

# A Revised and Extended Holocene Glacial History of Icy Bay, Southern Alaska, U.S.A.

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## Abstract

Tidewater glaciers have coalesced to advance through Icy Bay, Alaska, three times during the past 3800 yr. Radiocarbon ages show that the first of these expansions was underway by 3750 cal yr B.P. and culminated at the outer coast between 3505 and 3245 cal yr B.P. Subsequent recession and readvance brought the ice margin back to the outer coast by 1525 cal yr B.P. (cal A.D. 425) where it remained for about 650 yr before retreating. Tree-ring cross-dates of glacially killed trees show that the most recent ice advance was underway through the inner bay by the A.D. 1640s and reached into the outer bay in the 1810s. Historical data support ice expansion through the outer bay in the early 19th century and show a late 19th century maximum prior to 20th century retreat. These results are a significant revision and extension of previous studies of the Holocene glacial history of Icy Bay. Average advance rates for the most recent expansion were typical of modern tidewater glaciers in the inner bay but much faster in the outer bay; shallow water here may have been important to this latter phase of unusually rapid advance.

## Introduction

Icy Bay and its tributary fiords were revealed by over 40 km of tidewater glacier retreat during the 20th century (Fig. 1). Subfossil remnants of shoreline forests abound in the deglaciated areas, and radiocarbon ages of these materials show that the glaciers of this system have coalesced to make two major expansions through Icy Bay during the past 2000 yr (Plafker and Miller, 1958; Porter, 1989). However, the exact timing of the more recent of these advances is unresolved due largely to differing interpretations of historical data. Maddren (1914), Tarr and Martin (1914), and Taliaferro (1932) suggest that ice advanced through Icy Bay after 1794 when the explorer George Vancouver visited Icy Bay. In contrast, the more generally held interpretation is that of Russell (1893), Davidson (1904), Plafker and Miller (1958), Miller (1964), Alpha (1975), Molnia (1977), and Porter (1989), who suggest that ice had already reached the outer coast by 1794 and that the “Icy Bay” seen by Vancouver was actually a small interlobate bay in the area of the modern Yahtse River delta (Fig. 1).

Resolving this chronologic question is important to studies of fiord sedimentation rates and landscape evolution in the Icy Bay area (Molnia, 1977, 1985; Jaeger and Nittrouer, 1999; Meigs and Sauber, 2000). It is also important to regional studies of vegetational (Heusser, 1995), glacial (Calkin et al., 2001), and cultural (de Laguna, 1958) history. There are also glacial dynamic implications; calculations by Porter (1989) suggest that past advances of the Icy Bay glacier were unusually rapid relative to expansions of other Alaskan iceberg-calving glaciers, and this significant result depends directly on a well-constrained glacial history.

In this paper we address the timing of the most recent ice advance using high precision tree-ring cross-dates of glacially killed trees. We also re-examine the historical data and consider historical sources that have not previously been applied to this question. In addition, we use new radiocarbon ages to extend the Holocene glacial history of Icy Bay back to 3800 yr ago.

## Setting

Icy Bay comprises a shallow outer bay and a deeper inner bay (Fig. 1). Low relief forelands adjacent to the outer bay are composed of late

Quaternary coastal, glaciofluvial, and glacial deposits, with the latter being divided into “older” and “younger” moraine systems (Plafker and Miller, 1958; Plafker et al., 1982). Coastal mountains formed of uplifted late Neogene glaciomarine strata rim the inner bay (Eyles et al., 1991), while Cretaceous metamorphic and igneous intrusive rocks form the high peaks of the Saint Elias Mountains (Plafker et al., 1994). Peaks in the coastal ranges reach altitudes of 1000 to 2000 m, while Mount Saint Elias, just 20 km from tidewater, reaches 5489 m.

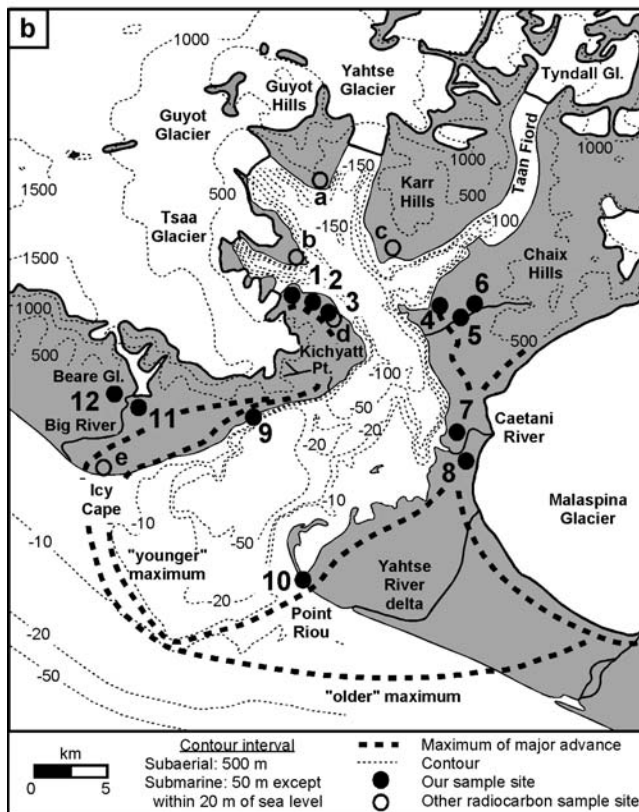
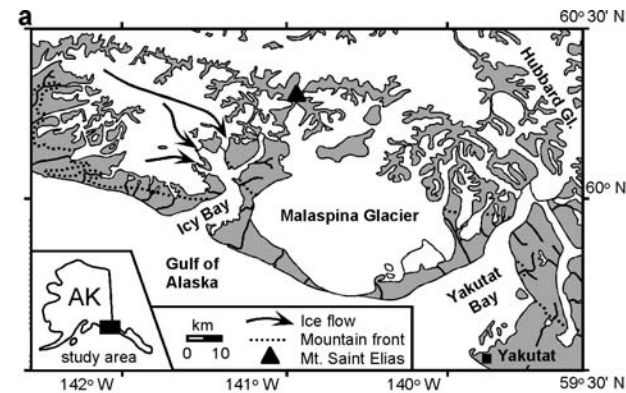
Four fiords radiate from inner Icy Bay and each has a major tidewater glacier at its head (Fig. 1). Guyot is the trunk glacier of the Icy Bay system and shares névés with Yahtse and Tsaa glaciers between the coastal ranges and the Saint Elias Mountains for a combined area of 1624 km<sup>2</sup> (Viens, 1994). Tyndall Glacier in Taan Fiord is an independent system covering 154 km<sup>2</sup> on the southern slopes of Mount Saint Elias. The piedmont lobe of Malaspina Glacier is situated immediately east of the study area and currently supplies meltwater and glaciofluvial sediment to Icy Bay via the Caetani River.

The study area has a maritime climate with Yakutat (Fig. 1) recording mean temperatures of  $-3.4^{\circ}\text{C}$  in January,  $12.0^{\circ}\text{C}$  in July, and a mean annual precipitation of 407 cm for the period 1971 to 2000 (National Climatic Data Center normals). Glaciers in this region are very active with high annual mass turnovers; firn lines vary from 520 to 980 m on the Yahtse-Guyot-Tsaa system and from 730 to 1100 m on Tyndall Glacier (Viens, 1994).

