TIMING AND SIGNIFICANCE OF LATE-GLACIAL AND HOLOCENE CIRQUE GLACIATION IN THE SIERRA NEVADA, CALIFORNIA

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Mapping and radiocarbon dates of cirque moraines in the Sierra Nevada demonstrate that the last significant pre-Little Ice Age glacier advance in the range, the Recess Peak, resulted from snowline lowering roughly twice that of the Matthes (Little Ice Age) advance, and that the Recess Peak advance is late Pleistocene in age. We mapped Recess Peak and Matthes deposits in 64 cirques along a profile of the main Sierran crest that spans the north–south limits of 'Neoglacial' deposits in the range. Equilibrium-line altitudes for the reconstructed Recess Peak glaciers vary greatly but coherently with those of the Matthes advance. The variability of both sets of deposits reflects strong topographic influences on snow accumulation and ablation patterns in their deep cirques.

Tephrochronology and radiocarbon dates from lake-sediment cores provide limits on the timing of the two advances. Previous work documenting the absence of a young, regionally extensive tephra on Matthes moraines in the central Sierra demonstrates that they formed after ~700 ^{14}C years BP (~650 cal. years BP). The age of the Recess Peak advance has been less certain; we therefore collected and dated sediment cores from lakes dammed behind terminal moraines correlating to the Recess Peak advance in four widely separated drainages along the Sierran crest (north to south): South Fork American River, Lee Vining Creek, Middle Fork San Joaquin River, and Bishop Creek. Twenty-three high-precision AMS radiocarbon dates on gyttja, peat, and macrofossils from the cores are internally consistent and demonstrate that the Recess Peak advance, previously thought to be of late Holocene age (~2500 years BP), ended before 11,190±70 ^{14}C years BP (~13,100±85 cal. years BP). Recess Peak is therefore late Pleistocene in age and probably predates the North Atlantic Younger Dryas climatic reversal. The absence of any glacial deposits on the bedrock between the Recess Peak and Matthes deposits indicates that: (1) any advance related to the Younger Dryas event in central California was smaller than the Matthes advance; (2) the Matthes advance was the most extensive, and possibly the only, Neoglacial event in the range; and (3) climate in the Sierra between ~13,000 cal. years BP and 650 cal. years BP was apparently too warm and/or dry to support glaciers larger than those of the Little Ice Age. Other mapping indicates that the Recess Peak is the first significant glacier advance after retreat of Tioga (local late-Wisconsin maximum) glaciers. These results suggest a regionally variable climate in western North America during the Younger Dryas event, because glaciers appear to have expanded in the Canadian Rockies at that time.

The new Recess Peak age limits, combined with other dated lake cores, indicate that the Sierra was essentially deglaciated by 14,000–15,000 cal. years BP (~12,000–13,000 ^{14}C years BP), substantially earlier than previously estimated. This finding indicates that current production rates of some *in situ* cosmogenic nuclides, calibrated on an assumed deglaciation of the range at 11,000 cal. years BP (~10,000 14C years BP), may be systematically too high by as much as 20%. Copyright © 1996 INQUA/Elsevier Science Ltd

INTRODUCTION

The Sierra Nevada forms an unbroken, ~700-km-long mountain chain that is the first major orographic barrier to storms propelled by the westerlies off the Pacific Ocean into the southwestern U.S.A. Its size, altitude (to >4400 m), and orientation form a physiographic boundary between mild, marine-dominated climate to the west and drier, continental conditions in the Great Basin to the east. Because of this position as the first major landward barrier to the westerlies, the Sierra Nevada sensitively records changes in strength and position of the Pacific storm track. Extensive glaciation in the range during the past 2 million years provides a useful record of past climate.

The Sierra Nevada has been the focus of glacial and climatic studies for more than a century (e.g., LeConte, 1873; Muir, 1873; Russell, 1885; Gilbert, 1904; Matthes, 1930; Blackwelder, 1931; Birman, 1964; Birkeland, 1964; Wahrhaftig and Birman, 1965; Sharp, 1968, 1969,

1972; Clark, 1976; Burke and Birkeland, 1983; Burbank, 1991; Gillespie, 1991). Few of these studies, however, discuss the less-extensive glacial deposits that post-date the marine isotope stage 2 'Tioga' glaciers. The earliest workers described moraines being formed by the modern glaciers, and Russell (1885, p. 322) first noted a small, 'ancient' moraine a short distance below a glacier near Mono Lake. Matthes, 1940, p.339; Matthes, 1960, p.39, observed that two sets of small moraines typically occur immediately downstream from many glaciers in the Sierra, and considered both to be equivalents of the historical advances in the European Alps (Matthes, 1940, 1941). Yet, these apparently young deposits were largely ignored in geological reports until Birman (1964) published a detailed transect of glacial deposits across the central part of the range. In his study, Birman distinguished three post-Tioga glacier advances, all of which he felt were late-Holocene age: Hilgard, Recess Peak, and Matthes (Little Ice Age), in decreasing age.

In this paper, we introduce new data on the age and significance of the Recess Peak advance and its relationship to earlier and subsequent advances. In particular, we reconstruct 64 Recess Peak and adjacent Matthes glaciers

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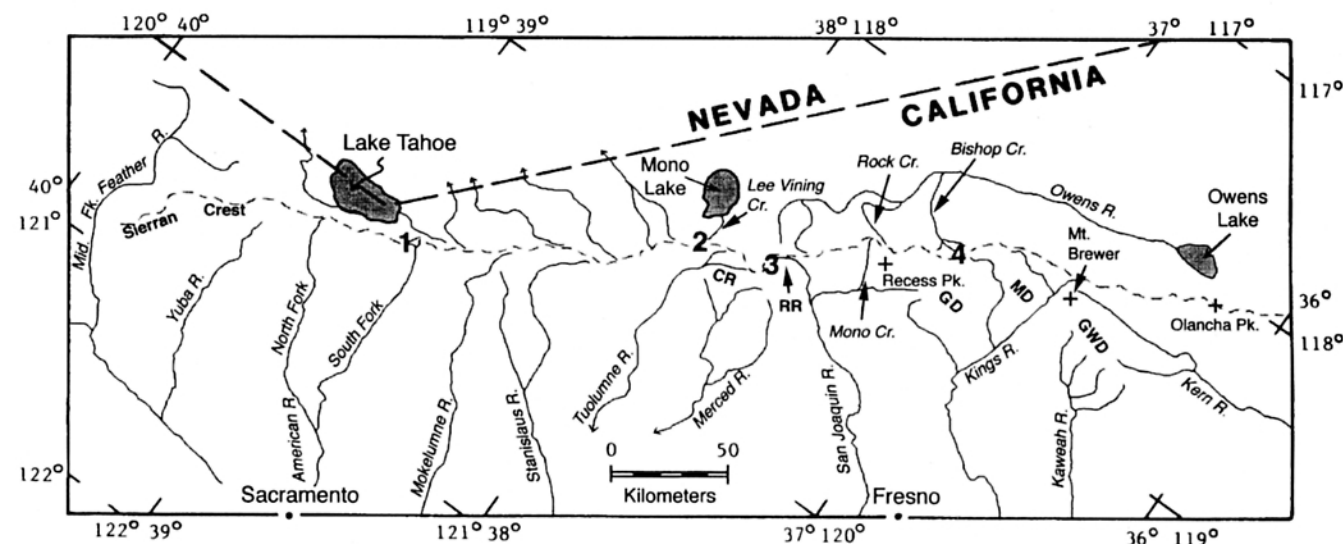
FIG. 1. Map of Sierra Nevada, California. Recess Peak and Matthes deposits occur along the range crest from southern Lake Tahoe to Olancha Peak. Thin black lines show major drainages and rivers discussed in text; dashed gray line shows crest of Sierra Nevada. Numbers refer to four coring sites discussed in text: 1 — tarn above Lake Aloha, South Fork American River; 2 — Green Treble Lake, Lee Vining Creek; 3 — upper Garnet Lakes, Middle Fork San Joaquin River; 4 — Baboon Lakes, Middle Fork Bishop Creek. CR, Cathedral Range; GD, Goddard Divide; GWD, Great Western Divide; MD, Monarch Divide; RR, Ritter Range. Modified from Wahrhaftig and Birman (1965).

and their equilibrium-line altitudes (ELAs) along a 400-km profile of the Sierran crest, from the southernmost deposit at Olancha Peak to the northernmost well-documented deposit, near Lake Tahoe (Fig. 1). We also present a series of high-resolution, minimum-limiting radiocarbon dates from lake sediments next to Recess Peak moraines in four widely separated locations. Our findings demonstrate that Recess Peak deposits represent a small but significant Late-Pleistocene climatic shift that led to a glacier readvance in the Sierra Nevada, and that this readvance predates the North Atlantic Younger Dryas event. Furthermore, these results require that glaciers were either quite small or absent in the Sierra during the Younger Dryas period, and indeed, have not reached beyond the Matthes ice limits during the entire ~12 ka interval that appears to separate the two advances. Other work (Clark and Clark, 1995) indicates that the 'Hilgard advance' (Birman, 1964) is probably related to Tioga recession.

Previous Studies

The Recess Peak and Matthes advances were originally defined on the basis of relative weathering (RW) parameters and topographic position (Birman, 1964). The type deposits are near the headwaters of Mono Creek (Fig. 1). As described by Birman, Recess Peak moraines typically look fresh, have ~70–90% unweathered boulders with substantial lichen cover, and slightly developed soils. Moraine slopes are stable with only minor incision and post-depositional erosion (Figs 2 and 3) (Birman, 1964). Scattered small trees and shrubs occur on the moraines, but vegetation is generally scarce (Fig. 3). As Birman (1964) noted, these features are very different from those of nearby Matthes deposits, which

are typically still unstable, unweathered, with no significant gullying or vegetation cover, and little or no lichen cover. Many Matthes moraines are still associated with thinning or retreating modern glaciers. The distinction between the two deposits is useful because the Recess Peak deposits invariably lie close to, and are locally partially overridden by, the younger Matthes moraines. Both are generally within 1–3 km of the cirque headwalls (Fig. 2). The outer set of 'historic' moraines described by Matthes (1940) almost certainly corresponds to the Recess Peak advance. Small moraines mentioned by Russell (1885) and Matthes (1960) also correlate to the Recess Peak advance.

Tephrochronology provides the best numerical age limits for the Matthes advance. Wood (1977) noted that his 'tephra 1', a Mono Craters tephra erupted 720±60 ^{14}C years BP (650–680 cal. years BP), overlies all glacial deposits in the Ritter Range (Fig. 1) except the Matthes moraines (Janda, 1966). Yount et al. (1982) observed that what is probably the same tephra (with a minimum radiocarbon date of 700±60 ^{14}C years BP (570–670 cal. years BP)) covers N3 (Recess Peak) deposits but does not blanket N1 (Matthes) moraines in the Recess Peak area. Thus, as Wood (1977) concluded, Matthes glaciers in the central Sierra reached maximum positions after ~700 ^{14}C years BP (~650 cal. years BP).

The age of the Recess Peak event has been disputed (Fig. 4). Birman (1964) originally proposed that RW criteria and correlation with the glacial records of the Rockies and Europe indicated that the Recess Peak advance occurred during the last millennium, most likely during the 16th or 17th century A.D. On the basis of lichenometry, Curry (1969, 1971) subsequently argued that Recess Peak moraines formed during two mid-Neoglacial advances occurring roughly 2700 and 2000 years ago. Using a lichen growth curve based on Curry's
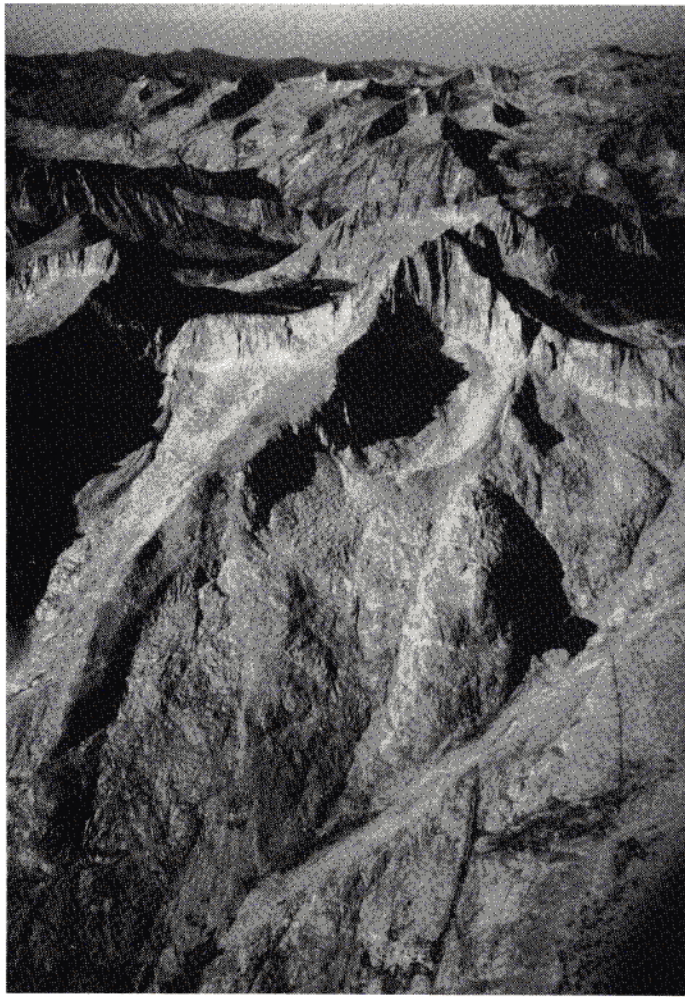
FIG. 2. Oblique aerial photo of northeast side of Mt. Brewer, southern Sierra Nevada (Fig. 1), showing typical relationship of the two major cirque deposits in the range: Matthes (Little Ice Age) moraine under cirque headwall, and Recess Peak moraine below it in lower foreground. A small, shaded, probably stagnant modern remnant of Matthes glacier occupies highest part of cirque. Note stable but uneroded appearance, small volume, and closely spaced multiple crests of Recess Peak moraine, in contrast with unstable, more voluminous, and simple structure of Matthes moraine. Extensive bare granitic bedrock and absence of any moraines between Recess Peak and Matthes moraines shown here is typical throughout the Sierra. Photo by M.M. Clark, September 23, 1977.

