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Latest Pleistocene and Holocene glacier fluctuations on Mount Baker, Washington

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ABSTRACT

Glaciers on stratovolcanoes of the Pacific Northwest of North America offer opportunities for dating late Pleistocene and Holocene glacier advances because tephra and fossil wood are common in lateral moraines and in glacier forefields. We capitalize on this opportunity by examining the Holocene glacial record at Mount Baker, an active stratovolcano in northwest Washington. Earlier workers concluded that glaciers on Mount Baker during the early Holocene were more extensive than during the Little Ice Age and hypothesized that the explanation lay in unusual climatic or hypsometric effects peculiar to large volcanoes. We show that the main argument for an early Holocene glacier advance on Mount Baker, namely the absence of ca 10,000-year-old tephra on part of the south flank of the mountain, is incorrect. Moreover, a lake-sediment core indicates that a small cirque moraine previously thought be of early Holocene age is also likely older than the tephra and consequently of late Pleistocene age.

Lateral and end moraines and wood mats ca 2 km downvalley of the present snout of Deming Glacier indicate that an advance during the Younger Dryas interval was little more extensive than the climactic Little Ice Age advance. Tephra and wood between tills in the left lateral moraine of Easton Glacier suggest that ice on Mount Baker was restricted in the early Holocene and that Neoglaciation began ca 6 ka. A series of progressively more extensive Neoglacial advances, dated to about 2.2, 1.6, 0.9, and 0.4 ka, are recorded by stacked tills in the right lateral moraine of Deming Glacier. Intervening retreats were long enough to allow establishment of forests on the moraine. Wood mats in moraines of Coleman and Easton glaciers indicate that Little Ice Age expansion began before 0.7 ka and was followed by retreat and a readvance ca 0.5 ka. Tree-ring and lichen data indicate glaciers on the south side of the mountain reached their maximum extents in the mid-1800s.

The similarity between glacier fluctuations at Mount Baker and those elsewhere in the Cascades and in British Columbia suggests a coherent history of Holocene climate change over a broad area of the western Cordillera. We found no evidence that glaciers on stratovolcanoes behave differently than glaciers elsewhere.

1. Introduction

Glaciers are sensitive to climate, and their fluctuations provide insights into Quaternary climate change. Stratovolcanoes in the Cascade Range of the Pacific Northwest are well suited for studies of past glacier activity because they support large glaciers that repeatedly descended below treeline and overran forests, their lateral moraines commonly comprise multiple tills separated by paleosols, and they preserved well dated local and regional tephras that help to constrain times when glaciers advanced.

In this paper, we summarize our work aimed at developing a latest Pleistocene and Holocene glacial chronology for Mount Baker, a stratovolcano in northwest Washington. We use dated tephras (Bacon, 1983; Hallet et al., 1997, 2001; Foit et al., 2004; Tucker et al., 2007) and radiocarbon ages on fossil wood and vegetation mats

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within several lateral moraines to constrain the magnitude and times of past glacier advances. Our motivation to work on Mount Baker was to examine the geologic evidence for extensive early Holocene glaciers on the volcano reported by others (Thomas et al., 2000; Kovanen and Begét, 2005; Kovanen and Slaymaker, 2005). Furthermore, some researchers have suggested that the times and magnitude of glacier advances on volcanoes in the Pacific Northwest differ from those at other mountains in western North America, perhaps due to climatic or hypsometric effects (Beget, 1981, 1983, 1984; Kovanen and Easterbrook, 1996, 1997, 1998, 1999, 2001, 2002; Heine, 1998; Burrows et al., 2000; Thomas et al., 2000; Burrows, 2001; Kovanen et al., 2001; Kovanen, 2003; Kovanen and Slaymaker, 2005). Such effects have been invoked, particularly by Kovanen et al. (1996), Kovanen and Easterbrook (2001), and Kovanen and Begét (2005), to explain why purported early Holocene glacier advances on some Cascade volcanoes were more extensive than advances during the Little Ice Age.

We first briefly review the physiography, regional geology, and climate of the study area, and then describe the methods that we used in our study. We then summarize our new field and laboratory data and discuss our findings in relation to previous work on the mountain. We conclude by comparing our glacial record to other chronologies of alpine glaciation in the Pacific Northwest and Canadian Cordillera, and critically consider the hypothesis that glaciers on stratovolcanoes behave anomalously due to climatic or hypsometric factors.

2. Regional setting

2.1. Physiography and geology

Mount Baker is located at the north end of the Cascade Range in northwest Washington (Fig. 1). Its summit is 3289 m above sea level (asl); the mountain stands above adjacent peaks in the North Cascades by several hundred meters. Relief from the summit to the floors of Nooksack and Baker River valleys, which drain the volcano, is about 2500 m. Nine major glaciers (Easton, Deming, Roosevelt, Coleman, Mazama, Rainbow, Park, Boulder, and Squak) radiate from the upper slopes of the volcano (Fig. 2). These glaciers share a common accumulation zone at the summit. The total glacierized area is 39 km^2 (Post et al., 1971).

The active andesitic stratovolcano rests on a basement of Mesozoic and Paleozoic rocks (Misch, 1988). The Cascade volcanic arc, of which Mount Baker is part, became active 36 Ma (Vance et al., 1987; Smith, 1993), but episodic volcanic activity at Mount Baker has extended over only the past 1.3 Ma. The volcanic history is summarized by Crandell (1975), Easterbrook (1975), Frank et al. (1975), Hyde and Crandell (1978), Easterbrook and Kovanen (1996), Hildreth et al. (2003), Scott and Tucker (2003, 2004), and Scott et al. (2003a, 2003b).

The edifice is composed of andesitic lava flows capped by glaciers and glacial and non-glacial debris. Southeast of and 200 m below the summit is Sherman Crater, the source of a major Late-glacial eruption. Another large eruption occurred in the early Holocene from a vent in Schreiber's Meadows on the south flank of the mountain (Scott et al., 2003b). Tephras derived from eruptions of Mount St. Helens, Glacier Peak, Crater Lake, and Mount Baker mantle moraines, lahar deposits, and the weathered surfaces of lava flows (Table 1). Four or five different tephras have been identified in some subalpine meadows (Mullineaux, 1974). Their presence or absence on moraines and other landforms constrains the ages of these features.

2.2. Climate

Regional climate at Mount Baker is strongly influenced by weather from the eastern North Pacific Ocean. Winters are wet and mild, and summers are relatively cool and dry. Mean annual

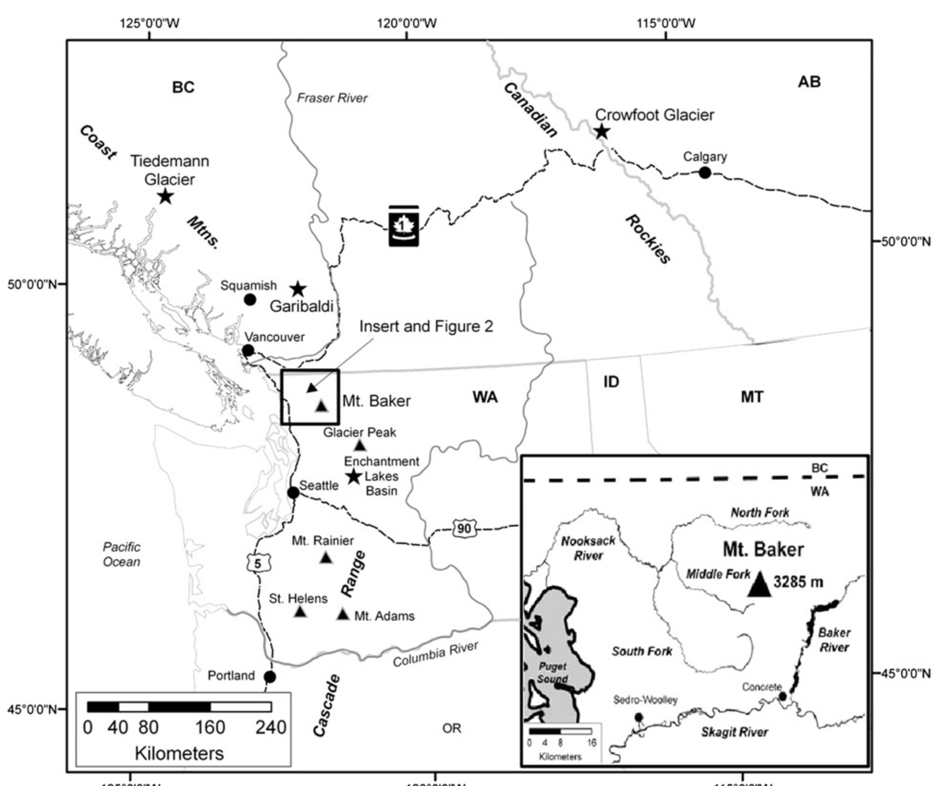

Fig. 1. Regional setting of the study area, showing place names mentioned in text.

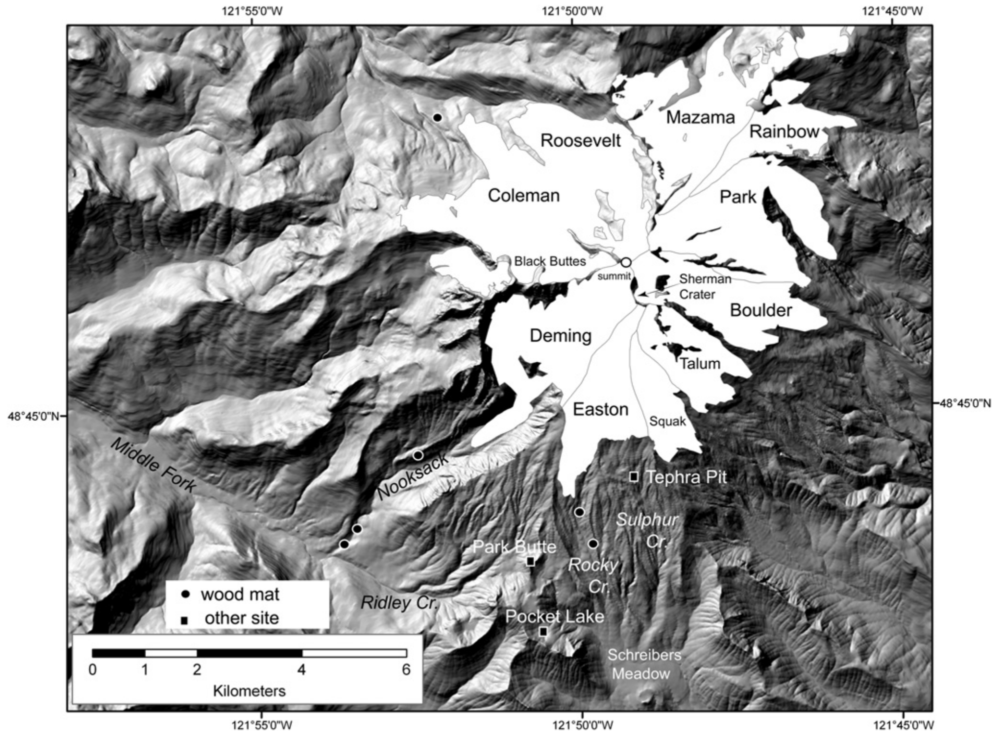

Fig. 2. DEM of Mount Baker, showing glacier cover, sample sites, and place names. Modern glacier margins provided by Courtney Brown. "Tephra pit" is shown in Fig. 6.

temperature at the Wells Creek weather station at 1228 m asl on the north side of the mountain is 3.8 °C, with a range of −20.4−33.8 °C (www.wcc.nrcs.usda.gov/nwcc). At Wells Creek annual precipitation is about 2 m, with an average end-of-accumulation-season (May 1) snow water equivalent of 70 cm.

Precipitation rapidly increases above 1500 m asl in the North Cascades, and most precipitation falls as snow between November and April. In addition to seasonal changes, climate is marked by pronounced inter-annual and decadal variability. Winter snowfall varies annually with the El Niño-Southern Oscillation, with strong El Niño conditions resulting in winter precipitation about 50 percent of average, whereas in the La Niña phase, winter precipitation can be twice that of an average year. Temperature is also influenced by the Pacific Decadal Oscillation; the cool phase of the PDO brings colder air to the Mount Baker area, which when combined with La Niña conditions can deliver exceptional amounts of snowfall (Bitz and Battisti, 1998).

