Pleistocene glaciations of the Rocky Mountains

Kenneth L. Pierce

U.S. Geological Survey, Northern Rocky Mountains Science Center, Montana State University, Bozeman, Montana, 59717-3492, USA; kpierce@usgs.gov

Introduction

This chapter presents the status of Rocky Mountain glacial studies in 1965 and progress from that time to the present. The Rocky Mountains and the adjacent Basin and Range of the United States consist of about 100 ranges distributed in a northwest trending belt 2000 km long and 200–800 km wide. Glaciation created much of the grandeur of the high parts of these ranges. Figure 1 shows the extent of late Pleistocene glaciers as well as a measure of snowline altitude across the western U.S.

Early in the 20th century, some noteworthy regional Rocky Mountain glacial studies included: the Uinta and Wasatch Mountains of Utah (Atwood, 1909), western Wyoming (Blackwelder, 1915), the San Juan Mountains of Colorado (Atwood & Mather, 1932), western Montana (Alden, 1953), and southern Rocky Mountains (Ray, 1940).

For simplicity in communication, we use the following regional terms and their probable correlations with marine oxygen-isotope stages (MIS): Pinedale (Late Wisconsin, MIS 2), early Wisconsin (MIS 4), Bull Lake (now thought to be largely MIS 6 and perhaps 5d), and pre-Bull Lake (pre-MIS 6).

Status in 1965

Blackwelder (1915) named the Bull Lake and Pinedale glaciations for moraines on the east and west sides of the Wind River Range. In glaciated valleys of the Rocky Mountains, researchers generally distinguished a younger set of moraines (Pinedale) from an older set 5–10% further downvalley (Bull Lake). In 1965, G.M. Richmond summarized the status of glacial studies in the Rocky Mountains in two publications: (1) an INQUA chapter on the glacial geology (Richmond, 1965); and (2) a guidebook and 16-day INQUA field trip through much of the Northern and Middle Rocky Mountains (Richmond *et al*., 1965). Also in 1965, Crandall (1967) mapped and described the glacial sequence on the Wallowa Mountains of eastern Oregon. In 1965, non-quantitative morphology was the prime basis for distinguishing and correlating Bull Lake and Pinedale moraines. Richmond (1965) noted Bull Lake moraines were bulky with smooth slopes, did not retain lakes, and were less bouldery than Pinedale moraines. Bull Lake moraines were commonly subdivided into early and late stades. In contrast, Pinedale moraines were described as steep, irregular, having kettles commonly with ponds, and studded with numerous relatively unweathered boulders. Pinedale moraines were commonly subdivided into early, middle, and late stades (Richmond, 1965). Moraines of the early and middle stade were distinguished at and near the terminus, whereas the late stade moraines were 25–75% farther upvalley from the terminal moraines to the valley heads.

In 1965, Rocky Mountain glacial subdivisions and correlations were closely linked with those of the mid-continent. The Bull Lake and Pinedale glaciations were correlated with the early and late Wisconsin respectively (Richmond, 1965). Curiously, Leverett (1917) had correlated the Bull Lake with the Illinoian Glaciation of the mid-continent that he defined in 1899, but this correlation was not accepted in 1965. Three pre-Bull Lake glaciations were correlated with the Illinoian, Kansan, and Nebraskan Glaciations (Richmond, 1965). Also in 1965, erratic boulders and diamictons well beyond or above moraines of Pinedale and Bull Lake age had been noted at many sites in the Rocky Mountains; these were attributed to an older glaciation vastly more extensive than the Bull Lake or Pinedale.

Soil development was then emerging as the primary relative-age method (Birkeland, 1964; Morrison, 1965; Richmond, 1962). Pinedale deposits have an "immature zonal soil" with "B-horizons 0.3–0.6 m thick, that display very little illuviation and weak to moderate structural development" (Richmond, 1965). In contrast, Bull Lake deposits have "mature zonal soils" with "B-horizons 0.3–1.2 m thick, with sufficient illuvial clay to be slightly plastic . . . and moderately developed subangular blocky structure."

The 1965 synthesis was primarily descriptive; glacial-geologic sequences were correlated according to succession and the general appearance of moraines. Pleistocene ELA's were estimated to be about 1000 m lower than present ELAs and both ELAs and moraines decreased in altitude northward through the Rocky Mountains (Richmond, 1965).

Advances since 1965

The next major synthesis of Rocky Mountain glaciations was by Porter *et al*. (1983). It included chronology, ELA patterns, basal shear stress, types of glaciers based on valley slope and glacier thickness, and contrasting mass balance between ranges based on the modern snowpack at the Pleistocene ELA. This study was followed by Richmond (1986a), who summarized glacial extents, stratigraphy, and chronology for glaciated ranges in the Rocky Mountains. Additionally Richmond (1986b) presented a detailed chronology of Yellowstone. Madole (1976) summarized the Colorado Front Range. For the Great Basin west of the Rockies,

