The McCarty Fjord iceberg-calving glacier and its land-terminating tributaries have fluctuated with some asynchronicity during the past two millennia. During advance, McCarty Glacier shed outwash along the fjord, and into ice-dammed tributaries inundating forests. A radioacarbon framework has revealed at least two major late Holocene glacial advances that occurred following a poorly documented expansion about 3600 BP. These two later advances are resolved within this fjord with tree-ring dating of \textit{in situ} and transported tree trunks. The first event was an early medieval expansion of the McCarty trunk glacier beyond midfjord about 596 A.D.; this followed an interval of tree growth of at least 206 years. Tributary glaciers probably also advanced at this time. However, continuous tree-growth occurred in the distal (southern) tributary valleys during this advance, while northern tributaries were being dammed by the advancing trunk glacier. The down-valley extent of this expansion is thus constrained to a position within 12 km of the present contracted ice margin.

The tree-ring refined chronology shows that a second McCarty ice expansion began in the 9th century, and reached midfjord by 900 A.D., and continued to advance through the Little Ice Age. In contrast, expansions of land-terminating glaciers here began after 1300 A.D. in concert with mountain glaciers worldwide. A log from a diamict cross-dated with a living tree-ring chronology shows that McCarty Glacier was advancing within a kilometer of its Little Ice Age maximum at 1790 A.D. Since about 1905 A.D., dramatic ice retreat has uncovered more than 20 km of McCarty Fjord.

**INTRODUCTION**

**Objectives**

A record of late Holocene glacier fluctuations is preserved in sediments at the forefields of tongues, such as McCarty Glacier, which emanate from the Harding and the Grewingk-Yalik icefields of the southern Kenai Mountains (Fig. 1; Wiles and Calkin, 1990). Preserved in these sediments are \textit{in situ} and detrital trees representative of forests overrun by ice during three intervals of late Holocene time. Our investigations in this area have generally focused on variations of land-terminating glaciers as proxies of climate change. These studies provide baseline data from which we can examine fluctuations of the fjord-calving outlet tongues on the east flank of the mountains.

Observations of the temperate fjord glaciers in Alaska show that while in the calving condition, termini frequently undergo large-scale, slow advance and rapid disintegration. These are often asynchronous with adjoining land-terminating tongues and with climatic fluctuations (Mann, 1986; Meier and Post, 1987). Such fluctuations may be primarily related to water depth at the terminus, fjord configuration, and changes in hypsometry with respect to equilibrium line altitudes (Mercer, 1961; Post, 1975; Brown et al., 1982).

McCarty Fjord is remarkably uniform in both length and depth between the McCarty Glacier margin and inside its Holocene terminal moraine (Fig. 2). In addition, confluent ice masses have been relatively small. This geometry simplifies our objectives in the study reported here, which are to define the Holocene chronology of McCarty Glacier and to compare this with that of local land-terminating glaciers.

**Setting**

Multiple glacial fluctuations and tectonic subsidence of approximately 1 m per century have resulted in the deeply incised McCarty trough stretching oceanward 60 km from the margin of McCarty outlet tongue. Mesozoic graywackes and slates that form the bedrock walls of the upper 20 km occupied by ice during Holocene time, rise from sea level up to 1500 m altitude; they also produce a relatively uniform maximum depth of 270 m through this reach. Fjord walls are interrupted by the valleys of the Dinglestadt outlet tongue and by a set of contracted mountain glaciers in Delectable Bay (unofficial name) that were tributary to McCarty Glacier during the Holocene (Fig. 2).

The climate of the eastern mountain flank is maritime. Moisture-laden Pacific air masses that move westward from the Gulf of Alaska are intercepted by the icefield, producing an estimated 3–10 m year$^{-1}$ of precipitation (Rice, 1987) of which over 50–70% may be snow (Clagett, 1988). The mean annual temperature from Seward (Fig. 1), located about 50 km northeast of McCarty Glacier, is 4.2°C (Ruffner and Bair, 1987). Glacier tongues are fringed by a Sitka spruce and mountain hemlock forest that have colonized the deglaciated areas at lower elevations since 3000 BP (Ager, 1983).

