Latest Pleistocene alpine glacier advances in the Sawtooth Mountains, Idaho, USA: Reflections of midlatitude moisture transport at the close of the last glaciation

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ABSTRACT

Mountain glaciers in the Sawtooth Mountains responded strongly to reinvigorated atmospheric moisture transport following the last ice-sheet maximum. The glaciers constructed an extensive moraine belt in the southeastern Sawtooth Mountains, allowing determination of a detailed radiocarbon chronology from lake and marsh cores. Moraine morphometry and soil data indicate construction of seven to nine moraines in each of four valleys during two main late Pleistocene ice advances. A basal radiocarbon date from marsh cores in the Alturas valley documents that the maximum advance during marine oxygen isotope stage 2 occurred shortly before ca. 16,900 calibrated (cal.) yr B.P. Minimum limiting dates on glacial-lacustrine sediment in lake and marsh cores from three valleys, clustered around 13,950 cal. yr B.P., document the maintenance or reestablishment of extensive ice volume during early late-glacial time. The ca. 16,900 cal. yr B.P. advance postdates the last ice-sheet maximum by ~4000 yr and is broadly correlative with maximum advances of the North Yellowstone outlet glacier and the Puget Lobe of the Cordilleran Ice Sheet and a near-maximum advance of Wallowa Mountain glaciers. These synchronous advances indicate response of a variety of ice systems to reinvigorated moisture transport following the ice-sheet maximum, as does the subsequent Sawtooth advance during early late-glacial time. Together, these responses indicate strong sensitivity of certain ice systems to moisture-delivery fluctuations.

Keywords: glaciation, late Pleistocene, radiocarbon, Idaho, paleoclimate, precipitation.

INTRODUCTION

Mountain glacier chronologies have long been used to elucidate past climate variations. Because of their responsiveness to regional climate variations, mountain glaciers have proved to be sensitive indicators of both long-term (10^4 yr) and shorter-term (10^3–10^2 yr) climate fluctuations. However, the relationship between mountain glaciers and climate is complex, because mountain glacier fluctuations integrate changes in both temperature and precipitation. Despite this complex relationship to climate, mountain glacier advances are commonly attributed largely to cooling, particularly to intense cooling at the time of the Last Glacial Maximum (LGM, ca. 21,000 ± 2000 calibrated [cal.] yr B.P.; e.g., Chadwick et al., 1997). As chronologies of glacier fluctuations improve in accuracy and geographic breadth, however, it has become clear that precipitation variations have exerted strong influences on glacier fluctuations (e.g., Thackray, 2001; Shulmeister et al., 2004; Licciardi et al., 2004).

The end of the last glaciation involved large-scale reorganization of oceanic, atmospheric, and cryospheric systems. The complexity of deglaciation is particularly stark in western North America, where the final growth and subsequent shrinkage of the Laurentide-Cordilleran ice-sheet system strongly influenced atmospheric circulation patterns and, thus, precipitation-delivery patterns (e.g., Bartlein et al., 1998). Coupled with the diverse orography of the cordillera, those precipitation patterns exerted variable influences on mountain glacier systems during the LGM (ca. 21,000 ± 2000 cal. yr B.P.) and late-glacial time (ca. 17,000–11,000 cal. yr B.P.). Consequently, the timing of maximum and late-glacial alpine glacier advances shows considerable variation across the region (e.g., Chadwick et al., 1997; Thackray, 2001; Licciardi et al., 2001, 2004; Clark and Gillespie, 1997; Gosse et al., 1995), as predicted by Hostetler and Clark (1997) from atmospheric modeling.

We describe extensive mountain glacier fluctuations in central Idaho following the LGM (ca. 17,000–16,000 cal. yr B.P.) and during early late-glacial time (ca. 14,000–13,000 cal. yr B.P.) that clearly required reinvigoration of moisture transport into the northwestern interior of the United States. We propose that these moisture-dependent glaciers responded to post-LGM increases in westerly atmospheric flow, influenced, in turn, by orbital variations transmitted to regional climate via two indirect paths: weakening of ice-sheet anticyclonic circulation (e.g., Kutzbach et al., 1993), and strengthening of westerly flow by increasing Northern Hemisphere seasonality.