DEVELOPMENT IN QUATERNARY SCIENCE
VOLUME 1 ISSN 1571-0866
DOI:10.1016/S1571-0866(03)01004-2

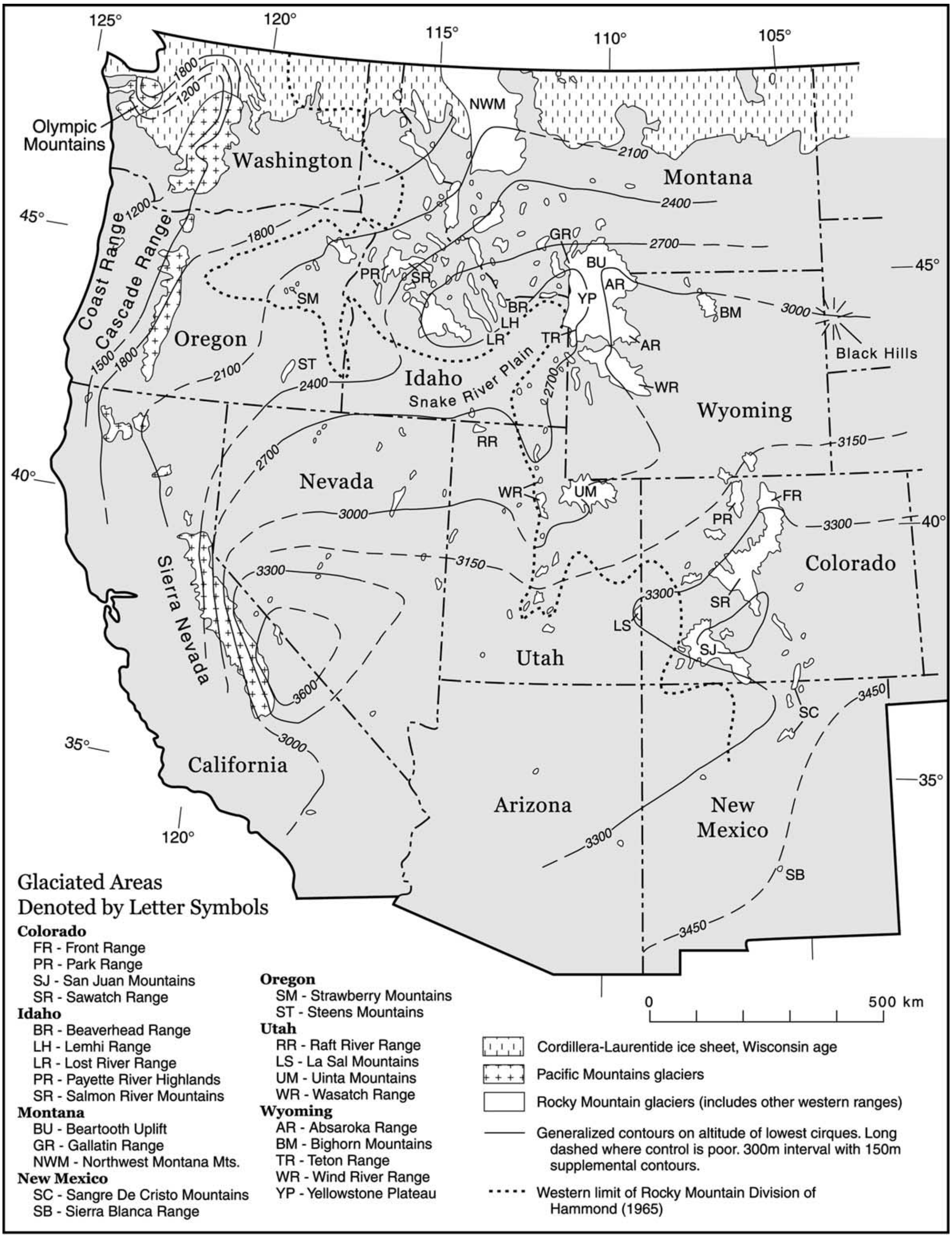

Fig. 1. Map showing extent of Late Wisconsin glaciers in the Rocky Mountains and other mountains in the western United. States (from Porter et al., 1983). Contours in meters are on the lowest cirque floors. This measure of late Pleistocene snowline increases in altitude both inland from the Pacific Ocean as moisture decreases, and southward as temperature increases (Hammond, 1965).

Wayne (1984) made a detailed study of the Ruby-Humboldt area, and Osborn & Bevis (2001) achieved an extensive overview including mapping and sequence descriptions and mapping for many ranges.

Quaternary Geochronologic Studies

Dating and correlation of glacial and other Quaternary deposits depend on a variety of dating techniques, as recently described in Noller *et al.* (2000). Dating techniques may be classified (Colman & Pierce, 2000) as: (1) relative age (chemical, biologic, geomorphic methods that include soils and weathering rinds, some of which can be refined to calibrated age; (2) numerical age (sidereal, isotopic, and radiogenic); and (3) correlated-age methods.

Selected Relative-Age Methods

Relative-age methods are broadly applicable and are useful in distinguishing deposits in a sequence. Correlation between sequences is better established if variables such as climate and lithology can be controlled. Methods may be combined; for example, Miller (1979) measured six relative age parameters on a glacial moraine sequence and applied statistical clustering techniques to define two ages of Pinedale moraines, two ages of Bull Lake moraines, and one age of pre-Bull Lake moraine.

Soil development. After 1965, soils became a primary basis for distinguishing glacial and other deposits in the Rocky Mountains, and other western mountains, where Pete Birkeland, his students and his text (1974, 1999) played a central role. Studies of his students include: (1) soils along a Rocky Mountain glacial transect (Shroba, 1977; Shroba & Birkeland, 1983); moraine-terrace transects in Colorado (Nelson & Shroba, 1998; Netoff, 1977); (2) the moraine sequence in the Wallowa Lake area, Oregon (Fig. 1, northeast of Strawberry Mountains) as well as part of the Sierra Nevada (Burke, 1979; Burke & Birkeland, 1979); (3) a terrace sequence near the Wyoming-Montana border (Reheis, 1987); (4) a toposequence in central Idaho from moraine crest to foot slope on Bull Lake and Pinedale glacial moraines (Berry, 1987). Some other important contributions were the formulation of a soil development index by Harden (1982), and quantitative studies of soils in the type areas of the Bull Lake and Pinedale glaciations (Dahms, 1991; Hall & Shroba, 1993; Swanson, 1985).

Weathering rinds and carbonate coats. Motivated by the results of Porter (1975), Colman & Pierce (1981) measured weathering rinds on basalt and andesite in the western U.S. and found that rind thicknesses systematically increased with stratigraphic sequence of moraines. They calibrated this method based on dating of the West Yellowstone Bull Lake as MIS 6. For the glacial succession near McCall, Idaho, weathering rinds show a clear difference between moraines correlated with MIS 2, 4, and 6. But for the corresponding soils, clay increase expressed as grams/cm^2 shows little change between moraines correlated with MIS 4 and MIS 6 based on weathering rinds. In areas of calcic soils (pedocals), carbonate coats on the undersides of stones increase in thickness with time. Based on Uranium-series ages, carbonate coats in central Idaho accumulate at $\sim$0.6 mm/10^3 yr (Pierce, 1985; Pierce & Scott, 1982).

Numerical age methods. Few numerical ages existed in 1965 for glacial deposits in the Rocky Mountains. The establishment of marine oxygen isotope stages provided a reference standard for the large number of late Cenozoic glacial-interglacial oscillations and potentially associated glacial advances. The AGU Handbook (Noller *et al.*, 2000) describes many numerical-age techniques useful to dating glacial deposits, including radiocarbon and luminescence that can be applied to glacially related deposits such as bogs and loess. For Rocky Mountain and other glacial sequences, cosmogenic dating (Gosse & Phillips, 2001) is producing a numerical chronology that is based on the accumulation of isotopic changes in morainal boulders based on the duration of surface exposure to cosmic rays, provided one can account for surface erosion of the boulders and possible exhumation of the boulders. It has yielded ages that suggest a younger age than indicated by radiocarbon dating for the Pinedale glaciation and a possible MIS 5d correlation for type Bull Lake deposits.

Pre-Bull Lake Glacial Deposits

We use the designation pre-Bull Lake for glacial deposits that are older than MIS 6 (or 8?) and include deposits as old as the late Pliocene. Most deposits once attributed to very large pre-Bull Lake glaciations are now interpreted to have non-glacial origins. Primary reasons are lack of till fabric and glacial striations, and their satisfactory explanation as deeply weathered fluvial gravel. In addition, many of these deposits are located well outside Pinedale and Bull Lake glaciated areas; this requires an earlier, much more extensive glaciation generated during a much more severe glacial climate. However, the marine isotope record shows no glacial intervals much more severe than MIS 2 or 6, and suggests that pre-Bull Lake glaciations were not much more extensive than those of the Bull Lake or Pinedale.