Dominant tree species around outer Icy Bay are western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], mountain hemlock [*Tsuga mertensiana* (Bong.) Carr.], and Sitka spruce [*Picea sitchensis* (Bong.) Carr.]. Sitka spruce is also found around inner Icy Bay together with black cottonwood (*Populus trichocarpa* Torr. and Gray) and Sitka alder [*Alnus sinuata* (Reg.) Rydb.], and the latter alone forms dense thickets along the shores of the tributary fiords. This distribution of arboreal taxa is a seral sequence, with faster colonizers found in areas that have been deglaciated more recently (Heusser, 1995).

## Methods

Landforms and surficial stratigraphy around the shores of Icy Bay were mapped in the summers of 1995 and 1996. Subfossil logs were



**FIGURE 1.** Location maps for Icy Bay. Light shade is land; snow, ice, and water are white. Ice margins are ~1991–1995. Based on U.S. Geological Survey Yakutat, Icy Bay, Bering Glacier, and Mount Saint Elias sheets, 1:250,000 series, 1959 and 1961 (limited revisions 1982 and 1983); NOAA Icy Bay 1:40,000 chart, 1990; and aerial photographs, 1948–1991.

found in many areas with some still rooted in place and buried in glacial sediments, while others were reworked into till, recently eroded into streams, or simply lying on the land surface. Radiocarbon samples were collected from the outer rims of logs and calibrated to calendar years using CALIB 4.3 (Stuiver and Reimer, 1993). Central-point age estimates were calculated as the weighted average of the calibration probability distribution function (Telford et al., 2004) and are denoted as cal yr B.P. or cal A.D. to distinguish them from tree-ring and historical dates that are precise to the year.

Tree-ring samples were collected as cores or disks from the lower part or least-rotted portion of each suitable log. In the laboratory, ring-widths along one or two radii from each log were measured to the nearest micrometer and species identified based on gross features of the sanded surface (Brown et al., 1949). Samples were examined to estab-

lish the preservation of the last years of growth, with the presence of bark or a pristine outer ring around much of a disk indicating that no rings had been lost to decay or abrasion and that the outermost ring was the actual “kill-date” for the tree.

Cross dating was only attempted for spruce and hemlock logs with more than 65 rings, with shorter ring-width series and other species rejected as unsuitable for tree-ring analysis. Samples were first cross-dated with other subfossil logs from the same sampling area; the five resulting site chronologies were then placed into calendar years by cross dating with a master chronology developed from Sitka spruce growing on outwash at Yakutat (Fig. 1). Many of the samples were quite complacent, and this two-step cross-dating process enabled the group ring-width signal for each area to be enhanced prior to comparison with trees from other microclimates and substrates. The computer program COFECHA (Holmes, 1983) was used to suggest cross-date positions, and all cross-dates were verified by visual examination (Stokes and Smiley, 1968).

## Radiocarbon Ages for Older Advances

We obtained 13 new radiocarbon ages and used them with selected recalibrated ages from Plafker and Miller (1958), Plafker et al. (1982), and Porter (1989) to constrain events before A.D. 1500 (Table 1).

## RESULTS

Sites 11 and 12 (Fig. 1) are on opposite sides of Big River where it cuts through a large terrace of glacial sediments. The lowest horizon of *in situ* stumps at Site 11 gave an age of 3505 cal yr B.P. (Fig. 2) and was overlain by outwash gravel. Stumps rooted in the top of this unit gave an age of 3245 cal yr B.P. and were buried in 11 m of till. Similar-aged stumps were found at Site 12 to the northwest but were buried in outwash rather than till. Alder and spruce stumps in the upper forest horizons at sites 11 and 12 vary in age from 1435 to 875 cal yr B.P. (cal A.D. 515 to 1075) and were interbedded with sand and gravel outwash.

Other ages were obtained from small stratigraphic sections at the Chaix Hills and around inner Icy Bay. At Site 5 (Fig. 1) an age of 3750 cal yr B.P. was from an alder root associated with a condensed forest horizon overlain by compact clay-rich till (Fig. 2). A transported spruce log in a lateral moraine at Site 4 had an age of 1700 cal yr B.P. (cal A.D. 250), and ages of 415 and 285 cal yr B.P. (cal A.D. 1535 and 1665) were from spruce logs at sites 3 and 6, respectively (Table 1). These latter two dates are superseded by tree-ring cross-dates and so will not be considered further.

## INTERPRETATION

The oldest four ages (Table 1) suggest an entire advance-retreat cycle prior to the “older” advance of Plafker and Miller (1958) and Porter (1989). This earliest known Holocene expansion advanced over Site 5 in 3750 cal yr B.P., reached close to Site 11 at 3505 cal yr B.P., and culminated around 3250 cal yr B.P. with deposition of till at Site 11 and outwash at Site 12. The exact limits of this advance are unknown, but might be approximated by the “older” maximum that extends across the mouth of Icy Bay (Fig. 1).

Subsequent recession and readvance of the coalesced Icy Bay glaciers is recorded by ages of cal A.D. 1 and 170 from glacially buried logs in inner Icy Bay (Porter, 1989; Table 1). An age of cal A.D. 250 from Site 4 records continuation of this advance into the outer bay, and the presence of the ice margin at the outer coast is recorded by wood samples from the Icy Cape “older” end moraine with ages of cal A.D. 425 and 845 (Plafker and Miller, 1958; Plafker et al., 1982; Table 1). Outwash aggradation at sites 11 and 12 resumed around cal A.D. 515 and continued episodically for the next 550 yr. The culmination of this

second known Holocene expansion is marked by the moraine and related outwash of the “older” maximum at both Icy Cape and Point Riou (Fig. 1).

An alternate source of sediment to sites 11 and 12 is Beare Glacier, a small valley glacier nearby that was at an advanced position in about cal A.D. 600 and again in the A.D. 1640s (G. Wiles and D. Frank, unpublished data). However, we attribute most of the deposition at sites 11 and 12 to the coalesced Icy Bay glaciers based on the size and lateral continuity of this deposit and the similar timing of much of the outwash aggradation here with construction of the nearby “older” end moraine.

The penultimate retreat of ice into the tributary fiords is recorded by ages of cal A.D. 1075, 1155, and 1175 from wood and organic layers in inner Icy Bay (Table 1; Porter, 1989). The two standard deviation radiocarbon age range of these samples overlaps with the age range of the later outwash aggradation events at Site 11; this suggests that ice recession was very rapid, allowing these radiocarbon ages to appear almost coeval.

### Tree-Ring Cross-Dates for Recent Advance

Tree-ring chronologies were developed for five distinct sampling areas (Fig. 3, Table 2), and these were then fixed in time by cross dating with the Yakutat master tree-ring-width chronology. The Caetani and Riou chronologies both contain a mix of spruce and hemlock samples; the successful cross dating of these taxa reflects their similar dendroclimatic response in the northern Gulf of Alaska region (Wiles et al., 1998). The other four chronologies are composed of just Sitka spruce. All cross-dates, both within and between site chronologies, are significant at or above the 99% confidence level (Table 2). A total of 53 subfossil logs were cross-dated and we consider next the implications of their individual kill-dates (Table 3) to the glacial history of Icy Bay.

