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Tree ring–dated glacial history for the first millennium C.E., Casement Glacier and Adams Inlet, Glacier Bay, Alaska, U.S.A.

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ABSTRACT

Calendar dating of tree-ring series from 16 logs sampled near the margin of Casement Glacier combined with tree-ring dates on 36 detrital logs from Adams Inlet, Glacier Bay National Park and Preserve, Alaska, show killing of trees by ice and lake sediments from the mid-sixth through mid-seventh centuries C.E. The dates from the land-terminating Casement Glacier show ice advance into a forest between 560 and 570 C.E. within a few kilometers of the 2011 retreating margin. Advance of the tidewater glacier in Muir Inlet blocked off Adams Inlet forming Lake Adams between 540 and 640 C.E. This glacier and lake history for Glacier Bay is consistent with other land-terminating ice expansions across the Gulf of Alaska that similarly show advance centered on 600 C.E., as well as other proxy records from lakes all suggesting cooling during this interval. The cooling closely follows a series of eruptions in the mid to late sixth century, which may have contributed to the cooling. Radiocarbon ages in Adams Inlet suggest that Lake Adams persisted through 880 cal. yr C.E. and drained by 1170 cal. yr C.E. Ice retreat and this lake drainage are broadly coincident with Medieval warming recognized along the Gulf of Alaska in dendroclimatic reconstructions. Shortly after this retreat, Little Ice Age readvance occurred with Casement Glacier coalescing with glaciers in Adams Inlet and the West Arm, subsequently filling all of Glacier Bay to its Holocene maximum by 1750 C.E.

Introduction

The fjords and mountains of Glacier Bay National Park and Preserve (GBNPP), located ~100 km west-northwest of Juneau, occur in one of the most tectonically and glacially active regions of southeastern Alaska (Fig. 1). The Glacier Bay watershed, within the central part of GBNPP, is bounded by the Fairweather Range to the west, the Saint Elias Mountains and the Takhinsha Mountains to the north and the Chilkat Range to the east (Fig. 1). Glaciers covered southeast Alaska during the Pleistocene and had retreated onto land from Last Glacial Maximum (LGM) positions in the Gulf of Alaska by ~16,000 yr B.P. (Mann and Hamilton, 1995). Ice appears to have retreated into the upper part of the West Arm fjords in Glacier Bay by ~15,200 yr B.P. (Powell and Carlson, 1997). During the Holocene, ice advanced and retreated several times in both the East and West Arms; closely following retreats, forest regrowth occurred, from which interstadial stumps and logs were often preserved by subsequent ice expansions (Muir, 1895; Cooper, 1937; Goldthwait, 1963, 1966; Haselton, 1966; McKenzie and Goldthwait, 1971; Lawson et al., 2007; Connor et al., 2009; Wiles et al., 2011).

This study area includes Adams Inlet, which is a dumbbell-shaped embayment and eastern tributary to Muir Inlet in the East Arm (Fig. 1) of Glacier Bay. To the north, Casement Glacier's outwash