**FIELD DATA AND METHODS**

The dramatic retreat of the whole McCarty Glacier...
system over the past century has uncovered extensive exposures of glacial sediments. These sediments include stratigraphic sections of multiple units, paleosols and buried forests. Radiocarbon ages from organics in these sediments from the McCarty Fjord and a few from adjoining areas are summarized in Table 1. Ages have been converted to calibrated years using the Radiocarbon Age Calibration Program of Stuvier and Reimer (1986). Discussion below will refer to the mean calibrated age.

Sections of subfossil logs obtained from a variety of stratigraphic settings have provided the opportunity to fine-tune the radiocarbon-based glacial history of the fjord using tree-ring cross dating. Ring-width time series were constructed at the Tree-Ring Laboratory of Lamont-Doherty Geological Observatory, Columbia University. Cross-dating and quality control for ring-width chronologies were performed using the computer program COFECHA (Holmes, 1983).

Chronologies have been built using the ARSTAN computer program (Cook, 1985; Cook and Holmes, 1984). This program produces tree-ring chronologies from ring-width measurement series. Detrending and indexing the series removes most of the age-trend effects which are primarily caused by trees tending to...
grow rings of decreasing width with increasing age. Individual ring-width indices are calculated by dividing the actual measurements by values from the growth-trend curve. Means of indices for each year are computed using a biweight robust estimate. The processing also reduces the effects of any unusual individual tree growth variations and quantifies the common growth variations of all trees in a sample set. Climate variations are usually the common factor influencing growth ring variations for all trees from one location. The resulting chronologies were used in computer cross-dating of trees of uncertain age.

Tree-ring dating of logs preserved in sediments here was implemented using two strategies. In the first strategy, logs of known radiocarbon age were cross-dated with those of unknown age. These logs were derived primarily from forests composed of up to 20 in situ and transported trees located in tributary valleys along the east side of the fjord (Fig. 2). Most of these subfossil logs are rotted; however, enough logs were sampled to construct a ‘floating’ tree-ring chronology (Fig. 3a) from trees in Delectable Bay and near Desire Lake (Fig. 2). This chronology was pinned down in absolute time by a calibrated \(^{14}\)C age of 897 A.D. (BETA-39629) from the outer rings of one of the cross-dated trees. That is, while the relative timing of events could be resolved in terms of years to decades, the absolute age was limited by the calibrated radiocarbon date. This chronology spans 508 years from 408 to 916 A.D. and is composed of 15 time series of ring-width radii from 11 trees.

The second strategy used in dating involved the construction of a living tree-ring chronology (Fig. 3b). This chronology, taken from the nearby Petrof Glacier area (Fig. 1), is made up of 26 cores from 21 trees and spans 373 years, from 1616 to 1988 A.D. Cross-dating tree-ring series from subfossil logs with this living chronology allows us to assign calendar dates to the logs preserved in the sediments.

**CHRONOLOGY OF THE McCARTY TRUNK GLACIER**

**Early Advances**

The earliest indication of McCarty Glacier advance during the Holocene is inferred from glacial stratigraphy and two radiocarbon ages. Post (1980) obtained an age of 3674 BP (UW-513, Loc. 1, Fig. 2; Table 1) from detrital wood lying on an erosion surface, 6 km beyond the present east margin of McCarty Glacier and 10 m above high tide. We obtained wood of similar age, 3563 BP (BETA-39631) in this area near sea level from a diamict overlain by tens of meters of sand and gravel.

**FIG. 3.** Tree-ring series: (a) Floating tree-ring chronology from subfossil logs of Delectable Bay and Desire Lake in McCarty Fjord. Also shown are the ranges of the 15 time series from the 11 subfossil trees; (b) Petrof living tree-ring chronology and correlative time series from a subfossil log in McCarty Fjord used in dating.
Together these occurrences suggest McCarty Glacier may have been advancing near its present margin at this time.

Drift containing both in situ tree remains and transported subfossil wood comprise evidence of a second advance (early medieval advance, Fig. 4). A branch collected by Post (1980) from a bouldery till, 80 m above sea level at Location 1 (Fig. 2), yielded an age of 554 A.D. (UW-514). He also obtained an age of 561 A.D. (UW-512) from a log 6 m above sea level at midfjord, Location 2 (Fig. 2). Furthermore, we obtained an age of 596 A.D. (BETA-33345, Table 1) from the outer rings of an in situ tree that was apparently overwhelmed by outwash along the margin at midfjord (Loc. 3, Fig. 2). Ring counts from this stump indicate ice-free conditions existed for at least 200 years previous to burial.