(1969) work, Scuderi (1987b) proposed a similar sequence. However, both Curry's (1969) and Scuderi's (1987b) curves were not well controlled beyond historic times (~100 years); in fact, Curry's long-term growth rates are calibrated on moraines that he assumed were ~1000, ~2000, and ~2600 years old, introducing a circularity in his (and therefore Scuderi's) age assignments, in that all the control moraines probably correlate to the type-Recess Peak deposits.

Yount et al. (1979, 1982) compiled multiple RW measurements on Recess Peak and Matthes deposits in the type region (Fig. 1). On the basis of these measurements, tephrochronology, and several mid- to late-Holocene radiocarbon dates from soil pits within a set of Recess Peak moraines, they concluded that at least some of the deposits mapped as Recess Peak by Birman (1964) were probably late Pleistocene or early Holocene in age. However, the temporal and spatial relationships between possible late Pleistocene and Neoglacial (i.e. late-Holocene) deposits remained unclear and Yount et al. (1982) retained 'Recess Peak' as an early-Neoglacial advance (Fig. 4). Deposits correlative to Recess Peak

have been mapped locally elsewhere in the range (e.g. Birkeland, 1964; Gillespie, 1982; Scuderi, 1984, 1987b; Mezger, 1986; Mezger and Burbank, 1986; Whiting, 1985, 1986), but the regional implications of the deposits were generally not considered. Burbank (1991) pointed out that reconstructed equilibrium-line altitudes (ELAs) for Recess Peak deposits mapped in the southern end of the range appeared discordant with those in the type area. He surmised that the deposits actually represented two separate populations, a late-Pleistocene advance in the south and a Neoglacial advance in the north. Subsequent work by Clark et al. (1994a, b) demonstrates that most of the deposits are from a single population, and that the discordant ELAs reflect strong local influences of debris cover and orography on the formation and maintenance of small cirque glaciers such as those of the Recess Peak advance. The results we present in this paper build on our initial work (Clark et al., 1994a) in defining the climatic regime that formed the Recess Peak glaciers, and provide new information on the timing and extent of Late-glacial and Holocene glaciation in the Sierra.

We note that a separate 'glaciation', the Hilgard,

FIG. 3. View to SSE (upvalley) of left-lateral Recess Peak moraine above Baboon Lakes (see Fig. 10). Former glacier occupied left side of photo, flowing from peaks visible in background. This moraine is typical of most Recess Peak moraines, with low volume, fresh but stable boulders and slopes, incipient soil formation, and small scattered clumps of trees (Whitebark Pines here).

defined by Birman (1964) as occurring between Tioga and Recess Peak advances, has been extensively referenced in glacial studies as a Late-glacial or Holocene event. Birman distinguished these deposits primarily on the basis of relative weathering estimates. Clark (1976) and Clark and Clark (1995), however, reevaluated
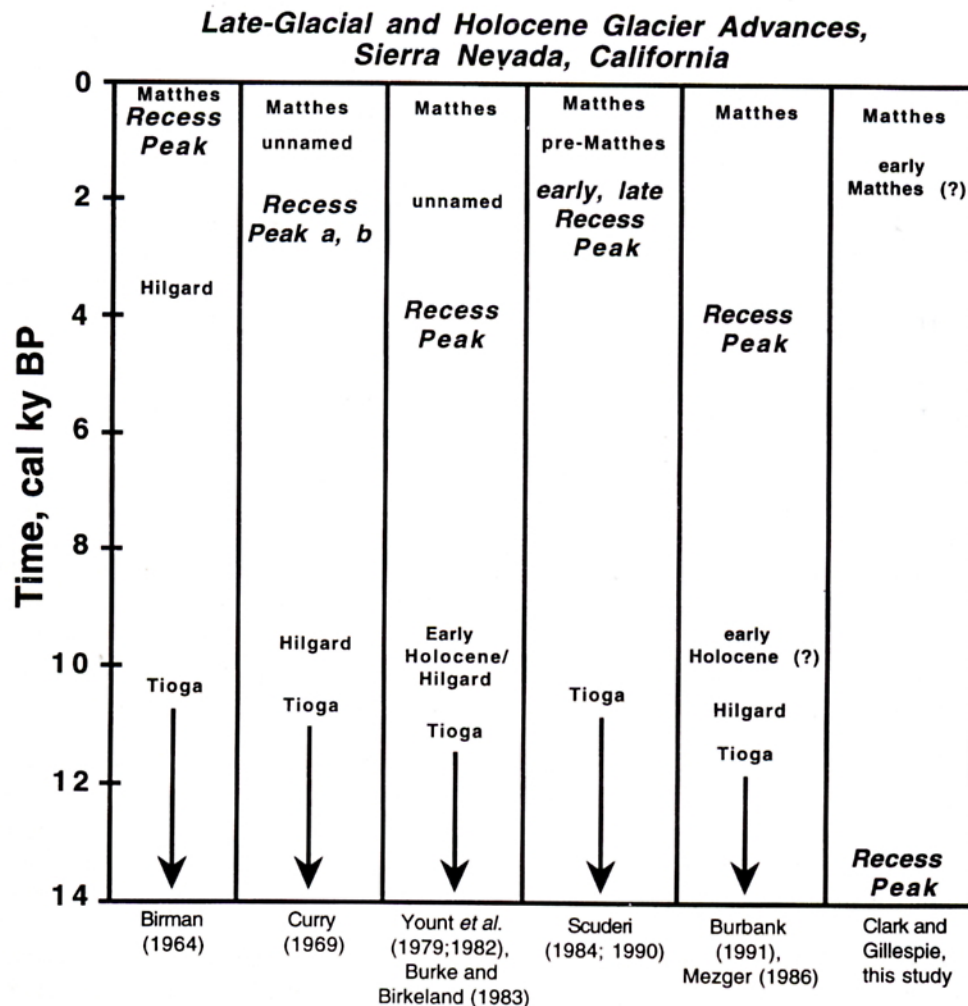

FIG. 4. Summary of published latest-Pleistocene and Holocene stratigraphic names and ages assigned to moraines in the Sierra Nevada. Recess Peak advance emphasized.

Hilgard deposits in the type area and elsewhere in the range and failed to find these distinctions. Their evidence indicates that type Hilgard moraines are probably recessional moraines of the Tioga stade, as previously suggested by Birkeland et al. (1976). We briefly discuss the implications of these findings later in this paper.

METHODS

Our study has two main components: estimates of ELA depression, and thereby relative climate, associated with the Recess Peak and Matthes glacier advances; and dating of sediments from alpine lakes associated with Recess Peak moraines in order to gain new limits on timing of cirque glaciation in the range. The first component involves mapping and reconstructing the extent of glacier ice during the two advances, and the second involves coring lakes that began sedimentation after the Recess Peak glaciers disappeared. All mapping and correlations we use in this study are our own, including those from areas previously mapped by others (Birman, 1964; Janda, 1966; Yount et al., 1982; Scuderi, 1984; Whiting, 1985; Mezger, 1986; Gillespie, 1982, 1991; M. Clark, pers. commun.). However, our mapping does not generally differ greatly from that of the earlier studies.

Mapping

Mapping for this study follows that described in Clark et al. (1994a). We mapped Recess Peak and Matthes deposits in 64 cirques near the Sierran crest from 36°16′N, 118°07′W to 38°52′N, 120°10′W. This interval spans the documented N–S extent of Recess Peak and Matthes deposits in the range, although some small protalus ramparts and cirque deposits mapped near the north end of Lake Tahoe (Birkeland, 1964) and near the divide between the Feather and Yuba rivers (D. Clark and M. Clark, unpublished data) may also correlate with the Recess Peak event. Reconnaissance mapping indicates that small moraines formed in the northeastern cirque of Patterson Mountain in the Warner Mountains, northeastern California, may represent yet more northerly expressions of the Matthes and Recess Peak advances, (D. Clark, unpublished data) and other northern equivalents may also exist (e.g. Waitt et al., 1982).

We combined field investigations and measurements with photo-interpretation of 1:16,000 scale color and 1:60,000 and 1:80,000 black-and-white aerial photographs to reconstruct the extent of the former glaciers. We distinguished moraines and deposits of Matthes and Recess Peak advances on the basis of stratigraphic position, morphologic character, lichen cover, and general weathering characteristics. Matthes deposits are fresh and commonly unstable, exhibit no significant erosion, soil development, or vegetation cover, and generally occur next to modern glaciers or snowfields. Matthes moraines commonly appear to be very bulky, generally reflecting the presence of a glacier-ice core beneath the morainal debris; in many, especially in the southern end of the

range, the ice cores continue to flow, forming active rock glaciers (or debris-covered glaciers) with oversteepened front slopes (Clark et al., 1994a). These youthful features allow Matthes deposits to be readily identified. In contrast to the Matthes moraines, Recess Peak moraines are low-volume, generally stable, and show incipient gullying by streams, substantial lichen cover on boulders, and significant soil development and tree growth (Fig. 3). They occur 0.1–3 km downstream from most Matthes deposits (Fig. 2), but commonly remain separated by many kilometers from the next older (Tioga recessional) moraines. As with the Matthes deposits, many of the Recess Peak glaciers in the southern Sierra appear to have had extensive covers of debris (Clark et al., 1994a). The insulation provided by the surficial debris on these glaciers enabled them to extend to lower elevations than equivalent bare-ice glaciers (Clark et al., 1994a). However, their RW characteristics and stratigraphic position relative to Matthes deposits remain consistent, and they clearly correlate to the bare-ice Recess Peak deposits to the north.

ELA Estimates

Equilibrium lines, which separate areas of net accumulation and ablation on glaciers, are often used as proxies for alpine climatic snowlines, and thus climate, both modern and ancient. In the Sierra Nevada, regional ELA gradients for modern and late Pleistocene glaciers rise approximately 12 to 16 m/km to the northeast across the range crest and about 2 m/km to the southeast parallel to the crest (Burbank, 1991; Gillespie, 1991).

The most common method of estimating ELAs of former glaciers, the accumulation-area ratio (AAR) method, relies on an empirical ratio derived from modern bare-ice glaciers that relates the former accumulation area to the total glacier area (e.g. Meierding, 1982; Leonard, 1984). The commonly used steady-state value for AARs of bare-ice glaciers is 0.65, although the ratio may get as small as 0.05 for extensively debris-covered glaciers (valley-floor rock glaciers; Clark et al., 1994a). For our study, we follow Clark et al. and use an AAR of 0.65 for glaciers that were not extensively buried by debris, and an AAR of 0.15 for those that were. We distinguished the two types of deposits on the basis of extent and continuity of till (formerly the surficial rubble) upslope of the terminal moraines (Clark et al., 1994a).

The accuracy of ELA estimates using AARs depends on the former glaciers having mass balances and area/altitude distributions similar to those of modern glaciers; however, errors are typically estimated as ±100 m (e.g. Meierding, 1982; Gillespie, 1991). Because of the small size and restricted altitudinal range of the glaciers in this study (typically less than 3 km in length, ~300–400 m altitudinal range), our accuracy using AARs is probably closer to ±50 m. Furthermore, the deposits we studied all lie within several kilometers of the Sierran crest, so that errors due to projection to a line that approximates the crest are within the error of the methods of estimation.