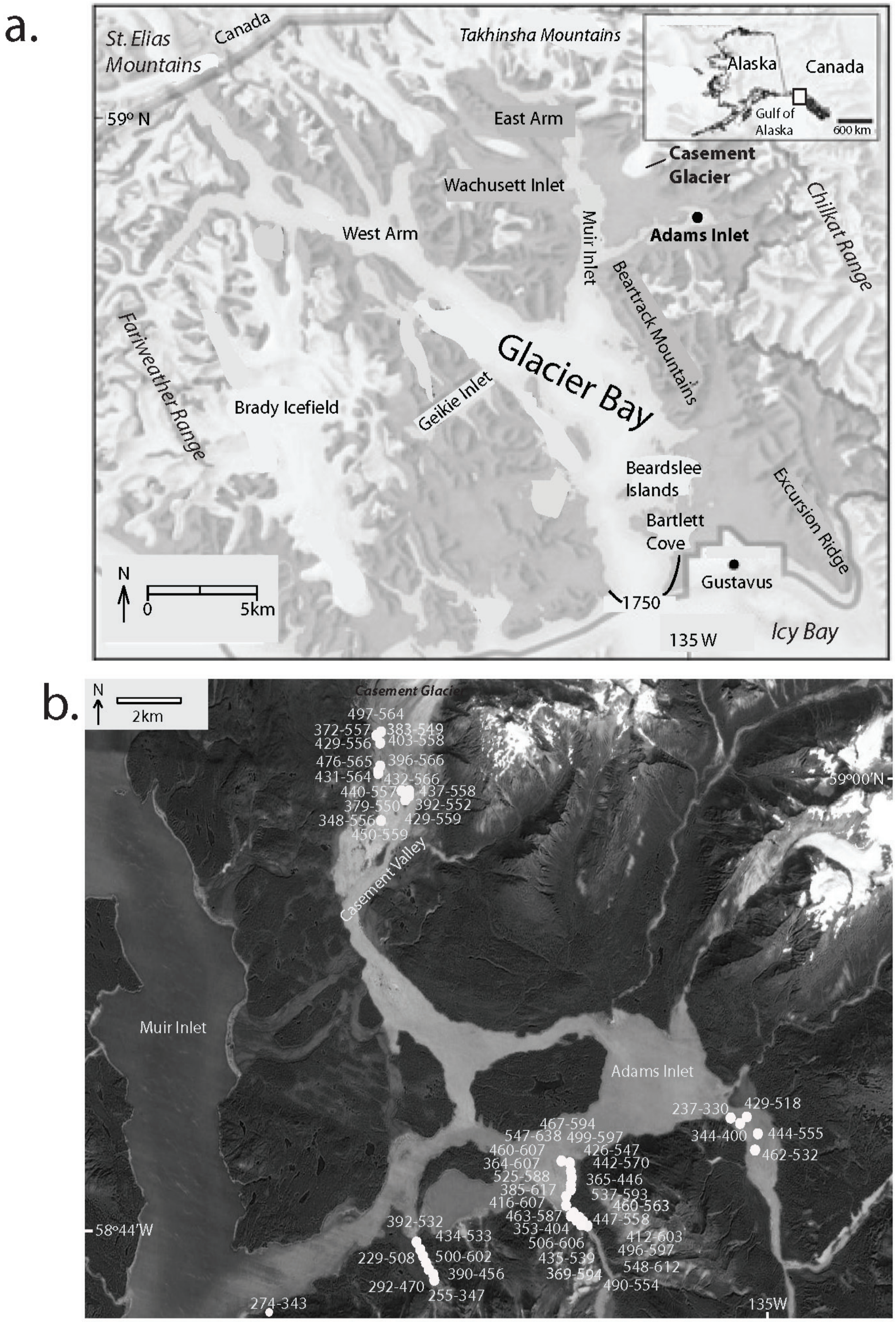

FIGURE 1. (a) Location map of Adams Inlet and Casement Glacier, Glacier Bay National Park and Preserve, and the geographic setting of the region. (b) Detailed map of calendar-dated samples and the tree-ring ages of the logs at each location.

TABLE 1

Radiocarbon Dates from Muir and Adams Inlet.

ID number	Uncalibrated age (^{14}C yr. B.P.)	Weighted average (cal. yr. B.C.E./C.E.)*	Relevance to study	Reference
Y-305	850 ± 100	1170 C.E.	Minimum age on damming of Lake Adams	Goodwin (1988)
DIC-1316	1640 ± 50	410 C.E.	End of Lake Muir	Goodwin (1988)
I-1302	1400 ± 120	630 C.E.	Log on the west side of Casement Glacier	Goodwin (1988)
I-1610	2120 ± 115	160 B.C.E.	Ice advancing into Muir Inlet	Haselton (1966)
I-2687	1700 ± 100	340 C.E.	Beginning of Lake Adams	Haselton (1966)
B-9259	1150 ± 60	880 C.E.	End of Lake Adams	Goodwin (1988)
GB99-192-01	1700 ± 40	340 C.E.	New evidence for Lake Adams	Lawson (2007)
GB00-199-02	1730 ± 40	310 C.E.	New evidence for Lake Adams	Lawson (2007)
GB01-118-02	1410 ± 40	630 C.E.	New evidence for Lake Adams	Lawson (2007)

