Late Pleistocene Glaciations in the Northwestern Sierra Nevada, California

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Pleistocene fluvial landforms and riparian ecosystems in central California responded to climate changes in the Sierra Nevada, yet the glacial history of the western Sierra remains largely unknown. Three glacial stages in the northwestern Sierra Nevada are documented by field mapping and cosmogenic radionuclide surface-exposure (CRSE) ages. Two CRSE ages of erratic boulders on an isolated till above Bear Valley provide a limiting minimum age of $76,400 \pm 3800$ [10]Be yr. Another boulder age provides a limiting minimum age of $48,800 \pm 3200$ [10]Be yr for a broad-crested moraine ridge within Bear Valley. Three CRSE ages producing an average age of $18,600 \pm 1180$ yr were drawn from two boulders near a sharp-crested bouldery lateral moraine that represents an extensive Tioga glaciation in Bear Valley. Nine CRSE ages from striated bedrock along a steep valley transect average $14,100 \pm 1500$ yr and suggest rapid late-glacial ice retreat from lower Fordyce Canyon with no subsequent extensive glaciations. These ages are generally consistent with glacial and pluvial records in east-central California and Nevada. © 2002 University of Washington.

Key Words: **Sierra Nevada Quaternary climate; last glacial maximum stratigraphy; cosmogenic radionuclides.**

INTRODUCTION

Few numeric ages exist for western Sierra Nevada Pleistocene glaciations. While the late-glacial stratigraphy in the east-central Sierra is relatively well established (Benson *et al*., 1996; Phillips

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et al., 1996; Bursik and Gillespie, 1993), the degree to which it corresponds with events in the northwestern Sierra Nevada is not known. This paper presents cosmogenic radionuclide surface-exposure (CRSE) ages collected to examine spatial patterns of glacial erosion (e.g., Fabel and Harbor, 1999). Three late Quaternary glacial stages in the northwestern Sierra Nevada are documented and compared with glacial and pluvial records in eastern California and Nevada.

Sierra Nevada glacial stratigraphy has been reviewed elsewhere (Wahrhaftig and Birman, 1965; Fullerton, 1986) and is outlined only briefly here. Allostratigraphic units below the last glacial maximum are poorly constrained in the region, lack type sections, and are largely defined by relative age rather than lithologic characteristics (Fullerton, 1986). Blackwelder's (1931) Tahoe and Tioga glacial stages were expanded by Sharp and Birman (1963) who added the Mono Basin as a pre-Tahoe advance and recognized the Tenaya between the Tahoe and Tioga advances.

The Tahoe allostratigraphic unit has been associated with problems and stratigraphic complexities that need to be addressed before it can be applied in the northwestern Sierra Nevada. For example, Gillespie (1982; cited in Bursik and Gillespie, 1993) recognized that a Tahoe moraine ridge in Bloody Canyon was a palimpsest *Tahoe II* moraine crest overlying an older *Tahoe I* moraine. Gillespie (1984) also recognized that the two Tahoe moraines probably spanned marine oxygen isotope stages 6 and 4, and this was corroborated by CRSE [36]Cl ages of boulders by Phillips *et al*. (1990) who, like Gillespie, divided Tahoe moraines into *younger Tahoe* and *older Tahoe* units. Unlike Gillespie, however, Phillips *et al*. inserted the Mono Basin

(A)P

advance between the Tahoe advances, on the basis of ^{36}Cl ages, that have recently been revised downward from ~103,000 to 80,000–60,000 ^{36}Cl yr using a new ^{36}Cl production constant (F. M. Phillips, written communication, 2001; cf. Phillips *et al.*, 2001). (Phillips' revised ages based on erratics in Bishop Creek will henceforth be referred to as "revised.") Placement of the Mono Basin between the younger and older Tahoe departs from the conventional stratigraphy (e.g., Sharp and Birman, 1963; Bursik and Gillespie, 1993). One important numerical constraint on Tahoe moraine ages is a mean ^{40}Ar-^{39}Ar date on a basalt flow that is intercalated between a Wisconsinan moraine and an older moraine in Sawmill Canyon in Inyo County (Gillespie *et al.*, 1984). Bursik and Gillespie (1993) constrained younger Tahoe (Tahoe II) moraines to <118,000 ± 7000 (2σ) yr B.P. on this basis. Revision of the Tahoe nomenclature is needed but is beyond the scope of this paper.

Chronostratigraphic control is better constrained with later moraines for which CRSE ages are more consistent with independent evidence (Bursik and Gillespie, 1993). Maximum ^{36}Cl surface-exposure ages of younger Tahoe moraine boulders in Bloody Canyon were initially found to group around 60,000 ^{36}Cl

yr B.P. (Phillips *et al.*, 1990) and have been revised to between 50,000 and 42,000 ^{36}Cl yr B.P. A late glacial chronology developed elsewhere in the east-central Sierra Nevada appeared to differentiate four moraines, Tioga 1 through 4, with ages of 31,000, 25,000, 19,000, and 16,000 ^{36}Cl yr B.P., respectively (Phillips *et al.*, 1996; Benson *et al.*, 1996). Clark and Gillespie (1997) concluded that the Sierra Nevada was largely deglaciated by 15,000–14,000 yr B.P. and that a high-elevation Recess Peak readvance ended by 13,100 ± 85 cal yr B.P. Revised ^{36}Cl ages of Tioga erratics in Bishop Creek indicate similar ages (with ±1σ analytical precisions): Tioga 3 = 18,000 ± 600 ^{36}Cl yr (10 samples), Tioga 4 = 15,900 ± 300 ^{36}Cl yr (four samples), surfaces between Tioga 4 and Recess Peak = 14,800 ± 400 ^{36}Cl yr (15 samples), and Recess Peak = 12,600 ± 500 ^{36}Cl yr. For comparisons with calendar years, the total systematic precision of these revised ages (not shown here) should be used.

