RELATIVE AGES OF PLEISTOCENE MORAINES DISCERNED FROM PEBBLE COUNTS: EASTERN SIERRA NEVADA, CALIFORNIA

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Abstract: A modified Wolman pebble count, traditionally used in fluvial science, is used to assess relative ages for glacial moraines at Bloody and Sawmill canyons, eastern California. Results show statistically separable size distributions among surface deposits of five known moraine groups, with finer distributions associated with older deposits. Large variance in clast size prevents robust distinction of younger moraines, but not older moraines that are most difficult to date. Results contribute to ongoing debate about the locale's oldest age groups, with Mono Basin predating Tahoe 1 moraines. [Key words: Pleistocene, size distribution, weathering, glacial geomorphology, Sierra Nevada.]

INTRODUCTION

Glacial chronologies interpreted from the large and well-preserved moraine sequences of California's eastern Sierra Nevada have provided much insight into past episodes of North American glaciation (Phillips et al., 1990; Gillespie and Molnar, 1995; Clark and Gillespie, 1997) and paleohydrology (Benson et al., 1996). Inferred episodes of glacier advance correlate with Heinrich events in the North Atlantic, successfully establishing the region's teleconnection to the global-scale climate system (Phillips et al., 1996). Nested moraines at Bloody and Sawmill canyons, in particular, represent a classic-type locale (Russell, 1889) for the region. Matthes (1925) recognized at least two glaciations, owing to geomorphic contrasts between older and younger sets of moraines. Blackwelder (1931) named four glacial advances—McGee, Sherwin, Tahoe, and Tioga—in order from oldest to youngest, also using geomorphic differences. Sharp and Birman (1963) identified two additional events: the Tenaya intermediate between the Tioga and Tahoe advances; and the Mono Basin intermediate between the Tahoe and Sherwin advances. Subsequent research, based on ^{36}Cl (Phillips et al., 1990, 1996) and clast sound-

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velocity (CSV) techniques (Crook and Gillespie, 1986; Bursik and Gillespie, 1993), further divided Tahoe moraines into separate events.

Considerable debate exists over the relative age relationship among the two oldest and most distal moraine sets; older Tahoe and Mono Basin. Traditional geomorphic and relative age dating methods suggest Mono Basin deposits to be oldest (Sharp and Birman, 1963). However, this interpretation has been challenged by ^{36}Cl cosmogenic dating of exposed boulders on moraine crests (Phillips et al., 1990) leading to conflicting interpretations of their chronology (Bursik and Gillespie, 1993). Such cosmogenic dating is a powerful tool for establishing numerical dating control on moraine deposits and was in fact developed at this locale (Phillips et al., 1990). However, it is possible for cosmogenic strategies to yield ages that are too young (Bierman, 1994; Hallet and Putkonen, 1994; Clark et al., 1995; Phillips et al., 1996; Putkonen and Swanson, 2003) when till matrix erosion exposes boulders long after moraine deposition.

Although relative dating (RD) techniques do not establish numerical ages, many geomorphologists still view them as useful for determining chronological age relationships among a suite of moraine deposits (Sharp and Birman, 1963; Sharp, 1969; Carrara, 1972; Carrara and Andrews, 1972; Dugdale, 1972; Burke and Birkeland, 1979; Crook, 1986; Bursik, 1991; Bursik and Gillespie, 1993; Berry, 1994; Pinter et al., 1994; Nicholas and Butler, 1996). For example, older moraines tend to be broader and lower in surface elevation (Bursik, 1991), with decreased abundance of surface boulders (Blackwelder, 1931; Sharp and Birman, 1963; Birman, 1964; Sharp, 1969; Burke and Birkeland, 1979; Berry, 1994; Pinter et al., 1994), thicker weathering rinds (Burke and Birkeland, 1979; Nicholas and Butler, 1996; Berry, 1994), and deeper pit depths (Burke and Birkeland, 1979; Berry, 1994). Clast-sound velocities (CSV) also decrease with increasing moraine age (Crook and Gillespie, 1986; Bursik and Gillespie, 1993). The core assumptions implicit in these and other RD methods are that: (1) the comparison moraines are all derived from similar rock material; and (2) that they undergo uniform processes of weathering and erosion such that differences in weathering-related physical properties progress uniformly over time from the same initial state.

