Expansion of alpine glaciers in Pacific North America in the first millennium A.D.

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ABSTRACT

Radiocarbon ages and lichen-dated moraines from 17 glaciers in coastal and near-coastal British Columbia and Alaska document a widespread glacier advance during the first millennium A.D. Glaciers at several sites began advancing ca. A.D. 200–300 based on radiocarbon-dated overridden forests. The advance is centered on A.D. 400–700, when glaciers along an ~2000 km transect of the Pacific North American cordillera overrode forests, impounded lakes, and deposited moraines. The synchroneity of this glacier advance and inferred cooling over a large area suggest a regional climate forcing and, together with other proxy evidence for late Holocene environmental change during the Medieval Warm Period and Little Ice Age, provide support for millennial-scale climate variability in the North Pacific region.

Keywords: Alaska, British Columbia, glacier, Holocene, neoglaciation, paleoclimate.

INTRODUCTION

Glacier fluctuations are sensitive indicators of past climate change. The recent global retreat of alpine glaciers (Dyurgerov and Meier, 2000) is frequently cited as evidence of twentieth century warming, and records of Holocene glaciation (e.g., Denton and Karlén, 1973) commonly provide a framework within which other paleoclimatic proxies are evaluated (Mayewski et al., 2004). The timing and extent of glacier fluctuations during the Little Ice Age, defined here as the period of expanded glacier cover spanning most of the last millennium (Luckman, 2000), have been well documented in northwestern North America, where they integrate decadal- to centennial-scale variations in temperature and precipitation (Luckman, 2000; Wiles et al., 2004). However, earlier periods of glacier advance are only broadly understood.

Identification of glacier activity prior to the Little Ice Age is difficult because the evidence was generally destroyed or obscured by subsequent, commonly more extensive, advances. Nevertheless, several decades of research in North America have provided a general framework for middle and late Holocene glacier activity, with advances, separated by periods of reduced ice extent, ca. 6000–5000 ^{14}C yr B.P., 3500–2500 ^{14}C yr B.P., and A.D. 1200–1900 (Denton and Karlén, 1973; Ryder and Thomson, 1986; Luckman et al., 1993; Calkin et al., 2001). This chronology is widely cited as an independent reconstruction of Holocene climate change (e.g., Bond et al., 2001; Cumming et al., 2002).

Little is known, however, about glacier activity in Pacific North America during the first millennium A.D., a period of increasing importance due to its association with the so-called Medieval Warm Period. Sparse proxy climate records show some evidence for cooling during the first millennium A.D. (Hu et al., 2001), but other records suggest protracted warming followed by a short-lived glacier advance late in the first millennium A.D. (Denton and Karlén, 1973). Here we compile new and previously published glacial geological data that document a widespread advance of alpine glaciers during the first millennium A.D. in coastal British Columbia (Canada) and Alaska.

EVIDENCE FOR GLACIER ADVANCE

The main evidence for glacier expansion in Pacific North America (Fig. 1) during the first millennium A.D. consists of radiocarbon ages on plant material recovered from glacial sediments. These ages can directly date when a glacier advanced over a particular site (e.g., where tree stumps or roots in growth position are buried by till), or can provide maximum or minimum ages for glacier advance (e.g., detrital wood in till or a paleosol overlying till). Radiocarbon ages are supplemented by tree-ring cross dates (e.g., Wiles et al., 1999) at sites where overridden forests are preserved and by lichen-dated moraines.

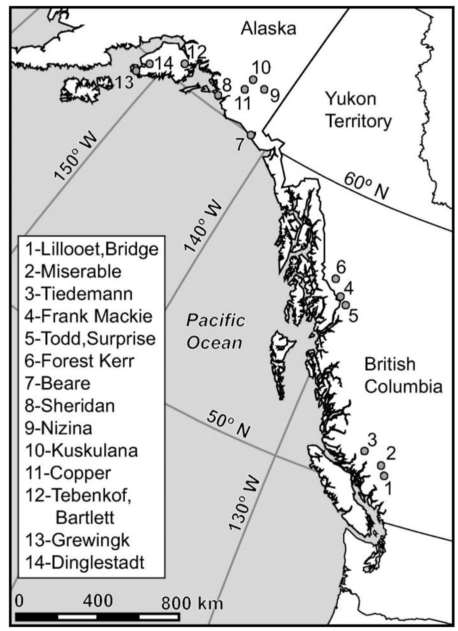

Figure 1. Location of study glaciers in Pacific North America.