METHODS

The study area is located in the upper South Yuba and Bear River basins between 1200 and 2300 m elevation (Fig. 1). The
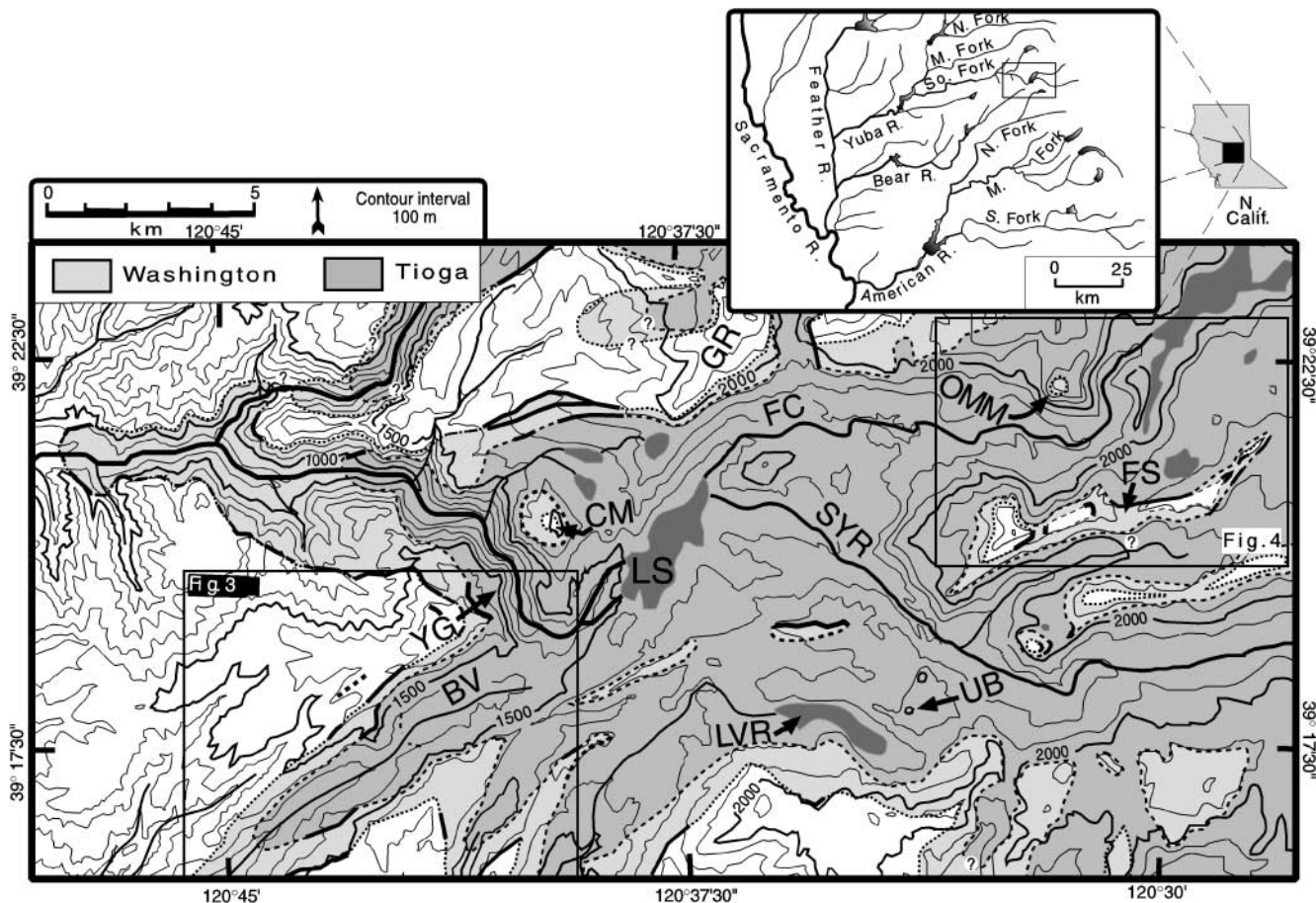

FIG. 1. Outermost Tioga and broad-crested moraines. Darkest shades are lakes. BV, Bear Valley; CM, Clyde Mtn; FC, Fordyce Creek; FS, Fordyce Summit; GR, Grouse Ridge; LS, Lake Spaulding; LVR, Lake Valley Reservoir; OMM, Old Man Mountain; SYR, South Yuba River; UB, unnamed Butte (site of cosmogenic sample BB-1B); Y6, Yuba Gorge.

northwestern Sierra Nevada is characterized by deep canyons and broad basins eroded in pre-Cenozoic metamorphic and granodiorite rocks bordered by ridges capped with Miocene to Quaternary volcanics.

Field Mapping

Before 1995, the only map of the area showing glacial features was Lindgren's (1900) 1:125,000 geologic map that does not identify moraine ridges or distinguish between advances. Birkeland (1964) mapped Quaternary deposits along the Truckee River on the east side of the Sierra Nevada across the crest from this study. Reconnaissance mapping around Bear Valley (James and Davis, 1994; James, 1995) has been extended up to 2300 m above mean sea level (amsl) to delineate the maximum extents of late Pleistocene glacial stages (Fig. 1). Accumulation zones beyond this mapping extend west up to almost 2800 m amsl at the Sierra crest. Mapping concentrated on lateral moraines or boulder lines on ridges and valley sides that were followed in serpentine traverses, crossing contacts up and down slope while progressing along valleys. Abundant granitic erratics on metamorphic or volcanic bedrock facilitated mapping contacts in most valleys. Uncertainty was greatest in areas of granodiorite bedrock where erratic frequencies are difficult to assess.

Moraines and other glacial features were grouped into three alloformations by conventional morphostratigraphic criteria.

The large area mapped (>100 km^2) precluded detailed application of relative-age methods or mapping of surface geology. Instead, surface criteria such as elevation, moraine-ridge morphology, degree of erosion, boulder frequencies, and weathering were used qualitatively to delineate paleoglacier upper boundaries. Local names were initially used for alloformations due to the lack of numeric ages by which regional correlations could be made (James, 1995; James and Davis, 1994). Isolated erratics above or beyond the most extensive lateral moraine ridges were mapped as points and interpreted as older undifferentiated tills. Broad-crested moraines at high topographic positions were grouped into the Washington alloformation (James, 1995). In areas of poor preservation, the uppermost relatively fresh boulder erratics in the appropriate elevation range were used to map this unit. Tills on Washington moraines tend to have thin but distinct weathering rinds on andesitic clasts in the epipedon (20–40 cm deep) and thick, rubified soils, but may not exhibit argillia (Bt) Bt horizons. Moraines are discontinuous, so grouping the uppermost and outermost features fitting this description may include more than one glacial advance.

