Chemical analyses, correlations, and ages of late Cenozoic tephra units of east-central and southern California

by

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ABSTRACT

Eight widespread upper Pliocene and Pleistocene tephra units of east-central and southern California are characterized and correlated on the basis of neutron activation analysis of volcanic glass, stratigraphic criteria, and petrographic characteristics. In order of increasing age, these are the Pearlette type O ash (about 0.6 m.y.), the Bishop ash (about 0.7 m.y.), the "ash of Mono Glass Mountain" (estimated to be about 0.8 m.y.), the Gray ash (estimated to be about 1.0 m.y.), the Bailey ash (about 1.2 m.y.), the middle white ash of the Manix basin, the Pearlette type B ash, and the lowermost gray ash of the South Mountain area (all three estimated to be about 2.0 m.y.). Three chemical types of the Bishop ash are recognized and assigned to an informal Bishop ash group. The Friant Pumice ash of east-central San Joaquin Valley is one of the members of this group. The apparent 0.1 m.y. difference in K-Ar ages of the Friant Pumice (0.6 m.y.) and Bishop Tuff (about 0.7 m.y.) may be due to factors other than differences in the true ages of these tephra units. The Pearlette type B ash in Manix basin is correlated to a locality in Kansas, over a distance of about 1500 km. Results of analyses permit correlation of sedimentary strata deposited in diverse environments: marine, fluvial, and lacustrine.

Chemical characteristics of tephra permit identification of source areas from which the tephra was erupted: for instance, the Long Valley-Mono Glass Mountain area of east-central California, the Coso volcanic field of southeastern California, and the Yellowstone area of Wyoming and eastern Idaho. Systematic depletion trends in tephra units of the Long Valley-Mono Glass Mountain family suggest the possibility of an independent method of estimating the ages of some tephra units of this family.

Introduction

This report is the first in a series by the Tephrochronology Project of the Western Region, USGS, summarizing tephrochronological studies of specific regions. The primary purpose of this work is to provide age and stratigraphic information for site-specific and regional geologic hazard studies, including regional tectonic syntheses, determination of ages, rates, and directions of crustal movements, calibration and evaluation of provincial and regional faunal, paleomagnetic, isotopic, and chemical age dating methods, and correlation of marine and continental faunal and marine isotopic stages. An important aspect of this work is the refinement of existing radiometric ages. Radiocarbon, potassium-argon, and fission-track analyses are subject to analytical errors and errors due to contamination. Such errors are particularly large for a wide range of Quaternary igneous rocks and tephra. Tephrochronology correlations make it possible to cross-check age determinations from different localities of the same tephra unit, and identify those ages that are determined on the best available materials, have the least possibility of contamination, the lowest analytical error, or are in best agreement with other available stratigraphic, and geochronologic data.

Tephra layers (volcanic ashes and tuffs) are extremely useful in correlation of stratified sediments and rocks. A tephra layer produced by an explosive eruption can be spread over a large area within a short period of time--a matter of days or even minutes. Consequently tephra units from past eruptions represent virtually instantaneous time horizons that can be used for correlating deposits containing tephra. Tephra units that have been well

dated by isotopic or other methods at specific sites can be correlated to new sites, allowing absolute as well as relative age correlations between separate basins of deposition, and refining age assignments determined by other methods through cross-checking of independently dated, correlated localities.

This report summarizes results of chemical and petrographic analyses of late Cenozoic tephra of east-central and southern California (fig. 1). On the basis of these analyses, we propose a number of new correlations, and confirm or reject several correlations suggested previously by others. The correlations presented here make it possible to assign relative and absolute ages to late Cenozoic deposits at a number of locations in the study area, and correlate deposits of diverse depositional environments--fluvial, glaciofluvial, laucustrine, and marine (fig. 2, plate 1).

The present study should be considered as a progress report, due to the on-going nature of our work. Some correlations are made here on the basis of preliminary analyses only; subsequent work may require revision of our conclusions.

For a successful correlation, tephra units of different age must possess characteristics by which they can be uniquely identified. The principal method of correlation used in this study is chemical "fingerprinting" of volcanic glass separated from tephra. Pure glass separates are analyzed by neutron activation and electron microprobe and samples with similar trace-element composition are matched to establish correlations. These correlations are further supported by petrographic analysis of tephra and, where available, by independent stratigraphic, biostratigraphic, and paleomagnetic age control.

Previous studies (Jack and Carmichael, 1968; Sarna-Wojcicki, 1971, 1976; Sarna-Wojcicki and others, 1979) suggest that trace- and minor-element chemistry of volcanic glass is one of the more distinctive characteristics by which tephra of specific volcanic eruptions can be identified. This is possible because a number of minor and trace elements in volcanic glass can be analyzed with a high degree of precision, because silicic volcanic glass tends to be relatively homogenous within tephra units derived from the initial, explosive plinian phase of silica- and volatile-rich magma, and because tephra usually tends to be sufficiently differentiated through time from one eruption to the next, and from one source area to another.

In the present study we assume that the minor- and trace-element composition of volcanic glass from successive eruptions cannot be exactly duplicated. This is an assumption that cannot be proved conclusively, because all tephra units from the study area have probably not been analyzed and chemically identified. But a sufficient number of cases have been studied (Sarna-Wojcicki, 1976; Sarna-Wojcicki, Mullineaux, and Waitt, unpublished data, and this report), in which stratigraphic positions, and consequently, relative ages, of tephra units are known; in such instances, the chemical compositions of volcanic glasses are not repeated, except for very closely spaced units representing multiple eruptions from one center during a single eruptive episode of short duration. From these studies, we estimate that compositions of tephra of individual eruptions can be resolved analytically to within periods of about 1000 years, and possibly within periods of a hundred years or less. The minimum time over which tephra from successive eruptions can be distinguished depends on the precision of the analytical method used,

Figure 1

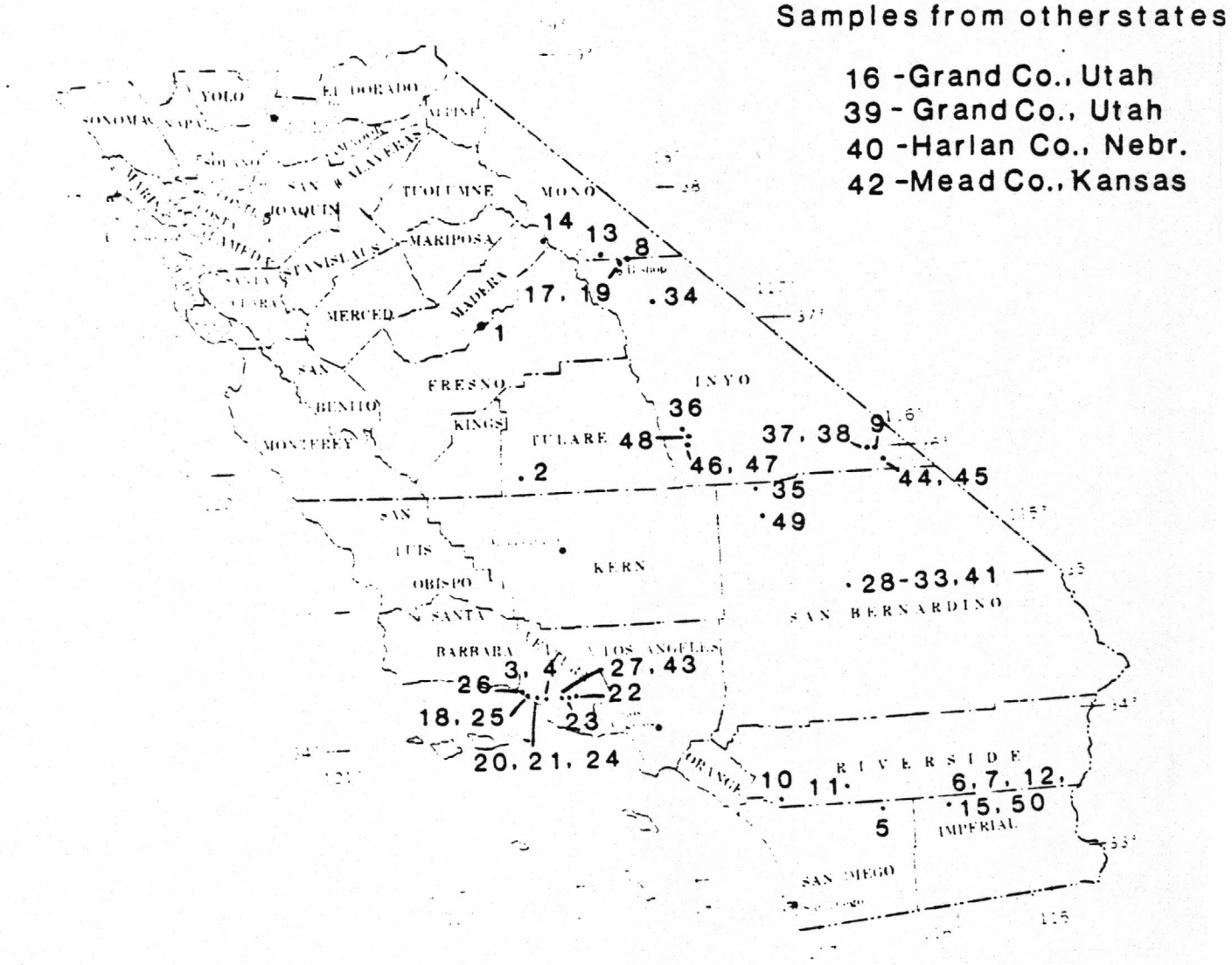

Figure 1. Generalized sample localities of tephra collected in east central and southern California. For detailed locality information see table 7.

and probably on the nature of magma-formation and differentiation processes at the magma chamber from which the tephra was erupted.

The basic assumption of the compositional uniqueness of magmas seems reasonable in view of the many complex factors that affect magma generation and differentiation. Rocks are compositionally heterogenous assemblages and it is unlikely that any two batches of magma formed from the fusion of rocks would ever be exactly alike. Additionally, magmatic differentiation and crystallization proceed at different temperatures, pressures, and rates, resulting in formation of different kinds and amounts of crystals in the melt. Crystals take-up varying amounts of elements from the magma, leaving variable concentrations of elements in the residual liquids. Furthermore, wall rocks, the "crucible" in which magma is contained, are not inert; they continually interact with the melt, resulting in continuous compositional changes through time. Thus, it seems improbable that all such variables could be exactly repeated in an identical sequence and at identical rates.