SETTING AND CONTEXT

The Sawtooth Mountains are one of the highest ranges in central Idaho. They trend roughly north-south and rise to ~3300 m, exposing Cretaceous granitic rocks and Paleozoic metasedimentary wall rocks of the Idaho batholith. Most important, the Sawtooth Mountains represent one of the first high orographic barriers encountered by moist Pacific air masses east of the Cascade Range. Today, the Sawtooth Mountains receive the bulk of their precipitation from winter and spring Pacific storms and mark the transition between the wetter forested ranges of western Idaho and drier, largely unforested ranges to the east. Inferred late Pleistocene equilibrium-line altitudes (ELAs) rise steeply across the range from west to east (Meyer et al., 2003), indicating a similar past influence of prevailing, moist, westerly winds.

Major valleys marking the eastern and western flanks of the Sawtooth Mountains hosted large valley glaciers (>10 km length) during middle and late Pleistocene glacial episodes (Williams, 1961). On the eastern flank, glaciers constructed a broad moraine belt in the adjoining extensional basin.

METHODS

We employed surficial geologic mapping, relative weathering assessment of glacial landforms, analysis of sediment cores, and radiocarbon dating. Surficial geologic mapping utilized aerial photograph and topographic map interpretation, digital terrain analysis, and field observation. In order to determine relative-age moraine groups, we collected soil and morphometric data from the moraine sequences and performed simple statistical analyses on those data. We then collected sediment cores from 10 sites, including lakes, marshes, and fens, in order to analyze glacial and postglacial sediment patterns. We collected several

TABLE 1. RADIOCARBON AGES FOR CORE SAMPLES

Sample number	CAMS*	Radiocarbon age (^{14}C yr B.P. $\pm$ 1σ)	Calibrated age (cal. yr B.P. $\pm$ 1σ)[†]	Material dated
McDonald Lake				
Mac2-126	60638	10,590 ± 50	12,780 ± 60	Wood
Mac3-132	60639	11,640 ± 50	13,570 ± 100	Gyttja
Mac3-140	60637	11,920 ± 90	13,960 ± 140	Gyttja
Pettit Lake				
P1-94	73098	10,010 ± 50	11,390 ± 60	Conifer needle
P2-63	73099	11,930 ± 40	13,940 ± 150	Charcoal
Lost Boots Marsh[§]				
LBM1	41458	9960 ± 40	11,300 ± 40	Aquatic plant fragments
LBM2	41457	10,300 ± 40	12,010 ± 60	Gyttja
LBM3	41459	11,990 ± 60	13,980 ± 120	Gyttja
LBM4	41460	13,660 ± 70	16,400 ± 240	Aquatic plant fragments
LBM5b	51315	14,060 ± 300	16,860 ± 410	Aquatic(?) plant fragments
LBM5a[#]	41461	11,030 ± 120	N.D.**	Aquatic(?) plant fragments

Note: Additional radiocarbon dates from other core sites are reported in Borgert (1999) and Lundeen (2001).

*Laboratory reference number, Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory.

[†]Calibrated per Stuiver et al. (1998). Age ranges with the highest probability are reported.

[§]Lost Boots Marsh is an informal designation.

[#]Sample 5a produced an initial date on this horizon, derived from a very small amount of carbon; therefore, this date is disregarded. Two additional cores were obtained subsequently from the site and the horizon was resampled to obtain sample LBM5b.

**Not determined.

types of data from the cores, including visual description, magnetic susceptibility, total organic carbon, and grain-size distribution. Our methods and results were described fully in Borgert (1999) and Lundeen (2001). We submitted 19 samples to the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory for radiocarbon dating (Table 1).

RESULTS

Moraine Sequences

Seven to nine end moraines were delineated in each of four valleys (Fig. 1). We consider all moraines in this study to be of late Pleistocene age. This broad age determination is consistent with that of Williams (1961).

