QUATERNARY RESEARCH 39, 24–35 (1993)

Late Pleistocene Glaciation of Mono Basin, California

MARCUS I. BURSIK[1]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

AND

ALAN R. GILLESPIE
Remote Sensing Laboratory, University of Washington, Seattle, Washington 98195

Received February 7, 1991

Moraines in the canyons of Mono Basin are separable into relative-age groups on the basis of clast-sound velocities in exposed boulders, moraine morphology, and weathering features on boulder surfaces. Tioga, Tenaya, Tahoe, and Mono Basin moraine deposits each have distinct weathering characteristics and therefore constitute different relative-age groups. The Tioga glacial episode at June Lake may postdate ~25,200(?)-yr-old basaltic lavas, and the Tenaya episode may have occurred ~30,700 yr ago. A comparison of the glacial and lacustrine records of Mono Basin over the past 40,000 yr, based on new interpretations of radiometric ages, is consistent with the hypothesis that maximum glacial and maximum pluvial periods were not necessarily synchronous. ©1993 University of Washington.

INTRODUCTION

The moraines of Mono Basin are among the most prominent of the eastern Sierra Nevada (Fig. 1), and have been separately mapped or characterized by numerous workers (McGee, 1885; Blackwelder, 1931; Kesseli, 1941; Putnam, 1949; Birman, 1964; Kistler, 1966, Chesterman and Gray, 1975; Lachmar, 1977; Clark, 1979; Mathieson, 1984; Crook and Gillespie, 1986; Birkeland and Burke, 1988; Bailey, 1989; Phillips *et al.*, 1990; Bursik, 1991). In particular, the moraines at Bloody Canyon have yielded controversial data on the sequence of late Pleistocene Sierran glaciations (Blackwelder, 1931; Sharp and Birman, 1963; Burke and Birkeland, 1979; Gillespie, 1982, 1984). However, no recent study of moraines in all major drainages, integrated with the unique lacustrine and volcanic records of Mono Basin, has been published (Russell, 1889; Putnam, 1950; Lajoie, 1968). Such a study could help clarify the relative-age sequence of the Sierra Nevada by revealing morainal features, hence relative-age groupings, that are consistent between canyons within a single major drainage basin. In addition, use of interfingering stratigraphic relationships between glacial, lacustrine, and volcanic deposits, and modern radiometric ages obtained for them, could help to constrain our knowledge of past climate as recorded by the coupled sequences of glacial advances and lake-level fluctuations. Our goals in the present paper are (1) to characterize the weathering and geomorphic features of the late Pleistocene moraines in the piedmont regions of Mono Basin; (2) to correlate moraines between canyons, thus demonstrating a distinct, consistent sequence of glacial events; (3) to suggest possibilities for constraining our knowledge of the ages of the moraines by looking in greater detail at the volcanic, lacustrine, and glacial records together; and (4) to offer a brief comparison of the latest Pleistocene glacial record and the record of fluctuations in the level of Pleistocene Lake Russell.

METHODOLOGY

Previous workers, beginning with Matthes (1930) and Blackwelder (1931), have developed relative-dating (RD) techniques to establish age relationships among moraines. These techniques are based on observations of features on moraines that weather and change appearance with age. Objective measurements of these features can serve to differentiate moraines within a canyon and to correlate moraines between canyons, even if radiometric ages are unobtainable. We used three RD techniques, based on the following: (1) clast-sound velocity (CSV) in granitic boulders (Crook, 1986), (2) moraine morphology and topographic relationships (Blackwelder, 1931), and (3) semiquantitative weathering measurements (Birman, 1964; Sharp, 1969; Burke and Birkeland, 1979). The CSV technique is based on the assumption that the speed of sound, (V_p) in weathering boulders decreases monotonically with age because of the formation of microcracks. Of the three methods, we have found that the CSV technique provides the most objective and consistent results in differentiating moraines in Mono Basin, in keeping with the conclusions of Gillespie (1982) and Crook and Gillespie (1986). Moraine morphology is important because the form of a moraine changes systematically with

[1] Present address: Department of Geology, State University of New York, Buffalo, New York 14260.

0033-5894/93 $5.00

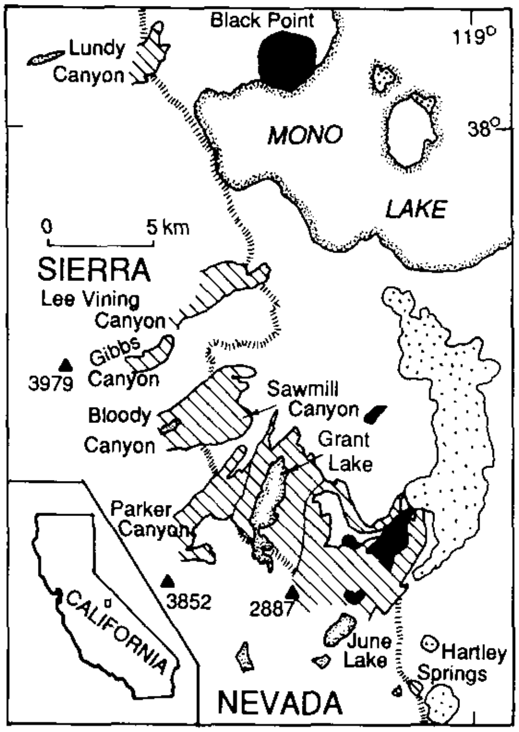

FIG. 1. Map showing location of Mono Basin and surrounding geographic features. Diagonal lines = late Pleistocene piedmont moraines; black areas = late Pleistocene basaltic rocks; stippled areas = late Quaternary silicic volcanic rocks.

age, as erosion and redeposition degrade pristine landforms. Semiquantitative weathering data consist of visual estimates and measurements of features related to the amount of weathering of boulders and soils on moraines.

Measurements of V_p in granitic boulders were made according to the procedure of Crook (1986). This involved making a three-point travel time curve for a transect on the top surface of each boulder greater than 30 cm in diameter within a restricted area (a site). Boulders that broke under testing, had high color index, or had cracked or recently spalled surfaces were rejected for use. V_p was taken to be the average speed calculated from the travel time curve. It was determined for 15 to 50 boulders at a site and for several sites on the crest of each moraine. The difference in average V_p between boulders from separate moraines is a statistical measure of the distinct weathering characteristics, hence ages, of the moraines. Two adjacent groups of moraines were considered to be of different relative ages if their respective samples of V_p were formally separable at the 10% significance level (Gillespie, 1982; Bursik, 1988).

Moraines with certain morphological features were consistently given particular names by Blackwelder (1931). In this study, moraines have been assigned different relative ages based foremost on the statistical separability of CSV samples, but also on differences in morphological characteristics and semiquantitative data. Assignment of the name of a glaciation to a particular moraine or group of moraines (e.g., Tioga) was then made based on conformity with the morphological characteristics outlined in Table 1, to preserve continuity with Blackwelder and later workers. Although moraines in different canyons have been assigned the same age based on their morphological features, the features do not provide sufficient proof that the moraines were formed simultaneously. However, the CSV data that we present are generally compatible with this interpretation, because V_p values were typically similar for deposits of a given relative age in different canyons.

