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A latest Pleistocene and Holocene glacial history and paleoclimate reconstruction at Three Sisters and Broken Top Volcanoes, Oregon, U.S.A.

Shaun A. Marcott [a,*], Andrew G. Fountain [b], Jim E. O'Connor [c], Peter J. Sniffen [b], David P. Dethier [d]

[a] Department of Geosciences: Oregon State University, Corvallis, OR, 97331, USA
[b] Department of Geology: Portland State University, Portland, OR, 97201, USA
[c] U.S.G.S. Oregon Water Science Center, Portland, OR, 97201, USA
[d] Department of Geosciences: Williams College, Williamstown, MA, 01267, USA

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ABSTRACT

At least three sets of moraines mark distinct glacial stands since the last glacial maximum (LGM) in the Three Sisters region of the Oregon Cascade Range. The oldest stand predates 8.1 ka (defined here as post-LGM), followed by a second between ~2 and 8 ka (Neoglacial) and a third from the Little Ice Age (LIA) advance of the last 300 years. The post-LGM equilibrium line altitudes were 260±100 m lower than that of modern glaciers, requiring 23±9% increased winter snowfall and 1.4±0.5°C cooler summer temperatures than at present. The LIA advance had equilibrium line altitudes 110±40 m lower than at present, implying 10±4% greater winter snowfall and 0.6±0.2°C cooler summer temperatures.

Introduction

Alpine glaciers are sensitive recorders of climate change (Meier and Tangborn, 1965; Meier et al., 1977; Oerlemans, 2005), though this relationship can be obscured in some situations due to non-climatic factors such as glacier aspect, topography, debris cover, or volcanic activity (Lillquist and Walker, 2004). While ice sheets typically respond relatively slowly to climate variations (10^2–10^3 years) due to their large size (Imbrie and Imbrie, 1980), small mountain glaciers respond relatively quickly (~10^1 years) (Johanneson et al., 1989) and are therefore more sensitive to subtle climatic changes. Consequently, glacial deposits (e.g., moraines, glaciolacustrine sedimentation) may record climate changes not well documented by other proxies (Bradley, 1999). This relationship between climate change and glacier response was observed as early as the 1830s by Louis Agassiz (1840).

Recent glacial research in the western-most states of the U.S.A. has focused primarily in the North Cascades of Washington (e.g., Porter, 1977; Waitt et al., 1982; Heine, 1998; Bilderback, 2004) and the Sierra Nevada of California (e.g., Birkeland, 1964; Birman, 1964; Clark and Gillespie, 1997; Bowerman and Clark, 2005), with work scattered elsewhere in Idaho (Thackray et al., 2004), Montana (Hall and Heiny, 1983; Carrara, 1986; Licciardi et al., 2001) and eastern Oregon (Kiver, 1974; Licciardi et al., 2004). The existing dates from these locations suggest several glacial advances occurred after the LGM (19–23 ka). However, despite this spatially extensive research, little work to define the timing of glacial episodes following the LGM has been published on the Oregon Cascade Range. This report fills this geographic hole and examines post-LGM glacier activity, placing new constraints on the timing and magnitude of major latest Pleistocene and Holocene climate events in the western U.S.A. We identify the major glacial deposits of the eastern and northern flanks of the four stratovolcanoes comprising Three Sisters and Broken Top volcanoes in the Cascade Range of Oregon, constrain the timing of the glacial deposits, and develop a first-order approximation of paleoclimatic conditions associated with advanced glacier positions. This is an ideal site because at this latitude (~44°) the glaciers are small and responsive to subtle climate changes, but the tall, steep, and highly erodible volcanoes promote the formation of prominent moraines that clearly define maximum glacier limits.

Study site

The tall volcanoes in the Three Sisters region are composite lava cones located in the Cascade Range of central Oregon (Fig. 1). With four individual peaks higher than 2800 m, this terrain supports 17 named glaciers with a total early-1990s area of 7.5 km^2 (O'Connor et al., 2001) between elevations of 2100–3100 m. Our study focused on

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* Corresponding author. Fax: +1 541 737 1200.
E-mail address: marcotts@science.oregonstate.edu (S.A. Marcott).

