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A New Method of Alluvial Age Dating Based on Progressive Weathering, with Application to the Time-History of Fault Activity in Southern California

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Abstract

A new quantitative, repeatable method for determining relative ages of Quaternary deposits containing granitic clasts has been developed and tested. The technique makes use of a microseismic timer to determine the compressional wave velocity (clast-sound-velocity, CSV) of a group of clasts from a deposit. This yields a group mean velocity that is proportional to the age of the deposit; the youngest deposits having the highest velocity.

The CSV method was used to study the faulted Quaternary deposits in the San Gabriel Valley, California using the four-part age classification proposed by Crook et al. (1979). The CSV group means for the four age groups were found to be statistically separable at better than 99 percent confidence.

A velocity/age correlation curve was determined for these deposits using two radiocarbon dates and one paleomagnetic determination. This curve indicates that the method may be used to determine absolute dates up to a million years B.P. when calibrated with sufficient radiometric dates.

A CSV study of Wisconsin-age glacial moraine deposits in the eastern Sierra Nevada indicates that the method can distinguish between moraines deposited during different glacial advances at high confidence levels.

INTRODUCTION

The most critical problem facing the Quaternary geologist is that of dating the deposits he is working with. Present methods are restricted to finding radiometrically datable materials which are generally very rare, or to highly subjective relative dating (RD) techniques (Blackwelder, 1931; Birman, 1964; Sharp and Birman, 1963; Sharp 1969, 1972; Carroll, 1974; Porter, 1975, Harden and Marchand, 1977; Burke and Birkeland, 1979 and Bull et al, 1979) often with questionable reproducibility, especially between individual workers (Burke and Birkeland, 1979). There is a great need for a RD technique based on a precise, quantitative method of measuring some monotonically changing parameter that is dependent principally on elapsed time since sediment deposition. The measurements must be of the sort that can be rather easily obtained, statistically treatable and reproducible by other workers.

We have developed such a method that can be applied to many bouldery deposits up to approximately a million years old and possibly much older. Called the Clast Sound Velocity (CSV) method, the technique is to measure the compressional (P) wave velocity for each of a series of clasts from a single deposit and determine a group mean velocity. The group means for different deposits can then be compared statistically.

The technique makes use of an instrument developed for use in non-destructive testing of engineering materials (Phelps), which consists of a microseismic timer, a hammer-switch-energy source, and a detector.

A preliminary test, discussed fully in previous project reports and summarized in Table 1, demonstrated the ability of the method to discriminate between deposits of different ages, but also revealed weaknesses, such as difficulties in data reproductibility. Further laboratory tests have resolved most of the problems regarding the measurement technique. A subsequent more comprehensive field test showed that it is possible to distinguish between at least four, and possibly a continuous series, of different ages of Quaternary alluvial deposits in the San Gabriel Valley, southern California. A test in the eastern Sierra Nevada showed that the technique also has application to glacial deposits. It appears that the method has great potential as an RD technique, and possibly as an absolute dating method if and when sufficient radiometric dates for calibration become available.

Table 1

P-Wave velocities of clasts of Mt. Lowe Granodiorite from a sequence of Quaternary alluvial deposits near the mouth of the Arroyo Seco, Pasadena, California. Unpublished data obtained by Richard Lewis, 1977.

Alluvial-deposit sequence	Average clast velocity (km/sec)	Standard deviation of mean	Number of clasts measured
A_1 (youngest)	1.95	.08	18
A_2	2.08	.08	15
A_3	1.99	.08	12
A_4	2.03	.11	12
$A_1+A_2+A_3+A_4$	2.01	.04	57
B_1	1.69	.14	9
B_2	1.49	.11	8
B_1+B_2	1.60	.09	17
C_1	1.75	.08	12
C_2	1.75	.09	18
C_3	1.80	.14	18
$C_1+C_2+C_3$	1.77	.06	48
D_1	1.61	.10	18
D_2	1.55	.08	18
D_1+D_2	1.58	.06	36
E_1	1.41	.12	9
E_2	1.39	.09	19
E_1+E_2	1.40	.07	28
F_1 (oldest)	1.12	.12	19
F_2	1.34	.09	18
F_3	1.34	.09	18
$F_1+F_2+F_3$	1.27	.06	55

CSV METHOD

A high speed clock, called a microseismic timer (DynaMetric, Inc. Fig. 1) is used to record the travel time (in microseconds) of a compressional (P) wave between an energy source (hammer blow) and a sensing transducer (piezolectric phonograph cartridge). The transducer is placed on the clast and three or more impact points are carefully located on a line passing through the detection point. At each point a series of impacts is made by striking a hammer on a steel ball held in place at the impact point with a wand. The impact initiates the P wave and simultaneously starts the timer. Detection of the P wave at the piezolectric transducer stops the timer, which then displays the measured travel time. The lowest value in a consecutive series of travel times is chosen as the first arrival of the P wave. Using the values determined for several different impact points, a line is fitted by least squares to a plot of distance versus time, which yields the P wave velocity for the clast.

Fig. 1

Photograph showing Dynametric instrument in use

LABORATORY TESTING OF THE CSV MEASUREMENT METHOD

In order to improve our insight into what is actually measured with the instrument, we arranged to display the output of the sensing transducer (piezoelectric phonograph cartridge) on an oscilloscope (Hewlett-Packard 181A), and could then examine the wave form of the signal presented to the timer. Representative wave forms seen at three distances from the sound-wave source (hammer impact) are shown in Fig. 2. The seismic timer triggers on the first negative swing of the wave that exceeds a threshold level determined by the electronics, which can be controlled to some extent by the gain setting. It is evident from the wave shapes in Fig. 2 that different threshold level settings can result in significant differences, amounting to several tenths of a millisecond, in the recorded first-arrival time and hence travel time. For example, the first negative swing at the 2.5 and 7.5 cm distances has low amplitude compared to the second negative swing, and.the latter is comparable to the first negative swing at the 12.5 cm distance. This would yield a smaller difference in travel times between the 7.5 and 12.5 cm distances than if the first positive arrival were measured at each distance. The opposite situation probably also occurs. From the oscilloscope display it is possible to determine directly the wave velocity corresponding to propagation of the first arrival and subsequent features in the wave form, and to compare these velocities with those obtained from the arrival times read from the micro-seismic timer. We found that the wave velocities obtained with the oscilloscope for various features on the incoming wave varied by as much as 19 percent, confirming the desireability of using the first positive swing. We also found that the wave velocities obtained with the oscilloscope were consistently higher, by 5 to as much as 30 percent, than those obtained with the micro-seismic timer. This bias toward low