This paper explores use of the pebble count procedure (Wolman, 1954) as an additional RD technique for establishing relative age relationships among moraines of the same locale. Pebble counts were originally developed in fluvial science to obtain statistically sound characterizations of particle-size distributions in river channels (Wolman, 1954; Diplas and Lohani, 1997) and are used widely in fluvial studies (Kondolf, 1997). Similar applications to other fields include studies of glacier transport mechanisms and history (Fleisher, 1993; Benn and Ballantyne, 1994; Mahaney et al., 2000; Harris et al., 2004), geological outcrops (Mohan and Rao, 1992), and alluvial fans (Ibbeken et al., 1998). Bäumler (2004) used bulk samples of fine particles (<2 mm) from six terminal moraines to characterize soil development on Quaternary glacial deposits in Nepal. The analysis revealed all soils to be of similar particle size and were therefore interpreted to be of similar soil age (Bäumler, 2004). Here, we apply a modified pebble-count procedure to the well-studied (Russell, 1889; Matthes, 1925; Blackwelder, 1931; Sharp and Birman, 1963; Burke and Birkeland, 1979; Phillips et al., 1990; Bursik and Gillespie, 1993;

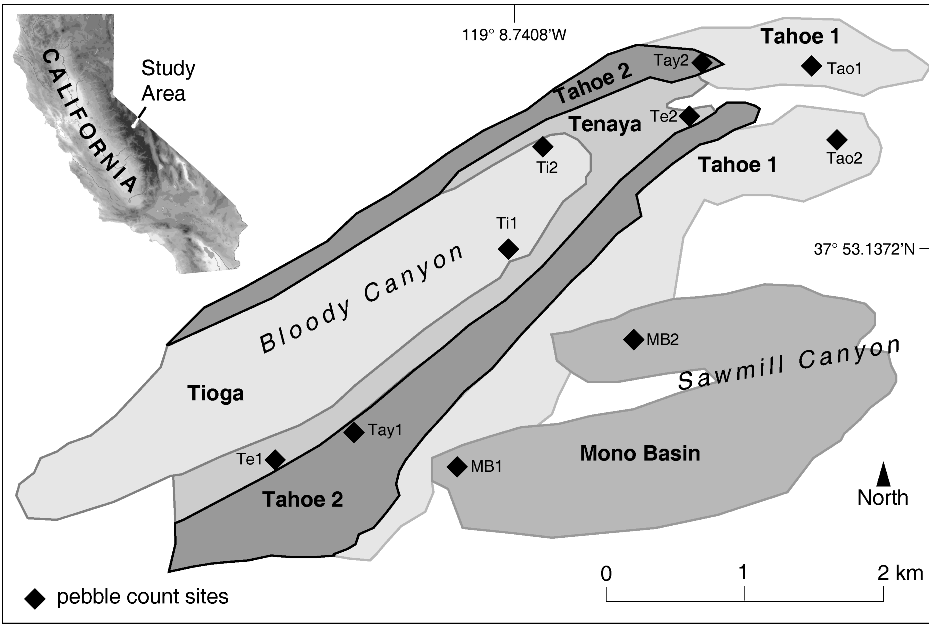

Fig. 1. Moraine deposits of Bloody and Sawmill canyons and location of pebble count sample sites. Deposit nomenclature (Tioga, Tenaya, Tahoe 2, Tahoe 1, Mono Basin) is based on previous mapping by Blackwelder (1931), Sharp and Birman (1963), Phillips et al. (1990), and Bursik and Gillespie (1993).