At most of our study sites (Data Repository Table DR1[1]), a buried surface marked by de-

[1]GSA Data Repository item 2006009, Table DR1 (study sites) and Table DR2 (radiocarbon ages), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

Figure 2. Dated logs (arrows; A.D. 540–770) and paleosol (thin dashed line; A.D. 420–620) buried by till during first millennium A.D. glacier advance at Lillooet Glacier in southern Coast Mountains (Reyes and Clague, 2004). Thick dashed line marks wood layer and paleosol developed on first millennium A.D. till that was buried during Little Ice Age glacier advance. Buried surfaces are separated by 4–6 m of vertical distance.

trital and/or in situ wood and commonly associated with a paleosol is covered by glacial sediments dating to the first millennium A.D. (Fig. 2). A similar buried surface typically separates these glacial sediments from overlying Little Ice Age till or outwash.

We limit our discussion here to nonsurging, land-terminating glaciers with direct stratigraphic or geomorphic evidence for glacier expansion during the first millennium A.D. Radiocarbon ages are presented as the 2σ range of calibrated years A.D. (Fig. 3; Table DR2 [see footnote 1]).

Southern Coast Mountains, British Columbia

Glacier expansion during the first millennium A.D. has been recognized at four sites in the southern Coast Mountains (Fig. 1). Reyes and Clague (2004) described paleosols and layers of woody debris in a lateral moraine of Lillooet Glacier. Radiocarbon ages on logs at three sites along an ~2.5 km length of the moraine indicate that the glacier was advancing by A.D. 130–540 and that the maximum ice margin extent was reached at or after A.D. 540–770, but prior to A.D. 780–1030. A ^{14}C-dated in situ stump within a meltwater channel 200 m downvalley from the 2002 terminus of nearby Bridge Glacier was overridden by advancing ice ca. A.D. 430–650 (Allen and Smith, 2004). Lichenometric dating of lateral moraines in Tchaikazan Valley north of Bridge Glacier suggests that Miserable Glacier advanced and constructed two nested moraines during the latter half of the first millennium A.D. (D.J. Smith, personal commun. 2003). Farther north, a ^{14}C age on a log in glaciofluvial sediments (Ryder and Thomson, 1986), another on basal peat in a bog impounded by a lateral moraine (Fulton, 1971), and a lichen-dated moraine (Larocque and Smith, 2003) suggest that Tiedemann Glacier advanced and constructed a moraine during the latter half of the first millennium A.D.

Northern Coast Mountains, British Columbia

A first millennium A.D. glacier advance in the northern Coast Mountains (Fig. 1) was first recognized at Frank Mackie Glacier, which impounded a large lake during each of its late Holocene advances. Radiocarbon-dated plant macrofossils in deltaic and glaciolacustrine sediments record an advance that was under way by A.D. 340–570 and likely persisted for several hundred years (Clague and Mathews, 1992).

Ongoing research at glaciers flowing from Todd Icefield near Bear Pass provides additional evidence for first millennium A.D. advances in the northern Coast Mountains. Radiocarbon ages and floating tree-ring chronologies built from detrital wood in till show that Todd Glacier and one of its tributary glaciers were advancing into forests at or shortly after A.D. 230–540 and A.D. 410–650, respectively (Laxton, 2005). Radiocarbon ages and tree-ring cross dating of woody debris exposed in the proximal face of the south lateral moraine of nearby Surprise Glacier suggest two distinct periods of ice margin expansion, an earlier one at A.D. 220–540 and a later one at A.D. 530–780 (Smith et al., 2005).

North of Iskut River, recent retreat of Forrest Kerr Glacier and meltwater incision in the glacier forefield have revealed numerous glacially sheared in situ stumps and overridden trees (Lewis and Smith, 2005). Three ^{14}C ages and tree-ring cross dates show that the glacier was advancing into a mature forest ca. A.D. 100–500. A ^{14}C age on detrital wood eroded from till 2 km downvalley of the overridden forest indicates that Forrest Kerr Glacier was still advancing at A.D. 430–660.

Northern Gulf of Alaska

Two land-terminating glaciers and several tidewater and surging glaciers (Calkin et al., 2001) in the northern Gulf of Alaska region (Fig. 1) advanced during the first millennium A.D. An in situ stump beneath till at Beare Glacier, west of the mouth of Icy Bay, records an advance to near the Holocene limit of the glacier by A.D. 420–670 (Johnson et al., 1997). Trees outside the Holocene limit were buried at this time by outwash likely derived from both Beare Glacier and nearby Icy Bay Glacier (Barclay et al., 2005).