Bouldery, sharp-crested moraines (Fig. 2) or clusters of fresh boulder erratics at slightly lower topographic positions were grouped into an alloformation initially named Jolly Boy (James, 1995). These surfaces often have abundant granitic surface gravel, lack B horizons, and have thin weathering rinds on

FIG. 2. Sharp-crested bouldery lateral moraine across Fordyce Summit; typical of Tioga moraines. View to east.

TABLE 1
Apparent Surface Exposure Dates

ID no.	Elevation (m)	Correction factor	[^{10}Be] ×10^5 atom g^{-1}	[^{26}Al] ×10^5 atom g^{-1}	Apparent ages ^{10}Be (×10^3 yr)	^{26}Al (×10^3 yr)	Surface character	Location
Late Tioga								
97-31	1820	0.98	0.82 ± 0.07		14.7 ± 1.6 (3.4)		weathered	OOM base
97-32	1910	0.75		4.20 ± 0.59		13.6 ± 1.9 (3.4)	polished	OMM
97-33	2000	0.83		4.33 ± 0.51		14.0 ± 1.6 (3.3)	striated	OMM
97-35	2120	0.84		3.71 ± 0.36		12.0 ± 1.2 (2.7)	striated	OMM
97-36	2140	0.85		4.62 ± 0.43		15.0 ± 1.4 (3.3)	polished	OMM
97-37	2160	0.84		4.21 ± 0.38		13.6 ± 1.2 (3.0)	striated	OMM
97-38	2190	0.69		4.08 ± 0.40		13.2 ± 1.3 (3.0)	polished	OMM
97-39	2210	0.98		4.37 ± 0.51		14.1 ± 1.6 (3.3)	striated	OMM
BB-1B	1990	1.00			13.8 ± 1.1 (3.0)	13.0 ± 1.0 (2.8)	boulder	Unnamed Butte
Early Tioga								
97-40	2240	0.99		5.18 ± 0.49		16.8 ± 1.6 (3.8)	striated	OMM high
97-22	1510	0.99	1.07 ± 0.08	5.33 ± 0.39	21.0 ± 1.5 (4.5)	17.3 ± 1.3 (3.7)	large boulder	BV Bench
97-18	1510	0.99	0.94 ± 0.07		18.5 ± 1.4 (4.0)		boulder	BV Bench
Washington Moraine								
97-21	1430	0.99	2.48 ± 0.16		48.8 ± 3.2 (10.4)		boulder	BV Moraine
Steephollow Till								
97-17	1680	0.98	3.85 ± 0.19		76.4 ± 3.8 (15.9)		boulder	BV nr Steephlw
97-16	1690	0.99	3.24 ± 0.18		64.0 ± 3.5 (13.4)		sm Boulder	BV nr Steephlw
Holocene								
97-41	2290	0.99		2.60 ± 0.48		8.4 ± 1.6 (2.3)	striated	OMM depression

Latitudes: Bear Valley = 39.31°N; Old Man Mountain = 39.36°N. Correction factor includes geometric shielding and sample thickness corrections. Quartz [Al] measured by atomic adsorption spectrophotometry and assigned 5% uncertainty. ^{10}Be/^{9}Be was measured against standards derived from NIST SRM 4325, with an assigned ratio of 3.05 × 10^{-11}. Uncertainties represent one standard error measurement uncertainty, with systematic uncertainties in total production rates (20%), and radioactive decay rates (3%) added in quadrature and shown in parentheses. See text for details.

andesitic clasts. It was not feasible to distinguish different stades within either group of lateral moraines based on reconnaissance relative age criteria, nor are recessional moraines delineated.

Cosmogenic Radionuclide Surface-Exposure Ages

Accumulations of cosmogenic radionuclides were used to date boulder erratics and striated bedrock surfaces. Rock was chiseled from the top 1 to 5 cm of large granodiorite erratics in stable positions on lateral moraine crests and from striated or polished bedrock surfaces indicating glacial erosion with little subsequent erosion. Samples were crushed and sieved to 0.25–0.5 mm, and 20 g of quartz was purified by selective chemical dissolution (Kohl and Nishiizumi, 1992), dissolved in HF and HNO$_3$, and spiked with ~0.7 mg ^{9}Be carrier. Total aluminum concentrations in aliquots of the dissolved quartz were determined by flame atomic adsorption spectrophotometry (AAS) and assigned a 5% uncertainty. After expelling fluorides, Al and Be were separated and purified by ion chromatography and selectively precipitated as hydroxides. Precipitates were dried, oxidized, and mixed with Ag powder for accelerator mass spectrometry (AMS) determination of ^{10}Be/^{9}Be and ^{26}Al/^{27}Al at PRIME Lab. Measured ratios were normalized to sea level and high latitude (>60°) using Stone (2000). Ages were calculated assuming sea-level, high-latitude production rates (at g^{-1} yr^{-1})

of 5.1 ± 0.3 and 31.1 ± 1.9 for ^{10}Be and ^{26}Al, respectively. Production rates were corrected for sample thickness and geometric shielding (Dunne et al., 1999). Results are present in Table 1 with two separate uncertainties; the first value represents one standard error of analytical uncertainty and is calculated from AMS counting statistics and 5% AAS uncertainty. The second (parenthetical) uncertainty also includes systematic uncertainties in radioactive decay constants (3%) and total production rates (20%), with each uncertainty added in quadrature, that is, the square-root of the sum of squares of individual errors. Analytical uncertainties are given when comparing exposure dates within this study and expressed as "yr"; total uncertainties are given when comparing data to calendar ages and expressed in "yr B.P."

