QUATERNARY RESEARCH 36, 294–306 (1991)

Late Quaternary Snowline Reconstructions for the Southern and Central Sierra Nevada, California and a Reassessment of the "Recess Peak Glaciation"

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Received April 10, 1989

In the Sierra Nevada, the "Recess Peak Glaciation" has been previously defined on the basis of deposits exhibiting relative-age characteristics intermediate between those of the Little Ice Age deposits and those of early Holocene or older moraines. In the absence of reliable chronological control, the Recess Peak deposits were assigned an early Neoglacial age. Although numerous moraines in the central and southern Sierra have been attributed to this interval, regional snowline gradients reconstructed from these deposits lack internal consistency and appear to represent several distinctly different episodes of glacier advance. As a basis for comparison with the Recess Peak data, modern and late Pleistocene regional snowlines were reconstructed using accumulation-area ratios and cirque-floor altitudes. These reconstructions display regionally consistent gradients, rising gradually southward and more steeply eastward. Based on these data, the full-glacial late Pleistocene snowline depression is estimated to have been ≥800 m. Estimates of Recess Peak snowline depression vary widely, ranging from 140 to 500 m, and a reconstructed regional gradient rises northward, in opposition to the late Pleistocene and modern snowlines. Limited radiocarbon dating and the irregular pattern derived from the Recess Peak snowline data suggest that, even in the type area, these deposits resulted from both pre- and post-Hypsithermal glacier advances. © 1991 University of Washington.

INTRODUCTION

Numerous times during the Pleistocene Epoch, an elongate ice cap formed along the crest of the Sierra Nevada in California and nourished tongues of ice that flowed down valleys on both the east and west sides of the range. Now only small glaciers remain, nestled in steep-walled cirques in the highest segments of the range. Young-looking moraines found near the termini of these modern glaciers and in adjacent valleys appear to support an interpretation (Birman, 1964) that, following the Hypsithermal interval, these alpine glaciers expanded at least twice during late Holocene time. The higher, younger moraines have been attributed to the Little Ice Age (Matthes) advances of the last several hundred years (Matthes, 1942; Birman, 1964). During the 1950s, while working along Mono Divide (Fig. 1), Birman (1964) defined an early Neoglacial episode of glacier expansion which he named the "Recess Peak Glaciation." The deposits that he attributed to this advance (Fig. 2) were typically located within 1 or 2 km of the termini of glaciers found in high-altitude cirques of the First through Third Recesses along Mono Divide and in adjacent high terrain. Considerably farther (3–10 km) down several valleys, there are successions of moraines that Birman (1964) assigned to the "Hilgard Glaciation," described as an earlier interval of post-Hypsithermal advances. Subsequently, based on soil studies and limited radiometric dating, Curry (1969, 1971) suggested that the Hilgard advances were early Holocene in age. On the basis of lichenometry, Curry also defined two Recess Peak advances (2600 and 2000 yr B.P.) and an unnamed advance dating to ca. 1100 yr B.P.

In more recent studies farther south in the Sierra Nevada, Gillespie (1982) and Scuderi (1984, 1987a,b) have each identified glacial deposits that they attribute to

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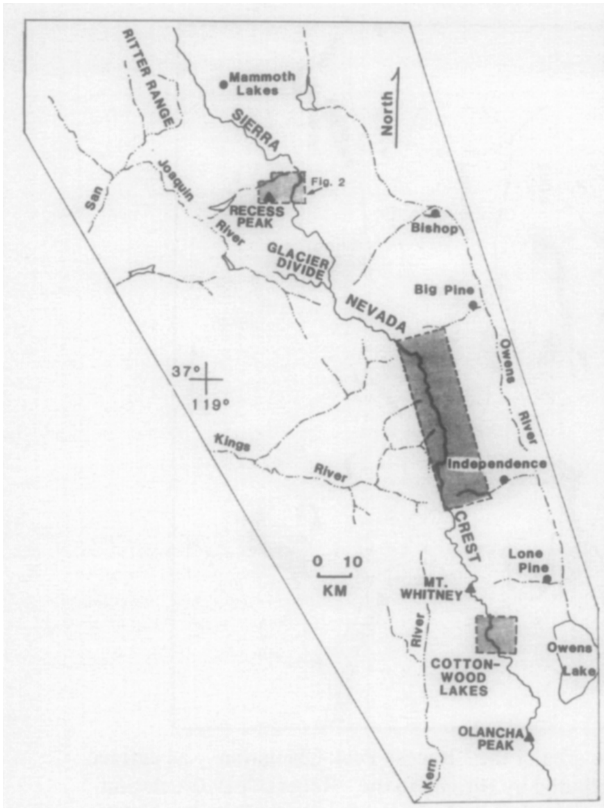

FIG. 1. Map showing location of the central and southern Sierra Nevada and the glaciated areas examined in this study. Highlighted boxes indicate areas in which moraines attributed to the Recess Peak glaciation have been described. The central zone between Big Pine and Independence was investigated by Gillespie (1982) and the southern area around Cottonwood Lakes was studied by Scuderi (1984).

Recess Peak advances. Gillespie used relative-dating criteria to distinguish Recess Peak deposits from those attributed to the Matthes, Hilgard, and Pleistocene advances. Working in the Cottonwood Lakes area south of Mount Whitney (Fig. 1), Scuderi (1984, 1987b) used lichenometric dating based on a modification of Curry's (1969) lichen-growth curves to provide dates for the timing of moraine stabilization. Scuderi's data suggest two intervals of glacier expansion within Recess Peak time, one centered around 2400 yr B.P. and the other spanning 1400–1000 yr B.P. Moreover, by utilizing tree-ring width variations and timberline fluctuations, Scuderi (1987a) made a persuasive argument for moderate amounts of climatic deterioration leading to 60–80 m of treeline depression (relative to Hypsithermal treeline) during both of these intervals.