The same arguments apply to tephra units erupted from different volcanic fields. Certainly, the minor- and trace-element composition of glasses erupted from different volcanic fields is very different as this has been confirmed in a number of instances (Sarna-Wojcicki, 1971, 1976, and this report). Glass of tephra erupted at the same time from different vents tapping a single magma chamber, however, might not be distinguishable. This would depend on the shape of the magma chamber relative to the levels at which magma was being tapped, and the geometry and degree of zoning in the magma chamber. Zoning within a magma chamber may present problems in identification of tephra if the range of chemical compositions of tephra erupted during a single eruption overlaps with the range of compositions of tephra erupted at different times from the same caldera or source area. Zoning has been well documented for some caldras (Hildreth, 1977), and the spectrum of compositions erupted during a single eruption or eruptive sequence can be quite wide. The silica- and volatile-rich early plinian phase of most explosive eruptions, however, is compositionally rather narrow for glass of tephra units we have studied, and consequently presents little or no ambiguity in characterization of the tephra.

Lastly, if our assumption with respect to the compositional uniqueness of magmas, and consequently of volcanic glasses, cannot be proved conclusively, neither can it be disproved, because all methods of chemical analysis are subject to analytical error, and differences in composition may exist that are smaller than the error of the most precise analytical method available--such differences would not be detected with presently available analytical techniques.

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Methods

General

We disaggregated and sieved tephra samples, separating the volcanic glass for chemical analysis and the mafic heavy minerals for petrographic analysis. Glass samples were analyzed by instrumental neutron activation for abundances of about forty major, minor, and trace elements. About 16 to 20 elements were used in correlating tephra (see below). We also analyzed glass samples by electron microprobe for 12 elements: silicon, aluminum, iron, magnesium, manganese, calcium, barium, titanium, sodium, potassium, chlorine, and phosphorus. For a further description of sampling, sample preparation, and analyses, see the Appendix.

Data reduction

Selection of elements for correlation based on neutron activation analysis

For purposes of correlation, we selected elements on the basis of their natural variability within and between tephra units of different age, as well as according to precisions attainable for each element in neutron activation analysis. Analyses of samples from superposed tephra units at several localities in the study area allow us to evaluate the internal and external variability of these units, and determine the resolution available for each element relative to stratigraphic position. In other words, we can test whether the range of concentration of a particular element within glass of a single tephra unit, as determined from replicate analyses, overlaps with ranges determined for tephra units situated stratigraphically above and below and we can determine the extent of the overlap, if any exists. On the basis of our experience in this and previous studies (Sarna-Wojcicki, 1976, Sarna-Wojcicki and others, 1979), an element is useful in characterizing tephra if the mean of replicate analyses within a single tephra unit is significantly different from the mean of replicate analyses of another unit of demonstrably different age, at alpha equal to or less than 0.05 (in other words, if we are 95% confident that the means are truly different). An element is useful in correlation if 1) it is relatively homogenously distributed within the glass of a single tephra unit, 2) there is a natural compositional contrast between the concentration of this element in a tephra unit relative to its concentration in another unit of demonstrably different age and, 3) the analytical precision for this element is sufficiently high relative to its concentration in the glass that such compositional contrasts can be measured. In practice we use those elements for which analytical error is equal to or less than about 7 percent of its concentration in the glass. In neutron activation analysis, between 16 and 20 minor and trace elements are usually most useful for correlation of dacitic and rhyolitic tephra. These elements are: scandium, manganese, iron, zinc, rubidium, cesium, barium, lanthanum, cerium, neodymium, samarium, europium, terbium, dysprosium, ytterbium, lutecium, tantalum, hafnium, thorium, and uranium. The utility of a certain element will vary from one volcanic source area to another and, consequently, between suites of tephra derived from different volcanic provinces. For instance, barium and europium are near detection limits of neutron activation analysis in tephra derived from the Long Valley-Mono Glass Mountain province east of the Sierra Nevada in eastern California, consequently the error in precision of these elements is high or higher than

compositional variations between tephra units of different age erupted from this province. Consequently these elements cannot be used to discriminate between different tephra units belonging to this tephra family. Barium and europium can be used, however, for distinguishing tephra units derived from volcanic provinces where their concentration in silicic glass is higher.

Analytical precision for the elements used, as determined by replicate analyses of tephra samples from the same tephra units, and expressed as a percentage of concentration present in the glass, ranges from less than one to about seven percent, and averages about three to four percent.

Methods of evaluating chemical data for correlation

For the purpose of visual representation of element concentrations in glass, we calculated ratios of concentrations of elements of selected samples to concentrations of the same elements in USGS rock standard G-1. Histograms of these ratios are shown in fig. 3. Suggested or recommended values and magnitudes (Fleisher, 1969) are used except for cesium, terbium, and ytterbium, for which values of 6, 1, and 2.5 ppm, respectively, were arbitrarily assigned in order to minimize high ratios. This graphic method was chosen because one can plot on a single scale elements that vary in concentration by as much as seven orders of magnitude. Differences between pairs of histograms have also been calculated and are shown adjacent to sample histograms (fig. 3).

Similarity coefficients (Borcherdt and others, 1972) have been calculated for every sample pair. The similarity coefficient is an average of ratios of element concentrations in two glass samples. Ratios of individual elements are calculated by dividing the concentration in one sample by the concentration in another. Unless concentrations in samples are identical, the higher concentration is divided into the lower, so that the ratio is always less than or equal to one. The coefficients are averaged for all elements in the comparison. The ideal value of this coefficient is 1 for a chemically identical sample pair. This coefficient is given by:

$$d_{(A.B.)} = \frac{\sum_{i=1}^{n} R_i}{n},$$

where

$d_{(A.B.)} = d_{(B.A.)}$ = similarity coefficient for comparison between sample A and sample B,

i = element number,

n = number of elements,

R_i = $\chi_i A/\chi_i B$ if $\chi_i B > \chi_i A$; otherwise $\chi_i B/\chi_i A$,

$\chi_i A$ = concentration of element i in sample A, and

$\chi_i B$ = concentration of element i in sample B.

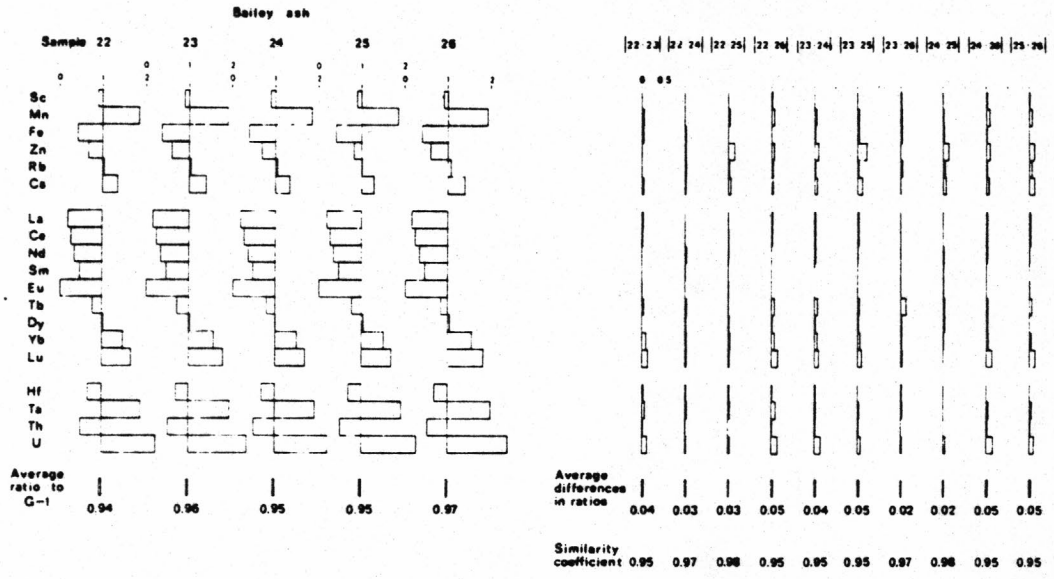
Figure 3. Trace- and minor-element compositions of selected glass samples of tephra, shown as ratios to U.S. Geological Survey rock standard G-1, and differences between histogram pairs.

3a. The left side of the figure shows glass compositions of five samples of the Bailey ash. The right side shows the absolute difference between samples. Thus 22-23 is a histogram showing the absolute difference between samples 22 and 23. Sample numbers are the same as in other tables and figures. Method of plotting ratios is adapted from O'Keefe (1978).

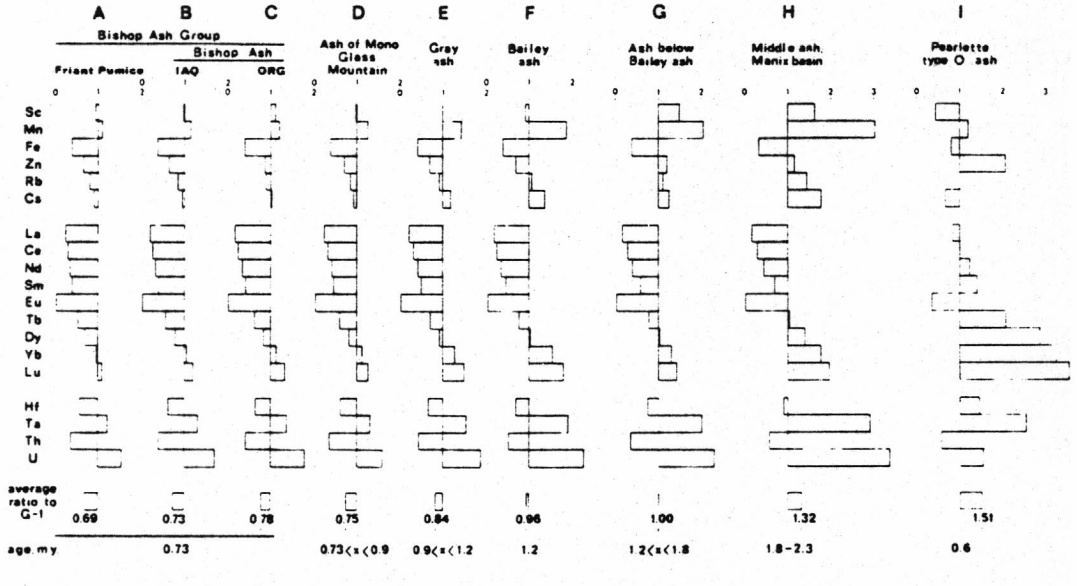
3b. The left side of the figure shows glass compositions of tephra units of the Long Valley-Mono Glass Mountain family (A-H), and the Pearlette type O ash (I), as ratios to G-1. Average values of analyzed samples are used for each tephra unit. The right side of the figure shows absolute differences between ratios of the Friant Pumice and ratios of each successive tephra unit to the right. Thus A-B shows the absolute difference between the Friant Pumice and the Bishop ash, IAQ (Insulating Aggregates quarry) type; A-C shows the absolute difference between the Friant Pumice and the Bishop ash, ORG (Owens River Gorge and Red's Meadow) type, and so-on.