Richmond (1965 and references therein) defined three pre-Bull Lake glacial deposits on the east side of the Wind River Range, from oldest to youngest: Washakie Point, Cedar Ridge, and Sacagawea Ridge. Later work establishes that only the Sacagawea Ridge has a glacial origin. At the type section for the Cedar Ridge and Washakie Point deposits, Hall & Jaworowski (1999) conclude that the only pre-Bull Lake glacial till present is the Sacagawea Ridge till. Chadwick *et al.* (1997) also did not confirm the presence of Cedar Ridge or Washakie Point glacial till. Moraines and associated outwash terraces of the Sacagawea Ridge glaciation (Richmond & Murphy, 1989) are somewhat older than the Lava Creek Ash dated at 640,000 ± 2000 yr (Christiansen, 2001), and probably correlate with MIS 16 (Chadwick *et al.*, 1997).

Three extensive pre-Bull Lake glaciations were also named and defined from diamictons of inferred glacial origin in the La Sal Mountains of Utah (Richmond, 1962). Shroder & Sewell (1985) concluded that these diamictons are extensive mass-movement deposits. They found the total area glaciated was only one twentieth (5%) the area mapped as glaciated in pre-Bull Lake time by Richmond (1962).

Madole (1982) concluded that upland bouldery deposits on the Colorado Front Range previously considered to be glacial were Tertiary deposits of non-glacial origin. For the southern Rocky Mountains, Scott (1975) concluded that all pre-Bull Lake glacial deposits are close to Bull Lake and Pinedale moraines, and that bouldery deposits once attributed to an extensive icecap glaciation are weathered Cenozoic fluvial gravels. In Jackson Hole, deposits of the "ghost" glaciation (Love, 1977) are either outlying deposits of no necessary glacial origin, or are part of the Munger (Bull Lake) glaciation of Pierce & Good (1992).

The best evidence for multiple pre-Bull Lake glaciations is exposed in sections just east of the Rocky Mountains near the US-Canada border. A succession of pre-Bull Lake diamictons identified as glacial by striations, till fabrics, stone shapes, and erratics from the Rocky Mountains are separated by soils but do not require a much more extensive glaciation than the Bull Lake (Karlstrom, 2000 and references therein; Fullerton *et al*., 2003). Karlstrom (2000) identifies, from youngest to oldest, the following: two glaciations early in the Brunhes normal Chron (0–0.78 myr ago), at least three glacial events during the Matuyama reversed Chron (0.78–2.6 myr ago), and two events with normal polarity either in the Gauss Chron (2.6–3.6 myr ago), or possibly the Reunion or Olduvai events (2.23–2.20 or 1.93–1.76 myr ago).

Terrace sequences, which include pre-Bull Lake terraces, represent climatically modulated cycles of erosion followed by lateral planation and deposition. However, few terraces are tied directly to pre-Bull Lake glacial moraines. With age control on one or more terraces, the ages of other terraces can be approximated by incision rates (Reheis, 1987; R.C. Palmquist, written comm., 1989; Chadwick *et al*., 1997). Locally such terrace sequences have age control provided by one or more volcanic ashes, such as the 640,000-yr-old Lava Creek ash in Verdos Alluvium roughly 100 m above drainage in the Colorado Piedmont (Scott, 1975).

Bull Lake Glaciation

Combined K-Ar and Obsidian Hydration Dating

In 1965, Bull Lake moraines were widely considered to be early Wisconsin in age (Richmond, 1965). However, the Bull Lake moraines near West Yellowstone are clearly older than the West Yellowstone rhyolite flow (Pierce *et al*., 1976; Richmond, 1986b; Waldrop, 1975), which is best dated as 122,300 ± 2200 yr old (Obradovich, 1992, and spoken comm., Sept. 2002, based on the three older sanidine ages selected because complete degassing is a primary concern). Thickness of hydration rinds on glacial pressure cracks in obsidian clasts from the Bull Lake moraines at West Yellowstone are calibrated by hydration thicknesses on cooling cracks of dated rhyolite flows. A plot through time shows that the Bull Lake glacial cracking is ~30,000 yr older than the 122,000-yr-old West Yellowstone flow, and is ~40,000 yr younger than the 183,000 ± 3000 yr old Obsidian Cliff flow. Thus the age is about 150,000–140,000 yr (Pierce *et al*., 1976) and correlates with the later part of MIS 6 (190,000–130,000 yr ago, Martinson *et al*., 1987). A younger, less extensive glacial margin is indicated by the unusual embayed and perlitic eastern margin of the West Yellowstone rhyolite flow (Christiansen, 2001, p. G44). This recessional(?) glacial margin is about 15 km east of the Bull Lake terminus. Christiansen (2001, p. G46) estimates the K-Ar ages have a geologic uncertainty of ±10,000 yr. Thus, the age of the West Yellowstone flow may be from ~135,000 to 110,000 yr, and the glacier related to the embayed flow margin may date from late MIS 6 time, during recession from Bull Lake moraines, *or* a separate advance during MIS 5d time.

Wave-cut bluffs eroded into the Bull Lake end moraines at The Narrows of Hebgen Lake near West Yellowstone expose a 10-cm ash bed between imbricate thrusts of till. The ash had an apparent K-Ar age of 481,000 yr (Obradovich, 1992; Richmond, 1986b). Richmond (1986b) defined two glaciations based on position relative to the ash: the 610,000–481,000-yr-old "Till of Horse Butte" below the ash and the 481,000–399,000-yr-old "Till of Hebgen Lake" above the ash. J.D. Obradovich (spoken comm., 2002) and I conclude that contamination of the feldspar concentrate is likely. The ash chemistry is similar to the 162,000 ± 2000 yr old tuff of Bluff Point (G.A. Izett, written comm., 1990; Obradovich, 1992). I interpret the till thrust above the 162,000 yr old ash to be the same as the surface Bull Lake till and consistent with late MIS 6 time, and the till beneath the glacially thrusted ash to possibly be older than 162,000 yr and perhaps of an early MIS 6 age.

Cosmogenic Exposure Dating of Bull Lake Deposits

At the type Bull Lake on the east side of the Wind River Range, boulder exposure ages (^{36}Cl supplemented by ^{10}Be; Phillips *et al*., 1997) from a sequence of 15 Bull Lake moraines (Chadwick *et al*., 1997) yield the following ages and suggested MIS correlations:

Moraine Group & No.		Moraine Dated	Cosmogenic Age (10^3 yr)	MIS
D	XII–VX	XIII	95–120	5d
D		XII	95–120	5d
C	IX–XI	IX	100–130	5d
B	IV–VIII	(*not dated*)	>130	6
A	I–III	II–III	>130	6

Phillips *et al*. (1997) caution that in addition to laboratory analysis, additional uncertainty is about 10–15%.