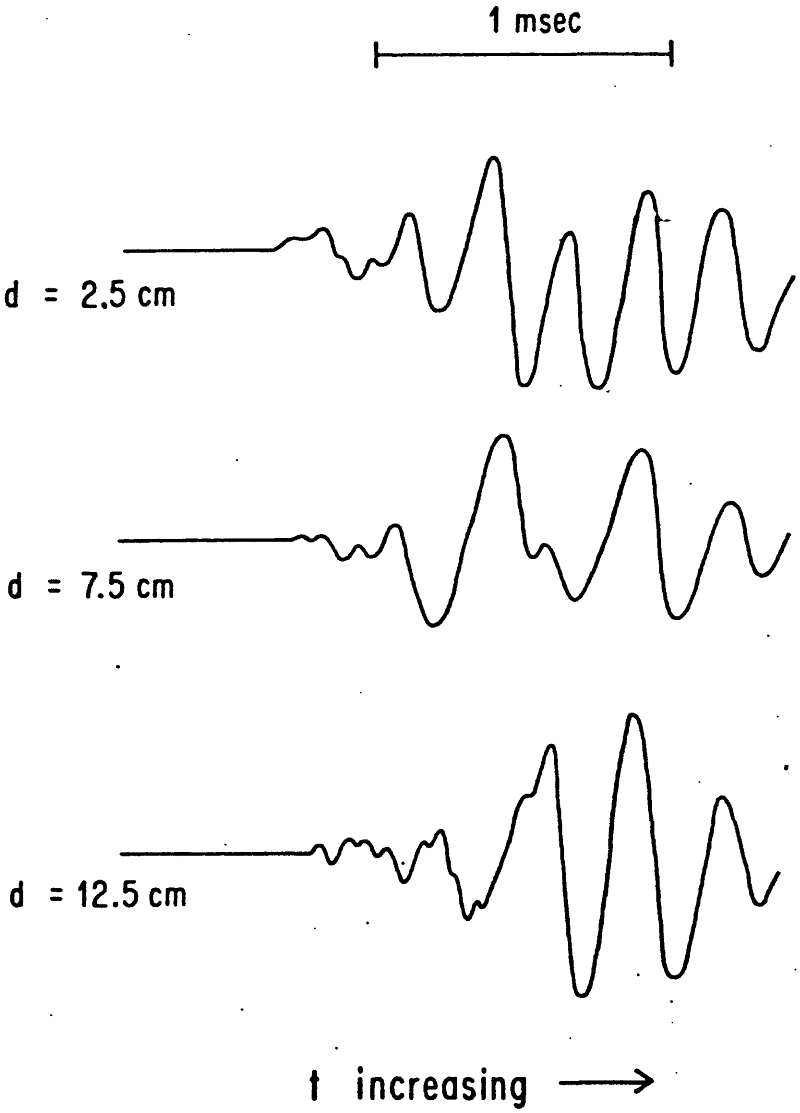


Fig. 2. Oscilloscope trace of acoustic wave forms sensed by micro-seismic timer as indicated by output of sensing transducer, at three distances d from the sound source (hammer blow). Time increases to the right.

velocities from the seismic timer was eliminated when use of the detector support supplied by the timer manufacturer was discontinued and the detector was instead mounted directly on the clast surface, using a putty compound. This technique also eliminated velocity variability due to gain settings, and decreased background vibrations, thereby increasing the signal to noise ratio.

The oscilloscope studies revealed a further complication in the measurement technique in which, at certain hammer impact points on some clasts, there is a change of the received wave form, such that the first arrival has negative rather than the normal positive polarity. This situation could cause erroneous travel times to be given by the micro-seismic timer, because the instrument is designed so that the timer stops on the first negative swing of the signal above the chosen threshold level. The resulting error cannot be recognized from the timer readings themselves, but is apparent when the received wave is observed on the oscilloscope. The local wave-form modification appears to be due to effects of local interal heterogeneities or surface irregularities in the rock sample. With the oscilloscope it was observed that the resulting error can usually be eliminated by offsetting the hammer impact point while keeping a fixed distance from impact point to transducer. This procedure can also be used with the micro-seismic timer.

Having traced the source of travel-time variability to the aspects of measurement technique discussed above, and having determined that the micro-seismic timer, when used with a suitably standardized technique, is capable of good precision, we ran a series of tests to determine CSV repeatability on single clasts, and also on a group of clasts. Single-clast tests were carried out on two clasts, from deposits of significantly different age, to see if CSV variability is affected by the weathered condition of the clast. Each of the clasts was tested ten times using identical detector and impact points for each test. We found that the variability of the travel times for the older clast was more than twice that of the younger clast (3.38 μ sec and 1.44 μ sec respectively). There was also a definite trend in which travel times tended to decrease progressively in successive measurements. This appears to be due to progressive penetration of a thin weathered rind by the hammer, leading to progressively more efficient instrument-rock contact on successive tests. The mean velocities calculated for each test were not affected by the resulting variability. The fresh clast yielded an average velocity and standard deviation of 2.11 km/sec and 0.036 km/sec, as compared with 1.91 km/sec and 0.040 km/sec for the weathered clast. The standard error is approximately two percent for both clasts. This is probably the minimum possible experimental error and is actually slightly better than expected error due to measurement errors in the travel distance and in the placement of the impacting instruments, and considerably better than the 10 percent minimum error suggested by Birch (1960).

The clast-group test was run to ascertain further the portion of CSV variability due to variations from measurements on individual clasts. A group of 19 clasts was measured three times, on different days. Each measurement run on an individual clast was made on a different portion of the clast, without regard to foliation. A single factor analysis of variance was run on the data with each run treated as a replicate. The total estimated standard deviation of the group was 0.449 km/sec while the calculated estimate of the estimated standard deviation due to individual clast variability was 0.269 km/sec. Similar analyses were done on three different age groups of clasts on which two velocities had been determined, parallel and perpendicular to foliation, which were treated as replicates. The individual clast standard deviations were 0.310, 0.296, and 0.234 km/sec respectively for

Qal_1, Qal_3, and Qal_4, age deposits and total group standard deviations were 0.539, 0.373, and 0.397 km/sec.

In determining the sources of variability we found that instrumental precision (repeatability) contributes approximately one percent of the total; single clast variability 35 percent; and the remainder to deposit variability. This argues strongly for testing more clasts per deposit and determining only one velocity per clast rather than two determinations per clast and fewer clasts as done in the early stages of the study.

A measurement of the repeatability of the CSV method is shown by the results of the three independent runs on the group of 19 clasts. Although the variation between repeated runs on individual clast ranged from 0.04 to 1.07 km/sec, the mean values for the three runs were 2.09 km/sec, 2.09 km/sec, and 2.08 km/sec, thus differing less than one percent. This precision is quite high when compared to other RD methods (Gillespie and Crook, in preparation, and Burke and Birkeland, 1979).