### RESULTS

The earliest tree-ring dates for ice advance are from the southwestern shore of inner Icy Bay. At Site 1 (Fig. 1), three spruce logs were found in a thin till unit overlying a soil horizon (Fig. 2); the outer rings of all three were intact and cross-dates show that they died in A.D. 1647 (Table 3). Four spruce logs from a narrow gully at Site 2 were less well preserved but record growth until at least 1648. And a kill-date of 1650 was obtained from the two best-preserved logs at Site 3, this being a deposit of till and ice-marginal gravel overlying a soil horizon, plus the adjacent surface of a modern fan delta.

Trees in growth position were found along the Caetani River at sites 7 and 8. These stumps were encased in outwash and truncated at the base of an overlying till unit (Fig. 2). Cross-dates of the best-preserved samples indicate tree deaths clustered into 1705 and the 1740s (Table 3).

Over 100 subfossil logs and stumps were found between 110 and 125 m a.s.l. in a southwest-draining valley at Site 6 (Figs. 1 and 2). They were buried in lacustrine and deltaic sediments, and the kill-dates of well-preserved samples range from 1811 to 1819. In outer Icy Bay, eight trees encased in outwash at Site 9 were killed in about 1810, and three logs in till at Site 10 record growth until at least 1823 (Table 3).

### INTERPRETATION

The kill-dates of trees along the southwest shore of inner Icy Bay (sites 1 to 3) suggests advance of a coalesced Yahrtse-Guyot-Tsaa ice margin in the A.D. 1640s. This would have made an oblique convergence with the shoreline in this area and so would account for the rapid southeastward succession of kill-dates. Although most of these samples were from displaced logs rather than *in situ* stumps, the rugged

**TABLE 1**  
New and recalibrated radiocarbon ages from Icy Bay. See Figure 1 for locations and Figure 2 for stratigraphy.

Laboratory number	Uncalibrated age <sup>a</sup> (B.P.)	Calibrated age <sup>b</sup>		Sample location and description <sup>d</sup>	
		2σ range (cal yr B.P.)	Weighted average <sup>c</sup> (cal A.D.)		
β-98,980	3480 ± 50	3885–3615	3750	—	Site 5. Alder root in a soil.
β-95,985	3270 ± 70	3680–3360	3505	—	Site 11. Wood from forest bed.
β-84,921	3060 ± 70	3445–3005	3250	—	Site 12. Wood from forest bed.
β-95,986	3050 ± 60	3385–3075	3245	—	Site 11. Wood from forest bed.
I-12,280	1990 ± 80	2145–1735	1950	1	c. Po89. Wood beneath till.
UW-530	1855 ± 105	2035–1535	1780	170	d. Po89. Wood beneath till.
β-98,981	1780 ± 50	1820–1565	1700	250	Site 4. Spruce log in till.
W-4510	1630 ± 70	1695–1355	1525	425	e. PI82. Log in till.
β-84,920	1540 ± 60	1535–1310	1435	515	Site 12. Wood from forest bed.
β-84,922	1400 ± 50	1410–1190	1310	640	Site 12. Wood from forest bed.
β-95,988	1270 ± 60	1290–1060	1185	765	Site 11. Wood from forest bed.
W-374	1200 ± 160	1405–790	1105	845	e. PI58. Wood in till.
β-84,923	1090 ± 60	1170–920	1015	935	Site 12. Wood from forest bed.
β-95,989	1000 ± 60	1055–760	895	1055	Site 11. Wood from forest bed.
β-95,987	980 ± 60	1045–740	875	1075	Site 11. Wood from forest bed.
I-12,214	1000 ± 90	1065–675	875	1075	c. Po89. Base of peat layer.
I-12,281	865 ± 80	925–670	795	1155	b. Po89. Log in drift.
I-12,303	860 ± 80	930–565	775	1175	a. Po89. Peat layer.
β-93,993	380 ± 60	515–310	415	1535	Site 3. Spruce log in gravel.
β-93,995	250 ± 40	435–5	285	1665	Site 6. Spruce stump in gravel.

<sup>a</sup> Ages for sites 3, 4, 5, and 6 are corrected for isotopic fractionation using measured <sup>13</sup>C/<sup>12</sup>C ratios.

<sup>b</sup> Calibrated using decadal dendrocalibration curve (Stuiver et al., 1998) in CALIB 4.3 program (Stuiver and Reimer, 1993). Peat samples calibrated using assumed δ<sup>13</sup>C of  $-27 \pm 3\text{‰}$ .

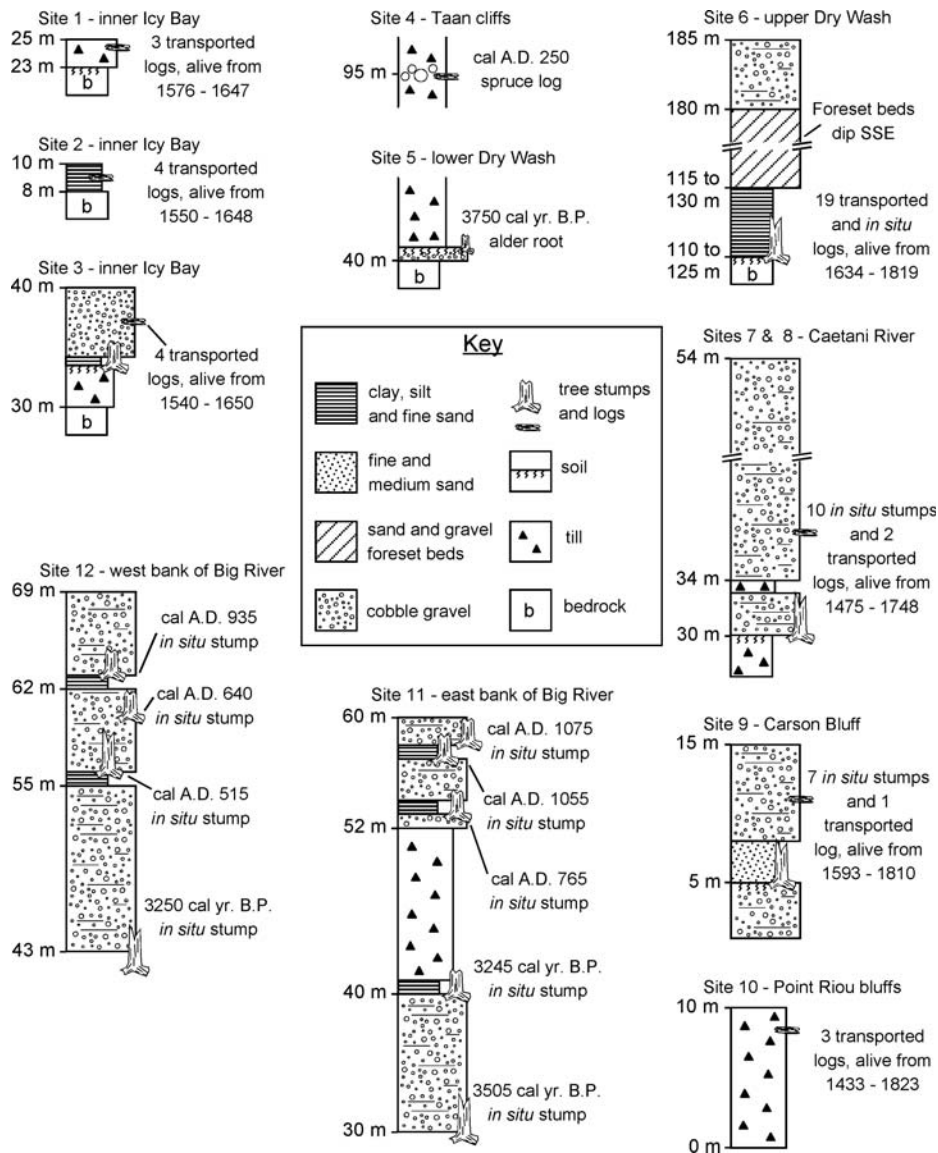
<sup>c</sup> Central-point estimates calculated as weighted average of the probability distribution (Telford et al., 2004).