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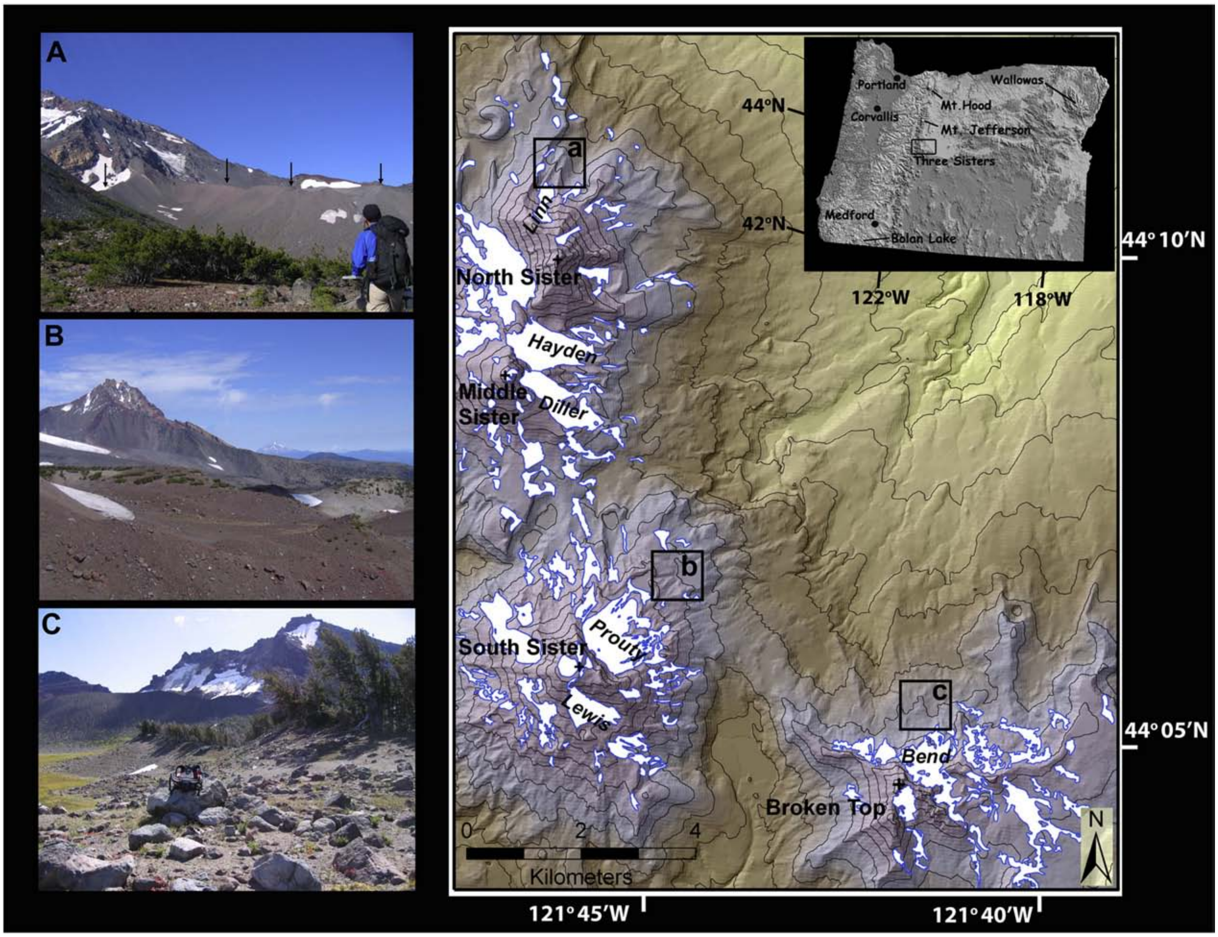

Figure 1. Digital elevation maps (USGS, 2005) and field photographs of Three Sisters and Broken Top volcanoes, Oregon Cascade Range. Displayed on digital elevation map are present glaciers (e.g., Prouty), snowfields and notable topographic features discussed in text (as depicted on modern USGS 7.5-minute topographic quadrangles). Contour interval is 100 m. Photographs depict (A) LIA, (B) Neoglacial, and (C) post-LGM moraines at sites indicated on map.

larger modern glaciers on the east flanks of the Three Sisters and on the north flank of Broken Top volcanoes (from north to south: Linn, Diller, Hayden, Prouty, Lewis, and Bend glaciers). These glaciers average ~0.60 km^2 in area and cover a total area of ~3.5 km^2 (Driedger and Kennard, 1986). Ice thicknesses for most of the glaciers (Diller, Hayden, Prouty, and Lewis) were measured with ground-penetrating radar and estimated for the others using an assumed area–volume correlation (Driedger and Kennard, 1986). The maximum ice thickness of the glaciers were 45–75 m and average thicknesses were approximately 15–30 m, making the total volume of ice (excluding Bend Glacier where no measurements were made) close to ~0.07 km^3 (Driedger and Kennard, 1986).

Average annual snowfall from snow telemetry (SNOTEL) sites in the high Oregon Cascades ranges from 750–1300 cm with the largest recorded annual snowfall being 2230 cm, corresponding to a maximum snow depth of 615 cm at Crater Lake National Park (WRCC, 2005). From 1971 to 2000 at Santiam Pass (1475 m elevation), just to the north of the Three Sisters region, average summer temperatures (June to August) were 10–15°C, average winter temperatures (October to March) were −5–5°C, and mean annual snowfall was 985 cm (WRCC, 2005).

The glacial geology in Three Sisters region indicates at least three advances since the LGM. O'Connor et al. (2001) described a Little Ice Age (LIA) advance just outside the modern glacier termini that likely reached its maximum extent roughly 150–200 years ago, as well as an earlier Neoglacial advance that locally left moraines a few hundred meters downvalley from LIA moraines. Similarly, a reconnaissance study at South Sister and Broken Top by Dethier (1980a, 1980b) revealed one and possibly two minor Neoglacial stands, locally preserving moraines outboard of the maximum LIA advance. This Neoglacial activity may correlate with the advances described by Scott (1977) in the Metolius River area, approximately 75 km north of the Three Sisters volcanic center. Sherrod et al. (2004) and Scott and Gardner (1992) identified late Pleistocene and early Holocene moraines at the Three Sisters and Broken Top extending as much as 3 km downvalley from modern termini. These postdate the local LGM ice cap that developed in this region but must be late Pleistocene or early Holocene because they are mantled with the 7.6 cal ka BP Mazama tephra and, locally, a 10,570–11,170 cal yr BP (9520 ± 100 ^{14}C yr BP) scoria (Scott and Gardner, 1992). Our work at the Three Sisters region refines the mapping and chronology based on these previous studies.

Methods

Moraine sequence

To identify the glacial deposits and associated glacial landforms we focused our mapping efforts on the deposits associated with Linn, Hayden, Diller, Prouty, Lewis, and Bend glaciers on the north, south and east flanks of the Three Sisters and Broken Top (Fig. 2). Field mapping was compiled on 1:24,000-scale USGS topographic quadrangle maps and refined in the office using both aerial and field photographs. To define the age of the moraine deposits, we used their stratigraphic position, qualitative plant/tree/lichen cover estimates, morphology, tephra deposits, and two limiting ^{14}C dates on glaciolacustrine deposits from a sediment core at Broken Top. All radiocarbon dates were calibrated to calendar years before present with the INTCAL98 program (Stuiver et al., 1998) (see supplementary materials).