Mount Baker is exposed to strong winter winds that redistribute snow from the windward southwest side of the mountain to the leeward northeast side. Climatic asymmetry on the mountain is also a function of altitude and aspect. Exposed southern slopes above 1500 m asl receive significantly more solar radiation than those on the north side.

Mass balance monitoring on Mount Baker began in 2008, and ELA and net balance of Easton and Rainbow glaciers have been monitored since 1980 (Pelto, 2008). Mass balance and ELA of four glaciers within 100 km of Mount Baker have been measured since 1993, including Noisy Glacier, 20 km southeast of the mountain. Mass balance of Easton and Nisqually glaciers on Mount Rainier have been measured since 2003 (Riedel and Larrabee, 2011a), and mass balance at South Cascade Glacier, 70 km to the southeast of Mount Baker, has been measured since the mid 1950s (Riedel and Larrabee, 2011b). Modern ELAs of these glaciers range from 1600 to 2100 m, with annual variability of 200–300 m.

3. Methods

3.1. Field procedures

We completed a preliminary study of the moraine record on Mount Baker using 1:12,000 air photos, 1:24,000 topographic maps, and 1:100,000 geologic maps (Tabor et al., 1994, 2003). Field work was limited to the southern half of the mountain and was done during the summers of 2005 and 2006, the fall of 2006, and the spring of 2007. Five sites are the focus of this study: 1) Easton Glacier; 2) the Coleman Glacier left lateral moraine; 3) the south

Table 1
Tephras used as time-stratigraphic markers at Mount Baker.

Tephra	Age (ka cal yr) [^{14}C yr BP]	Composition	Source	Reference
Set YP	AD 1843	Lithic, locally with significant vitric andesitic ash	Mt. Baker	Tucker et al. (2007)
Layer BA	6.41–6.79 [5860–5740]	Juvenile andesitic ash	Mt. Baker	Hildreth et al. (2003)
Layer OP	6.41–6.79 [5860–5740]	Lithic andesitic ash and lapilli	Mt. Baker	Hildreth et al. (2003)
Layer O	7.48–7.46 [6720–6760]	Juvenile rhyodacite ash	Mt. Mazama (Crater Lake)	Hallett et al. (1997)
Layer MY	9.40–8.77 [8130–8110]	Lithic ash	Mt. Baker	This study
Set SC	10.17–9.55 [8850–8750]	Juvenile, basaltic ash and lapilli	Schriebers Meadow cinder cone	Tucker et al. (2007)
Set SP	12.95–12.55 [10,870–10,720]	Juvenile andesite ash	Mt. Baker	Hyde and Crandell (1978) and Tucker et al. (2007)

flank of Mount Baker between Easton and Squak glaciers, 4) Pocket Lake, and (5) Deming Glacier (Fig. 2).

Diamicts were interpreted as tills, as opposed to lahars or other varieties of colluvium, if they (a) occur high in lateral moraines, (b) are heterolithic, and (c) contain subrounded, faceted, and in some cases striated clasts (Crandell and Mullineaux, 1975; Scott et al., 2003a).

3.2. Tephrochronology

We collected tephras from within the Easton Glacier left lateral moraine and from a sediment core collected from Pocket Lake. Coloration, degree of weathering, lithic content, and shard vesicularity were used to identify tephras in the field. Shard morphology, including the approximate size and shape of grains, was also recorded because it is diagnostic of some tephras (Westgate and Gorton, 1981). The relative abundance of microphenocrysts was later determined with a scanning electron microprobe.

We analyzed individual glass shards from tephra samples at the University of Calgary Laboratory for Electron Microbeam Analysis (UCLEMA) to determine their provenance. Prior to analysis, organic matter was removed with hydrogen peroxide, the samples were washed and wet-sieved through a 230 mesh screen, and the coarse fraction was mounted in epoxy, polished, and carbon-coated. Typically 60 inclusion-free glass shards were analyzed for K_2O, CaO, FeO, SiO_2, Na_2O, TiO_2, MnO, MgO, and Al_2O_3 with the wavelength-dispersive spectrometer (WDS) JEOL JXA-8200 electron microprobe. The accelerating voltage used was 15.0 kV with a beam current of 10 nano-amps and a beam width of 5 μm. Data were adjusted using the ZAF matrix correction scheme to account for differences between the standards used and the samples (Armstrong, 1984). Further details on the analytical methods and calibration standards used for the microprobe analysis are provided by Ryane (2009).

3.3. Lake sediment analysis

We cored Pocket Lake from its frozen surface during the spring of 2007 with a percussion version of a Livingston piston corer. The Pocket Lake core was split, photographed, and logged at Western Washington University. Each core section was extruded into split PVC pipes double-lined with plastic wrap for subsequent storage and analysis. We performed a routine sedimentological analysis on the core, including determination of magnetic susceptibility and mineral matter content.

3.4. Dendrochronology

Dendrochronology was used to date moraines between Easton and Squak glaciers. The age of the oldest tree on a moraine provides a minimum estimate for moraine formation and stabilization (Lawrence, 1946; Sigafoos and Hendricks, 1969; Luckman, 1998). Two increment cores were extracted from several trees, believed to be the oldest based on size, on each moraine using a 4.3-mm-diameter increment borer. Cores were mounted and prepared for analysis by sanding with progressively finer grades of sandpaper to enhance the definition and contrast of annual tree-ring boundaries. Ring widths were measured with a precision of ±0.001 mm.

A living tree-ring chronology was built from all sampled trees growing on the moraines. The series was checked and verified using the International Tree-Ring Data Bank (ITRDB) software program COFECHA and crossdated (50-year dated segments lagged by 25 years, with a critical level of correlation [99 percent] set at 0.32), thus creating a master ring-width chronology (Holmes, 1983). A floating chronology was developed from two logs found in the west lateral moraine of Easton Glacier. Outermost rings of one sample included in the floating chronology were radiocarbon-dated and provide a limiting age of the associated advance.

A more accurate estimate of the age of a moraine is obtained by adding the ecesis interval – the time from surface stabilization to seedling germination – to the age of the oldest tree growing on the moraine (Sigafoos and Hendricks, 1969; McCarthy and Luckman, 1993; Koch, 2009). Ecesis was not investigated in this study, but previous work on Mount Baker (Heikkinen, 1984; Oliver et al., 1985) established a value of less than 30 years, which is similar to ecesis values reported in other studies in the region (Koch, 2009). We therefore added 20 years to the ring count of each tree to correct for ecesis and assume the error range is less than 10 years. A correction must also be made for the time that trees take to grow to sampling height (McCarthy et al., 1991; Winchester and Harrison, 2000; Koch, 2009). In this study we cored all trees as close to the ground as possible and therefore made no correction for sampling height.

3.5. Lichenometry

We used lichenometry to provide minimum limiting ages for the non-forested west lateral moraine of Easton Glacier and the moraines between Easton and Squak glaciers. The long and short axes of 30–70 thalli of *Rhizocarpon geographicum* spp. were measured on each moraine to the nearest ±0.1 mm using a dial caliper. Sampling was limited to near-circular lichens to avoid anomalously large or coalesced thalli (Innes, 1985; McCarthy, 1997). We initially used a published lichen growth curve for the North Cascades that includes data for lichens on Mount Baker (Porter, 1981; O'Neal and Schoenenberger, 2003). However, the lichen and tree ages for the three moraines that we dated with both lichenometry and dendrochronology do not agree, thus we also estimated lichen ages using a growth curve from sites on Vancouver Island, about 300 km to the northwest (Lewis, 2001; Lewis and Smith, 2004).

3.6. Radiocarbon dating and age conventions

Conventional (beta) or accelerator mass spectrometry (AMS) ages were obtained on 23 samples of wood and one sample of basal lake sediment (Table 2). Only the outermost rings of wood samples were submitted for radiocarbon analysis. We also report previously published radiocarbon ages that pertain to glacier fluctuations on Mount Baker (Table 2).

To facilitate comparison of our results with those of other workers, we report all ages as kilo calibrated years (ka) BP (before AD 1950), except for those of the past millennium, where we use calendar years AD. We converted radiocarbon ages to 2σ calendar age ranges using the calibration program CALIB 5.02 (Stuiver et al., 2005), and we follow standard convention in discussing surface exposure ages (e.g. 2.2–2.5 ^{10}Be ka).

3.7. Equilibrium line altitude reconstruction

Lateglacial hypsometry of Deming glacier was reconstructed by matching glacier area to lateral and end moraines, and checking ice thickness with a modified glacier-flow law that included a shape-factor (F) of 0.65–0.74 (Paterson, 1981). ELA was then determined using the area-balance ratio approach with a spreadsheet developed by Osmaston (2005).

4. Results

4.1. Shelf on the south flank of Mount Baker

A southward-sloping shelf, hereafter referred to as the "south flank site", is located between Squak and Easton glaciers on the

Table 2
Radiocarbon ages pertinent to Holocene glacier activity on Mount Baker.

Laboratory no.[a]	Reference	Material and context	^{14}C age (yr BP)[b]	Calibrated age (kyr BP)[c]	Latitude	Longitude	Elevation (m asl)[d]
South flank					**48°43.9'N**	**121°49.3'W**	**1600**
AA-22225	Thomas el al., 2000	Charcoal within set SC scoria.	8420 ± 70	9.54–9.28			
I-18595	Thomas el al., 2000	Organic layer beneath Mazama tephra	7630 ± 130	8.76–8.17			
AA-22219	Thomas el al., 2000	Charcoal beneath Mazama tephra	7045 ± 65	8.00–7.72			
TO-12444	This study	Charcoal beneath tephra layer MY	8110 ± 70	9.28–8.78			
TO-12445	This study	Charcoal beneath tephra layer MY	8130 ± 80	9.40–8.77			
WW-954	Tucker et al., 2007	Charcoal within set SC ash	8750 ± 50	10.10–9.55			
WW-1456	Tucker et al., 2007	Charcoal within set SC ash	8830 ± 50	10.16–9.70			
WW-1468	Tucker et al., 2007	Charcoal within set SC ash	8850 ± 50	10.17–9.74			
WW-6462	This study	Charcoal below set SC ash	11 460 ± 35	13.43–13.22			
Easton Glacier					**48°43.9'N**	**121°50.0'W**	**1600**
Beta-207260	This study	Log below till	5260 ± 70	6.26–5.91			
Beta-207279	This study	Log below till	5240 ± 70	6.26–5.80			
Beta-221569	This study	Log below till	410 ± 40	AD 1430–1630			
WW-660	This study	Log below till	455 ± 35	AD 1410–1610			
Coleman Glacier					**48°47.7'N**	**121°51.6'W**	**1580**
Unknown	Easterbrook, 2007	Log in till	740 ± 80	AD 1050–1410			
Unknown	Easterbrook, 2007	Log in till	690 ± 80	AD 1190–1420			
Beta-207929	This study	Log in till	970 ± 50	AD 980–1190			
Beta-221568	This study	Log in till	870 ± 50	AD 1040–1260			
Pocket Lake and Park Butte					**48°42.7'N**	**121°50.6'W**	**1400**
Unknown	Easterbrook and Kovanen, 1999	Charcoal in moraine	8455 ± 75	9.55–9.30			
Unknown	Easterbrook and Kovanen, 1999	Charcoal in diamicton outside moraine	8820 ± 110	10.18–9.56			
CAMS 133428	This study	Bulk sediments from base of core	11 450 ± 110	13.57–13.11			
CAMS-133428	This study	Terrestrial plant macrofossil at 1.06 m depth	7640 ± 50	8.54–8.38			
Deming Glacier					**48°44.4'N**	**121°52.3'W**	
UCIAMS-68591	This study	Tree stump[e]	375 ± 15	AD 1450–1620			1190
WW-6082	This study	Log[f]	430 ± 30	AD 1420–1620			1020
UCIAMS-68592	This study	Branch[f]	585 ± 15	AD 1310–1410			1190
UCIAMS-68593	This study	Tree stump[e]	955 ± 15	AD 1020–1150			1185
UCIAMS-68594	This study	Tree stump[e]	975 ± 15	AD 1020–1150			1185
UCIAMS-45048[d]	This study	Tree root[e]	1585 ± 25	1.54–1.41			990
WW-6081	This study	Tree stem[f]	1595 ± 30	1.55–1.40			970
WW-6463	This study	Tree stem[f]	1595 ± 45	1.60–1.38			955
BETA-234078	This study	Tree stem[e]	1750 ± 50	1.81–1.55			1170
UCIAMS-40546	This study	Tree stem[e]	1820 ± 20	1.81–1.71			1170
UCIAMS-40549	This study	Tree stem[e]	2115 ± 15	2.15–2.01			1165
UCIAMS-40547	This study	Branch[f]	2285 ± 15	2.35–2.21			1160
Unknown	Easterbrook and Donnell, 2007	Log	2205 ± 30	2.33–2.15			Unknown
Unknown	Easterbrook and Donnell, 2007	Log	2440 ± 30	2.70–2.34			Unknown
Unknown	Easterbrook and Donnell, 2007	Log	2960 ± 30	3.24–3.01			Unknown
Unknown	Easterbrook and Donnell, 2007	Log	2970 ± 35	3.26–3.00			Unknown
CAMS-47757	This study	Tree stem[f]	10 510 ± 40	12.60–12.20			840
CAMS-47758	This study	Tree stem[f]	10 520 ± 50	12.62–12.22			840
CAMS-93590	This study	Tree stem[f]	10 550 ± 40	12.61–12.41			835
CAMS-47756	This study	Tree stem[f]	10 600 ± 40	12.65–12.43			840
BETA-136163	Kovanen and Easterbrook, 2001	Log	10 500 ± 70	12.60–12.14			Unknown
BETA-124911	Kovanen and Easterbrook, 2001	Log	10 680 ± 70	12.74–12.43			Unknown