<sup>d</sup> PI58 (Plafker and Miller, 1958), PI82 (Plafker et al., 1982), Po89 (Porter, 1989).

topography of the side valleys here would have limited glacial transport of these trees from their immediate areas of growth.

The samples from sites 6, 9, and 10 show continued ice margin advance into the outer bay in the 1810s and 1820s. At Site 6 the deposits and setting indicate that the trees drowned in an ice-marginal lake, and the range in kill-dates likely reflects a gradual rise in water level behind a thickening ice dam at the valley mouth. Outwash aggradation over the stumps at Site 9 could only have occurred with the ice margin well south of Kichyatt Point (Fig. 1). The logs at Site 10 were glacially reworked into a till unit; we found no evidence for a paleo-land surface here and so suggest that these logs originally grew on islands in the outer bay to the north of Point Riou.

The Caetani River is situated between Malaspina Glacier and Icy Bay and so the tree deaths at sites 7 and 8 could relate to ice advance



**FIGURE 2. Stratigraphy of sample sites. Ages are either the weighted average of the probability distribution function for radiocarbon ages (cal yr B.P. or cal A.D.) or total duration of forest growth at site based on tree-ring cross-dates. Elevations are in meters a.s.l. See Figure 1 for site locations.**

from either direction. Given the historical data (discussed next) and that trees at sites 6, 9, and 10 around Icy Bay were alive until the early 19th century, we infer that these Caetani River trees were killed by outwash aggradation related to advance of Malaspina Glacier.

### Historical Data for Recent Advance

Historical observations of Icy Bay and its environs in the 18th through 20th centuries provide a useful record of the areas' geography during the most recent ice advance. However, application of these data to the glacial history is complicated by some misidentification of landforms and a general lack of consistently named geographic reference points. Also, some of these accounts have possibly been filtered during translation. We consider these possible errors below, and in presenting the pertinent details we have used, as much as possible, the language of our sources so as to limit our own filtering of their meaning and context.

#### RESULTS: 18TH CENTURY

##### 1788: Izmailov and Bocharov

The 1788 Russian expedition led by Gerasim Izmailov and Dimitrii Bocharov explored Icy Bay in small boats and on foot between

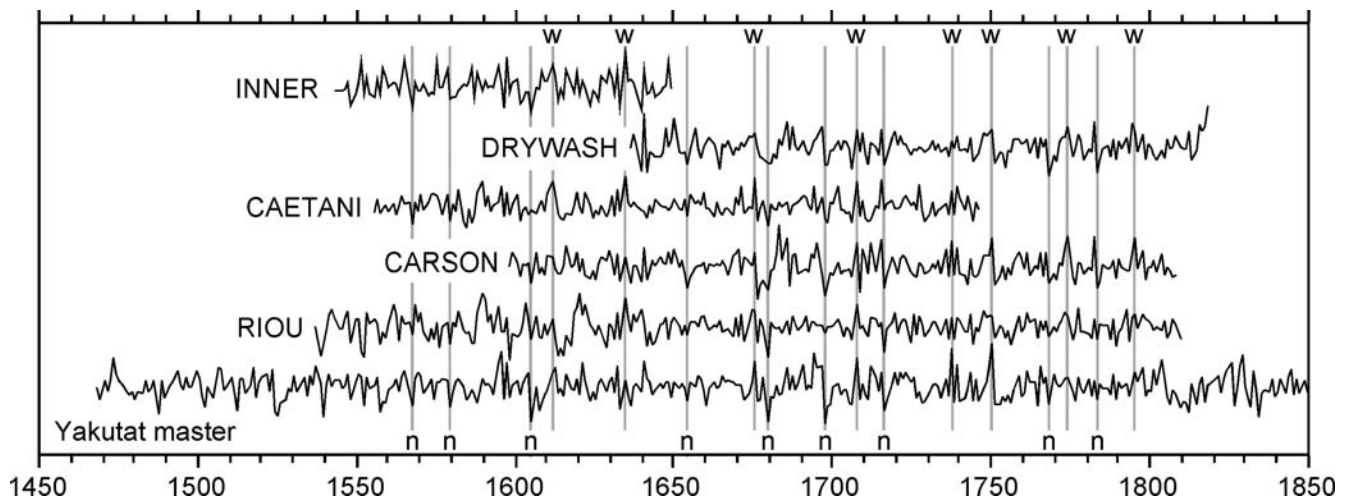
4 and 8 June (Shelikhov, 1981). They described a "creek" in what was probably the area of the modern Caetani River, and an ice-covered "river" farther from the coast that was bounded by a rocky promontory and high ridges. In late June they tried to re-enter Icy Bay in their large vessel but turned around after being alarmed by large icebergs.

##### 1791: Malaspina

The boats of the Spanish expedition led by Alejandro Malaspina were becalmed in fair weather off Icy Bay from 22 to 26 July 1791 (Malaspina, 2003). They stayed offshore making observations and paintings, including a detailed landscape view (Fig. 4a) generally attributed to the expedition geographer Felipe Bauzá but probably by the artist Tomás de Suría (Wagner, 1936). Two inlets or coves were noted within Icy Bay, an eastern one that was probably close to the bay mouth and one in the west that was ice-bound (Malaspina, 2003). De Suría also noted a "passage" or "river" between the coastal mountains and the high peaks of the Saint Elias range (Wagner, 1936).

##### 1794: Vancouver

The British expedition led by George Vancouver spent the last three days of June 1794 offshore of Icy Bay in generally poor weather



**FIGURE 3.** Tree-ring cross-dates of site chronologies. All series have been pre-whitened to enhance year-to-year variability on which cross dating is based. Key narrow (n) and wide (w) marker rings are indicated.

(Vancouver, 1884). A “high cliffy point” that was probably Kichyatt Point was described at the west side of the bay, against which stood a “solid body of ice or frozen snow.” The expedition doctor, Archibald Menzies, noted that Icy Bay was choked with ice and formed a considerable valley that extended to the western side of Mount Saint Elias (Menzies, 1993). Sketches by midshipman Thomas Heddington were subsequently used to make a slightly stylized view of the landscape (Fig. 4b). Vancouver’s chart (Fig. 5a) shows Icy Bay as a broad embayment bounded by Point Riou on the east and centered significantly west of Mount Saint Elias. This chart has a systematic error in longitude of about 15’ (Lamb, 1984; Davis, 1997); this error is evident in Figure 5 where we have used the longitude of Mount Saint Elias to align Vancouver’s chart with a modern map.