Dating of glacial landforms by CRSE methods has limitations. Frequency distributions of exposure ages on older moraines may be young-skewed if erosion and reworking is substantial (Phillips et al., 1990; Zreda et al., 1994), so several samples should be processed and only the oldest ages used to estimate old moraine ages. This assumes that inheritance of cosmogenic radionuclides is negligible, which has been shown to be justifiable for moraine boulders in Bloody Canyon based on age distributions (Phillips et al., 1990). Boulders that stand <0.5 m above moraine surfaces often produce anomalously young ages, while higher boulders produce an age distribution in accord with theory (Zreda et al., 1994). Therefore, only tall boulders should

be sampled and young age outliers should be disregarded in interpreting moraine ages. Phillips *et al*. (1990) used the mean of the oldest three or four boulders to date Tioga and Tenaya moraines. Because burial and erosion both result in erroneously young age interpretations, apparent ages are viewed as minimum limiting ages if inheritance is negligible. The small number of boulder samples from older moraines in this study limits interpretations of those ages to minimum-age constraints. No age outliers were identified in the samples of Tioga boulders in Bear Valley, but the highest of the 10 striated bedrock samples on Old Man Mountain was a low outlier and was not used in subsequent calculations. Average ages are simple means, except for the average age of single boulders that are derived from measurements of both ^{10}Be and ^{26}Al concentrations, for which means are weighted by inverse variance (Bevington and Robinson, 1992).

GLACIATION OF THE NORTHWEST SIERRA NEVADA

Field mapping and surface-exposure ages document at least three glacial stages: a high old till, an extensive set of broad-crested moraines, and a less extensive set of sharp-crested bouldery moraines (Table 1; Fig. 1). In addition, late glacial retreat is constrained by surface-exposure ages of striated bedrock in Fordyce Canyon. These ages are consistent with topographic, morphostratigraphic, and weathering relationships.

Steephollow Till

Two granodiorite boulder erratics were sampled north of Bear Valley (Table 1) beyond the outermost broad-crested lateral moraine ridge (Fig. 3). The surface lacks moraine morphology and there is no local source of colluvium, so the erratics are interpreted as a primary glacial deposit referred to here informally as the Steephollow till. Severe erosion is suggested by lack of moraine morphology, thin weathering rinds on andesitic clasts, and limited pedogenesis in a soil pit near boulder 97-17, for example, little B horizon clay or rubification (10 YR 3/4). Boulder weathering and disintegration are suggested by a low surface boulder frequency, and the site is densely forested so boulder spallation from fires is possible. Boulder 97-16 protrudes only 40 cm above ground and has a CRSE age of only $64,000 \pm 3500$ ^{10}Be yr (Table 1). Boulder 97-17 stands 1.3 m above ground and has an age of $76,400 \pm 3800$ ^{10}Be yr that is interpreted as the minimum age of the Steephollow till.

Washington Alloformation

Broad-crested lateral moraines are preserved at enough locations to allow mapping of the approximate maximum extent of
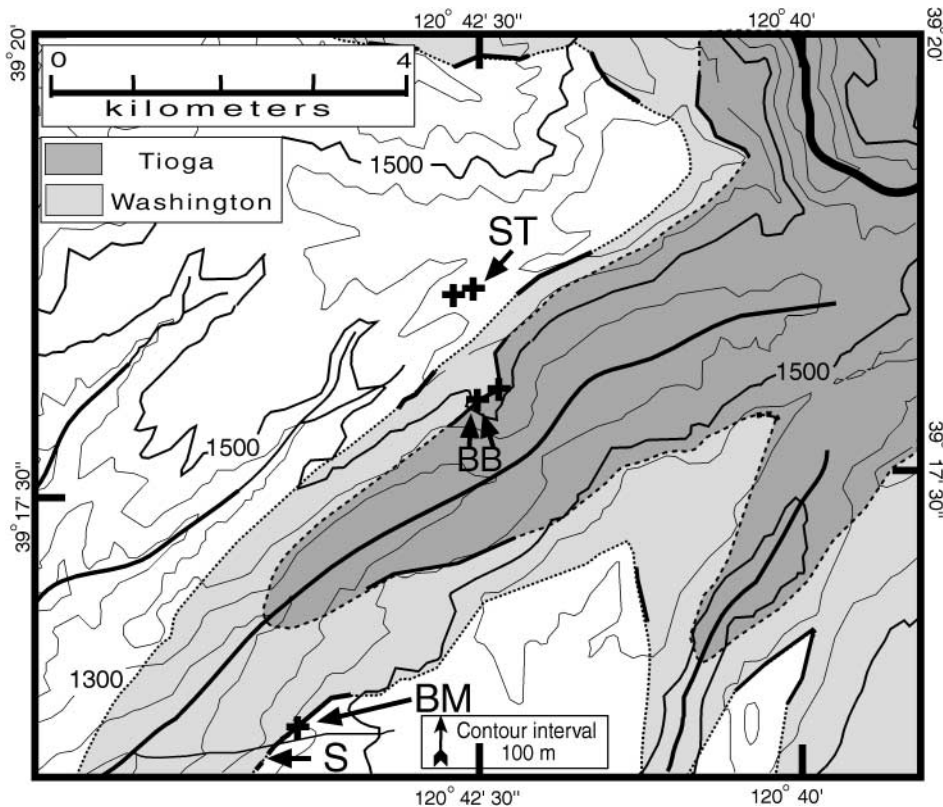
FIG. 3. Maximum glacial extents and sample sites (crosses) in Bear Valley. BB, bedrock bench; BM, broad-crested moraine (site of cosmogenic sample 97-21); S, soil charcoal site; ST, Steephollow Till.

this alloformation (Fig. 1). On the southeast side of lower Bear Valley (Fig. 3) the outermost moraine-ridge remnant is about 30 m high and extends about 200 m. A granodiorite boulder on the ridge crest, dated at 48,800 ± 3200 [10]Be yr (Table 1), stands 0.7 m above the surface, and is well away from the valley wall, so deposition by mass wasting or burial by colluvium is unlikely. The ridge extends obliquely downvalley toward a tributary that has cut through more than 25 m of till exposing a deeply rubified soil (5 YR 4/6) on the moraine. On the southeast side of the tributary, this soil contains charcoal yielding an AMS age >47,510 ^{14}C yr B.P. (Beta-123309). An older till upslope from the charcoal site has stronger soil development with more than 25% clay and more than 5% dithionite Fe in a B_t horizon (James and Davis, 1994).