[a] Laboratories: Beta – Beta Analytic Inc., UCIAMS – Keck Carbon Cycle AMS Facility; CAMS – Lawrence Livermore AMS Facility; TO – University of Toronto AMS Facility; WW – USGS Radiocarbon Laboratory.
[b] Laboratory-reported error terms are $\pm 1\sigma$. Ages are normalized to $\delta^{13}C = -25‰$ PDB.
[c] Calendar ages ($\pm 2\ \sigma$) determined using CALIB 6.0 (Stuiver et al., 2005). The range is the 95 percent confidence interval ($\pm 2\sigma$) derived from the reported radiocarbon age. Values rounded off to nearest ten-year age.
[d] Elevation approximate (± 10 m).
[e] In growth position; outer rings dated.
[f] Detrital wood; outer rings dated.

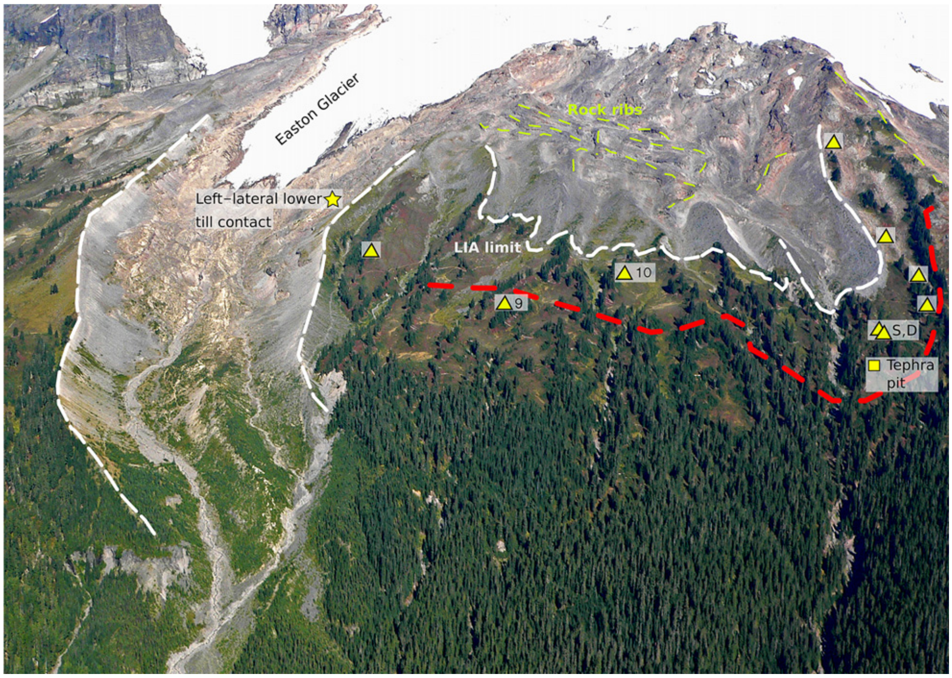

Fig. 3. Oblique aerial photograph showing volcanic rock ribs (thin, yellow-green dashed lines), limit of Little Ice Age moraines (white dashed line), approximate location of the south boundary of the no-scoria zone of Thomas et al. (2000) (dark red dashed line), locations where substantial thicknesses of Set SC tephra were recovered (triangles), and location of the tephra pit (square) shown in Fig. 6. Site 9, in the scoria zone as originally defined, was considered a representative locality for Set SC; other sites are within the original no-scoria zone. Glass fractions from SC samples from sites 10, S, and D were microprobed. Photograph courtesy of John Scurlock. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

south flank of Mount Baker. A series of well preserved, sharp-crested terminal moraines, which we later in this paper interpret as Little Ice Age moraines, extends across this shelf between about 1280 and 1770 m asl (dashed white line in Fig. 3). Between the current ice limit and these moraines are a series of ridges mapped as "Little Ice Age moraines (?)" by Kovanen and Begét (2005) and Kovanen and Slaymaker (2005). Aerial photography, Google Earth, and field visits, however, show that these ridges are volcanic rock ribs (shown as "rock ribs" in Fig. 3). Thomas et al. (2000) mapped the sharp-crested terminal moraines as Little Ice Age moraines. Kovanen and Slaymaker (2005), however, mapped these ridges as middle or early Holocene moraines. Our lichenometric and dendrochronologic data (Table 3) confirm a Little Ice Age assignment for these deposits.

Downslope of these deposits are ridges parallel to slope that Thomas et al. (2000) and Kovanen and Slaymaker (2005) interpreted to be early Holocene moraines. Thomas et al. (2000) and Kovanen and Slaymaker (2005) assigned an early Holocene age to these ridges because (1) overlying Mazama tephra [7.48–7.46 ka] and related ^{14}C ages of buried organics indicate a minimum age for the ridges of ca 7.7 ka, and (2) they were believed to have no early Holocene Set SC scoria on them. The implication of these interpretations is that there was an early Holocene advance on Mount Baker that was significantly more extensive than the largest Little Ice Age advance.

However, our observations (Fig. 3) indicate that Set SC scoria is common within the "scoria-free zone" of Thomas et al. (2000) and is present on the purported early Holocene moraines. Set SC scoria is recognized by its small, red to orange, scoriaceous clasts. It has not accumulated in thick dunes such as occur in some areas farther south, but thicknesses of 20 cm are common on the moraines. The implication of this finding is that the "early Holocene moraines" could be late Pleistocene in age.

To test our field interpretation that the ridges in question are overlain by Set SC scoria, we collected four samples of scoria, one ("9") from a large dune of red scoria outside the "scoria-free zone" of Thomas et al. (2000), another ("10") from within the purported scoria-free zone, and two ("S", "D") from a south-trending ridge south of the Little Ice Age limit and east of Sulphur Creek. The ridge is one of the early Holocene moraines of Kovanen and Slaymaker (2005).

The glass compositions of the three samples within the "scoria-free zone" (10, S, and D) are within the range of the composition of the representative specimen from the scoria zone (sample 9) (Fig. 4). The morphology of glass shards from samples 10, S, and D is also similar to that of grains from sample 9; grains are typically 400–600 μm in size and contain spherical to sub-spherical voids, with generally pure and thick glass between the voids. Grain morphology in samples 9 and 10 is shown in Fig. 5. The non-scoriaceous nature of the other tephras found on Mt. Baker (Table 1) argues against other sources for these samples. We thus

Table 3
Dendrochronologic and lichenometric data for moraines on the south flank of Mount Baker.

Moraine[a]	Tree age (years)	Stabilization date (AD)	Largest lichen (mm)		Date AD using growth curves from:	
			Single	Mean of five	Vancouver Island[b]	Cascades[c]
Moraines between Easton and Squak glaciers						
A	164	1820s	63.2	56.3	**1820s**	1860s
B	119	1860s	57.1	48.6	**1850s**	**1870s**
C	nd	nd	40.5	35.8	1910s	1910s
D	nd	nd	28.9	24.4	1960s	1940s
Easton Glacier lateral	132	1850s	58.5	53.6	**1850s**	1870s

Note: Bold dates are in closest agreement with tree-ring ages.
[a] Limits denoted by white, dashed line in Fig. 3.
[b] Lewis (2001) and Lewis and Smith (2004).
[c] Porter (1981) and O'Neal and Schoenenberger (2003).

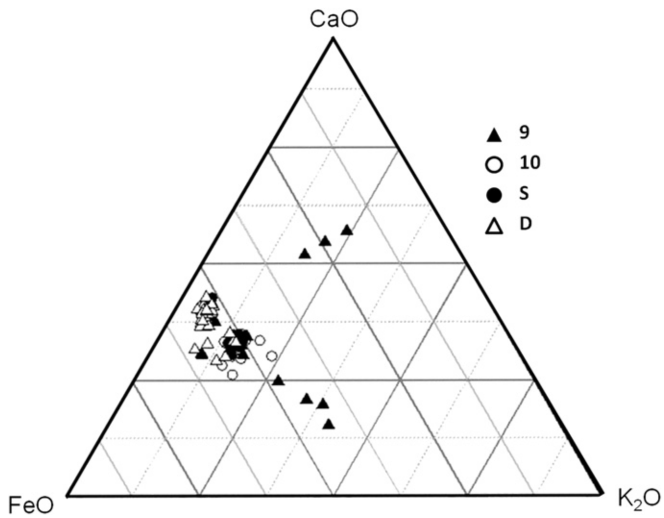

Fig. 4. Ternary diagram showing normalized CaO/FeO/K2O compositions of glass shards from tephra samples from the south flank. Sample 9 is considered representative SC scoria; samples 10, S, and D were recovered from within the "scoria-free zone" of Thomas et al. (2000).

conclude that all of the samples are Set SC tephra, there is no scoria-free zone as originally mapped, and any moraines in that area have a minimum age of 10.17–9.55 ka (Tucker et al., 2007).

We also examined areas between the ridges in the meadows south of the Little Ice Age limit (Fig. 3). We excavated shallow soil pits where the scoria was not visible at the surface. Most of the pits had similar stratigraphy, with basal diamicton overlain by volcanic tephra, silt, sand, and sandy to muddy peat. In one of the pits, labeled "tephra pit" in Fig. 3, we found five tephra layers interbedded with sand, silt, and peat (Fig. 6). Charcoal near the contact between the basal diamicton and peat in this pit yielded an age of 13.43–13.22 ka (Table 2). Above the charcoal are three thin, light-gray tephra layers interbedded with muddy peat and silt. We did not microprobe these tephras and base our tentative identification on bracketing radiocarbon ages, color, texture, and stratigraphic position (Table 1). The lower two tephra layers are bracketed by radiocarbon ages of 13.43–13.22 and 9.46–9.14 ka (Table 2), and thus are most likely tephra layer SP (Hyde and Crandell, 1978). The upper tephra layer is bracketed by radiocarbon ages of 9.40–8.77 ka on charcoal just below the tephra and 9.28–8.78 ka from charcoal just above the tephra. We refer to this previously unidentified tephra as Mount Baker tephra layer MY (Table 1). At the top of the pit is up to 30 cm of Mazama tephra and 3 cm of Mount Baker OP tephra.

4.2. Easton Glacier

Easton Glacier is located on the west side of the south flank site described above. Well preserved lateral moraines extend approximately 2 km downvalley of, and 400 m below, the 2006 glacier terminus.