Table 1. Sample Site Locations and Site Attributes[a]

Glaciation event	Published radiometric age (yr B.P.)[b]	Method	Source
Tioga	(>20,400–23,100)	^{36}Cl	Phillips et al. (1990)
	<25200 ± 2,500	CSV[c]	Bursik and Gillespie (1993)
Tenaya	>30,700 ± 2,700	CSV	Bursik and Gillespie (1993)
	(>23,300–25,500)	^{36}Cl	Phillips et al. (1990)
Tahoe 2	<118,000 ± 7,000	CSV	Gillespie (1982)
	(>55,900–65,800)	^{36}Cl	Phillips et al. (1990)
Tahoe 1	(>189,000–218,000)	^{36}Cl	Phillips et al. (1990)
	(>133,000–149,000)	^{36}Cl	Phillips et al. (1990)
Mono Basin	>131,000 ± 10,000	CSV	Gillespie (1982)
	(>92,000–119,000)	^{36}Cl	Phillips et al. (1990)

[a]Previously published age estimates for Bloody Canyon–Sawmill Canyon moraine deposits. Note the conflicting relative age relationship between the two oldest moraine groups (Tahoe 1 and Mono Basin), based on CSV and ^{36}Cl data. Age groups are arranged by relative age (youngest to oldest) as determined from our clast size statistics (Table 2).

[b]Ages are constraints on the age of the glacial maximum. Error bars are estimated $\pm 2\sigma$ (~95% confidence interval). Parentheses indicate experimental (^{36}Cl) ages.

[c]CSV indicates measure of clast-sound velocity.

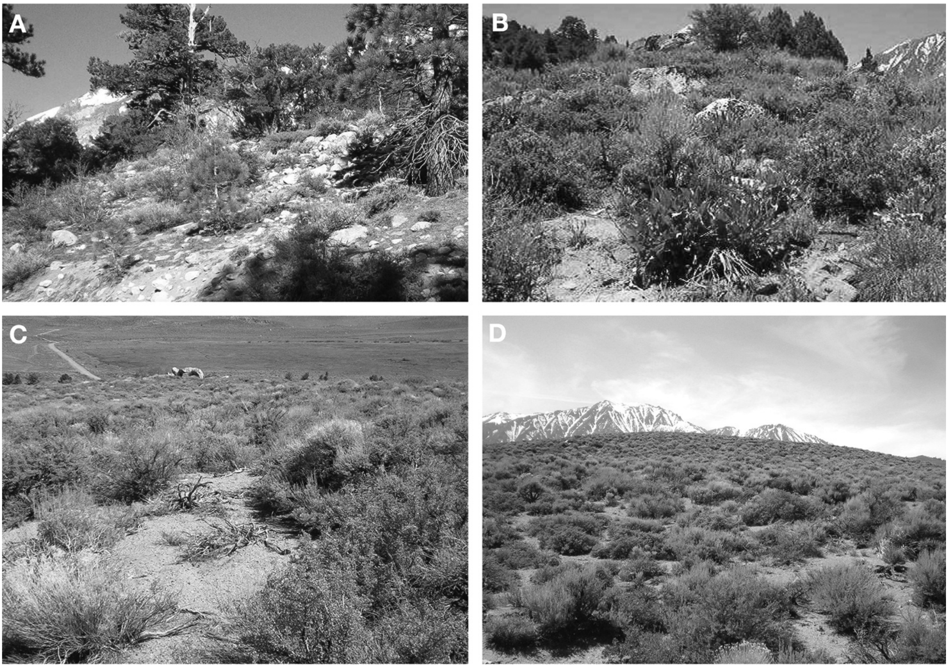

Fig. 2. Field photographs of Bloody Canyon and Sawmill Canyon glacial moraine deposits, ordered from "youngest" to "oldest" age groups: (A) Tenaya; (B) Tahoe II; (C) Tahoe 1; (D) Mono Basin. Surface deposits on the oldest moraines are characterized by finer particle size distributions of surface material, as well as less convexity and lower boulder frequencies.

Phillips et al., 1996) suite of nested moraines at Bloody and Sawmill canyons in California's eastern Sierra Nevada (Fig. 1).