APPLICATION OF THE CSV METHOD

The CSV method has been tested on two different types of Quaternary deposits: alluvial fan deposits, and glacial moraine deposits. Results of these tests indicate that the method is applicable to both types of deposits, but that there are problems peculiar to each, which must be evaluated and considered when planning a study using the method.

Alluvial deposits of the San Gabriel Valley

The first application of the CSV method was carried out on alluvial fan deposits in the San Gabriel Valley, Los Angeles County, California (Fig. 3). This area was picked for several reasons: (1) the Mt. Lowe granodiorite —— a unique, readily recognizable rock type, resistant to weathering —— is present in the area as a source of alluvial clasts that are particularly well suited to the CSV method; (2) a relative age classification of the deposits already existed (Crook et al., 1979); (3) a preliminary test on these deposits had yielded information on sampling, expected means, and variability, which was useful in designing a comprehensive study; (4) the project was funded by the U.S. Geological Survey's Seismic Hazard Reduction program, for the purpose of dating alluvial deposits involved with faulting in the Sierra Madre fault zone.

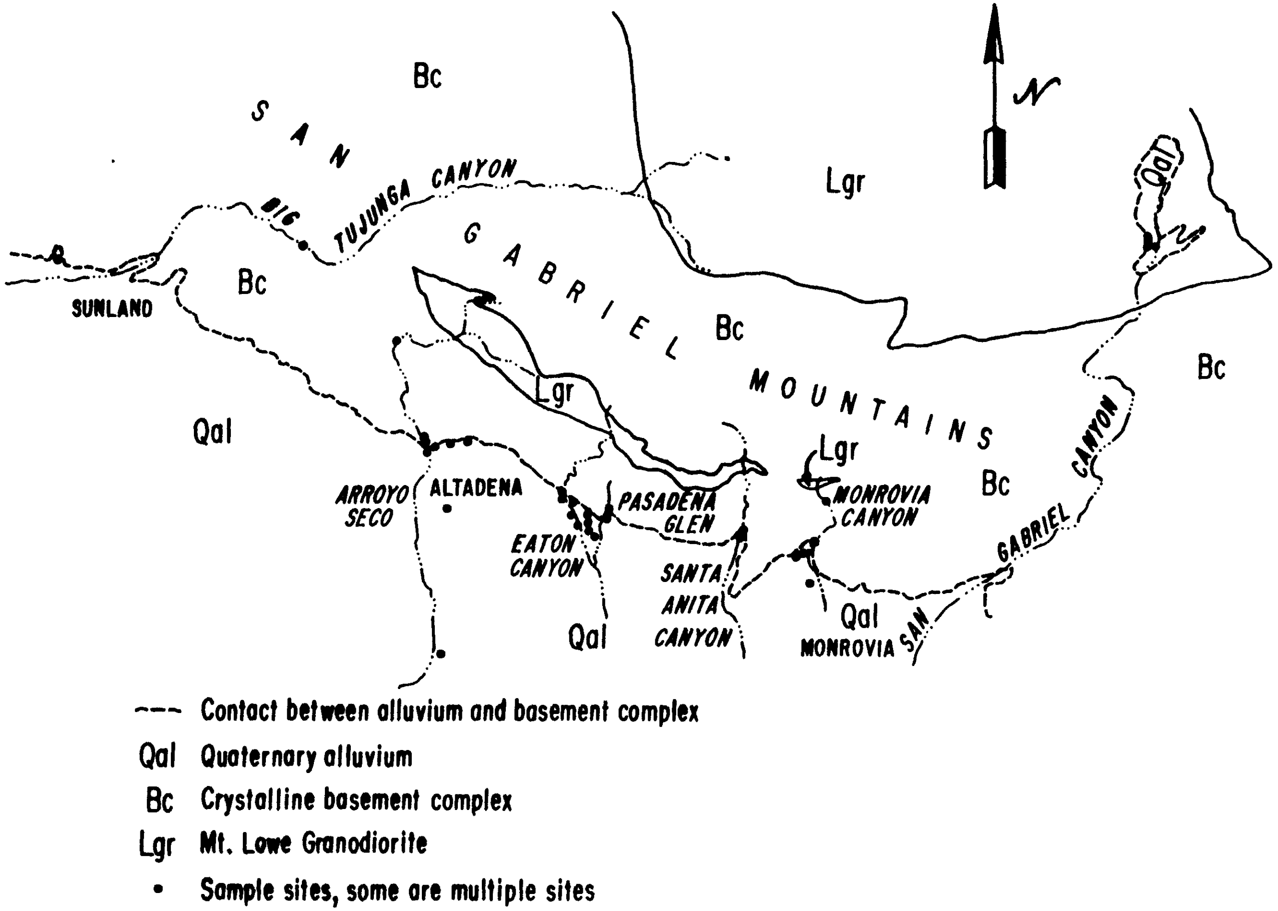


Figure 3. Index map of the study area in the San Gabriel Valley, California, showing major drainages, test sites, and distribution of clast sources (Mt. Lowe Granodiorite).

In the San Gabriel Valley area, our efforts to sample the alluvial units so as to obtain unbiased and representative clast collections suitable for statistical treatment of the resulting CSV data, were subject to expectable limitations on availability of suitable sampling sites. Alluvial exposures adequate for clast sampling were generally restricted to larger drainages that have incised their alluvial fans, or to deposits that have been uplifted and exposed by faulting. In two instances, suitable collections of clasts were obtained from backhoe trenches. A further factor that affects availability of samples is the minimum clast size of 14 cm, limited by the CSV measurement technique. The steepness of the alluvial exposures also plays a role.

The physical condition of the clasts introduces some bias in sampling the older deposits because some of the extremely weathered clasts disintigrate when impacted, rendering them untestable and thereby probably biasing the group average velocity toward higher values. The increase in abundance of these unstable clasts with deposit age will of course ultimately limit the age of deposit amenable to the CSV method.

A decision was made initially to avoid samples from soil zones, either buried or at the surface, because we expected that the weathering environment in the soil zone would be more intense at that depth and therefore clasts in the soil zone would be more strongly weathered and yield abnormally low velocities. Interestingly, the actual tests (Table 2) showed that this expectation is not fulfilled.

As discussed later, the CSV values are affected by clast size and by facies characteristics of clast lithology. To the extent that these factors vary between clast collections from different localities, a bias will appear in the CSV results, which needs to be evaluated and taken into

Table 2

Comparisons of average CSV values for clasts from a soil zone and from the same alluvial deposit below the soil zone.