These ages are consistent with a well-established, brief glacial advance dated at about 500 A.D., which is also displayed on the forefields of at least four outlet glaciers from the nearby icefields (Wiles and Calkin, 1990). This corresponds with the early medieval cold interval recorded in the Northern Hemisphere (Lamb, 1977).

The terminal position of the McCarty Glacier during this early medieval advance is not certain; however, limits of ice extent can be estimated based on the floating tree-ring chronology of Fig. 3a. Cross-dating of logs near Desire Lake, just beyond midfjord (Fig. 2), attests to continuous forest growth from 408 to 890 A.D., coincident with this early advance. East-trending sand and gravel fans exposed in Delectable Bay (Fig. 5) require a source from the adjacent advanced McCarty trunk glacier which must have dammed this tributary. This damming occurred prior to soil development, and spruce forest growth on these gravels, which began about 680 A.D. This age, obtained from the inner rings of the oldest tree cross-dated from Delectable Bay (Fig. 3a), also provides a minimum for ice removal from the adjacent fjord. Fan sedimentation into Delectable Bay (Fig. 5), continuous forest growth near Desire Lake, and forests buried in outwash with ages from the latter half of the 6th century (Fig. 2), all suggest early medieval ice reached a maximum at Delectable Bay. Delectable Bay corresponds to a marked southward widening (Fig. 2) of the fjord.

Later Advance

The extent of retreat that occurred from midfjord by 680 A.D. is not documented; however, a readvance brought the McCarty Glacier back through the Delectable Bay position (Fig. 2) within an interval as short as two centuries to a terminus at James Lagoon (Figs 2, 4). This terminus is now marked by a distinct end moraine shoal and occurs where opposing tributaries allowed the glacier width to double, thus inhibiting further ice advance.

All cross-dated trees (Fig. 3a) sampled within Delectable Bay were buried in outwash by 915 A.D., as based on a radiocarbon age of 897 A.D. (BETA-39629) for the floating chronology. Two other in situ tree stumps yielded ages of 968 and 968 A.D. (BETA-35927, BETA-39630), which are within one standard deviation of BETA-39629. In addition, trees near Desire Lake, to the south, were killed about 890 A.D. (Fig. 3a). This nearly contemporaneous killing of trees, about 900 A.D., points to a third expansion of the McCarty trunk glacier.

Current direction indicators measured in sand and gravel that buried the forest in Delectable Bay show that the sediment here was derived from within this tributary valley. However, better sorted east-dipping sequences of sediments that bear cross-dated tree trunks in Desire Bay suggest deposition from the trunk glacier into an ice-dammed lake. Therefore, we believe the McCarty Glacier was at an advanced position during the 9th century in order to dam Delectable and Desire Lakes. Aggradation within these tributaries must have occurred due to a change in base level resulting from the filling of McCarty trough by ice.

McCarty Glacier probably continued to advance into the 18th and 19th centuries. Cross-dating of trees that are preserved in diamicts with the Petrof tree-ring chronology (Fig. 3b) suggests that ice reached within a kilometer of its terminal moraine about 1790 A.D. (Loc. 6, Fig. 2). Grant and Higgins (1913) in 1909 estimated that ice reached its terminal position here about 1860 A.D. (Fig. 4). The motions of the ice margin between 915 A.D. when it dammed Delectable
Neoglacial Fluctuations and Sedimentation