We found the depth of weathering pits and the grain-scale roughness on granitic boulder surfaces to be the most useful semiquantitative weathering techniques for the deposits of Mono Basin. Weathering pits are depressions on boulder surfaces that range from grain size to several meters across and up to a meter deep. We measured the depth of the deepest weathering pit on every boulder at a site, excluding those pits that were formed by the coalescence of a number of smaller pits or that were anomalously deep because of unusually vigorous weathering along cracks. Grain-scale roughness or fret-

TABLE 1
Late Pleistocene Glaciations of the Sierra Nevada

Glaciation	Radiometric age (yr B.P.)[a]	Morphological characteristics[b]
Tioga	≥22,200 ± 2000[c] (19,050 ± 420) [≥20,400–23,100[d]] <25,200 ± 2500[e] (21,600 ± 800)	Minimal gullying of flanks Termini nearly complete except for narrow breaching by axial streams
Tenaya	[≥23,300–25,500[d]] ≥30,700 ± 2700(?)[e] (26,400 ± 600)	Crests sharper than Tahoe Termini widely breached by axial streams Lateral moraines generally overtopped by Tioga except at outer reaches ("topographic unconformity")
Tahoe (Tahoe II[g])	<118,000 ± 7000[f] [≥55,900–65,800[d]]	Flanks deeply gullied Termini eroded, mostly removed Voluminous lateral moraines
Mono Basin (Tahoe I[g])	>131,000 ± 10,000[f] [≥92,000–119,000[d]] [≥133,000–149,000[d]] [≥189,000–218,000(?)[d,h]]	Local throughgoing gullies[e] Generally preserved only where Tahoe ice streams followed different courses

[a] Tabulated ages are constraints on the age of the glacial maximum. Error bars are estimated $\pm 2\sigma$ (~95% confidence interval). Square brackets indicate experimental (^{36}Cl) ages. Ages in parentheses are uncorrected radiocarbon ages.

[b] Blackwelder (1931), Sharp and Birman (1963), Birman (1964).

[c] Dorn *et al.* (1987): "U–Th-calibrated." The "U–Th-calibrated" age of their last major Tioga recessional is 16,300 ± 1300 (13,910 ± 210 yr B.P.)

[d] Phillips *et al.* (1990).

[e] This study: ages are "U–Th-calibrated."

[f] Gillespie (1982).

[g] Bloody Canyon only (see Gillespie, 1982, 1984).

[h] The two older age ranges of Phillips *et al.* are for the Tahoe I moraines; the younger for the Mono Basin moraines. See text for interpretation of these ages.

ting is a measure of local erosion of a clast surface, which is assumed to have been glacially smoothed or freshly broken upon deposition. We categorized a boulder as "fresh" if more than 50% of its exposed surface exhibited differential mineral weathering to a depth less than the average grain size (Sharp and Birman, 1963). Boulders were "weathered" if more than 50% of the surface exhibited differential mineral weathering to a depth equal to or greater than the average grain size. In the next section, semiquantitative weathering data are summarized on scatter diagrams of the fraction of fresh boulders plotted against the fraction of boulders with weathering pits ≥2 cm deep.

RELATIVE AGES OF PIEDMONT MORAINES

Interpretive maps of the late Pleistocene moraines within Mono Basin were made from RD and mapping investigations both in the field and from U.S. Forest Service aerial photographs with a nominal scale of 1:16,000 (Fig. 2). Below we provide a brief synopsis of RD work in each of the major glaciated canyons, beginning with a review of work at the best-studied one, Bloody Canyon, and proceeding south and then north from this critical locale.

Bloody (and Sawmill) Canyons

The moraines of Bloody and Sawmill canyons have an extensive history of detailed study (Sharp and Birman, 1963; Burke and Birkeland, 1979; Gillespie 1982, 1984; Mathieson, 1984; Crook and Gillespie, 1986; Birkeland and Burke, 1988). Phillips *et al.* (1990) have determined experimental cosmogenic ^{36}Cl dates for the right-lateral moraines (Table 1). There are basically two interpretations of the glacial history: Sharp and Birman (1963) split the moraines into four ages, mostly on the basis of boulder surface weathering data collected at several localities on the moraine crests, whereas Burke and Birkeland (1979) lumped them into two, primarily on the basis of soil development and boulder surface weathering at one or two sites on each crest. The remaining references loosely agree with Sharp and Birman.

The key to the different interpretations is the outer (southern) flank of the right-lateral Tahoe moraine of Sharp and Birman (1963). If, as suggested by Gillespie

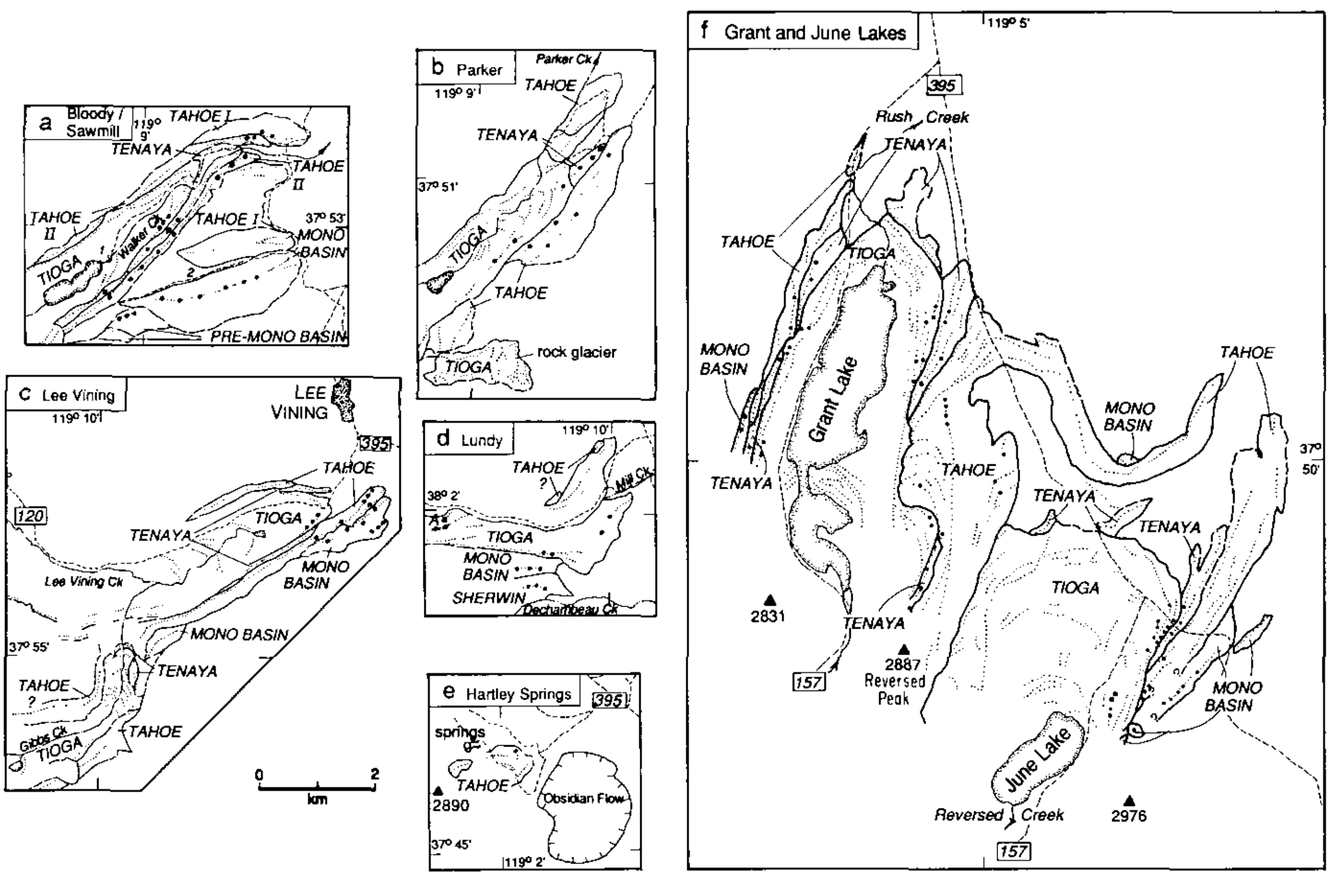

FIG. 2. Relative ages of the late Pleistocene piedmont moraines of Mono Basin. Filled circle = locality at which CSV or semiquantitative weathering data were collected; filled square = site with anomalously low V_p, i.e., "reversely weathered;" dotted line = moraine crest. Contacts are drawn at slope inflections between landforms. Except at Lundy Canyon, Sherwin deposits are not shown. In (a), 1 = Bloody Canyon, 2 = Sawmill Canyon.