	Sampling Area		
	Arroyo Seco	La Vina	Chaney Trail
Clasts from soil zone: CSV in km/sec	1.35	1.46	1.13
Clasts from below soil zone: CSV in km/sec	1.26	1.24	1.12
Approximate stratigraphic interval between sampling horizons, in meters	50	5	5-10

account to the fullest extend possible.

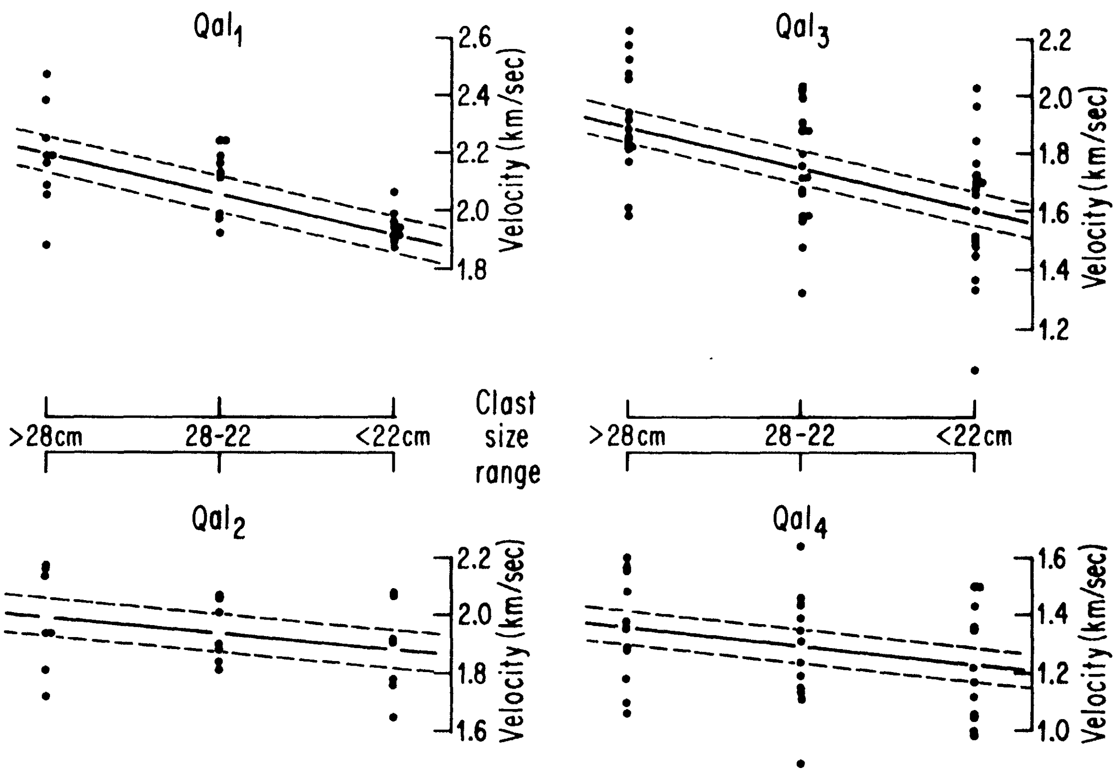
Considering all of the foregoing limitations and influencing factors, it is evident that fully random clast sampling of the alluvial units is not practical in many instances. This should be borne in mind in interpreting the CSV results.

Once CSV data had been accumulated for several alluvial deposits a correlation between clast size and sound velocity (CSV) became apparent. When the clasts are grouped into three size ranges (smaller than 22 cm; 22 to 28 cm; and larger than 28 cm), the mean CSV values generally show a significant increase with increasing clast size. Figure 4 is a plot showing the correlation between velocity and clast size range for the four age groups. It also shows that the correlation decreases significantly with increasing deposit age. These curves may be used to estimate the mean velocity for a group lacking clasts of a particular size range. This is discussed in the section on calibration of the technique. The data in Fig. 4 and statistical tests show that this trend is significant and must be taken into account in the sampling procedure and in interpreting CSV results. To hold this variable to a minimum it is preferable that an equal number of clasts from each size range be sampled. This sometimes is difficult, because the size distribution of clasts at some sites is biased, commonly against the larger sizes.

A detailed investigation of the correlation between CSV and clast size was carried out, because of its importance in evaluating CSV results. Tests were run on five clasts of different sizes, selected from deposits of different age (Table 3).

A velocity was determined for each clast in the normal manner by averaging 10 sepearte tests, each run on different portions of the clast to

Figure 4. Velocity/clast size range correlation.
These plots show the correlation between site mean velocity and clast size range, for each of the four age groups, as a solid line, and the attendant error ($\pm\sigma$) as dashed lines.



average any inhomogeneities in the clast. This we called the surface velocity. An additional 10 velocities were then determined through the center of the clast by impacting on the opposite side of the clast from the detector. The 10 velocity values were averaged and this value we called the body velocity. These terms should not be confused with surface wave and body wave terms as used by seismologists. The average surface velocity and body velocity was then compared (Table 3) for each clast size and clast deposit age. Although the velocities for the clasts tested do not necessarily decrease with increasing deposit age, the important thing is that the difference between the body and surface velocities of individual clasts do. This is similar to the trends shown on Fig. 4, and suggests that as a clast begins to weather, a rind develops at the surface which penetrates progressively with time, perpendicular to the clast surface, until the entire clast is uniformly weathered. As might be expected the smaller clasts become completely weathered in a shorter time than larger clasts. Note in Table 3 that clasts smaller than 20 cm are completely weathered in Qal_3 age deposits but clasts larger than 30 cm are not. Only in Qal_4 age deposits are clasts greater than 30 cm in size completely weathered. This would cause the clast size/velocity correlation because the farther the sound wave travels the greater the change that it is refracted into the fresher center of the clast allowing the higher velocities of the center to influence the resultant velocity (this was seen for many clasts). It follows then that the larger clasts which allow greater detector-impact distances would yield a higher velocity (low surface velocity plus higher center velocity) than a similarly weathered small clast with a short detector-impact distance which would detect only the lower surface velocity. That this occurs was substantiated by recalculating velocities for many of the

Table 3.

CSV DATA ON INDIVIDUAL CLASTS OF DIFFERENT SIZES AND FROM DEPOSITS OF DIFFERENT AGES

clast size >30 cm	body velocity (km/sec)	surface velocity (km/sec)	difference (km/sec)
Qal_2 (youngest)	2.72	2.22	.50
Qal_3	2.11	1.75	.36
Qal_4 (oldest)	2.32	2.31	.01

clast size <20 cm			
Qal_2	2.73	1.95	.78
Qal_3	2.09	2.00	.09

larger clasts using the same detector-impact distances as on the small clasts. The average velocities were nearly always reduced for the greater than 28 cm clast size range.