Whereas the studies of Birman, Gillespie, and Scuderi can be synthesized to provide an apparently coherent view of the Recess Peak advances, there appear to be important inconsistencies within the data set. In particular, the amount of snowline depression (400–500 m) required to expand glaciers to the Recess Peak limits defined by Gillespie and Scuderi appears to necessitate a climatic change approaching the magnitude of the last glacial maximum during which snowlines were depressed 700–1000 m. This paper utilizes modern, Holocene, and late Pleistocene snowline data to assess the age assignments of deposits attributed to Recess Peak advances in the central and southern Sierra. This evaluation suggests that many of these deposits are more likely to be late Pleistocene or perhaps early Holocene in age.

METHODOLOGY

Because radiometric dates are not available to constrain the ages of the deposits attributed to Recess Peak advances in many of the valleys where they have been identified, other methods (usually relative-dating techniques) have been used to group these deposits together and, in some cases, to assign them generalized ages. Here, I propose to use the coherence of regional snowline trends as a basis for assessing the validity of these groupings. In particular, coherence is used to evaluate whether those deposits classified as belonging to Recess Peak advances are likely to represent a single interval of Holocene glacier activity (Birman, 1964; Curry, 1969). In order to use coherence as a test, it must be assumed that regional snowlines vary smoothly over the length and breadth of a mountain range (e.g., Porter, 1977; Meierding, 1982), and it must be shown that other groupings of glacial deposits (e.g., those from the last glaciation or from the present time) exhibit an

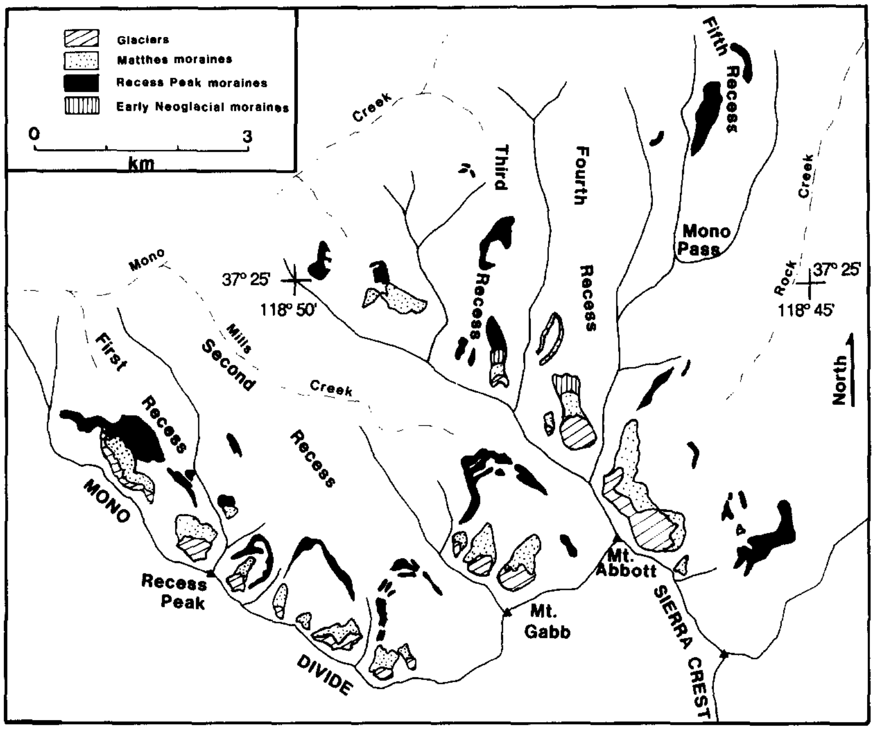

FIG. 2. Schematic glacial-geologic map of the type area of the "Recess Peak Glaciation," as defined by Birman (1964). Note the presence of deposits attributed by Birman to the "Recess Peak Glaciation" (black areas) up to 2 km from present-day glaciers, as well as their presence in some valleys, such as the Fifth Recess, that do not now contain glaciers. Vertically hachured moraines in the Third and Fourth Recesses have been reinterpreted by Yount *et al.* (1979, 1982) as early Neoglacial and chronologically equivalent to the originally defined "Recess Peak Glaciation." Modified from Birman (1964). For location, see Figure 1.

internal consistency in such characteristics as reconstructed snowline depression and gradients. The absence of a similar consistency and/or the presence of opposing or irregular trends in the Recess Peak data would suggest either that they were controlled by very different regional climatic patterns or that they do not represent a group of advances attributable to a single interval of glacier expansion, but rather a mix of deposits from several glacial episodes.

In this study, proxy data for past and present snowlines are used to examine the regional pattern of past and present glacier advances. For modern glaciers, the equilibrium-line altitude (ELA) was estimated on the basis of an accumulation-area ratio of 0.65 (Meier and Post, 1962). Areally restricted accumulations of perennial snow and ice may not accurately reflect the mean regional snowline (Meierding, 1982), either because the snow they receive is largely avalanche-derived or windblown or because their orientation affords them unusual protection from solar radiation. In an attempt to eliminate such accumulations from consideration, only glaciers more than 300 m wide were used in estimating modern snowline. In addition, only glaciers and cirques with a northwesterly to northeasterly orientation were included in this analysis.