Our analysis of soil and moraine morphometry data from the late Pleistocene moraine sequence delineated two relative age groups (Fig. 1; Lundeen, 2001; Borgert, 1999). Moraine crest angularity and the depth to the B horizon proved to be the most consistent relative age indices. The downvalley group of voluminous, broad-crested, multiple-ridged moraines (Busterback Ranch moraine group) is statistically distinct from the upvalley group of smaller, sharp-crested moraines (Perkins Lake moraine group; Lundeen, 2001). Because of the distinct differences between the moraine groups, we infer that the Busterback Ranch group is at least 10 k.y. older than the Perkins Lake group, and that the age difference probably is considerably larger. The difference between inferred ELAs of the two moraine groups is small. Paleo-ELA estimates, determined through the accumulation area method, are between 2400 and 2700 m; the moraine sequences reflect an ELA range of <200 m in each valley (Lundeen, 2001).

Sediment Cores and Radiocarbon Age Constraint

Cores from 3 of 10 locations provide reliable constraints on the timing of glacier fluctuations. At Lost Boots Marsh, which is ~0.5 km upvalley of the oldest moraine in the Perkins Lake moraine group in the Alturas valley (Fig. 1), we collected three cores with similar stratigraphy (Fig. 2A). The most notable feature of these cores is the radiocarbon date of 16,860 ± 410 cal. yr B.P., which was obtained on detrital (aquatic?) plant fragments from a silt layer ~15 cm above sandy gravel, the latter inferred to represent ice-proximal deposition. We consider this date to be a minimum limiting date, close to the actual age of the moraine 0.5 km downvalley. Overlying laminated silt and clay, with high magnetic susceptibility and low total organic carbon, represent glacial-lacustrine sedimentation, most likely in a lake larger than those of today, dammed by the moraine downvalley of the core site. Glacial-lacustrine sedimentation terminated and organic-rich sedimentation began ca. 16,400 cal. yr B.P. Also of note is an anomalous, 3-cm-thick, light brown layer within the organic-rich section; its anomalous color and minimum limiting date of 13,980 ± 120 cal. yr B.P., which correlates with dates in the two cores described next, suggest that it pertains to a glacial readvance upvalley or to a distinct climatic episode that reduced organic production or increased inorganic sedimentation in this valley.

The McDonald Lake 3 core (Fig. 2B), one of three taken from this small (9 ha) lake in the Yellow Belly drainage, constrains a later part of the glacial record. The youngest moraine in the Busterback Ranch group dams McDonald Lake, and three moraines of the Perkins Lake group are within 2 km upvalley (Fig. 1). Our core did not reach ice-proximal sediment. However, the base of the core contains ~30 cm of glacial-lacustrine sediment, with characteristics of a high glacier-activity index (sensu Souch, 1994). Because two sediment-trapping lakes are upvalley of the Perkins Lake moraines, we infer that the glacial-lacustrine sediment in the core was deposited as the glacier constructed those moraines. Thus, the minimum limiting date of 13,960 ± 140 cal. yr B.P. for the glacial-lacustrine sediment constrains, indirectly, the age of the moraines upvalley of the lake.

The Pettit Lake core (Fig. 2C), one of three obtained from the downvalley end of the lake, contains a similar sedimentary sequence, and we interpret similarly the relationship of cored glacial-lacustrine sediment with upvalley moraines. A minimum limiting date of 13,940 ± 150 cal. yr B.P. was obtained immediately above the glacial-lacustrine sediment.

In summary, these three cores provide minimum limiting ages for two glacier advances and/or significant recessional stillstands, both associated with the Perkins Lake moraine group. The near-basal date of ca. 16,860 cal. yr B.P. from Lost Boots Marsh provides a minimum limiting age for the oldest moraine in the Perkins Lake group. Because of the position of the dated material near the base of the core, we consider this date to be close to the actual age of the moraine. Closely correlative dates from the McDonald Lake and Pettit Lake cores provide a minimum limiting date of ca. 13,950 cal. yr B.P. for younger moraines of that group. A third date of 13,980 cal. yr B.P., in the Lost Boots Marsh core, lends support to those dates.