STUDY SITE AND METHODOLOGY

Excellent moraine preservation along the eastern Sierra Nevada led to early and extensive studies of these easily accessed deposits. Glaciers exiting Bloody and Sawmill canyons formed distinct lateral and end moraine sets (Fig. 1) studied by Blackwelder (1931), Sharp and Birman (1963), Burke and Birkeland (1979), Phillips et al. (1990), Bursik and Gillespie (1993), and Phillips et al. (1996). The Tioga, Tenaya, Tahoe 2, Tahoe 1, and Mono Basin deposits comprise a series of nested or adjacent moraines, extending the length of Bloody and Sawmill canyons. Names are assigned according to morphological relationships and in accordance with Blackwelder (1931), Sharp and Birman (1963), Phillips et al. (1990), and Bursik and Gillespie (1993). Published age estimates for these deposits range from ~22 ka to more than 200 ka (Table 1). In the field, the moraines clearly display a wide range of weathered and erosion states, ranging from sharp-crested ridges with fresh, bouldery deposits to broad, low-elevation moraines with deeply weathered surfaces (Fig. 2). Tioga moraines are characterized by high surface elevations, steep slopes, and large, less weathered boulders. Tenaya moraines surround those of Tioga and

Table 2. Statistics of Pebble Count Sample Data[a]

Rank	Sample	Study sites	No. samples	Location (lat N./long. W)	$\bar{x}$ (mm)	σ_M (mm)
1	Tioga (b)	Ti2	250	37°53.5542', 119°8.5992'	167.24	14.57
2	Tenaya	Te1, Te2	500	37°52.3134', 119°9.6306' 37°53.7066', 119°7.9200'	105.70	5.60
2	Tioga (a)	Ti1	250	37°53.1372', 119°8.7408'	101.08	10.11
3	Tahoe 2 (b)	Tay2	250	37°53.8536', 119°7.9890'	86.78	6.75
4	Tahoe 2 (a)	Tay1	250	37°52.4388', 119°9.3666'	69.65	6.07
5	Tahoe 1	Tao1, Tao2	500	37°53.8602', 119°7.5606' 37°53.5722', 119°7.4568'	26.57	2.95
6	Mono Basin	MB1, MB2	500	37°52.7814', 119°8.2656' 37°52.3290', 119°9.0390'	16.03	2.29

[a]Descriptive statistics for separable clast size populations identified in the pebble count data. Mean grain size ($\bar{x}$) and standard error (σ_M) decrease for relatively older moraines. Rank is relative age chronology based on the mean clast size. Six statistically separable size distributions were found among the five previously mapped age groups.

exhibit very sharp, high crests with some slightly weathered large boulders. Tahoe 2 moraines exhibit a variety of broken and weathered boulders, with more gullied flanks and eroded termini. The older Tahoe 1 moraines exhibit highly weathered surfaces, few boulders, greater soil development, and gentle slopes. Mono Basin moraines appear visually similar to the Tahoe 1 deposits. All investigators agree that Tahoe 1 and Mono Basin moraines are the oldest deposits in the locale and mark the maximum extent of past glaciations in the area.

We intensively sampled surface clast size distributions (Table 2) for each of the five previously recognized moraine age groups (Fig. 1; Table 1) using pebble counts. Paired measurement sites on opposite laterals for each moraine set permit testing for self-consistency within age groups, with the exception of the Tenaya deposits, which do not form a distinct left lateral moraine crest (Fig. 1). The pebble count method for sampling coarse river-bed material (Wolman, 1954) uses a grid-based sampling scheme to measure a representative population of clast sizes for an entire stream reach, a strategy developed to obtain adequate sample sizes from gravel beds (Church et al., 1987). Although other variants exist (Bevenger and King, 1997), Diplas and Lohani (1997) strongly recommend collecting samples systematically or at grid points. When used properly, the method generates reproducible size distributions for individual gravel deposits (Wolman, 1954; Kondolf, 1997).