Past snowlines were estimated by two means. First, cirque-floor altitudes (defined as the altitude of the inflection in slope between the cirque floor and the cirque headwall) for late Pleistocene times were derived from isolated peaks where there were no apparent sources of ice above the individual cirques and where there was no topographic evidence for an extension of ice beyond the cirque itself, i.e., the glacier was contained wholly within the cirque. In localities where several cirques were available, the elevation of the lowest cirque floor was used to approximate a past snowline. Except in the southern Sierra, no such cirques where ice was self-contained were found in the crestal area of the range. This is due to the large late Pleistocene ice cap that was centered just west of the range crest and that inundated the highest portions of the range, such that only isolated nunataks rose above its surface. Because of the precipitous slopes along most of the eastern escarpment of the Sierra, very few former cirque glaciers are identifiable on this side of the range.

In the second approach, ELAs were estimated for past glaciers based on the mapped extent of former glaciers of a particular age. As with the modern glaciers, an accumulation-area ratio of 0.65 was used to estimate the position of the ELA on the reconstructed glaciers. However, because the precise position of the former ice divide of the Sierra ice cap is not well established, it is difficult in many valleys to establish the actual area contained within the accumulation area. Therefore, only those glaciers that appeared to have been isolated from the ice cap were used in calculations based on accumulation-area ratios. The data on cirque-floor altitudes and on ELAs based on the extent of both late Pleistocene and modern glaciers were complied from USGS 15-minute quadrangle maps.

Whereas modern glaciers >300 m wide are largely confined to the highest parts of the central Sierra Nevada, the distribution of cirque floors along the flanks of the range permits a regional, contoured surface of cirque-floor altitudes to be generated and allows gradients along the length and breadth of the range to be examined. These data permit reconstructed late Pleistocene snowlines, both parallel and perpendicular to the range crest, to be examined for their internal consistency and to be compared with other groupings of snowline data, such as those related to Recess Peak advances or the present-day glacier cover.

One critical assumption here is that cirques were occupied by late Pleistocene glaciers and are not relicts of earlier glaciations characterized by lower snowlines. Both the similar extent of many pre-Holocene glaciers and the similar magnitude of calculated snowline lowering during the late and middle Pleistocene glaciations in the Sierra Nevada suggest that this is a reasonable assumption.

RESULTS

Modern Glacier Extent

The region examined extends from north of the Ritter Range (37.7°N) to Olancha Peak (36.3°N) where the southernmost Pleistocene cirque glaciers were located (Fig. 1). Only the northern half of this area contains modern glaciers larger than the minimum width (300 m) used in this analysis, and these lie either along the main Sierra crest, along high east–west-trending ridges near the main crest (such as Glacier Divide), or among isolated high peaks (e.g., the Ritter Range). Transects of the calculated modern ELAs approximately parallel to and perpendicular to the range crest (upper data, Figs. 3 and 4) illustrate gradients that would be predicted from modern climatic conditions. Linear regressions explain approximately 50–90% of the variance in the glacial data. The resulting regression lines show a rise from north to south, as predicted from both present-day and past regional climatic data (Dohrenwend, 1984), and a rise from west to east, as is typical of western coastal ranges that receive orographically controlled precipitation from storms off the Pacific Ocean (Meier and Post, 1962; Porter *et al.*, 1983). The modern, WSW-to-ENE ELA gradient, rising at ca. 16 m/km, is considerably steeper than the north-to-south gradient approximately parallel to the crest, which rises southward at ca. 2.0 m/km. Nonetheless, both transects exhibit generally coherent trends along their lengths. The relatively small modern glaciers examined here are nestled

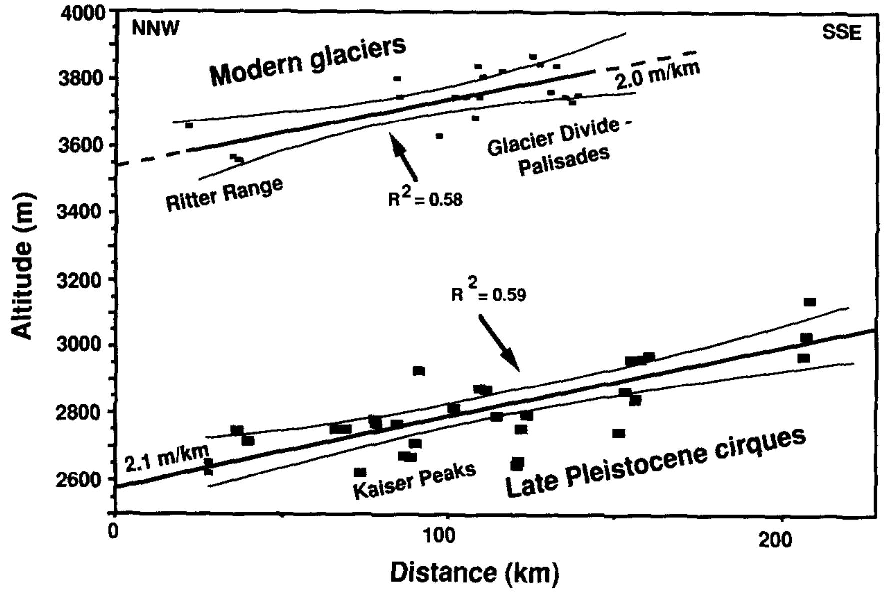

FIG. 3. Plot of ELAs of modern glaciers along and adjacent to the Sierra Crest and of cirque-floor altitudes along a NNW–SSE transect ca. 25 km west of the main range crest, where there is a sufficient density of data to construct a transect. The modern and late Pleistocene gradients are subparallel and rise southward at ca. 2 m/km. The southward projection of the ELA for modern glaciers (dashed line) is used as a basis for calculating ELA changes in the southern areas. For location of transect, see Figure 5.

in cirques where they are effectively protected from solar insolation. Consequently, the "true" modern snowline may be some 100–200 m higher than that derived from the modern ELAs (Meierding, 1982).