As discussed in Clark *et al.* (1994a), ELAs of small cirque glaciers such as those in this study strongly reflect local orographic effects on accumulation and ablation. ELAs of progressively smaller glaciers are increasingly influenced by these local effects. Burbank (1991) tried to minimize this effect by including only ELAs for glaciers that were at least 300 m wide. Clark *et al.* (1994a) demonstrated that even the glaciers that met this criterion remain strongly influenced by local topography, though typically less so than smaller glaciers. We therefore include even small glaciers in this study, although we distinguish glaciers that are smaller than Burbank's 300 m width limit to test this effect. Because local shading and accumulation patterns also depend on cirque aspect, we include only glaciers that had a northeasterly to north-westerly aspect, except where noted.

Sediment Coring

Because datable organic material is notoriously scarce in Sierran moraines, we focused on collecting and dating sediments from small lakes and bogs associated with Recess Peak moraines that were correlated as part of the ELA study above. AMS radiocarbon dating of small samples (<1 g) of basal organic sediments from the cores provide high-precision minimum limiting ages for the Recess Peak advance. Furthermore, such sediment cores supply a continuous sedimentary and palynologic record of climate change in the basin. This paper presents new radiocarbon dates from lakes formed inside Recess Peak ice limits. We also cored one bog that lies downstream from a Recess Peak moraine to obtain a maximum limiting age on the advance, but were unable to penetrate the apparent Recess Peak outwash.

We cored four widely separated sites, spanning much of the latitudinal extent of Recess Peak deposits in the Sierra (Fig. 1). North to south, the sites are: (1) a small unnamed tarn above Lake Aloha in the headwaters of the South Fork American River; (2) Green Treble Lake in Lee Vining Creek, immediately east of Yosemite National Park; (3) upper Garnet Lakes in the headwaters of Middle Fork San Joaquin River; and (4) Baboon Lakes on the Middle Fork, Bishop Creek. The cores comprise the highest suite of lake cores yet analyzed in the Sierra. We used a number of criteria were used in selecting the sites: (1) other than the exception mentioned above, sampled lakes all lie within or adjacent to the innermost Recess Peak moraines in that drainage; (2) the lakes are largely isolated from outwash of Matthes glaciers in the same drainages, except for the upper Garnet Lakes site; (3) upstream bedrock in the drainages is entirely granitic or other silicic rock and contain no significant sources of 'old' carbon that could potentially contaminate radiocarbon dates; (4) the small size of the cored lakes relative to the annual precipitation in the basins means that residence times of water in the lakes is on the order of years; and (5) maximum water depths are 4 m or less. We correlate the Recess Peak and Matthes moraines for all sites on the basis of our mapping for the ELA study.

We collected cores using a 2" (~5 cm)-diameter modified Livingston piston corer, operated from a portable floating plywood platform. The uppermost ~5 cm below the water–sediment interface typically was not recovered. Cores were extruded in the field, wrapped in plastic film and ABS casing, transported back to the lab, and stored in a cold room. In the lab, we split the cores from bottom-to-top to minimize effects of contamination by 'young' carbon, and we logged and photographed the sediments. Total organic carbon analyses on selected horizons, measured using the vapor-phase acidification method on a Carlo Erba CHN microanalyzer (Hedges and Stern, 1984), detected no significant inorganic carbon. Organic carbon percentages from the same analyses ranged from ~0.05% for glacial outwash gravel to 16.25% for post-glacial gyttja.

All dates in the cores are AMS-radiocarbon analyses performed at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Most dates are from small (<1 g) samples of gyttja or organic silt, which span less than 1 cm of depth in the cores. We dated basal gyttja samples from the longest cores at each site, as well as one or more other horizons from higher up in all but one core to establish the validity of the basal dates. Analysis of adjacent samples of gyttja and macrofossils or peat and macrofossils in several cores allowed us to assess directly the accuracy of dating the peat or gyttja directly. All radiocarbon dates presented here are corrected for ^{13}C fractionation (Stuiver and Polach, 1977) and show 1σ analytic-error ranges. Calibrated radiocarbon ages (cal. years BP), corrected for variations in atmospheric ^{14}C content (Bard *et al.*, 1990; Stuiver *et al.*, 1991) were calculated using the calibration program CALIB,(v. 3.0.3b; Stuiver and Reimer, 1993) with age-ranges reflecting combined 1σ analytic and calibration-curve standard errors. In this paper, we present only the radiocarbon dates and basic stratigraphies of the cores. Detailed sedimentological and palynological analyses of the cores are underway at Desert Research Institute, Reno, Nevada.

RESULTS

ELA Estimates

ELA estimates of Recess Peak and Matthes glaciers along the Sierran crest exhibit large but systematic variability (Fig. 5). The regional trend shows ELAs declining to the north, as would be anticipated from modern precipitation and temperature gradients (Dale, 1966). The trend is not monotonic, however; substantial local variability at several different scales is superimposed on the broad latitudinal trend. Major negative deviations coincide with the headwaters of major river gorges on the western slope (e.g. the San Joaquin and Kings river gorges) whereas intervening major positive deviations lie east of secondary drainage divides west of the range crest (e.g. Great Western, Monarch, and Goddard divides, Cathedral Range; Fig. 1). The negative deviations probably reflect funneling of Pacific storms
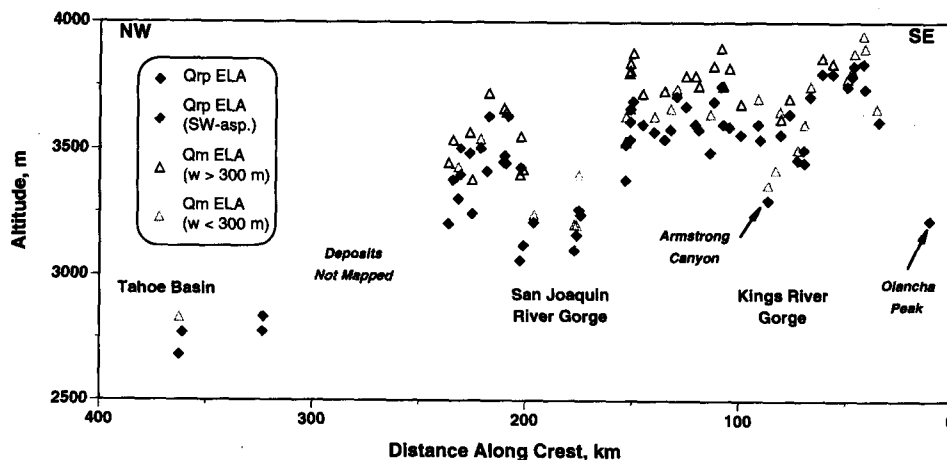
FIG. 5. NW–SE profile of reconstructed Recess Peak (Qrp) and Matthes (Qm) ELAs along crest of Sierra Nevada from Olancha Peak to Lake Tahoe. ELAs calculated and plotted following Clark *et al.* (1994a). All ELAs are for glaciers with northerly aspects, except for three Recess Peak ELAs with southwestern aspects (gray diamonds) north of San Joaquin River Gorge. Matthes ELAs are divided into those from glaciers having widths (w) greater than 300 m (black triangles) and those with w < 300 m (gray triangles). All reconstructed Recess Peak glaciers have w > 300 m, and are no more than 3 km from line of profile. Compare with Fig. 8 of Clark *et al.* (1994a).

along major NE-trending drainage troughs, allowing greater precipitation to reach further into the range and thereby lowering ELAs; conversely, the positive deviations reflect rainshadow effects of high divides in the upwind (southwest) direction (e.g. Porter, 1975; Burbank, 1991). As we predicted in our earlier paper (Clark *et al.*, 1994a), the largest apparent deviation coincides with the headwaters of the San Joaquin River Gorge, which forms the largest topographic gap in the southern half of the range (Figs 1 and 5).

Within these major deviations, ELAs vary on a more local scale. These local fluctuations mimic topographic variations in the adjacent crest, and apparently reflect local orographic effects, such as shading, avalanching, and wind-drifting, which increase accumulation and reduce ablation at those sites (Clark *et al.*, 1994a). The most pronounced examples of these influences occur in the unusually deep cirques at Armstrong Canyon, opposite the headwaters of the Kings River gorge, and off the northeastern slope of Olancha Peak at the southern end of the glaciated range (Fig. 5). The unusually low altitudes of glaciers at both sites, however, also probably reflect regional topographic influences on accumulation patterns as well: storm funneling in the Kings River gorge for the former, absence of significant topographic divides to the southwest of Olancha Peak for the latter. It is also possible that, because there is no Matthes deposit against which to compare it, the putative Recess Peak deposit at Olancha Peak may instead be related to Tioga recession. We consider this unlikely, however, because of the distinctive morphologies and spatial separation (several kilometers) between the Recess Peak and Tioga moraines.

Together, these orographic influences locally overwhelm the regional latitudinal trends of the Matthes and Recess Peak ELAs. This finding underscores the concept that the ELAs of small cirque glaciers generally reflect the orographic snowline, rather than the climatic snowline (e.g. Matthes, 1942; Meierding, 1982; Clark *et al.*, 1994a). The influence of these local factors was smaller when the glaciers were at their maximum late-Pleistocene

positions (Burbank, 1991; Gillespie, 1991). The difference may be (1) that large glaciers partially filled many of the canyons on the western slope, blocking the storm funneling; and (2) that accumulation zones reached well beyond the conserving confines of the cirques, thus allowing the climatic snowline to overwhelm the orographic snowline (Clark *et al.*, 1994a).

We emphasize that, despite their irregularity, Recess Peak ELAs generally vary coherently with Matthes ELAs, typically remaining 100–200 m lower than Matthes ELAs in the same cirques (Figs 5 and 6). Similarities in the gross trends are especially apparent (Fig. 5), although differences in the ELAs (ΔELAs) show substantial variability (Fig. 6). The differences, however, are less than the variability of the regional trends (up to 400–500 m). Differences in hypsometries of some cirques accounts for some of the variability in ELAs between the two advances, as in the case of the glaciers near Banner Peak (Fig. 6). The steep slopes there apparently permitted the Recess Peak glaciers to have ELAs nearly 300 m lower than those of the much smaller Matthes glaciers (Fig. 6; see also Fig. 10 in the section on coring). In contrast, there seems to be smaller separations between the ELAs of the two advances at the southern end of the range. Apparently, glaciers of both advances were restricted to the cirque headwalls because of greater dependence on local factors such as shading, accumulation, and debris cover in this more rugged part of the range. When local factors such as those discussed above are considered, however, the ΔELAs remain relatively consistent, especially considering that they can vary by more than 100 m in a single drainage. Moreover, if the two outliers at Banner Peak are ignored, the ΔELA-trend is relatively flat with distance along the crest. The similar ELA trends, in combination with the spatial distribution and geomorphic character of the moraines, help confirm our correlations of the two advances from the type area (Birman, 1964). They also demonstrate that the spatial fluctuations of the ELAs for both advances are valid, as also shown by Clark *et al.* (1994a) for a smaller sample.
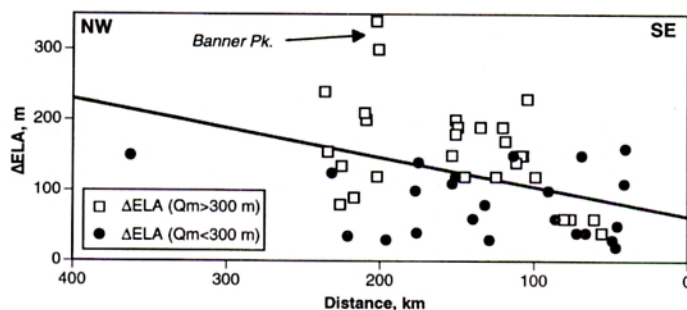
FIG. 6. Difference in ELAs (ΔELA) from reconstructed Matthes and Recess Peak glaciers shown in Fig. 5. ΔELAs separated according to maximum width (w) of Matthes (Qm) glaciers (Fig. 5). Line is regression to all data (r^2 = 0.15). Variability reflects strong local orographic effects on ELAs for these small glaciers. Slope of line primarily reflects large ΔELAs for former glaciers at Banner Peak, and smaller ΔELAs towards southern end of range where both Recess Peak and Matthes glaciers depended increasingly on local orographic shading and accumulation and thus were both restricted to heads of cirques.

Recess Peak glaciers in south-facing cirques were rare and generally much smaller than those in adjacent north-facing cirques. We estimated ELAs of three such glaciers in order to assess the affect of aspect on ELAs (Fig. 5). Although the sample is small, it suggests that southern aspects raised ELAs by ~50–200 m. Because the effects of shading in south-facing cirques are far less than in north-facing cirques, glaciers in the former may more closely represent the climatic snowline. We found no evidence for Matthes glaciers with southern aspects.

