it terminated in meltwater lakes. Only after the ice lobe had largely receded from the Puget Lowland was a large sector of its front in contact with deep marine water that would have favored overall retreat rates comparable to the highest recorded for modern Alaskan glaciers.

CONCLUSIONS

1. During the last glaciation, the southern margin of the Cordilleran Ice Sheet advanced southward from British Columbia, crossed the latitude of the international boundary after ca. 18,750 cal yr ago, reached the latitude of Seattle ca. 17,600 cal yr ago, and overrode a proglacial delta at Issaquah shortly after 17,400 cal yr ago.

2. Assuming an average advance rate near its midline of ca. 135 m/yr, based on the average maximum advance rate between southern British Columbia and Seattle, the Puget Lobe reached its southern limit ca. 16,950 cal yr ago, having traversed the length of the Puget Lowland in about 1000 yr.

3. The ice margin likely remained near its maximum limit for ca. 100 yr, after which it receded along the Lake Carpenter flowline at an overall average rate of 340 m/yr, reached the latitude of Lake Carpenter by ca. 16,500 cal yr ago, and passed the northern limit of the Puget Lowland ca. 450–500 yr after retreat began.

4. Different segments of the ice margin retreated at different rates, depending on whether the terminus was grounded on upland interfluve platforms or calving in a system of deep proglacial meltwater lakes.

5. The maximum interval that the glacier covered the landscape was ca. 1230 yr at Lake Carpenter and ca. 1020 yr at Seattle.

6. Available dates for wood, peat, and gyttja permit a limited range of possible advance and retreat rates, but imply that the average (grounded) rate of glacier retreat was about twice that of glacier advance.

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