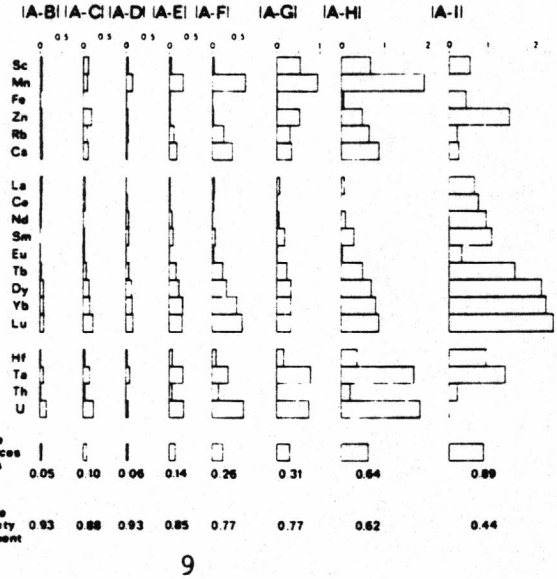
Figure 3

a.


Bailey ash
Sample 22
23
24
25
26
Sc
Mn
Fe
Zn
Rb
Cs
La
Ce
Nd
Sm
Eu
Tb
Dy
Yb
Lu
Hf
Ta
Th
U
Average ratio to G-1
0.94
0.96
0.95
0.95
0.97
Average differences in ratios
0.04
0.03
0.03
0.05
0.04
0.05
0.02
0.02
0.05
0.05
Similarity coefficient
0.95
0.97
0.98
0.95
0.95
0.95
0.97
0.98
0.95
0.95

b.


A
B
C
D
E
F
G
H
I
Bishop Ash Group
Bishop Ash
Friant Pumice
IAQ
ORG
Ash of Mono Glass Mountain
Gray ash
Bailey ash
Ash below Bailey ash
Middle ash, Manix basin
Pearlette type O ash
Sc
Mn
Fe
Zn
Rb
Cs
La
Ce
Nd
Sm
Eu
Tb
Dy
Yb
Lu
Hf
Ta
Th
U
average ratio to G-1
0.69
0.73
0.78
0.75
0.84
0.96
1.00
1.32
1.51
age, my
0.73
0.73<x<0.9
0.9<x<1.2
1.2
1.2<x<1.8
1.8–2.3
0.6


IA-BI
IA-CI
IA-DI
IA-EI
IA-FI
IA-GI
IA-HI
IA-II
Sc
Mn
Fe
Zn
Rb
Ca
La
Ce
Nd
Sm
Eu
Tb
Dy
Yb
Lu
Hf
Ta
Th
U
Average differences in ratios
0.05
0.10
0.06
0.14
0.26
0.31
0.64
0.89
Average similarity coefficient
0.93
0.88
0.93
0.85
0.77
0.77
0.62
0.44

In practice, the values of the coefficient for replicate analyses of splits of the same sample, or of samples from a single emplacement unit, range from about 0.93 to 0.99 owing to inhomogeneities in the glass, variations in purity of glass separations, presence of microlites, or analytical errors. The actual range of values for replicate analyses within single emplacement units also varies to some extent depending on the elements selected for comparison and the volcanic source area from which the tephra suite has been erupted.

Values of similarity coefficients for tephra units of demonstrably different age (for instance, tephra units superposed within an exposed continuous stratigraphic section) range from about 0.35 to about 0.94, the exact range depends on the variables mentioned above. Tephra units derived from the Long Valley-Mono Glass Mountain volcanic province are very similar in chemical composition and are harder to distinguish than tephra units from other provinces. Similarity coefficients for different tephra units of this family are sometimes as high as 0.95. Consequently, the range of similarity coefficients from 0.93 to 0.95 represents an interval of uncertainty and correlations based solely on similarity coefficients within this interval must be regarded as uncertain. This degree of uncertainty can be quantified and expressed in probabilistic terms by using a modification of the similarity coefficient, whereby the average ratio is calculated for sample pairs by dividing element concentrations in one sample by those of another, the concentrations of the first being in the denominator, those of the second, in the numerator regardless of which is the greater. Since deviations from the ideal value of 1 for different elements of a sample pair in this instance may average out to give a misleadingly high average ratio, this modification is not as useful a guide to indicate correlation as the similarity coefficient, but the standard deviation of the mean of these ratios for a population of variables (elements) is useful, because it measures the dispersion of values about 1, and the distribution of these values should be normal.

Because ranges of similarity coefficients for replicate analyses of individual tephra units generally do not overlap with those of tephra units of different age, similarity coefficients can be used as quantitative guides to indicate correlation or its lack where stratigraphic control is not available. The actual ranges of values for acceptance or rejection of correlation must be derived empirically for each suite of tephra erupted from a particular volcanic source area, calibrated and verified by replicate analyses of individual units and multiple superposed units at critical localities.

A similarity coefficient matrix is given in fig. 4 (plate 1) which compares every sample pair (2346 pairs) in the group of 69 samples analyzed. Average values for major groups have also been calculated and are given in the appropriate positions in fig. 4 (plate 1). The matrix shown in fig. 4 (plate 1) is based on the best 13 elements analyzed for in all 69 samples. This includes scandium, iron, rubidium, cesium, lanthanum, cerium, samarium, terbium, ytterbium, lutecium, hafnium, tantalum, and thorium. Elements excluded are manganese, dysprosium, and uranium, which were not determined for some samples, and zinc, neodymium, and europium, for which precision was low in some of the sample groups.

A dendrogram (fig. 5) shows the relationships between the samples and sample groups based on highest values of the similarity coefficient between individual sample pairs, and highest average values for the sample groups shown in the matrix (fig. 4, plate 1).

Correlation of tephra units

Figure 2 (plate 1) summarizes correlations presented in this study, together with available isotopic, stratigraphic, and paleomagnetic data. Correlations are made primarily on the basis of glass chemistry (table 1) and stratigraphic sequence, supported by petrographic, isotopic, and paleomagnetic data.

It was not possible to resolve differences in glass chemistry for a number of tephra units on the basis of electron microprobe analysis alone (table 3). This was particularly true for ashes of the Long Valley-Mono Glass Mountain suite situated in close stratigraphic proximity. Likewise, it was not possible to distinguish definitively between ashes derived from the Yellowstone area (Pearlette-like ashes) by this method. However, it is possible to readily distinguish between suites of tephra derived from different volcanic source areas, and to identify tephra units from certain other source areas, such as Crater Lake, Mount St. Helens, and Glacier Peak, by this method (Smith and others, 1977; Davis, 1978; and Meyer and Sarna-Wojcicki, unpublished data). Attempts to differentiate among ashes of the Long Valley-Mono Glass Mountain provenance by electron microprobe analyses alone can result in misidentification.

Discussion of specific correlations

In the following discussion of specific correlations, we will be referring to samples analyzed in this study by locality numbers shown in fig. 1. The same numbers are used in fig. 2 (plate 1), the summary correlation chart; tables 1 and 3, which present chemical analyzes; and table 8 (plate 1), which gives specific location information.

Pearlette type O ash

The Pearlette type O ash is the youngest of three widespread tephra units that are important stratigraphic markers in the central and western United States. Our chemical data confirms (Izett and others, 1972) presence of the Pearlette type O ash in lake deposits of Pleistocene Lake Tecopa. Sample 37 (table 1), taken from the basal 7 cm of a 2.1 m thick, water-deposited ash

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Figure 5. Dendrogram showing relations between glass chemistry of individual samples and sample groups, based on values of the similarity coefficient. Highest values of individual similarity coefficients are used to link adjacent samples; highest values of averages of sample groups are used to link adjacent groups. The position of each link is drawn at the appropriate value of the similarity coefficient, indicated by the scale at the top.

Figure 5

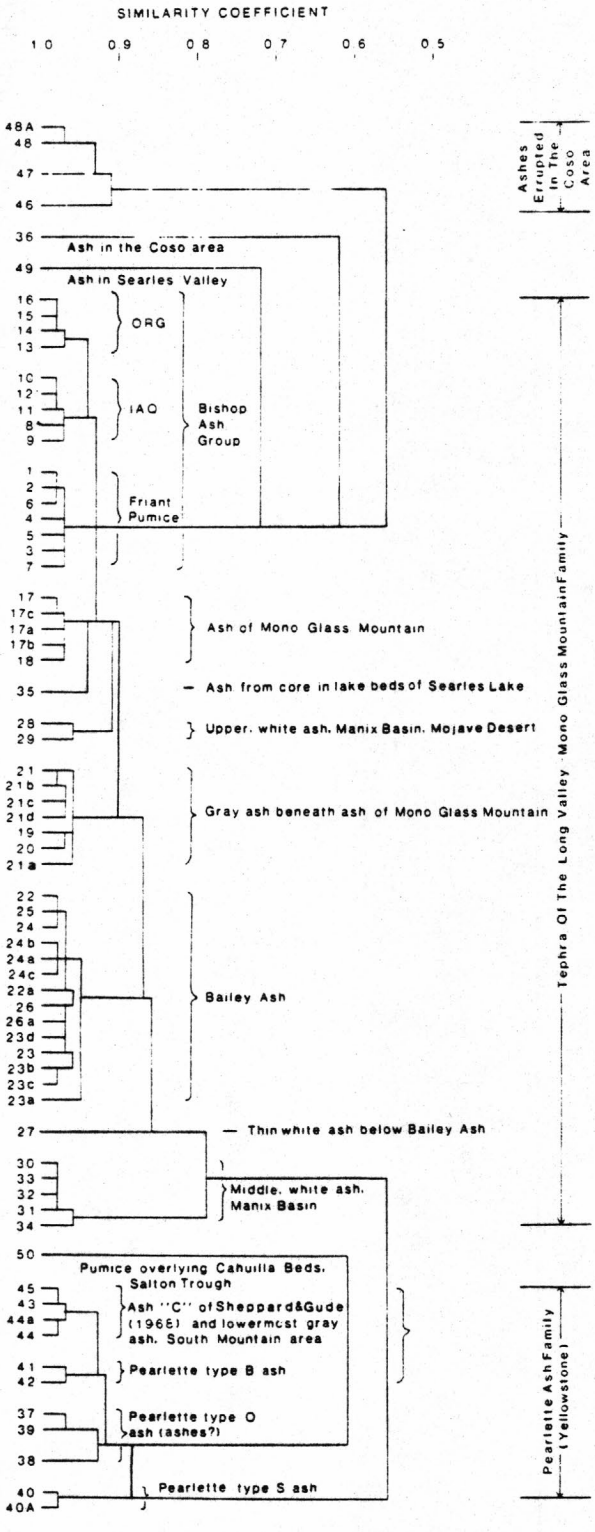
SIMILARITY COEFFICIENT
1.0
0.9
0.8
0.7
0.6
0.5
48A
48
47
46
36
Ash in the Coso area
49
Ash in Searles Valley
16
15
14
13
ORG
10
12
11
8
9
IAO
Bishop Ash Group
1
2
6
4
5
3
7
Friant Pumice
17
17c
17a
17b
18
Ash of Mono Glass Mountain
35
Ash from core in lake beds of Searles Lake
28
29
Upper, white ash, Manix Basin, Mojave Desert
21
21b
21c
21d
19
20
21a
Gray ash beneath ash of Mono Glass Mountain
22
25
24
24b
24a
24c
22a
26
26a
23d
23
23b
23c
23a
Bailey Ash
27
Thin white ash below Bailey Ash
30
33
32
31
34
Middle, white ash, Manix Basin
50
Pumice overlying Cahuilla Beds, Salton Trough
45
43
44a
44
Ash "C" of Sheppard&Gude (1968) and lowermost gray ash, South Mountain area
41
42
Pearlette type B ash
37
39
Pearlette type O ash (ashes?)
38
40
40A
Pearlette type S ash
Ashes Erupted In The Coso Area
Tephra Of The Long Valley - Mono Glass Mountain Family
Pearlette Ash Family (Yellowstone)

Table 1. Neutron activation analysis of volcanic glass from late Cenozoic tephra of east central and southern California.