*Teben’kov’s Chart*

Although published in 1852, a chart by Mikhail Teben’kov (Fig. 5c) shows Icy Bay in the late 18th century because it is based largely on Vancouver’s chart with longitude corrected and reports by Russian explorers from between 1788 and 1807 (Teben’kov, 1981). A river is shown along the axis of inner Icy Bay and a hatched pattern is used to depict something along the west side of the outer bay (the chart has no legend). The embayment roughly matches that shown on Vancouver’s chart, except that it extends farther inland, and Point Riou is renamed Lowland Cape.

**INTERPRETATION: 18TH CENTURY**

These accounts variously describe an icy “river,” an ice-bound cove, and a “solid body of ice or frozen snow” at the back of the bay

in the late 18th century, and we suggest that these were observations of the Yahtse-Guyot-Tsaa glacier in the inner bay plus an ice-choked entrance to Taan Fiord. This is consistent with the relief described around the icy “river,” the depiction by Teben’kov (Fig. 5c) of a river along the axis of inner Icy Bay, and the implication that this feature was the source of floating ice to the outer bay. These early explorations of the Icy Bay region occurred before scientists began detailed studies on glaciers (Clarke, 1987) and we suggest that these 18th century mariners were unaware of the true nature of the glaciers that they were viewing.

Support for our interpretation comes from the 1794 landscape view (Fig. 4b) that looks north-northwest from an offshore location (Fig. 5b) and shows a large glacier in inner Icy Bay. A sloping ice surface behind the margin is depicted and, based on its angle and the height of the adjacent hills, we infer that this is the Yahtse tributary descending between the Karr and Guyot hills (Fig. 1) with the mouth of Taan Fiord imperceptible from this perspective. The 1791 painting (Fig. 4a) looks north-northeast into Taan Fiord from offshore (Fig. 5b) and shows open water behind Kichyatt Point. The base of the shoreline beyond has a narrow white band that extends halfway to the Chaix Hills shore and, although faint, we suggest that this is the Yahtse-Guyot-Tsaa glacier terminus partially across the mouth of Taan Fiord. The terminus would only rise a couple of hundred meters above sea level at this stage of advance, and Hubbard Glacier looks similar today (Barclay et al., 2001) when viewed from a comparable distance and perspective.

The modern shorelines of both Icy Cape and Point Riou are conspicuously absent in the landscape views (Fig. 4) and the charts by Vancouver and Teben’kov (Fig. 5), and we infer that these areas were below sea level in the late 18th century. At Icy Cape we place the old shore (Fig. 5b) at the inland limit of Terrace IV of Plafker et al. (1982)

**TABLE 2**  
**Descriptive statistics for Icy Bay tree-ring-width chronologies.**

Chronology	Sample sites	Mean series intercorrelation <sup>a</sup>	Number of series	Number of trees	Chronology time span <sup>b</sup>	Years	Correlation with Yakutat master
INNER	1, 2, and 3	0.577	15	11	1543–1649	107	0.471
DRYWASH	6	0.504	27	19	1636–1818	183	0.487
CAETANI	7 and 8	0.482	18	12	1555–1746	192	0.488
CARSON	9	0.660	17	8	1598–1808	211	0.622
RIOU	10	0.567	8	3	1537–1809	273	0.490
Yakutat master chronology		0.641	8	8	1468–1995	528	—

<sup>a</sup> Mean of correlations between series and their respective site chronologies.

<sup>b</sup> Chronology time span is the interval when the chronology has at least two trees and so is slightly shorter than the total duration of forest growth given in Figure 2.

**TABLE 3**

**Cross-dated subfossil trees at Icy Bay. See Figure 1 for locations and Figure 2 for stratigraphy.**

Site 1—Till close to Tsaa Fiord in inner Icy Bay			
1580–1647 <sup>a</sup>	1582–1647 <sup>a</sup>	1576–1647 <sup>a</sup>	
Site 2—Glaciolacustrine silty sand in inner Icy Bay			
1569–1635 <sup>b</sup>	1569–1648	1552–1642	1550–1647
Site 3a—Ice marginal gravel in inner Icy Bay			
1546–1647			
Site 3b—Fan delta surface just downstream of Site 3a			
1554–1650 <sup>a</sup>	1543–1650 <sup>a</sup>	1540–1638 <sup>b</sup>	
Site 6—Dry Wash valley in southern Chaix Hills			
1724–1818 <sup>a</sup>	1687–1811 <sup>a</sup>	1703–1799	1690–1816 <sup>a</sup>
1658–1817 <sup>a</sup>	1714–1819 <sup>b</sup>	1653–1811 <sup>a</sup>	1729–1813 <sup>d</sup>
1654–1812 <sup>a</sup>	1636–1811 <sup>a</sup>	1634–1817 <sup>a</sup>	1677–1816 <sup>a</sup>
1643–1816 <sup>cd</sup>	1714–1819 <sup>d</sup>	1645–1817 <sup>cd</sup>	1695–1809 <sup>d</sup>
1719–1816 <sup>d</sup>	1713–1815 <sup>cd</sup>	1674–1811 <sup>d</sup>	
Site 7—Outwash on north bank of Caetani River			
1475–1663 <sup>b</sup>	1604–1708 <sup>cd</sup>	1555–1667 <sup>b</sup>	
Site 8—Outwash on south bank of Caetani River			
1629–1746 <sup>c</sup>	1640–1744 <sup>ac</sup>	1622–1748 <sup>ac</sup>	1648–1747 <sup>ac</sup>
1633–1743 <sup>c</sup>	1677–1746 <sup>ac</sup>	1592–1730 <sup>bc</sup>	1628–1705 <sup>ac</sup>
1627–1705 <sup>ac</sup>			
Site 9—Outwash at Carson Bluff			
1598–1807 <sup>cd</sup>	1597–1808 <sup>cd</sup>	1593–1807 <sup>cd</sup>	1618–1810 <sup>d</sup>
1732–1808 <sup>cd</sup>	1729–1807 <sup>cd</sup>	1623–1809 <sup>cd</sup>	1724–1809 <sup>cd</sup>
Site 10—Till at Point Riou bluffs			
1654–1823 <sup>d</sup>	1433–1805 <sup>d</sup>	1536–1809 <sup>d</sup>	

<sup>a</sup> Outermost ring preserved.

<sup>b</sup> Outer rings badly rotted or abraded.

<sup>c</sup> Stump still in growth position.

<sup>d</sup> Core sample, so outer ring quality not assessed.

and at Point Riou at the contact between coastal deposits and old moraine farther inland (Plafker and Miller, 1958). No buried land surfaces were found seaward of these lines to suggest sub-aerial exposure in the 18th century or earlier, and Icy Cape has been uplifted at least 13 m since deposition of the “older” moraine (Plafker et al., 1982). Much of this uplift may have occurred during the series of great earthquakes that shook this area in 1899 (Jacoby and Ulan, 1983), when part of inner Yakutat Bay co-seismically rose over 14 m (Tarr and Martin, 1912). Both Vancouver and Teben’kov place Point Riou (Lowland Cape) where the “older” moraine meets the coast (Fig. 1), and we infer that this slightly elevated area formed the eastern headland of Icy Bay in the late 18th century.