Based on the minimum limiting CRSE age, the age of the Washington broad-crested moraine is at least 48,800± 10,400 [10]Be yr B.P. Although this age is compatible with the age of younger Tahoe moraines in the east-central Sierra Nevada (~60,000 [36]Cl yr B.P., Phillips *et al*., 1990; revised to 50,000 to 42,000 [36]Cl yr B.P.), a single apparent age can be substantially in error. Interregional correlations will require more surface-exposure dating to determine ages of broad-crested moraines in this area. Yet the well-preserved moraine morphology indicates limited erosion and, unless the CRSE age is grossly in error, this moraine should be early or middle Wisconsinan in age. This would indicate that glaciation in the northwestern Sierra Nevada during that period was somewhat higher and much more extensive than ice during the last glacial maximum. Given the moraine age uncertainties and ambiguities surrounding Tahoe nomenclature, we defer assigning Washington broad-crested moraines a stratigraphic designation.

Tioga Moraines (Jolly Boy Alloformation)

Bouldery, sharp-crested moraines in the northwestern Sierra Nevada represent a less extensive glaciation although they are better preserved than the broad-crested Washington moraines. A sharp-crested lateral moraine ridge on the north side of Bear Valley, mapped as Jolly Boy by James (1995), extends from where Highway 20 crosses a prominent bedrock bench south to near the edge of the bench (Fig. 3). Two large granodiorite erratics on the southwest edge of the bench were sampled. Both boulders lie on metamorphic rock with little soil or vegetation, adjacent to a steep slope, and away from colluvial sources, so postglacial redeposition, burial, and fire played little role in their exposure histories. The largest boulder (97-22) stands 6 m above the surface and yielded two ages (Table 1) averaging 18,800 ± 957 yr. Sample 97-18 yielded a similar age and the average age of the two boulders is 18,600 ± 1180 yr (Table 2). Zreda *et al.* (1994) found age distributions of samples from boulders on young moraines were symmetrical about the mean due to limited surface and boulder erosion and were able to use mean values to date young moraines. This approach presumes a minimum of moraine erosion and is best applicable to sharp-crested moraines. Thus, we consider the mean value of 18,600 ± 1180 yr to be the

TABLE 2
Average Cosmogenic Radionuclide Surface Ages

Location/Group	N	Mean age[a] yr B.P.	Measurement uncertainties[b] yr	Total uncertainties[b] yr B.P.
Bear Valley/Tioga	3	18,600	±1180	±3950
Old Man Mountain	8	13,800	±1490	±3160
Old Man Mountain	9	14,100	±1500	±3230
Hill 6642	2	13,400	±740	±2800

[a] Mean ages combine [10]Be and [26]Al ages.
[b] 1 SD. Measurement and total uncertainties are reported in the text as yr and yr B.P., respectively.

best age estimate of this moraine pending more data. This age is similar to the age of Tioga 3 moraines in the east-central Sierra Nevada (19,000 [36]Cl yr, Phillips *et al*., 1996; 18,000 [36]Cl yr, revised) and clearly indicates that the sharp-crested Jolly Boy moraines mapped by James (1995) are of Tioga age. Samples are from the highest Tioga moraine preserved at the site, although there may have been earlier or more extensive Tioga advances in this area.

Late Tioga Glaciation and Rapid Retreat

Ten surface-exposure samples were collected from striated granodiorite bedrock along a transect from 1820 to 2290 m elevation up the southeast flank of Old Man Mountain in Fordyce Canyon (Figs. 4, 5, 6). The highest sample (2290 m) from a shallow recess yielded an anomalously young Holocene age (Table 1), which is interpreted as the result of postglacial burial or nivation. The next highest sample (2240 m) yielded an age of 16,800 ± 1600 [26]Al yr. While this sample is higher than the next eight samples and may have had a longer exposure history, the age is not significantly different from the average age of either the younger samples lower on the transect or the older 18,600 ± 1180 yr erratic ages in Bear Valley. The sample elevation is consistent with a sharp-crested bouldery moraine across and 3 km down Fordyce Canyon on Fordyce Summit at an elevation of 2180 m (Fig. 2; "FS" on Fig. 4), which is the highest Tioga moraine on that ridge. More surface-exposure dates are needed to determine if this surface was associated with the earlier advance in Bear Valley or with the later ice indicated by the samples below. Whether this age is treated separately or grouped with lower samples, maximum Tioga ice thickness was at least 440 m in Fordyce Canyon near Old Man Mountain, 440 m at the upper south rim of Yuba gorge, and 200 m at the bedrock bench in Bear Valley.