*Calibrated with IntCal13 calibration curve (CALIB 7.1). Central point estimate is the weighted average of probability distribution function rounded to the nearest year (Telford et al., 2004).

enters Adams Inlet, and during the Little Ice Age (LIA), Casement was tributary to the valley glaciers flowing out of the mountains surrounding Adams Inlet, which together drained into Muir Inlet (Fig. 1). The Holocene history of Adams Inlet includes the advance and retreat of glaciers, formation of glacial lakes through damming by ice in Muir Inlet, and infilling by significant amounts of lacustrine and fluvial sediments (McKenzie and Goldthwait, 1971).

Previous glacial studies based on radiocarbon ages (McKenzie and Goldthwait, 1971; Goodwin, 1988) indicated that Muir Inlet was dammed at least twice over the last 3000 years by ice expansions down the West Arm. An early lake, Glacial Lake Muir, formed about 2500 yr B.P. and drained sometime about 2000 yr B.P. based on ring counts of trees radiocarbon dated growing on Lake Muir sediments (Goodwin, 1988; McKenzie and Goldthwait, 1971). A second advance formed Glacial Lake Adams about 340 cal. yr C.E., killing forests within Adams Inlet, and then drained several hundred years later, shortly after 880 cal. yr C.E. (Table 1; McKenzie and Goldthwait, 1971; Goodwin, 1988). As early as 1170 cal. yr C.E. (Goodwin, 1988), ice flowing out of Muir Inlet merged with ice flowing out of the West Arm reaching a maximum extent during the LIA at Icy Strait by ~1750 C.E. (Fig. 1; Larsen et al., 2005; Mann and Streveler, 2008). Within several decades of 1750 C.E., the tidewater terminus of the Glacier Bay Glacier began its retreat, reaching into the uppermost parts of the West Arm at the head of Tarr Inlet by about 1916 C.E. (Cooper, 1937). Ice margins retreated into Muir Inlet by about 1870 C.E. (Seramur et al., 1997), evacuating ice from Adams Inlet by about 1940 C.E. (Price, 1965), and reaching the upper parts of Muir Inlet by about 1990 (Cowen et al., 2010).

To improve upon the late Holocene glacial history for the region, we have assembled a tree-ring record from logs at Casement Glacier and Adams Inlet associated with glacial advance and recession. This work is part of an ongoing project building the tree-ring record for a portion of the Holocene (Lawson et al., 2007; Capps et al., 2011; Wiles et al., 2011). To date, tree rings have been used to calendar-date Little Ice Age advances at Brady Glacier and two pre-LIA advances in the Geikie Glacier drainage (Fig. 1). These records and this present study allow for comparisons of glacier histories across the Gulf of Alaska. The calendar-dated land-terminating glacial histories based on dendrochronology from the Gulf of Alaska (Barclay et al., 2013; Wiles et al., 2011) can also be used to infer times of cooling based on glacier expansion, and thereby help to identify potential climate forcings.

Methods

Interstadial logs as well as in situ, rooted stumps are being exposed by the continuing ice recession and erosion of glaciolacustrine and glaciofluvial de-