Wolman (1954) proposed sampling 100 pebbles within a grid, with even spacing between grid points. Hey and Thorne (1983) and Olsen et al. (2005) proposed larger sample sizes (>100) to capture the greater variability exhibited by poorly sorted river bed material. Due to poor sorting inherent in glacial tills, we used a sampling of 250 particles, with one clast sampled at every intersection of a 1 m × 1 m grid within a 10 m × 25 m sample area along the crest of each sample site identified in Figure 1. A measuring tape suspended across the grid transects enabled

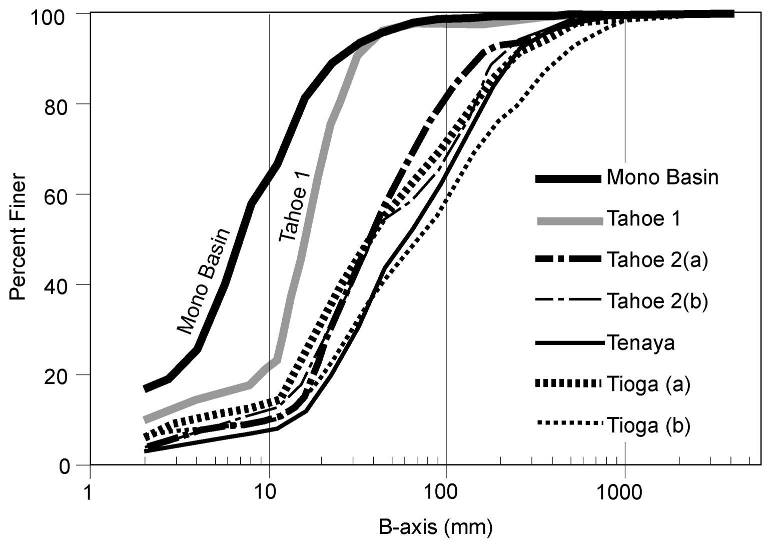

Fig. 3. Cumulative clast size distributions for statistically separable sample groups. The two oldest moraine deposits, Mono Basin (MB) and Tahoe 1 (Ta1), have the finest size distributions and are clearly separable from all younger moraines and from each other.

sample collection every 1 m by lowering a thin metal stake from the tape to the ground. The first clast encountered by the stake was then retrieved for measurement.

Pebble counts can be subject to user-dependent bias (Marcus et al., 1995). Use of the metal stake reduced known bias toward oversampling of large stones that can be introduced into pebble counts by finger counting (Hey and Thorne, 1983; Diplas and Lohani, 1997). All partially buried clasts were excavated for measurement. In an additional attempt to mitigate sampling bias and improve the ability of the pebble count to delineate trends between sites (Marcus et al., 1995), only one individual selected and measured clasts during this study.

Convention identifies three perpendicular axes for each clast: long A-axis, intermediate B-axis, and short C-axis (Krumbein, 1941; Kondolf, 1997). The intermediate axis offers the best single-axis representation of the clast size (Wolman, 1954). Once retrieved, we used metric calipers (for clasts <150 mm) or a meter stick (>150 mm) to measure B-axis dimensions. Particles less than 2 mm in size were considered too fine for caliper measurement and were recorded as "fine."

Cumulative clast-size distributions (Fig. 3) and binned class-size histograms (Fig. 4) of B-axis data enable direct comparison between moraine groups of differing age. First-order descriptive statistics (mean $\bar{x}$, standard error σ_M) facilitate simple comparisons between the groups. A two-sample *t*-test assuming unequal variance of distribution means provides a measure of the statistical significance of overall size differences between moraine groups (Table 3).

Sample data from paired sites on corresponding lateral moraines were grouped if their means were not found to be significantly different from each other at the