Surface-exposure ages from the next eight samples down the Old Man Mountain transect average 13,800 ± 1,490 yr (Fig. 6; Tables 1 and 2). When sample 97-40 is grouped with these eight samples the mean age of the Old Man Mountain Tioga surfaces is 14,100 ± 1500 yr. Available data do not indicate if ice retreated upvalley after the high Tioga advance in Bear Valley and readvanced to the late Tioga position, as it apparently did in the
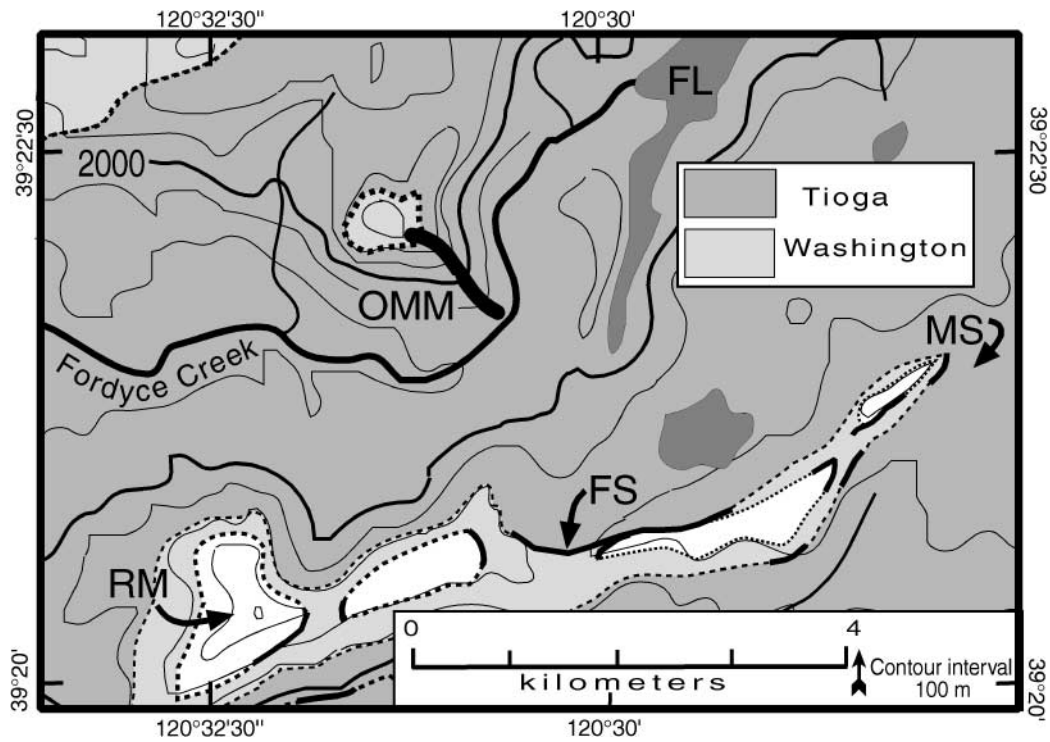
FIG. 4. Maximum glacial extents and sample transect on Old Man Mountain (OMM). FL, Fordyce Lake; FS, Fordyce Summit; MS, Magonigal Summit; RM, Red Mountain.

FIG. 5. View to north–northeast across transect on southeast flank of Old Man Mountain.
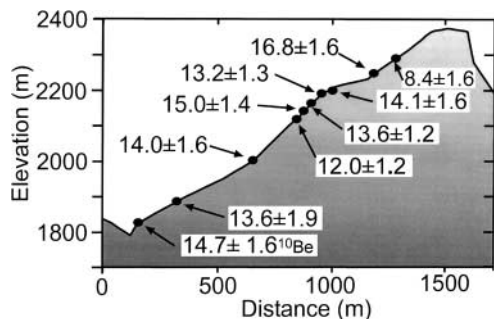
FIG. 6. Old Man Mountain section with surface exposure ages in thousands of years B.P. (view down valley). All dates are ^{26}Al except as noted. Sample details in Table 1.

east-central Sierra Nevada (Benson *et al.*, 1996). One sample from a 1.5-m-high granodiorite boulder at 1990 m elevation on the crest of a roche moutonnée in upper South Yuba Canyon (Hill 6642, "UB" on Fig. 1) produced two surface-exposure ages (Table 1) with a weighted mean age of $13,400 \pm 740$ yr. This minimum-limiting age indicates that late Tioga ice in the South Yuba valley was at least 320 m thick and overtopped the two buttes near Red Mountain.

Although large uncertainties prevent an unequivocal assessment, uniform sample ages on the Old Man Mountain transect suggest rapid melting of late Tioga ice from Fordyce Canyon around $14,100 \pm 3230$ yr B.P. Independent dates are compatible and further constrain the time of ice recession. First, ablation from Fordyce Canyon most likely occurred after the climatic deterioration that resulted in deposition of Tioga 4 moraines in the east-central Sierra Nevada around 16,000 ^{36}Cl yr (Phillips *et al.*, 1996; revised to $15,900 \pm 300$ ^{36}Cl yr). Second, at higher elevations elsewhere in the Sierra Nevada, Tioga ice had retreated and Recess Peak ice had advanced and was gone by $13,100 \pm 85$ cal yr B.P. (Clark and Gillespie, 1997).

DISCUSSION

Late Pleistocene glacial advances documented by this study are compared here with (1) glacial stratigraphy elsewhere in the Sierra Nevada, (2) pluvial lake records, and (3) proxy records of climate change. Emphasis is on Tioga advances for which our data are most reliable.

Relations to East-Central Sierra Nevada Glaciations

More surface-exposure ages are needed to ascertain the abundance and age of early tills. Isolated, well-weathered tills and erratics beyond the most extensive moraine ridges and boulder lines are not uncommon in this area, but no attempt to group or correlate them was made. Although older till remnants are found higher in the landscape, they were not necessarily deposited by glaciers containing larger ice volumes than subsequent glaciers because the amount of valley deepening during and between glacial stages is not known.

A single CRSE age on a Washington lateral moraine does not allow assignment of an age for broad-crested moraines in the region. Yet the freshness of many of these moraine remnants in regards to morphology, weathering, and pedogenesis is suggestive of an early or middle Wisconsinan age, and this is advanced as a testable hypothesis. In many alpine valleys of western North America late Wisconsin ice was less extensive than in early or middle Wisconsinan time (Gillespie and Molnar, 1995). Yet benthic marine oxygen isotope records have long suggested that continental late Wisconsinan glacial advances were much more extensive than in the early or middle Wisconsin. However, the apparent weak early advances may be less of a discrepancy than previously believed. Shackelton (2000) isolated the ice-volume signal from deep-ocean temperature signals and concluded that much of the benthic ∂^{18}O signal was due to cold water rather than ice volumes. His reconstructed curves show that early and middle Wisconsinan global glacial advances were more closely comparable to late Wisconsinan glacial volumes than previously believed. Washington broad-crested moraines represent a glaciation that was much more extensive than last glacial maximum (Tioga) glaciers in the northwest Sierra Nevada. The hypothesis that Washington glaciers were early or middle Wisconsinan in age and were more extensive than late glacial Tioga ice is not at all outrageous.