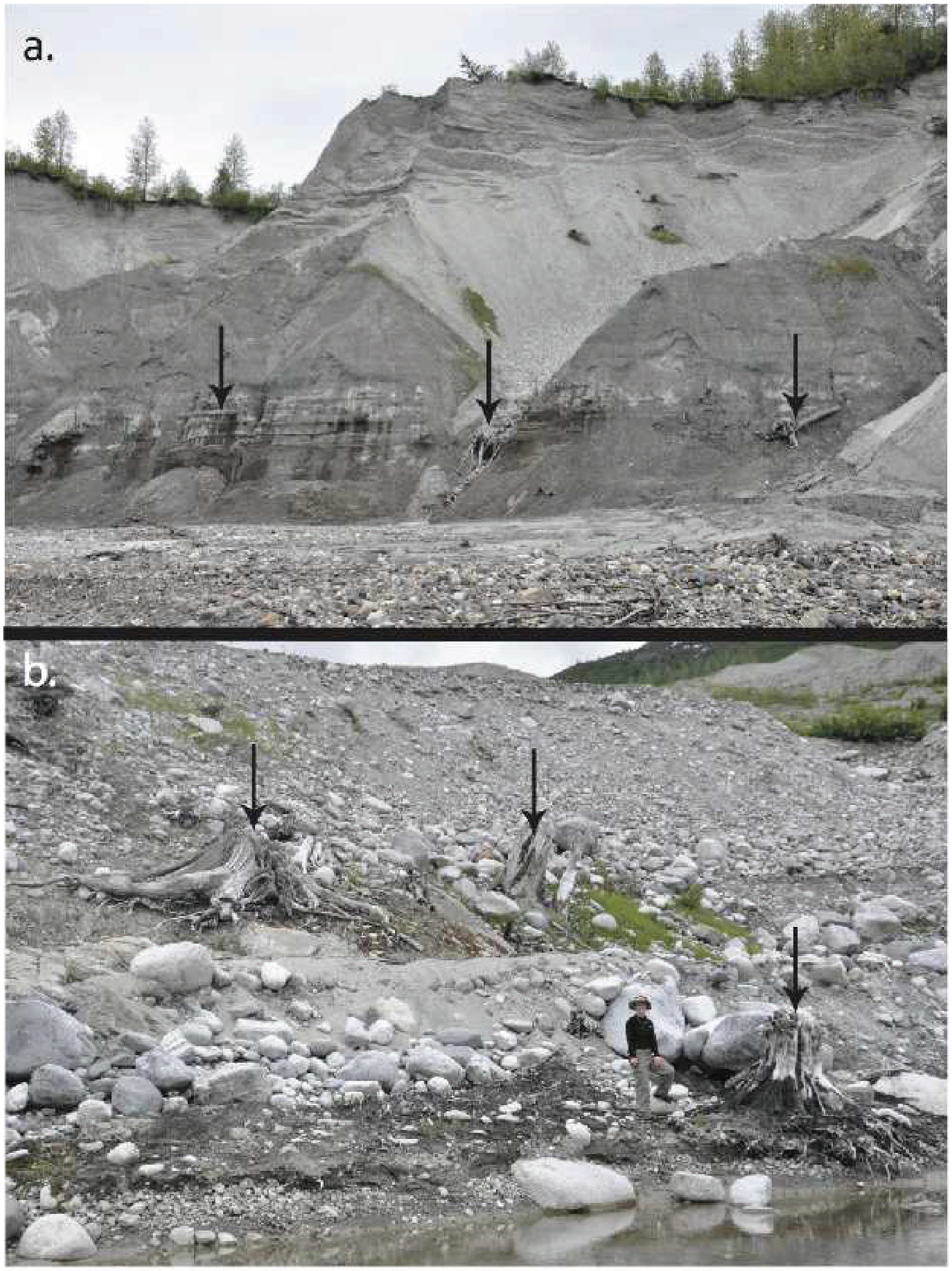

FIGURE 2. (a) Logs encased in lacustrine sediments from Adams Inlet. Note that the logs are preserved in silts and clays and overlying these is a sequence of deltaic sands and gravels. (b) In situ stumps located within 2 km of the 2011 ice margin in front of Casement Glacier. The glacigenic sediments at this site include outwash gravels and diamicts.

posits within the Casement Valley and, Adams and Muir Inlets. A total of 52 tree-ring samples were collected at various times between 2008 and 2014. These samples consisted of increment cores from 12 trees and 24 log cross sections from Adams Inlet and increment cores from 16 trees in the northern Casement Valley (Fig. 1). Most logs sampled in Adams Inlet are generally located within deltaic and lacustrine sediments exposed by erosion (Fig. 2). The tree sections are both western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka Spruce (*Picea sitchensis* (Bong.) Carr.). Most of the samples do not include the outer rings due to abrasion and degradation because they have been exposed over the past several decades. As a result, we consider the outer tree-ring calendar dates as minimum limiting ages for the interpreted glacial events.