The three most prominent tephras in the area are the Devils Hill, Rock Mesa, and Mount Mazama deposits. Both the Devils Hill and the Rock Mesa are local rhyolitic tephra from numerous vents on South Sister that were deposited during eruptive episodes between 1.7 and 2.5 cal ka BP (Scott, 1987). In lieu of resolving the very similar Rock Mesa and Devils Hill tephras, we simply consider moraines capped by coarse rhyolitic tephras as pre-dating at least 1.7 cal ka BP. The Mazama tephra originated from the volcanic peak that once occupied present-day Crater Lake (~120 km southeast of the Three Sisters). The tephra was deposited at approximately 7630±150 cal yr BP (Zdanowicz et al., 1999) and provides a good age marker because of its regional extent and distinctive character of coarse, yellow ash with fine lapilli (Scott et al., 1990). Identification of the local rhyolitic tephra in the field was based on hand specimen descriptions outlined by Scott (1987) and confirmed directly by Scott (personal communication, 2005) for select samples. The Mazama deposits were also identified in the field based on hand specimen descriptions (Scott et al., 1990) as well as glass shard chemistry (99% similarity coefficient) from a single sample from a sediment core collected at Broken Top (see supplementary materials).

The stratigraphy and sedimentology of the glacial deposits at the Three Sisters and Broken Top were interpreted from ~30 auger pits, stream cutbank exposures along the North Fork of Whychus Creek, two lake cores from Camp Lake located between Middle and South Sisters, and a continuous sediment core from a meadow on the northern flank of Broken Top volcano.

Equilibrium line altitude reconstructions

We calculated equilibrium line altitudes (ELAs) for the modern and pre-existing glaciers in the study site using both the accumulation area ratio (AAR) (Meier and Post, 1962) and the balance ratio methods (BR) (Furbish and Andrews, 1984). Typical AAR values for modern glaciers in a steady-state condition range from 0.5 to 0.8 (Meier and Post, 1962). Following previous work in Oregon by Scott (1977), Carver (1972), and Bevis (1995), we use an AAR value of 0.65±0.1 to determine present and past ELAs. The BR method was implemented with a net-balance ratio of 2±1, which is representative of maritime mid-latitude glacier, such as South Cascade in central Washington with a balance ratio of 2.2 (Furbish and Andrews, 1984) as well as Collier Glacier at the Three Sisters with a ratio of ~3 (McDonald, 1995). While both methods account for the area of the glaciers residing in the ablation and accumulation zone, the BR method has been proven most useful for glaciers that have a "complex" shape (Furbish and Andrews, 1984; Benn and Gemmell, 1997) similar to most of the glaciers at Three Sisters and Broken Top, leading us to favor the BR method for determining ELAs for this study. Because the modern glaciers at the Three Sisters and Broken Top are rapidly retreating and not in equilibrium, as interpreted from multi-year aerial photographs, we consider our modern ELA values as minimums. The average modern ELA in the Three Sisters region is 2630±40 m (BR) or 2540±70 m (AAR) (Table 2), which corresponds well with ELAs measured on the east side of Mt. Jefferson and Three-Fingered Jack (2590±35 m) in which a similar AAR value of 0.65±0.1 was used (Scott, 1977) and at Collier Glacier on North Sister (~2470±70 m) where a mass-balance study was conducted (McDonald, 1995).