The hatched pattern used by Teben’kov (Fig. 5c) along the west side of the outer bay is probably a plume of icebergs shed from the Yachtse-Guyot-Tsaa margin. The same pattern was used by Teben’kov (1981) at the head of Yakutat Bay in areas shown by Barclay et al. (2001) to have been dense floating ice in the late 18th century, and at present the Icy Bay iceberg plume hugs the west side of the outer bay due to the local pattern of water circulation. Both the Russian and British explorers noted considerable floating ice in Icy Bay during their visits.

#### RESULTS: 19TH AND 20TH CENTURIES

##### 1837: Belcher

A British expedition led by Edward Belcher tried to enter Icy Bay on 6 September 1837 with the expressed purpose of resolving dis-

crepancies between the surveys of Cook and Vancouver for the longitude of Mount Saint Elias (Belcher, 1843). However, they found the entire bay to be filled with “snow ice” that formed a 9-m-high cliff at the Gulf of Alaska shore. Vancouver’s Point Riou could not be identified with confidence, with only a low sand or muddy spit being observed in the general vicinity.

##### 1886 to 1891: Climbing Expeditions

Three groups of climbers traveled inland from the Yachtse River delta (Fig. 1) in the late 19th century while attempting to ascend Mount Saint Elias. Descriptions and sketch maps by these 1886 (Libbey, 1886; Seton-Karr, 1887a, 1887b; Schwatka, 1891), 1888 (Topham, 1889; Broke, 1891), and 1891 (Russell, 1893) expeditions show that a glacier completely filled all of Icy Bay and merged inland with both Malaspina and Tyndall glaciers. The Yachtse-Guyot-Tsaa tributary in inner Icy Bay stood considerably higher than Tyndall at their confluence, and the ice surface at the Chaix Hills margin was still thickening and encroaching on forest (Topham, 1889). The Yachtse River delta was at the head of a small embayment between Malaspina and the glacier filling Icy Bay, and was an actively prograding shoreline (Seton-Karr, 1887b; Russell, 1893).

##### 20th Century Observations

Recession of the Icy Bay glaciers began in the 1900s (Madden, 1914; Tarr and Martin, 1914) and continued into the late 20th century (Porter, 1989). The western side of outer Icy Bay eroded rapidly following deglaciation, while slower erosion of Point Riou yielded sediment for the hook spit at the eastern bay mouth (Molnia, 1977). Drainage from the western Malaspina Glacier reverted back into Icy Bay via the Caetani River, and Yachtse River today has been almost completely abandoned.

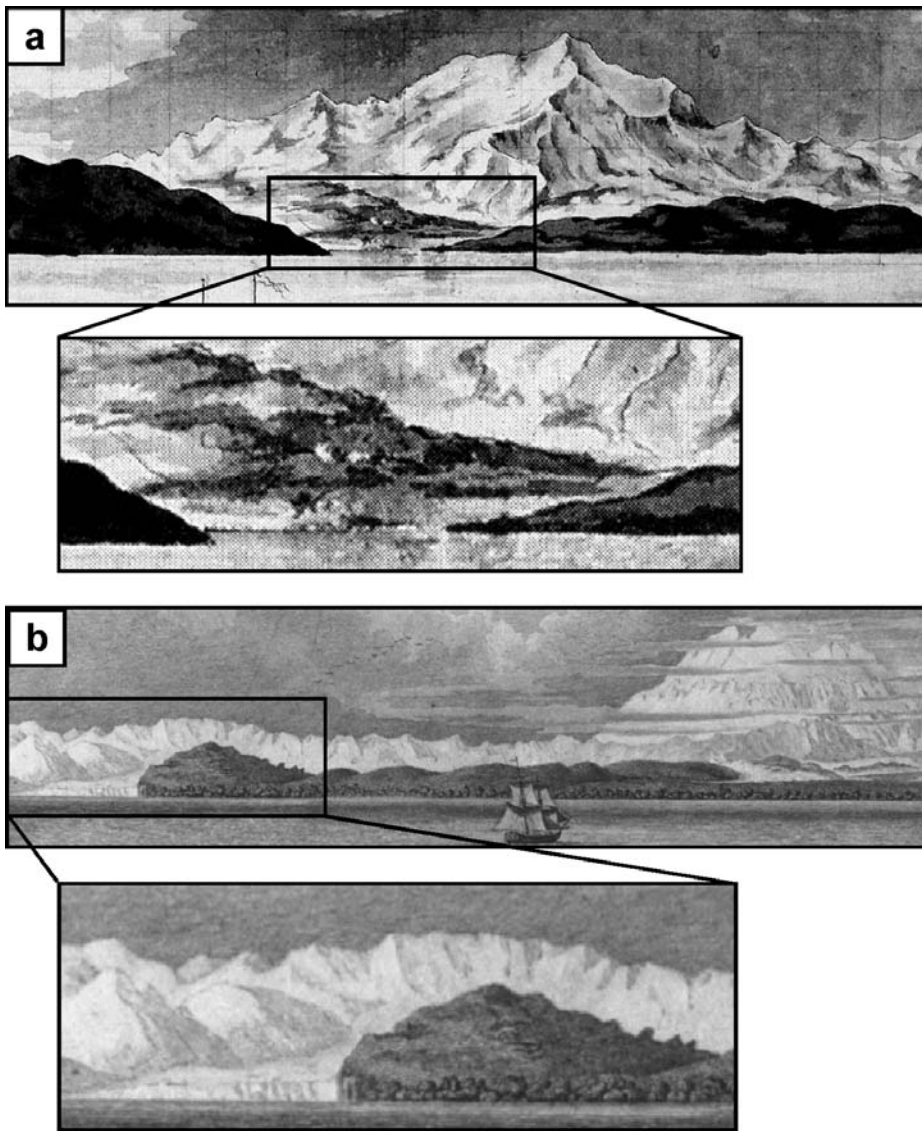
##### Tlinget Oral History

A tale of the local Tlinget people tells of a glacier advance through Icy Bay that overwhelmed one or more native settlements. Topham (1889), Broke (1891), Miller (1964), and de Laguna (1972) all recount similar versions of this tale, and the presence of Tlinget living at Icy Bay in the late 18th century is independently corroborated by both the Russian and Spanish expeditions (Wagner, 1936; Shelikhov, 1981; Malaspina, 2003).

#### INTERPRETATION: 19TH AND 20TH CENTURIES

These observations indicate that the coalesced Icy Bay glaciers advanced through the outer bay in the early 19th century, stood at the “younger” maximum (Fig. 1) in the late 19th century, and retreated during the 20th century. It is clear that the “snow ice” observed by Belcher (1843) was a glacier rather than floating ice from the descriptions of an ice cliff, crevasses, glacial debris, evidence for ice motion, and comparisons drawn to earlier observations at Bering Glacier. Support for this expansion comes from the Tlinget oral history; although the tale is undated and the versions differ in their details, all suggest that a large ice advance occurred in Icy Bay within recent local memory.