Sediment Cores

We collected several cores from each of the four sites in order to confirm the general post-Recess Peak stratigraphy at each site. The cores vary in length from 15 cm to 212 cm (measured in the lab) and are dominated by dark brown, generally massive gyttja; all cores except those from upper Garnet Lakes are from the deepest parts of the lakes. Only cores from the southernmost site (Baboon Lakes) bottomed in reduced, inorganic outwash; all others bottomed in gyttja or tephra some distance above the basal (Recess Peak) outwash. Because all sites except upper Garnet Lakes are isolated from Matthes outwash, we did not observe nor expect Little Ice Age inorganic sediment spikes. Compression of sediments in the cores during coring was typically 10–15%. Descriptions of AMS-radiocarbon dates from all cores related to the Recess Peak advance are listed in Table 1.

South Fork American River. The northernmost coring site is a small unnamed tarn formed inside lateral and terminal moraines of a Recess Peak glacier above Lake Aloha (Fig. 7). The moraines in this drainage were initially mapped by M. Clark (1973, *unpublished data*) and Whiting (1985, 1986). Two cores from the tarn were the shortest of any cores in this study (Fig. 8A). The cores bottomed in a thick, fine-grained, gray tephra initially encountered at roughly 25 cm depth. A thinner, coarser tephra unit occurs at about 19–21 cm depth. Liquification of the lower tephra, which is at least 25 cm thick, prevented coring through it. Radiocarbon dates on charcoal and organic sediments directly overlying each of these layers demonstrate that they are related to the eruption of Mt. Mazama (ancestral Crater Lake,

Oregon)(Table 1). Dates of 7130±230 and 7140±70 ^{14}C years BP (~7900 cal. years BP) on charcoal and organic silt, respectively, from a single horizon immediately above the lower tephra indicate that it may be related to the Tsoyawata eruption, a precursor event to the culminating Mazama eruption (Bacon, 1983). The date of 6740±60 ^{14}C years BP (~7500 cal. years BP) on gyttja overlying the upper tephra indicates that it may represent the culminating eruption (Sarna-Wojcicki *et al.*, 1991). Further petrographic and geochemical analyses of the tephras should confirm this assessment. Adam (1967) and Edlund (1993) found Mazama tephra in cores of a nearby bog and lake, respectively, dammed behind a Tioga recessional moraines, supporting our inferences on the tephras.

We find no sedimentological evidence for post-Recess Peak glacier advances in the cores. The post-Mazama deposits are very thin, however, and suggest that deposition may have slowed or ceased for a period during the latter half of the Holocene, perhaps as a result of late-Holocene desiccation of the shallow (~2 m) pond (e.g. Stine, 1994). Unconformities are not apparent, so
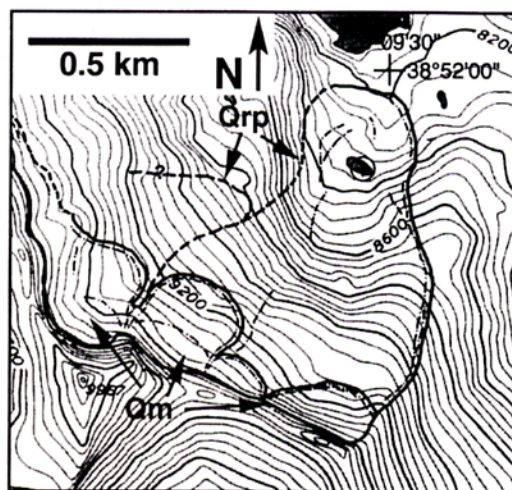

FIG. 7. Map of Matthes (Qm) and Recess Peak (Qrp) moraines and ice limits near Lake Tahoe basin. Coring site in small tarn near Recess Peak terminus shown by circle-and-crosshair. Moraine crests shown as dash-dot lines; former glacier limits shown by bold lines, dashed where approximate, queried where uncertain. Lake Aloha shown along upper edge of figure. Topography from U.S. Geological Survey Pyramid Peak 7.5' quadrangle, 40 ft. (12.2 m) contours.

TABLE 1. Radiocarbon ages from Recess Peak cores, Sierra Nevada

Sample name	Location	Material	Core #	Depth, cm	^{14}C years BP (1σ error)[§]	cal. years BP (1σ)[*]
GT-C-1	Green Treble Lk., Hall Wilderness	basal organic silt	GTL-4	115–116	7750±60	8550–8415
GT-C-2	Green Treble Lk., Hall Wilderness	basal gyttja above highest basal organic silt	GTL-4	101–102	5870±60	6750–6645
GT-C-3	Green Treble Lk., Hall Wilderness	gyttja, base of lower tephra	GTL-4	91–92	4630±50	5330–5300
GT-C-4	Green Treble Lk., Hall Wilderness	gyttja, base of upper tephra	GTL-4	28–29	2080±50	1970–1960
DW-C-1a	Desolation Wilderness tarn	charcoal, top of lower tephra	DW-5	16–17	7130±230	8130–7670
DW-C-1b	Desolation Wilderness tarn	organic silt next to DW-C-1a, top of lower tephra	DW-5	16–17	7140±70	7960–7895, 7855–7840
DW-C-2	Desolation Wilderness tarn	gyttja, top of upper tephra	DW-5	7	6740±60	7585–7530, 7490–7480
BL-C-1	upper Baboon Lks., Bishop Cr.	organic silt, near top of gyttja/outwash transition	BL-2	115–116	11,190±70	13,185–13,015
BL-C-2	upper Baboon Lks., Bishop Cr.	charcoal in gyttja	BL-2	106.5	9450±50	10,780–10,765, 10,545–10,365
BL-C-3	upper Baboon Lks., Bishop Cr.	chip from large branch	BL-2	95.5	8490±60	9495–9435
BL-C-4	upper Baboon Lks., Bishop Cr.	gray-green gyttja, next to BL-C-3	BL-2	95–96	9360±70	10,390–10,290, 10,250–10,220
BL-C-5	upper Baboon Lks., Bishop Cr.	wood chips below upper clayey silt	BL-2	40	7050±70	7915–7755
BL-C-6	Baboon Lks. bog	peaty silt above basal sandy unit	BL-3	151–152	9040±110	10,045–9925
BL-C-7	Baboon Lks. bog	wood chip	BL-3	139.5	6950±50	7790–7665
BL-C-8	Baboon Lks. bog	peat, next to BL-C-7	BL-3	140	7020±60	7900–7855, 7845–7720
BL-C-9	Baboon Lks. bog	top of peat below middle sandy unit	BL-3	114–115	5710±90	6640–6410
BL-C-10	Baboon Lks. bog	basal peat above middle sandy unit	BL-3	83	5580±90	6450–6290
BL-C-11	upper Baboon Lks., Bishop Cr.	twig immediately above thin tephra	BL-2	83	7900±60	8945–8905, 8725–8555
BL-C-12	upper Baboon Lks., Bishop Cr.	gyttja next to wood in BL-C-11	BL-2	83	7890±60	8945–8910, 8725–8550
BL-C-13c	central Baboon Lks., Bishop Cr.	charcoal, base of dark green gyttja	BL-1	150–151	10,170±170	12,145–11,425
BL-C-13g	central Baboon Lks., Bishop Cr.	gyttja, next to BL-C-13c	BL-1	150–151	10,120±80	11,955–11,430
BL-C-14	central Baboon Lks., Bishop Cr.	gyttja, top of gyttja/outwash transition	BL-1	160–161	10,880±60	12,880–12,725
UGL-C-1	upper Garnet Lks., Ritter Range	basal gyttja	UGL-2	158	3420±50	3620–3700

[§] All samples analyzed at CAMS, Lawrence Livermore National Laboratory.
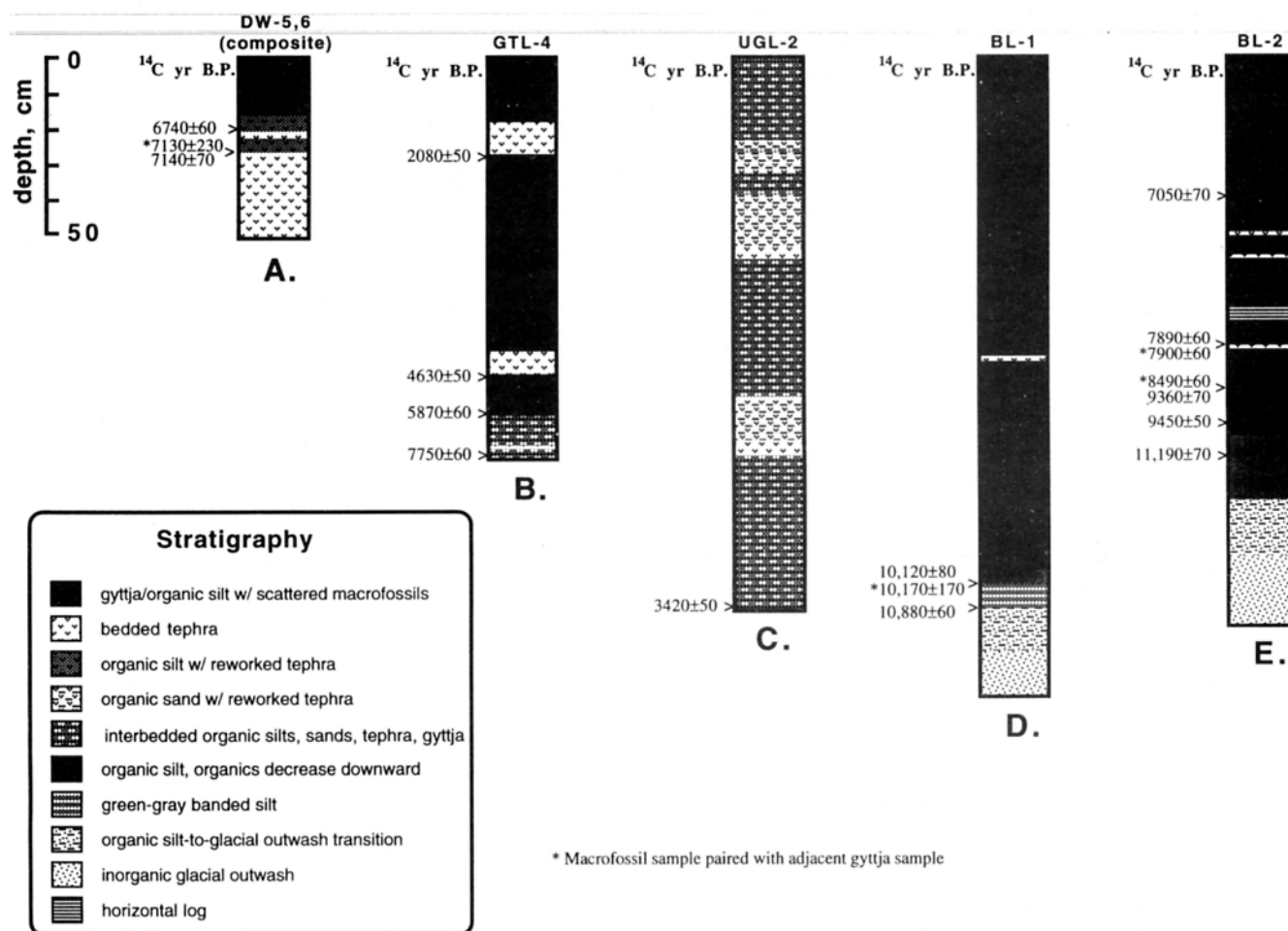[*] Stuiver and Reimer (1993).

FIG. 8. Simplified stratigraphies of cores for (A) tarn above Lake Aloha, (B) Green Treble Lake, (C) upper Garnet Lakes, (D, E) Baboon Lakes, in the Sierra Nevada. Core A is a composite of two cores. Locations and ^{14}C ages (with 1σ errors) of AMS radiocarbon samples are shown to the left of each column. Paired ages at single location indicate adjacent macrofossils and gyttja samples. These dates and others from cores not shown are listed in Table 1. Cores from Baboon Lakes (D, E) terminate in outwash.

substantial erosion is unlikely. Whiting (1985, 1986) divided moraines adjacent to the pond into two ages, late-Pleistocene and Neoglacial, primarily on the basis of relative weathering (RW) estimates. Whiting's (1985, Table 7) data, however, are equivocal; he had four sampling sites on his 'late-Pleistocene' moraines, and only two directly adjacent sites on a single short 'Neoglacial' moraine. The primary RW distinction between the moraines is that boulders on the former moraines are apparently more rounded than in the latter; differences in other RW parameters (e.g. weathering rinds, fresh-to-weathered ratios, moraine morphologies, etc.) are either inconsistent or statistically insignificant. However, striae and polish on the boulders from the 'late Pleistocene' moraines clearly indicate that they were transported and rounded subglacially, whereas those on the putative 'Neoglacial' moraine are not polished or striated. The small size, uniform lithology, and angularity of the latter indicate that they formed as a supraglacial rockfall deposit. The lack of rounding in this deposit is therefore probably original and not a result of a 'young' age, especially considering the similarity of the other RW measurements. We thus concur with M. Clark's (1973, *unpublished data*) original mapping that the moraines below the small Matthes moraines all belong to a single

Recess Peak advance. Bedrock and moraine geometries (Fig. 7) dictate that any Neoglacial advance as large as that proposed by Whiting (which would have terminated at or in the pond) would have poured substantial outwash into the pond. The absence of any significant post-Mazama clastic sediments in the pond, or any moraines between the Matthes and Recess Peak deposits, demonstrates that the Matthes advance was the most extensive of the late Holocene in this area.