The extensive late-glacial ice advance in the Sawtooth Mountains predated the Younger Dryas interval by at least 1000 cal. yr, but our results do not rule out a subsequent Younger Dryas advance. Because our cores do not record Younger Dryas fluctuations in sediment characteristics, we infer that such a readvance would have been confined to cirques upvalley of the sediment-trapping lake basins in each valley.

We infer, from ages of the Perkins Lake group and from relative weathering data, that the Busterback Ranch moraine group was constructed during marine oxygen isotope stage (OIS) 3 or 4. We infer from relative weathering data that the Busterback Ranch moraine group is at least 10 k.y. older than the Perkins Lake group; therefore, we estimate that the

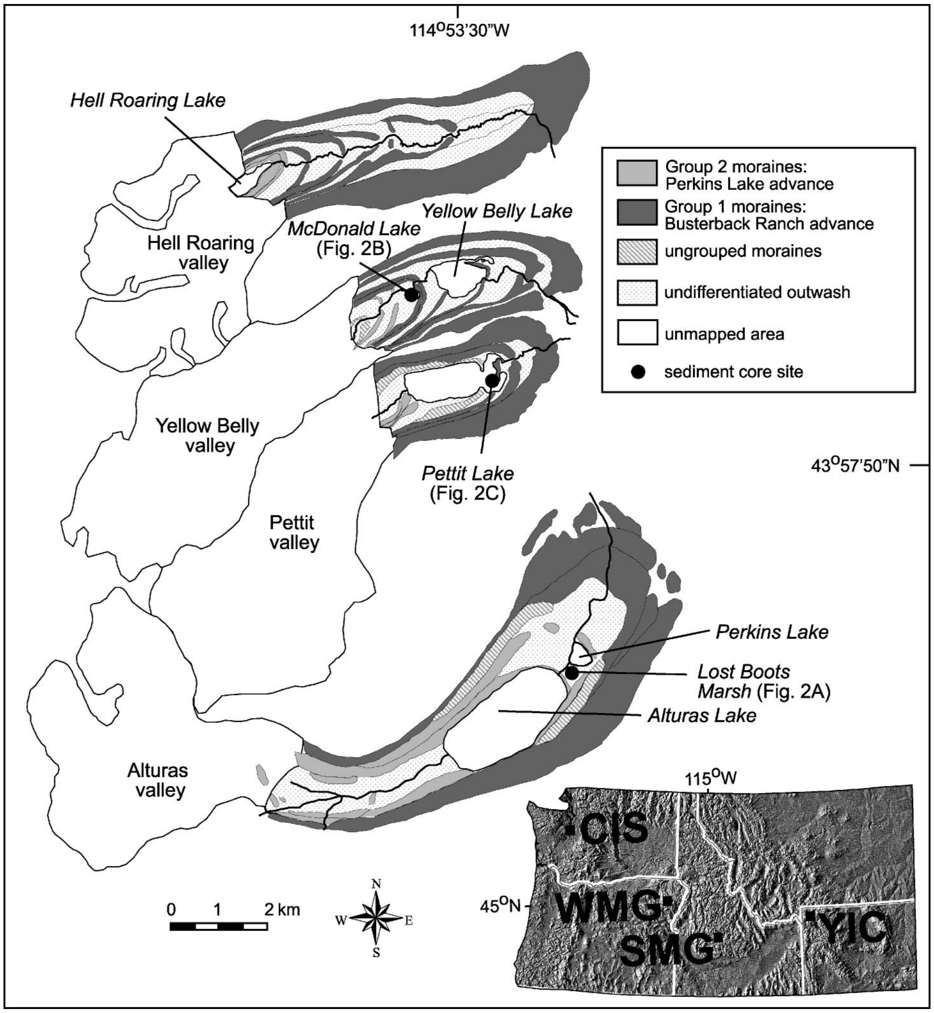

Figure 1. Moraine groups in four valleys of southeastern Sawtooth Mountains, delineated by relative-weathering criteria. We infer that two moraine groups are separated in age by at least 10 k.y. Inset map shows locations of Sawtooth Mountains glaciers (SMG), Wallowa Mountains glaciers (WMG), Puget Lobe of Cordilleran Ice Sheet (CIS), and Yellowstone ice cap (YIC).

older group was constructed prior to 27,000 yr B.P.