It is unclear when Tyndall Glacier advanced, but it was certainly confluent with the Yachtse-Guyot-Tsaa glacier by the late 19th century. The observation that the Tyndall ice surface was lower than the ice in inner Icy Bay suggests that the Yachtse-Guyot-Tsaa névés dominated ice supply to the Icy Bay glacier, which is consistent with their combined area being an order of magnitude larger than the névés of Tyndall Glacier.



**FIGURE 4.** Landscape views of Mount Saint Elias and Icy Bay. (a) 1791 painting showing Kichyatt Point (left) and the Chaix Hills (right) as dark foreground hills. From Museo de America 2-248. (b) 1794 lithograph showing a glacier in inner Icy Bay. See Figure 5b for vantage points.

Ice advance through outer Icy Bay left an embayment between its eastern edge and Malaspina Glacier where the Yahtse River delta is today (Fig. 1), and by the late 19th century the name “Icy Bay” had shifted in local usage to refer to this small embayment rather than the glacier-filled bay to the west. The Yahtse River delta grew rapidly as meltwater from both the Icy Bay and Malaspina glacier systems was focused into this interlobate area. Shoreline progradation here would have been aided by advance of Malaspina Glacier during the 18th and 19th centuries, and such advance is suggested by the burial of forest in outwash at sites 7 and 8 (Fig. 2, Table 3), the disappearance of Lowland Lake and southward growth of the shore around Sitkagon Cape on Teben’kov’s map (Fig. 5c), and the cross-cutting relationship between the “older” Icy Bay end moraine and Malaspina Glacier (Fig. 1; Plafker and Miller, 1958).

## Discussion

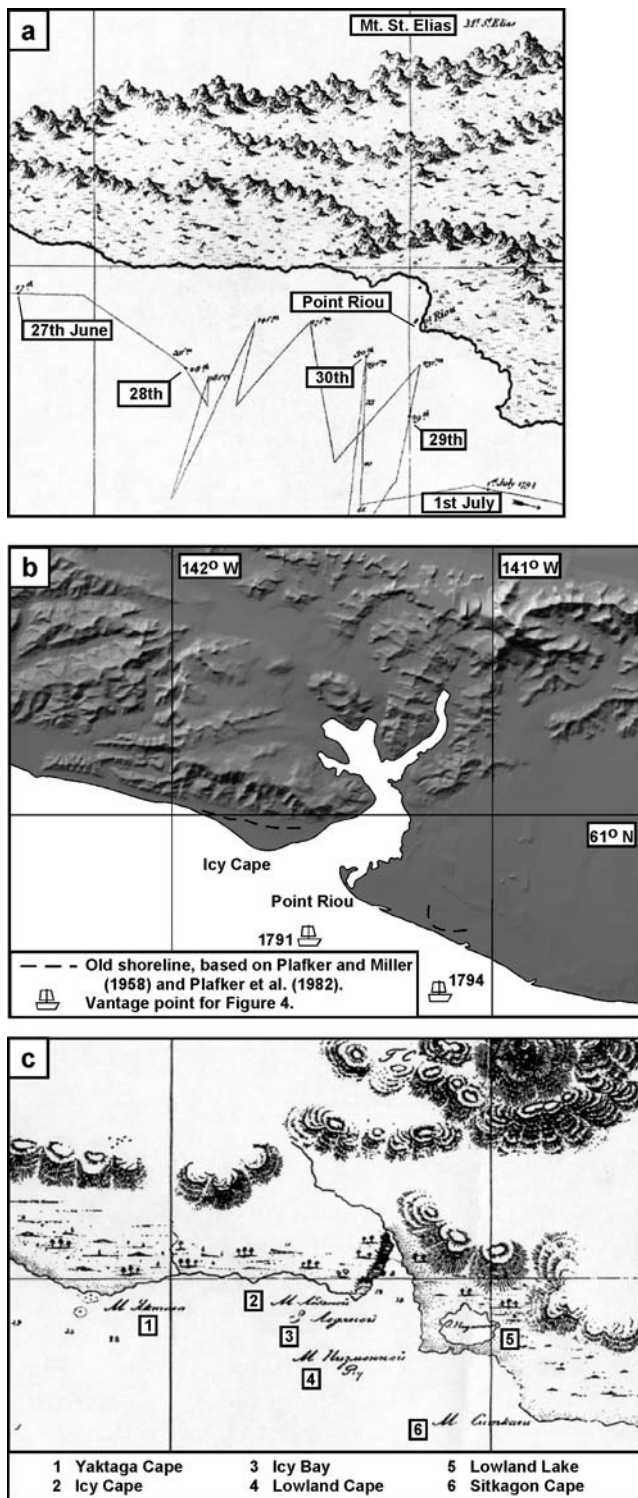
### COMPARISON WITH PREVIOUS STUDIES

Our tree-ring cross-dates of tree death show that the most recent glacier expansion through Icy Bay occurred about 200 yr later than suggested by Porter (1989). This discrepancy can be attributed to the inherent imprecision of radiocarbon ages; for example, all of our

radiocarbon ages (Table 1) have two standard deviation ranges (95% probability) that span over 200 yr. We note that our tree-ring cross-dates fall within the two standard deviation range of Porter’s radiocarbon ages from comparable areas and proffer our tree-ring dates as a more precise basis for reconstructing the most recent ice advance.

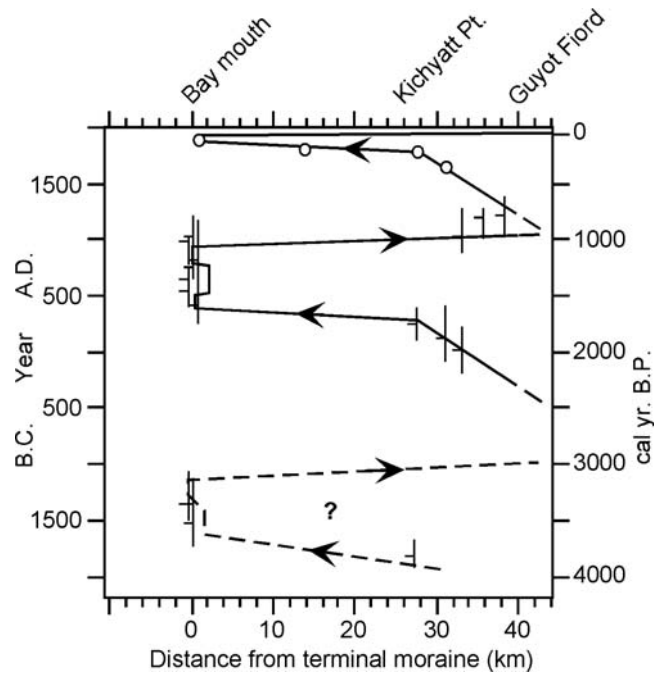
Porter (1989) suggested that the most recent advance through Icy Bay began with a surge of Tyndall Glacier to near Kichyatt Point and blockage of a large ice-dammed lake in inner Icy Bay. This hypothesis was proposed to explain glacial lake deposits in many areas of inner Icy Bay and fit with the apparent sequence of radiocarbon ages in these areas. However, Porter’s large lake hypothesis is inconsistent with our tree-ring results; the last years of growth recorded at sites 1 to 3 (Figs. 1 and 3) show neither a southwestward expansion of the relatively small Tyndall Glacier nor a simultaneous inundation and killing of trees in inner Icy Bay. Rather, the last years of growth are best explained by advance of the much larger Yahtse-Guyot-Tsaa glacier. We interpret the lacustrine deposits throughout inner Icy Bay to be the result of many small ice-marginal lakes dammed in the rugged fiord-side valleys of this area during glacial advance.