We studied a 50-m-high exposure in the left lateral moraine of Easton Glacier approximately 400 m downvalley from the 2006 glacier terminus (Fig. 7). Here, the moraine consists of three tills and stratified sediments that include wood, peat, and tephra. We refer to the stratigraphic breaks between the tills as "till contacts".

The lower till contact (Fig. 7 inset), 20 m below the moraine crest, slopes down-glacier at an angle steeper than that of the crest of the moraine and also eastward into the moraine. It includes a mélange of logs up to 0.4 m in diameter, at least six, 2–3-cm thick convoluted and sheared peat layers, and three tephras (Fig. 8). Two of the logs (*Tsuga heterophylla*) yielded radiocarbon ages of 6.26–5.91 ka and 6.26–5.80 ka. One of these logs contained 181 rings. The convoluted and sheared nature of the peat and tephra beds and the abundant detrital wood record overriding of a former vegetated and tephra-bearing moraine crest by Easton Glacier.

Two of the three tephras at the lower till contact occur as pods and stringers 1–3 cm thick within peat. We identified one of the two in the field as Baker Set OP based on its unique characteristics – it is a pale ivory to yellowish lithic tephra. The second tephra (sample name OBM) is white to tan. Microprobe analysis (Appendix A) of glass from sample OBM indicates that it is Mazama tephra, which has been dated to approximately 7.48–7.46 ka (Hallet et al., 1997). Mazama tephra is common on the mountain (Easterbrook, 1975). The third, and lowermost, tephra (sample name OUT) is part of a 15-cm-thick unit of reddish-brown unconsolidated sediment that underlies the peat mats, detrital wood, and other tephras (Fig. 8). Angular volcanic clasts 1–3 cm in size are dispersed in a matrix of reddish-brown silt. Glass from sample OUT has similar geochemistry to that of sample 9 from the south flank of Mount Baker, indicating that it is Set SC tephra.

A second till contact, several meters stratigraphically above the lower till contact and 4 m below the crest of the moraine, is marked by a line of logs up to 40 cm in diameter and partly decomposed

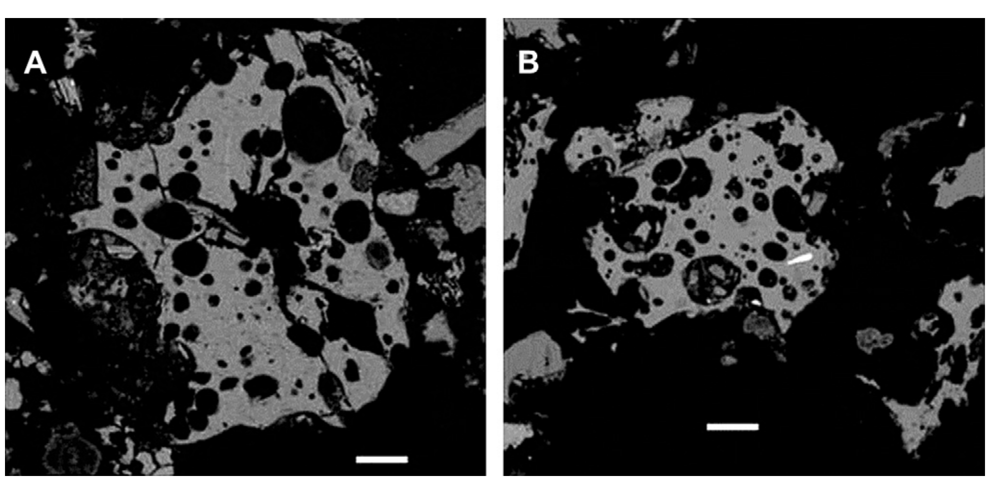

Fig. 5. Photographs showing similarity of glass-shard habit in sample 10, from the "scoria-free zone" of Thomas et al. (2000) (B), to that of the Set SC scoria represented by sample 9 (A). Scale bars: 100 μm.

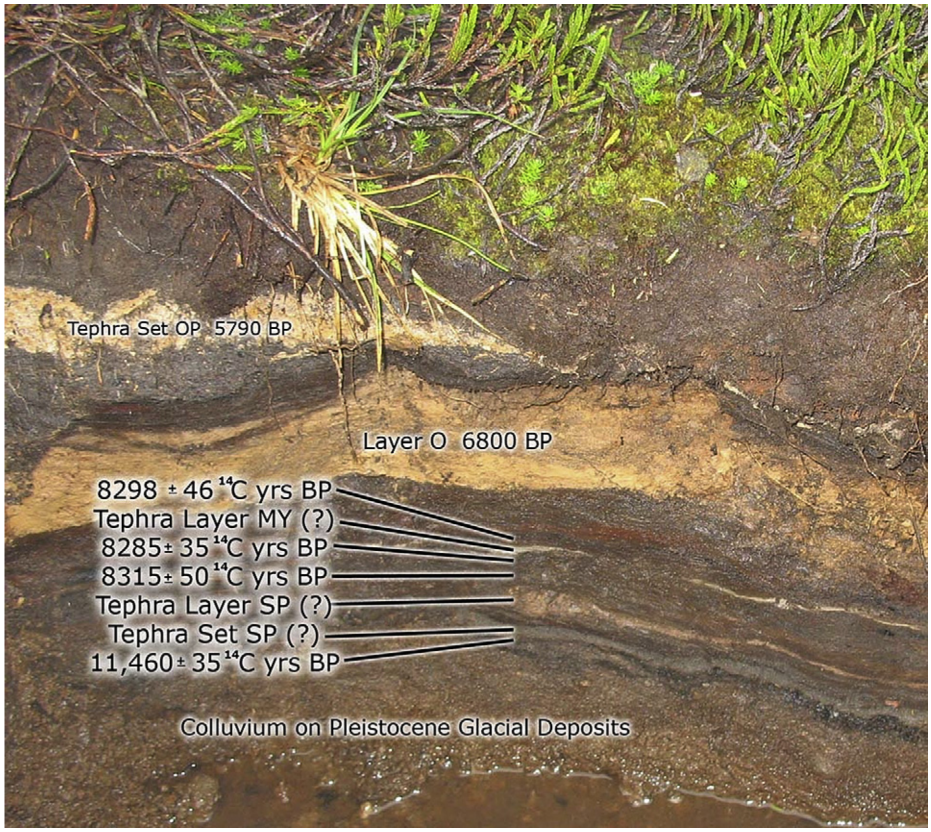

Fig. 6. Soil pit in meadows (labeled "tephra pit" on Fig. 3), on the south flank of Mount Baker, showing interbedded tephra, sand, silt, and peat. Calibrated radiocarbon ages, from top to bottom, are 9.43–9.14, 9.42–9.14, 9.46–9.14, and 13.43–13.22 ka. The basal radiocarbon age indicates that the ridges interpreted to be early Holocene moraines by previous workers are older than 13.43–13.22 ka. Although the pit is within the general area where Set SC tephra is present, none was found at this site.

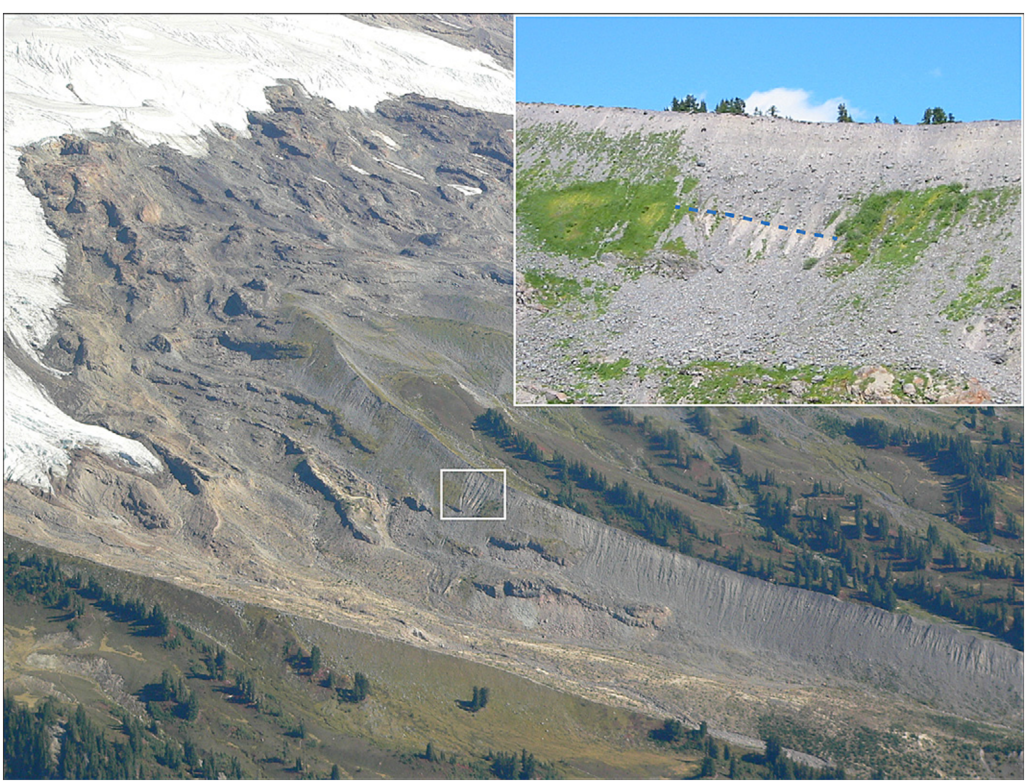

Fig. 7. Oblique aerial photograph showing proximal flank of the Easton left lateral moraine. Inset shows position (dashed line) of lower till contact and interbedded tephras and wood (see Fig. 8). Photograph courtesy of John Scurlock.

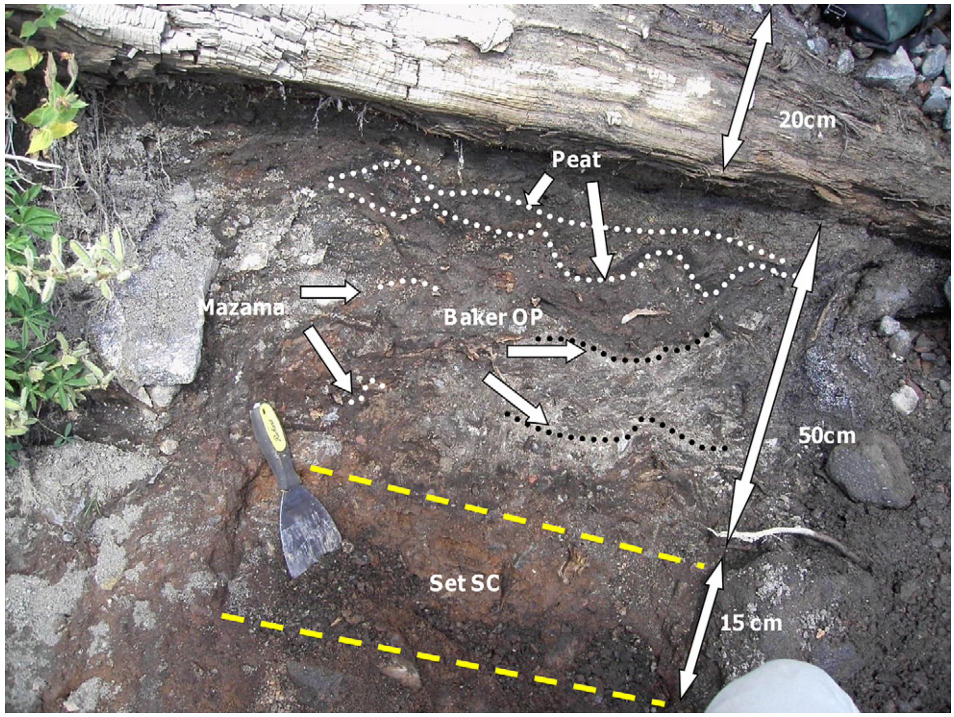

Fig. 8. Close-up photo of deformed, interbedded tephras, peat, and wood at the lower till contact of the Easton left lateral moraine. Lenses and stringers of pale ivory-colored tephra were identified as Baker OP tephra in the field. Deformed lenses of white tephra were identified as Mazama tephra by microprobe analysis. Dashed lines demarcate a zone of red tephra mixed with other debris; this tephra was identified as Set SC by microprobe analysis.

wood fragments that are typically about 1 cm in diameter. There are also some small orange to red-brown peat clasts along the contact, but we found no continuous stratified sediment layer. Larger wood fragments are aligned parallel to the moraine crest and dip approximately 20° towards the distal side of the moraine. Outer rings from a 40-cm-diameter log returned an age of AD 1410–1610 (Table 2). Outer rings from a partially decayed but bark-bearing log, 20 cm in diameter, yielded an age of AD 1430–1630.