Regional Correlations and Paleoclimatic Inferences

Two aspects of this glacial record are noteworthy. First, the minimum limiting date of ca. 16,900 cal. yr B.P. pertains to the apparent maximum ice advance during OIS 2; the maximum OIS 2 advance thus appears to postdate the LGM by ~4000 cal. yr. Second, the dates of ca. 14,000 cal. yr B.P., pertaining to the youngest moraines in this sequence, imply that extensive ice volume—with paleo-ELAs <200 m above those of the outermost moraines—was maintained into or reestablished during early late-glacial time.

Coupled with chronologies from three other glacial systems, the ca. 16,900 cal. yr B.P. Sawtooth advance implies influences of reinvigorated westerly flow during the early deglacial period. Many glacial sequences from around the globe reflect an advance at around that time. Most relevant to regional atmospheric circulation patterns are chronologies of three glacial systems. The Puget Lobe of the Cordilleran Ice Sheet reached its maximum extent ca. 16,950 cal. yr B.P. (Porter and Swanson, 1998). The northern outlet glacier of the Yellowstone ice cap reached its maximum extent at 16,200 ± 300 ^{10}Be yr B.P. (16,500 ± 400 ^{3}He yr B.P.) (Licciardi et al., 2001). Thus, it appears that the Cordilleran, Yellowstone, and Sawtooth glacial systems reached their maximum extent at roughly the same time, ~4000–5000 yr after the LGM and likely under the influence of a common forcing mechanism. In the Wallowa Mountains, Oregon, Licciardi et al. (2004) also dated a prominent moraine to 17,000 ± 300 ^{10}Be yr B.P., a short distance upvalley of an LGM-correlative moraine, dated to 21,100 ± 400 ^{10}Be yr B.P.

Despite differences in scale between the ice systems, all four are united by their exposure to moist westerly flow. The Cordilleran Ice Sheet accumulated in the British Columbia Coast Ranges; the Wallowa Mountains and Sawtooth Mountains are two of the highest orographic barriers east of the Cascade Range; and the Yellowstone Plateau receives abundant Pacific moisture funneled eastward by the Snake River Plain. We propose that these moisture-dependent glacial systems—typically exposed to moist westerly flow and with mass-balance characteristics adjusted to abundant precipitation—reached their maximum or near-maximum extents after the LGM because of reinvigorated westerly flow. At the time of the LGM, westerly flow was likely weakened by the inferred Laurentide Ice Sheet anticyclone and by a minimum in orbitally modulated seasonality (e.g., Kutzbach et al., 1993; Thompson et al., 1993). We infer that the weakened westerly flow starved these glacial systems of moisture, as was clearly the case in the Olympic Mountains (Thackray, 2001). After the LGM, the glacial anticyclone weakened, seasonality increased, and westerly flow consequently was strengthened, as evidenced in regional pollen records (e.g., Thompson et al., 1993; Bartlein et al., 1998). These four moisture-dependent glacial systems, nourished by enhanced winter-spring precipitation, expanded to their maximum or near-maximum extents ca. 16,000–17,000 yr B.P. under temperature conditions that likely remained cool, but warmer than at the time of the LGM.

Licciardi et al. (2004) similarly discuss variability of regional mountain glacier fluctuations. They delineate two subregions of the western United States: a northern region, in which the ice-sheet anticyclone inhibited LGM advances, and a southern region, in which mountain glaciers reached their maximum extent during the LGM. Our interpretation of regional patterns is similar except that, in our view, the response of mountain glaciers to diminished westerly flow hinged on their mass-balance characteristics. Moisture-dependent glaciers responded more strongly to LGM aridity than did glaciers with mass-balance characteristics adjusted to cooler summer temperatures. Similar variability in mountain glacier chronologies was predicted by Hostetler and Clark (1997) from atmospheric modeling results.