A ^{14}C-dated, glacier-pushed log at the outer margin of the forefield of Sheridan Glacier in eastern Prince William Sound indicates that the glacier was advancing near its Holocene limit by A.D. 230–650 (Tuthill et al., 1968). Radiocarbon and tree-ring cross dating of in situ stumps in nearby gravel indicate burial during two closely spaced episodes of outwash aggradation between A.D. 210 and 570 (D.J. Barclay, personal commun. 2001). The buried stumps cross date with detrital logs recovered from till in the glacier forefield, which strengthens the association of the glacier advance and outwash aggradation.

Wrangell Mountains, Alaska

Radiocarbon and lichen ages indicate that three glaciers in the Wrangell Mountains (Fig. 1) advanced during the first millennium A.D. (Wiles et al., 2002). Nizina Glacier advanced after A.D. 60–400, the age of detrital plant material recovered from till at the base of a lateral moraine. A ^{14}C-dated alder branch between two tills at a nearby exposure suggests that the advance occurred prior to A.D. 770–1020. Recent meltwater incision in the forefield of nearby Kuskulana Glacier has exposed a white spruce forest overlain by till and outwash. Two of the buried trees yielded ^{14}C ages that indicate burial ca. A.D. 130–440. Copper Glacier, in the northwestern Wrangell Mountains, constructed its outermost Holocene moraine during the first millennium A.D., based on lichen measurements tied to the age-growth curve of Denton and Karlén (1973).

Kenai Mountains, Alaska

Tebenkof Glacier in the northern Kenai Mountains advanced ca. A.D. 430–680, based on a ^{14}C-dated hemlock log buried in till near the glacier terminus. The log cross dates with

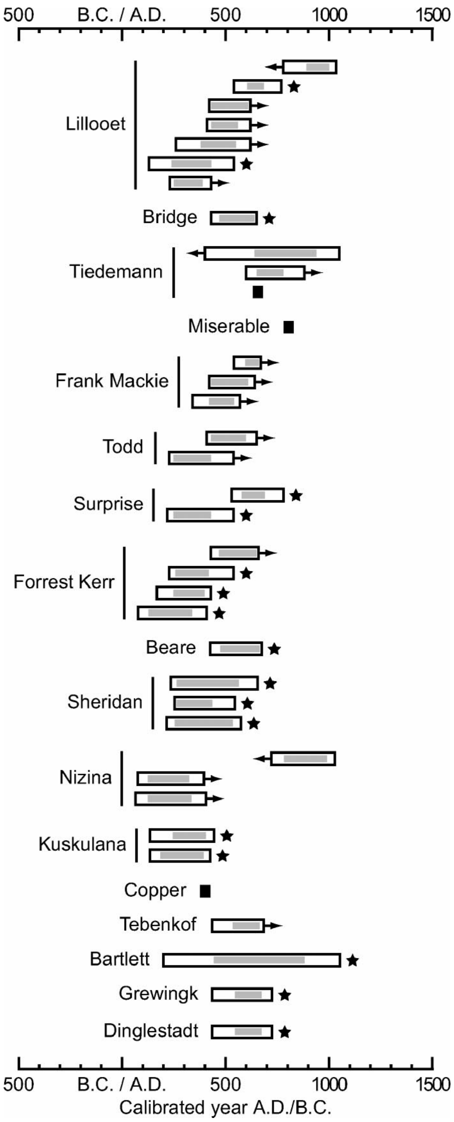

Figure 3. Calibrated radiocarbon ages pertaining to first millennium A.D. glacier advances in Pacific North America. Shaded and white bars are, respectively, 1σ and 2σ calibrated age ranges (Table DR2; see footnote 1). Black bars are estimated moraine ages based on lichen growth curves; see Wiles et al. (2002) and Larocque and Smith (2003) for discussions of errors associated with lichen ages for Copper and Tiedemann glaciers, respectively. Stars—samples that directly date ice margin expansion; left- and right-pointing arrows—samples that provide, respectively, maximum and minimum constraining age ranges for ice margin expansion.

six nearby glacially abraded logs, suggesting that all were killed during first millennium A.D. expansion of the glacier (Wiles et al., 1999). To the west, Bartlett Glacier also advanced during the first millennium A.D., based on a ^{14}C-dated stump between two tills (Karlstrom, 1964). The radiocarbon age, however, yields a large calibrated age range (A.D. 200–1050).

Two glaciers in the southern Kenai Mountains advanced during the first millennium A.D. (Wiles and Calkin, 1994). A forest in the forefield of Grewingk Glacier was overridden between A.D. 430 and 720, based on a ^{14}C age from an in situ stump. A stump in a buried forest horizon in the nearby Dinglestadt Glacier forefield yielded a similar calibrated ^{14}C age of A.D. 430–720.