Late Pleistocene Glaciation

The reconstructed gradients based on late Pleistocene cirque floors can now be compared with the modern trends in order

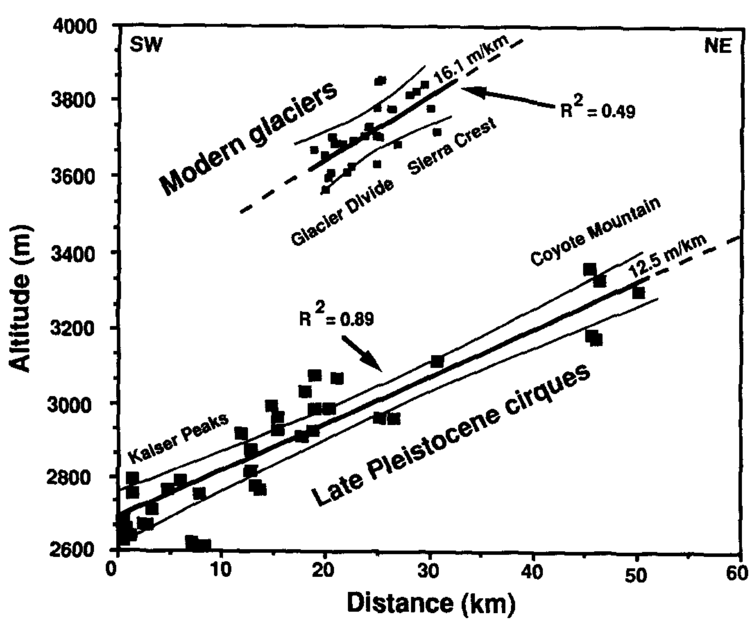

FIG. 4. Plot of ELAs for modern glaciers and cirque-floor altitudes along an NE–SW transect across the range crest. The gradient of the modern glaciers is less well defined and apparently somewhat steeper (16 m/km) than that of the late Pleistocene glaciers (13 m/km). For location of transect, see Figure 5.

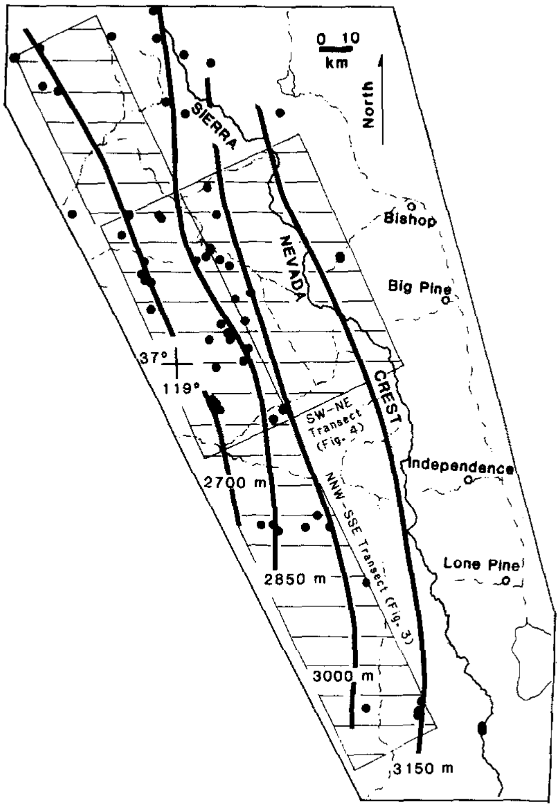

FIG. 5. Contour map of cirque-floor altitudes across the central and southern Sierra Nevada. Dots represent data points that meet the criteria defined in the text. The locations of the transect depicted in Figures 3 and 4 are shown by the hachured areas.

to examine the coherence along various transects, as well as the snowline departures from modern conditions. Similar coherence would suggest that the cirque-floor data for the late Pleistocene are reasonably reliable proxy snowline indicators and that snowline varied in a regionally consistent manner. Similar gradients along parallel transects would suggest that climate changed in a systematic fashion.

Despite the paucity of self-contained cirque glaciers in the crestal region of the Sierra, the abundance and distribution of cirque floors is sufficient to permit regional contouring of these data. The resulting map (Fig. 5) exhibits relatively smooth gradients with contours of equal cirque-floor altitude trending at a slight angle to the range crest and rising both to the south and east. Slight eastward deflections of this cirque-floor surface, such as that seen in the vicinity of the San Joaquin River, may represent topographic troughs where storms penetrate the range more effectively (Porter, 1964, 1977) and deliver greater precipitation to the interior of the range. One might anticipate that a similar deflection would occur along the Kings River valley, but data are insufficient in this region to define such a deviation. In both cases, the amount of scatter in the cirque-floor data suggests that conclusions concerning the presence and significance of localized deviations in the trend surface should be regarded as speculative.