The conclusion reached from the above test is that the data as collected for this CSV study must be treated so that the clast size is accounted for, (using equal numbers of clasts in each size range) although subsequent use of the method may avoid this treatment by standardizing the clast size or length of detector-impact distance as was done for the glacial moraine study.

Analysis of all of the test data suggested rock facies is an additional influence on the determination of group velocities. Although it was recognized that the Mt. Lowe grandodiorite was made up of two distince facies, determined by the presence or absence of potassium feldspar phenocrysts, the groups tested usually contained both facies. Fortunately the facies was recorded during the testing, as subsequent analysis suggests a possible bias toward lower velocities for the phenocryst facies. While this could be significant as a few of the deposits do not contain this facies, the evidence was not compelling enough to warrant its inclusion in the present study.

Grouping of deposits

Grouping the Qal_1 age deposits is quite simple as by definition they are the deposits of the present day drainage and no older than 1,000 years B.P. Inspection of the group means suggests however that there may be a problem with this grouping such as a bimodality with means near 2.10 km/sec and 2.03 km/sec. If these values are truly representative it may mean that the source rock is not quite as homogeneous as we have assumed or that the lower values have been influenced by reworked clasts from older alluvial deposits within the drainage. Nevertheless the standard deviation of all the means is surprisingly small.

Grouping of the Qal_2 age deposits presents the greatest problem. Based on the definition by Crook et al. (1979), deposition of this unit occurred after the widespread beginning of Qal_3 fan incision inferred to have been caused by a climatic change at the Pleistocene-Holocene boundry. Deposits within the incised drainage are generally easily recognized but deposits of the same age from drainages too small to incise the Qal_3 fans will be at the fan surface and difficult to distinguish from late Pleistocene (Qal_3) deposits. Because the boundry is an artificial one and the episodic processes forming the deposits are probably not everywhere in phase in the erosion-deposition cycle, we should expect to get a continuous variation from Qal_1 to Qal_3 velocities for Qal_2 deposits.

The Qal_3 deposits are easily recognized (Crook, et al, 1979), except for the case explained above. Several of the deposits of this age in the Eaton Canyon drainage do present a problem however because of anomolously high velocities. At one locality the mean velocity actually increased with stratigraphic age (D_3b and D_3d in Table 4). This is as yet unexplained.

The Qal_4 deposits are easily recognized except where exposures are small and erosion has removed the distinctive reddish soil at the surface. There is also a distinct possibility that deposits D_{4a}, D_{4b}, and F_{4a} (Table 4) are considerably older than the Qal_4 designation and should be designated Qal_5. Bull et al. (1979) have estimated the F_{4a} deposit in San Gabriel Canyon to be at least 500,000 years old and L. D. McFaddin (personal communication 1979) believes the D_{4a} and D_{4b} deposits from the Millard Canyon drainage to be comparable in age. Both of these estimates are based on degree of soil development.

Table 4

CSV Data for Mt. Lowe Granodiorite Clasts from Alluvial Deposits from big Tujunga Canyon, Arroyo Seco, Millard Canyon, Eaton Canyon, Pasadena Glen, Santa Anita Canyon, Monrovia Canyon and San Gabriel Canyon, Los Angeles County, California

A:	sample groups	from	Big Tujunga Canyon	drainage
B:	"	"	Arroyo Seco	"
C:	"	"	Millard Canyon	"
D:	"	"	Eaton Canyon	"
E:	"	"	Pasadena Glen	"
F:	"	"	Santa Anita Canyon	"
G:	"	"	Monrovia Canyon	"
H:	"	"	San Gabriel Canyon	"

Alluvial age group	Sample group	Mean CSV (km/sec)	s.d. of mean (km/sec)	No. of clasts
Qal_1	A_1	2.03	.08	20
(youngest)	B_{1a}	2.12	.12	20
	B_{1b}	2.03	.10	20
	C_1	2.01	.08	20
	D_1	2.10	.07	24
	E_1	2.03	.11	21
	F_1	2.12	.12	20
	G_1	2.14	.07	20
	H_1	2.05	.08	21
Combined:				
$A_1+ B_{1a}+ B_{1b}+ C_1+ D_1+ E_1+ F_1+ G_1+ H_1$		2.07	.03	186

(continued)

Age group	Sample group	Mean CSV (km/sec)	s.d. of mean (km/sec)	No. of clasts
Qal$_2$	B$_{2a}$	1.90	.08	14
	B$_{2b}$	1.84	.09	20
	B$_{2c}$	1.84	.08	20
	D$_{2a}$	2.00	.11	11
	D$_{2b}$	1.97	.07	35
	G$_2$	2.04	.11	20
	H$_2$	1.89	.10	21
Combined $B_{2a}+B_{2b}+B_{2c}+D_{2a}+D_{2b}+G_2+H_2$		1.93	.03	141
Qal$_3$	A$_3$	1.81	.08	20
	B$_{3a}$	1.68	.09	20
	B$_{3b}$	1.65	.09	20
	B$_{3c}$	1.62	.07	22
	D$_{3a}$	1.60	.11	20
	D$_{3b}$*	2.09	.10	20
	D$_{3c}$	1.83	.12	20
	D$_{3d}$*	2.03	.09	20
	D$_{3e}$	1.72	.15	12
	E$_{3a}$	1.70	.09	24
	E$_{3b}$	1.70	.09	24
	E$_{3c}$	1.74	.08	20

(continued)