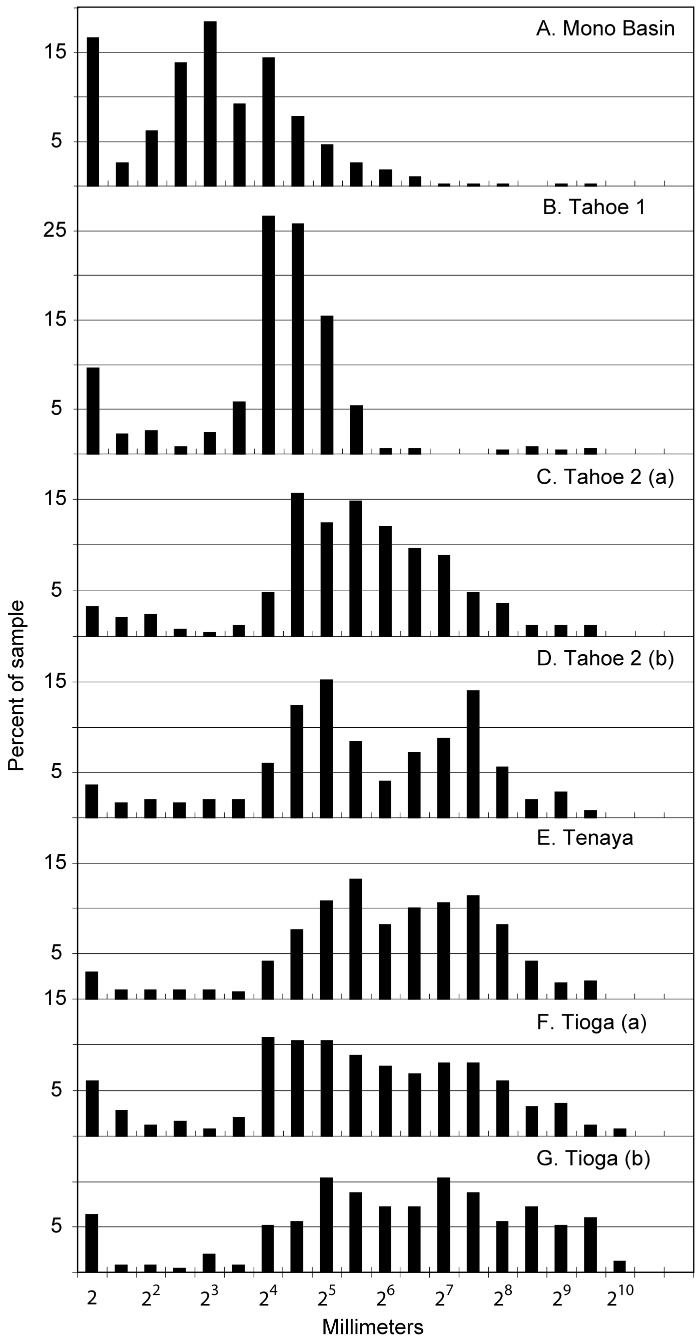

Fig. 4. Clast size histograms for different moraine age groups. The oldest moraines (Mono Basin, Tahoe 1) show finer size distributions, particularly Mono Basin, which is clearly distinct from Tahoe 1 and all other moraine age groups.

Table 3. Standardized *t*-test Statistics for All Groups of Moraines[a]

Age group	Mono Basin	Tahoe 1	Tahoe 2 (a)	Tahoe 2 (b)	Tenaya	Tioga (a)	Tioga (b)
Mono Basin	–	***-2.83***	***-8.27***	***-9.93***	***-14.82***	***-8.20***	***-10.25***
Tahoe 1	***2.83***	–	***-6.39***	***-8.18***	***-12.51***	***-7.07***	***-9.46***
Tahoe 2 (a)	***8.27***	***6.39***	–	**-1.89**	***-4.36***	***-2.66***	***-6.18***
Tahoe 2 (b)	***9.93***	***8.18***	**1.89**	–	**-2.16**	-1.18	***-5.01***
Tenaya	***14.82***	***12.51***	***4.36***	**2.16**	–	0.40	***-3.94***
Tioga (a)	***8.20***	***7.07***	***2.66***	1.18	-0.40	–	***-3.73***
Tioga (b)	***10.25***	***9.46***	***6.18***	***5.01***	***3.94***	***3.73***	–

[a]Standardized *t*-test statistics for the seven clast size populations identified in Table 2. Nearly all test statistics show that clast size distributions differ significantly (p = .01) between moraines of different age. Note that paired sample sites on Tahoe 2 and Tioga moraines were statistically different and therefore not combined (n = 250). All others are paired samples that were statistically indistinguishable and therefore combined (n = 500) before testing to yield a single measure for the moraine. Bold entries are statistically significant at (p = .10). Bold italicized entries are statistically significant at (p = .01).