Although the lack of cirque-floor data along the crest itself precludes direct comparison between Pleistocene cirque-floor gradients and the modern ELA trends in this specific area, sufficient data exist along the western slope of the range to create a transect subparallel to the range crest, but displaced ca. 25 km to the west. This transect (lower data, Fig. 3) shows a gradient of cirque floors rising southward at ca. 2.1 m/km. This gradient is nearly parallel to the modern ELA gradient along the crest (upper data, Fig. 3), but it is more than 1000 m lower in altitude, in part due to its position 25 km west of the range crest. When a WSW–ENE transect is examined, the eastward-rising gradient of cirque floors (ca. 13 m/km) is seen to be subparallel to the modern ELA gradient, but it is slightly gentler and displaced some 600–800 m below the modern ELA (Fig. 4). Because these latter data are plotted along a single geographic transect approximately perpendicular to the contours of equal cirque-floor altitude (Fig. 5), they provide a more direct comparison of snowlines, and they suggest that the magnitude of late Pleistocene snowline depression across the Sierra Nevada was about 700 m.

The mapping of Gillespie (1982), Scuderi (1984), and Mezger (1986) permits estimation of ELAs based on accumulation-area ratios from both late Pleistocene and Recess Peak deposits in their study areas. Late Pleistocene (Tioga) ELAs from the

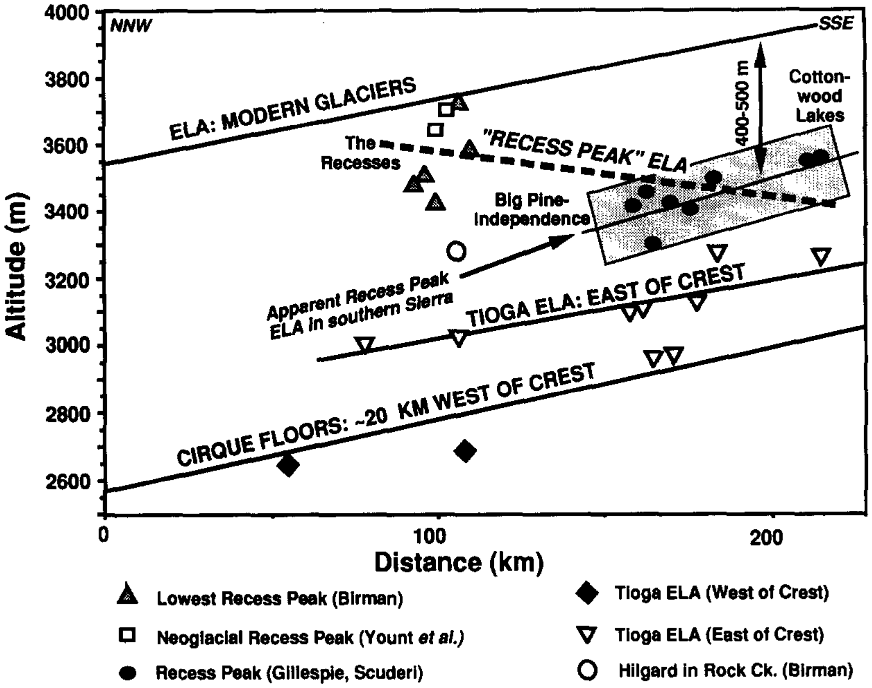

FIG. 6. Plots of ELAs in the central and southern Sierra Nevada for the late Pleistocene (Tioga) and Recess Peak advances. ELA altitudes for individual late Pleistocene glaciers east (open triangles) and west (filled diamonds) of the crest are based on AAR calculations. The apparent discrepancy between the late Pleistocene snowline depression east and west of the crest results from their comparison along a longitudinal, rather than a transverse, section. ELAs for moraines attributed to Recess Peak advances by Gillespie (1982) and Scuderi (1984) on the eastern flank of the southern Sierra Nevada (in the stippled box) lie 400–500 m below the modern ELA. The southward-rising gradient suggested by these sites can be projected northward to intercept the Hilgard ELA (open circle) in Rock Creek. When the southern Sierra data are combined with Recess Peak data from the type locality, they yield a northward-rising gradient (dashed line).

eastern escarpment of the central Sierra (Gillespie, 1982) and from the Cottonwood Lakes area south of Mt. Whitney (Mezger, 1986) show an average of ca. 800 m of snowline depression (Fig. 6) with respect to the modern ELA (extrapolated linearly to the south of the last control point; Fig. 3). When combined with data from Rock Creek (Fig. 2; Birman, 1964) and Convict Lake (Sharp, 1969), the Tioga glaciers along the eastern escarpment of the Sierra Nevada yield a NNW–SSE gradient (1.5 m/km) that is subparallel both to the gradient of cirque floors and to that of the modern ELA (Fig. 6).

Late Pleistocene reconstructions from other Cordilleran ranges exhibit similar amounts of snowline depression (Porter *et al.*, 1983) and suggest that the snowline estimates described here for the Sierra are reasonable. In the context of the problems being examined, it is equally important to note that the data on late Pleistocene cirque-floor altitudes show coherent regional patterns and exhibit gradients that are very similar to those shown by the ELAs of modern glaciers. The consistency of these results provides a context within which to assess the deposits that have been attributed to Recess Peak advances.