TABLE 1. Radiocarbon ages from the southern Kenai Mountains

<table>
<thead>
<tr>
<th>Laboratory no.</th>
<th>Uncalibrated age</th>
<th>Calibrated interval</th>
<th>Location on Fig. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGS-1278</td>
<td>1440 ± 70</td>
<td>1397 (1329) 1292</td>
<td>—</td>
</tr>
<tr>
<td>BETA-33345</td>
<td>1480 ± 70</td>
<td>1416 (1354) 1307</td>
<td>5</td>
</tr>
<tr>
<td>BETA-33800</td>
<td>690 ± 70</td>
<td>685 (669) 643</td>
<td>1265 (1281) 1379</td>
</tr>
<tr>
<td>BETA-35927</td>
<td>1080 ± 70</td>
<td>1064 (982) 938</td>
<td>886 (968) 1012</td>
</tr>
<tr>
<td>BETA-39629</td>
<td>1120 ± 60</td>
<td>1070 (1053) 96</td>
<td>880 (897) 986</td>
</tr>
<tr>
<td>BETA-39630</td>
<td>1090 ± 50</td>
<td>1059 (982) 950</td>
<td>891 (968) 1000</td>
</tr>
<tr>
<td>BETA-39631</td>
<td>3310 ± 60</td>
<td>3631 (3563) 3470</td>
<td>BC 1682 (1614) 1521</td>
</tr>
<tr>
<td>*UW-512</td>
<td>1500 ± 90</td>
<td>1516 (1389) 1307</td>
<td>434 (561) 643</td>
</tr>
<tr>
<td>*UW-513</td>
<td>3915 ± 75</td>
<td>3816 (3681, 3674, 3641) 3569</td>
<td>BC 1867 (1732, 1725, 1692) 1620</td>
</tr>
<tr>
<td>*UW-514</td>
<td>1510 ± 95</td>
<td>1524 (1396) 1310</td>
<td>420 (554) 640</td>
</tr>
</tbody>
</table>

*From Post (1980). Post (pers. commun., 1993) has noted that the locations of UW-512 and UW-514 were reversed in his original reference.

Bay, and 1790 A.D. when it reached near its terminus 9.5 km to the south, are unknown. A continuous advance during this interval could have averaged about 11 m year\(^{-1}\). Details of recent recession from its terminal position are considered in a separate section below.

INTERACTION BETWEEN McCARTY AND LAND-TERMINATING GLACIERS

The chronologies of tributary glaciers are constrained by glacial stratigraphy and radiocarbon ages. A maximum age for cirque glacier advance in Delectable valley (Loc. 5, Fig. 2) is inferred from a date of 1281 A.D. (BETA-33800) obtained from the upper organic-rich beds of a lake sequence. These sediments, which occur within a few hundred meters of the rapidly backwasting margin of the easternmost glacier, are capped by a diamict recording subsequent ice advance down Delectable valley. This evidence is interpreted to suggest that ice buildup in tributary valleys and major ice expansion lagged behind the McCarty advance (∼1300 A.D.) by more than 400 years.

Near the mouth of Delectable Bay two superimposed diamict facies overlie alluvial sediments preserving the buried forest (Fig. 5). The lower diamict consists of 10 cm to more than a meter of pebbly compact silt and is apparently a basal till. This lower till may record advance of ice from within Delectable Bay across lacustrine sediments prior to eventual confluence with McCarty Glacier. The superjacent diamict is a gravely, loose deposit interpreted as a supraglacial meltout till. The upper coarser till (Fig. 5), which occurs sporadically and up to a meter in thickness, represents the medial and lateral moraine debris shown in aerial photographs of 1950 A.D.

Dinglestadt is the other significant land-terminating glacier entering McCarty Fjord (Figs 1, 2). The west-flowing tongue of the Dinglestadt transection glacier on Kachemak Bay (Fig. 1) was advancing over forests at its present margin by 621 A.D. (BGS-1278; Wiles and Calkin, 1990). Therefore, it seems likely that the eastern tongue of Dinglestadt Glacier entering McCarty Fjord may also have been advancing across its present marginal position and confluent with the McCarty trunk glacier at this time.

Evidence of later ice advance at Dinglestadt Glacier consists of an undated deltaic sequence overlain by a till

![FIG. 5. Stratigraphic section at Delectable Bay (Loc. 4, Fig. 2).](image)
uncovered by margin retreat after 1950. This section records initial empounding of lake waters by McCarty Glacier in front of the advancing Dinglestadt tongue during the most recent advance of the trunk glacier and subsequent Dinglestadt (tributary) ice advance. Therefore, this stratigraphy from the forefields of Delectable and Dinglestadt Glaciers support near-synchronous expansions of these land-terminating glaciers with the McCarty iceberg-calving tongue during the early medieval advance. However, two of these stratigraphic sections also support a later Little Ice Age advance of the land-terminating glaciers that occurred at least 400 years after that of McCarty Glacier.