(1982), this moraine is composite, consisting of a younger Tahoe II moraine mostly burying an older Tahoe I moraine, the observations of all the researchers can be explained. The anomalously youthful appearance of the Tahoe crest (Burke and Birkeland, 1979), attributed to boulder spalling by forest fires, is simply the result of the younger age of the Tahoe II deposits that constitute the crest where samples were taken (Gillespie, 1982). Bierman and Gillespie (1991) have shown that range fires on the same desert scrub that covers the unforested moraines also spall boulders; thus, differential spalling due to vegetational differences is a poor explanation for the weathering data. From the data of Birkeland and Burke (1988), it appears that soil development on the catenas is more consistent with the interpretation of Sharp and Birman than are data from their 1979 study of weathering on moraine crests. Their Tahoe catena (Fig. 2 in Birkeland and Burke, 1988) is significantly more weathered in its footslope, which is on the partly overtopped Tahoe I moraine of Gillespie (1982), than it is above on the Tahoe II moraine. The change in degree of soil development downslope is more pronounced than on nearby younger (Tioga) and older (Mono Basin) catenas. These observations are best explained by a compound Tahoe moraine. The remaining differences in interpretation may hinge on the inherent temporal resolution of various RD techniques and sampling strategies (Gillespie, 1982, 1984; Birkeland and Burke, 1988). The soils and boulder weathering data of Burke and Birkeland (1979), collected to maximize the number of parameters measured at a small number of sites, did not distinguish Tenaya and Mono Basin deposits of Sharp and Birman (1963) from Tioga and Tahoe deposits, respectively. The V_p data of Crook and Gillespie (1986), consisting of one quantitative parameter measured at a large number of sites, did (Fig. 3a).

We have mapped the glacial geology of Bloody Canyon (Fig. 2a) with relative ages after Sharp and Birman (1963), as modified by Gillespie (1982). At least three post-Sherwin (<~800,000 yr) glaciers advanced down Sawmill Canyon (one Mono Basin advance and two pre-Mono Basin). Subsequently, there were four major advances down Bloody Canyon (Tahoe I, Tahoe II, Tenaya, and Tioga). The moraines from these glaciers overtop and crosscut the older Mono Basin moraines of Sawmill Canyon. Burke and Birkeland (1979) found little difference in soil development between the Sawmill Canyon Mono Basin moraines and the oldest of the Bloody Canyon moraines (Tahoe I in Fig. 2a), and Gillespie (1982) and Crook and Gillespie (1986) likewise found little difference in V_p. Evidently, RD data are not sensitive in this age range, or the two sets of moraines are nearly the same age. The experimental cosmogenic ^{36}Cl dates of Phillips *et al.* (1990) suggest that the Tahoe I glacier advanced one or more times between ~140,000 and ~220,000 yr, and that the Mono Basin glacier was younger (~110,000 yr; Table 1). These data contradict the geomorphic cross cutting relationships of Sharp and Birman (1963) and Crook and Gillespie (1986), who concluded that the right-lateral Tahoe I moraines were deposited over, hence after, the Mono Basin moraines (Fig. 2a). Because the older ^{36}Cl dates are inconsistent with the stratigraphy, because inadequate allowance may have been made for erosion of the sampled boulders in calculating their apparent ages, and because little is known about the accuracy of ^{36}Cl dating in the age range being considered, we view the Tahoe I and Mono Basin ^{36}Cl dates with skepticism. The ^{36}Cl dates of the Tioga through Tahoe II moraines have a much higher probability of being accurate (Table 1). They do not contradict the stratigraphy and are less likely the result of different degrees of boulder erosion. A large percentage of boulders on Tioga through Tahoe II moraines have fresh unweathered surfaces (Gillespie, 1982). The ^{36}Cl ages suggested that Tioga and Tenaya may be separate pulses of a single event, and that Tahoe is considerably older. Overall, we consider the CSV data to be the most useful for relative dating and correlation in Mono Basin because they generally provide the most sensitive results that do not contradict the stratigraphic relationships.

Parker Canyon

Distinct Tioga, Tenaya, and Tahoe moraines occur at Parker Canyon (Fig. 2b). The Tioga moraines of Parker Canyon have an unusually prominent terminal loop, which choked the axial valley sufficiently to cause glacial Parker Creek to cut a path through the lateral moraines. Tioga boulders are characterized by high values of V_p, similar to those measured at Bloody Canyon, and a large fraction of fresh boulder surfaces and shallow weathering pits (Figs. 3b and 4a). An inactive rock glacier south of Parker Canyon is also probably of Tioga age, because of its relatively sharp crests and bouldery surfaces (Bursik, 1988). Within the cirque, which faces east and lies at the base of numerous snow and rock chutes, the rock glacier may be ice cored. Tenaya lateral moraines jut from the base of the Tioga loop and are covered with boulders having distinct, slightly lower values of V_p and marginally fewer fresh surfaces than the Tioga. Elongate Tahoe moraines enclose the Tenaya. Boulders are much more weathered than those on the Tenaya moraines, with some deep pits and only about half of the surfaces being fresh. Although boulders on the outer right-lateral Tahoe crest have slightly lower V_p and the moraine is more gullied than the inner, the two CSV data sets are not statistically distinct and we have grouped the two moraines together.

Grant Lake

At Grant Lake, the moraines again fall into at least three clearly distinguishable relative age groups (Fig. 2g). Sharp-crested, discontinuous Tioga-age ridges and abun-

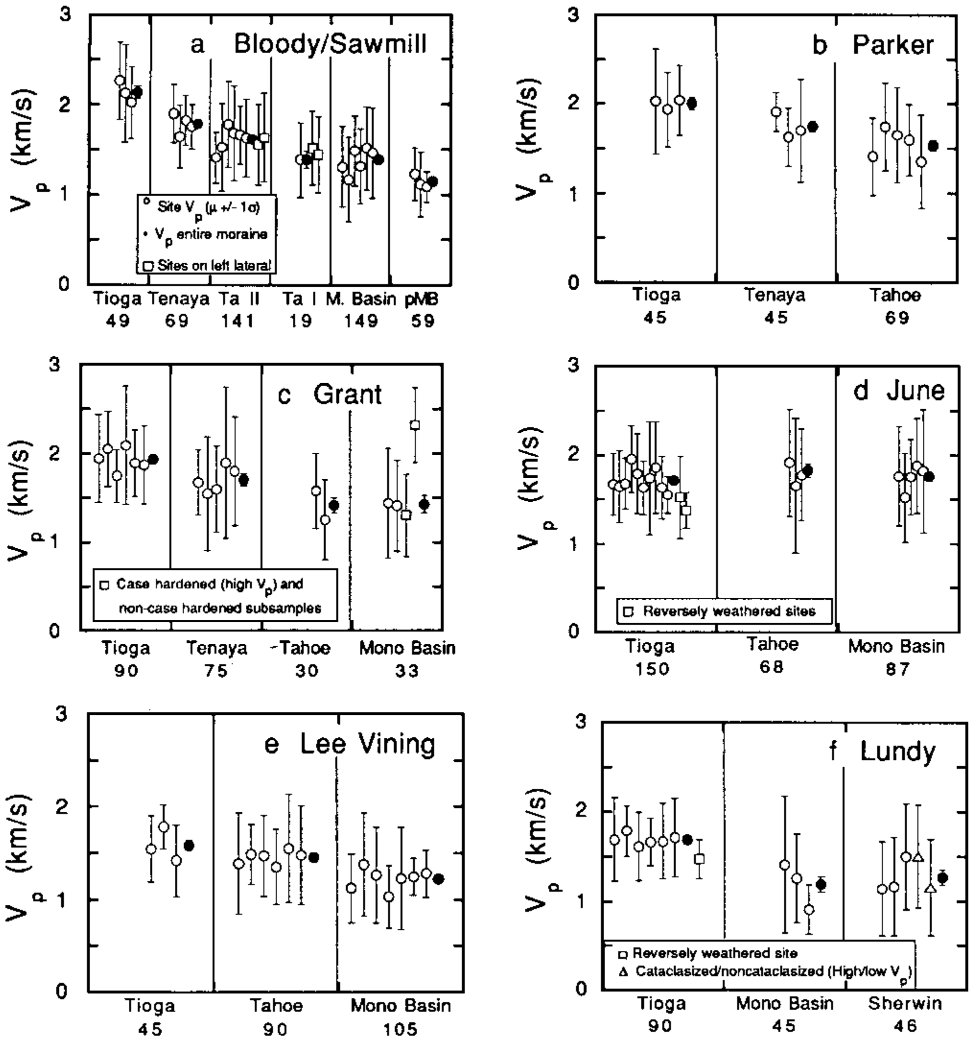

FIG. 3. V_p data for the Mono Basin moraines. Sites shown to the right of the filled symbols were not included in computing mean V_p. The number below each relative-age name is the sample size used to compute mean V_p.