Recess Peak Advances

In the type area of the Recess Peak advances (Fig. 2), Birman (1964) mapped numerous Recess Peak moraines at a distance of 1–2 km beyond small glaciers in the First through Third Recesses and near the head of Rock Creek below Mt. Abbott. More recently, deposits attributed by Birman (1964) to Matthes and Recess Peak advances in this area were reevaluated using radiometric, tephrochronologic, and multiparameter relative-dating techniques (Yount *et al.*, 1979, 1982). One ^{14}C date indicates that the outermost Recess Peak moraine at Mills Creek (Fig. 2) is older than ca. 7000 yr B.P. This moraine is less weathered than associated Hilgard deposits, but is more weathered than inset moraines contained within the type "Recess Peak" deposits. Identifiable tephras constrain these younger Recess Peak moraines to an interval between ca. 3000 and 1000 yr B.P. Finally, relative dating suggests that ice-cored rock glaciers that were attributed by Birman (1964) to Matthes advances actually predate the Little Ice Age (Yount *et al.*, 1979).

Despite the apparent temporal range (ca. >7000 to 1000 yr B.P.) represented by the type Recess Peak moraines, they all occur within a relatively restricted altitudinal range in the type area (3200–3400 m). This suggests that snowlines did not vary greatly among these multiple Holocene advances. When the snowline data from Birman's (1964) Recess Peak advances in the type area and from the Neoglacial advances of Yount *et al.* (1982) are compared with the reconstructed modern and late Pleistocene snowlines from the Sierra, some important distinctions can be drawn. ELAs based on Birman's outermost Recess Peak moraines, including those moraines that predate Hypsithermal times, show considerable scatter but yield an ELA depression of 140–280 m (mean of ca. 200 m) relative to modern ELAs in each valley (Fig. 7). In contrast, Yount *et al.*'s (1982) data show less variability among the type Recess Peak moraines that are post-Hypsithermal in age. The reconstructed geometries of these glaciers imply an early Neoglacial ELA depression of 100–150 m (Fig. 7).

A comparison of these data from the Recess Peak type locality with those derived from glacial deposits attributed to the Recess Peak advances in the central and southern Sierra shows striking inconsistencies. Recess Peak ELAs from these latter areas (Gillespie, 1982; Scuderi, 1984) show a snowline depression of ca. 500 m below the modern ELA surface (Fig. 6). Although an apparent ELA gradient for these deposits from Big Pine to Cottonwood Lakes lies approximately parallel to the Pleistocene and modern snowline gradients, when these data are compared with those from the type locality of the Recess Peak advances, they are seen to exhibit far greater amounts of snowline depression. In addition, if a regression were to be made through all of the individual ELAs attributed to Recess Peak advances, it would appear to consist of two disjoint data sets (Fig. 6), and it would yield a regional gradient that is inconsistent with

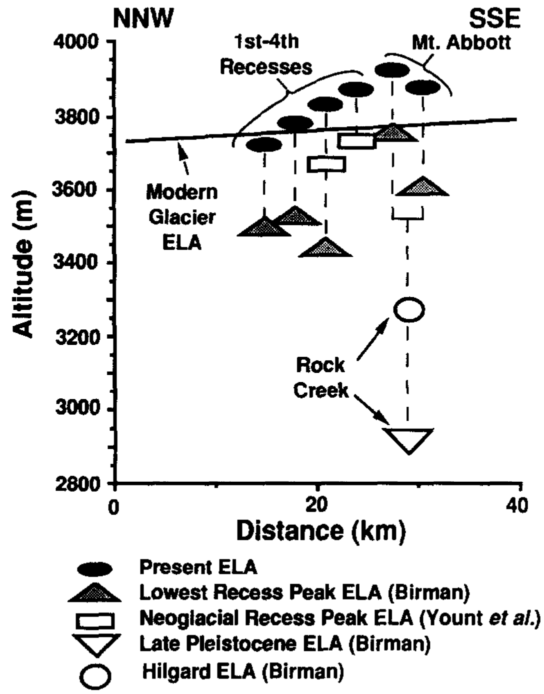

FIG. 7. Calculated ELAs in the Recess Peak and Mt. Abbott region (see Figs. 1 and 2 for location). The modern ELA is calculated from existing glaciers. The scatter of the modern ELAs around the regional gradient depicts expected variability and reflects the localized climatic conditions and varied cirque orientations. The late Pleistocene (open triangle) and Hilgard (open circle) ELAs represent reconstructed glaciers in Rock Creek. Although other deposits exist in this area that would be considered equivalent in age and position to Yount *et al.*'s (1982) Recess Peak or early Neoglacial moraines, only the two valleys depicted here have been studied thoroughly.

each of the previously described snowline trends, i.e., rising toward the north (dashed line, Fig. 6).

DISCUSSION

This analysis clearly indicates that regional snowlines in the Sierra Nevada, during both modern and late Pleistocene times, yield smooth, subparallel trends. The gradual rise in the snowline to the south is expected (Flint, 1971), and it is subparallel to the gradient displayed by nivation hollows in the adjacent Basin and Range (Dohrenwend, 1984). The amount of late Pleistocene snowline depression derived from comparing cirque-floor altitudes with the ELAs of modern glaciers (ca. 700 m) is somewhat less than that observed in other Cordilleran ranges (Porter *et al.*, 1983). This apparent difference may result from the comparison of two different parameters. It may also result either from an underestimation (100–200 m) of the modern snowline due to the protected position of the modern Sierran glaciers or an overestimation of the altitude of former snowlines if the late Pleistocene glaciers flowed considerably beyond their cirques, such that cirque-floor altitudes were not a reliable proxy for snowlines. Meierding (1982) has suggested that accumulation-area ratios (AARs) yield more reliable snowline reconstructions than do cirque-floor altitudes. Using the estimated position of the modern snowline and the Tioga glacier reconstructions based on AARs, approximately 800 m of snowline depression occurred east and west of the Sierra crest during late Pleistocene times (Fig. 6). This is ca. 100 m greater than the value calculated from cirque-floor altitudes (Fig. 4) and is probably a better approximation of the actual ELA depression during the last glacial maximum.