**ICE-MARGINAL RECESSION IN McCARTY FJORD**

Retreat of the glacier tongues from McCarty Fjord is well-documented by observations and aerial photography (Fig. 6). During July and August of 1909, Grant and Higgins (1913) recorded the ice margin as still grounded on the end moraine about 360 m behind its terminal position. The oldest spruce tree cored on this terminal moraine in James Lagoon, provided a minimum date for retreat of 1905 A.D. This date is based on a ring count with an added regional estimate of 15 years for the time of tree establishment (Wiles and Calkin, 1990).

A series of photographs taken by Paul Smith of the U.S. Geological Survey in 1925 (Whitney, 1932) showed the margin 1.5 km behind its 1909 position. Observations by Whitney (1932) in 1927 recorded an additional 1.6 km of recession. More recent analysis of aerial photographs by Post (1980) indicated that the glacier had receded approximately 5 km from 1927 to 1942. By 1950, McCarty Glacier had backed off an additional 11 km and in 1960, 1.6 km more, putting it within a few kilometers of the fjord head. Post (1980) reports a slight readvance from this 1960 position by 1977. Analysis of photographs taken in 1979 show the margin near its 1977 position. Bud Rice (pers. commun., 1990) has recorded an advance of approximately 1 km from 1988 to 1990.

This late Holocene retreat from a 20-km reach of the fjord (Fig. 6) has occurred in approximately 55 years. Calving rates (Table 2) as a function of water depth can be calculated from the bathymetric data of Post (1980). Iceberg-calving rates \( V_c \) of fjord glaciers are proportional to the average water depth at the glacier margin with a constant of proportionality of 27 m\(^{-1} \) (Brown et al., 1982). Ice velocities can be calculated using the continuity equation \( V_c = V - \dot{X} \), where \( V \) is ice flow velocity and \( \dot{X} \) is the rate of change of glacier length (which is positive in the direction of flow). Table 2 shows the calving rates and ice velocities of McCarty Glacier over the past 50 years (Fig. 6). Fjord depths (Post, 1980) are considered to be minimum values since sedimentation followed deglaciation. Calving speeds and ice velocities, by continuity, must also be minima.

Calving rates have exceeded ice velocities over the 51-year interval resulting in this dramatic retreat. The retreat rates have increased as the glacier margin has revealed deeper waters to the north and then, have decreased as the ice margin was again grounded near the head of its fjord. The interval with the highest rate of retreat is that between 1942 and 1950 (Fig. 5) where McCarty Glacier was entering the deepest reach of its basin.

Contrasting with this rapid retreat of the McCarty fjord glacier has been the slow wasting of the land-terminating tributary glaciers. U.S. Geological Survey
Dinglestadt and Delectable valleys still in their ex-deglaciated fjord with tributary glacier margins from glaciers is consistent with many studies (e.g. Mann, chronologies that vary with those of land-terminating earlier than the characteristic advances of the Little Ice Age, as well as that of the Lituya Bay ice tongue, is major characteristic of the McCarty Glacier chronology, as well as that of the Lituya Bay ice tongue, is that the last ice margin expansion began considerably earlier than the characteristic advances of the Little Ice Age (Grove, 1988). In the southern Kenai Mountains as elsewhere in the Northern Hemisphere (Porter, 1986), these advances began during the 13th century or later. That these iceberg-calving glaciers may have chronologies that vary with those of land-terminating glaciers is consistent with many studies (e.g. Mann, 1986), but differs somewhat from interpretations of synchronicity made by Porter (1989) from his Alaskan studies. In the sense that episodes of advance encompass 300–1000 years compared with those of deglaciation in less than 200 years, the existing record from McCarty Glacier is compatible with the work of Porter (1989) in Icy Bay and Mann and Ugolini (1985) in Lituya Bay. A more detailed chronology may show that the 1000-year interval encompasses many shorter advances and retreats of the ice margin. Whether recent advance of McCarty Glacier is recorded beginning by 900 A.D. This preceded the Little Ice Age, and spanned a local nonglacial interval correlated with the medieval warm period (Optimum).

Tree-ring dating constrained more precisely the intervals of ice expansion and contraction than the radiocarbon chronology alone. For example, without the aid of tree-ring analysis, the nearly contemporaneous killing of at least 10 trees in tributary valleys along the eastern margin of McCarty Fjord within a 50-year period from 867 to 915 A.D. would not have been recognized from the few radiocarbon ages.

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