dant nested terminal loops are covered with boulders having high values of V_p and fresh surfaces (Figs. 3b and 4b). Tenaya moraines consist of bulky laterals grading to subdued remnants of a terminal loop (Table 1). At the upstream end of the Tenaya moraine, Tenaya debris lies atop or veneers a Tahoe landform, causing the nominally Tenaya crest to seem unusually broad. As at Parker Canyon, Tenaya boulders are only slightly more weathered than those on the Tioga moraines, but have distinctly lower values of V_p. Boulders on the round-crested Tahoe moraines display surfaces somewhat more weathered than those at Parker Canyon. The existence of numerous recessional Tahoe loops north of Reversed Peak, inboard of the most extensive lateral, suggests that retreat from the Tahoe maximum was incremental, involving many stillstands or readvances. In addition, the Tahoe glacier seems to have merged downstream with both the Parker Canyon and June Lake glaciers. A subdued Mono Basin left-lateral moraine contains a distinct subpopulation of case-hardened boulders (Conca and Rossman, 1982), suggesting that it is considerably older than the Tahoe, even though the respective values of V_p are not statistically separable.

June Lake

Late Pleistocene till at June Lake is interstratified with volcanic deposits (Figs. 1 and 2g). Widespread Tioga moraines rest above basaltic cinder cones and lava flows that were erupted during(?) and after deposition of the Tenaya moraines. These relationships are discussed more fully in a later section. The Tioga moraines contain boulders with fresh and nearly unpitted surfaces (Fig. 4c). At their upstream end, two sharp-crested Tenaya laterals are separated from the Tioga moraines by a subtle topographic unconformity (Table 1). They are also covered with boulders that are distinctly more weathered than are Tioga boulders. A set of extensive Tahoe moraines with discontinuous crests surrounds the Tenaya. Interglacial

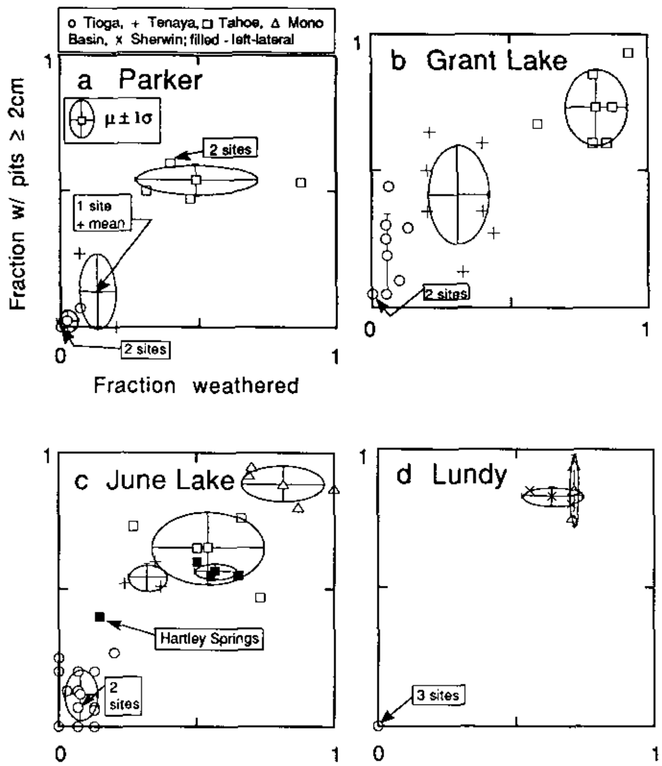

FIG. 4. Semiquantitative weathering data. Each open circle represents a sample locality. The least-weathered (youngest) deposit plots closest to the origin.

range front uplift and headward erosion of Reversed Creek have contributed to excellent preservation of a Mono Basin moraine by downcutting of the canyon floor, so that Tahoe and later moraines were deposited lower on canyon walls. Although both Mono Basin and Tahoe moraines have been displaced by faulting and dissected by erosion, boulders on the Mono Basin moraine are more weathered than those on the Tahoe moraines. Scattered erratics and till sheets near Aeolian Buttes, not shown in Figure 2g, may also be of Tahoe or Mono Basin age (Bailey, 1989).

CSV data do not have the same systematics found in other canyons (Fig. 3c). Some of the ambiguous results here can be related to extensive case hardening of boulder surfaces on both Tahoe and Mono Basin moraines. Although more than half the boulder surfaces on the Mono Basin and Tahoe moraines are weathered (Fig. 4c), only 2% are composed mostly of disaggregated mineral grains that can be rubbed off with boot or hand. Thus, previously decomposed minerals and the boundaries between them appear to have been infilled with secondary minerals, or case-hardened. Since 15% of the boulders on these moraines display eolian fluting, we hypothesize that the hardening is somehow related to ventifaction. Recrystallization of windblown particulates is thought to be an important case-hardening mechanism (Conca and Rossman, 1982).

Hartley Springs

Small bodies of diamicton crop out at Hartley Springs (Fig. 2e). The deposit may constitute an inactive rock glacier or landslide, based on the locally corrugated topography of its upper surface. Because the diamicton overlies Bishop Tuff, it is post-Sherwin in age (Sharp, 1968). The source region is small and relatively low in elevation (<3000 m), and there is no evidence that the diamicton was deposited during multiple events. The lateral ridge (western outcrop in Fig. 2e) has a rounded crest, similar to pre-Tenaya moraines elsewhere. Most granitic boulder surfaces are weathered to an extent similar to that on the Tenaya moraines at June Lake, where boulder lithology and vegetation (Jeffrey Pine) are the same (Fig. 4c). However, the edges of large surficial flakes that have spalled from boulder surfaces clearly crosscut weathering fronts, suggesting that fire has recently spalled many of the boulder surfaces (Burke and Birkeland, 1979) and that weathering characteristics are anomalously young. We tentatively correlate the deposits to the Tahoe glaciation.

Lee Vining Canyon

At least four late Pleistocene glacial maxima are suggested by RD at Lee Vining Canyon (Fig. 2c). Steep-walled Tioga lateral moraines grade to a prominent V-shaped terminus, and contain boulders with low V_p values that are more characteristic of Tenaya-age boulders in some of the adjacent canyons (Fig. 3d). Birman (1964) showed that the fraction of weathered boulders on the Tenaya right-lateral morainal bench and on similarly disposed left-lateral moraines is distinctly different from that on adjacent Tahoe and Tioga moraines. However, RD results may be skewed on the right-lateral moraine by boulders that rolled down from the Tahoe crest, and no RD data were collected there for this study. Two extensive Tahoe moraines merge upstream into the most prominent lateral. Boulders on these crests have values of V_p only slightly lower than, but still distinct from, those on the Tioga. Moreover, Bursik (1991) showed that the Tahoe moraines are distinct from both Tioga and Mono Basin moraines in the degree to which the landform itself has been degraded. Mono Basin moraines are deeply gullied, are crosscut by the Tahoe moraines, and have boulders with distinctly lower V_p. The downstream termini of the Tahoe and Mono Basin moraines are downfaulted and cut by shorelines of Pleistocene Lake Russell.