[Concentrations in parts per million except for iron, which is in percent]

Sample[1] number	Sc	Mn	Fe	Zn[2]	Rb	Cs	La	Ce	Nd[2]	Sm	Eu[2]	Tb	Dy[2]	Yb	Lu	Hf	Ta	Th	U
Ashes Having Chemical Affinity to Tephra of the Long Valley-Mono Basin Area																			
Pumice (1), near Friant, and correlative ashes																			
1[3]	2.83	252	0.52	32	171	5.4	24.1	50.8	20	3.57	0.04	0.53	3.42	2.39	0.30	3.64	1.91	19.4	6.08
2	2.89	252	.54	28	169	5.3	25.0	52.2	17	3.56	.06	.52	3.53	2.40	.31	3.56	1.91	19.0	6.08
3	2.87	254	.53	36	182	5.7	22.6	48.7	19	3.64	.04	.58	3.57	2.48	.37	3.57	2.00	19.5	6.38
4	2.75	258	.50	34	179	5.1	23.6	50.9	19	3.59	.04	.55	3.61	2.49	.35	3.46	1.96	19.2	6.18
5	2.80	258	.52	21	186	5.3	22.6	51.9	20	3.64	.05	.55	ND	2.40	.32	3.64	1.96	19.5	6.09
6	2.68	245	.52	31	170	5.3	25.2	51.9	20	3.53	.06	.52	3.28	2.29	.33	3.48	1.87	19.5	5.80
7	2.96	252	.52	25	178	5.6	21.6	48.6	18	3.61	.04	.55	3.70	2.54	.31	3.53	2.04	20.1	6.50
$\bar{x}$	2.83	253	0.52	30	176	5.4	23.5	50.7	19	3.59	0.05	0.54	3.52	2.43	0.33	3.55	1.95	19.3	6.16
σ	.09	4	.01	5	7	.2	1.3	1.5	1	.04	.01	.02	.15	.08	.03	.07	.06	.5	.23
a.a.e.[4]	.02	2	.01	2	6	.1	.5	.6	2	.01	<.005	.03	.09	.03	.02	.06	.01	.2	.05
Bishop ash at Insulating Aggregates Quarry (8), and correlative ashes																			
8	3.06	265	0.54	30	187	6.0	19.4	47.1	20	3.74	0.04	0.56	4.10	2.70	0.37	3.74	2.15	21.0	6.69
9	2.99	254	.50	20	185	5.9	18.7	42.9	17	3.59	.04	.58	3.99	2.66	.36	3.79	2.10	21.0	7.44
10	2.85	262	.50	32	181	5.4	20.3	46.6	18	3.60	.03	.57	3.74	2.55	.34	3.67	2.04	19.8	6.53
11	2.95	266	.51	32	188	5.4	20.0	46.8	20	3.65	.04	.57	4.02	2.64	.37	3.60	2.10	20.9	6.70
12	2.92	266	.49	33	186	5.6	20.2	46.2	17	3.62	.04	.58	3.91	2.64	.35	3.67	2.09	20.2	6.69
$\bar{x}$	2.95	263	0.51	29	185	5.7	19.7	45.9	18	3.64	0.04	0.57	3.95	2.64	0.36	3.69	2.09	20.6	6.91
σ	.08	5	.02	5	3	.3	.7	1.7	2	.06	<.005	.01	.14	.06	.01	.07	.04	.5	.36
a.a.e.[4]	.02	3	.01	2	7	.1	.5	.7	1	.02	.01	.03	.10	.04	.02	.07	.01	.1	.06
Bishop ash at Owens River Gorge (13) and at Red's Meadow (14), and correlative ashes																			
13	3.17	281	0.55	66	200	6.1	18.5	42.2	20	3.89	0.04	0.60	4.21	2.84	0.37	3.92	2.18	21.4	7.13
14	3.22	274	.50	33	195	6.1	18.3	42.1	18	3.77	.03	.63	3.98	2.87	.41	3.99	2.25	21.9	7.19
15	3.20	272	.50	29	195	6.1	17.7	42.6	19	3.74	.03	.61	4.27	2.77	.39	3.84	2.25	21.9	7.22
16	3.16	279	.51	27	202	6.2	18.1	43.4	17	3.79	.03	.65	4.26	2.80	.42	3.74	2.27	22.0	7.20
$\bar{x}$	3.19	277	0.52	39	196	6.1	18.0	42.6	19	3.78	0.03	0.62	4.19	2.32	0.40	3.87	2.24	21.9	7.14
σ	.03	4	.02	18	8	.1	.4	.6	1	.08	.01	.02	.14	.04	.02	.11	.01	.3	.08
a.a.e.[4]	.03	3	.01	3	8	.2	.5	.7	1	.01	.01	.03	.08	.04	.02	.07	.01	.2	.06

Table 1.--Continued.

Sample[1] number	Sc	Mn	Fe	Zn[2]	Rb	Cs	La	Ce	Nd[2]	Sm	Eu[2]	Tb	Dy[2]	Yb	Lu	Hf	Ta	Th	U
"Ash of Mono Glass Mountain" (17, 17a-c) and correlative ash, Ventura area (18)																			
17	2.91	276	0.50	29	189	5.7	24.0	53.2	22	4.15	0.02	0.63	3.99	2.74	0.38	3.76	2.09	19.7	6.55
17a[5]	2.91	ND	.52	34	186	5.3	24	58	26	4.6	.07	.59	ND	2.8	.36	3.6	2.11	19.0	ND
17b	2.90	ND	.51	26	184	5.3	23	53	22	4.0	.02	.58	ND	2.8	.38	3.6	1.98	19.2	6.1
17c	2.95	ND	.51	31	186	5.6	24	55	23	4.1	.12	.59	ND	2.9	.39	3.8	2.10	19.6	6.3
18	3.01	301	.58	39	186	5.4	22.7	54.9	22	4.34	.02	.64	4.22	2.77	.38	3.76	2.19	19.5	6.65
$\bar{x}$	2.94	289	0.52	32	186	5.5	23.5	54.8	23	4.2	0.05	0.61	4.10	2.80	0.38	3.7	2.09	19.4	6.4
σ	.05	---	.03	5	2	.2	.6	2.0	2	.2	.04	.03	---	.06	.01	.1	.03	.3	.2
a.a.e.[4]	.03	2	.01	1	5	.2	.3	.7	2	.04	<.005	.02	.09	.05	.01	.1	.03	.2	.1
Gray ash beneath "ash of Mono Glass Mountain" (19) and correlative ash, Ventura area (20, 21, 21a-d)																			
19	3.09	313	0.54	36	211	6.0	22.2	52.6	21	4.48	0.03	0.71	4.51	3.00	0.42	4.04	2.31	22.0	7.27
20	3.00	315	.53	(111)	204	6.0	22.8	57.9	24	4.33	.02	.69	ND	2.90	.40	4.00	2.26	21.7	6.60
21	2.87	348	.54	27	210	6.6	22.3	52.3	23	4.50	.03	.75	4.68	3.21	.45	3.93	2.52	22.7	7.48
21a	2.98	ND	.57	37	198	6.9	23	60	28	5.0	.05	.73	ND	3.3	.49	4.2	2.52	23.5	ND
21b	2.87	ND	.55	29	201	6.5	22	53	22	4.5	.04	.73	ND	3.3	.46	4.0	2.56	23.1	8.2
21c	2.94	ND	.56	31	191	6.5	22	50	21	4.3	.04	.64	ND	3.3	.46	4.0	2.41	22.6	6.7
21d	2.96	ND	.56	31	203	7.1	22	52	22	4.4	.04	.75	ND	3.3	.47	3.9	2.76	23.8	9.0
$\bar{x}$	2.96	326	0.55	31	200	6.5	22.3	54.0	23	4.5	0.04	0.71	4.60	3.19	0.45	4.02	2.47	22.8	7.5
σ	.08	---	.01	4	9	.4	.4	3.6	2	.2	.01	.04	---	.17	.03	.09	.17	.8	.9
a.a.e.[4]	.03	4	.01	2	5	.2	.3	.7	2	.04	.01	.03	.13	.06	.02	.06	.04	.2	.12
Bailey ash, South Mountain (22, 22a, 23, 23a-d), and Ventura (24, 24a-c, 25, 26, and 26a) areas																			
22	2.68	426	0.57	30	227	8.1	20.2	45.8	19	4.36	0.04	0.77	5.14	3.71	0.50	4.01	3.02	26.7	8.95
22a	2.73	ND	.58	36	256	8.1	19	45	20	4.2	.08	.76	ND	3.8	.55	4.1	3.04	26.7	8.8
23	2.68	438	.50	27	229	8.4	17.2	42.6	19	4.36	.03	.73	5.14	3.95	.54	4.28	3.14	27.6	9.42
23a	2.82	ND	.53	30	244	8.5	20	49	17	(5.5)	(.21)	.81	ND	4.0	.56	4.3	3.05	27.8	ND
23b	2.67	ND	.48	29	233	7.7	17	41	19	4.0	.05	.75	ND	3.9	.55	4.1	2.87	26.1	8.2
23c	2.74	ND	.50	34	240	8.0	18	41	21	4.0	.06	.75	ND	3.9	.55	4.0	2.97	26.9	8.2
23d	2.78	ND	.50	34	249	8.8	18	42	18	4.3	.06	.79	ND	4.1	.58	4.2	3.27	28.4	10.4
24	2.68	426	.52	31	233	8.0	20.1	48.4	21	4.44	.04	.81	5.03	3.78	.51	4.14	3.08	26.7	8.86
24a	2.70	ND	.51	30	231	8.3	20	46	19	4.2	.05	.76	ND	3.8	.54	4.2	2.95	26.4	8.7
24b	2.70	ND	.53	29	222	8.0	20	47	21	4.1	.06	.79	ND	3.8	.53	4.2	2.79	26.0	8.5
24c	2.67	ND	.51	32	241	8.4	20	47	18	4.3	.06	.79	ND	3.8	.55	4.1	3.25	27.3	10.2
25	2.65	428	.55	37	223	7.7	20.0	47.1	20	4.35	.03	.78	5.27	3.81	.51	4.17	3.08	26.7	9.13
26	2.72	444	.55	27	237	8.4	17.4	42.4	19	4.35	.04	.85	5.23	3.90	.55	4.16	3.19	27.5	9.56
26a	2.79	ND	.57	31	233	8.8	17	42	19	4.1	.05	.80	ND	3.8	.57	4.2	3.19	27.9	9.6
$\bar{x}$	2.72	432	0.53	31	236	8.2	18.9	44.7	19	4.24	0.05	0.78	5.16	3.86	0.54	4.15	3.06	27.1	9.1
σ	.05	8	.03	3	10	.3	1.3	2.8	1	.15	.01	.03	.09	.10	.02	.09	.14	.7	.7
a.a.e.[3]	.03	3	.01	2	6	.2	.3	.7	2	.03	.01	.03	.10	.06	.01	.08	.05	.3	.14

Table 1.--Continued.