Lee Vining Creek. Green Treble Lake is dammed by the innermost Recess Peak terminal moraine of a glacier that flowed off the northeastern ridge of White Mountain, in the headwaters of Lee Vining Creek (Fig. 9). One of the sample sites used by Nishiizumi *et al.* (1989) to calibrate *in situ* production rates of cosmogenic ^{10}Be and ^{26}Al lies directly downstream of similar Recess Peak deposits in the adjoining Conness Lakes drainage 3 km north of Green Treble Lake.

A core from the deepest part of the lake bottomed in laminated green organic silt at roughly 175 cm depth, with 126 cm recovered (Fig. 8B). Hole collapse and friction prevented us from coring deeper. Sediments in the upper part of the core consist primarily of massive green-brown gyttja with scattered sand grains and thin sand layers. Two thick fine-grained, well bedded, light-
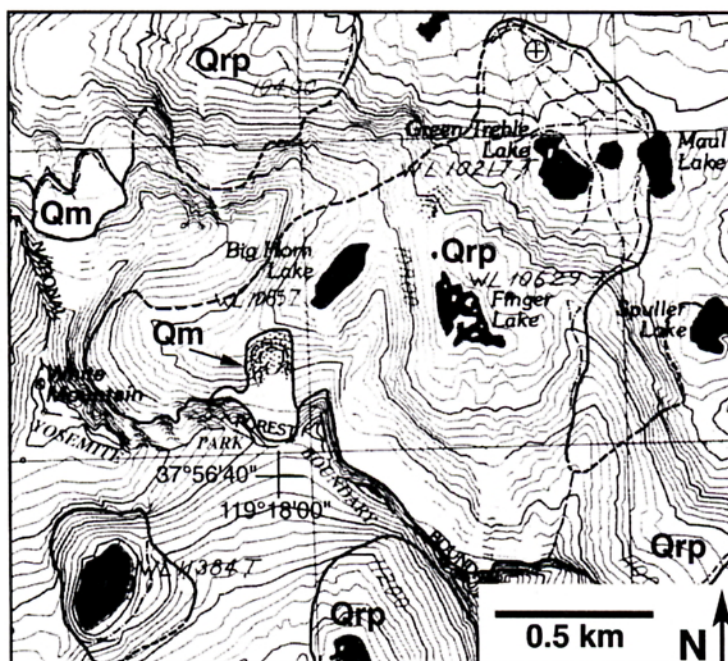
FIG. 9. Map of Matthes (Qm) and Recess Peak (Qrp) moraines and ice limits on eastern slope of White Mountain in the headwaters of Lee Vining Creek. Coring sites, including Green Treble Lake, shown by circle-and-crosshair in upper right. Shallow core from meadow north of Green Treble Lake not analyzed. Symbols as in Fig. 7. Sierran crest forms Yosemite National Park–Inyo National Forest boundary. Topography from U.S. Geological Survey Tioga Pass 7.5′ quadrangle, 40 ft. (12.2-m) contours.

gray tephras occur at 28–38 cm depth and 94–101 cm depth. The tephras are very pure and have sharp upper and lower contacts. A radiocarbon date of 2080 ± 50 ^{14}C years BP (1960–1970 cal. years BP) on gyttja underlying the younger tephra indicates that it correlates with a tephra occurring at similar depths and overlying gyttja dated at 1910 ± 80 ^{14}C years BP (1730–1930 cal. years BP) in a pond at Tioga Pass, 5 km southeast of Green Treble Lake (Anderson, 1990). The older tephra may correlate with two thin tephras in the Tioga Pass pond core, which overlie gyttja dated to 4060 ± 160 ^{14}C years BP (4310–4830 cal. years BP) (Anderson, 1990). However, gyttja underlying the lower Green Treble Lake tephra yields a date of 4630 ± 50 ^{14}C years BP (5300–5330 cal. years BP), suggesting that the tephra is from a separate, earlier eruption. Anderson indicates that the tephras in his cores are related to eruptions in the Mono and Inyo craters to the southeast. The bottom 14 cm of the Green Treble Lake core consists of interbedded brown–green organic sands and silts. Because we did not reach outwash in this core, the age of the basal sediments (7750 ± 60 ^{14}C years BP; 8410–8550 cal. years BP) do not closely date the retreat of the Recess Peak glacier.

Middle Fork San Joaquin River. A set of small, shallow lakes on a bench above Garnet Lake, informally referred to here as upper Garnet Lakes, is formed behind Recess Peak moraines from a glacier that flowed down the northeastern slope of Banner Peak (Fig. 10). The uppermost and largest of these lakes lies within the innermost distinct Recess Peak moraine. The receding remnant of a small Matthes glacier occupies the head of the cirque. Other well developed Recess Peak and Matthes moraines occupy the upper end of Thousand Island Lake and the other slopes of Banner Peak (Fig. 10).

We were unable to retrieve cores longer than ~30 cm from behind these moraines, however.

We collected cores in water depths of ~1 m from each of the two sub-basins that comprise the largest upper Garnet lake. Both reached sediment depths of about 160 cm; friction and collapse of the holes between successive pushes prevented deeper cores. Stratigraphy in both cores is complex, consisting of interbedded sands, organic silts, and tephras (Fig. 8C). Reworked tephras are ubiquitous in the cores. Oxidized horizons in the upper part of the cores suggest that the shallow lakes have been periodically exposed subaerially in the late-Holocene. Neither core encountered inorganic outwash, and coarseness of the sediments suggest relatively high sedimentation rates in these lakes. The basal age of core UGL-2, 3420 ± 50 ^{14}C years BP (3620–3700 cal. years BP), also supports relatively high sedimentation rates. The young basal age and high sedimentation rate indicate that the basal age does not closely date the retreat of the Recess Peak glaciers in this area.

Although this site is fed by meltwater from a small Matthes glacier (unlike the other coring sites), there are no obvious changes in sedimentation in the cores to indicate the onset of Neoglaciation. However, the high clastic sedimentation rate in the lakes, largely resulting from the abundant Holocene tephra-fall in the basin, probably obscures any changes in sedimentation that may have accompanied the formation of the Matthes glacier. Furthermore, considering the small size of the glacier, a large change in sedimentation during its formation is unlikely. It is possible, however, that Neoglaciation in the drainage began before ~3700 cal. years BP (i.e. pre-Little Ice Age), although previous palynologic, dendrochrono-logic, and isotopic work elsewhere in the region (e.g.
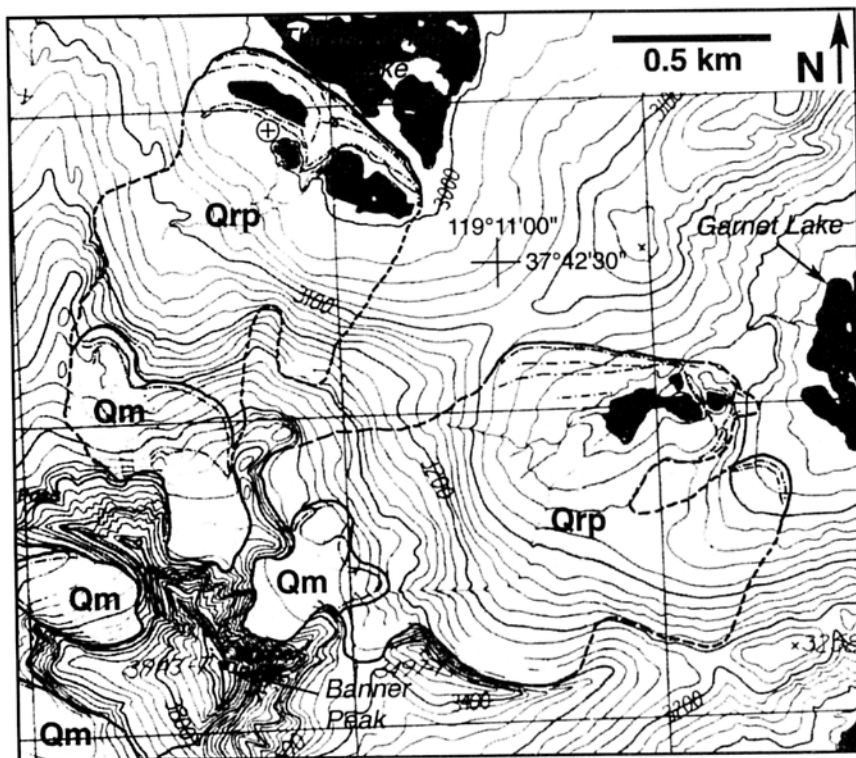
FIG. 10. Map of Matthes (Qm) and Recess Peak (Qrp) moraines and ice limits next to Banner Peak, headwaters of the Middle Fork San Joaquin River. Coring sites shown by circle-and-crosshair. Shallow core from meadow behind Thousand Island Lake Qrp moraine not analyzed. Symbols as in Fig. 7. Topography from U.S. Geological Survey Mt. Ritter 7.5′ quadrangle, 20 m contours.

Adam, 1967; LaMarche, 1973; Scuderi, 1984; Scuderi, 1987a; Anderson, 1990; Feng and Epstein, 1994) suggest this is unlikely. In any case, any such advance would have been even smaller than the Matthes.

Bishop Creek. Baboon Lakes comprise a suite of small- to medium-sized lakes formed behind a bedrock sill that cuts across a tributary to Middle Fork Bishop Creek (Fig. 11). A Recess Peak glacier originating on the northwest slope of Mt. Thompson terminated against this buttress and flowed into the lowest and largest of the lakes. Three Matthes debris-covered glaciers (ice-cored rock glaciers) that are still active occupy the headwaters of the drainage. There are no moraines between those of the Recess Peak and Matthes advances. We cored two small lakes that are separated from the main drainage by till-mantled bedrock inside the innermost Recess Peak recessional moraine (Fig. 11). The lakes are thus isolated from outwash of Matthes and modern glaciers in the headwaters of the creek. A small, inactive valley-wall rock glacier terminates near the upstream edge of the upper lake that was cored. The rock glacier appears to have formed during or shortly after retreat of the Recess Peak glacier, as indicated by its inactivity and morphologic and weathering similarities to the adjacent Recess Peak moraines.

The cores from both lakes, taken from water depths of 2–3 m, are about 180 cm long and dominated by massive dark green–brown gyttja, with intermittent slightly lighter and siltier intervals and scattered macrofossils (Fig. 8D, E). The cores also contain several very thin, indistinct tephras that probably correlate to Holocene Mono or Inyo Crater eruptions (Anderson, 1990). The bottom 10–15 cm

of both cores consists of reduced, inorganic silty sand that we interpret as Recess Peak outwash. The transition from inorganic outwash to gyttja occurs over about 30–40 cm in the cores, although there is a relatively distinct light-grayish–green organic silt unit within the transition in core BL-1 (Fig. 8D). Dates from the upper part of the outwash–gyttja transition in these cores are $10,880\pm60$ ^{14}C years BP ($\sim$12,800 cal. years BP) for BL-1 and $11,190\pm70$ ^{14}C years BP ($\sim$13,100 cal. years BP) for BL-2. The older of these dates provides the closest minimum age estimate yet determined for the end of the Recess Peak glaciation in the Sierra. Absence of oxidized layers or unconformities indicates that the lakes, although shallow, have not desiccated during the Holocene.

We cored a small bog immediately downstream from the right-lateral moraine in an attempt to gather a maximum date on the Recess Peak advance, but we were unable to penetrate a coarse sand layer, possibly from the Recess Peak glacier. The radiocarbon age of the basal peat in this core (BL-3; Table 1), 9040 ± 110 ^{14}C years BP ($\sim$10,000 cal. years BP), does not appear to be a close limiting minimum age for the Recess Peak advance, because it is younger than the basal ages of the cores from inside the moraines. It may instead represent a period of moraine instability after the glacier had left, as suggested by a gap in the right-lateral moraine above talus that feeds into the bog.