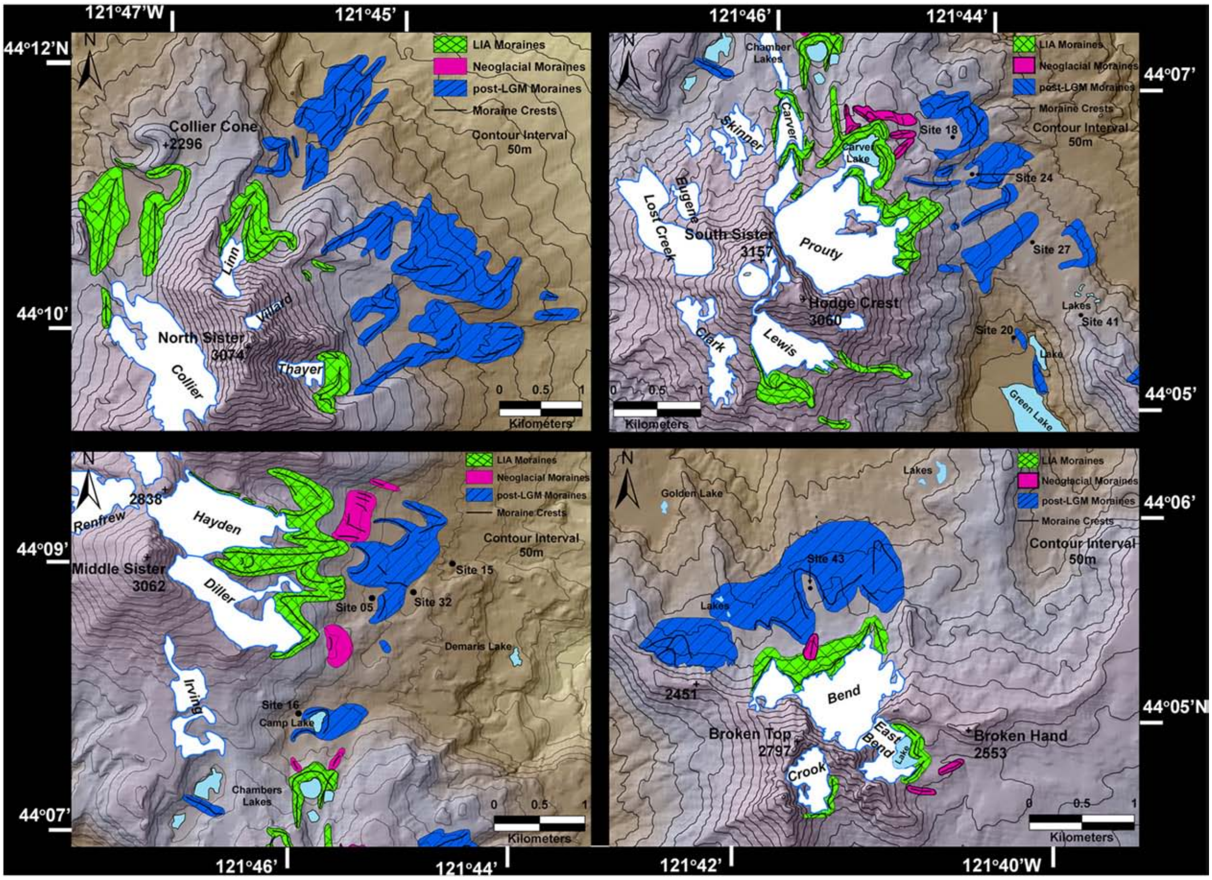

Figure 2. Geomorphologic map of glacial deposits, modern glaciers (e.g., Hayden) and lakes at Three Sisters and Broken Top volcanoes. Contour interval is 50 m. Site numbers (e.g., Site 16) correspond to stratigraphic columns as recorded from sediment, lake, and auger pits.

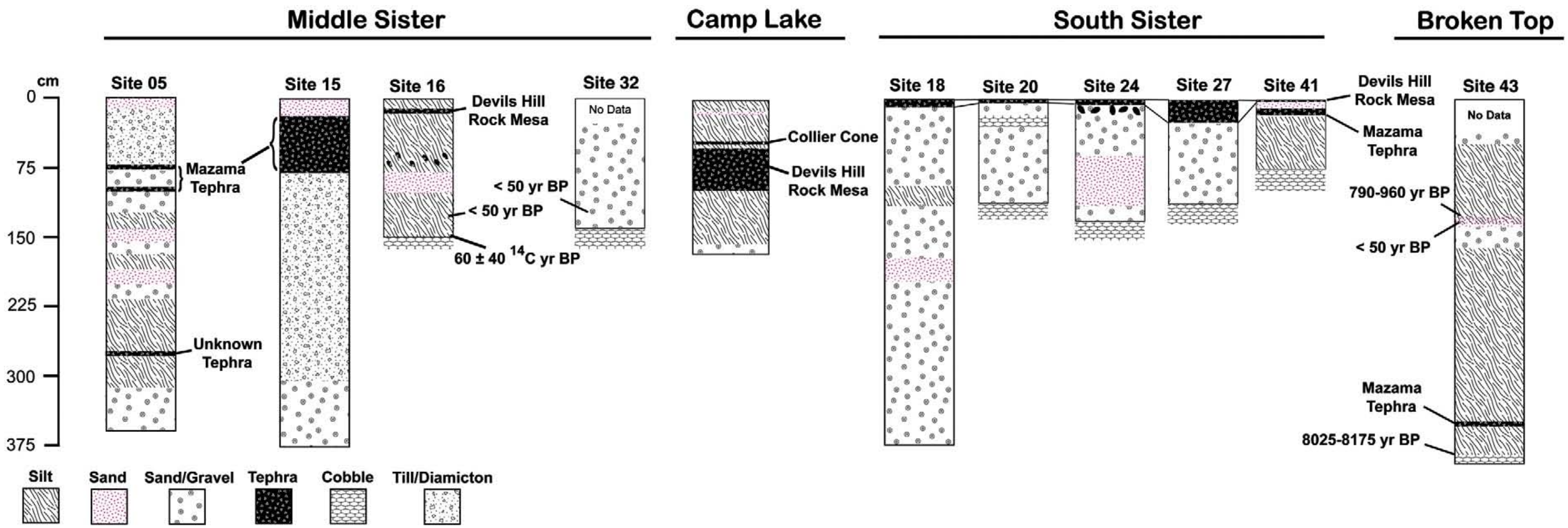

Figure 3. Stratigraphic representation of stream cut-bank exposure (left most), auger pits (middle), lake core (i.e., Camp Lake) and sediment core (right most) collected on the eastern flanks of Middle and South Sisters and the northern flank of Broken Top. Ages marked <50 yr BP are modern carbon ages and were most likely incorporated into the cores during the auguring process. All other ages except one (i.e. ^{14}C yr BP) are cal yr BP with 2-sigma error. A more detailed stratigraphic section for Camp Lake is included in the supplementary materials.

Table 1
Moraine characteristics on the eastern slopes of the Three Sisters and the northern slope of Broken Top volcanoes

	Height	Slope angle	Soil thickness	Vegetation cover	Elevation	Tephra cover
Little Ice Age	60 m	30–45°	0–5 cm	<5%	2200–2600 m	None
Neoglacial	20–30 m	25–35°	0–5 cm	5–10%	2200–2300 m	Devils Hill/Rock Mesa tephra
Post-LGM	10–30 m	15–25°	15–45 cm	10–30%	2000–2300 m	Devils Hill/Rock Mesa and *Mazama tephra

* Locally absent from exposed sites, but common in soils directly up- and down-slope of the moraines.

Climate reconstructions

To reconstruct climate we followed methods similar to those described by Leonard (1989). By plotting the highest monthly mean winter accumulation in snow water equivalent (swe) against mean summer temperatures (°C) (June–August) at the equilibrium line of 32 modern glaciers with worldwide distribution, a relationship between summer temperature and winter accumulation was established for present ELAs (Loewe, 1971; Kotlyakov and Krenke, 1982; Sutherland, 1984; Leonard, 1989). This relationship is defined by a climate envelope where all modern alpine glaciers are thought to exist (Kotlyakov and Krenke, 1982). Assuming that the ELA for a past glacier is known and summer temperature and winter accumulation vertical gradients are similar today as they were in the past, the summer temperature and winter accumulation values at the past glacier's ELA can be estimated and the difference between those values and the values at the modern ELA can be used to approximate past climate. To establish the temperature and accumulation at the Three Sister ELAs, linear lapse rates for mean summer temperature (−0.53°C/100 m) and highest monthly mean winter accumulation (32 cm/100 m) were derived using meteorological stations located at lower elevations (see supplementary materials).