Sample[1] number	Sc	Mn	Fe	Zn[2]	Rb	Cs	La	Ce	Nd[2]	Sm	Eu[2]	Tb	Dy[2]	Yb	Lu	Hf	Ta	Th	U
Ash below Bailey ash, South Mountain area																			
27	4.47	472	0.52	54	245	7.5	17.2	48.7	22	5.28	0.04	0.78	5.14	3.26	0.43	4.55	3.21	18.7	9.20
a.e.[6]	0.03	3	0.01	3	9	0.2	0.4	0.6	1	0.01	0.01	0.03	0.07	0.04	0.02	0.08	0.01	0.1	0.05
Upper, white ash, Manix basin, Mojave Desert																			
28	3.76	346	0.52	42	192	5.8	19.5	49.9	20	4.59	0.01	0.57	3.83	2.60	0.39	4.17	2.39	17.9	7.38
29	3.67	354	.50	36	197	5.8	18.4	48.8	22	4.47	.01	.61	4.03	2.50	.34	4.12	2.36	18.1	7.22
$\bar{x}$	3.72	350	0.51	39	192	5.8	19.0	49.4	21	4.53	0.01	0.59	3.93	2.56	0.37	4.15	2.38	18.0	7.30
a.a.e.[3]	.02	3	.01	3	4	.2	.6	.6	1	.02	<.005	.03	.11	.03	.02	.07	.01	.2	.06
Middle, white ash, Manix basin, Mojave Desert (30-33), and ash in Waucoba lake beds, E. Owens Valley (34)																			
30	4.89	688	0.45	48	317	10.3	17.1	51.0	25	6.30	<0.005	1.08	7.0	4.34	0.56	5.73	4.57	29.5	13.51
31	4.95	696	.44	51	315	10.8	17.3	51.5	21	6.44	<0.005	1.00	6.7	4.46	.64	5.85	4.67	30.2	13.78
32	4.86	698	.46	52	327	11.1	17.5	52.3	27	6.33	.02	1.04	7.1	4.52	.60	5.81	4.71	29.7	13.49
33	4.92	701	.45	50	321	10.6	16.9	52.3	27	6.37	.03	1.04	7.2	4.38	.58	5.91	4.74	29.7	13.37
34	4.66	701	.46	61	323	10.7	16.0	45.3	24	6.00	.06	1.06	6.9	4.39	.59	5.53	4.61	30.5	13.24
$\bar{x}$	4.86	697	0.45	52	318	10.7	17.0	50.5	25	6.29	0.02	1.04	7.0	4.42	0.59	5.77	4.66	29.9	13.48
σ	.11	5	.01	5	9	.3	.6	2.9	2	.17	.02	.03	.2	.07	.03	.15	.07	.4	.20
a.a.e.[3]	.03	5	.01	3	10	.2	.5	.7	1	.02	.01	.04	.1	.05	.03	.09	.02	.2	.10
Ash in late Cenozoic lake beds of Searles Lake																			
35	2.86	507	0.51	36	174	5.9	23.3	50.7	19	3.92	0.12	0.66	ND	2.86	0.36	3.51	2.23	17.0	4.84
a.e.[6]	0.02	8	0.01	2	6	0.1	0.5	0.7	1	0.01	0.01	0.03		0.04	0.02	0.06	0.01	0.1	0.04
Unwelded, pumiceous ash flow tuff in the Coso area																			
36	2.48	484	0.36	23	228	10.7	6.2	15.8	7	0.99	0.09	0.16	1.34	1.67	0.26	3.60	1.59	16.5	7.75
a.e.[6]	0.02	4	0.01	2	10	0.2	0.3	0.5	1	0.01	0.01	0.02	0.11	0.03	0.01	0.06	0.01	0.1	0.05

Table 1.--Continued.

Sample[1] number	Sc	Mn	Fe	Zn[2]	Rb	Cs	La	Ce	Nd[2]	Sm	Eu[2]	Tb	Dy[2]	Yb	Lu	Hf	Ta	Th	U
Ashes having Chemical Affinity to Tephra of the Yellowstone Area, Wyoming Uppermost ash (ash "A"), Tecopa area (37, 38), and Pearlette type "O" ash, Grand Co., Utah (39)																			
37	1.33	259	1.05	94	222	4.2	81	160	66	12.47	0.37	2.08	14.27	8.35	1.11	8.50	4.29	30.0	6.62
38	1.33	290	1.15	94	199	3.7	92	182	73	13.39	.59	2.10	13.89	7.91	1.00	9.26	3.84	29.2	5.77
39	1.29	270	1.05	90	235	4.0	83	161	63	12.60	.41	2.05	14.20	7.95	1.11	8.59	4.03	29.0	6.29
$\bar{x}$	1.32	273	1.08	93	219	4.0	84	168	67	12.63	0.46	2.08	14.25	8.07	1.06	8.78	4.05	29.4	6.13
a.a.e.[4]	0.01	5	0.01	7	8	0.1	1	2	2	0.09	0.01	0.09	0.15	0.08	0.03	0.10	0.03	0.2	0.06
Pearlette type "S" ash, Harlan County, Nebraska[8]																			
40[9]	1.70	240	0.99	69	264	4.6	81	161	58	11.41	0.40	1.92	13.00	7.53	1.09	7.11	3.79	33.9	7.25
40A[9]	1.74	244	1.03	69	269	4.6	83	161	60	11.50	.42	1.88	13.20	7.68	1.04	7.20	3.81	34.1	7.37
$\bar{x}$	1.72	242	1.01	69	266	4.6	79	161	59	11.01	0.41	1.90	13.20	7.61	1.03	7.16	3.80	34.0	7.03
a.a.e.[4]	0.02	3	0.02	3	13	0.1	1	2	2	0.02	0.01	0.06	0.17	0.08	0.04	0.10	0.02	0.2	0.05
Lower gray ash, Manix basin (41), and Pearlette type B ash, Borchers locality, Meade County, Kansas (42)																			
41	1.77	297	1.21	106	201	3.7	92	181	73	13.78	0.69	2.20	13.9	7.93	1.08	9.51	3.53	29.9	6.24
42	1.68	281	1.20	103	211	3.5	96	187	74	13.95	.72	2.13	14.5	7.89	1.15	9.10	3.56	29.8	6.17
$\bar{x}$	1.73	284	1.21	105	206	3.6	92	184	74	13.54	0.71	2.17	14.38	7.91	1.09	9.31	3.55	29.9	6.21
a.a.e.[4]	0.02	3	0.02	3	8	0.1	1	2	2	0.03	0.01	0.08	0.17	0.08	0.04	0.12	0.02	0.1	0.06
Lower gray ash, South Mountain area (43), and gray ash (ash "C")[7], Tecopa area (44, 45)																			
43	1.74	301	1.24	122	196	3.0	104	203	78	14.45	0.82	1.98	13.91	7.62	1.03	9.39	3.30	28.6	5.70
44	1.75	305	1.25	120	189	2.8	102	189	78	14.29	.81	1.98	13.37	7.05	1.00	8.97	3.01	27.8	5.57
44a	1.71	ND	1.24	104	189	2.9	102	188	78	13.99	.81	1.98	ND	7.22	.98	9.25	3.13	27.5	5.25
45	1.80	310	1.28	125	192	3.2	102	202	80	14.28	.89	2.03	13.60	7.62	1.05	9.60	3.25	28.1	5.63
$\bar{x}$	1.75	305	1.25	118	192	3.0	103	196	79	14.25	0.83	1.99	13.63	7.38	1.02	9.30	3.17	28.0	5.54
σ	.04	5	.02	9	3	.2	1	8	1	.19	.04	.03	.27	.29	.03	.26	.13	.5	.20
a.a.e.[4]	.02	2	.02	3	8	.1	1	2	2	.05	.01	.05	.12	.07	.03	.11	.02	.2	.07

Sample[1] number	Sc	Mn	Fe	Zn[2]	Rb	Cs	La	Ce	Nd[2]	Sm	Eu[2]	Tb	Dy[2]	Yb	Lu	Hf	Ta	Th	U
Tephra Having Chemical Affinities to other Volcanic Provinces																			
Air-fall pumice of the Coso area																			
46	1.41	251	1.02	48	111	2.9	25.1	44.4	16	2.31	0.49	0.20	1.60	1.03	0.17	3.74	0.66	7.95	2.49
a.e.[6]	0.02	3	0.02	3	6	0.1	0.6	.8	1	0.01	0.01	0.02	0.10	0.03	0.02	0.07	0.01	0.06	0.04
47	1.05	284	0.95	42	105	2.6	24.1	44.1	14	1.97	0.44	0.20	1.48	0.91	0.12	3.91	0.71	7.67	2.34
a.e.[6]	0.02	3	0.02	3	5	0.1	0.6	0.7	1	0.01	0.01	0.02	0.11	0.03	0.01	0.08	0.01	0.06	0.04
48	0.91	281	0.90	41	101	2.8	24.4	45.9	13	1.87	0.41	0.15	1.25	0.85	0.13	3.81	0.74	8.19	2.48
48A	0.87	283	0.86	36	103	2.7	25.3	43.6	14	1.82	0.41	0.15	1.17	0.86	0.14	3.60	0.72	8.16	2.44
$\bar{x}$	0.89	282	0.88	39	102	2.8	24.9	44.8	14	1.85	0.41	0.15	1.21	0.86	0.14	3.71	0.73	8.18	2.46
a.a.e.[4]	.02	3	.02	3	5	.1	.6	.7	1	.01	.01	.02	.10	.03	.01	.07	.01	.06	.04
Ash in Searles Valley																			
49	2.46	479	0.79	43	88	4.5	19.8	39.3	17	3.14	0.57	0.44	3.14	2.51	0.36	4.30	0.50	8.74	3.90
a.e.[6]	0.02	4	0.02	2	4	0.1	0.4	0.6	1	0.01	0.01	0.02	0.12	0.31	0.02	0.70	< 0.005	0.06	0.04
Pumice overlying Cahuilla Beds, Salton trough																			
50	3.88	403	1.90	68	137	4.0	45.9	107	51	12.18	1.76	0.40	16.7	12.1	1.72	12.8	1.75	19.1	5.40
a.e.[6]	0.03	3	0.03	5	8	0.1	0.6	1	2	0.02	0.02	0.05	0.1	0.1	.05	0.2	0.01	0.2	0.04

[1]Sample numbers are the same as in Fig. 1.