90% confidence level. This allowed sample populations to be combined (to n = 500) for three of the five currently known moraine age groups. Because the "fine" designation represents ordinal data, these entries were omitted from statistical testing. However, we do include ordinal size classes for computation of size histograms and frequency distributions.

RESULTS

Clast size distributions obtained through pebble counts differ among moraines of different age groups, with greatest contrasts found between oldest and youngest deposits (Figs. 3 and 4; Table 2). A simple *t*-test finds six statistically separable clast size populations among the five mapped moraine age groups (Table 2). Most strikingly, the deposits of Mono Basin and Tahoe 1 are clearly separable from each other as well as from all younger deposits (Figs. 3 and 4; Table 2). The Mono Basin clasts have the smallest average particle size ($\bar{x}$ = 16.0 mm) and standard error (σ_M = 2.29 mm), of all sampled sites. Tahoe 1 deposits exhibit the second-smallest average pebble size ($\bar{x}$ = 26.6 mm) and standard error (σ_M = 2.95) found in this study. The Mono Basin and Tahoe 1 distributions are significantly separable at the 99% confidence level ($p < .01$). Tables 2 and 3, therefore, provide a measure of statistical confidence in the use of pebble counts to distinguish the size distributions of moraine surface deposits. Figure 3 illustrates the anomalous slopes in the cumulative size distributions for the oldest moraines in the study. Although more work is needed to validate the use of simple Gaussian statistics for significance testing between measured moraine clast size distributions, it is clear that the Mono Basin surface deposits are significantly finer than all other sampled moraines.

Data from the youngest moraines (Tahoe 2, Tenaya, Tioga b) also yield separable differences consistent with relative age chronologies previously identified by other investigators. Samples from both of the Tioga and Tahoe 2 moraines are statistically separable so their sample populations were not combined (Tables 2 and 3). For the Tahoe 2 sites, both population means were still between population means for younger (Tenaya) and older (Tahoe 1) populations, respectively. However, one test site (Ti1) from the Tioga group does not follow the expected age chronology, possibly owing to inputs of material from the adjacent, higher-elevation Tenaya deposit (Fig. 1). Nine out of ten sample sites therefore yield simple clast size statistics that are consistent with previous interpretations of relative moraine ages in the area.

DISCUSSION AND CONCLUSION

Our exploration of moraine surface clast size distributions suggests that they contain useful information for discerning relative age relationships among moraine sets. In particular, the pebble count method shows potential for discriminating older moraines that have experienced sufficient weathering duration to form mantles of homogenous clast populations with low variance (Table 2). Younger moraines, in contrast, display high variance and a close similarity of clast size distributions, making their age relationships more difficult to establish (Fig. 3). Complications associated with exhumed boulders (Hallet and Putkonen, 1994) may make pebble counts a useful alternative to previous RD methods that focus on large clasts, but a disadvantage of our approach is that data collection is more arduous and time-consuming than other RD methods emphasizing topographic, weathering ratio, and/or boulder frequency metrics (Sharp and Birman, 1963; Burke and Birkeland, 1979; Bursik, 1991). As such, we suggest that the method is probably best reserved for use on highly weathered, older moraines that are difficult to date using other methods.

Similar to other RD methods, a core assumption of our approach is that weathering rates are constant regardless of the timing of moraine deposition. A problem with this assumption is that the eastern Sierras are known to have experienced wetter climate in the past (MacDonald and Case, 2005). Nevertheless, the region is generally characterized as semi-arid with low weathering rates, which is in fact why moraines are so well preserved in the area (Phillips et al., 1990; Berry, 1994). Other uncertainties include fault activity and groundwater changes, which can affect weathering, and volcanic eruptions, which can mantle moraines with fine rhyolitic ash. Similarly, it is conceivable that episodes of aeolian dust deposition could mantle moraines. However, for this study site and others in the eastern Sierra Nevada, the influx of atmospheric dust is low (Berry, 1994). The length of time between glacial advances also alters the "inherited" weathering of rocks that end up in the moraine. This issue is particularly problematic for the oldest moraines, as smaller particle sizes measured for the Mono Basin till could potentially reflect a longer preceding interglacial. A second core assumption is that the size distribution of weathered particles is a function of time alone. This ignores the role of rock type and also lithologic and jointing variations that can cause boulders to not necessarily follow the same particle-size diminution trajectory. Fortunately, these problems are again mitigated at our study site, where source rocks consist chiefly of Cretaceous granites and granodiorites with low jointing (Wieczorek and Jager, 1996).