The Casement Glacier had retreated onto land from Muir Inlet about 1907 and has since developed drainage to the south into Adams Inlet (Price, 1965). The logs sampled in this forefield occurred within the current active outwash plain, as well as in diamict and glaciofluvial sediments (Fig. 2) along the outwash margin. Both in situ rooted stumps and detrital logs were sampled with increment borers to collect cores from 16 trees at four different sites along a north-south transect (Figs. 1 and 2).

Wood sections and cores were prepared and processed using standard tree-ring techniques (Stokes and Smiley, 1996). Both cores and sections were sanded and polished to a high finish using 400–600 grit sandpaper. Two ring-width radii per log and two cores per tree were measured to the nearest 0.001 mm using a Velmex stage and binocular microscope at the College of Wooster Tree Ring Lab. Cross-dating was initially done with two or more series from one log, then between logs sampled in a common stratigraphy. Dating was done visually and supported and checked statistically using the COFECHA routine (Holmes, 1983; Grissino-Mayer, 2001) to produce floating chronologies. These floating series were then compared with calendar-dated ring-width records from across the Gulf of Alaska (Barclay et al., 2009a, 2013; Wiles et al., 2008, 2011) that, combined, begin in 114 C.E. The dating among floating chronologies from the first millennium C.E. are consistent, and the correlations are highly significant (Table 2). The final calendar-dated chronology is then a combined ring-width chronology, consisting of 110 ring-width series from 52 logs from the Casement Glacier and Adams Inlet.

Calendar-dated tree-ring ages in this paper are reported as year C.E. We also have assembled radiocarbon ages for the study area based on past work (Table 1). Radiocarbon ages are presented as cal. yr C.E. and they were calibrated with the IntCal13 calibration curve using the program CALIB 7.1 (Stuiver and Reimer, 1993; Stuiver et al., 2005). We used the weighted average of the probability distribution function rounded to the nearest decade (Telford et al., 2004; Table 2) as a best estimate of radiocarbon ages. Approximately 10 outer rings were submitted for radiocarbon analysis for those ages cited in Lawson et al. (2007), the remainder of radiocarbon ages reported here were previously published (Table 1).

Results and Discussion

The combined tree-ring record from the Adams and Casement Glacier series spans 410 years during the interval of 229–638 C.E. (Table 2; Fig. 3). The earliest inner ring calendar age is 229 C.E. in Adams Inlet and 348 C.E. in the Casement Valley. Dating of the former forest at Casement Glacier shows tree growth between 348 and 568 C.E. with inferred advance at about 560–568 C.E. (Figs. 1 and 3) killing the forest. Logs dated in Adams Inlet were spanned 229–638 C.E., with kill dates over greater than a 100-year period between 540 and 640 C.E. (Fig. 3). Casement Glacier, as well as other local valley glaciers, likely coalesced to fill Adams Inlet with ice inundating most of the region after 640 C.E. Radiocarbon dates of 310, 340, and 630 cal. yr C.E. (Table 1) on wood in Adams Inlet support the tree-ring dates, although our calendar dates tied to tree rings are more accurate as a time of tree death and thus improve on the radiocarbon-based history of previous workers (Goodwin, 1988; McKenzie and Goldthwait, 1971).

The kill dates for the century-long (540–640 C.E.) interval of tree death in Adams Inlet likely reflect the complex history of the damming of Glacial Lake Adams by ice in Muir Inlet. The tightest cluster of kill dates in the tree-ring series occurred between 600 and 620 C.E. (Fig. 3), although dates on transported

TABLE 2

Correlations of the Adams Inlet and Casement ring-width series with four masters from the Gulf of Alaska.

Location of master*	Name (Glacier)	Interval (C.E.)	Years of overlap	Correlation**
Kenai Peninsula[1]	Tebenkof	437–611	174	0.49
Cordova[1]	Sheridan	465–608	144	0.56
Icy Bay[2]	Beare	403–604	201	0.52
Glacier Bay[3]	Geikie	247–621	374	0.65

[1]Barclay et al. (2013); [2]Wiles et al. (2009); [3]Wiles et al. (2011).
*Location shown on map (Fig. 4, part b).
**All correlations are highly significant at >0.0001 level.