Living trees and lichens on the crests of the left and right lateral moraines help constrain the Little Ice Age history of Easton Glacier. A living tree-ring chronology of all trees sampled in this study (Table 3) spans the period from AD 1841–2005 (inter-series correlation: $r = 0.497$). The lichenometric age of the right lateral moraine differs depending on the lichen growth curve used (Table 3). The Cascades growth curve gives a minimum age of sometime in the AD 1870s for moraine stabilization, whereas the

Fig. 9. Oblique aerial photograph showing Pocket Lake on the southwest flank of Mount Baker (courtesy of John Scurlock).

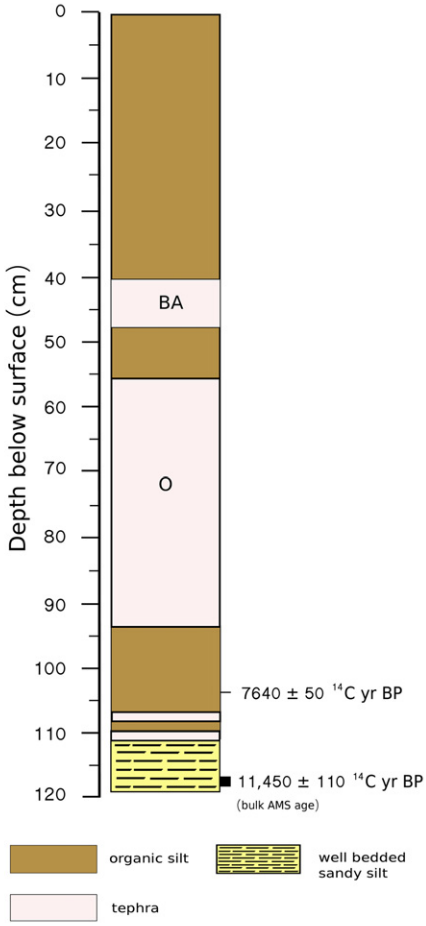

Fig. 10. Stratigraphy of the Pocket Lake sediment core.

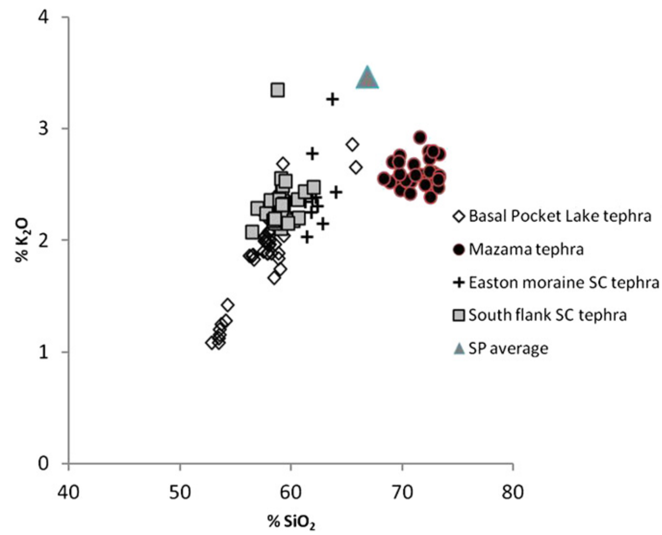

Fig. 11. Binary plot of SiO_2/K_2O composition of glass shards from tephra at the very base of the Pocket Lake sediment core, compared to glass compositions from other Mt. Baker SC samples and Mazama tephra (from this study), and Set SP tephra (unpublished data provided by Dave Tucker, Western Washington University and Cascades Volcano Observatory).

curve from Vancouver Island yields a minimum age of sometime in the AD 1850s.

4.3. Pocket Lake

Pocket Lake has an area of 0.75 ha and a maximum depth of 4.3 m; it is located in an east-facing cirque southwest of Mount Baker (Fig. 9). The lake is dammed by a small moraine left by a glacier that occupied the cirque after retreat of the Cordilleran ice sheet at the end of the Pleistocene. An apparently correlative moraine remnant lies at the same elevation below Park Butte cirque, 0.7 km north of Pocket Lake. These moraines have been used to support significant early Holocene glacier advance(s) in the North Cascades, postulated by Thomas et al. (2000) and Kovanen and Slaymaker (2005).

We obtained several sediment cores from the center of Pocket Lake. Basal sediments in the longest (1.20 m) core consist of inorganic sands and silty tephra beds at 1.18, 1.10, and 1.08 m depth (Fig. 10). We were unable to find terrestrial macrofossils in the basal sediments of the core and thus submitted a 1-cm-thick bulk sample from a depth of 1.18–1.19 m for radiocarbon dating. The sample yielded an age of 13.48–13.06 ka. A macrofossil from 1.06 m depth returned an age of 8.54–8.38 ka. Two additional tephras, identified as Mazama [7.48–7.46 ka] and Baker Set BA [6.41–6.79 ka] occur higher in the core, at depths of 0.93–0.55 and 0.48–0.41 m, respectively (Fig. 10).

We analyzed five samples of the pre-Mazama tephras in the Pocket Lake core (Ryane, 2009). All five tephra samples contain a substantial fraction of non-volcanic mineral matter, and many of the glass shards are devitrified. Based on the geochemistry of the glass shards, we interpret the basal tephras of the core to be reworked contaminated beds of Baker Set SC. The tephras at 1.10 and 1.18 m are particularly good matches, except that the basal tephra contains significantly less Al_2O_3 than either sample 9 from the south flank site or the other Pocket Lake tephra layers (Appendix 1). It is possible that variations in aluminum content in Set SC result from variable mixing of high-aluminum basalt (Green, 1988). Our interpretation of Set SC is corroborated by the process of elimination: the only other sub-Mazama basaltic or andesitic tephra known on the mountain is Set SP (Table 1), and SP is more felsic than SC (Fig. 11).

4.4. Deming Glacier

Deming Glacier, on the southwest side of Mount Baker, comprises two lobes that coalesce below a rock buttress and descends to a terminus at 1300 m asl. Two main groups of moraines are present in the forefield of Deming Glacier (Fig. 12). One group comprises a series of subdued lateral moraines that extend about 1500 m south-southwest from 1050–1150 m asl to 780 m asl, at the confluence of Middle Fork Nooksack River and Ridley Creek (Fig. 12). Gravel and diamicton are exposed in a 30-m-high section through one of these moraines on the south side of the Middle Fork, 0.5 km upstream of its confluence with Ridley Creek and about 3 km below the present terminus of Deming Glacier (Fig. 2). These sediments contain numerous detrital logs, six of which have returned radiocarbon ages ranging from 12.74 to 12.14 ka (Table 2: Kovanen and Slaymaker, 2005).

The second group of moraines consists of left and right lateral moraines inboard and upvalley of the late Pleistocene moraines (Fig. 12). The left lateral moraine is nearly continuous over a distance of 2 km, from steep rock slopes at about 1380 m asl to an elevation of 950 m asl, 2.2 km below the glacier terminus. The right lateral moraine extends over a distance of 2 km from a steep rock slope at 1380 m asl to an elevation of about 1140 m asl. A vegetation trimline extends 1.3 km from the upvalley end of the right lateral moraine to 2100 m asl. Sections of the proximal slopes of the two lateral moraines have been eroded, providing exposures of the sediments forming the moraines.

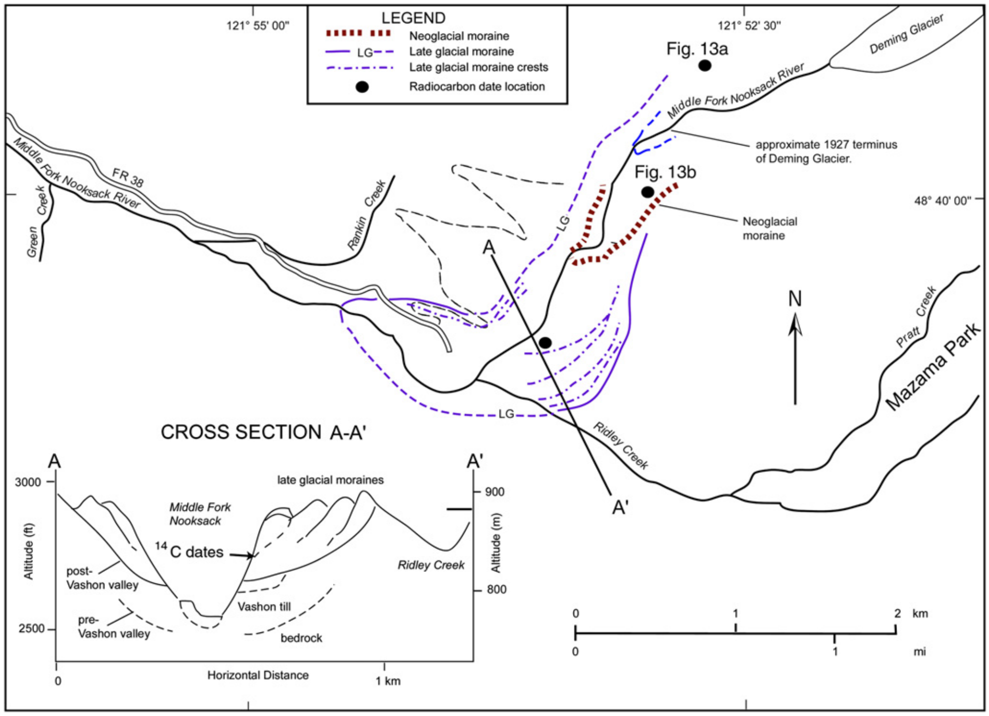

Fig. 12. Map of Lateglacial and Holocene moraines deposited by Deming Glacier in the vicinity of the confluence of Ridley Creek and Middle Fork Nooksack River.

The right lateral of the upper moraines is composed of several till units separated by wood mats and weakly developed paleosols. A key exposure, some 300 m long and up to 65 m high, located 1.2–1.4 km below the terminus of Deming Glacier, reveals up to five till units and intervening soils (Fig. 13a). The till units range from a few meters to nearly 30 m thick and consist of matrix-supported diamicton with 25–40 percent clasts up to boulder size set in a silty sand matrix. Wood mats separating the till units comprise tree stems, branches, and other woody detritus and are typically a few tens of centimeters to almost 1 m thick. Roots and stumps in growth position were present in all of the wood mats, demonstrating that the surfaces were vegetated. Some stumps extend up to 2 m vertically upward from their roots; others are flat-lying but still attached to their root boles. The latter are oriented downvalley in the direction of glacier flow and presumably were overridden and toppled by the advancing glacier. Till directly below some of the wood mats is oxidized, but no other evidence was observed of in-situ soil development.

The lowest diamicton, which is olive-gray in color and at least 15 m thick, is not well exposed in the section. It is overlain by up to 15 m of yellow-brown diamicton (Fig. 13a). This unit is similar to the diamicton units higher in the section, except that it includes zones of with subangular to angular clasts. A flattened, downvalley-oriented tree stem, still in growth position, and a branch, both of which were recovered from the wood mat at the upper contact of the yellow-brown diamicton, gave ages of, respectively, 2.15–2.01 ka and 2.35–2.21 ka (Table 2).

A second wood mat at the upper contact of the next higher diamicton contains tree stumps up to 1 m in diameter in growth position; outer rings from one of these stumps yielded an age of 1.82–1.71 ka. Two stumps in growth position from a third wood mat returned identical ages of AD 1020–1150 (Table 2). A tree stump in growth position and a branch in the highest wood mat of the section returned ages of AD 1450–1620 and AD 1310–1410, respectively (Table 2).