The extensive early late-glacial Sawtooth glaciers (ca. 14,000 cal. yr B.P.) likely had similar precipitation controls. In most glacial systems in western North America, ELAs rose and glaciers retreated substantially by late-glacial time (e.g., Gosse et al., 1995; Clark and Gillespie, 1997). Regional pollen data, as well as paleoclimatic model simulations, indicate an increase in precipitation during late-

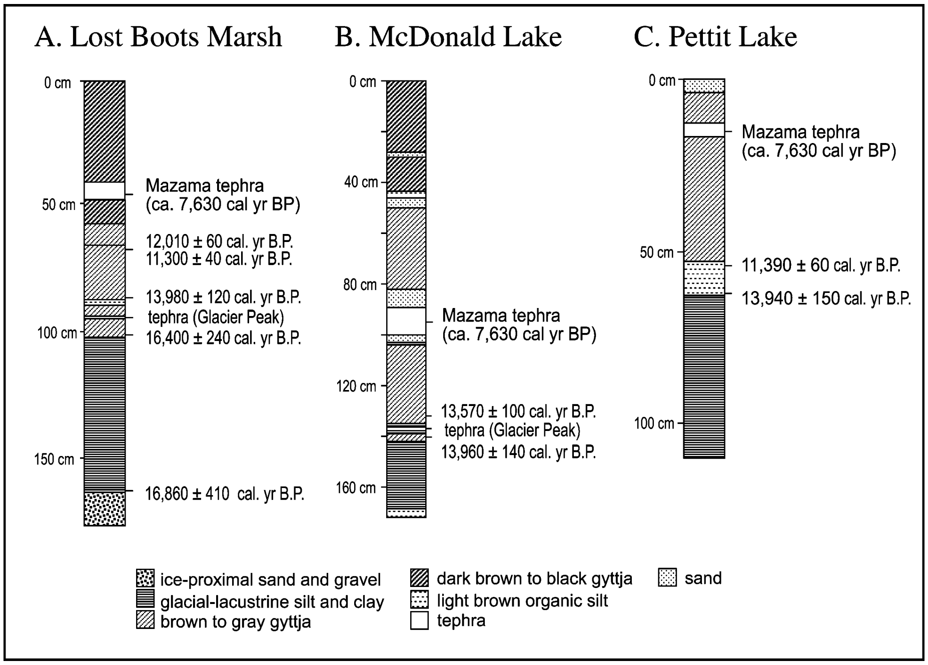

Figure 2. Stratigraphy and dates from three cores that provide reliable age constraint for Perkins Lake moraine group. A: Lost Boots Marsh, Alturas valley. Three cores with similar stratigraphy were collected from center of marsh; stratigraphy and dates shown are from single core. B: McDonald Lake 3, Yellow Belly valley. C: Pettit Lake (composite of two cores), Pettit valley.

glacial time (e.g., Thompson et al., 1993). Furthermore, there is no indication of dramatic cooling ca. 14,000 cal. yr B.P. in regional pollen records (e.g., Bartlein et al., 1998). Therefore, we infer that the maintenance or reestablishment of extensive ice volume in the Sawtooth Mountains required abundant winter precipitation. General circulation model results of Kutzbach et al. (1993) suggest that increasing insolation and increasing seasonality during this time generated vigorous westerly circulation.

In summary, we conclude that extensive alpine glacier advances ca. 16,900 and ca. 14,000 cal. yr B.P.—occurring several thousand years after the LGM—were driven by enhanced winter precipitation from moist Pacific air masses, rather than by dramatic temperature decrease. These moisture-dependent glacial systems responded more strongly to reinvigorated westerly flow following the LGM than to the intense cooling at the time of the LGM. Further, we suggest that other moisture-dependent glacial systems likely responded similarly. Improved glacial chronologies across the western United States should further constrain temporal and spatial patterns of Pacific moisture delivery.

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