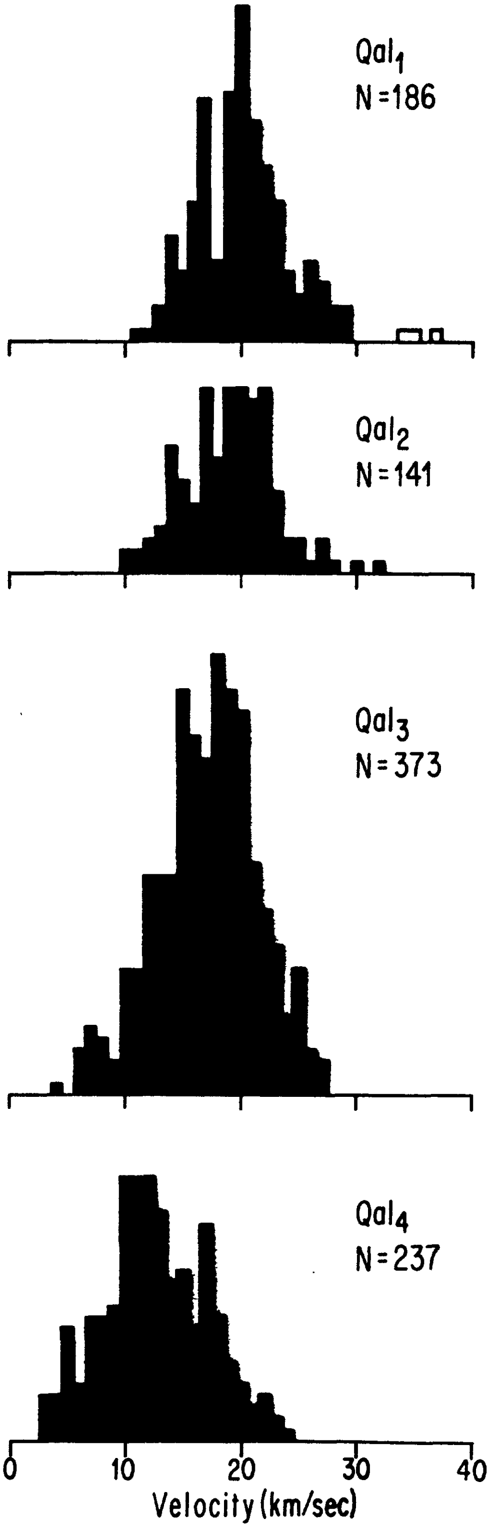
	Sample group	Mean CSV (km/sec)	s.d. of mean (km/sec)	No. of clasts
	E_{3d}	1.72	.13	20
	E_{3e}	1.88[2]	.04	20
	F_3	1.68	.12	22
	G_{3a}	1.79	.09	20
	G_{3b}	1.58	.10	21
	G_{3c}	1.56	.07	23
Combined $A_3 + B_{3a} + B_{3b} + B_{3c} + D_{3a} + D_{3b} + D_{3c} + D_{3d} + D_{3e} + E_{3a} + E_{3b} + E_{3c} + E_{3d} + E_{3e} + F_3 + G_{3a} + G_{3b} + G_{3c}$		1.74[1]	.02	373
Qal_4				
(oldest)	B_{4a}	1.30	.07	20
	B_{4b}	1.26	.06	23
	B_{4c}	1.35	.08	24
	B_{4d}	1.25	.13	18
	C_{4a}	1.46	.15	20
	C_{4b}	1.24	.11	20
	C_{4c}	1.13[3]	.08	20
	C_{4d}	1.12[1,3]	.07	17
	E_4	1.44	.10	20
	G_4	1.46	.12	18
	H_{4a}	1.07	.09	20
	H_{4b}	1.42	.10	17
Combined $B_{4a} + B_{4b} + B_{4c} + B_{4d} + C_{4a} + C_{4b} + C_{4c} + C_{4d} + E_4 + G_4 + H_{4a} + H_{4b}$		1.29	.03	237

[1] non-normally distributed at >95% confidence

[2] probably Qal_2

[3] probably older than Qal

Figure 5. Histograms of clast velocities of the four age groups.



Statistical Treatment

We have tried to keep the statistical treatment of the CSV data as simple as possible. We have therefore assumed that the samples were randomly selected and that clast velocities are normally distributed. This was done to allow the use of parametric statistical tests for comparing means and for analysis of variance. Nevertheless, the Kolmogorov-Smirnov (K-S) single-sample test (Tate and Clelland, 1957) for normality was run on each group as a check on this assumption, and in fact five groups proved to have non-normal distributions at 95 percent or greater confidence. In addition both the combined Qal_1 and Qal_3 deposits proved non-normal at greater than 95 percent confidence. Histograms of the four age groups are shown on Fig. 5.

Each of the four age groups contains at least one site that is non-normally distributed. There are several possible explanations for this: random chance; facies bias; or mixing of populations due to reworked clasts from older deposits. Regardless of the reason we felt there were not enough non-normal distributions to rule out use of parametric statistical tests.

The non-normality of the Qal_1 and Qal_3 groups is a more serious problem than the individual non-normal sites. The non-normality of the Qal_1 group may be due to facies bias or a false assumption of homogeneity of the clast source (Mt. Lowe granodiorite intrusive body). In the case of the Qal_3 group the explanation may be that the non-normality is caused by sampling of multiple populations because the age range of the included deposits is too great.

Without a clear cut case for either normal or non-normal distributions we elected to try and discriminate between the groups by several methods. We felt this would not only increase our confidence in our conclusions but would give us a better idea of the necessity of adhering strictly to the normality requirements for parametric tests.

We applied the one-tailed student t test to comparison of the group means using all clasts; the one-tailed student t test to the group means using individual site means and the Kolmogorov-Smirnov two sample test, to the group distributions. All groups are distinguishable at greater than 99% confidence by all tests except between the Qal_1 and Qal_2 groups with the K-S test (Table 5).

Because of the non-normal distributions the validity of the t test using all the clasts is open to question. However, the use of the t test using sites means is valid because the distribution of sample means of a population is, by definition, a normal distribution. The K-S test does not have the requirements of a normal distribution and compares distributions rather than means.

We have shown that the CSV method can distinguish between the four different age groups at high levels of confidence and that the departures from normal distributions in our data are not severe enough to preclude the use of parametric statistics.

Table 5

Comparison of the ability to discriminate between the four age groups by the t test and Kolmogorov-Smirnov test. Data from Table 4.

	t Test, all clasts calc t	Conf.	t Test, site means calc t	Conf.	K-S Test, all clasts D max	Conf.
Qal_1- Qal_2	3.163	>99.5%	4.034	>99.95%	14.2%	>90%
Qal_2- Qal_3	4.345	>99.95%	3.244	>99.5%	18.7%	>99%
Qal_3- Qal_4	12.184	>99.95%	8.332	>99.95%	41.2%	>99%

We originally grouped the samples into the four-part classification of Crook et al. (1979). In light of more recent work by the authors and others (Bull et al. 1979, William Bull and Les McFaddin personal communication 1980) this classification appears over-simplified. Erosional and depositional processes in and along the south front of the San Gabriel Mountains are controlled in large part by climate and tectonics, both of which undoubtedly have been highly variable since the mid-Pleistocene, resulting in alternating degrading and aggrading cycles with little evidence of significant hiatuses. This would likely result in a nearly continuous variation in deposit ages throughout the study area which seems to be borne out by our data. The velocity ranges obtained for the Qal_1, Qal_2, and Qal_3 groups overlap with the adjacent group (Table 4). While this variability could be due to high deposit variability, the data from areas where we have good stratigraphic control, in the Arroyo Seco and Pasadena Glen drainages (Table 6), argue that it is intrinsic. Therefore the four-part classification is useful only as an approximation with the real distribution in ages relatively continuous from Qal_1 through Qal_3 age deposits.