Contrasting cosmogenic ages on boulders on the *same* Bull Lake moraines on the west side of the Wind River Range are illustrated and described in Fig. 2. Gosse & Phillips (2001) show that both ^{10}Be and ^{26}Al ages increase with increasing resistance to erosion (Fig. 2A), and conclude that these Bull Lake moraines are ~150,000 yr old. For the same moraines (Fig. 2B), Phillips *et al*. (1997) find an age of 120,000–100,000 yr, an age 20–35% younger than the ^{10}Be and ^{26}Al ages, but similar to the ^{36}Cl ages on Group C and D across the range at Bull Lake. In light of the U-series dating discussed next, it seems likely that the ^{36}Cl ages are too young, on both sides of the range.

U-series dating of terraces along the Wind River in the type area of the Bull Lake glaciation (Blackwelder, 1915) produces ages older than the cosmogenic ages of the nearby correlative moraines. Multiple analyses determining ^{230}Th/U ages on micro-stratigraphic layering of the carbonate coats on stones from soils on the terraces yield the following ages (Sharp *et al*., 2003):

Terrace	Age (10^3 yr)	MIS	Glacial Unit
WR2	55 ± 8.6	4	Early Pinedale correlative
WR3	150 ± 8.3	6	Late Bull Lake
WR4	167 ± 6.4	6	Early Bull Lake

Based on these ages, the early and late Bull Lake terraces at the type area correlate with early and late MIS 6. In the Colorado Front Range, ^{10}Be and ^{26}Al ages on only 2(?) boulders in Bull Lake moraines are 122,000 ± 26,000 yr and those from a Bull Lake terrace are 136,000 ± 28,000 yr, both with no correction for erosion of boulder surface (Schildgen *et al*., 2002; Dethier *et al*., 2003).

Discussion of Age and Correlation of the Bull Lake Glaciation

In the West Yellowstone area using combined K-Ar and obsidian hydration dating, Pierce *et al*. (1976) determined a MIS-6 age (Illinoian) for the Bull Lake Glaciation, revising the widely accepted early Wisconsin correlation (MIS 4?). Next, for Bull Lake moraines of the Wind River Range primarily based on ^{36}Cl ages, Phillips *et al*. (1997) dated Groups A and B as MIS 6 and Groups C and D as MIS 5d. However, dating the firmest boulders, Gosse & Phillips (2001) determined a mid-MIS-6 ^{10}Be age on the same moraine that Phillips *et al*. (1997) determined a MIS 5d ^{36}Cl age. Finally, U-series ages by Sharp *et al*. (2003) date the type terrace of the Bull Lake glaciation (WR3) as late MIS 6, and an older Bull Lake terrace (WR4) as early MIS 6, arguing against a MIS 5d age for the Bull Lake.

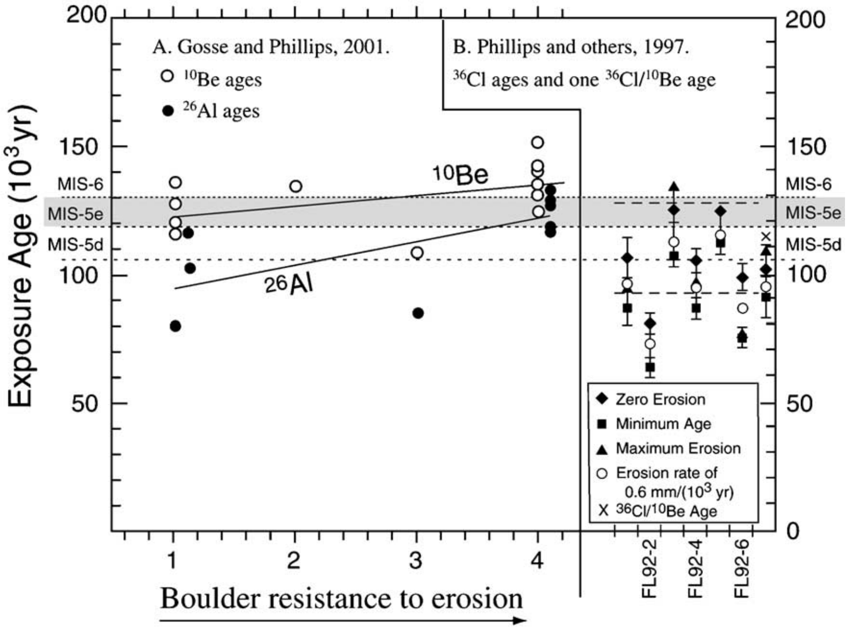

Fig. 2. Plots showing differences between two cosmogenic-dating studies on boulders from the same Bull Lake moraine on west side of Wind River Range near Fremont Lake. These differences illustrate the current difficulty in using exposure ages to distinguishing MIS 5d from MIS 6. (a) Plot of ages in order of increasing resistance to erosion and difficulty in sampling, from (1) weathered plagioclase porphyroblastic granodiorite to (4) unweathered granite. Both ^{10}Be and ^{26}Al exposure ages increase with increasing resistance of boulders to erosion. Gosse & Phillips (2001) conclude these moraines are ~150,000 yr old (MIS 6). (b) Plot of ^{36}Cl ages supplemented by ^{36}Cl/^{10}Be age for the same moraine as in Fig. 2A (Phillips et al., 1997). Phillips et al. (1997) conclude "the distribution of ^{36}Cl ages as quite similar to that for the Bull Lake IX moraine at Bull Lake, giving limits of 120 to 100 × 10^3 *yr." This age range would suggest correlation with MIS 5d, but appears too young.*

The ice-contact West Yellowstone flow is either recessional Bull Lake or a younger advance. Its age of 122,300 ± 2200 yr favors correlation with MIS 5d, although recession from the Bull Lake moraines (MIS 6) is permissible with the time scale of Martinson *et al.* (1987). However, if Winograd *et al.*'s (1997) dates at Devils Hole in southern Nevada are correct, and the last interglaciation (MIS 5e) in the western U.S. began 142,000 yr ago and lasted until 120,000 yr ago, then it follows that correlation of the ice-contact flow with MIS 5d is implied.

An extensive mountain glaciation during MIS 5d appears plausible in that a major minimum in solar insolation for the Northern Hemisphere culminated about 110,000 yr ago (Berger, 1978), and cool summers combined with enhanced precipitation from warm oceans then could have fostered the expansion of mountain glaciers. For Mono Basin moraines in Bloody Canyon of the Sierra Nevada, Phillips *et al.* (1990) advocate a MIS 5d age, although this age is appears to be out of stratigraphic sequence (see Kaufman *et al.*, this volume). Glaciation during MIS 5d at high latitudes is advocated for the Lake Baikal area, Siberia (Karabanov *et al.*, 1998). One implication of the assignment of some Bull Lake advances to MIS 5d is that glaciers more extensive than the Pinedale glaciers advanced and retreated in only ~12,000 yr (the MIS-5d age-span of Martinson *et al.*, 1987). Studies of ice cores in Antarctica and Greenland indicate it has taken ~10,000 yr *or longer* to accumulate the upper 1 km of ice in these areas of relatively slow accumulation. The Pinedale icecap on the Yellowstone Plateau built up to a thickness of a kilometer *after* an advance from the adjacent mountains (Good & Pierce, 1996). Also, the Wind River Pinedale icecap on the east side of the range locally was 600 m thick (William Locke, Earth Sciences web site at Montana State University, 2002, http://www.homepage.montana.edu/~ueswl/winds.html). Thus, there is a question whether adequate time exists between warm periods MIS 5c and 5e to build up icecaps thicker than the Pinedale, and then to deposit multiple, large-volume moraines. If this did occur in the 12,000-yr span of MIS 5d, it demonstrates the rapidity of icecap buildup, moraine deposition, and recession.