Terminal loops of Tioga and Tenaya age in Gibbs Canyon (Fig. 2c) suggest that the Gibbs glacier did not contribute ice to the Lee Vining glacier during those times. However, the Tahoe and Mono Basin glaciers of Gibbs Canyon were probably tributary to the Lee Vining glacier, based on the merging of the lateral moraines.

Lundy Canyon

Only one prominent set of moraines extends past the range front at Lundy Canyon (Fig. 2d). Those on the canyon's south side are made up of a series of sharp-crested hummocks, with little evidence for erosion between them, suggesting they constitute an incomplete terminal loop. Based on the pristine appearance of boulders, they are Tioga (Fig. 4d). Except for moraine A (Fig. 2e), boulders also have relatively high V_p (Fig. 3e). Somewhat more extensive and degraded left-lateral moraine remnants are questionably Tahoe. Two prominent, elevated right-lateral moraines are truncated by the range-front fault. Because of the large amount of canyon downcutting postdating deposition of the more proximal of the two, and because of the advanced weathering of boulders (Figs. 3e and 4d), we concur with Sharp and Birman (1963) that it resembles Mono Basin moraines elsewhere. The disposition of moraines at Lundy Canyon thus resembles that at June Lake, where the history of range-front uplift is similar (Bursik and Sieh, 1989). The highly degraded form of the outermost moraine suggests that it is a mid-Pleistocene Sherwin deposit (Blackwelder, 1931). A large fraction of granitic boulders on its surface are of a statistically distinct, slowly weathering cataclastic facies with average V_p significantly higher than that in the remainder of the sample (Fig. 3e). We hypothesize that most normally weathering boulders have weathered away, as on the pre-Mono Basin I moraine at Bloody Canyon and on the Sherwin moraines at Green Creek in Bridgeport Basin (Gillespie, 1982).

DISCUSSION OF RELATIVE AGES

Each study bearing on the late Pleistocene glaciation of the Sierra Nevada requires a reevaluation of the number and significance of glacial advances, especially since Burke and Birkeland (1979) questioned the ability of RD techniques to resolve Tenaya and Mono Basin moraines. Although a full reevaluation would require a review article, it is important for us to place our work in perspective relative to its predecessors. In this respect, we concur with those who have found that Tenaya and Mono Basin do constitute glacial pulses distinct from Tioga and Tahoe (Sharp and Birman, 1963; Birman, 1964) and that CSV provides a powerful RD tool with which to unravel late Pleistocene glacial history (Gillespie, 1982; Crook and Gillespie, 1986). At Bloody Canyon, Parker Canyon, June Lake, and Grant Lake, boulders on Tenaya moraines were consistently weathered to a degree intermediate to that of boulders on both Tahoe and Tioga moraines, justifying our conclusion regarding Tenaya moraines. At Bloody/Sawmill and Lee Vining canyons, Mono Basin deposits were statistically distinct from Tahoe deposits using CSV. At June Lake, semiquantitative weathering criteria differentiated Mono Basin from Tahoe drift, but there and at Grant Lake, CSV did not. In both areas, a significant fraction of Tahoe and Mono Basin boulders are case-hardened, and this may be responsible for the ambiguous CSV results. Except at Bloody Canyon (Gillespie, 1982, 1984), Tahoe moraines were not separable into younger (Tahoe II) and older (Tahoe I) deposits based on CSV (Fig. 2a), possibly because of smaller average sample sizes in canyons other than Bloody/Sawmill, but probably because the glacier changed course from Sawmill Canyon to Bloody Canyon during the Mono Basin glaciation, leaving a glacial record that is not repeated elsewhere.

We have found that CSV provides an objective RD method because of the quantitative nature of the data and the possibility for rigorous statistical testing. The technique is also powerful in that it generally has a higher resolution than other methods, in part because a large data set can be gathered rapidly over an extensive region. The method consistently distinguished at least three relative-age groups in every canyon but one (Fig. 5a). In addition, Tenaya through Mono Basin boulders in different canyons were each characterized by consistent average values of V_p and by monotonic decrease of average V_p with age, except where case-hardening was important. One-way analysis of variance showed that, at the 5% significance level, the relative-age groups (Fig. 5a) are distinct, and no moraine was incorrectly grouped with others within one of the groups. These results support the hypotheses that (a) the most important variable controlling V_p is time, (b) moraines of the same relative age were deposited synchronously, and (c) a consistent, distinct sequence of moraines of at least three relative ages occurs in each canyon. Considered together, the CSV data from the different canyons provide strong evidence for the existence of distinct Tioga, Tenaya, Tahoe, and Mono Basin deposits.

Despite the generally consistent results obtained with CSV, data from Tioga deposits in different canyons are more scattered than are data from older deposits (Fig. 5a). This greater spread is probably the result of several factors. The logarithmic relationship between V_p and age hypothesized by Crook and Gillespie (1986) implies that the resolution of the technique is markedly better for younger deposits (Fig. 5b). Thus, it may be that some Tioga deposits with lower average values of V_p are somewhat older than those with higher values. In addition, inherent variations in the degree of boulder weathering upon deposition, which may yet be reflected in Tioga deposits, will tend to become less pronounced with time. On the other hand, some of the variations in Tioga V_p do correlate with factors that either affect or are affected by weathering rates. Weathering of Tioga boulders at Lundy and Lee Vining canyons may have been accelerated by local, high concentrations of salt in atmospheric aerosols

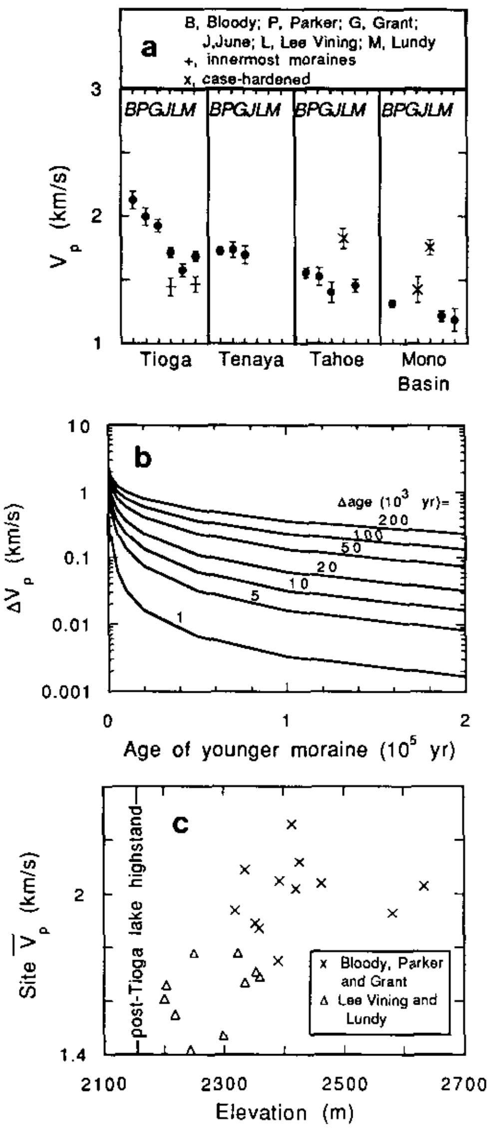

FIG. 5. (a) Mean V_p for different relative-age groups. Each data point in every age group represents a separate canyon. (b) Model of the difference in V_p between two moraines separated in age by the values shown next to curves. The relationship between V_p and age is taken from Crook and Gillespie (1986) for Bloody Canyon. (c) Mean V_p for sites on Tioga moraines at Lee Vining and Lundy canyons, and Bloody Canyon, Parker Canyon, and Grant Lake. Elevation of the late Tioga high stand is from Benson *et al.* (1990).