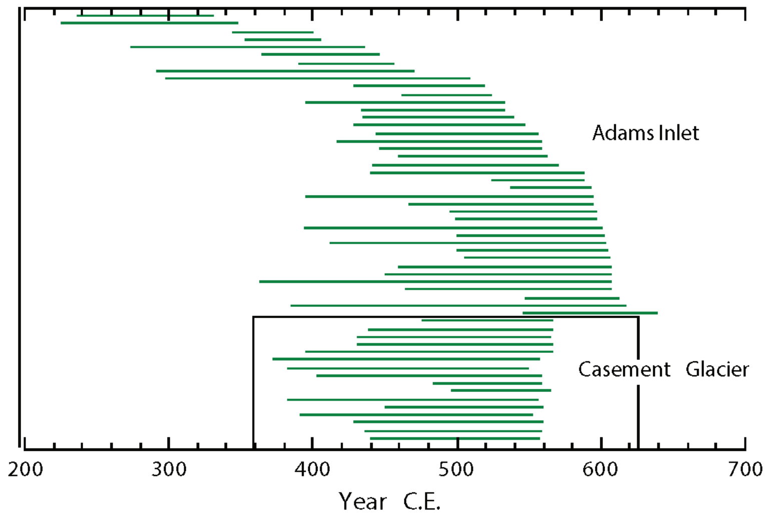

FIGURE 3. Calendar dated tree-ring series showing an interval of at least 400 years of forest growth within Adams Inlet prior to forest death at around 640 C.E. Each line represents the calendar-dated lifespan (C.E.) of an individual tree. The advance of Casement Glacier dates to about 560 C.E., whereas the damming of Glacial Lake Adams spans at least 540–640 C.E.

logs prior to this time could also have been killed by lake damming. Our calendar dates on trees killed as a result of burial by glaciolacustrine and deltaic deposition clearly limits the timing of the formation of Lake Adams, as well as on the ice encroaching and filling Adams Inlet (Fig. 3). In our study, no tree survived past 640 C.E., which suggests that the glacial lake reached its maximum depth about this time.

Previous studies (Goodwin, 1988; McKenzie and Goldthwait, 1971) based on radiocarbon dates suggested that Muir Inlet was already filled with ice by ~340 cal. yr C.E. (Table 1), with the entrance of Adams Inlet probably dammed by a combination of infilling by outwash from Muir Glacier and ice flowing out of the West Arm (Table 2; Goodwin, 1988). Other evidence in Glacier Bay similarly based on calendar dates on forest debris shows advance of ice about 850 C.E. (Wiles et al., 2011) across Geikie Inlet, 40 km down bay to the southwest from Adams Inlet. This advance in Geikie Inlet may be a continuation of ice advance recognized at Casement and Adams glaciers. Whether advance persisted through the study area into the 9th century is uncertain.

The timing of ice advance and lake formation in Adams Inlet as well as the advance into Geikie Inlet is consistent with Mann and Streveler's (2008) relative sea level (RSL) history for Icy Strait (Fig. 1). A high RSL stand is linked to isostatic depression of the Icy Strait shorelines under glacier loading. This high stand (ice advance) was reconstructed during the interval of 700–1100 cal. yr C.E. (Mann and Streveler, 2008), which broadly matches with the expansion of Casement Glacier, the subsequent damming of Lake Adams with advance past Muir Inlet, and the continued advance south to Geikie Inlet as causing the isostatic depression.

A radiocarbon age of 880 cal. yr C.E. that may record the final stages of Lake Adams and another radiocarbon age on a stump located 2 km south of Wachusett Inlet shows ice-free conditions at this time, and it is likely that Lake Adams with its outlet south of here was drained by 1170 cal. yr C.E. (Table 2; Goodwin, 1988; McKenzie and Goldthwait, 1971). After an unknown ice-free interval, ice then readvanced across this region shortly thereafter and filled the full Glacier Bay by 1750 C.E. (Goldthwait, 1963; Motyka, 2003).