We also studied a 100-m long, 30-m high exposure in the left lateral moraine, 1 km downvalley of the section described above (Fig. 13b). The lowermost 25 m of the section consists of an unoxidized, matrix-supported diamicton. The upper 0.5 m of the unit is oxidized and mottled, and is abruptly overlain by a wood mat containing stumps in growth position and detrital logs up to 1 m in diameter (Fig. 13b). Many of the logs have several hundred annual rings. The root of a small tree stem in growth position in this wood mat yielded a calibrated radiocarbon age of 1.53–1.41 ka. The wood mat is overlain by 8–12 m of weakly stratified matrix-supported diamicton, which in turn is covered by a wood mat. A log from this mat, 3 m below the moraine crest, yielded a radiocarbon age of AD 1420–1500. The uppermost unit of diamicton, above this wood mat, must be younger than AD 1420.

4.5. Coleman Glacier

Coleman Glacier flows northwest from the summit of Mount Baker (Fig. 2). A prominent left lateral moraine rises ca 70 m above the glacier surface approximately 750 m upstream of its 2006 terminus. A prominent wood mat is exposed over a distance of about 100 m in the proximal flank of the moraine, 12 m below its crest (Fig. 14). Large logs, some over 3 m in length and 40 cm in diameter, dip at a 30° angle into the moraine, suggesting that the discontinuity between the overlying and underlying tills is parallel to the distal flank of the moraine. Outer rings from two logs yielded radiocarbon ages of AD 1020–1210 and AD 1040–1260. These ages supplement two similar ages of AD 1050–1410 and AD 1190–1420, obtained from the same wood mat by Easterbrook (2007).

5. Discussion: Mount Baker glacier chronology

Here we synthesize our field and laboratory data and observations to establish a chronology of glacier activity on the volcano. To facilitate discussion, we discuss these events from late Pleistocene to present. A chronologic summary showing results from the different sites on the mountain is given in Table 4.

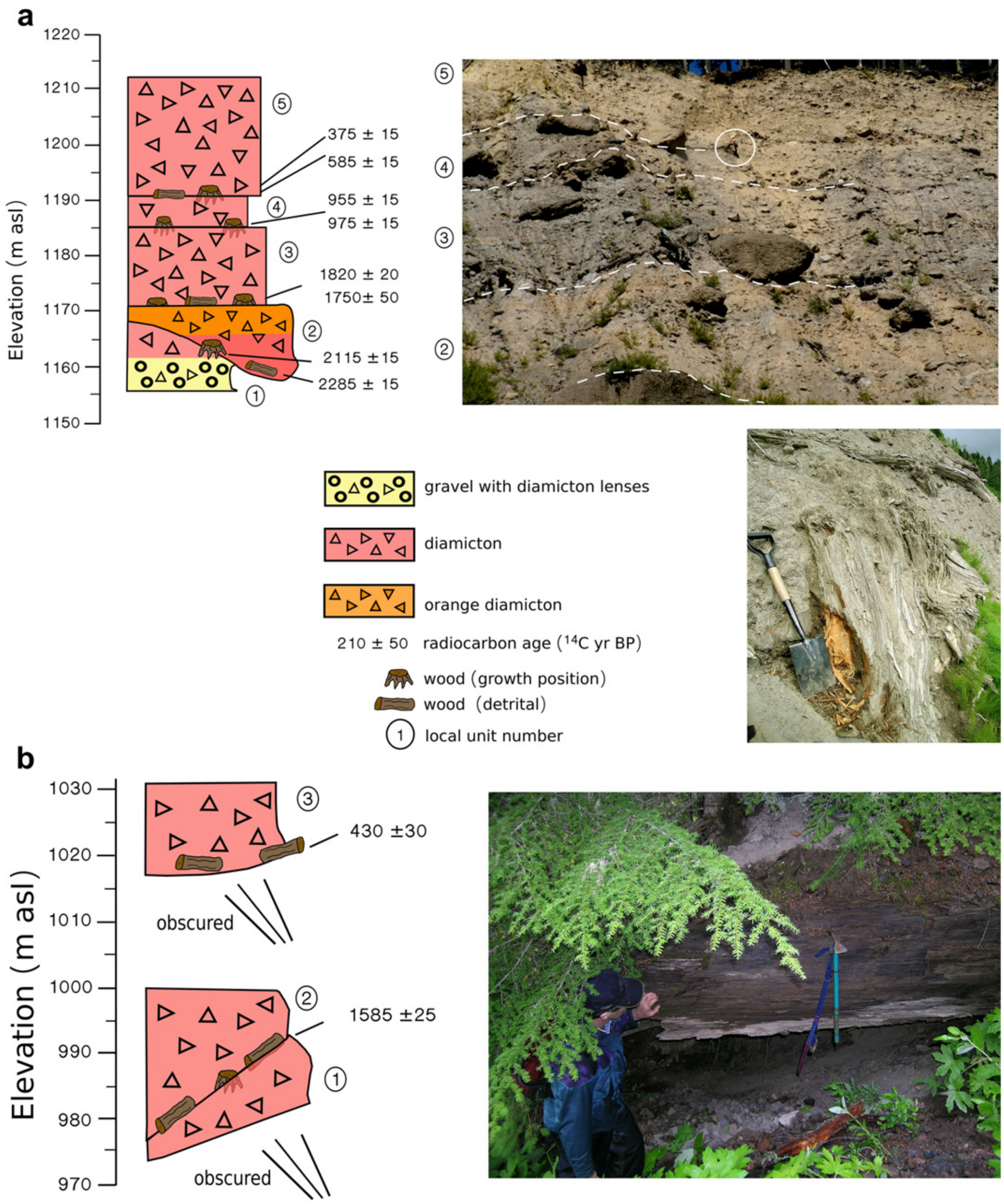

Fig. 13. (a) Stratigraphy in the right lateral moraine of Deming Glacier. Upper photograph: white dashed lines indicate wood mats separating till units; rappeling person is circled. Lower photograph: in-situ stump in the wood mat between units 2 and 3. (b). Stratigraphy in the left lateral moraine of Deming Glacier. Photograph shows an example of one of the large logs between units 1 and 2.

5.1. *Latest Pleistocene*

Moraines deposited by Deming Glacier near the confluence of the Middle Fork Nooksack and Ridley Creek are late Pleistocene in age, ca 12.8–11.3 ka. A number of radiocarbon ages constrain the most recent of these advances to sometime after ca 12.5 ka (Kovanen and Easterbrook, 2001; Scott and Tucker, 2003). Kovanen and Easterbrook (1996, 1998, 2001) suggested that these ages relate to an advance of Deming Glacier that reached 25–45 km beyond Mount Baker. Stratigraphic, geomorphic, and gechronologic data indicate, however, that the Lateglacial advances of Deming Glacier only reached 4–5 km beyond Neoglacial limits. Furthermore, recent reassessment of the putative "alpine moraines" described by Kovanen and Easterbrook in the lower parts of the Nooksack valley indicates that they are instead deposits related to decay of the Cordilleran Ice Sheet (Harrington and Clark, 2011). Consistent with this reinterpretation, the Lateglacial moraines in the Middle Fork Nooksack River and Sulphur Creek drainages that we investigate here are the same age and relative extent as other Lateglacial moraines in the North Cascades (Riedel, 2007; Porter and Swanson, 2008).

Lateral moraines at the Middle Fork Nooksack site were used to reconstruct the area and ELA of Deming Glacier during the most extensive and least extensive of the Lateglacial advances. The glacier during the most extensive and earliest advance had an area of ~9 km^2 and an ELA of about 1740 m asl; the glacier of the smallest, latest advance had an area of 8 km^2 and an ELA of 1849 m asl (Riedel, 2007). The ELA depression for the latter advance was about 350 m, similar to that found in previous studies in the region (e.g., Burrows et al., 2007).

Fig. 14. Sampling the wood mat separating two till units in the proximal flank of the Coleman Glacier left lateral moraine.

5.2. Early Holocene

Claims of significant early Holocene glacier advances on Mount Baker have been made by Kovanen and Easterbrook (1996, 1997, 1998, 1999, 2001, 2002), Thomas et al. (2000), Burrows et al. (2000), Burrows (2001); Kovanen et al. (2001), Kovanen (2003), and Kovanen and Slaymaker (2005). Based on our field data and an evaluation of the published literature, we find no evidence that glaciers were more extensive during the early Holocene than during the Little Ice Age.

Thomas (1997), Thomas et al. (2000), and Kovanen and Slaymaker (2005) interpreted ridges in the upper Sulphur Creek drainage between Squak and Easton glaciers (our "south flank" site) to be moraines formed by an extensive early Holocene ice. The principal evidence for their argument is the inferred absence of Set SC tephra, dated to 10.17–9.55 ka (Tucker et al., 2007), on the ridges. But Set SC tephra does top these ridges; its presence and a stack of tephras in the adjacent meadows indicate that the ridges predate the Holocene. A basal age of 13.43–13.22 ka on a sample collected from the previously described "tephra pit" between the ridges is a minimum for the age of the ridges.

Additionally, the ridges that have been previously interpreted to be lateral moraines may not be moraines at all. They are straight to slightly curved; there are no transverse ridges indicative of end moraines. Diamicton does occur near the tops of the ridges, but the interiors are not exposed. It is possible that they are ridges composed of volcanic rock or lahar levees. Indeed, isolated, parallel radial ridges are characteristic of stratovolcanoes. Gardner et al. (1995), for example, described radial ridges on the unvegetated flanks of Mount Baker between Squak and Easton glaciers and concluded they are of volcanic origin. Other Cascade volcanoes, such as Mount St. Helens and Mount Adams, have similar radial ridges at about the same elevations (Fig. 15). At Mount Adams,

Table 4
Chronologic summary showing ages of glacial advances inferred at study sites on Mt. Baker.

Time (ka BP)	South flank	Easton Glacier	Pocket Lake	Deming Glacier	Coleman Glacier
0		>0.17 < 0.5		0.9–0.4	<1.0
				1.4–1.5?	
2				1.7–1.8	
4				2.0–2.3	
6		ca 6			
8					
10		>9.5			
12				12.6–12.2	
14	>13.3		>13.1?		

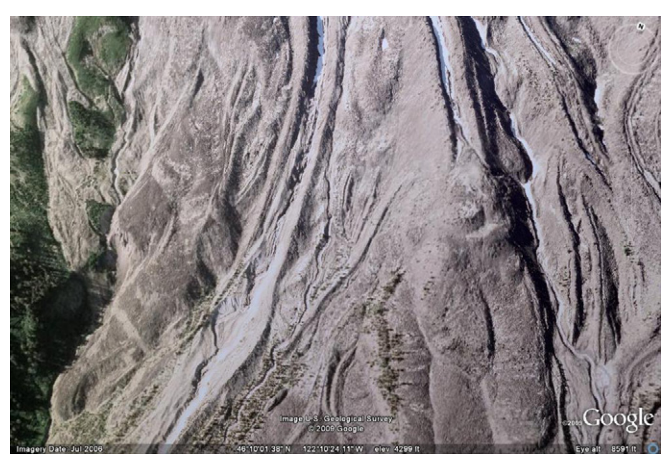

Fig. 15. Radial ridges of volcanic origin on Mount St. Helens. Similar radial ridges mantled by diamict on the south flank of Mount Baker have been interpreted by previous workers to be moraines.

Hildreth and Fierstein (1995) observed similar ridges located on top of a Holocene lava flow.

The till underlying the three tephras in the left lateral moraine of Easton Glacier was deposited by a glacier advance that is older than ca 10 ka, the age of Set SC tephra. The youngest of the three tephras dates to ca 6.5 ka; all three were deposited on an eroded flank of a late Pleistocene moraine crest. For the tephras to be preserved, the depositional surface must have been ice-free from before 10 ka to after 6.5 ka. Accordingly, Easton Glacier had a limited extent over this period. Collectively, the data argue for a glacier whose early Holocene extent was similar to, or possibly smaller than, its extent today.