The validity of the oldest dates in the Baboon Lakes cores is supported by many other dates from overlying sediments in each core (Fig. 8D, E). Dates of adjacent macrofossils and gyttja (Table 1) at 83 cm depth in core BL-2 (samples BL-C-11, -12) and 150 cm in core BL-1
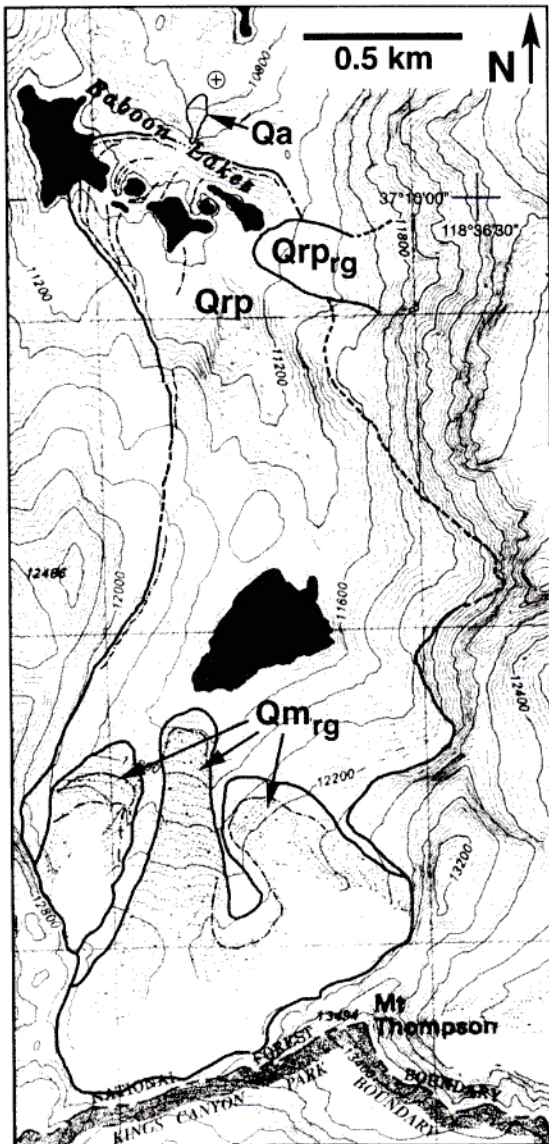
FIG. 11. Map of Matthes (Qm) and Recess Peak (Qrp) moraines and ice limits on northwest slope of Mt. Thompson in headwaters of Middle Fork Bishop Creek. Coring sites shown by circle-and-crosshair. Symbols as in Fig. 7. Qm$_{rg}$ and Qrp$_{rg}$ denote rock glacier deposits of respective advances; former are still advancing, latter probably formed at end of Recess Peak advance and is now extinct. Qa indicates avalanche debris originating from Recess Peak right-lateral moraine. Sierran crest forms Kings Canyon National Park–Inyo National Forest boundary. Topography from U.S. Geological Survey Mt. Thompson, California 7.5′ quadrangle, 40 ft. (12.2 m) contours.

samples involve small macrofossils (e.g. small twigs) that would not have been affected by this problem.

Summarizing, our coring data from four widely separated areas along the crest of the Sierra support a late-Pleistocene age for the Recess Peak advance. Cores from the southernmost site, Baboon Lakes, are the only ones that terminated in outwash, and therefore give the closest minimum dates for the event. Cores from the other sites terminated in stratigraphically higher horizons and therefore do not provide close limiting ages for the advance. However, none supports a Neoglacial age for the advance, and our regional mapping and ELA estimates strongly support our correlations of Recess Peak deposits between coring sites.

DISCUSSION

Our re-evaluation of the Sierran glacial sequence indicates that the Recess Peak advance was a late-Pleistocene event and was the most extensive glacier advance after the end of the Tioga glaciation. Geomorphic mapping and sediment cores from alpine lakes and meadows in the central Sierra indicate that no significant glaciation (e.g. the 'Hilgard glaciation' of Birman (1964) occurred between the Tioga and Recess Peak advances (Clark, 1976; Clark and Clark, 1995). Spatial separation and differences of thousands of years in oldest minimum ages for Tioga and Recess Peak deglaciations (Clark et al., 1995; D. Clark, unpublished data) suggest that the Recess Peak was a separate advance and not merely a Tioga recessional event. Stratigraphic and morphologic affinities with adjacent Tioga moraines and Birman's (1964) type Hilgard moraines in Mono and Rock creeks show that the 'Hilgard' deposits are actually late-stage Tioga medial and recessional moraines. Moreover, recent reevaluations (Clark and Clark, 1995; M. Clark, pers. commun.) of the boulder-weathering ratios that Birman relied on to distinguish the type Hilgard moraines from adjacent Tioga recessional moraines failed to find such a distinction. The moraines instead appear to record the last major stillstand or readvance of the retreating Tioga glaciers before they stagnated and likely disappeared (Clark, 1976; Clark and Clark, 1995). Our mapping further supports Clark's (1976) contention that there is no substantive evidence for a separate stade between the Tioga and Recess Peak advances.

The absence of any moraines in the cirques between Matthes and Recess Peak deposits also demonstrates that no glacier advance greater than the Matthes has occurred since the Recess Peak advance. Therefore, in the Sierra Nevada, the Matthes glaciers of the last millennium are generally the most extensive of the Holocene. Detailed relative weathering measurements on moraines and rock glaciers mapped as Matthes-age suggest that some may have formed before the last millennium (Yount et al., 1979, 1982). However, these 'older' moraines are not physically separate from, nor significantly or consistently larger than, those of the last thousand years, being preserved only locally where subsequent, more extensive

(samples BL-C-13c, -13g), and adjacent peat and a macrofossil at 140 cm in BL-3 (samples BL-C-7, -8), are indistinguishable within one standard deviation. Similar results were yielded by adjacent samples in other cores (e.g. charcoal and organic silt in samples DW-C-1a, -1b, Table 1; Fig. 8A), indicating stable carbon in all cores. A sample of a large branch at 95 cm depth in core BL-2 (sample BL-C-3) was roughly 1000 years younger than adjacent gyttja (sample BL-C-4); considering the similar ages of the adjacent macrofossils and gyttja mentioned above, and the slow sedimentation rates in the lakes, it seems likely that this large branch sank into older flocculent gyttja when it was deposited. All other paired
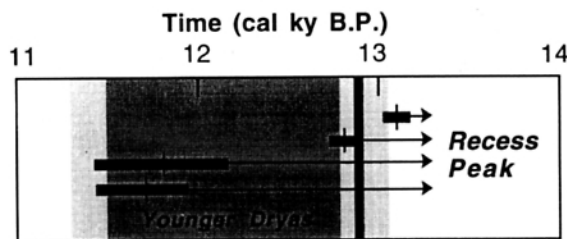
FIG. 12. Time-line showing relationship between the four oldest limiting radiocarbon dates (calibrated according to Stuiver and Reimer, 1993) of Recess Peak advance and sidereal age of Younger Dryas cooling recorded in Greenland ice cores (medium gray band; Johnsen *et al.*, 1992; Alley *et al.*, 1993). Black boxes indicate 1σ age range of AMS dates; arrows indicate that all ages are minima for end of Recess Peak advance. Light gray bands show outer limits of combined error of Johnsen *et al.* (1992) and Alley *et al.* (1993). Dark gray line indicates calibrated radiocarbon age estimate of onset of Younger Dryas cooling in Scandinavia (Mangerud *et al.*, 1974). Minimum age for end of Recess Peak advance and maximum age of onset of Greenland Younger Dryas event overlap only at outer limits of both error fields.

Matthes advances have not buried them. A recent Holocene climate record based on stable isotopes in tree rings from the White Mountains, immediately east of the southern Sierra, indicates that the last 500 years were the coolest of the past 8000 years (Feng and Epstein, 1994), supporting our contention that the Matthes advance was the largest of the Holocene. Tree-line fluctuations in the southern Sierra (Scuderi, 1987a) and the White Mountains (LaMarche, 1973) are also consistent with this concept.

Rock glaciers in Sierran cirques — actually debris-covered glaciers — may preserve an integrated late-Holocene history. Many of Yount *et al.*'s (1982) 'older Holocene' RW sites occur on rock glaciers that are still actively advancing, and thus may be more properly thought of as 'modern', though potentially long-lived, glaciers. Indeed, many debris-covered Matthes glaciers are still advancing despite significant shrinkage or disappearance of their accumulation zones (Clark *et al.*, 1994a, b).

Early direct observations of Sierran glaciers indicate that in the late 19th and early 20th centuries, glaciers were at or very close to the maximum position of their Matthes moraines (LeConte, 1873; Muir, 1873; Russell, 1885; Gilbert, 1904; Matthes, 1930, 1936, 1939). Whiting (1985) cited moraine morphology and lichenometry as evidence that the small, now-extinct Matthes glaciers in Desolation Wilderness (Fig. 7) were probably active until this century. Together, these observations indicate that the snowline depression of the past century in the Sierra Nevada was at or near the maximum for the entire interglaciation.

Regional ELA depressions during Recess Peak and Matthes advances in the study area show that both events involved significant changes of climate relative to modern conditions. Modern and Matthes-age ELAs estimated by Gillespie (1991) indicate that Matthes ELAs were typically ~60 m lower than their modern equivalents. Our work shows that Recess Peak ELAs average ~150 m lower than Matthes ELAs in the same cirques, or roughly 210 m below the ELAs of the modern glaciers. Although there is considerable scatter about these averages, and the

ELAs of the modern, rapidly retreating glaciers do not represent steady-state conditions, the estimates indicate that the Recess Peak advance resulted from a lowering of regional snowline more than twice that which occurred during the height of the Little Ice Age. ELAs in the same drainages during the Tioga glaciation were roughly 700–800 m below the modern ELAs (Gillespie, 1991; see also Burbank, 1991). Burbank estimated that the ELAs of the small, protected modern Sierran glaciers were roughly 100–200 m below the regional, or climatic snowline, and therefore total snowline lowering during full glaciation was closer to 900–1000 m relative to modern conditions. Thus, the Recess Peak advance resulted from snowline-lowering to roughly 20% of full-glacial conditions. Snowline depression during the Little Ice Age was generally less than 10%. The large local influence of enhanced shading and accumulation in these small glaciers preclude quantitative estimates of the magnitude of precipitation and temperature changes from modern values that are represented by these shifts in snowline (e.g. Leonard, 1989).

The relatively consistent difference between Matthes and Recess Peak ELAs along the Sierran crest suggests that the regional climates that caused each advance were similar in character, and did not have markedly different precipitation and temperature patterns. The consistent spatial distribution of, and relationship between, the two deposits along the crest of the range also indicate that our local age control on the moraines is representative of deposits throughout the range. Recess Peak deposits we have mapped along the range crest therefore represent a single event rather than several distinct events.

Whereas the age of the maximum Matthes advance has been restricted to the last 700 years (Wood, 1977; Yount *et al.*, 1982), the timing of the Recess Peak advance has remained controversial. Although it has generally been regarded as a late-Neoglacial event (e.g. Birman, 1964; Curry, 1969; Scuderi, 1990), our basal dates from cores of alpine lakes behind Recess Peak recessional moraines demonstrate that the advance was of late Pleistocene age. The oldest basal dates, 11,190±70 ^{14}C years BP (13,115–13,180 cal. years BP) and 10,880±60 ^{14}C years BP (12,730–12,880 cal. years BP) on gyttja from cores BL-2 and BL-1, respectively, are minima and indicate that the Recess Peak advance had *ended* before the *onset* of the European Younger Dryas climatic reversal (~11,000 ^{14}C years BP, Mangerud *et al.*, 1974; 12,700–12,800±100–250 sidereal years, Johnsen *et al.*, 1992; Alley *et al.*, 1993)(Fig. 12).

Although we recognize that there are uncertainties in the dating of the onset of the Younger Dryas, which may allow a small statistical overlap with our minimum date for the end of the Recess Peak advance, several lines of evidence indicate that the events are of different ages: (1) our oldest dates come from inside the innermost recessional Recess Peak moraines, and thus postdate the last significant stillstand (rather than the maximum extent) of the glacier before it disappeared; (2) the sediments that provide our oldest dates are well above the initial organic (e.g. postglacial) deposits within the cores,

and therefore may significantly post-date the end of the Recess Peak advance (e.g. Davis and Davis, 1980); at the least, they represent some period of time *after* the demise of the glacier; (3) core BL-2, from which the oldest date came, is not from the deepest part of the lake; (4) the many AMS-radiocarbon dates on gyttja, peat, and macrofossils we have collected from similar high-altitude lakes in the Sierra are all internally consistent (e.g. Fig. 8, Table 1; D. Clark, *unpublished data*); and (5) with the one exception in core BL-2 explained above, dates of adjacent macrofossils-peat and macrofossils-gyttja are indistinguishable within the 1σ analytic error (typically < 1%). Both (4) and (5) indicate that the ^{14}C ages in our cores are accurate; (6) the silicic basins upstream of the coring sites, well into the accumulation zones of the Wisconsin glaciers, had been thoroughly stripped of any organic material by glacial plucking for nearly 100,000 year prior to the Recess Peak advance; thus there would have been no significant sources of 'old' carbon to contaminate the lakes and sediments we cored, and all dates from the cores are minima for the Recess Peak advance.