The subparallel gradients exhibited by modern ELAs, late Pleistocene cirque-floor altitudes, and late Pleistocene (Tioga) ELAs calculated from AARs (Figs. 3–6) suggest that present and Pleistocene climatic gradients across the Sierra Nevada were similar along transects both parallel and perpendicular to the range crest. The deposits of the Recess Peak advances, however, yield irregular regional gradients with a slope that diverges strongly from that of the modern and of the late Pleistocene ELA. Although there is considerable variation in reconstructed snowlines within Birman's Recess Peak data, it is not too dissimilar to the variability in the modern ELAs along the Recesses and at the head of Rock Creek (Fig. 7). Furthermore, there is sufficient coherence among the Recess Peak snowline data in the type area, when compared to the modern data, that the validity of Birman's Recess Peak classification cannot be excluded on the basis of snowline data alone. However, if we accept the chronologic data of Yount *et al.* (1979, 1982) from the same area, Birman's Recess Peak deposits would range from early Holocene to Neoglacial in age. Based solely on those deposits attributed by Yount *et al.* (1979, 1982) to early Neoglacial advances, snowline depression would be only 100–150 m (Fig. 7), an amount that is consistent with Neoglacial snowline lowering determined for numerous other Cordilleran regions (Porter, 1981, 1986; Burke and Birkeland, 1983).

The ELAs calculated for the central and southern Sierra Nevada based on Gillespie's (1982) and Scuderi's (1984) Recess Peak moraines indicate a generally consistent snowline lowering of 400–500 m (Fig. 6). This is 2 to 3 times greater than the snowline lowering calculated for Recess Peak advances in the type area, as shown above. As a consequence, the combined Recess Peak data fail the previously described consistency test.

It might be argued that, in comparison to areas north of Independence (Fig. 1), the Cottonwood Lakes area lies deeper in the rain shadow due to the presence of a second, north–south drainage divide lying to the west of the Kern River. Although there are insufficient data to assess this possible effect in the present or in late Pleistocene times, a more intense rain shadow should raise the snowline, and consequently, it would be expected to reduce the amount of apparent snowline lowering. Such an effect, if present, would make the large snowline depression calculated for Recess Peak deposits in the Cottonwood Lakes area even more strikingly different from that in the type area.

The northward-rising snowline gradient resulting from a synthesis of the regional Recess Peak data (Fig. 6) could be explained in at least two ways. It may indicate that the regional climate gradient was significantly different from either present or late Pleistocene times during the Recess Peak advances, such that snowlines were actually considerably lower in the southern Sierra than in the northern portions of the range. Alternatively, the gradient may result from the comparison of two temporally unrelated data sets that represent very different climatic conditions.

Arguments in favor of the first explanation include model predictions of significantly strengthened monsoonal conditions in the southwestern United States resulting from early Holocene seasonality that was enhanced in comparison to present or late Pleistocene times (Kutzbach and Guetter, 1986). Southerly moisture sources would be expected to have increased importance under these circumstances and might have forced an inversion of the regional snowline gradient. Support for enhanced moisture regimens comes from the latest Pleistocene to early Holocene "pluvial" lakes in the southwestern United States (Smith and Street-Perrot, 1983) and from early to middle Holocene glacial, timberline, and pollen records in western Colorado (Friedman *et al.*, 1988; Markgraf and Scott, 1981; Carrara *et al.*, 1984) which have been interpreted to indicate more moderate climatic conditions that perhaps resulted from a northerly displacement of the summer monsoon. However, these were times of higher timberline in southwestern Colorado in comparison to today, and it seems unlikely that warm–moist summer conditions in the early and middle Holocene would have lowered the snowline or caused an inversion of the snowline gradient along the eastern Sierra Nevada. Because enhanced seasonality and summer monsoonal conditions were most pronounced in the early Holocene, a regional snowline inversion attributed to these conditions would require that the Recess Peak advances were, at least in part, of this age.

There is also clear evidence for moderate climatic deterioration during Neoglacial times in the mountains of California (Adam, 1967; LaMarche and Stockton, 1974). The rather sparse data, including that based on estimates of timberline depression in the south (Cottonwood Lakes: Scuderi, 1987a) and the north (White Mountains: LaMarche, 1973), are not supportive of an inversion of the regional climatic gradient at that time.

Arguments in support of the contention that temporally distinct glacial deposits along the length of the range have been classified as belonging to the Recess Peak advances are threefold. First, limited chronological data related to moraines within the type area itself suggest a range of ages spanning much of Holocene time (>7000 to 1000 yr B.P.) during which there were discrete intervals of glacier advance. The relative-dating techniques utilized by Birman (1964) apparently failed to distinguish these age differences.

Second, the snowlines calculated for Recess Peak advances south of the type area exhibit a southward-rising gradient subparallel to the calculated modern and late Pleistocene regional snowlines (stippled box, Fig. 6). Against the background of the modern and late Pleistocene snowlines, the southerly Recess Peak data appear to represent a coherent response to climatic conditions that caused ca. 400–500 m of snowline depression. Not only is a snowline depression of this magnitude considerably greater than that reconstructed for the Recess Peak type area (including moraines that are >7000 yr B.P.), it is also much larger than the Neoglacial snowline lowering typical of most other Cordilleran ranges. In fact, it more closely corresponds to the amount snowline change associated with the latest Pleistocene advances (ca. 12,000–10,000 yr B.P.) in adjacent ranges, such as the Cascades (Porter, 1976; Scott, 1977; Porter *et al.*, 1983).