[2]These elements were not used in calculation of the similarity coefficient and other statistical sample comparisons.

[3]Samples with a number designation only were analyzed at Lawrence Berkeley Laboratory. H. W. Bowman, Frank Asaro, and Helen Michael, analysts.

[4]Average analytical error based on counting statistics. Generally taken as plus or minus one sigma of the mean.

[5]Samples with a number followed by a small letter designation are splits of single samples designated by number only, and were analyzed at the U.S. Geological Survey, Radiochemistry Laboratory, Reston, VA. J. J. Rowe and P. A. Baedecker, analysts. Concentrations for these samples are predicted ($\hat{y}$) values from regression analysis of 22 sample pairs analyzed jointly by Lawrence Berkeley Laboratory (x) and the U.S. Geological Survey Radiochemistry Laboratory, Reston, VA (y).

[6]Analytical error. See footnote 4.

[7]Sheppard and Gude, 1968.

[8]Izett and others, 1972.

[9]Samples with a number followed by a capital letter designation are splits of a single sample analyzed by Lawrence Berkeley Laboratory.

(referred to as ash A by Sheppard and Gude, 1968) at the north end of Lake Tecopa matches well with sample 39 of the Pearlette type O ash from the locality at Onion Creek, Grand County, Utah (Izett and others, 1972). The similarity coefficient for this sample pair is 0.97. Another sample of this ash at Lake Tecopa, taken at 91-106 cm above the base (sample 38), is somewhat different from the lower sample (37), and suggests that this tephra unit may actually represent more than one eruption or that slightly different chemical phases came out during one eruption, perhaps as a consequence of zoning in a magma chamber. The similarity coefficients between sample pairs 37-38 and 38-39 are 0.92 and 0.93, respectively, considerably lower than similarity coefficients for replicate analyses from a single emplacement unit of this type of tephra. Eight additional samples collected from this tephra unit are currently being analyzed to test whether multiple emplacement units are present. The Pearlette type O ash has also been identified in the Searles Lake Area (G. A. Izett, written communication, 1979).

The age of the Pearlette O ash is 0.6 m.y. on the basis of fission-track ages (Naeser and others, 1971, 1973; Izett and others, 1971). The ash was probably erupted from volcanic sources in the Yellowstone area, and its correlation with the Lava Creek Tuff, dated at 0.6 m.y. (Christiansen and Blank, 1972) has been proposed by Naeser and others (1971, 1973).

Bishop ash group

The Bishop ash is another important and widespread stratigraphic marker in the western and central United States (Izett and others, 1970). This ash was erupted from the Long Valley caldera east of the central Sierra Nevada in California (Gilbert, 1938; Bateman, 1965; Sheridan, 1965; Bailey and others, 1976). Near the source, north of Bishop, and at several localities in the vicinity of Long Valley, there are good exposures of a thick, basal air-fall, (sample localities 8, 13) that underlie the later ash flows of the Bishop Tuff. At locality 8, the air-fall ash has a minimum thickness of 4.5 m. Three chemical types of the Bishop ash are recognized on the basis of minor- and trace-element chemistry of the associated glass. These three types are referred to as 1) the Friant Pumice, 2) the Bishop ash at the Insulating Aggregates quarry (or Bishop ash, IAQ type), and 3) Bishop ash at Owens River Gorge and at Red's Meadow (or Bishop ash, ORG type). The three types are very similar to each other chemically. The small differences between the three types may be due to zoning in the pre-eruption magma chamber, or to several eruptions spaced closely in time. At present we do not have a sufficient number of analyses to determine whether compositional variations among these three chemical types are continuous or discontinuous. Work is currently underway to answer these questions.

Friant Pumice

Ash and pumice are exposed in quarries near the town of Friant in east-central San Joaquin Valley. According to Janda (1965),..."The pumiceous alluvium in the quarries of the California Industrial Minerals Company...lies near the base of the alluvium deposited during the youngest aggradational cycle of the Turlock Lake Formation. In these quarries, 60 feet of rhyolitic ash and pumice rest on a weathered surface that has 25 feet of relief developed on sand and silt of an older part of this alluvial unit. The basal 10 to 30 feet of the rhyolitic material consists of flat-lying, remarkably

even beds of fine ash 1 to 30 mm thick. The rhyolitic alluvium is progressively coarser, more impure, and thicker-bedded upward in the section. Large scale fluviatile cross-bedding is present. The upper 30 feet of the deposit commonly contains light-gray to grayish pink pumice pebbles 25 to 50 mm in diameter."

Sample 1 (fig. 2, plate 1; table 1) is from pumice pebbles picked from the coarser, upper part of the gravelly alluvium. Sample 2, a fine ash, is from the subsurface, from a Bureau of Reclamation bore hole some 120 km to the south, near the town of Alpaugh. At this locality, the ash is interbedded with lacustrine clays of the Corcoran Clay. Although the Turlock Lake Formation overlies the Corcoran Clay in the Friant area, the Turlock Lake Formation probably grades laterally into the Corcoran Clay to the south, in the vicinity of Alpaugh, since the tephra at these two localities is essentially identical. The similarity coefficient comparing samples 1 and 2 is 0.98.

The age of the Friant Pumice is 0.62 ± 0.02 m.y.[1/], as determined by K-Ar analysis of sanidine separated from pumice cobbles at the quarry locality (Janda, 1965). As will be discussed below, we tentatively correlate the Friant pumice and associated ash with that of the Bishop Tuff, dated at about 0.73 m.y. (Dalrymple and others, 1965). An Irvingtonian vertebrate fauna is found stratigraphically below the Friant pumice (Janda, 1965; J. Firby-Durham, oral commun., 1974).

Other sites where the Friant-Pumice-type ash has been found are:

1) In the Salton trough, where it is interbedded in a 2 meter thick, composite ash bed in the highly deformed lacustrine Borrego Formation east of the Salton Sea, immediately adjacent to the San Andreas fault (samples 6 and 7; fig. 1; fig. 2, plate 1; table 1).

2) In the Bautista beds of Frick (1921) in the Anza Borrego area west of the Salton trough, in the southern Peninsular Range, interbedded with fluvial sand, gravel, and lacustrine silt and clay deposits (sample 5; R. V. Sharp, written commun., 1978).

3) Interbedded with deformed, well-bedded marine silts and clays of the Santa Barbara Formation near the town of Ventura in the western Transverse Ranges. According to Natland (1952), the stratigraphic interval within which this ash is situated is close to the boundary between the Hallian and Wheelerian microfaunal foraminiferal stages.

Similarity coefficients for the seven samples belonging to this chemical type (samples 1-7) range from 0.93 to 0.98, and average 0.96 ± 0.01 (fig. 4, plate 1). Sample 7 appears to be transitional between the other Friant

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[1/] Janda (1965) cites a K-Ar age of 0.60 ± 0.02 m.y. for this pumice based on written communication with Dalrymple in 1963. This age has been multiplied by 1.0268 to convert to values based on new I.U.G.S. decay constants (G. B. Dalrymple, written commun., 1979). All subsequent K-Ar ages cited here have been similarly converted.

Pumice samples (1-6) and the Bishop ash, IAQ type (samples 8-12). The average similarity coefficient between sample 7 and the average of the other Friant Pumice ash samples is only slightly higher (0.96 ± 0.01) than between this sample and the Bishop ash IAQ type (0.95 ± 0.01).

Bishop ash at the Insulating Aggregates quarry (Bishop ash IAQ)

Sample 8 (fig. 1; fig. 2, plate 1; and table 1), is taken from a 4.6 m section of air-fall pumice lapilli ash which underlies the Bishop Tuff at the southeast margin of the volcanic tableland, about 11 km north of the town of Bishop. The ash sample was taken about one meter below the contact with the overlying, unwelded ash-flow tuff. Dalrymple and others (1965) dated samples obtained from this locality, using sanidine separated from pumice lapilli. Ages of 0.76 ± 0.07 and 0.77 ± 0.08 m.y. were obtained by the K-Ar method on samples from this locality, with an average of 0.73 m.y. for all dated samples of the Bishop Tuff (Dalrymple and others, 1965). Tephra of this chemical type is also found at the following localities:

1) Interbedded with alluvium of Pleistocene Lake Tecopa in southeastern California (sample 9; this ash is equivalent to ash B of Sheppard and Gude, 1965; also see Hildreth, 1977). At this locality, the ash (sample 9) is situated approximately 9 m below the Pearlette type O ash (samples 37, 38).

2) In deformed Pleistocene alluvium exposed in the Chaney Hills, along the Elsinore fault zone in the Peninsular Range of southern California (sample 10, M. Kennedy, written commun., 1976).

3) In alluvium of the Bautista beds of Frick (1921) (R. V. Sharp, written commun., 1979) of the Anza-Borrego area of the southeastern Peninsular Ranges, west of the Salton trough (sample 11).

4) In the previously mentioned 2 m thick bed in deformed lacustrine beds of the Borrego Formation in the Salton trough east of the Salton Sea, immediately west of the San Andreas fault (sample 12). This ash underlies the Friant Pumice-ash type samples 6 and 7 by 1.32 and 1.17 m, respectively.

Similarity coefficients for Bishop ash of this chemical type (samples 8-12) range from 0.95 to 0.98, and average 0.97 ± 0.01 (fig. 4, plate 1).

Bishop ash at Owens River Gorge and at Red's Meadow (Bishop ash, ORG type), east-central Sierra Nevada

Fine to medium-grained air-fall ash is exposed beneath unwelded Bishop ash-flow tuff in the west wall of Owens Gorge north of Bishop in the Casa Diablo quadrangle (sample 13; Hildreth, 1977), and at Red's Meadow, in the Devil's Postpile quadrangle, within the headwaters of the San Joaquin River drainage basin in east-central Sierra Nevada, west of the Long Valley caldera (sample 14) (R. J. Janda, oral commun., 1972). Air-fall pumice from this locality has been dated at 0.66 ± 0.04 m.y. by the K-Ar method (Huber and Rinehart, 1967).

This chemical type has been found at two additional localities:

1) Again, at the previously mentioned locality in the Borrego Formation east of the Salton Sea (sample 15), where it overlies ash of the Friant Pumice type, samples 6 and 7, by about 1 and 23 cm, respectively (fig. 2, plate 1; and fig. 6), and

2) at Onion Creek, Grand County, Utah (sample 16), where this ash again underlies Pearlette type O ash (sample 39; Izett and others, 1972; G. A. Izett, written commun., 1978).