(Mustoe, 1982; Birkeland, 1984). The CSV sites at these canyons are the lowest in elevation and are or would have been closest to the saline waters of Mono Lake or glacial Lake Russell, and therefore perhaps most likely to receive windblown, saline aerosols derived from wave splash (Fig. 5c). Possibly the low values of V_p measured in boulders on the Tioga moraines at June Lake are related to rapid weathering of the dominant rock type, the granite of June Lake (Bailey, 1989). Crook and Gillespie (1986) report that V_p for coarse-grained lithologies generally decreases more rapidly with time than for fine-grained types. The granite of June Lake is characterized by orthoclase phenocrysts often 1 cm or more long (Huber and Rinehart, 1965). Rock types in the other canyons are fine- to medium-grained.

At both Lundy Canyon and June Lake, where a number of Tioga moraines were tested, V_p in boulders on the innermost recessional moraine was significantly lower than on other Tioga moraines. The boulders on these moraines could be considered "reversely weathered" (Birman, 1964), because of characterization by an RD parameter as older than underlying moraines. In both canyons, three older Tioga moraines had statistically inseparable V_p. Lachmar (1977), using semiquantitative weathering data, found that boulders on the low V_p moraine at Lundy Canyon (moraine A in Fig. 2d) displayed advanced weathering. Boulders at the reversely weathered sites (Fig. 2f) at June Lake are unusually homogeneous relative to those at other sites. The sites lack boulders of a flaggy, epidotized facies that generally has higher V_p than other types when tested. Thus, the low V_p in boulders on moraine A at Lundy Canyon, although yet inexplicable, is consistent with other data suggestive of anomalously advanced weathering. At June Lake, the existence of sites with boulders having low V_p may result from a difference in boulder provenance.

Our data do resolve a Tenaya relative-age group, but they do not imply that the Tenaya should necessarily be construed as a distinct "first-order" advance (glaciation). In fact, the nature of the CSV technique is such that it may resolve at the stade level for younger deposits and at the glaciation level for older deposits (Fig. 5b). Nevertheless, radiometric-age data that we present in the following section suggest that it may be at least 5000 yr older than the Tioga.

POSSIBLE SIGNIFICANCE OF THE STRATIGRAPHY AT JUNE LAKE

It has long been recognized that the occurrence of both glacial and lacustrine deposits in Mono Basin provides a unique opportunity to study the response of these two systems to climate change (Russell, 1889; Putnam, 1950; Lajoie, 1968; Lajoie and Robinson, 1982; Benson and Thompson, 1987). Our research, coupled with recent advances in radiometric dating (Edwards *et al.*, 1987; Bard *et al.*, 1990; Phillips *et al.*, 1990), allows us to undertake a preliminary comparison of the two records constrained by radiometric ages for both. The singular interstratification of latest Pleistocene till and basalt at June Lake is crucial to the comparison, since it helps to constrain our knowledge of the timing of the glacial advances.

There is evidence consistent with the eruption of some of the basaltic lavas at June Lake at the same time as the Tenaya glaciation. Unit Qb_1 (Fig. 6a) is composed of flow slabs overlying(?) fragmental material. Although achne-

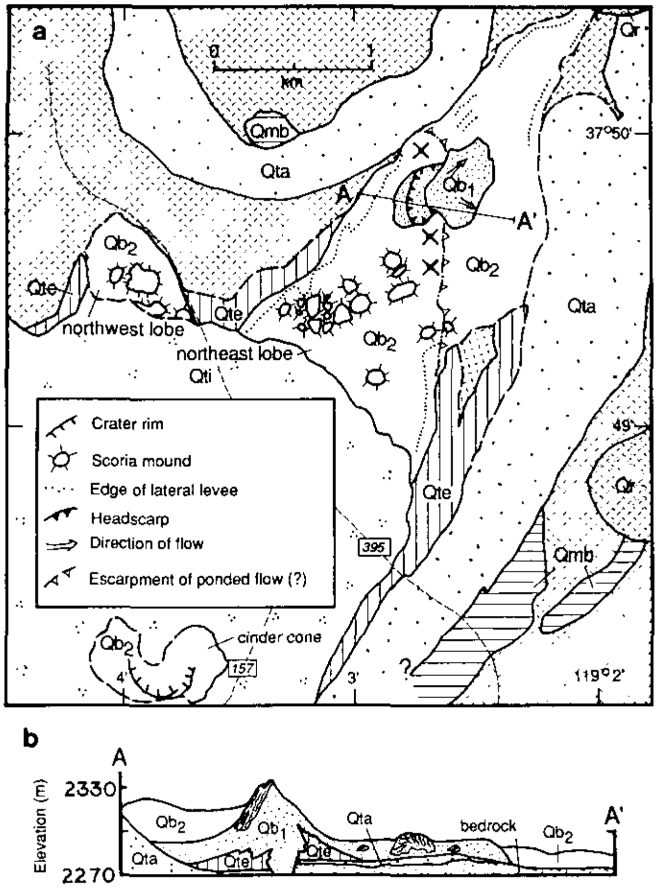

FIG. 6. (a) Detailed map of volcanic and glacial landforms at June Lake. Qmb, Mono Basin; Qta, Tahoe; Qte, Tenaya; Qti, Tioga; Qb_1, older basalt (crosses = small outcrops of Qb_1); Qb_2, younger basalt; Qr, rhyolitic domes of the Mono Craters. Unlabeled areas are surfaces of low relief defining the top of pumice or drift sheets and Bishop Tuff. (b) Schematic cross section through A–A′ as shown in (a). The wavy patterns within parts of unit Qb_1 show the dips of flow foliations in coherent lava sheets and blocks.

liths (pyroclasts shaped by flight) are common among the ejecta, a substantial proportion of pyroclasts are also angular and poorly vesiculated. Some exposures even contain ellipsoidal features with glassy and breadcrusted rinds reminiscent of pillow lava (Jones, 1970). Xenoliths of the granite of June Lake are common, and palagonitization is pervasive although not extensive. Structurally, Qb_1 is the result of the collapse of an earlier more substantial landform. The outcrop pattern (Fig. 6b) suggests that collapse may have occurred in two episodes, that to the west by tilting of the flow slabs and that to the east by landsliding. The data suggest that the original landform may have been composed of fragmental material overlain by a relatively flat-topped flow—a small table mountain. The common occurrence of xenoliths of the granite of June Lake suggests that Qb_1 entrained a considerable amount of till upon eruption, because the local bedrock is quartz monzonite of Aeolian Buttes (Kistler, 1966), not the June Lake lithology. If the Tenaya moraine remnants are extrapolated to the position of a terminal loop, that loop could have closed at the present position of the Qb_1 outcrop. These data are consistent with eruption of Qb_1 through the Tenaya terminal loop. Furthermore, the eruption of Qb_1 may have occurred as the loop was being deposited. The pyroclast assemblage has features characteristic of subglacial debris formed by magma–water interaction (numerous bedrock fragments; some angular, poorly vesiculated juvenile clasts), and steep-sided, constructional table mountains are common subglacial landforms (Jones, 1970). Our interpretation is tentative because subaerial "agglutinate mounds," with gross stratigraphy similar to that inferred for Qb_1, have also been described (Holm, 1987), and because other interpretations of outcrop relationships may be reasonable. For example, magma rising within the eruptive conduit could have encountered water impounded behind the Tenaya loop. However, the interpretation that best fits most data seems to be that presented above.

Basaltic lavas were probably erupted more than once at June Lake during the latest Pleistocene. Unit Qb_2 probably postdates the Tenaya and predates the Tioga glaciations. It consists of flows and scoria mounds, as well as a cinder cone consisting of interstratified scoria and glacially striated lava northeast of June Lake (Oh! Ridge). The scoria is well vesiculated and achneliths are common. Xenoliths are absent and palagonite rare. Cinder cones, scoria mounds, and associated flows are typical subaerial features. The mounds and flows can be genetically linked to the cinder cone by the occurrence of lateral levees on the northeast flow lobe that project to the southwest and scoria mounds overtopped with till and erratics from the southern quadrant on the northwest flow lobe, both of which suggest a source in the southern quadrant: the cone near June Lake. The occurrence of the subaerial cone 2 km upcanyon from the Tioga terminus indicates that ice had retreated beyond that point during the time between Tenaya and Tioga glacial pulses. The lava within the cone was subsequently striated when the Tioga glacier advanced.