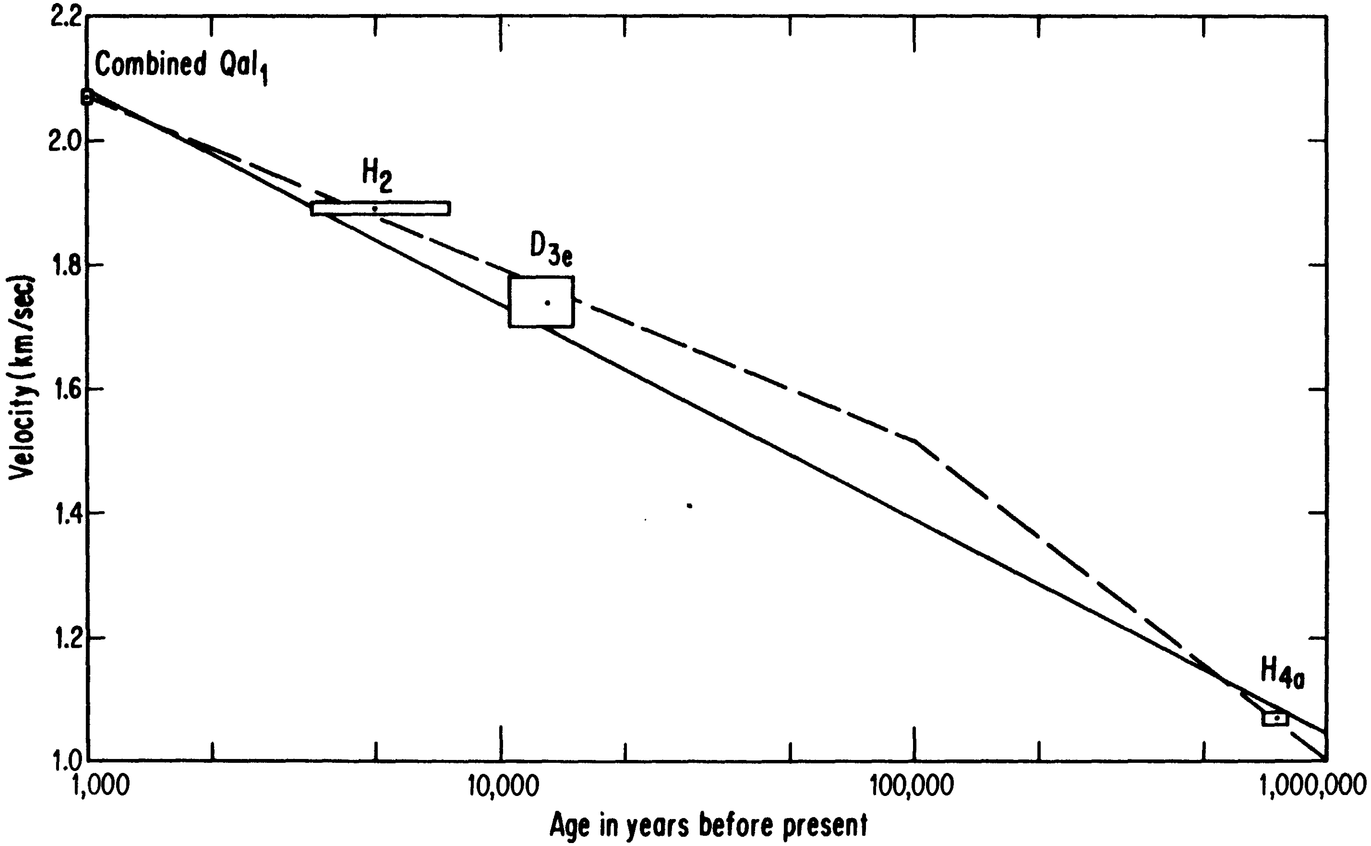
There does appear, however, to be a significant gap of about 0.10 km/sec in the velocity values between Qal_3 and Qal_4 age deposits. This is a gap of 3 to 4 times the standard deviation of the group means (Table 4). This suggests that either the lower part of the Qal_3 section was not sampled or that there was an actual hiatus between Qal_3 and Qal_4 deposition. An even greater velocity gap between deposits C_{4c}, C_{4d}, and H_{4a} (Table 4) and the rest of the Qal_4 age group suggests a similar hiatus of equal or greater magnitude, arguing for a fifth age designation (Qal_5) based solely on the CSV data.

Calibration of the CSV method

The CSV technique was developed to assist in estimating the actual age of alluvial deposits. At present there are no radiometric nor other absolute deposit ages which could be used to calibrate our Pleistocene alluvia data, and only one Holocene radiocarbon date. Thus only the youngest one percent of the estimated age range of the studied deposits has any age control. The dated deposit (H_2, Table 4) is valley fill, rather than alluvial fan, in San Gabriel Canyon and yielded two preliminary uncorrected dates of 6,700 and 6,500 years BP (William Bull, written communication, 1980). The dates refer to the bottom of a 40 m thick deposit, which Bull estimates was deposited in less than 3,000 years. A velocity of 1.89 km/sec was obtained from the top of this unit from clasts estimated to have been deposited about 5,000 years ago.

Twelve clasts from the Eaton Canyon drainage were collected from a trench across the Raymond fault at San Marino High School prior to the present study. All but one of the clasts were less than 22 cm in diameter, but were included in this study because they were collected near a layer with a radiocarbon date. Unfortunately, the stratigraphy between the dated layer and the clast layer was complex and we can only estimate that the clasts were stratigraphically lower and therefore older than the 10,600 year BP dated layer. Using sedimentation rates calculated by Crook et al. (1979), the deposit is estimated to be between 10,000 and 14,000 years old. Use of this tenuous date is further complicated by the restricted clast sizes; eleven are in the smallest size grouping. If the clast size and velocity are assumed to be related as shown in Fig. 4, a mean velocity value for a uniform population of the three size ranges may be calculated. This value

Figure 6. Proposed velocity/age curves for the San Gabriel Valley alluvial deposits.



is 1.72 km/sec.

The inherent limitations of the radiocarbon technique preclude its use for calibrating the velocity/age relationship of deposits older than 40,000 years. Because Bull et al. (1979) estimate the oldest alluvium included in this study to be in excess of 500,000 years old we needed an alternate method for dating these deposits. We have sampled several of our oldest deposits and tested them for remnant magnetization from the Matuyama reversed polarity epoch. Two deposits appear to contain a component of primary reversed magnetization, suggesting they are older than the now thought to be 0.73 million years BP (Mankinen and Dalrymple, 1979). One of these deposits (H_4, Table 4) contained clasts large enough to test which yielded the lowest mean velocity (1.07 km/sec) of any deposit tested. A sample from the soil developed on the H_4 deposit showed no trace of remnant reversed magnetization; hence the soil developed the alluvium itself must be only slightly older than the reversal boundry.