Results

Auger pit, sediment core and river exposure stratigraphy

Auger pits were typically 100 cm deep with the modern soil composing the first 5–30 cm and the rest of the pit consisting of sand and gravel outwash (Fig. 3). The pits generally contained no organic materials and were almost always underlain by impenetrable gravel and cobble-sized glacial outwash or moraine deposits. Tephra found in the pits were either from the local South Sister vents (1.7–2.5 cal ka BP) or from the Mount Mazama eruption (~7.6 cal ka BP). Because little pertinent information was obtained from the majority of the auger sites, only select sites are described and mentioned.

The auger pits from Sites 16 and 43 were 150 to 400 cm deep, with silt- to clay-sized particles making up the bulk of the core's sediments (Fig. 3). The pit at Site 16 near Camp Lake is directly downslope of the post-LGM glacial deposits. The pit contained a horizon of the Devil's Hill and/or Rock Mesa tephra (1.7–2.5 cal ka BP) at 20-cm depth and small pieces of detrital wood near the bottom (150 cm). These wood fragments dated to 60±40 ^{14}C yr BP and 110 yr pMC (post-modern carbon, i.e., post-AD 1950). If the tephra was deposited in-place, then the organic materials likely fell into the core during augering. Alternatively, the tephra deposit could be reworked from the adjoining hills, which would explain the wood fragment ages.

The auger pit at Site 43 near Broken Top volcano is directly upslope of the post-LGM deposits (Fig. 3) and the location of the pit most likely represents the location of a preexisting, moraine-dammed lake based on lacustrine deposits in the pit itself. No distinct tephra horizons were identified in the pit. Abundant organic material (grass) was found at 60- to 180-cm depth from which two radiocarbon samples provided ages of 790–960 cal yr BP (980±40 ^{14}C yr BP) and 120 yr pMC. The younger of the two dates was most likely from sediment that collapsed into the pit while augering. Regardless, neither of these dates can be used as a robust minimum age of the post-LGM moraines because the core never extended to the bottom of the lake sediments. At approximately 180-cm depth, the mud layer liquefied as it came into contact with the water table, making further extractions impossible. A sediment core approximately 400 cm long was collected the following summer (2005) at the same location and expanded the stratigraphic history at Site 43. Below 200-cm depth, the stratigraphy of the sediment core was predominantly silt-spaced to clay-sized sediments that we interpret to be lake mud or gyttja. At 330-cm depth there was a 3-cm-thick tephra deposit within the mud unit identified as Mazama tephra based on glass chemistry analysis preformed at Washington State University (see supplementary materials). Additionally, a basal radiocarbon date of 8025–8175 cal yr BP (7290±30 ^{14}C yr BP) was obtained from a charcoal fragment removed from the base of the core.

The river exposures along North Fork Whychus Creek ranged from a few meters depth in the upper reaches (Site 05) to several meters further downslope (Site 15) (Fig. 3). The exposure at Site 05 has a distinct Mazama tephra layer that underlies a glacial outwash deposit. Several silt, sand, and gravel beds underlie the tephra layer. From 130 cm to 225 cm, the sediments grade from gravel at the base to silt at the top. These gradational beds may represent a time when Whychus Creek was meandering across the surface before it incised the path it follows today. Laminated silt deposits lie below the gradational beds and were likely deposited in a moraine-dammed lake, but they could not be dated due to the absence of organic materials. Approximately 600 m downslope of Site 05, the exposure of river-cut sediments increased to ~10 m. At this exposure (site 15), a clearly visible Mazama tephra deposit directly overlies the post-LGM till, thus giving a relative age marker for the moraine deposit.

Lake core stratigraphy

Two replicate lake cores were collected between Middle and South Sister at Camp Lake, which is dammed by a post-LGM end moraine

Table 2
Equilibrium line altitudes for the modern, LIA, and post-LGM glaciers

Modern		Little Ice Age		Post-LGM	
Glacier	ELA (m)	Glacier	ELA (m)	Glacier	ELA (m)
BR					
Diller	2580±20	Diller	2470±30	Diller	2290±40
Hayden	2630±20	Hayden	2540±30	Hayden	2320±50
Bend	2470±20	Bend	2430±20	Bend	2330±20
Prouty	2670±20	Prouty	2540±30	Prouty	2360±20
Lewis	2770±10	Lewis	2650±40		
Linn	2650±10	Linn	2480±40		
Average (m)=	2630±40		2520±30		2330±20
AAR					
Diller	2490±30	Diller	2360±40	Diller	2190±60
Hayden	2550±40	Hayden	2450±60	Hayden	2250±110
Bend	2380±20	Bend	2340±20	Bend	2300±30
Prouty	2580±30	Prouty	2440±40	Prouty	2270±30
Lewis	2690±20	Lewis	2570±70		
Linn	2570±10	Linn	2370±30		
Average (m)=	2540±40		2420±40		2250±30

Top results are from the balance ratio (BR) method and bottom results are from the accumulation area ratio (AAR) method. The corresponding uncertainties for the individual ELA measurements are associated with the range in balance ratios (1 to 3) and accumulation area ratios (0.55 to 0.75) for each while the uncertainty associated with the average ELA for each time period is the standard deviation of the mean.