Agreement between surface-exposure ages and other numeric, stratigraphic, and relative ages of Tioga moraines has led to growing confidence in the reliability of surface-exposure dating techniques (Bursik and Gillespie, 1993). Although the number of samples and sites is limited and uncertainties are substantial, the ages for the last glacial maximum in the northwest Sierra Nevada reported here are compatible with records in the east-central Sierra Nevada (Phillips *et al.*, 1996; Benson *et al.*, 1996). Two of the four Tioga stades recognized there appear to be represented in this area. An extensive Tioga advance in Bear Valley around $18,600 \pm 3950$ yr B.P. is compatible with the Tioga 3 stade of Phillips *et al.* (1996) around 19,000 ^{36}Cl yr or the Tioga 3 age of $18,000 \pm 600$ ^{36}Cl yr as revised by Phillips (Fig. 7). The Tioga 3 advances had the second lowest equilibrium line (ELA) of the Tioga stades in the east-central Sierra Nevada Phillips *et al.* (1996). An interstade between the Tioga 3 and Tioga 4 stades recognized in the east-central Sierra can neither be shown nor negated with data from this study. Retreat of ice from Fordyce Canyon around $14,100 \pm 3230$ yr B.P. apparently occurred after the Tioga 4 stade in the east-central Sierra Nevada around 16,000 ^{36}Cl yr (Phillips *et al.*, 1996; $15,900 \pm 300$ ^{36}Cl yr, revised). The younger age of Fordyce Canyon surfaces is consistent with ablation from middle elevations some time after the glacial maximum.

Other Tioga stades may have occurred in the northwest Sierra Nevada that are not represented by the samples reported here. Evidence is not widespread for Tioga 1, a less extensive early Tioga stade on the east side ($\sim$31,000 ^{36}Cl yr B.P.; Phillips *et al.*, 1996). If such early moraines were present in the study area, they may have been overridden by later Tioga ice. Minimum
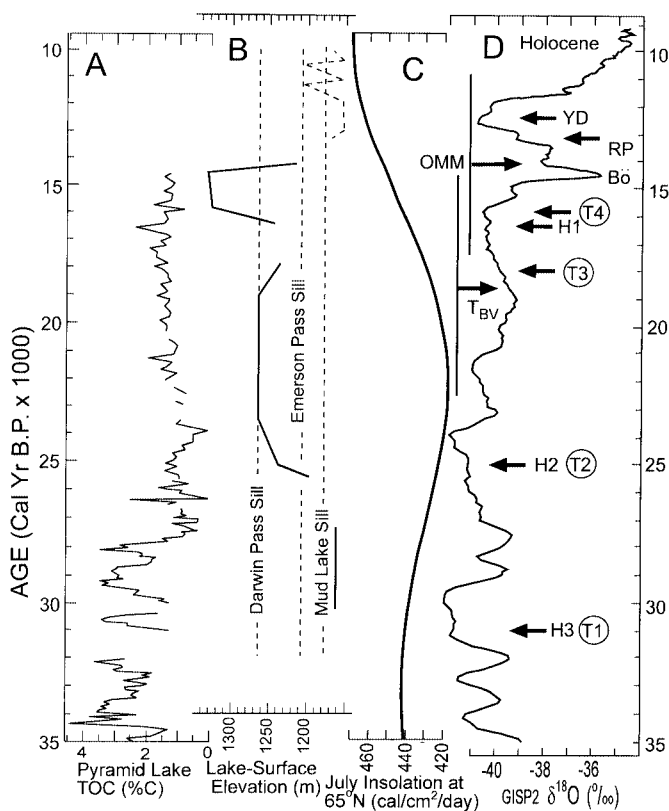
FIG. 7. Ages of Tioga moraine in Bear Valley (T$_{BV}$) and late Tioga retreat from Old Man Mountain (OMM) with total uncertainties (bars) compared with other late glacial records. (A & B) Total organic carbon (TOC) and stage elevations of Pyramid Lake (Benson, 1999; Benson, unpublished manuscript, 2001). (C) July solar insolation at 65°N showing minimum at 21,500 yr B.P. before the Tioga advance in Bear Valley (orbital reconstruction by Berger and Loutre, 1991). (D) Oxygen isotope (δ^{18}O ‰) data from GISP2 Greenland ice core (cf. Stuiver and Grootes, 2000), 2-m data smoothed by 7-point moving average (data from Quaternary Isotope Laboratory, 2000). Bö, Bölling, YD, Younger Dryas, Tn, four Tioga stades in east-central Sierra Nevada (Phillips *et al.*, 1996; Benson *et al.*, 1996; T3 and T4 are revised ages, F. W. Phillips, written communication, 2001); Hn, last three Heinrich events in north Atlantic; RP, end of Recess Peak high glacial advance (Clark and Gillespie, 1997).

Tioga ELAs in the east-central Sierra Nevada occurred during the Tioga 2 stade around 25,000 ^{36}Cl yr B.P. (Phillips *et al.*, 1996). The Tioga 2 is not represented in the limited age data reported here, but some Tioga maximum moraines mapped here may have been deposited by older Tioga advances not differentiated by the mapping criteria used.

*Relationships to Pluvial Lake Records
and Climatic Implications*

Cores from Pyramid Lake, a terminal lake northeast of Reno, Nevada, reflect glacial events in the northern Sierra because the lake is fed by the Truckee River directly east of this study. During glacial maxima the same ice fields fed both sides of the range, including valley glaciers that produced most of the outwash delivered to the Truckee River (Lake Tahoe traps sediment from the south). Thus, the sedimentary record from Pyramid Lake should provide independent evidence of glaciation in the northwestern Sierra Nevada. Benson *et al.* (1998) (cf. Benson, 1999) developed an age model for the Pyramid Lake sedimentary record between 10,000 and 40,000 ^{14}C yr B.P. These records were converted to calibrated years assuming a 600-yr carbon reservoir effect (L.V. Benson, unpublished manuscript, 2001), allowing comparisons to this study.