Basaltic ash associated with these eruptions possibly occurs in the beds of the 12,000 to 36,000-^{14}C-yr-old Wilson Creek Formation (Lajoie and Robinson, 1982). Within the Wilson Creek Formation, Lajoie (1968) found three layers bearing basaltic lapilli, which he designated as ash layers 2, 7*, and 13*. Ash layer 2, dated by him at 13,300 ^{14}C yr B.P., clearly is derived from Black Point (Fig. 1), for it thickens toward that volcano. However, ash layer 7* is thicker to the south and east of Mono Lake than it is near Black Point. Ash layer 13* does not crop out on the north side of Mono Lake, near Black Point. There is no evidence for a hiatus or erosion of these layers. No potential ash sources exist east of the lake. Therefore, the depositional patterns suggest that the sources for ash layers 7* and 13* must be south of Mono

Lake. Although an undated basaltic flow crops out north of Aeolian Buttes (Putnam, 1949) and others may underlie the Mono Craters (Kelleher, 1986), the data presented above suggest that the eruptions at June Lake may have occurred at about the same time that the Wilson Creek beds were being deposited. We therefore tentatively correlate the subglacial(?) eruption of Qb_1 to ash layer 13* and the subaerial eruption of Qb_2 to ash layer 7*.

Recently, Bard *et al.* (1990) have presented a comparison of the U–Th timescale with the ^{14}C timescale over the past 30,000 yr. They argue that the U–Th scale can be used to calibrate the ^{14}C scale in this period and present convincing arguments that this is reasonable at least back to 11,000 yr B.P. If we assume that the calibration is valid for even greater ages, and that a least-squares regression to the U–Th and conventional ^{14}C data sets given in their Table 1 provides a reasonable first-order calibration (r^2 = 0.99 for the regression), we can correct the ^{14}C ages of the ash layers for variations in cosmogenic production rate. We stress that these adjusted ages are model ages only, and that a thorough correction of ^{14}C ages from Mono Lake cannot be undertaken because of local variations in reservoir exchange rate and incorporation of young, secondary carbon (Benson *et al.*, 1990). We correct the age of ash layer 7* from 21,600 yr B.P. (Benson *et al.*, 1990) to 25,200 "U–Th-calibrated" yr B.P. and that of layer 13* from 26,400 yr B.P. (Lajoie, 1968; Benson *et al.*, 1990) to 30,700 "U–Th-calibrated" yr B.P., where "U–Th-calibrated" means that a correction using the Bard *et al.* data has been made. Based on the arguments outlined above, we suggest that the 25,200 ± 2500 yr date is a maximum-limiting age for the Tioga glaciation, and the 30,700 ± 2700 yr date is either a minimum-limiting age for, or possibly the age of, the Tenaya glaciation at June Lake (Table 1). The possibility that the Tioga maximum followed the Tenaya by ≥~5000 yr suggests that they could differ in age by a significant amount, thus leaving open the possibility that they are separate glaciations.

SPECULATIONS ON THE GLACIAL AND LACUSTRINE RECORDS

Given possible constraints on the ages of the Tioga and Tenaya glaciations in Mono Basin and its vicinity, we can compare the hypothesized latest Pleistocene glacial record with the record of Lake Russell surface elevation (Fig. 7). The synthesis of glacial data is based upon several studies. The data presented here and those of Phillips *et al.* (1990) for Bloody Canyon are directly relevant to lake-level data, because the level of Pleistocene Lake Russell must have responded to the same climatic factors responsible for the volume fluctuations of glacier ice in these canyons. We tentatively accept the ages of Phillips

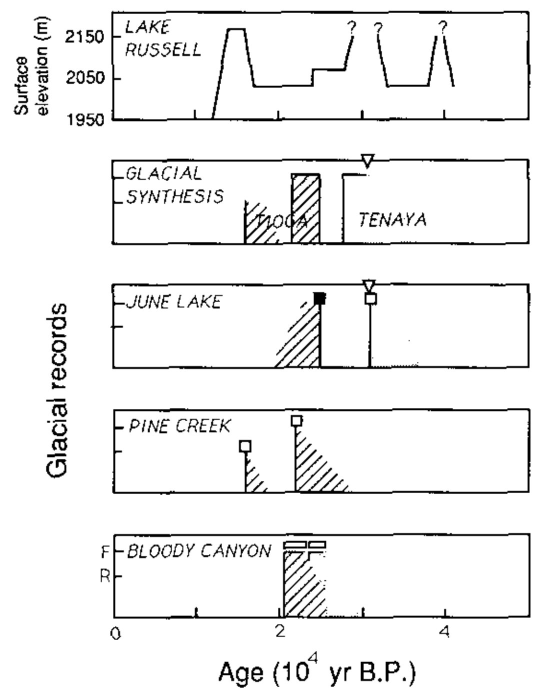

FIG. 7. Schematic comparison of glacial records with the lake-level record for latest Pleistocene time. F, full-glacial; R, recessional. Filled square = maximum limiting "U–Th-calibrated" age; open rectangle or square = minimum limiting "U–Th-calibrated" age; open triangle = possible "U–Th-calibrated" age of the Tenaya maximum. For the "Glacial Synthesis," where two pertinent limiting ages exist, their mean is plotted. Data are from the sources shown in Table 1.

et al. for the Tioga and Tenaya moraines because the problem of erosion of boulder surfaces is much less serious than it is for the profoundly eroded boulders on the Tahoe I and Mono Basin moraines. Many of the boulders on the Tioga and Tenaya moraines retain fresh, striated surfaces. The data from Dorn *et al.* (1987) on the timing of the pulses of Tioga ice in Pine Creek are less directly applicable. However, the close agreement between the inferred age of the Tioga maximum at Pine Creek and that within Mono Basin suggests that the age of the last major Tioga recessional moraines, best developed at Grant Lake (Fig. 2g), may also be the same in the two areas. The lacustrine record in Figure 7 is based on the extensive work of K. Lajoie presented in Benson *et al.* (1990).

The important features of the comparison are the following: (1) The Tenaya maximum may have occurred during or before a high stand from 33,000 to 28,000 yr B.P. (2) The Tioga maximum appears to have occurred at some time during a brief relative intermediate to low stand between 28,000 and 17,000 B.P. Thus, periods of greatest ice volume may correspond with maximum pluvial conditions in some instances, but with relatively "dry" conditions in others. Russell (1889), Lajoie (1968), and Lajoie and Robinson (1982) have shown clearly that the Tioga maximum did not occur during a high stand; (3) A shortlived lacustrine maximum about 16,000 "U–Th-calibrated" yr B.P. is synchronous with the final major Tioga recessional pulse (≥16,300 "U–Th-calibrated" yr B.P.; Dorn *et al.* 1987). This paired glacial/lacustrine maximum may be the result of the latest major occurrence of cold, wet conditions. It is unlikely that enhanced glacial melting is the cause of the lacustrine maximum. Data collected by M. M. Clark (1976; personal communication, 1990) suggest that Tioga ice melted rapidly somewhat after deposition of the recessional moraine, probably as the result of a distinct amelioration of climate.

ACKNOWLEDGMENTS

A number of people provided invaluable assistance during the course of this work. Kerry Sieh edited an earlier version of the manuscript and spent some time studying the moraines with us in the field. Malcolm Clark, Jerry Weber, Oliver Chadwick, and Roy Bailey are heartily thanked for their many useful comments on the present manuscript. Peter Birkeland and Doug Burbank are thanked for insightful formal reviews. Bob Sharp and Joe Birman are also thanked for their help. Dick Crook helped to debug the microseismic timer. Steve Barsi of Lee Vining let M.I.B. charge the timer numerous times. Andy Thomas helped collect some of the CSV data.