DISCUSSION AND CONCLUSIONS

Evidence for one or more advances of glaciers in Pacific North America during the first millennium A.D. includes overridden forests in glacier forefields, buried paleosols and forest vegetation in lateral moraines, lichen- and ^{14}C-dated moraines, and glacier-dammed lake sediments. Several glaciers in Alaska and the British Columbia Coast Mountains were advancing as early as ca. A.D. 200, and most of the glaciers we studied were advancing between ca. A.D. 400 and 700 (Fig. 3). At most sites it was not possible to determine the time of maximum ice extent associated with these glacier advances. However, ^{14}C-dated overridden trees near the Holocene limits of Beare and Sheridan glaciers suggest that the first millennium A.D. expansion of these glaciers may have been comparable in magnitude to their maximum Little Ice Age advances. The magnitude of recession from first millennium A.D. glacial limits is poorly understood, although the presence of stacked tills at several sites clearly differentiates the glacier expansions of the first millennium A.D. and the Little Ice Age.

Given the limited resolution of radiocarbon dating, the diverse size and aspect of individual glaciers, and the large study region, the similar timing of the first millennium A.D. advances suggests that glaciers in Pacific North America responded to a regional climate forcing that led to prolonged periods of positive mass balance. Recent compilations of Little Ice Age glacier activity in this region, dated with decadal-scale resolution using tree rings and lichen, show a similarly coherent response of glaciers to regional climate variability (Larocque and Smith, 2003; Wiles et al., 2004).

Our record of first millennium A.D. glacier advances is supported by several independent proxy climate records that show regional cooling ca. A.D. 400 to 700, when most of the glaciers we studied were advancing. Geochemical proxies in lake sediments suggest pronounced cooling in southern Alaska centered on A.D. 600 (Hu et al., 2001). This regional cooling is consistent with a centennial-scale negative Northern Hemisphere temperature anomaly reported by Moberg et al. (2005), increased flux of iceberg-rafted debris to the North Atlantic (Bond et al., 1997), and reduced occurrence of stand-replacing forest fires in northwestern United States (Pierce et al., 2004). Glacier advances during the first millennium A.D. have also been documented in the Canadian Rocky Mountains (Luckman, 1996), Iceland (Gudmundsson, 1997), the European Alps (Holzhauser et al., 2005), and New Zealand (Gellatly et al., 1988).

Other proxy data are less consistent with our glacier record. Tree line in the St. Elias Mountains of Yukon Territory and Alaska is thought to have been higher than at present during most of the first millennium A.D. (Denton and Karlén, 1973). Cumming et al. (2002) reconstructed high lake levels in southwestern British Columbia for most of the first millennium A.D., but postulated low lake levels during the Little Ice Age and middle Neoglacial interval of glacier advance. Fire history studies in the southern Coast Mountains show that the first half of the first millennium A.D. was a time of high fire frequency, whereas lower fire frequencies were inferred for the Little Ice Age and middle Neoglacial (Hallett et al., 2003). Variable Holocene solar irradiance has been proposed as a potential forcing mechanism for millennial and centennial-scale climate change (e.g., Denton and Karlén, 1973; Bond et al., 2001). However, reconstructed irradiance during the first millennium A.D., based on production rates of cosmogenic nuclides, is close to the Holocene mean and is higher than values reported for other established periods of late Holocene glacier advance (Bond et al., 2001).

Denton and Karlén (1973) were the first to suggest millennial cyclicity of Holocene climate. However, due to the limited data available at that time, they did not recognize a prominent glacial advance during the first millennium A.D. and proposed an ~2500 year cycle that fit their glacial geological data. Later workers (e.g., Bond et al., 1997), using a more complete suite of proxy indicators, identified a quasi-periodic, ~1500 yr Holocene climate cycle.

This paper documents a glacier advance that was not fully recognized at the time of the pioneering work of Denton and Karlén (1973). The first millennium A.D. glacier advances reported here, together with evidence for glacier expansion ca. 3500–2500 ^{14}C yr B.P. (Denton and Karlén, 1973; Ryder and Thomson, 1986; Desloges and Ryder, 1990; Clague and Mathewes, 1996; Wiles et al., 2002), regional climate amelioration ca. A.D. 850–1200 (Hu et al., 2001) during the Medieval Warm Period (Cook et al., 2004; Moberg et al., 2005), and subsequent Little Ice Age glacier expansion (Larocque and Smith, 2003; Wiles et al., 2004), are consistent with a millennial-scale climate cycle in the North Pacific region.

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Notes

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