Together, these observations indicate that small Sierran lakes are stable and uncontaminated carbon sinks, and support the validity of the oldest dates. Furthermore, although some of the large Scandinavian glaciers and pollen series on which the Younger Dryas event was originally defined (e.g. Mangerud et al., 1974) may have responded more slowly to a change in climate than Sierran cirque glaciers, changes in accumulation and isotopes recorded in the Greenland ice cores are nearly instantaneous and can be resolved to annual to decadal levels during the late-glacial period (e.g. Johnsen et al., 1992; Alley et al., 1993). Therefore, to have the Recess Peak advance and the Younger Dryas cooling actually responding to the same climatic force would require (1) that the oldest date from our cores to be too old, or that the dates for the onset of the Younger Dryas cooling to be too young, both for unspecified reasons, and (2) the Recess Peak to be a nearly instantaneous event that began and ended well before the height of the Younger Dryas cooling in the North Atlantic. We feel such a scenario is untenable.

Our new dates, in conjunction with the consistent absence of moraines between those of the Recess Peak and Matthes advances, therefore, imply that any glaciers that may have existed in the Sierra Nevada during the Younger Dryas or any subsequent period were smaller than those of the Matthes advance of the last millennium. This finding requires a reevaluation of the classic sequence of late-glacial and Holocene glaciation for the range (Fig. 4). Moreover, it contradicts a recent correlation of moraines in the eastern Sierra to the Younger Dryas on the basis of ^{36}Cl surface-exposure ages of morainal boulders (Phillips et al., 1993). Dates that bracket a distinct light green silt near the base of core BL-1 (Fig. 8D) indicate that this interval accumulated between ~10,900 and 10,100 ^{14}C years BP (12,800–11,700 cal. years BP), closely coincident with the Younger Dryas chronozone. The distinguishing color, grain-size, and organic content of the silt layer relative to the sediments above and below suggest it represents a distinct environmental, and thus possibly climatic, event during its deposition. The sharp upper boundary of the unit suggests that the event ended rapidly. Palynologic work (in progress) on the cores may help refine the climatic interpretation of this interval.

IMPLICATIONS

Our new age limits on Sierran deglaciation have several general implications. Of particular interest to glacial geology and geomorphology, our research indicates that published production rates of two *in situ*-produced cosmogenic isotopes, ^{10}Be and ^{26}Al, are probably too low by 20% or more (Clark et al., 1995). Current production rates for the isotopes are calibrated on samples of glacier-polished Sierran bedrock that were assumed to have been deglaciated 11,000 cal. years BP (~10,000 ^{14}C years BP) (Nishiizumi et al., 1989). All of Nishiizumi et al.'s calibration sites lie outside of Recess Peak ice limits in those drainages. Our results suggest that substantial unrecognized systematic errors exist in these production rates. In particular, our data indicate that Nishiizumi et al.'s calibration sites were deglaciated, then Recess Peak glaciers advanced and disappeared, all before ~13,100 cal. years BP (~11,200 ^{14}C years BP). Combined with basal ages from cores of other moraine-dammed Sierran lakes outside Recess Peak ice limits, (e.g. Batchelder, 1980; Anderson, 1990; E. Edlund, 1994 *written commun.*; Clark et al., 1995) it is likely that the Sierra Nevada was essentially deglaciated by ~14,000–15,000 cal. years BP (~12,0000–13,000 ^{14}C years BP).

Together, these observations indicate that the current production rates for ^{10}Be and ^{26}Al may be too high, and thus exposure dates are too low, by as much as 20% for the late-glacial period. Such a large systematic error calls into question correlations of landforms to brief climatic events that use the current production rates. For example, measurements of ^{10}Be and ^{26}Al in morainal boulders have recently been used to claim a Younger Dryas glacier advance in the Wind River Range (e.g. Evenson et al., 1994; Gosse et al., 1995). Considering the new data on Sierran deglaciation, the moraines in the Wind River Range may actually predate the Younger Dryas event. Such a conclusion agrees with Zielinski and Davis (1987), who obtained radiocarbon dates of 11,700±710 (12,970–14,630 cal. years BP) and 11,400±630 ^{14}C years BP (12,700–14,040 cal. years BP) on lacustrine sediments associated with the Temple Lake moraines, also in the Wind River Range, which correlate to those dated by Gosse et al. (Hall, 1989). The older dated sediments overlie outwash from the outer Temple Lake moraine, whereas the younger dated sediments overly outwash inside the inner moraine. Thus, the dates appear to be minima for the maximum position and final retreat of the Temple Lake glacier, respectively. In particular, the older date, although referred to by Fall et al. (1995) as a 'maximum' age for the outer moraine, is stratigraphically

a close minimum limiting age for the formation of the moraine (P.T. Davies, written commun., 1995).

Although both radiocarbon dates are conventional and measured on bulk sediments, Zielinski and Davis (1987), and more recently Fall et al. (1995), state that there are few sources for contamination (particularly from 'old' carbon), and that the residence time of water in the lakes (i.e. the carbon reservoir effect) is probably no more than a few hundred years. Any reservoir effects, particularly for the lakes formed inside the moraines, would be even less when the glacier first retreated, because they were newly formed and water through-put would presumably be high during deglaciation. The absence of sources of 'old' carbon, coupled with the large size of the dated sediment samples (integrating 30 and 9 cm of core length, respectively; Zielinski and Davis, 1987), indicate that the dates are probably accurate minima for the advance and retreat of the glacier. Therefore, the Temple Lake advance as dated by Zielinski and Davis is consistent with a pre-Younger Dryas Recess Peak advance in the Sierra.

Dated sediments in Crowfoot Lake in the Canadian Rockies indicate that the type Crowfoot moraines likely did form during Younger Dryas time (Reasoner et al., 1994; Osborn and Gerloff, 1997). An increase in cold-water foraminifera in the waters off the coast of British Columbia also occurred at this time (Mathewes et al., 1993), lending credence to the Crowfoot-Younger Dryas correlation. Taken at face value, these results suggest a regionally variable climate in North America during Younger Dryas time, with glaciers advancing in Canada, but not in California. Initial results from the lake cores behind small moraines near Mt Rainer in the Cascade Mountains indicate that glaciers there may have advanced before and after the Younger Dryas, but not during (J. Heinz, pers. commun., 1996). Unfortunately, adequate glacial or other climatic data for this period are absent in the intervening region, leaving the nature and cause of this possible difference in climatic response unresolved. However, the regional difference does suggest that the response to the Younger Dryas climatic event was not everywhere the same, or that the effect was not global. Such results also suggest that records of local glacier advances outside the North Atlantic that apparently coincide with the Younger Dryas (e.g. Denton and Hendy, 1994; Rodbell et al., 1994) do not necessarily signify global climatic forcing for the event.

CONCLUSIONS

The late-Pleistocene and Holocene glacial record in the Sierra Nevada is well preserved. Yet the timing and climatic significance of the deposits has been unclear. Our mapping confirms that two cirque-glacier advances originally defined by Birman (1964) in the central Sierra (the Matthes and the Recess Peak) occur throughout the range from the southern limit of glaciation as least as far north as Lake Tahoe. Other work in progress indicates that they are also the only two regional advances since the

stagnation of the large late-Wisconsin Tioga glaciers. The spatial, stratigraphic, and morphologic relationships between the two advances remain consistent wherever both occur in the range, supporting our correlations. Reconstructions of the glaciers along the range crest indicate that during the Matthes and Recess Peak advances, ELAs dropped by ~10% and ~20%, respectively, of the maximum late-Pleistocene ELA change throughout the range. The relatively consistent difference between the snowline lowering of the two advances suggests that the climatic events that caused each were similar in character and differed mainly in magnitude.

Dated sediment cores from small tarns formed behind Recess Peak moraines demonstrate that it was a late Pleistocene event that ended before ~13,100 cal. years BP, not a late-Holocene event as previously thought. These minimum dates further demonstrate that the advance also predated the North Atlantic Younger Dryas cooling event. Late-Holocene Matthes glaciers reached their maximum extents within the last 600–700 cal. years BP, during the Little Ice Age. Earlier Neoglacial advances, if any, apparently did not extend further than did the Matthes glaciers. Thus, there is no evidence for glaciation greater than the Little Ice Age during the ~12,000 years that separate the Recess Peak and Matthes advances.

The apparent absence of a glacier advance in the Sierra Nevada during the Younger Dryas time implies that the Sierra was too warm or too dry to support even small glaciers equivalent to the Matthes in size. However, evidence for a contemporary advance in the Canadian Rockies suggests regionally variable responses of local climate in North America during this event. The Sierran record also calls into question the global extent of the Younger Dryas cooling, at least as a glacial event.

The new age limit on the Recess Peak advance is a minimum for deglaciation of the Sierra Nevada. Dates from sediment cores in other lakes in the range support the Recess Peak age limits, and suggest that the range may have been deglaciated to Recess Peak ice limits by 14,000–15,000 cal. years BP (Clark et al., 1995). These new constraints on the timing of deglaciation of the Sierra may require revision of current production rates for cosmogenic ^{10}Be and ^{26}Al during the late-glacial and Holocene periods. These rates were established from glacier-polished bedrock in the range that lies outside Recess Peak ice limits and which was assumed to have been deglaciated 11,000 cal. years ago. Such a change in production rates casts doubt on the accuracy of ^{10}Be and ^{26}Al exposure ages obtained using current production rates, including those used to correlate glacial events with short-lived climatic events. Thus moraines in the Wind River Range previously correlated with the Younger Dryas event on the basis of ^{10}Be exposure ages may actually predate the event; increasing these ages by ~20%, as suggested by our findings, brings these dates into agreement with limiting radiocarbon ages from nearby lake cores, and implies that the moraines may correlate with the pre-Younger Dryas Recess Peak advance.

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REFERENCES

Adam, D.P. (1967). Late Pleistocene and recent palynology in the central Sierra Nevada, California. In: Cushing, E.J. and Wright, H.E., Jr (eds), *Quarternary Paleoecology*, pp. 275–301. Yale University Press, New Haven.

Alley, R.B., Meese, D.A., Shuman, C.A., Gow, A.J., Taylor, K.C., Grootes, P.M., White, J.W.C., Ram, Ram, Waddington, E.D., Mayewski, P.A. and Zielinski, G.A. (1993). Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature*, **362**, 527–529.

Anderson, S.R. (1990). Holocene forest development and paleoclimates within the central Sierra Nevada, California. *Journal of Ecology*, **78**, 470–489.

Bacon, C.R. (1983). Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, U.S.A.. *Journal of Volcanology and Geothermal Research*, **18**, 57–118.

Bard, E., Hamelin, B., Fairbanks, R.G. and Zindler, A. (1990). Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature*, **345**, 405–410.

Batchelder, G.L. (1980). A Late Wisconsin and early Holocene lacustrine stratigraphy and pollen record from the west slope of the Sierra Nevada, California. *American Quaternary Association, Abstracts and Program*, **6**, 13–.

Birkeland, P.W. (1964). Pleistocene glaciation of the northern Sierra Nevada, north of Lake Tahoe, California. *Journal of Geology*, **72**, 810–825.

Birkeland, P.W., Burke, R.M. and Yount, J.C. (1976). Preliminary comments on Late Cenozoic glaciations in the Sierra Nevada. In: Mahaney, W.C. (ed.), *Quaternary Stratigraphy of North America*, pp. 283–295. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pennsylvania.

Birman, J.H. (1964). Glacial geology across the crest of the Sierra Nevada, California. *Geological Society of America Special Paper*, **75**, 80–.

Blackwelder, E. (1931). Pleistocene glaciation in the Sierra Nevada and Basin Ranges. *Geological Society of America Bulletin*, **42**, 865–922.

Burbank, D.W. (1991). Late Quaternary snowline reconstructions for the southern and central Sierra Nevada, California and a reassessment of the Recess Peak Glaciation. *Quaternary Research*, **36**, 294–306.

Burke, R.M. and Birkeland, P.W. (1983). Holocene glaciation in the mountain ranges of the western United States. In: Wright, H.E., Jr (ed.), *Late-Quaternary Environments of the United States, Volume 2, The Holocene*, pp. 3–11. University of Minnesota Press, Minneapolis.