Lake-sediment records from the U.S. have not been interpreted to show a major glaciation in MIS 5d comparable in magnitude with MIS 6 or 2. Such records have been studied from Lake Bonneville (Oviatt *et al.*, 1999), Owens Lake, California (Bischoff *et al.*, 1997, using the timescale of Bischoff & Cummings, 2001; Litwin *et al.*, 1999), or from the mid-continent (Zhu & Baker, 1995). For Clear Lake, California, Adam (1988) shows that MIS 5d consisted of three cold intervals, each lasting only 1400–2400 yr. They were separated by two warm intervals of 3100–4700-yr duration. The oxygen-isotope record from Devils Hole, Nevada (Winograd *et al.*, 1997) also shows MIS 5d as shorter than MIS 2, 4, and 6. Whitlock *et al.* (2000; and spoken comm., 2002) concluded from pollen studies of cores from Carp Lake, western Washington, that MIS 5d was cool and humid, and not as severe than MIS 2. The MIS-5d landscape was covered by open forest.

In conclusion, early and late Bull Lake moraines have been distinguished in many Rocky Mountain areas (Richmond, 1965), locally on the basis of an intervening soil. Distinction as early and late Bull Lake may correlate either with: (1) MIS 6 and 5d respectively, as suggested for the Wind Rivers (Phillips *et al.*, 1997; Chadwick *et al.*, 1997); or (2) early and late MIS 6 (190,000–170,000 and 150,000–130,000 yr ago) as indicated by: (a) Sharp *et al.* (2003) for the Wind River areas (b) Fullerton *et al.* (2003) for early and late Bull Lake in the Glacier Park area, and (c) this paper for the West Yellowstone area. For different places, such contrasting correlations may be valid and show that different areas have contrasting surviving successions of Bull Lake-like moraines, a topic extensively developed in Gillespie & Molnar (1995). Nevertheless, I consider surviving Bull Lake moraines of MIS 5d yet to be established, where whereas those of MIS 6 are quite credible.

MIS 4 or Early Wisconsinan Glaciation

Based on weathering-rind thickness, Colman & Pierce (1981, 1986, 1992) found three successions in the western U.S. had early Wisconsin moraines (~60,000–70,000 yr old), including the Rocky Mountain sequence at McCall, Idaho. Other information also favors glaciation during MIS 4. On the east side of the Wind River Range, an outwash(?) terrace (WR2) between the Pinedale (WR1) and late Bull Lake (WR3) has a ^{230}Th/U age on carbonate coats of 55,000 ± 8600 yr (Sharp *et al.*, 2003), suggesting an early Wisconsin glacial advance, but with moraines subsequently overridden by younger glaciers. For Owens Lake, eastern California, abundant rock flour signifies Sierran glaciation from 78,000 to 66,000 yr ago (Bischoff & Cummings, 2001). A relatively deep lake in the Bonneville Basin, Utah dates 59,000 ± 5000 yr, and probably represents cooler conditions near the MIS 4/3 boundary (Kaufman *et al.*, 2001). A high stand of Summer Lake, southeastern Oregon dates between 89,000 and 50,000 yr, a period that includes MIS 4 (Cohen *et al.*, 2000). A loess-buried soil section in southern Jackson Hole records glacial(?) loess deposition ~65,000–75,000 yr ago based on TL ages, ^{10}Be accumulation, soil development, and minimum ^{14}C ages (K.L. Pierce, unpub. data). At Carp Lake, Washington, a cool-humid interval from 58,000 to 43,000 yr ago and cool-dry interval from 72,000 to 58,000 yr ago may represent glaciation in MIS 4 and early MIS 3 time, bracketed by warmer intervals (Whitlock *et al.*, 2000). Thus, an early Wisconsin (MIS 4) glacial advance probably has occurred in the Rocky Mountains, but surviving moraines are not recognized (see Gillespie & Molnar, 1995), excepting for the McCall, Idaho area.

Numerical Ages of Pinedale Deposits

Ages of the Pinedale (last) glaciation based on calibrated (cal) radiocarbon and obsidian-hydration dating are greater than new ages based on cosmogenic methods (Fig. 3). Fig. 3B shows the extent of Pinedale glaciation based on a 1983 compilation of ^{14}C and obsidian-hydration ages (Porter *et al.*, 1983, Fig. 4–28). Between Fig. 3A and B, the correction of ^{14}C age (right) to calibrated age (left) is show by the sloping

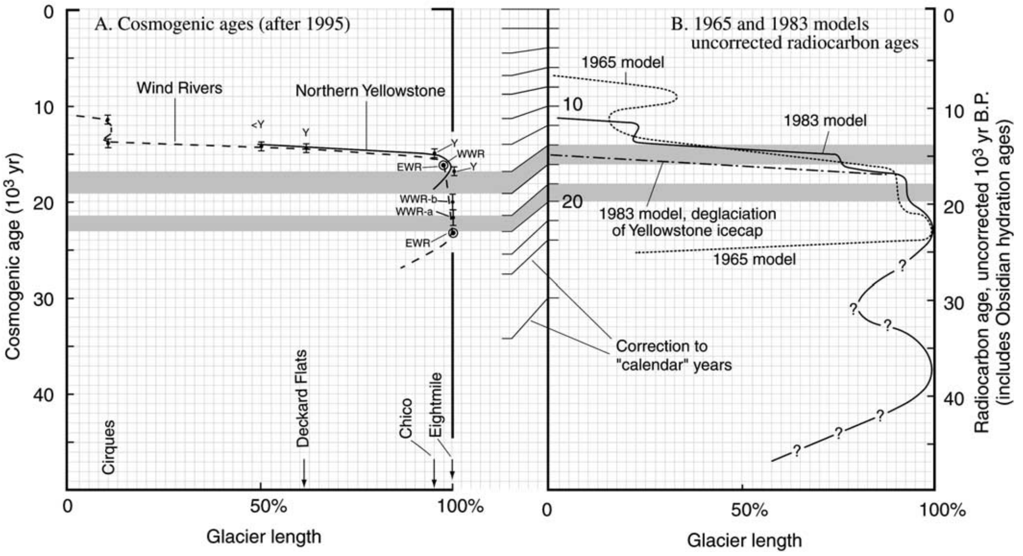

Fig. 3. Development of chronologies of the last (Pinedale) glaciation of the Rocky Mountains showing age vs. percent full-glacial length. A. Current cosmogenic dating for Wind River Range (Gosse et al., 1995a, b) and the Yellowstone icecap (Licciardi et al., 2001). EWR and WWR-east and west Wind River Range with WWR-a, original terminal moraine age of Goss and WWR-b, age calculated by J.M. Licciardi (written comm., 2003) using current scaled production rates; Y-Yellowstone. B. Plots on radiocarbon time scale showing 1965 model and 1983 compilation (both from Porter et al., 1983). For 1983 compilation of mountain glaciers and icecaps, control points are plotted and indexed to three tables (Porter et al., 1983, Figs 4–28, Tables 4–6 to 4–8). The center column between A and B shows the increase in age between radiocarbon ages (right) to calibrated ages (left). The cosmogenic chronology dates recession from near the terminal moraine position about 15,000 yr ago, whereas the calibrated ^{14}C compilation indicates an age nearer 20,000 cal yr B.P.