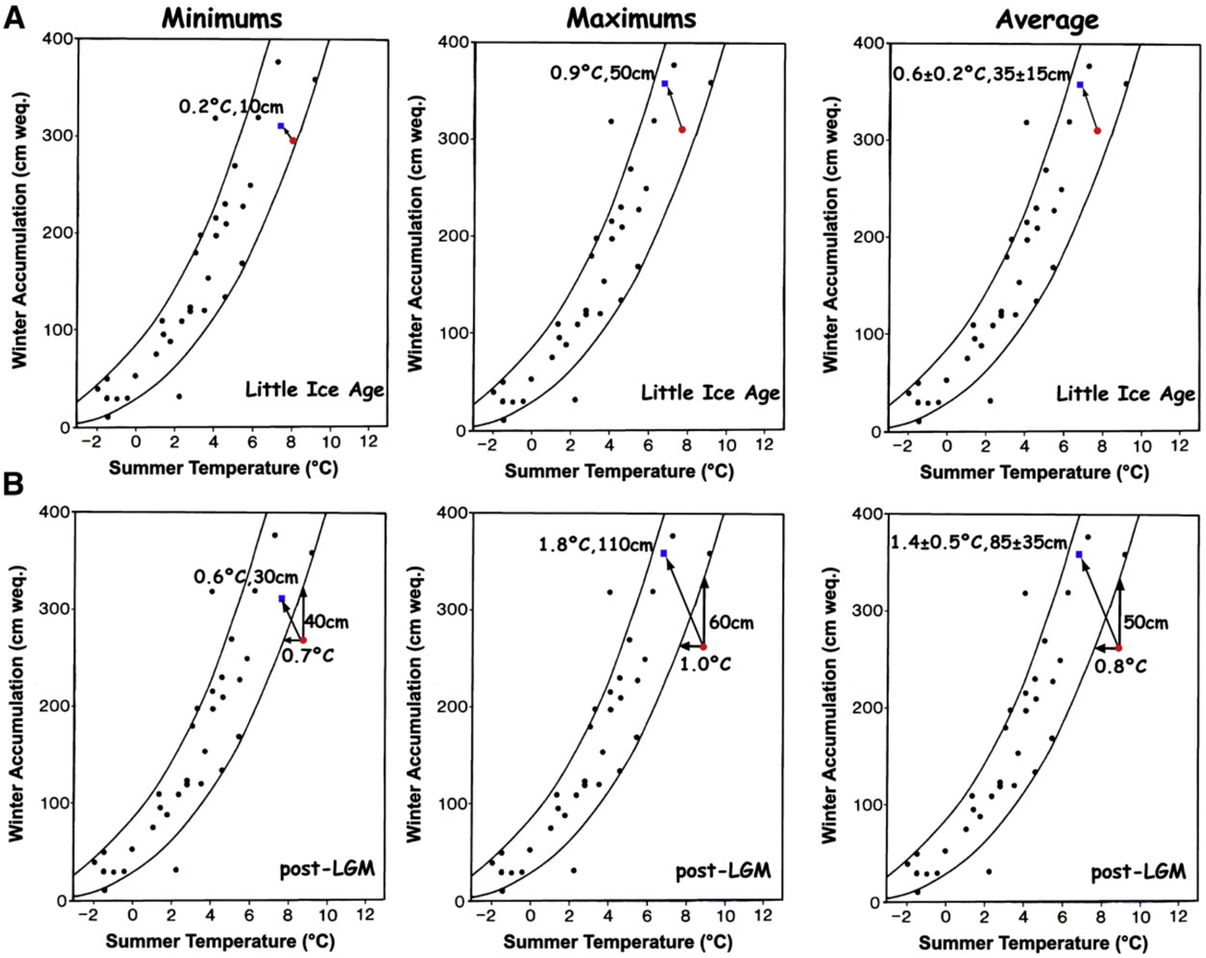

Figure 4. Climate at the ELA of present and past glaciers at Three Sisters and Broken Top plotted on Leonard's (1989) figure of winter accumulation versus mean summer temperature. Row A represents climate conditions at modern and LIA ELAs. Row B represents climate conditions at modern and post-LGM ELAs. The circles represent modern climate conditions at the paleo-ELAs and the squares represent modern conditions at the present ELAs. Arrows and numbers indicate minimum (left column), maximum (center column), and average ± standard deviation (right column) summer temperature depressions and winter accumulation increases needed to sustain the glaciers at the paleo-ELA values or within the modern envelop of glacier conditions (between black lines). The error bars associated with each individual point were not included for clarity.

(Fig. 3). The cores were 160 and 170 cm long and were composed of fine silt- and clay-sized lake sediments and sand- to gravel-sized tephra deposits. No macroscopic organic material for radiocarbon dating was recovered from either core.

The first 45 cm of the cores were composed of brown laminated lake muds. A small (~5 cm) deposit of fine sand at ~15-cm depth, with sharp contacts, was found within the mud layer. Directly underlying the lake muds between 45 and 50 cm depth was a basaltic tephra likely erupted from Collier Cone (W.E. Scott, personal communication, 2005) near North Sister at 1350–1570 cal yr BP (Sherrod et al., 2004). The proximity of the lake core to the basaltic andesite cone (<10 km), coupled with the fact that the tephra is relatively coarse grained (0.10–0.25 cm), make it a good candidate to be from a local source, and the stratigraphic position of the tephra in the core relative to other known stratigraphic markers (see below) place it in the right sequence to be from Collier Cone.

Below the basaltic tephra deposit, separated by 5 cm of lake mud, was the Devils Hill/Rock Mesa tephra (50–95 cm depth). The rhyolitic tephra contained small (<1 cm) red cinders below ~70 cm depth. Between 95 and 155 cm depth, the cores were composed of red oxidized mud (2.5YR–3/4 and 3/6) with faint remnants of alternating color bands, similar to the mud at the beginning of the core but faded due to oxidation. The oxidation of these lake sediments was most likely caused by the lake drying up, thus exposing the sediments to the surface where they began to oxidize. The large increase in the magnetic susceptibility through the bottom-most mud layer is consistent with the oxidized state of the core. The remainder of the cores contained gravel-sized basalt clasts that were impenetrable during coring beyond 5–15 cm.