Our probe data from the Pocket Lake sediment core indicate that the moraine damming the lake formed before eruption of Set SC tephra in the late Pleistocene and thus that the 9.55–9.30 ka age for the moraine reported by Easterbrook and Kovanen (1999) must be a minimum. The bulk basal radiocarbon age of 13.50–13.07 ka requires a depositional hiatus of several thousand years immediately before eruption of Set SC tephra (10.17–9.55 ka). Two scenarios could account for this hiatus: 1) warm dry conditions caused the shallow lake to desiccate before deposition of Set SC tephra; 2) the bulk radiocarbon age is contaminated with old carbon (Reasoner and Jodry, 2000), making it too old. The basal age from the lake, however, is nearly identical to the basal age (13.43–13.22 ka) obtained from the "tephra pit" excavated between the ridges on the south flank (Fig. 3).

The Park Butte moraine, 0.7 km north of Pocket Lake, also has been interpreted to be early Holocene in age (Easterbrook and Burke, 1972; Easterbrook, 1975, 1986). An age of 10.18–9.56 ka was obtained on charcoal "in a diamicton on lake sediments next to (outside) a moraine at Park Butte" (Easterbrook and Kovanen, 1999). Based on field relations, there is no obvious connection between the diamicton that contained the charcoal and the moraine that lies on the opposite side of the cirque, and Easterbrook and Kovanen (1999) do not provide a definitive link. The age of this moraine thus remains unknown.

5.3. Early Neoglaciation (ca 6–3 ka)

Most of our sites provide no record of early Neoglacial events. The wood mat on the lower till in the Easton Glacier left lateral moraine, however, indicates an early Neoglacial advance following a long interval of recessive ice during the early Holocene. The two dated logs have nearly identical calibrated ages of ca 6 ka. They lie on top of the youngest of the tephras, the ca 6.5 ka Baker Set BA. An advance of Easton Glacier around 6 ka is the most parsimonious explanation for the kill dates of these trees, given the lack of slopes that could feed avalanches to the site and the presence of till above the unconformity.

Fuller (1980) and Fuller et al. (1983) reported three Holocene glacial advances on Mount Baker. The oldest till is overlain by Mazama tephra and peat radiocarbon-dated to about 6 ka. However, there is no evidence that this till is closely associated with the tephra in time.

5.4. Late Neoglaciation (the last 3 ka)

Evidence for late Neoglacial advances prior to the Little Ice Age maximum is provided by wood mats in the lateral moraines of Easton, Deming, and Coleman glaciers.

5.4.1. Easton Glacier

Two wood fragments collected from the upper wood mat in the left lateral moraine of Easton Glacier date to about AD 1500. The stratigraphy and radiocarbon ages demonstrate that the glacier thickened to nearly its maximum Little Ice Age elevation at the site, then thinned, and thickened again about AD 1500 to overtop the old moraine crest. Because no avalanche terrain exists above the exposure, we interpret the detrital wood samples to be fragments of trees that grew in the glacier forefield or on the lateral moraine and were later killed by a glacier advance.

About 16 m of till separate the lower and upper wood mats in the left lateral moraine of Easton Glacier. The only certainty regarding the middle till is that it is younger than 6 ka and older than AD 1500, but it is possible that it was deposited by two or more Neoglacial advances for which there is no observable evidence in the moraine stratigraphy.

The extent of Easton Glacier since the early 19th century is constrained by lichen and tree-ring data from the lateral moraines. Trees on the right lateral moraine of Easton Glacier, sampled in 2005, yielded a maximum age of 132 years. Trees on the two outermost moraines between Easton and Squak glaciers were 164 and 119 years old in 2005. Adding ecesis values to the ring counts date the formation of the right lateral moraine of Easton Glacier to the AD 1850s, and the two outermost moraines between Easton and Squak glaciers to the AD 1860s and 1820s.

These ages are corroborated by lichen data, if it is assumed the lichen growth curve from Vancouver Island is valid. Our findings support previous work indicating that the Vancouver Island lichen growth curve is applicable to adjacent areas (Osborn et al., 2007; Koch et al., 2007a).

5.4.2. Deming Glacier

The composite stratigraphy of the right lateral inner moraine of Deming Glacier records at least four late Neoglacial advances, separated by periods of glacier retreat, during which the moraine became forested. During each of the periods of moraine stability, Deming Glacier terminated at, or upvalley of, our key study site 1.4 km below the present terminus. Periods of moraine stability ended with renewed deposition of till on the moraine. Some of the forests were simply buried in till, whereas other trees were overridden by ice. Erect tree stems, buried in till, are evidence for the former, whereas flat-lying stems, pointing downvalley but still attached to root boles, are evidence of the latter. Vertical stacking of progressively younger tills in the right lateral moraine shows that the advances of Deming Glacier were progressively more extensive over time (Fig. 13). The first recorded advance at our key section destroyed forest 80 m above the valley floor, whereas the last advance reached elevations 50 m higher.

The oldest Neoglacial advance recorded by a wood mat at this site occurred ca 2.35–2.01 ka. One of the overridden trees contained more than 300 annual rings, indicating that the interval of moraine stability preceding this advance was lengthy. The till underlying the wood mat is not directly dated, but may be a product of a ca 3.1 ka advance suggested by Easterbrook and Donnell (2007). The advance at 2.35–2.01 ka is probably the same event that killed trees about 2.2 km downstream of the present glacier terminus at about 2.5–2.2 ka (Easterbrook and Donnell, 2007).

Deming Glacier advanced again into forest ca 1.82–1.71 ka. This advance is recorded by the till overlying the second wood mat. Again, some of the trees in this wood mat contain several hundred annual rings, consistent with the approximately 400 years intervening between this advance and the preceding one. It remains uncertain whether trees killed at the left lateral moraine at 1.53–1.41 ka, some 1 km downvalley, reflect a subsequent advance of Deming Glacier or just a slow expansion of the glacier. If the latter explanation is correct, Deming Glacier advanced at an average rate of 2.4–5.6 m yr^{-1} during the intervening period (0.18–0.42 ka). Fuller et al. (1983) reported glacially sheared-off tree stumps in the Deming Glacier forefield that they dated to "an average" of about 1.85 ka. But their abstract provides no specific locations or other context, so it is not possible to determine how the ages relate to the stratigraphy described above.

Deming Glacier advanced again around AD 1020–1150. The glacier killed trees that were 1.5 m diameter and several hundred years old. This advance, based on the elevation of the stumps and logs in the moraine, was more expansive than earlier events. The final, and most extensive, advance recorded in the right lateral moraine occurred at AD 1450–1620, when till was deposited over the uppermost wood mat. This till forms the crest of the right lateral moraine and thus was deposited during the most extensive Holocene advance of Deming Glacier. Dendrochronological evidence indicates that Deming Glacier advanced during the 16th, 17th, 19th, and 20th centuries (Fuller et al., 1983).

5.4.3. Coleman Glacier

Samples from the wood mat in the left lateral moraine of Coleman Glacier were first dated by Easterbrook and reported in 2007. We dated two other samples. The four ages are generally similar, but the youngest of the four, AD 1190–1420, provides the closest maximum age for the time of deposition of the overlying till. The orientation of the logs in the mat suggests they were lying on the distal flank of the pre-existing moraine. They were buried by 12 m of till during a later advance of the glacier that commenced sometime between the 12th and 15th centuries.

Previous workers used dendrochronology to date the Little Ice Age moraines of Coleman Glacier. Fuller et al. (1983) reported that the glacier advanced during the 19th and 20th centuries. In a more comprehensive study, Heikkinen (1984) documented advances of the glacier in the early 1500s, and AD 1740, 1823, 1855, 1886, 1908, 1922, and 1978.

5.4.4. Other glaciers

Fuller et al. (1983) also reported Little Ice Age advances in two valleys that we did not investigate. They concluded that Rainbow Glacier advanced during the 17th and 20th centuries, and Boulder Glacier advanced during the 16th, 19th, and 20th centuries.

5.5. Summary

Based on our work and the work of others, we propose a collective chronology of glacier advances on Mount Baker (Fig. 16). The pre-Mazama till at Easton Glacier is not closely bracketed in time, but we speculate that it may correlate with an advance of the glacier during the Younger Dryas, based on the evidence from Deming Glacier and from nearby sites in southern British Columbia (see below). There is no evidence of early Holocene glacial activity. Neoglaciation began ca 6 ka, but we found no evidence of either advances or retreats between ca 5 and 3 ka. The stacked tills at Deming Glacier show that ice generally expanded in a series of small advances and retreats over the past two millenia and reached its maximum extent in the Little Ice Age.

6. Discussion: regional comparisons

6.1. Latest Pleistocene

The latest Pleistocene advances of glaciers on Mount Baker are synchronous with advances of the Cordilleran ice sheet in the Fraser Lowland and Squamish Valley to the northwest (Armstrong et al., 1965; Clague et al., 1997; Kovanen, 2001; Kovanen and Easterbrook, 2001; Friele and Clague, 2002; Easterbrook et al., 2007), alpine glaciers elsewhere in the North Cascades (Riedel, 2007; Porter and Swanson, 2008), and cirque glaciers in the Canadian Rockies (Reasoner et al., 1994). The magnitudes of some of these advances differ, perhaps due more to variable downwasting and retreat of the ice sheet than to true climatic differences (Lakeman et al., 2008).

Davis and Osborn (1987) and Osborn et al. (1995) suggested that many outer cirque moraines in the North American Cordillera are Younger Dryas in age. These moraines are commonly less than 1 km beyond positions reached by glaciers during the Little Ice Age. One such set of moraines is that of the Crowfoot Advance, originally described in the Canadian Rockies (Osborn and Luckman, 1988). Only about 5 percent of the cirques in the Canadian Rockies contain Crowfoot Moraines, presumably because most Little Ice Age advances were more extensive than the Crowfoot Advance.

Late Pleistocene moraines of probable Younger Dryas age also occur in the eastern Cascades. The Brisingamen moraine in the Enchantment Lakes basin (Waitt et al., 1982) lies slightly beyond Little Ice Age moraines and trimlines. Evidence from lake sediments indicates that the advance that formed the Brisingamen moraine ended shortly before 11.30 ka, suggesting temporal equivalence with the Younger Dryas (Bilderback and Clark, 2003; Bilderback, 2004). The Lateglacial moraines of Deming Glacier in the Middle Fork Nooksack River drainage reported in this study are comparable in age and extent to these moraines and to other Younger Dryas moraines in the North Cascades (Riedel, 2007; Porter and Swanson, 2008) and the southern Coast Mountains (Friele and Clague, 2002). The till underlying the section containing the wood mat and tephras in the Easton left lateral moraine may be of Younger Dryas age. The Pocket Lake moraine is older than 10.2 ka and may be possibly older than 13.2 ka. Like the lowermost till in the Easton Glacier left lateral moraine, the Pocket Lake moraine lacks tight age constraint. Given the chronologic evidence for Younger Dryas advances of Deming Glacier, the Pocket Lake moraine may be coeval with the Younger Dryas.

Some researchers have suggested that glaciers in the Pacific Northwest did not advance during the Younger Dryas (Heine, 1998) or that Younger Dryas advances were significantly larger than those of the Little Ice Age (Porter and Swanson, 2008). Heine (1998) interpreted the McNeeley moraines near Mount Rainier,

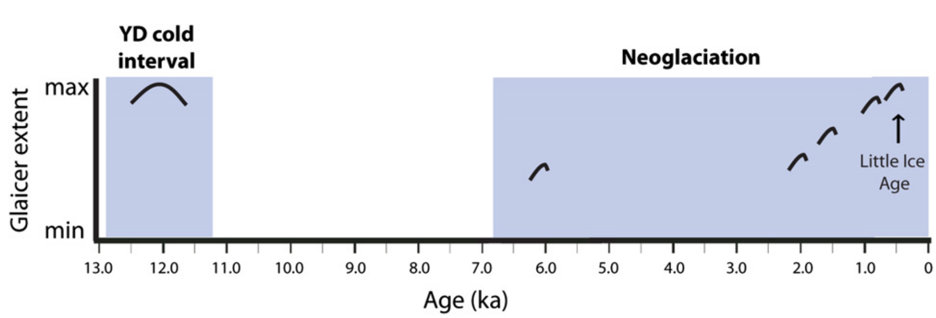

Fig. 16. Schematic diagram showing relative glacier extent on Mount Baker in Lateglacial and Holocene time.

which were originally mapped by Crandell (1969), as pre-Younger Dyras in age. His interpretation, however, is based on radiocarbon ages obtained from bulk sediments, and such ages can be unreliable (Reasoner and Jodry, 2000). Porter and Swanson (2008) obtained an age of 12.5 ± 0.5 ^{36}Cl ka on moraines in the Icicle Creek drainage in the North Cascades. These moraines descend to 550 m asl, some 1350 m below Little Ice Age end moraines 10 km to the north. It is too early to tell if this apparent discordant response is real, possibly due to different influences of the Cordilleran ice sheet at different latitudes, or whether the cosmogenic exposure ages should be regarded as minimum limiting ages, due for example to degradation of weathering of dated boulders (Heyman et al., 2011).