lines and is based on Stuiver & Reimer (1993, Calib. program) and Bard *et al.* (1998). Figure 3B shows the Pinedale glacial maximum occurred 25,000 to 20,000 ^{14}C yr B.P. (~23,400 to 29,200 cal yr B.P.) and was followed by rapid recession of ice-caps by 15,000 ^{14}C yr B.P. (~18,000 cal yr B.P.) and recession of valley glaciers to near cirque positions (shown as a small readvance) by 12,000 ^{14}C cal yr B.P. The 1983 model shows near complete deglaciation about 5000 yr earlier than the 1965 model (Fig. 3B, dotted line).

More recent ^{14}C ages also support the plot shown in Fig. 3B, with relatively old ages for the Pinedale maximum, and rapid recession to the cirques. For two glacially dammed lakes in the Colorado Front Range, Rosenbaum & Larson (1983) report the four oldest ages on finely disseminated plant debris were between 22,000 and 23,200 (± ~1000) ^{14}C yr B.P. (27,000 to 25,700 cal yr B.P.). These newer ^{14}C ages are consistent with the antiquity of ^{14}C ages from the Colorado Front Range that were used in plotting Fig. 3B: (1) organic matter concentrated from sediments in a moraine-dammed lake dates to 22,400 ^{14}C yr B.P. (Madole, 1980), and (2) a section of interbedded till and peat indicates that the Pinedale glaciation lasted from >30,000 to 13,700 ^{14}C yr B.P. (Nelson *et al.*, 1979). In the Yellowstone-Grand Teton area, Whitlock (1993) obtained basal ages from cores in sediments deposited during the Pinedale recession. These ages were as old as 14,580 ± 150, 17,160 ± 210, 16,040 ± 220, 15,640 ± 150 and 14,490 ± 700 ^{14}C yr B.P., which would indicate glacial recession there by 20,000–19,000 cal yr B.P.

Cosmogenic Surface Exposure Ages of Pinedale Deposits

Cosmogenic ages for the Wind Rivers and Yellowstone produce ages for the Pinedale glacial maximum and recession that are younger than the ^{14}C based time-distance plot (Fig. 3). For the type Pinedale moraines on the west side of the Wind River Range, Gosse *et al.* (1995a) determined a terminal moraine age of 21,700 ± 700 ^{10}Be yr. They also found that moraine building continued near the terminus for ~6000 yr, or until ~15,800 ^{10}Be yr ago. Similarly, on the east side of the Wind River Range, Phillips *et al.* (1997) measured ^{36}Cl ages supplemented by ^{10}Be ages for boulders on the three outer Pinedale moraines, and concluded the moraines are between 23 and 16,000 yr old.

From the values determined by Gosse *et al.* (1995a), recalculation of the *mean* of each moraine group using current scaled production rates yields the following ages for the type Pinedale moraines (J.M. Licciardi, written comm., 2003):

Moraine or Group	Age (×10^{3} ^{10}Be yr)
Terminal Pinedale	20.1 ± 1.0
Recessional group	17.6 ± 0.8
Difference	~2.5

In contrast, for the Pinedale sequence of the northern Yellowstone outlet glacier, Licciardi *et al.* (2001) analyzed a goodly number of boulders on each deposits and determined the following younger exposure ages:

Deposit (Number of Boulders Dated)	Cosmogenic Ages ($\times 10^3$ yr)
Eightmile terminal moraines (8)	16.5 ± 0.4 ^{3}He
Eightmile terminal moraines (9)	16.2 ± 0.3 ^{10}Be
Chico recessional moraines (8)	15.7 ± 0.5 ^{10}Be
Deckard Flats readjustment (10) (Yellowstone Plateau icecap no longer contributing)	14.0 ± 0.4 ^{10}Be
Late glacial outburst flood (6)	13.7 ± 0.5 ^{10}Be

These cosmogenic ages for the Eightmile (Pinedale) terminal moraines of the Yellowstone outlet glacier are about 3000–4000 ^{10}Be yr younger than the 20,100 ^{10}Be yr ages on outermost Pinedale terminal moraines on both sides of the Wind River Range (Fig. 3). This is probably a real age difference that can be explained by either: (1) the time interval required for the progressive buildup of the Yellowstone icecap; or (2) a climatic difference related to nearness to the Laurentide ice sheet (J.M. Licciardi, written comm., 2003). The 3000–4000 ^{10}Be yr contrast between the Yellowstone and the Wind Rivers in Pinedale terminal moraines shows that subdivision into early and middle stades does not necessarily indicate correlation from place to place.

For the Wallowa Range in eastern Oregon, the following are averages of cosmogenic ages on boulders on close-spaced moraines in the Wallowa Lake area (TTO, TTY, WTO) and in the glacial cirques (GL) (Licciardi, 2000; written comm., 2003):

Moraine (Number of Boulders Dated)	Age ($\times 10^3$ ^{10}Be yr)
TTO & some TTY (9)	21.1 ± 0.4
WTO & some TTY (9)	17.0 ± 0.3
GL (4), near cirques	10.2 ± 0.6

These ages are quite similar to those of the Wind Rivers.

From a Pinedale moraine site in Colorado Front Range, a few boulders yield an exposure age of 16,800 ± 3400 ^{10}Be and ^{26}Al yr B.P. (Dethier *et al.*, 2003). This age is also more than 5000 yr younger than corrected ^{14}C ages for moraine-dammed lakes in the same area.

The rate of retreat from the terminal-moraines areas to the cirques was remarkably fast (Fig. 3). For the Wind Rivers, glacial retreat of 33 km occurred at an average rate of 7.4 m/yr to moraines dated 12,100 ± 500 ^{10}Be yr in the cirque basins (Gosse *et al.*, 1995b). Retreat of the northern Yellowstone outlet glacier also occurred at the rapid rate of ~30 m/yr, given the 15,700 ^{10}Be yr for Chico recessional moraines and 13,700 ^{10}Be yr for flood deposits that originated more than 60 km upvalley (Licciardi *et al.*, 2001). For the Glacier National Park area (Carrara, 1987), much of deglaciation had occurred by about 12,000 ^{14}C yr B.P. (14,000 cal yr B.P., Carrara, 1995), also suggesting rapid retreat.