Total organic carbon (TOC) concentrations in lake cores serve as a proxy for glacial advances which raise turbidity and inhibit carbon production (Benson *et al.* 1996). Pyramid Lake TOC concentrations reveal stadial–interstadial oscillations of increasing intensity from ca. 35,000 to 28,000 cal yr B.P. representing the onset of Tioga glaciation (Benson, 1999) (Fig. 7A). Unfortunately, TOC concentrations may not be sensitive to brief interstades because they often reach minimum values before glacial maxima and may be lagged due to remobilization of fluvial sediment. Thus, sustained low TOC concentrations in Pyramid Lake after 28,000 cal yr B.P. do not preclude Tioga interstades.

Based on dated surface materials, Pyramid Lake began a rapid rise around 25,000 cal yr B.P. to the Darwin Pass sill level where it remained until 19,000 cal yr B.P. (Benson, 1999) (Fig. 7B). A substantial drop in Pyramid Lake levels between 19,000 and 16,300 cal yr B.P. was followed by an abrupt rise to the Lahontan high stand from 16,300 to 15,800 cal yr B.P. Lake levels dropped rapidly between 14,500 and 14,100 cal yr B.P. (Benson, 1999; L.V. Benson, unpublished manuscript, 2001; cf. Adams and Wesnousky, 1998). Lake recession between 19,000 and 16,300 cal yr B.P. presumably followed the high Tioga moraine deposition in Bear Valley around 18,600 ± 3,950 yr B.P. and suggests glacial retreat between Tioga stades in the northern Sierra Nevada. This Lake Lahontan regression, along with the rapid transgression after 16,300 cal yr B.P., suggests that the high Old Man Mountain age of 16,800 ± 3800 ^{26}Al yr B.P. represents a late Tioga readvance. Glacial histories should not be reconstructed from lake levels alone, however. In Mono Basin, for example, Tenaya and late Tioga glacial advances corresponded with high Mono Lake levels while a Tioga advance of intermediate age did not (Bursik and Gillespie, 1993). More evidence is needed to determine if there was a substantial late Tioga retreat and readvance in the northern Sierra Nevada.

Exposure of a 390-m vertical transect on Old Man Mountain at 14,100 ± 1500 yr suggests rapid retreat of late Tioga ice from Fordyce Canyon. Large analytical uncertainties associated with CRSE ages prevent testing of this hypothesis with the present data. Yet rapid deglaciation is consistent not only with the Pyramid Lake record but also with records of a Recess Peak readvance (Clark and Gillespie, 1997) and broad climatic indicators of substantial warming somewhat earlier. High-resolution Greenland ice-core records (GRIP and GISP2) show a rapid decrease in ∂^{18}O between 14,700 and 14,500 cal yr B.P. (Fig. 7D) that corresponds with the Bölling warm interval in the north Atlantic (Stuiver *et al.*, 1995; Stuiver and Grootes, 2000). This same interval has been detected in Owens Lake ∂^{18}O records

(Benson *et al.*, 1997) and in marine records in the Santa Barbara Channel (Hendy and Kennett, 1999). Warming in the region may have been time-transgressive with warming in the south beginning earlier than in the northern Sierra. However, rapid lowering of Pyramid Lake between 14,500 and 14,100 cal yr B.P. (Benson, 1999) suggests that warming at these latitudes may have occurred somewhat earlier than our mean age indicates, yet within our range of precision. If rapid deglaciation of Fordyce Canyon is accurate and was widespread, it would imply both rapid warming and decreased precipitation. Unlike glaciers in the northern Rockies, Sierra Nevada glaciers require much more precipitation than that of the present day to be sustained (Hostetler and Clark, 1997).

CONCLUSION

The CRSE ages of striated bedrock on canyon walls can provide ages and rates of deglaciation that complement ages of maximum glacial extent from the CRSE ages of moraine boulders. Both types of CRSE dating complement lake-core records with high temporal resolutions but sediment-transport complexities. Mapping and surface-exposure ages identify and constrain late Pleistocene glaciations in the northwestern Sierra Nevada where little previous Quaternary mapping has been done. The ages are generally compatible with more complete records from east-central Sierra Nevada glacial moraines and pluvial lakes. In Bear Valley, ages of erratic boulders represent three distinct glacial stages: $>76,400 \pm 3800$ [10]Be yr for a till lacking moraine morphology, $>48,800 \pm 3200$ [10]Be yr on a broad-crested moraine ridge, and $18,600 \pm 1180$ yr from boulder erratics near a Tioga moraine in Bear Valley. More surface exposure ages are needed to determine the age of broad-crested moraines in the area and to test the hypothesis that they represent a substantial early or middle Wisconsinan glacial advance in the northwestern Sierra Nevada.

A major Tioga advance in Bear Valley around $18,600 \pm 3950$ yr B.P. appears to have been approximately contemporaneous with the Tioga 3 in the east-central Sierra Nevada (Phillips *et al.*, 1996; Benson *et al.*, 1996). No moraines were dated that correspond to the maximum Tioga glaciation (Tioga 2) in the east-central Sierra Nevada around 25,000 [36]Cl yr B.P. (Phillips *et al.*, 1996). More dating is needed to determine the age of the Tioga maximum in the northern Sierra Nevada, but it clearly preceded the Lake Lahontan high stand which occurred during a somewhat less extensive but substantial late Tioga stade. Ages of striated granodiorite surfaces on an Old Man Mountain transect document retreat of late Tioga ice from Fordyce Canyon around $14,100 \pm 3230$ yr. This may represent rapid ice retreat and may correspond with rapid recession of Lake Lahontan.

Interregional paleoclimatic correlations of these results are tenuous given the limited precision of CRSE ages and the possible time-transgressive behavior of regional climate changes. Yet the general correspondence of late glacial events in the northwestern Sierra Nevada to detailed records in the east-central Sierra Nevada and pluvial lakes to the east provides a first-order indication that some late-Pleistocene climate changes extended across the Sierra Nevada. This climatic history is relevant to paleoecological and stratigraphic studies not only in the Sierra Nevada but also downstream in the Central Valley and San Francisco Bay where outwash and cold water from these glacial advances effected fluvial and aquatic systems.

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