The four deposits for which we have both the CSV and some absolute age data are plotted on Fig. 6. Estimated errors in age and velocity are shown as a box enclosing the estimated best point. A single straight line cannot be drawn through all four points. A best fit line passing through the H_2, D_{3e}, and H_{4a} error boxes passes above the Qal_1 error box corresponding to an error of about 10 percent. This may be explained by contamination by reworked clasts. The simple linear relationship shown in Fig. 6 would require the Qal_4 age alluvium to be as young as 60,000 years old rather than greater than 200,000 years old as previously estimated (Crook et al., 1979).

An alternative age-velocity relationship using two weathering rates fits the data also. In this scheme the three youngest sites (Qal_1, H_2, and

D_{3e}) weather at the same rate but H_4 has weathered more rapidly during part of its history. The weathering rate may have changed about 125,000 years ago, at the end of the Sangamon interglacial period. Perhaps there is some basis for this, as a similar relationship for glacial deposits in Bloody Canyon in the eastern Sierra Nevada has also been determined (Crook and Alan Gillespie, in preparation). Additionally, many workers have noted a striking increase in soil development on parent-materials believed to be pre-Wisconsin in age compared to soils on younger deposits (Janda and Croft, 1965; Hunt, 1972 and Birkeland, 1974).

Both proposed age-velocity relationships suggest that revision of the estimated ages or classification criteria used by Crook et al. (1979) is necessary. Work on soils in the area by Bull et al. (1979) appears to substantiate this.

Table 6

Variability of velocity within deposits of known relative age. The deposits in each group are listed in order of increasing stratigraphic age.

Deposit group & location	deposit site	site elevation (feet)	velocity (km/sec)	No. of clasts
Qal$_4$	B_{4a}	1600	1.35	20
Arroyo Seco	B_{4b}	1400	1.26	23
	B_{4d}^{*}	1400	1.25	18
	B_{4c}	1240	1.30	24
Qal$_3$				
Arroyo Seco	B_{3a}	1260	1.68	20
	B_{3b}	1200	1.65	20
	B_{3c}	1160	1.62	22
Qal$_3$	$E_{3e}^{\dagger}$	1240	1.88	20
Pasadena Glen	E_{3d}	1220	1.72	20
	E_{3c}	1080	1.74	20
	E_{3a}	960	1.70	24
	E_{3b}	880	1.70	24

*1.1 km east of other three sites

†may be a significantly younger aggraded deposit in incised Kinneloa Fan.

Correlation by the CSV method

Regardless of the CSV methods potential as an absolute dating technique it appears to be a very useful tool for positive or negative correlation of similar appearing deposits. To test this, CSV data from three areas having good stratigraphic control were compared (Table 6).

Although the relative ages of each deposit in each group is know, the actual age range is unknown. With only one significant exception (B_{4c}) all deposits show a decrease in velocity with increase in age. The two Qal_3 groups show a good clustering of mean velocity values (except for E_{3e}, which may not be part of the fan containing the other deposits) with a variability comparable to the determined experimental error of .05 km/sec. The Qal_4 group has a somewhat greater variability but this may be due to a greater age range as suggested by a buried soil horizon. A greater number of clasts per site may also help in decreasing the variability.

These results suggest that the CSV method is useful for determining whether deposits juxtaposed by faulting are significantly different in age or if faulted deposits of unknown relative age can be correlated with deposits in a nearby stratigraphic sequence where relative age is known.

Glacial moraine study

A second application of the CSV method was carried out on Wisconsin age glacial moraines in two drainages of the eastern Sierra Nevada. This study was suggested by Alan Gillespie, a graduate student whose thesis includes an attempt to discriminate between moraines deposited during different glacial advances. The drainages picked for the study were Independence Creek and adjacent South Fork of Oak Creek west of Independence, Owens Valley, California. The principle objective of the study was to determine if the method is sufficiently sensitive to discriminate between moraines of different glacial advances deposited within the last 100,000 years.

As in the alluvial fan study several features of the testing program had to be designed to accommodate restrictions imposed by the local geology and physical form of the deposits. To minimize the effects of different weathering environments on clast velocity, only clasts that are on the crests of moraines are measured. This is a widespread convention among glacial geologists. Additionally, only clasts exposed at the ground surface are measured because few moraines are sufficiently breached by streams or cut by roads to allow access to buried clasts. Lithologic variability at the source areas often restricts comparisons to moraines on a single side of a drainage and in most cases clasts from two or more plutons must be used to accumulate enough data. Care must be exercised that the site chosen for testing not be contaminated by clasts derived by slopewash or avalanches.

Moraines have some definite advantages over fans for a CSV study. There are generally sufficient boulders so that only clasts larger than 30 cm need be tested, which appears to eliminate the influence of clast size on apparent velocity. Generally the psysiographic form of the moraines is distinct enough to permit confident selection of several sites on a single moraine to evaluate the morainal variability. This improves the confidence with which moraines may be discriminated. The geology often allows visual correlation of some moraine pairs across a single drainage, providing greater flexibility in studying a drainage not having a complete set of moraines on either side of the valley.

Preliminary results of this study indicate that moraines from at least two Wisconsin age glaciations (locally known as Tahoe and Tioga) are separable at greater than 95 percent confidence using the Kolmogorov-Smirnov two sample test (Tate and Clelland, 1957). There is also a strong probability that additional Wisconsin and pre-Wisconsin age glacial deposits are detectable with proper statistical treatment of the data (Gillespie and Crook, in preparation).

CONCLUSIONS

A new quantitative, repeatable technique for relative age dating of Quaternary age deposits making use of P-wave velocities through clasts has been developed, with surprisingly precise results. Two tests of the method were carried out in regions of considerably different terraine, climate, and for deposits of different genesis. Each test required recognition and solution of problems unique to the local geology but both were based on the basic assumption that clast velocity is dependent on age of the deposit and decreases monotonically with time, as the degree of weathering of the clasts increases. The age range of the technique at present is limited by the resistance to weathering of the granitic clasts tested which appears to be around a million years. Clasts from older deposits are too weathered to test. There is the possibility of extending the range, however, by measuring more resistant clasts such as volcanic or metamorphic rocks.

The CSV technique may also have the potential for use as an absolute dating method when calibrated by radiometric dates.

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