Clark, D.H. and Clark, M.M. (1995). New evidence of late-Wisconsin deglaciation in the Sierra Nevada, California, refutes the Hilgard Glaciation. *Geological Society of America, Abstracts with Programs*, **27**, 10.

Clark, D.H., Clark, M.M. and Gillespie, A.R. (1994a). Debris-covered glaciers in the Sierra Nevada, California, and their implications for snowline reconstructions. *Quaternary Research*, **41**, 139–153.

Clark, D.H., Gillespie, A.R. and Clark, M.M. (1994b). Reply to comment by M. Jakob on Debris-covered glaciers in the Sierra Nevada, California, and their implications for snowline reconstruction. *Quaternary Research*, **42**, 359–362.

Clark, M. (1976). Evidence for rapid destruction of latest Pleistocene glaciers of the Sierra Nevada, California. *Geological Society of America, Abstracts with Programs*, **8**, 361–362.

Clark, D. H., Bierman, P. R. and Larsen, P. (1995). Improving *in-situ* cosmogenic chronometers. *Quaternary Research*, **44**, 367–377.

Curry, R.R. (1969). Holocene climatic and glacial history of the central Sierra Nevada, California. In: Schumm, S.A. and Bradley, W.C. (eds), *United States Contributions to Quaternary Research, Geological Society of America Special Paper 123*, pp. 1–47.

Curry, R.R. (1971). Glacial and Pleistocene history of the Mammoth Lakes Sierra–A geologic guidebook. *University of Montana, Department of Geology Geological Series Publication No. 11*, 49 pp.

Dale, R.F. (1966). Climates of the States: California, *Climatography in the United States 60-4*, Weather Bureau, U.S. Department of Commerce, 139 pp.

Davis, P.T. and Davis, R.B. (1980). Interpretation of minimum-limiting radiocarbon dates for deglaciation of Mount Katahdin area. *Maine Geology*, **8**, 396–400.

Denton, G.H. and Hendy, C.H. (1994). Younger Dryas age advance of Franz Josef Glacier in the Southern Alps of New Zealand. *Science*, **264**, 1434–1437.

Edlund, E. (1993). Bunker Lake paleoecological analysis. *Final Report to BioSystems Analysis, Inc., May 1*.

Evenson, E.B., Klein, J., Lawn, B., Middleton, R. and Gosse, J. (1994). Glacial chronology of the Wind River Mountains from measurements of cosmogenic radionuclides in boulders. *Geological Society of America Abstracts with Programs*, **26**, A-511.

Fall, P.A., Davis, P.T. and Zielinski, G.A. (1995). Late Quaternary vegetation and climate of the Wind River Range, Wyoming. *Quaternary Research*, **43**, 393–404.

Feng, X. and Epstein, S. (1994). Climatic implications of an 8000-year hydrogen isotope time series from Bristlecone pine trees. *Science*, **265**, 1079–1081.

Gilbert, G.K. (1904). Variations of Sierra glaciers. *Sierra Club Bulletin*, **5**, 20–25.

Gillespie, A.R. (1982). Quaternary glaciation and tectonism in the southeastern Sierra Nevada, Inyo County, California. Ph.D. dissertation, Caltech, 695 pp.

Gillespie, A.R. (1991). Testing a new climatic interpretation for the Tahoe glaciation. In: Hall, C.A., Doyle-Jones, V. and Widawski, B. (eds), *Natural History of Eastern California and High-altitude Research, White Mountain Research Symposium*, pp. 383–398. Los Angeles, University of California.

Gosse, J.C., Klein, J., Evenson, E.B., Lawn, B.R. and Middleton, R. (1995). Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence. *Science*, **268**, 1329–1333.

Hall, R.D. (1989). Contribution. In: Wind River Mountains, *Friends of the Pleistocene Field Trip Guide Book*, Indiana University-Purdue University, 50 pp.

Hedges, J.I. and Stern, J.H. (1984). Carbon and nitrogen determinations of carbonate-containing solids. *Limnological Oceanography*, **29**, 657–663.

Janda, R. (1966). Pleistocene history and hydrology of the upper San Joaquin River, California. Ph.D. dissertation, Berkeley, University of California.

Johnsen, S.J., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C.U., Iversen, P., Jouzel, J., Stauffer, B. and Steffensen, J.P. (1992). Irregular glacial interstadials recorded in a new Greenland ice core. *Nature*, **359**, 311–313.

LaMarche, V.C., Jr (1973). Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California. *Quaternary Research*, **3**, 632–660.

LeConte, J. (1873). On some of the ancient glaciers of the Sierra. *American Journal of Science and Arts*, **105**, 325–342.

Leonard, E.M. (1984). Late Pleistocene equilibrium-line altitudes and modern snow accumulation patterns, San Juan Mountains, Colorado, U.S.A.. *Arctic and Alpine Research*, **16**, 65–76.

Leonard, E.M. (1989). Climatic change in the Colorado Rocky Mountains: estimates based on modern climate at Late Pleistocene equilibrium lines. *Arctic and Alpine Research*, **21**, 245–255.

Mangerud, J., Andersen, S.T., Berglund, B.E. and Donner, J.J. (1974). Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas*, **3**, 109–126.

Mathewes, R.W., Heusser, L.E. and Patterson, R.T. (1993). Evidence for a Younger Dryas-like cooling event on the British Columbia coast. *Geology*, **21**, 101–104.

Matthes, F.E. (1930). Geologic history of the Yosemite Valley. *United States Geological Survey Professional Paper 160*, 137 pp.

Matthes, F.E. (1936). Report of committee on glaciers, 1935–36. *Transactions, American Geophysical Union*, 283–294.

Matthes, F.E. (1939). Report of committee on glaciers, April 1939. *Transactions, American Geophysical Union*, 518–523.

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Matthes, F.E. (1940). Committee on glaciers, 1939-40. *Transactions, American Geophysical Union*, 396–406.

Matthes, F.E. (1941). Rebirth of the glaciers of the Sierra Nevada during late post-Pleistocene time. *Geological Society of America Bulletin*, **52**, 2030–.

Matthes, F.E. (1942). Glaciers. *In*: Meinzer, O.E. (ed.), *Physics of the Earth. Part 9. Hydrology*, pp. 149–219. McGraw-Hill, New York.

Matthes, F.E. (1960). Reconnaissance of the geomorphology and glacial geology of the San Joaquin Basin, Sierra Nevada California. *U.S. Geological Survey Professional Paper 329*, 62.

Meierding, T.C. (1982). Late Pleistocene glacial equilibrium-line altitudes in the Colorado Front Range: a comparison of methods. *Quaternary Research*, **18**, 289–310.

Mezger, L.B. (1986). Pleistocene glaciation of Cottonwood Basin, southeastern Sierra Nevada, California. M.S. thesis, University of Southern California, 149 pp.

Mezger, L. and Burbank, D. (1986). The glacial history of the Cottonwood Lakes area, southeastern Sierra Nevada. *Geological Society of America Abstracts with Programs*, **18**, 157.

Muir, J. (1873). On actual glaciers in California. *American Journal of Science and Arts*, **105**, 69–71.

Nishiizumi, K., Winterer, E.L., Kohl, C.P., Klein, J., Middleton, R., Lal, D. and Arnold, J.R. (1989). Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. *Journal of Geophysical Research*, **94**, 17907–17915.

Osborn, G. and Gerloff, L. (1997). Latest Pleistocene and early Holocene fluctuations of glaciers in the Canadian and northern American Rockies. *Quaternary International*, **38/39**, 7–19.

Phillips, F.M., Zreda, M.G., Elmore, D. and Sharma, P. (1993). Evidence for a connection between dynamic behavior of the Laurentide ice sheet and mountain glaciation in western North America. *EOS, Transactions American Geophysical Union*, **74**, 360.

Porter, S.C. (1975). Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. *Quaternary Research*, **5**, 27–47.

Reasoner, M.A., Osborn, G. and Rutter, N.W. (1994). Age of the Crowfoot advance in the Canadian Rocky Mountains: a glacial event coeval with the Younger Dryas oscillation. *Geology*, **22**, 439–442.

Rodbell, D.T., Neboline, J., Seltzer, G.O., Abbott, M.B., Hansen, B.C.S. and Birkeland, P.W. (1994). The glacial geologic and palynologic record of the last deglaciation in the Andes of northern Peru and southern Ecuador. *Geological Society of America Abstracts with Programs*, **26**, A-446.

Russell, I.C. (1885). Existing glaciers of the United States. *Fifth Annual Report of the United States Geological Survey*, pp. 307–343.

Sarna-Wojcicki, A.M., Lajoie, K.R., Meyer, C.E., Adam, D.P. and Rieck, H.J. (1991). Tephrochronologic correlation of upper Neogene sediments along the Pacific margin, conterminous United States. *In*: Morrison, R.B. (ed.), *The Geology of North America, Quaternary Nonglacial Geology: Conterminous U.S.*, Geological Society of America, pp. 117–140.

Scuderi, L.A. (1984). A dendroclimatic and geomorphic investigation of Late-Holocene glaciation, southern Sierra Nevada, California. Ph.D. dissertation, University of California, Berkeley, 201 pp.

Scuderi, L.A. (1987a). Late-Holocene upper timberline variation in the southern Sierra Nevada, USA. *Nature*, **25**, 242–244.

Scuderi, L.A. (1987b). Glacier variations in the Sierra Nevada, California, as related to a 1200-year tree-ring chronology. *Quaternary Research*, **27**, 220–231.

Scuderi, L.A. (1990). Tree-ring evidence for climatically effective volcanic eruptions. *Quaternary Research*, **34**, 67–85.

Sharp, R.P. (1968). Sherwin Till-Bishop Tuff geological relationships, Sierra Nevada, California. *Geological Society of America Bulletin*, **79**, 351–364.

Sharp, R.P. (1969). Semiquantitative differentiation of glacial moraines near Convict Lake, Sierra Nevada, California. *Journal of Geology*, **77**, 68–91.

Sharp, R.P. (1972). Pleistocene glaciation, Bridgeport Basin, California. *Geological Society of America Bulletin*, **83**, 2233–2260.

Stine, S. (1994). Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature*, **369**, 546–549.

Stuiver, M., Braziunas, T.F., Becker, B. and Kromer, B. (1991). Climatic, solar, Oceanic, and geomagnetic influences on late-glacial and Holocene atmospheric ^{14}C/^{12}C change. *Quaternary Research*, **35**, 1–24.

Stuiver, M. and Polach, H.A. (1977). Discussion: Reporting of ^{14}C data. *Radiocarbon*, **19**, 355–363.

Stuiver, M. and Reimer, P.J. (1993). Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon*, **35**, 215–230.

Wahrhaftig, C. and Birman, J.H. (1965). The Quaternary of the Pacific mountain system in California. *In*: Wright, H.E., Jr and Frey, D.G. (eds), *The Quaternary of the United States*, pp. 299–340. Princeton University Press, Princeton.

Waitt, R.B., Jr, Young, J.C. and Davis, P.T. (1982). Regional significance of an early Holocene moraine in Enchantment Lakes basin, North Cascades Range, Washington. *Quaternary Research*, **17**, 191–210.

Whiting, J.D. (1985). Late Pleistocene and Holocene glacial history of the Pyramid Creek-South Fork American River drainage, Sierra Nevada, California. M.S. thesis, California State University, Fresno, 162 pp.

Whiting, J.D. (1986). Multiparameter relative dating of glacial and periglacial deposits, Pyramid Creek-South Fork American River (PCSFAM) drainage, northern Sierra Nevada, California. *Geological Society of America, Abstracts with Programs*, **18**, 198.

Wood, S.H. (1977). Distribution, correlation, and radiocarbon dating of late Holocene tephra, Mono and Inyo craters, eastern California. *Geological Society of America Bulletin*, **88**, 89–95.

Young, J.C., Birkeland, P.W. and Burke, R.M. (1979). Glacial and periglacial deposits of the Mono Creek recesses, west-central Sierra Nevada, California: Measurement of age-dependent properties of deposits. *In*: Burke, R.M. and Birkeland, P.W. (eds), *Field Guide to Relative Dating Methods Applied to Glacial Deposits in the Third and Fourth Recesses and along the Eastern Sierra Nevada, California, with Supplementary Notes on other Sierra Nevada Localities*. Friends of the Pleistocene, Pacific Cell.

Young, J.C., Birkeland, P.W. and Burke, R.M. (1982). Holocene glaciation, Mono Creek, central Sierra Nevada, California. *Geological Society of America, Abstracts with Programs*, **14**, 246.

Zielinski, G.A. and Davis, P.T. (1987). Late Pleistocene age of the type Temple Lake moraine, Wind River Range, Wyoming, U.S.A. *Géographie physique et Quaternaire*, **41**, 397–401.