The work was supported by U.S. Geological Survey Earthquake Hazards Reduction Program Grants 14-08-0001-22011, -G1098, and -G1370 (to Kerry Sieh) and by Geological Society of America Penrose Grant 3547-86. The microseismic timer was lent by the U.S. Geological Survey through Dick Crook. Use of facilities by M.I.B. at DES and ITG, Cambridge, is acknowledged. The manuscript was completed while M.I.B. held an NRC–JPL (Caltech) Research Associateship, under contract with NASA.

REFERENCES

Bailey, R. A. (1989). "Geologic Map of the Long Valley Caldera, Mono-Inyo Craters Volcanic Chain, and Vicinity, Eastern California. U.S. Geological Survey Miscellaneous Investigations Series Map I-1933.

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

Benson, L. V., Currey, D. R., Dorn, R. I., Lajoie, K. R., Oviatt, C. G., Robinson, S. W., Smith, G. I., and Stine, S. (1990). Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 years. *Paleogeography, Paleoclimatology, Paleoecology* **78**, 241–286.

Bierman, P., and Gillespie, A. R. (1991). Range fires: A significant factor in exposure–age determination and geomorphic surface evolution. *Geology* **19**, 641–644.

Birkeland, P. W. (1984). "Soils and Geomorphology." Oxford Univ. Press, New York.

Birkeland, P. W., and Burke, R. M. (1988). Soil catena chronosequences on eastern Sierra Nevada moraines, California, U.S.A. *Arctic and Alpine Research* **20**, 473–484.

Birman, J. H. (1964). "Glacial Geology across the Crest of the Sierra Nevada, California." Geological Society of America Special Paper 75.

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

Burke, R. M., and Birkeland, P. W. (1979). Reevaluation of multiparameter relative dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California. *Quaternary Research* **11**, 21–51.

Bursik, M. I. (1988). "Late Quaternary Volcano-Tectonic Evolution of the Mono Basin, Eastern California." Unpublished Ph.D. dissertation, California Institute of Technology.

Bursik, M. I. (1991). Relative dating of moraines based on landform degradation, Lee Vining Canyon, California. *Quaternary Research* **35**, 451–455.

Bursik, M., and Sieh, K. (1989). Range front faulting and volcanism in the Mono Basin, eastern California. *Journal of Geophysical Research* **94**, 15587–15609.

Chesterman, C. W., and Gray, C. H., Jr. (1975). "Geology of the Bodie Quadrangle, Mono County, California." California Division of Mines and Geology, Map Sheet 21.

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

Clark, M. M. (1979). Range-front faulting: Cause of the difference in height between Mono Basin and Tahoe moraines at Walker Creek. *In* "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. Field Trip Guidebook for Friends of the Pleistocene Pacific Cell" (R. M. Burke and P. W. Birkeland, Eds.), pp. 54–57.

Conca, J. L., and Rossman, G. R. (1982). Case hardening of sandstone. *Geology* **10**, 520–523.

Crook, R. (1986). Relative dating of Quaternary deposits based on p-wave velocities in weathered granitic clasts. *Quaternary Research* **25**, 281–292.

Crook, R., and Gillespie, A. R. (1986). Weathering rates in granitic boulders measured by p-wave speeds. *In* "Rates of Chemical Weathering of Rocks and Minerals" (S. M. Colman and D. P. Dethier, Eds.), pp. 395–417. Academic Press, Orlando, FL.

Dorn, R. I., Turrin, B. D., Jull, A. J. T., Linick, T. W., and Donahue, D. J. (1987). Radiocarbon and cation-ration ages for rock varnish on Tioga and Tahoe morainal boulders of Pine Creek, eastern Sierra Nevada, Calif., and their paleoclimatic implications. *Quaternary Research* **28**, 38–49.

Edwards, R. L., Chen, J. H., and Wasserburg, G. J. (1987). ^{238}U–^{234}U–^{230}Th–^{232}Th systematics and the precise measurement of time over the past 500,000 years. *Earth and Planetary Science Letters* **81**, 175–192.

Gillespie, A. R. (1982). "Quaternary Glaciation and Tectonism in the Southeastern Sierra Nevada, Inyo County, California." Unpublished Ph.D. dissertation, California Institute of Technology.

Gillespie, A. R. (1984). Evidence for both Wisconsin and Illinoian ages for the Tahoe glaciation, Sierra Nevada, California. *Geological Society of America Abstracts with Programs* **16**, 519.

Holm, R. F. (1987). Significance of agglutinate mounds on lava flows associated with monogenetic cones: An example at Sunset Crater, northern Arizona. *Geological Society of America Bulletin* **99**, 319–324.

Huber, N. K., and Rinehart, C. D. (1965). "Geologic Map of the Devils Postpile Quadrangle, Sierra Nevada, California." U.S. Geological Survey Map GQ-437.

Jones, J. G. (1970). Intraglacial volcanoes of the Laugarvatn region, southwest Iceland, II. *Journal of Geology* **78**, 127–140.

Kelleher, P. C. (1986). "The Mono Craters–Mono Lake Islands Volcanic Complex: Evidence for Several Magma Types, Magma Mixing, and a Heterogeneous Source Region." Unpublished M.S. thesis, University of California, Santa Cruz.

Kesseli, J. E. (1941). Studies in the Pleistocene of the Sierra Nevada, California. *University of California Publications in Geography* **6**, 315–362.

Kistler, R. W. (1966). "Geologic Map of the Mono Craters Quadrangle, Mono and Tuolomne Counties, California." U.S. Geological Survey Quadrangle Map GQ-462.

Lachmar, T. E. (1977). "Glacial Geology of Lundy, Virginia, and Green Canyons, Mono County, California." Unpublished M.S. thesis, Purdue University.

Lajoie, K. R. (1968). "Late Quaternary Stratigraphy and Geologic History of Mono Basin, Eastern California." Unpublished Ph.D. dissertation, University of California, Berkeley.

Lajoie, K. R., and Robinson, S. W. (1982). Late Quaternary glaciolacustrine chronology, Mono Basin, California. *Geological Society of America Abstracts with Programs* **14**, 179.

Mathieson, S. A. (1984). Comparison of glacial sequences between the Yuba-Feather Divide, northern Sierra Nevada and Mono Basin, central Sierra Nevada, California: Evidence for an Illinoian Tahoe glaciation. *Geological Society of America Abstracts with Programs* **16**, 320.

Matthes, F. E. (1930). "Geologic History of the Yosemite Valley." U.S. Geological Survey Professional Paper 160.

McGee, W. J. (1885). On the meridional deflection of ice streams. *American Journal of Science* **29**, 386–392.

Mustoe, G. E. (1982). The origin of honeycomb weathering. *Geological Society of America Bulletin* **93**, 108–115.

Phillips, F. M., Zreda, M. G., Smith, S. S., Elmore, D., Kubik, P. W., and Sharma, P. (1990). Cosmogenic chlorine-36 chronology for glacial deposits at Bloody Canyon, eastern Sierra Nevada. *Science* **248**, 1529–1532.

Putnam, W. C. (1949). Quaternary geology of the June Lake district, California. *Geological Society of America Bulletin* **60**, 1281–1302.

Putnam, W. C., (1950). Moraine and shoreline relationships at Mono Lake, California. *Geological Society of America Bulletin* **61**, 115–122.

Russell, I. C. (1889). Quaternary history of the Mono Valley, California. *In* "U.S. Geological Survey Eighth Annual Report," pp. 267–394. (Reprinted by Artemisia Press, Lee Vining, CA, 1984.)

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., and Birman, J. H. (1963). Additions to the classical sequence of Pleistocene glaciations, Sierra Nevada, California. *Geological Society of America Bulletin* **74**, 1079–1086.