Glacial deposits

Three glacial stands were identified at the Three Sisters and Broken Top volcanoes based on moraine stratigraphy, geomorphology, vegetation cover, tephrachronology, and ^{14}C dating: an outermost moraine set defined here as the post-LGM, a second moraine group locally preserved less than 400 m upslope of the post-LGM identified here as Neoglacial, and a third innermost group termed LIA.

The altitude of the post-LGM glaciers (Diller, Hayden, Prouty, and Bend) ranged from 2100 to 3200 m elevation (Fig. 2). These glaciers were more extensive than both the LIA and Neoglacial stands, extending 2–4 km from the glacial headwalls, but inset to the more extensive moraines 8–12 km downslope, which are thought to correlate to the local LGM ice cap (Sherrod et al., 2004). The post-LGM moraines were likely deposited in the early Holocene or latest Pleistocene, based on the 8025–8175 cal yr BP basal radiocarbon date from a sediment core upslope of the Broken Top moraines, and the common mantling of the moraines by the 7600 cal yr BP Mazama tephra (Fig. 2 and Table 1). Additionally, Scott and Gardner (1992) reported the presence of a 10,570–11,170 cal yr BP scoria mantling moraines of similar position and morphology on the south flank of Broken Top.

The Neoglacial moraines locally protrude less than 100 m down-valley from the LIA moraines. They are taller and have less weathering features than the post-LGM moraines and are more similar geomorphologically to the LIA moraines. However, unlike the LIA moraines, the Neoglacial moraines locally support krummholz-form whitebark pine at wind-protected sites and tend to have more rounded crests. The Neoglacial deposits are typically preserved as well developed lateral moraines mantled by the Devils Hill/Rock Mesa tephra (1.7–2.5 cal ka BP) but not the Mazama ash (7.6 cal ka BP), suggesting that these moraines formed sometime between ~2 and 8 ka (Table 1).

Based on both lateral and terminal moraines, the elevation of the LIA glaciers (Linn, Diller, Hayden, Prouty, Lewis, and Bend) ranged from 2200 to 3100 m (Fig. 2). The LIA advance at Three Sisters extended 1–2 km from the glacial headwalls and the glaciers remained at their maximum positions for sufficient time to construct the well-developed, tall (~60 m) terminal and lateral moraines. The lack of Devils Hill and Rock Mesa tephra (1.7–2.5 cal ka BP), the oldest tree age from a moraine near Skinner Glacier (AD 1865) (O'Connor et al., 2001), and the lack of developed soil horizons and plant cover on the moraine slopes (Table 1) all suggest that the innermost moraines at Three Sisters represent the culmination of the LIA advance and likely reached its position within the last 300 years, possibly culminating around AD 1850, though sufficient data is lacking to determine a specific date at this point (O'Connor et al., 2001).

Climate and ELA reconstructions

The results for the balance ratio (BR) and accumulation area ratio (AAR) methods are shown in Table 2, but only the BR results are discussed. The average ELA and standard deviation of the post-LGM moraines was 260 ± 100 m lower than modern glaciers (Table 2) with the total range between the glaciers being 110–340 m. No ELA reconstructions were performed for the Neoglacial because the geographic distribution of the moraines was insufficient for a complete analysis. The average ELA depression for the LIA glaciers was 110 ± 40 m with a total range of 40–170 m. Using the modern lapse rate for summer temperature (−0.53°C/100 m) and the winter accumulation gradient (32 cm/100 m), the modern mean summer temperature and winter accumulation at the paleo- and modern ELAs were determined for each individual glacier (see supplementary materials). Climatic conditions necessary to depress the ELAs to their former position are shown in Figure 4. For modern climate to equal post-LGM equilibrium line altitude conditions (diagonal arrows), the mean summer temperature would need to decrease by an average amount (with standard deviation) of 1.4 ± 0.5°C and increase in winter snow accumulation by 23 ± 9% (85 ± 35 cm swe). Alternatively, climate at the post-LGM glaciers would plot inside the modern climate envelope (Fig. 4) if mean summer temperature decreased by 0.7–1.0°C (horizontal arrows) or if mean monthly winter accumulation increased by 15–25% (40–60 cm swe) (vertical arrows) or some combination between. For modern climate to equal LIA equilibrium-line altitude conditions, the mean summer temperature would need to decrease by 0.6 ± 0.2°C and increase in winter accumulation by 10 ± 4% (35 ± 15 cm swe).

Discussion

The post-LGM moraines are stratigraphically and geomorphically similar to the latest Pleistocene Canyon Creek drift of the Cabot Creek advance at Mt. Jefferson (Scott, 1977) and the Zephyr Lake drift in the Mountain Lakes Wilderness (Carver, 1972), only 120–200 km away. Both the Canyon Creek and Zephyr Lake drifts are mantled by Mazama ash as well as having soil development of 15–45 cm, similar to the post-LGM deposits at Three Sisters. However, the post-LGM glaciers' ELAs in the Three Sisters region were only ~300 m lower than current glaciers, while those for the Canyon Creek and Zephyr Lake were depressed a much greater 700 to 750 m (Carver, 1972; Scott, 1977). This would suggest that the post-LGM stand of the Three Sisters and Broken Top area was either spatially subdued, compared to the Canyon Creek and Zephyr Lake, for unknown reasons or the two advances both pre-date the Mazama tephra but are separate glacial advances. Differences in orography or simply differences in the area-altitude distribution of the glaciers could not account for these large variations in the ELAs. Therefore, it is most likely that these deposits are separate glacial advances that pre-date the Mazama tephra, which given the age constrains on both deposits is entirely possible. The post-LGM moraines were most likely deposited during the latest Pleistocene or early Holocene, based on a basal radiocarbon date of 8025–8175 cal yr BP from a sediment core at Broken Top, and the common mantling of the moraines by the 7600 cal yr BP Mazama tephra. This could place the deposition of the post-LGM moraine into a similar timeframe (10–13 ka) as other sites across western North America (Reasoner et al., 1994; Heine, 1998; Owen et al., 2003; Bilderback, 2004; Licciardi et al., 2004).