Discussion of Pinedale Ages

The cosmogenic ages for moraines of the northern Yellowstone outlet glacier are thousands of years younger than the Yellowstone chronology based on ^{14}C, obsidian-hydration (Pierce *et al.*, 1976), and U-series ages (Sturchio *et al.*, 1994), although none of non-cosmogenic methods used directly dated moraines deposition. As discussed previously, the calibrated ^{14}C ages for deglaciation of the Yellowstone Plateau are as old as 20,000–19,000 cal yr B.P. (Millspaugh *et al.*, 2000; Porter *et al.*, 1983; Whitlock, 1993; see discussion in Licciardi *et al.*, 2001). Either the cosmogenic ages are too young, or the carbon samples contained a large fraction of old carbon. Many of the carbon samples dating deglaciation were of finely disseminated organic carbon, which could be contaminated by older carbon. But some samples such as a peaty mud dating ~15,800 cal yr B.P. (13,140 ± 700 ^{14}C yr B.P.; Porter *et al.*, 1983, W-2285) from near the center of the Yellowstone Plateau ice cap consisted of recognizable plant fragments and is inconsistent with the 14,000 ± 400 ^{10}Be yr age of the Deckard Flats readjustment which predates the complete deglaciation of the Yellowstone Plateau.

Obsidian-Hydration Age of Pinedale Glaciation

The obsidian-hydration dating for Yellowstone assumes that under a constant temperature the square of hydration thickness is a linear function of age and that the Yellowstone obsidians sampled hydrate at the same rate (Pierce *et al.*, 1976). Hydration was measured on pressure cracks resulting from glacial grinding *up to* the time of moraine deposition. Age calibration for obsidian in Bull Lake moraines is based on their hydration thickness compared to that on bracketing 122,000- and 183,000-yr-old rhyolite flows (Pierce *et al.*, 1976). But no bracketing rhyolite flows exists for the Pinedale moraines, and age estimation is particularly sensitive to both the difference in soil temperature between late Pleistocene and Holocene time *and* the present soil temperature difference between the Yellowstone Plateau and the West Yellowstone Basin (Pierce *et al.*, 1976). An age younger than the ~30,000–25,000 yr obsidian-hydration age calculated for the Pinedale moraines near West Yellowstone (Pierce *et al.*, 1976) would result either if (1) the Pleistocene-Holocene temperature difference was larger than the estimated 6 °C *or* (2) the temperature difference between the Yellowstone Plateau and West Yellowstone basin was larger than the estimated 0.5 °C, *or* (3) both.

Moraines Attributed to Younger Dryas

The younger Dryas (YD) was a dramatic cooling episode between 11,000 and 10,000 ^{14}C yr B.P. (12,800 ± 200 and

11,500 ± 300 cal yr B.P.) in Europe. It has been attributed to a dramatic southward extension of cold North Atlantic water. At several localities in the Rocky Mountains, dating studies correlate a minor readvance in or near high cirques with the YD. In the core of the Wind River Range, the Inner Titcomb Lakes moraine dates 13,800 ± 600 to 11,400 ± 500 ^{10}Be yr (Gosse *et al.*, 1995b; see Fig. 3). Calculation of the *mean* age using the latest scaled production rates yields a *mean* age of 12, 600 ± 500 ^{10}Be yr (J.M. Licciardi, written comm., 2003). The Titcomb Lakes moraines correlate with the nearby Temple Lake moraines dated by sediment changes in nearby lake sediments as between 13,800 ± 900 and 11,800 ± 700 cal yr B.P. (Davis *et al.*, 1998).

In the Colorado Front Range, the Triple Lakes cirque moraines of Benedict (1985) have minimum ^{14}C ages just over and under ~10,000 ^{14}C yr B.P. (11,200 cal yr B.P.) indicating a latest Pleistocene age and suggesting they are candidates for the YD event (Davis, 1987). Also in the Colorado Front Range, lake sediments reflecting a nearby glacier advance date between 13,200 and 11,100 cal yr B.P. (Menounos & Reasoner, 1997). In Colorado Mountains, pollen spectra suggest a YD cooling event between 13,500 and 12,900 cal yr B.P. in Black Mountain Lake and 13,600 and 12,900 cal yr B.P. in Sky Pond (Reasoner & Jodry, 2000). In the southern Sangre de Cristo Range of New Mexico, lake sediments date an YD advance about 11,500 to 11,00 cal yr B.P. (Armour *et al.*, 2002).

Other Rocky-Mountain Glaciation Studies

Modeling Glacial Flow

Basal shear stress, mass balance, and glacial flow have been reconstructed for some late Pleistocene glaciers in the Rocky Mountains. For the glacial geologic reconstruction of the northern Yellowstone outlet glacier, basal shear stress averaged 1.2 bars for strongly extending reaches (converging flow lines), 1.0 bars for 11 uniform reaches, and 0.8 bars for 16 strongly compressing reaches (Pierce, 1979). Assuming precipitation similar to present, best estimates of mass balance yielded an annual accumulation of 2.8 km^3 above the ELA of 2850 m and annual loss of 3.3 km^3 below the ELA. Based on these parameters for a cross-section downvalley from the ELA, annual ice discharge was 2.7 km^3, of which 10% is modeled by flow within the glacier and the remaining 90% is attributed to basal sliding (Pierce, 1979).

On the mountains of northwestern Montana, a large ice cap built up on a complex mountain topography that includes several ranges. Based on terminal moraine positions, divide crossings, and nunataks, Locke (1995) modeled this ice sheet assuming basal shear stress values near 1 bar to produce a contour map of the ice surface. His model revealed much about the sources and non-sources of the multiple glacial lobes that radiate outward from this glacial source area. For some canyons draining the east side of Wind River Range icecap, W. Locke (written comm., Earth Sciences web site at Montana State University, 2002) calculates that the basal shear stress was as high as 8 bars. Possible factors for such high values are: (1) the need to funnel accumulation from a central icecap into narrow, steep canyons; and (2) low subglacial water pressure due to the draining of the glacial-bed water into permeable limestones high above the base level of the Wind River Basin.

Sedimentology of Glacial Deposits

On the southern margin of the San Juan Mountains, Colorado, glacial system, Johnson & Gillam (1995) found that end moraines are primarily of debris-flow sediment interbedded with sandy stream sediment. They conclude that "existing moraines were built rapidly (in 10 yr to a few tens of years)" but that outwash deposits indicate that the glacier stood at its terminus for a long time.