The clast size data presented here are generally consistent with the expected relative age chronology for the Bloody Canyon–Sawmill Canyon moraine complex from youngest to oldest (Tioga, Tenaya, Tahoe 2, Tahoe 1, and Mono Basin). However, of particular interest is the strong separation ($p < .01$) between moraines of the oldest Mono Basin and Tahoe 1 age groups (Figs. 3 and 4; Tables 2 and 3). Despite their similarity in terms of geomorphology and visual appearance, Mono Basin surface clast sizes are finer and exhibit less variance than those of Tahoe 1, consistent with longer exposure to weathering processes and a greater relative age. We cannot rule out the possibility that the Tahoe 1 moraines experienced aeolian deflation during glacial episodes due to katabatic winds funneled between the lateral moraines, with Mono Basin moraines sheltered by the Tahoe 2 right lateral moraine from down-glacier winds. This scenario would explain the anomalous slope of the cumulative size distribution observed for Tahoe 1 moraines. Further, the possibility exists that the finer size distribution of Mono Basin surface material resulted from ash deposition by volcanic activity. However such mantling would also affect adjacent Tahoe 1 deposits if they were present at the time. In this case, the contrast in particle size could be caused by ashfall deposition occurring some time after the deposition of Mono Basin but prior to Tahoe 1 deposits. As such, the physical mechanism differs but the relative age chronology remains intact.

Early RD work by Sharp and Birman (1963) used traditional relative dating methods to map the Tahoe 1 and Tahoe 2 moraines as the same unit. Later work by Burke and Birkeland (1979) supported this assignment based on more detailed multiparameter relative dating. In contrast, Phillips et al. (1990) and Bursik and Gillespie (1993) divided the moraines mapped as uniform Tahoe by the previous investigators into older and younger units. The results of this study support interpretations by the latter (Phillips et al., 1990; Bursik and Gillespie, 1993) over the former (Sharp and Birman, 1963; Burke and Birkeland, 1979). The methods of Sharp and Birman (1963), however, suggest that the Mono Basin deposits are oldest, though this interpretation could not later be replicated by Burke and Birkeland (1979) using similar techniques. CSV data suggest that Tahoe 1 moraines are younger (Crook and Gillespie, 1986; Bursik and Gillespie, 1993; Hallet and Putkonen, 1994), but ^{36}Cl data suggest that the Tahoe 1 moraines predate Mono Basin deposits by as much as 126,000 years (Table 1; Phillips et al., 1990). We note, as have others (Sharp and Birman, 1963; Crook and Gillespie, 1986; Bursik, 1991; Bursik and Gillespie, 1993), that this interpretation could possibly contradict the "single-switch" interpretation of the geomorphic cross-cutting relationship between the two moraine sets (Sharp and Birman, 1963; Crook and Gillespie, 1986; Bursik and Gillespie, 1993; Hallet and Putkonen, 1994). In general, these conflicting interpretations have arisen because most RD studies of the Bloody Canyon and Sawmill Canyon moraines have provided good distinctions among younger moraines, but not the much older Tahoe 1 and Mono Basin deposits. The method described here, in contrast, reveals a good separation between Tahoe 1 and Mono Basin moraines, but is of more limited value for relative dating of the younger deposits. We conclude from the clast-size data that the Mono Basin glacial advance pre-dated the Tahoe 1 advance, in accordance with earlier interpretations by Sharp and Birman (1963), Crook and Gillespie (1986), and Bursik and Gillespie (1993).

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