Third, data on Neoglacial timberline lowering within the Cottonwood Lakes area (Scuderi, 1987a) is consistent with similar observations in other ranges, but is inconsistent with the lichenometric ages for nearby moraines attributed to Recess Peak advances (Scuderi, 1984). Neoglacial timberline lowering in the nearby White Mountains is estimated to have been 100–150 m (LaMarche and Mooney, 1967; LaMarche, 1973) and is comparable to the coeval snowline depression determined both for many Cordilleran glaciers and for the moraines defined as neoglacial in age by Yount *et al.* (1979, 1982) in the Recess Peak type area. There appears, however, to be little correlation in the southern Sierra between the observed amount of depression of timberline during Neoglacial times and the magnitude of Recess Peak snowline depression. The Recess Peak snowline lowering in the Cottonwood Lakes locality (ca. 400 m) is 5–6 times greater than the local timberline change (70 m) determined on nearby peaks (Scuderi, 1987a). These events were correlated on the basis of dendrochronological ages for the timberline record and lichenometric age estimates for the moraines (Scuderi, 1984). However, the large inconsistency between timberline and snowline changes suggests that, rather than being chronologically related, these are separate events of differing magnitude and age. The reasons for the apparent inaccuracies in the lichenometric age estimates are not clear, but they may be attributable either to inadequate calibration of the lichen-growth curve or to intervals of persistent Neoglacial snow cover that mantled older moraines and killed lichens growing on them.

It appears, therefore, that many moraines identified in the southern and central Sierra Nevada as resulting from Recess Peak advances are not correlative with Neoglacial moraines in the Recess Peak type area. Inconsistencies in the magnitude of snowline lowering suggest that these southern moraines are more likely to correlate with Hilgard advances (Birman, 1964) of either latest Pleistocene (Mezger, 1986; Mezger and Burbank, 1986) or early Holocene age (Burke and Birkeland, 1983). The maximum Hilgard advance in Rock Creek (Birman, 1964) displays ca. 450 m of snowline lowering (Fig. 7) with respect to the modern cirque glaciers, such that the associated ELA is apparently consistent with the anomalous Recess Peak snowlines from the southern Sierra Nevada (Fig. 6). Given the >7000 yr B.P. age of the outermost Recess Peak moraines in at least one of the valleys in the type area, it seems possible that they represent either recessional phases of the Hilgard advances or a separate early Holocene advance (Beget, 1983).

CONCLUSIONS

Calculations of modern and late Pleistocene snowline gradients in the central and southern Sierra Nevada demonstrate that proxy data for paleoclimatic conditions, such as cirque-floor altitudes and ELA estimates, can be used to generate coherent reconstructions of late Quaternary climatic gradients along the length and breadth of the range. The modern and late Pleistocene snowline gradients are subparallel to each other along transects both parallel and perpendicular to the range crest. The data indicate that at least 700 m of snowline lowering occurred during the last glaciation. Because of the protected nature of the modern glaciers and of the probable underestimation of past snowline altitudes when cirque-floor altitudes are used in such a reconstruction, it is likely that the true snowline depression was ⩾800 m. Calculations based on limited accumulation-area ratio data support this estimate of greater snowline change.

Although the modern and late Pleistocene data exhibit coherent trends, the data attributed to Recess Peak advances (Birman, 1964; Gillespie, 1982; Scuderi, 1984) lack such consistency, particularly in the central and southern Sierra Nevada. The magnitude of snowline depression is discordant from one area to the next, and the reconstructed regional gradients using all deposits assigned to Recess Peak advances rise northward in opposition to both modern and full-glacial snowline gradients. The amount of snowline lowering (400–500 m) in the southern Sierra Nevada is inconsistent with observed amounts of Neoglacial treeline depression and with Neoglacial snowline changes in other areas. Because a similar magnitude of snowline lowering is associated with Hilgard advances of latest Pleistocene to early Holocene age, it appears possible that the anomalous Recess Peak deposits in the southern and central Sierra Nevada are correlative with these advances. Finally, radiocarbon dates and relative-dating studies in the type area (Yount *et al.*, 1979, 1982) suggest that some of the deposits originally used to define the Recess Peak Glaciation are not Neoglacial in age.

Despite the numerous problems associated with the age of the Recess Peak deposits, Burke and Birkeland (1983) recommend retaining this name for early Neoglacial advances in the Sierra Nevada. As such, the Recess Peak classification still represents a useful category to which many moraines nestled close to modern Sierran glaciers could be assigned. This classification would necessitate a redefinition of the Recess Peak deposits in the type area, where it would eliminate the >7000-year-old moraines and their associated lowered snowlines from inclusion in this interval of glacier advance. Outside the type area, the problem remains to determine which deposits should be classified as Recess Peak in age, as well as to determine those relative-dating techniques that can, in the absence of radiometric dates, distinguish among latest Pleistocene, early Holocene, and early Neoglacial moraines.

ACKNOWLEDGMENTS

Very thorough reviews of an earlier version of this manuscript by Marcus Bursik, Peter Birkeland, Monique Fort, John Dohrenwend, and Alan Gillespie helped significantly to improve this manuscript. The support of the staff of the Department of Earth Sciences at the University of Cambridge and the assistance with data processing by Troy Rosenbush are also greatly appreciated.

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