Russell (1893), Davidson (1904), Plafker and Miller (1958), Miller (1964), Alpha (1975), Molnia (1977), and Porter (1989) all infer that Icy Bay was completely occupied by a glacier in 1794 and that Vancouver’s “Icy Bay” was a small embayment farther east. In



**FIGURE 5.** Coastal charts of the Icy Bay area. (a) 1794 survey by Vancouver, (b) 1983 digital elevation model (DEM) with old (dashed) and 1991–1995 shorelines, (c) late 18th/early 19th century compilation by Teben'kov. Dashed line in (a) shows ships track between 27 June and 1 July 1794. All three charts have been aligned using the longitude of Mount Saint Elias, and our annotations of (a) and (c) are in boxes.

contrast, we concur with Maddren (1914), Tarr and Martin (1914), and Taliaferro (1932) that the bay seen by Vancouver was a broader version of outer Icy Bay, through which the coalesced Icy Bay glaciers advanced in the decades after 1794. The bay observed by the late



**FIGURE 6.** Time-distance diagram for the coalesced Icy Bay glaciers. Distance is along the centerline of Icy Bay and Guyot Fiord. Control points are calibrated radiocarbon ages with two standard deviation range (T-bars) and tree-ring ages and historically defined ice marginal positions (open circles).

18th century explorers fits with the general appearance and location of outer Icy Bay, and Kichyatt Point is shown as ice-free to sea level in the 1791 painting (Fig. 4a). Furthermore, our tree-ring dates show that trees were alive at sites 6 and 9 until at least 1810, and this is hard to reconcile with complete glaciation of Icy Bay by 1794.

The hypothesis for rapid sediment infilling of Icy Bay due to progradation of the Yahtse River delta (Russell, 1893; Alpha, 1975; Molnia, 1977; Porter, 1989) remains applicable to the easternmost edge of outer Icy Bay. This area was open water in the late 18th century, was beyond the “younger” maximum (Fig. 1), and would have received focused meltwater and glaciofluvial sediment from both the Icy Bay and Malaspina glacier systems after the coalesced Icy Bay glaciers advanced past the Caetani River. However, sedimentation rates for this infilling should be re-evaluated on the basis of the revised glacial history presented herein.

#### CAUSES AND RATES OF ADVANCE

Synthesis of the radiocarbon, tree-ring, and historical data (Fig. 6) shows the late Holocene fluctuations of the coalesced Icy Bay glaciers to have been cyclic with rapid recessions following maxima, and this fits with the paradigm of a tidewater glacier cycle (Post, 1975; Meier and Post, 1987; Post and Motyka, 1995). Iceberg calving was probably the dominant form of ablation through most of these cycles and so these fluctuations primarily reflect glacier dynamics rather than climate change. The only time when surface melting, and thus climate forcing, could be important was when the coalesced Icy Bay glaciers were at or close to maxima (Mann, 1986; Wiles et al., 1995), and this is supported by the retreats initiated in circa A.D. 1075 and 1900 that were coincident with, respectively, the Medieval Warm Period (Cook et al., 2004) and the retreat of many tidewater and land-terminating glaciers in southern Alaska (Barclay et al., 2003) at the end of the Little Ice Age.

The average advance rate through the inner bay from 1650 to 1791 was at about  $20 \text{ m a}^{-1}$ , a rate that is typical for Alaskan tidewater



glaciers in deep fiords today (Meier and Post, 1987). In contrast, between 1791 and 1886 the terminus expanded over an area of about 370 km<sup>2</sup>, an along-flowline distance of about 28 km at an average of 295 m a<sup>-1</sup>. This latter phase of advance was far larger and faster than any other recent tidewater glacier expansion in Alaska. Taku Glacier in southeastern Alaska did advance rapidly between 1890 and 1973 at average rates of 50 to 150 m a<sup>-1</sup>, but total ice margin displacement for this interval only amounted to about 6 km (Post and Motyka, 1995). And the 150 m a<sup>-1</sup> maximum average advance rate at Taku was only sustained for 8 yr, whereas the 295 m a<sup>-1</sup> average advance rate at Icy Bay would have had to been sustained for 95 yr to accomplish the reconstructed ice margin displacement. Perhaps the only 20th century glacier expansion of comparable rate and magnitude was the 20 km surge advance of Bråsvellbreen in Svalbard between 1936 and 1938 (Schytt, 1969).

The reason for the rapid advance may have been a decrease in iceberg calving caused by shoaling at the terminus. The ice margin could not have advanced through inner Icy Bay without a submerged morainal bank (Post, 1975), and this feature may have become emergent as the terminus entered the shallow water of the outer bay. Post and Motyka (1995) inferred shoaling at the terminus to have been important to the 20th century rapid advance of Taku Glacier, and Belcher (1843) suggested that a muddy beach underlay the Icy Bay ice margin in 1837. We consider rapid advance during a surge to be less likely because Yahrtse, Guyot, and Tsaa glaciers have no record of surging, and both of the more recent expansions appear to have accelerated in the same place (Fig. 6), suggesting a geometric control on rapid advance in this area of Icy Bay.

## Conclusions

New radiocarbon ages were used to extend the glacial history of Icy Bay back to 3800 yr ago and to constrain a previously unrecognized cycle of advance and retreat. This earliest known Holocene expansion was underway by 3750 cal yr B.P. and reached to the bay mouth between 3505 and 3245 cal yr B.P. A second Holocene expansion, previously described by Plafker and Miller (1958) and Porter (1989), brought the ice margin back to the bay mouth where it remained from about 1525 to 875 cal yr B.P. (cal A.D. 425 to 1075).

Tree-ring and historical data were used to constrain the most recent ice expansion through Icy Bay. Cross-dates of glacially killed trees show that the coalesced Yahrtse-Guyot-Tsaa glacier was advancing in inner Icy Bay in the A.D. 1640s and expanded through the outer bay in the early 19th century; this was about 200 yr later than suggested in most previous studies. Descriptions, paintings, and charts by 18th and 19th century explorers support this revised history and suggest that a hypothesis for 19th century sediment infilling of Icy Bay only applies to the easternmost bay mouth.

Initiation of the last two ice recessions coincided with warming intervals in southern Alaska, suggesting that climate change may have triggered these rapid retreats. Advance through the inner bay was at a typical rate for Alaskan tidewater glaciers in deep-water fiords today; in contrast, expansion through the outer bay was far larger and faster than any Alaskan tidewater glacier advance in the 20th century. The penultimate advance also accelerated through outer Icy Bay, and decreased iceberg calving in the shallow water here may have caused these unusually large and rapid expansions.

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