While a great deal of work has been done studying and interpreting climatic events for the Gulf of Alaska during the past 1000 years (Wilson et al., 2007; Wiles et al., 2014; Barclay et al., 2009a, 2009b), less attention has focused on the first millennium C.E. This is due, in part, because the evidence for it was generally destroyed or obscured by the more extensive, subsequent LIA advances. A summary of radiocarbon-dated glacier expansions by Reyes et al. (2006) and Wiles et al. (2004, 2008) and, more recently, tree-ring dates (Wiles et al., 2011; Barclay et al., 2013) document widespread advance of glaciers across coastal and near-coastal British Columbia and Alaska during the first millennium C.E. These glacier advances have been attributed to a general cooling and multidecadal periods of low solar activity (Solomina et al., 2015). Lake records from southern Alaska also identify the First Millennium C.E. centered on 600 C.E. as a cold interval (Hu et al., 2001; Kaufmann et al., 2007). Additionally, the mid to late sixth century has been identified as an interval of strong high sulfate volcanic activity with events at 536, 540, 573 C.E. (Sigl et al., 2015) leading to cooling of European summer temperatures on the order of 2 °C and general cooling in the northern hemisphere. It is possible that decreases in solar radiation later (~700 C.E.; Steinhilber et al., 2009) may have also contributed to the persistence of ice expansion at this time.

At least on the timescale of multidecadal to century-scale variability, which well-dated glacier changes generally reflect, the reconstructed glacial history here is consistent with reconstructed climate variability using tree-ring and other glacier studies from along the Gulf of Alaska (Wiles et al., 2014; Barclay et al., 2009b, 2013). The chronology from Casement Glacier, itself a land-terminating glacier, is clearly synchronous with other calendar-dated ice advances (Fig. 4). The ice damming and eventual overrunning of Adams Inlet is also broadly consistent with the thermal history of the first millennium C.E. However, it is also likely that tidewater