Similarity coefficients for Bishop ash of this chemical type range from 0.96 to 0.98, and average 0.97 ± 0.01 (fig. 4, plate 1).

Individual similarity coefficients among the three chemical types of the Bishop ash group range from 0.85 to 0.96. Average coefficients are 0.88 ± 0.02 between the Friant Pumice type and Bishop ash (Owens River Gorge-Red's Meadow type), 0.93 ± 0.02 between the Friant Pumice type and Bishop ash (Insulating Aggregates quarry type), and 0.94 ± 0.02 between the two Bishop ash types.

The three chemical types comprising the Bishop group, as defined here, are considered to be members of a single eruptive episode of short duration. They are considered to be essentially contemporaneous for several reasons, the most important one being that all three chemical types are found in close stratigraphic proximity within a single, compound, 2 m thick bed in the Borrego Formation east of the Salton Sea (samples 6, 7, 12, and 15; fig. 6). Although this bed contains thin interbeds of tuffaceous silt and clay between some of the ash layers, the total aggregate time represented by this compound bed cannot be very long--certainly not as long as the 0.1 m.y. represented by the difference in isotopic ages of the Friant Pumice and the Bishop Tuff. The Friant Pumice at the Salton Sea locality (samples 6, 7) is actually situated stratigraphically between the two Bishop ash types (samples 12 and 15; fig. 6). Although there is a possibility that the stratigraphic order of these ashes has been reversed due to local reworking within the Salton trough depositional basin, such reworking would probably take place within a very short period of time. With respect to the 0.6 m.y. K-Ar ages of the Friant Pumice (Janda, 1965) we have not observed, nor seen any reference to, a widespread ash of Long Valley provenance which overlies the Bishop ash or Tuff. The Pearlette type O ash overlies the Bishop ash at a number of localities (as at Lake Tecopa, samples 9, 37, and 38; also at Onion Creek, Utah, samples 16 and 39, Izett and others, 1972), but this ash is chemically very different from ashes of Long Valley provenance, such as the Friant Pumice ash, the Bishop ash, or "ash of Mono Glass Mountain", and no Bishop-like ash is closely associated with it. Bailey and others (1976) report no widespread,

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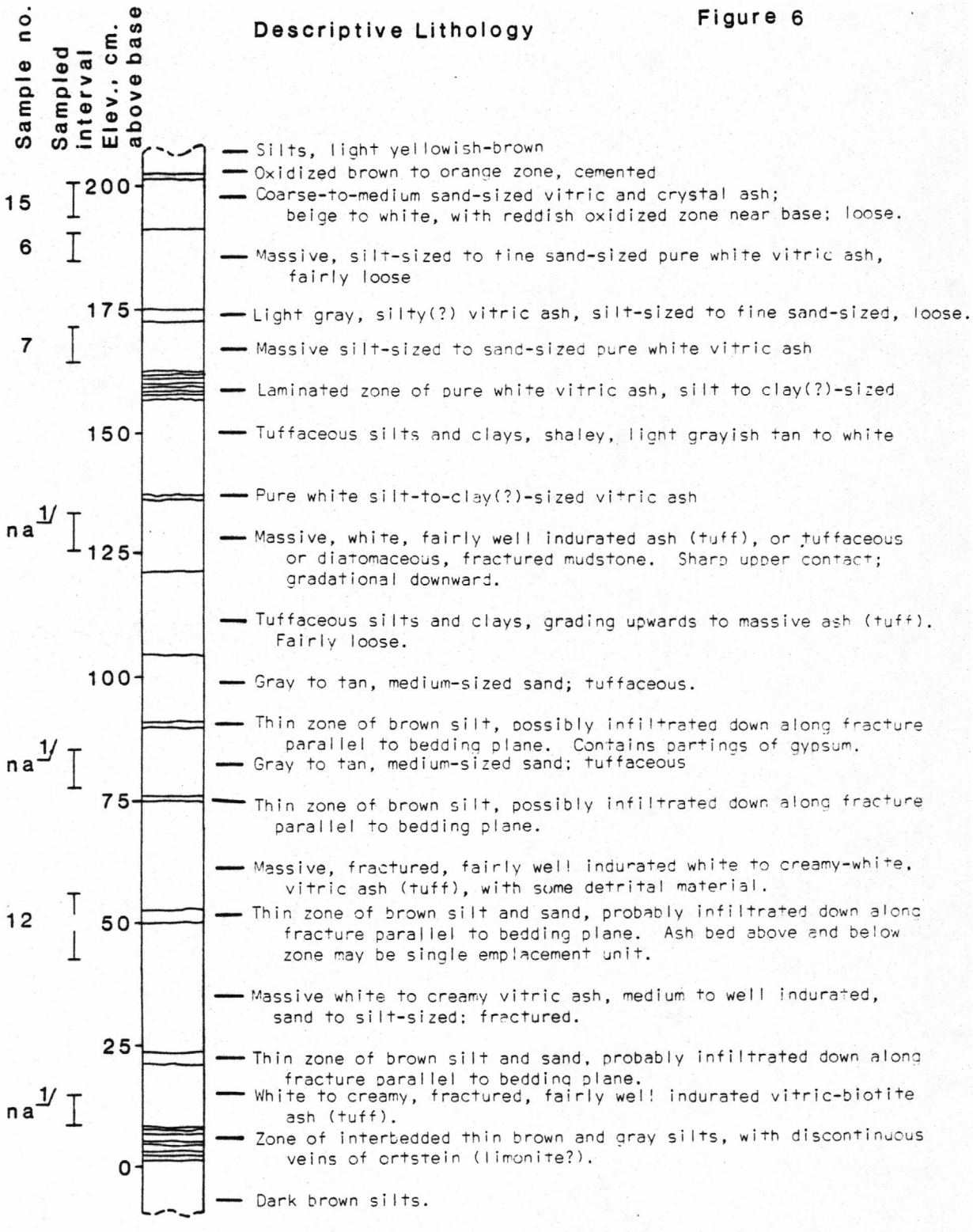
Figure 6. Generalized stratigraphic section of ash in Borrego Formation, east of the Salton Sea and immediately west of the San Andreas Fault. Top and base of this tephra unit are inferred from textural and bedding features because the unit is vertical at this locality. Locations of samples 6, 7, 12, and 15 are shown.



1/ Sample not analyzed, 1/1/79.

major post-caldera tephra eruption from Long Valley after the eruption of the Bishop Tuff. According to their data, there is a period of quiescence between the early post-caldera rhyolites (about 0.73 to 0.65 m.y.), and the early moat rhyolites (about 0.52 to 0.48 m.y.). Furthermore, it does not seem reasonable that one of the greatest climactic eruptions of Quaternary time, that of the Bishop Tuff, would not leave any trace of its products in the lower parts of a closely-adjacent drainage basin, while an eruption 100,000 years later would deposit large volumes of pumice and ash within this basin, but not anywhere else nearby--particularly not within its presumed source area. Lastly, if the ash and pumice at Friant represent only local reworking of a 0.6 m.y. tephra down the ancestral San Joaquin drainage, then we cannot explain the presence of the same tephra at the five other widely-separated locations in southern California (samples 3-7) in close association with the Bishop ash, unless there have been two or more separate eruptions of tephra of essentially identical composition, separated by over 100,000 years.

Some problems remain with respect to correlation of the Friant Pumice with the Bishop ash, as pointed out by several workers (R. A. Bailey, N. K. Huber, E. W. Hildreth, written communications, 1979). The problems relate to the mineralogy, glass chemistry, and isotopic ages of the two tephra units.

With respect to mineralogy, we did not detect any biotite in our initial petrographic examination of the magnetic heavy separate of the Friant Pumice. Biotite, however, is an ubiquitous phyric mineral in both the Bishop ash and Tuff. Subsequently, we resampled both the Friant Pumice and associated underlying fine ash, and found abundant biotite in both samples (samples 1 and 1a, table 2). Perhaps the initial magnetic fractions of the Friant Pumice were separated in liquids too heavy to permit biotite to settle. The fine ash at Friant contains, in addition to biotite, some allanite, zircon, and rare clinopyroxene, minerals typical of the Bishop Tuff and ash, as well as other, presumably detrital or xenocrystic minerals.

With respect to glass chemistry, it is difficult to understand why ash of a chemical composition identical to that of Friant Pumice has not been found near the source area, at the Owens River Gorge locality, the Insulating Aggregates quarry, or at Red's Meadow. Perhaps this absence can be attributed to inadequate sampling at the near-source localities. At each of these localities, only one sample of air-fall ash was collected. Only at the Salton trough locality (samples 6, 7, 12, and 15) do we have a more-or-less complete compositional spectrum of the Bishop ash group, including the Friant Pumice type. We have subsequently resampled the basal ash-fall unit at one locality at the south end of the volcanic tableland, north of the town of Bishop, and analyses on multiple samples collected vertically within this unit are now in progress.

With respect to isotopic ages, two identical K-Ar analyses of 0.62 $\pm$ 0.04[1/] m.y. were determined on sanidine separated from pumice pebbles of the Friant Pumice. K-Ar ages on the Bishop Tuff, by contrast, range from 0.66 to 0.77 m.y., with an associated error of about 0.07 to 0.08[1/] for individual analyses (0.66 $\pm$ 0.07, 0.71 $\pm$ 0.06, 0.74 $\pm$ 0.07, 0.75 $\pm$ 0.07, 0.76 $\pm$ 0.07, and 0.77 $\pm$ 0.08) (Dalrymple and others, 1965). In addition, an age of 0.68 $\pm$ 0.04[1/] m.y. was obtained on ash-fall pumice underlying ash-flow tuff at Red's Meadow (Huber and Rinehart, 1967). Within the error of the precision of the

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[1/] Estimate of the precision of the analysis at the 95 percent confidence level.

Table 2. Mineral abundances in tephra samples. Figures given represent line count of heavy mineral separates (> 2.85 specific gravity, unless otherwise noted) from the magnetic fraction (+ 0.6 amps). Size fraction used was 100-200 mesh (0.14-0.08 mm).