Pleistocene Climates

The contrast between present and glacial climates and departures of Pleistocene climate patterns from present can be made by comparison of late Pleistocene ELA's with modern snowpack patterns. For the Great Basin, Zielinski & McCoy (1987) located anomalies in the distribution of modern snowpack at late Pleistocene ELA's, in particular an anomaly in the NW Great Basin which appears to have been considerably wetter in Pleistocene times than present; this difference was also noted by Porter *et al.* (1983). Leonard (1984) found that contours on late Pleistocene ELA's for the San Juan Mountains in southern Colorado closely resembled modern snowpack pattern, suggesting little change in atmospheric circulation patterns. For the Sawatch Range in central Colorado, late Pleistocene mean summer temperatures are estimated to have been 7–9 °C colder (Brugger & Goldstein, 1999). Using modern climatic conditions at Pleistocene ELAs, Leonard (1989) found that Pleistocene glaciers could be maintained with either: (1) no change in total precipitation and 8.5 °C colder in summer, or (2) about 10–13 °C colder using Mears (1987) estimate of regional cooling and at least a 44% reduction in fall-through-spring precipitation. Locke (1990) used Mears (1987) estimate of regional cooling of 10 °C to infer an ~25% decrease in last glacial precipitation in Montana; Murray & Locke (1989) used ice-flow theory to independently estimate a similar drying.

Hostetler & Clark (1997), using a nested modeling strategy, determined that at 18,000 yr ago climatic conditions varied across the western U.S. Glaciers in the southern Rockies were sustained through decreases of 9–12 °C with little change in precipitation, whereas glaciers in the northern Rockies existed under relatively cold-summer and dry-winter conditions resulting from easterly anticyclonic wind flow off the Laurentide Ice Sheet. However, no evidence for this easterly flow was found by Muhs & Bettis (2000) based on late Wisconsin loess distribution, or by Locke (1990) or Gillespie (1991) based on changes in glacial ELA patterns in the northern Rocky Mountains and Sierra Nevada respectively.

Modeling of the climatic response in Western North America to the changes associated with sudden lowering of the Laurentide Ice Sheet in a Heinrich Event show a complex response that in different areas and times reinforce, cancel, or reverse local changes and thus make difficult simple correlations in the region (Hostetler & Bartlein, 1999).

Possible Uplift and Subsidence

Belts of uplift and subsidence may explain different patterns in the relative extent of Bull Lake and Pinedale glaciations near Yellowstone. The normal pattern is that Pinedale glaciers were ~90% as long as Bull Lake glaciers. But for both the Greater Yellowstone glacial system and nearby independent valley glaciers *on the western and southern* sides of Yellowstone, Pinedale glaciers are less than 80% and locally 60% the length of Bull Lake glaciers; whereas, *on the northern and eastern* sides of Yellowstone, Pindeale glaciers were >100% the length of Bull Lake glaciers and overran Bull Lake moraines (Pierce & Morgan, 1992). An explanation of this pattern is that the terrain to the northeast is rising and that to the southwest is subsiding. These areas appear to be on the currently uplifting (NE) and subsiding (SW) slopes of the “bow wave” of the Yellowstone hot spot. Compared to Bull Lake time, areas to the northeast became relatively higher in Pinedale time whereas those to the southwest became relatively lower (Pierce & Morgan, 1992).

Conclusions and Recommendations for Future Study

In their provocative paper “Asynchronous maximum advances of mountain and continental glaciers” Gillespie & Molnar (1995) cite much evidence that mountain glaciation did not proceed in lock step with either continental glaciation or its proxy, the marine oxygen isotope record. More dating may establish such variation for the Rocky Mountains. Global climate models (Kutzbach & Guetter, 1986) suggest that glacial-anticyclonic circulation weakened westerly flow and resulted in air cooler and drier than present, particularly for the northern Rocky Mountains. But Locke (1990) observed that the gradient of maximum glacial ELAs exactly parallels that of modern ELAs, indicating a similar rather than contrasting climatic pattern. In particular Locke noted no maximum glacial lowering of ELAs due to upslope precipitation on the east side of ranges that would be associated with such easterly flow. Assuming the Kutzbach & Guetter model results would suggest that differences in timing and relative magnitude of late Pleistocene glaciation is likely southward through the Rocky Mountains with greater distance from the continental ice sheet. Glacial culminations might follow storm tracks located at some distance south of the expanding or contracting continental ice sheet, a topic addressed by Licciardi (2000; written comm., 2003). More precisely dated glacial and lacustrine records may reveal patterns in such non-parallelism from south to north (colder) or east to west (wetter) throughout the Rocky Mountains.

Cosmogenic dating of Pinedale glaciers on both sides of the Wind River Range suggest a Pinedale culmination near the last glacial maximum 21,000 yr ago, but fail to reveal surviving older moraines of MIS 2, 3, or 4 age. Although imprecise, weathering rind thicknesses, some radiocarbon ages, and obsidian hydration suggest Wisconsin glacial advances in the 50,000–35,000 and 70,000–60,000 yr range (Colman & Pierce, 1981; Pierce *et al.*, 1976; Porter *et al.*, 1983). A 55,000-yr-old Wind River terrace (Sharp *et al.*, 2003) probably reflects early Wisconsin (MIS 4) glaciation. Records of glacial flour in lake sediments of the Rocky Mountains similar to that for the Sierra Nevada (Bischoff & Cummings, 2001) and the Cascades (Rosenbaum & Reynolds, 2003) could reveal much about the glacial record both preserved or subsequently overridden in the end moraine record, including helping resolve the relative magnitude of glacial activity in MIS 3, 4, 5d, and 6. For the many glacial cycles documented by the record older than MIS 6, only the Sacagawea Ridge moraines of MIS 16 are well correlated with a particular MIS.

The potential distinction of moraines of MIS 4, 5d and MIS 6 may present interesting contrasts. The conference on the last interglaciation (Kukla *et al.*, 2002 and references therein) presents current knowledge about MIS 5d and its contrasts with MIS 5e and 5c. A warm ocean, a major low in northern Hemisphere solar insulation, and glacial expansion particularly at high latitudes, accompanied MIS 5d.

What were the glacial and climatic conditions along a north-south transect through the Rockies? In MIS 2, climate was cold and probably drier in the northern Rockies (Whitlock *et al.*, 2000), and MIS 6 was probably similar. Was MIS 5d a different character of glaciation than MIS 2 and 6 in the Rockies? If MIS 6 was similar to MIS 2, why are Bull Lake moraines (MIS 6 or MIS 5e) more bulky? The cross-feed between data for Pleistocene glaciations across the western mountains and climatic models such as Hostetler & Clark (1997) and Hostetler & Bartlein (1999) will enhance understanding in both subject areas.

Cosmogenic dating can benefit by refinement in calibration and changes in cosmic-ray flux through time. For boulders on deposits ~100,000 yr and older, the history of the boulder needs to be better understood including erosion of the boulder surface, emergence of the boulder from the eroding moraine, deposition and deflation of loess, and burial by snow.

Acknowledgments

I thank Pete Birkeland, Bill Locke, Joe Licciardi, Linda Pierce, and Nicole Davis for helpful reviews and editing. In the preparation of this paper, I benefited from discussions with Peter Clark, Bill Locke, Alan Gillespie, Steve Colman, Dave Fullerton, Joe Licciardi, Warren Sharp, Darrell Kaufman, Dave Dethier, Cathy Whitlock, Pete Birkeland, Dennis Dahms, Ralph Shroba, Eric Leonard, John Good, Don Easterbrook, John Obradovich, and Joe Rosenbaum.

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