6.2. Early Holocene

Paleobotanical records, the clastic content of proglacial lake sediments, and climate models can be used to infer climate conditions during the Holocene. These data show that the early Holocene climate did not favor extensive ice cover in the Pacific Northwest and the southern Canadian Cordillera. Pollen and biogenic silica from lake sediments, and fossil wood found above current treeline indicate that the early Holocene was warm and dry (Clague and Mathewes, 1989; Reasoner et al., 2001; Gavin et al., 2011). A minor advance of alpine glaciers occurred between 8.63 and 8.02 ka (Menounos et al., 2004) in western Canada, but there is no evidence for glacier expansion beyond Little Ice Age limits in the Canadian Cordillera during the early Holocene (Menounos et al., 2009).

Although our data from Mount Baker do not support early Holocene advances of glaciers there, others have reported advances during that time at Mount Rainier (Heine, 1998) and Glacier Peak (Beget, 1981, 1983, 1984). For reasons noted above, the lacustrine evidence for early Holocene advances at Mount Rainier is questionable. Davis and Osborn (1987) visited Glacier Peak and argued against Begét's (1981, 1983, 1984) early Holocene "White Chuck Advance" and his notion of early Holocene "Mesoglaciation". But Begét stands by his interpretation at Glacier Peak (Kovanen and Begét, 2005) and the debate continues (Menounos et al., 2005). Meanwhile, a proposed early Holocene glacier advance in the nonvolcanic Enchantment Lakes basin in the central Washington Cascades (Waitt et al., 1982) has been reinterpreted to be late Pleistocene in age (Bilderback, 2004).

These previous interpretations of relatively extensive early Holocene ice are at odds with the regional paleoclimate history developed both from non-glacier proxies noted above and the records of alpine glacier fluctuations elsewhere in western North America (Ryder and Thomson, 1986; Davis, 1988; Osborn and Luckman, 1988; Osborn et al., 1995; Koch et al., 2007a, 2007b; Davis et al., 2009; Menounos et al., 2009), which suggest that early Holocene ice extent was minimal compared to that of the Little Ice Age.

6.3. Neoglaciation

Radiocarbon ages obtained from wood buried by till within the left lateral moraine of Easton Glacier suggest that Neoglaciation was underway at Mount Baker by 6.3 ka. This conclusion is bolstered by calibrated radiocarbon ages of 5.94, 5.75, and 5.30 ka on stumps in growth position from the forefield of South Cascade Glacier (F. Anslow, personal communication, 2010), consistent with previous studies (Meier, 1961; Miller, 1973). The data are also consistent with glacier records from the southern Canadian Cordillera that indicate widespread expansion of glaciers during the period 7.5–5.0 ka (Ryder and Thomson, 1986; Koch et al., 2007a; Menounos et al., 2009), as well as many other sites throughout the world (Davis et al., 2006). In contrast, Neoglacial expansion appears to have occurred a few thousand years later at sites in the Sierra Nevada (Bowerman and Clark, 2011). There is, as yet, no explanation for this difference.

The magnitude and timing of late Neoglacial advances on Mount Baker and those in the southern Canadian Cordillera are broadly similar (Menounos et al., 2009). Advances of Deming Glacier at ca 3.1 ka and 2.35–2.15 ka are coincident with the Tiedemann and Peyto advances, which are recorded at numerous glaciers in the Coast Mountains and the Canadian Rockies (Menounos et al., 2009).

The advance(s) of Deming Glacier at 1.82–1.71 ka and 1.53–1.41 ka is coeval with the First Millennium AD advance, documented throughout northwest North America (Reyes et al., 2006). Many glaciers, including Deming Glacier, reached to within a few hundred meters of their maximum Holocene limits during this event.

Mount Baker glaciers advanced and retreated many times during the past millennium. Coleman and Deming glaciers were advancing by AD 1020, hundreds of years earlier than the beginning of the Little Ice Age as it is classically defined (Grove, 2004), but synchronously with advances of many other glaciers in western North America (Koch et al., 2007a). Radiocarbon ages indicate that the final advances of the past millennium started about 400 years ago, and minimum-limiting tree and lichen ages suggest that glaciers on Mount Baker finished constructing their outermost Holocene moraines about 150 years ago. The timing of these advances accords with ages for the inception and termination of the latest Little Ice Age advances throughout the western Cordillera of the Americas (Luckman and Villalba, 2001) and especially with adjacent areas in western Canada and the US Pacific Northwest (Burbank, 1981; Heikkinen, 1984; Luckman, 2000; Lewis and Smith, 2004; Koch et al., 2007a, 2007b).

7. Discussion: the question of anomalous glacier response on stratovolcanoes

As mentioned at the beginning of this paper, Kovanen et al. (1996) and Kovanen and Slaymaker (2005) have argued that Cascade volcanoes have anomalous glacial histories, based on an assumption that their height and location on the windward side of the Cascade Range created more favorable mass balance conditions. But regional mass balance, equilibrium line altitude (ELA), and hypsometry data indicate that glaciers on Cascade volcanoes do not have these advantages. Indeed, comparison of ELA measurements on Easton Glacier by Mauri Pelto [www.nichols.edu/departments/glacier/index/htm] with those of five other glaciers in the region reveal that the ELA of Easton Glacier is 200 m higher than the others (Fig. 17). Reasons for higher ELA on the south side of Mount Baker include lack of shading, wind erosion of snow, and narrow accumulation zones. Adjacent glaciers on the summit cone share ice divides and their accumulation zones are wedge-shaped with small areas above 2500 m.

Large Lateglacial advances, such as those inferred by Easterbrook and Kovanen (1996) and Kovanen and Easterbrook (1996, 1997, 2001), are not favored by the topography of glacial valleys on Mount Baker. The major glaciers on the volcano are relatively insensitive to ELA lowering below about 1700 m asl because they enter narrow canyons below this elevation. ELA depression within narrow valleys adds relatively little to the accumulation zone and probably also explains why Lateglacial and Neoglacial moraines are located within a few kilometers of each other (Fig. 12).

A further argument against anomalous Lateglacial advances concerns relative Lateglacial and Little Ice Age extents, which were

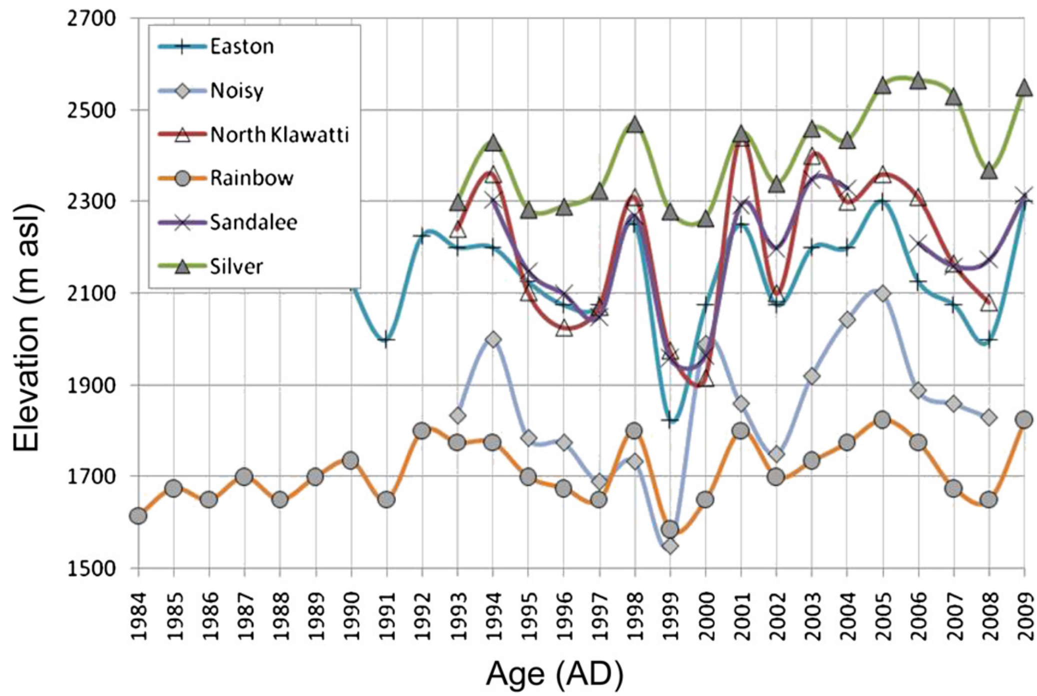

Fig. 17. Variability in glacial equilibrium line altitudes for six North Cascades glaciers. ELAs for Rainbow and Easton glacier data based on visual estimates (Mauri Pelto); ELAs for other glaciers calculated from mass balance measurements. The ELA of south-facing Easton Glacier is several hundred meters higher than that of northeast-facing Rainbow Glacier.

generally similar in magnitude throughout the western North American Cordillera (Davis, 1988; Menounos et al., 2009). If favorable mass balance conditions generated extensive Lateglacial ice on any particular mountain, they also should have generated extensive Little Ice Age ice, but there have been no suggestions of anomalous Little Ice Age advances. Our data suggest that glaciers in the Pacific Northwest and in western Canada responded in concert to regional climate change.

8. Conclusions

Our work and that of others at Mount Baker provide a rich record of glacier fluctuations over the past 12,000 years. The record indicates that: 1) Deming Glacier advanced during both Younger Dryas and Neoglacial times, but not in the early Holocene; 2) ridges at Mount Baker previously identified as early Holocene moraines are older than 13 ka; 3) the previously identified, early Holocene moraines may not be moraines in any case; 4) the Pocket Lake moraine is older than 10 ka and according to a bulk radiocarbon age older than 13 ka; 5) an early Holocene age for the Park Butte moraine is not established by previously reported evidence; geographic similarities suggest instead that it is probably the same age as the Pocket Lake moraine; 6) Neoglaciation at Easton Glacier was in progress by ca 6 ka; 7) Deming Glacier advanced successively greater distances downstream between ca 2.3 and 1.7 ka, 0.9, and 0.4 ka (AD 1020–1150 and AD 1450–1620); intervening intervals of retreats were long enough to allow establishment of forests on the moraine crests; 8) Coleman Glacier was advancing and within 12 m of the crest of its maximum Little Ice Age moraine by 0.6–0.8 ka; 9) Easton Glacier advanced to nearly its maximum Little Ice Age extent, and then retreated in the middle of the Little Ice Age, before advancing again by 0.5 ka; 10) glaciers on the south side of the mountain reached their maximum extents in the mid-1800s.

Taken together, these observations indicate that glaciers on Mount Baker were of minimal extent during the early Holocene, began to advance by ca 6 ka, and continued to advance to successively greater limits during the late Holocene, with intervening periods of retreat. Glaciers achieved their maximum Holocene extents in the 1800s at the end of a two-part Little Ice advance punctuated by retreat before ca 0.4 ka. The similarity between glacier fluctuations here and those in British Columbia and elsewhere in the Cascades suggests a common history of Holocene climate change over a broad area of the northern Cordillera. There is no evidence that glaciers on big volcanoes behave differently from glaciers elsewhere, and from a theoretical standpoint there is no reason to assume Cascade volcanoes would be subject to anomalous climatic effects. Regional mass balance, equilibrium line altitude, and hypsometry data indicate that glaciers on Cascade volcanoes do not experience anomalous mass balance conditions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.quascirev.2012.06.004.

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