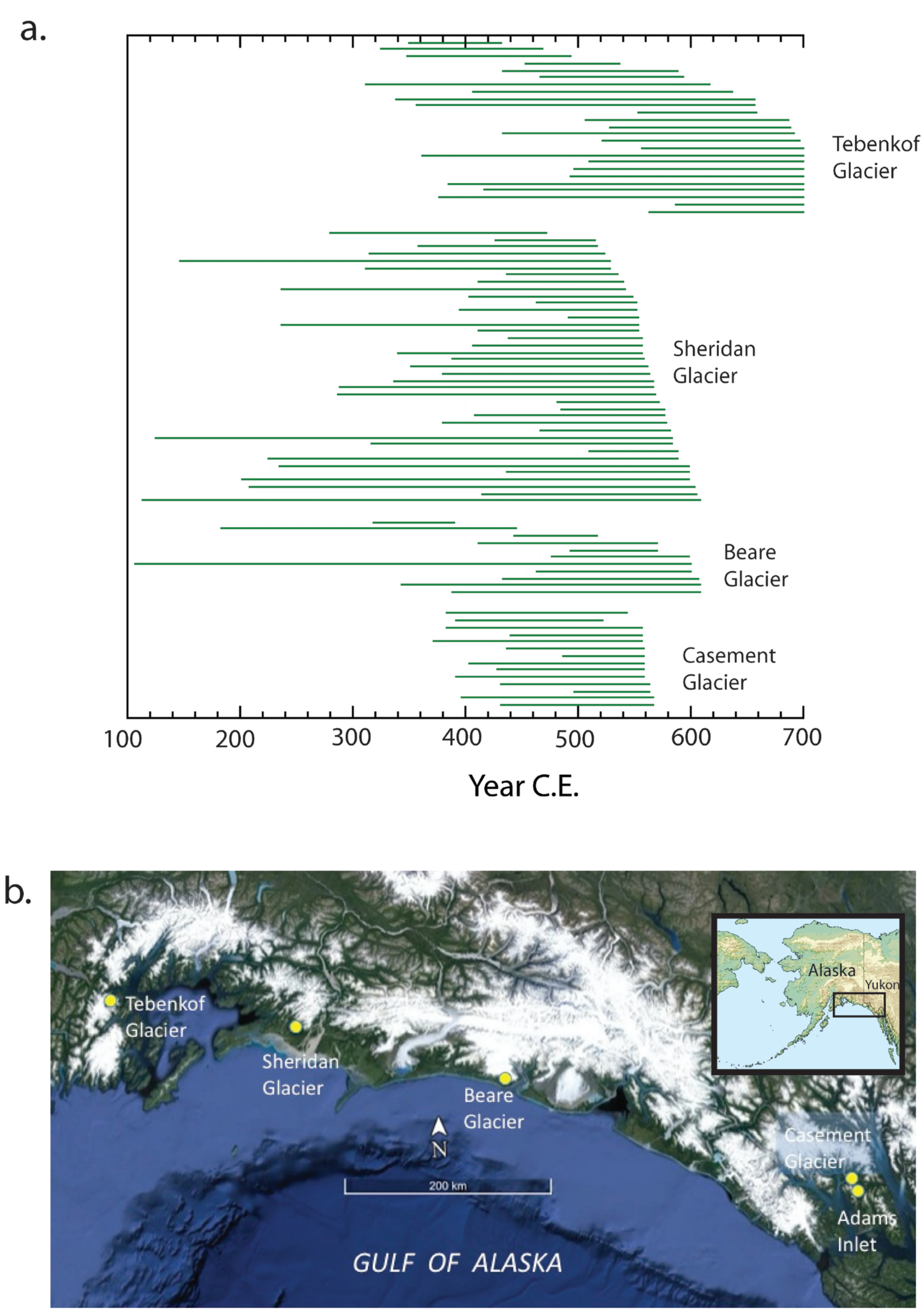

FIGURE 4. (a) Tree-ring dates of first millennium C.E. advances of land-terminating glacial advances across the Gulf of Alaska. Tebenkof Glacier data from Barclay et al. (2009a), Sheridan from Barclay et al. (2013), and Beare from Wiles et al. (2008). (b) Map showing the locations of Tebenkof (TG), Sheridan (SG), Beare (BG), Geikie (GK), and Casement (CG) Glaciers from the Gulf of Alaska.

glaciers participated in damming the Inlet (Goodwin, 1988), and we recognize tidewater glacier systems, such as those dominating Glacier Bay, are not always coincident with regional climate variations because of ice dynamics, fjord geometry, sediment budget, and critical water depth and its relationship with iceberg-calving (Mann, 1986; Post et al., 2011). However, despite these controls at least during the first millennium C.E., both tidewater and land-terminating ice masses were expanding within the same 100-year interval. This timing of ice retreat and draining of Lake Adams by about 1170 cal. yr C.E. is consistent with warming reconstructed in tree-ring-based temperature reconstructions for the Gulf of Alaska (D'Arrigo et al., 2006; Wiles et al., 2014) that shows a Medieval warming centered on 950 C.E.

Conclusions

This study presents new tree-ring calendar dates that provide more precise timing than the previous radiocarbon-based glacial history of Casement Glacier and Glacial Lake Adams in Adams Inlet, Glacier Bay, Alaska. Tree-ring dating of forests inundated by ice in Adams Inlet and killed by proglacial sedimentation between about 540 and 640 C.E. and ice advance in front of Casement Glacier shows expansion between 560 and 568 C.E. Combined with previous tree-ring data, other climate proxies, and radiocarbon dating, this study adds support to a widespread glacial advance and cooling period across southern Alaska that was centered on the sixth century of the Common Era. This cooling follows major climate-changing eruptions during the mid to late sixth century between 536–574 C.E., a potential source of widespread cooling that may have persisted later with a decrease in solar irradiance by 700 C.E.

Radiocarbon and tree-ring ages from other sites in Glacier Bay also suggest that by 850 C.E., ice may have been close to its first millennium C.E. maximum, and that retreat from these sites occurred by 1170 cal. yr C.E., during the Medieval warming centered on 950 C.E. (Wiles et al., 2014). Readvance during the LIA inundated the Casement Valley and Adams Inlet combining with other ice margins to fill Glacier Bay by 1750 C.E. A few decades later, the deglaciation started with revegetation and erosion of lake and forest beds of Muir and Adams Inlet continuing to the present.

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