To sustain the lowered ELAs of the post-LGM, mean summer temperature had to have been approximately 1.4 ± 0.5°C cooler combined with increased winter accumulation of 23 ± 9%. Other evidence of cooling during the latest Pleistocene comes from a sea-surface temperature (SST) record reconstructed from alkenones off the northern coast of California (ODP Site 1019) where the eastern Pacific SSTs were depressed by as much as 4°C from modern levels at the time of the Younger Dryas stade (11.6–12.9 cal ka BP) (Barron et al., 2003) (see supplementary figure). This cooling is also recorded by δ^{18}O from a terrestrial speleothem record collected at the Oregon Caves National Monument (Vacco et al., 2005), though the magnitude of the cooling associated with the δ^{18}O change is difficult to assess. Other evidence of a Younger Dryas influence in the western U.S.A. has come from pollen records collected in lake cores throughout western Oregon (Worona and Whitlock, 1995; Grigg and Whitlock, 1998) and enhanced sediment production with decreased organic content in the Cascade Range consistent with a cold and or wet period at about this time in the region (O'Connor et al., 2001; Briles et al., 2005). While the post-LGM advance at Three Sisters is not precisely constrained, it may be correlative in time with these other records and could be associated with the Younger Dryas stade, although better age constrains are required to confirm this hypothesis.

The Neoglacial stand likely represents a re-advance of glaciers in the central Oregon Cascade Range to a similar extent as the LIA. The timing of this stand appears broadly correlative with similar Neoglacial deposits found in Oregon (Williams, 1974; Scott, 1977), Washington (Crandell, 1969; Begét, 1984), and other sites across the western U.S.A. (Benedict, 1973; Miller, 1973; Miller and Birkeland, 1974; Anderson and Anderson, 1981; Hall and Heiny, 1983; Butler, 1984), though the uncertainty in the timing of deposition of these moraines at the Three Sisters precludes any precise comparison. Unlike other paleoglaciers in the western U.S.A. that advanced repeatedly during the Holocene, but never extended beyond their maximum LIA positions (Osborn et al., 2006; Clark and Bowerman, 2007), the Neoglacial moraines at the Three Sisters and Broken Top are locally preserved and extend just beyond the LIA deposits. This would imply that, at some point between ~2 and 8 ka, paleoclimatic conditions in the central Oregon Cascade Range were sufficient to induce an advance slightly larger in magnitude than the LIA. This is consistent with pollen data from western Oregon and California (Briles et al., 2005), which suggest cooler and wetter conditions between 4 and 6 ka.

The LIA deposits at Three Sisters and Broken Top are likely correlative in time with LIA moraine deposits in other regions of Oregon (Carver, 1972; Scott, 1977; Lillquist, 1988; Scott et al., 1990; Lafrenz, 2001) and the western U.S.A. (Crandell, 1969; Miller, 1969;

Madsen and Currey, 1979; Anderson and Anderson, 1981; Burrows et al., 2000). Early photographs and maps (Russell, 1905) show that many of these glaciers had thinned but were still in contact with these moraines in the early 20th century (O'Connor et al., 2001). This is consistent with temperature depressions recorded in other records. From land-based temperature data, global temperatures since AD 1850 have increased by 0.5°C (Jones and Bradley, 1992) and 0.8°C in the Pacific Northwest of the U.S.A. (Mote, 2003), which closely resembles the changes necessary for the ELA depression at Three Sisters. Tree ring data collected in the Pacific Northwest and elsewhere in the Northern Hemisphere (Mann et al., 1999; D'Arrigo et al., 2006) as well as temperature reconstructions based on glacier lengths (Oerlemans, 2005) (see supplementary figure) also indicates that summer air temperatures have increased by ~0.2–0.6°C over the last 100–200 yrs. Thus, it is conceivable that the LIA equilibrium line altitude depressions at Three Sisters may have been due primarily to a decrease in temperature rather than increased winter precipitation.

Conclusion

At least three glacial stades, indicated by moraines, occurred after the LGM on the eastern and northern flanks of the Three Sisters and Broken Top volcanoes, respectively. The youngest was the LIA glaciation, marked by 60 m high moraines less than 500 m downvalley from the modern glaciers, and which likely reached its maximum extent within the last 300 years, possibly culminating near AD 1850 though sufficient data is lacking at this point. Locally preserved less than 100 m downslope from the LIA moraines, a second set of sparsely vegetated lateral moraines mark a Neoglacial stand. These Neoglacial moraines predate the local rhyolitic eruptions from the Devils Hill and Rock Mesa volcanic chain on South Sister (1.7–2.5 cal ka BP) and postdate the Mount Mazama eruption (7.6 cal ka BP). Beyond the Neoglacial moraines, a third set of soil covered and vegetated moraines extends 200–900 m downslope of the modern glacier termini. These moraines record a post-LGM glacial advance that predates 8025–8175 cal yr BP and are likely latest Pleistocene or early Holocene in age.

Paleoclimate reconstructions using the empirically determined climate conditions at the ELA suggests summer temperatures were on average 1.4±0.5°C cooler and winter precipitation was 23±9% higher during the post-LGM stand. During the LIA stand, and possibly the Neoglacial, summer temperature would have been on average 0.6 ±0.2°C lower than present with 10±4% greater winter snowfall. The magnitude of this temperature depression is consistent with other LIA temperature reconstructions from western North America (Mann et al., 1999; Oerlemans, 2005; D'Arrigo et al., 2006).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.yqres.2008.09.002.

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