Sample number	Biotite	Gr.-Br. Hblde	Br. Hblde	Clino-pyroxene	Hypersth.	Allanite	Zircon	Ilmenite	Sphene	Epidote group	Tremolite-actinolite	Bl.-Gr. Hblde	Clear mica	Oxy-hblde	Apatite	Opaque (unident.)	Other
1[2]	250	9	---	1?	2	---	---	---	---	---	---	---	---	---	---	---	---
1a[3]	272	82	1	1	12	6	6	---	---	8	---	---	---	4	---	178	---
2	6	30	7[1]	27	3	1?	1	---	3	22	7	---	5	---	1	12	5
3	23	71	---	8	---	---	12	---	29	163	3	---	5	3	1	118	2
6	301	---	---	---	P	P	---	---	---	2?	---	---	---	---	---	---	---
8[4]	3	48	---	5	---	126	35	50	4?	38	---	---	---	---	---	191	3
8a[5]	145	83	---	4	---	17	11	4	---	19	3	---	18	---	---	12	16
8b[6]	11	117	2	11	2	86	24	---	---	86	4	---	---	---	---	57	2
12	552	---	---	---	---	---	---	---	---	---	---	---	26	---	---	---	16
19	131	140	---	1	1	1	1	---	1	9	4	---	---	---	---	6	---
21	---	4	---	3	---	---	2	---	18	28	1	---	15	---	---	8	---
22	243	15	---	1	---	---	1	---	---	5	---	---	3	---	---	7	---
23	210	35	2	4	1	---	3	---	---	5	3	---	3	1	---	29	8
24	290	7	2	3	---	---	3	---	2	9	---	---	---	2	---	8	6
27	24	228	2	3	1	---	1	2	15	28	---	---	---	2	2	33	---
35	603	2	---	---	---	---	P	---	---	---	---	---	---	---	---	1	---
36	512	---	---	---	---	---	2	2	15	---	2	---	---	---	---	8	3
41	---	56	1	80	1[1]	38[1]	57[1]	135[1]	13	38	---	---	1	2	5	538	12
43	153	---	5	2	---	P[1]	P	2	---	30	3	48	31	1	---	9	5
45	---	P	---	P	---	P	P[1?]	P[1]	---	P	---	---	P	P	---	---	---
48	274[1]	396[1]	1	1	5	---	---	---	---	---	---	---	---	---	---	1	---
49	97	69	7	31	28	1?	2	4	6	3	6	---	10	2	---	50	1

[1]Mineral grains with adhearing glass.

[2]Minerals separated from pumice pebbles only, with specific gravity >2.85.

[3]Minerals separated from fine ash underlying unit which contains pumice pebbles; specific gravity >2.85.

[4]Minerals separated from pumice lapilli only, with specific gravity >2.85.

[5]Minerals separated from pumice lapilli only, with specific gravity >2.65.

[6]Minerals separated from total sample, including matrix and pumice lapilli, with specific gravity >2.85.

Table 3. Electron microprobe analysis of volcanic glass from late Cenozoic tephra of east-central and southern California.
[Concentrations in atom weight percent. C. Meyer, analyst]

Sample number	Si	Al	Fe	Mg	Mn	Ca	Ba	Ti	Na	K	Cl	P
Ashes Having Chemical Affinity to Tephra of the Long Valley-Mono Basin area Pumice (1, 1A, 1B), near Friant and correlative ashes												
1	33.75	6.26	0.461	0.021	0.039	0.300	0.000	0.046	2.50	3.87	ND	0.000
1A[1]	35.12	6.35	0.467	0.015	0.035	0.313	0.003	0.034	2.53	3.82	ND	0.005
1B	34.30	6.44	0.469	0.016	0.014	0.313	0.000	0.041	2.61	3.48	0.044	ND
2	33.71	6.37	0.480	0.032	0.027	0.319	0.003	0.036	2.72	3.50	0.059	ND
3	34.30	6.10	0.483	0.024	0.028	0.317	0.020	0.030	2.60	3.76	ND	0.000
4	33.87	6.39	0.477	0.024	0.024	0.325	0.000	0.039	2.67	3.52	0.058	ND
5	33.58	5.71	0.462	0.016	0.022	0.307	0.006	0.039	2.37	4.12	0.044	ND
6	33.71	6.39	0.476	0.021	0.033	0.308	0.000	0.040	3.09	2.79	0.062	ND
$\bar{x}$[2]	34.04	6.25	0.472	0.021	0.028	0.313	0.004	0.038	2.64	3.61	0.053	0.002
s^2	0.51	0.24	0.008	0.006	0.008	0.008	0.007	0.005	0.21	0.40	0.009	---
Bishop ash at Insulating Aggregates Quarry (8), and correlative ashes												
8	34.06	6.34	0.458	0.025	0.029	0.301	0.000	0.035	2.34	4.08	ND	0.000
10	33.50	6.32	0.467	0.014	0.021	0.304	0.000	0.027	2.93	3.33	0.059	ND
11	32.52	5.59	0.400	0.013	0.013	0.280	0.000	0.037	2.72	3.39	0.037	ND
12	33.49	6.28	0.476	0.024	0.033	0.308	0.000	0.028	3.15	2.96	0.064	ND
$\bar{x}$	33.42	6.13	0.450	0.019	0.024	0.298	0.000	0.032	2.76	3.44	0.053	---
s	0.65	0.36	0.034	0.006	0.009	0.013	---	0.005	0.33	0.47	---	---
Bishop Tuff at Red's Meadow and ash at Onion Cr., Grand Co., Utah												
14	34.58	6.51	0.480	0.023	0.015	0.321	0.002	0.027	2.91	3.40	0.080	ND
15	33.73	6.27	0.465	0.019	0.033	0.301	0.005	0.038	2.68	3.43	0.067	ND

Table 3. Continued.

Sample number	Si	Al	Fe	Mg	Mn	Ca	Ba	Ti	Na	K	Cl	P
					"Ash of Mono Glass Mountain" (17), and correlative ash, Ventura area (18)							
17	34.75	6.18	0.457	0.016	0.040	0.281	0.003	0.037	2.50	3.96	ND	0.004
18	33.60	6.34	0.485	0.022	0.034	0.280	0.008	0.038	2.69	3.56	0.060	ND
					Gray ash beneath ash of Mono Glass Mountain (19), and correlative ash, Ventura area (21)							
19	34.14	6.45	0.51	0.019	0.024	0.292	0.000	0.030	2.71	3.59	0.053	ND
21	33.73	6.27	0.52	0.021	0.070	0.288	0.001	0.039	2.46	4.01	ND	0.007
					Bailey ash, South Mountain (22, 23) and Ventura (24, 25) areas							
22	33.27	6.00	0.496	0.018	0.036	0.336	0.001	0.033	2.61	3.85	ND	0.005
23	33.66	6.38	0.490	0.020	0.036	0.324	0.014	0.029	2.69	3.59	0.056	ND
24	33.65	6.37	0.481	0.020	0.030	0.316	0.009	0.033	2.64	3.52	0.057	ND
25	33.62	6.42	0.495	0.018	0.029	0.315	0.001	0.028	2.69	3.62	0.057	ND
x	33.55	6.29	0.491	0.019	0.033	0.324	0.006	0.031	2.66	3.65	0.057	---
s	0.19	0.20	0.007	0.001	0.004	0.010	0.006	0.003	0.04	0.14	0.001	---
					Ash below Bailey ash, South Mountain area							
27	33.69	6.40	0.478	0.017	0.040	0.235	0.006	0.025	2.87	3.56	0.058	ND
					Middle, white ash, Manix basin, Mojave Desert (33), and ash in Waucoba lake beds, E. Owens Valley (34)							
33	33.43	5.79	0.423	0.014	0.061	0.222	0.008	0.035	3.17	2.82	0.032	ND
34	33.77	6.09	0.411	0.015	0.062	0.215	0.009	0.031	2.50	4.14	0.037	ND
					Ash in old lake beds of Searles Lake							
35	33.32	6.23	0.481	0.019	0.037	0.325	0.010	0.034	3.54	1.28	ND	0.002

Table 3. Continued.

Sample number	Si	Al	Fe	Mg	Mn	Ca	Ba	Ti	Na	K	Cl	P
					Unwelded, pumiceous ash flow tuff in Coso area							
36	32.78	6.10	0.327	0.013	0.049	0.480	0.000	0.024	2.07	4.37	0.000	ND
					Ashes Having Chemical Affinity to Tephra of the Yellowstone Area, Wyoming							
					Pearlette type "O" ash, Grand Co., Utah[3] (39), and ash in Christmas Canyon Fm., Searles Valley (39A)							
39	33.78	6.08	0.954	0.013	0.022	0.363	0.000	0.059	2.49	3.89	0.116	ND
39A[2]	33.46	5.78	1.051	0.012	0.023	0.370	0.016	0.069	2.38	4.00	0.106	ND
					Pearlette type "S" ash, Harlan County, Nebraska[3]							
40	33.72	6.10	0.907	0.020	0.024	0.388	0.001	0.060	2.24	4.23	0.102	ND
					Lower, gray ash, Manix basin (41), and Pearlette type "B" ash, Borchers locality, Meade Co., Kansas[3] (42)							
41	33.68	6.50	1.037	0.017	0.023	0.416	0.016	0.076	2.86	3.43	0.142	ND
42	33.62	6.09	1.080	0.011	0.036	0.387	0.025	0.066	2.33	4.06	0.117	ND
					Lowermost ash, South Mountain area (43), and ash (ash "C")[4], Tecopa area (44, 45)							
43	33.70	6.04	1.16	0.010	0.039	0.402	0.038	0.058	2.53	3.92	ND	0.004
44	33.43	5.89	1.22	0.015	0.018	0.428	0.033	0.080	1.98	4.62	ND	0.007
45	33.37	6.20	1.18	0.013	0.023	0.433	0.030	0.065	2.41	4.08	0.109	ND
x	33.50	6.04	1.19	0.013	0.027	0.421	0.034	0.068	2.31	4.21	---	0.006
					Tephra Having Chemical Affinities to Other Volcanic Provinces							
					Air-fall pumice of the Coso area							
46	32.13	6.33	0.840	0.127	0.040	0.797	0.110	0.075	2.30	3.39	0.047	ND
48	32.49	6.49	0.785	0.101	0.019	0.778	0.103	0.076	2.40	3.38	0.029	ND
					Ash in Searles Valley							
49	33.74	7.00	0.722	0.125	0.050	0.568	0.085	0.116	2.42	3.42	0.147	ND

[1]Samples 1A and 1B are replicate analyses of sample 1.
[2]Sample standard deviation.
[3]Izett and others, 1973.
[4]Sheppard and Gude, 1968.

K-Ar analysis, the age of the Friant Pumice overlaps with the age of the ash at Red's Meadow and the younger individual ages of the Bishop Tuff, but not with the average calculated age of the Bishop Tuff, 0.73 m.y., and its associated error of $\pm$ 0.04, one standard deviation away from the mean of the six individual determinations. The errors associated with the K-Ar ages would overlap at two standard deviations from the mean.

The disparity in K-Ar ages of about 0.1 m.y. between the Friant Pumice and the Bishop Tuff may be due to reasons other than differences in the true ages of these units. Dalrymple and others (1965) have shown that certain early K-Ar analyses of samples containing xenolithic contamination have resulted in spuriously old ages for the Bishop Tuff, probably due to incomplete degassing of these accidental inclusions. Recent mineralogical work (P. C. Russell, A. M. Sarna-Wojcicki, unpublished data) on cleaned pumice lapilli separated from the Bishop ash indicates the presence of xenocrystic minerals within the lapilli. Heavy mineral separates from crushed, ultrasonically cleaned lapilli indicate presence of epidote, sphene, clear mica (muscovite?), blue, light green, and clear (metamorphic?) amphibole, brown to green (plutonic?) hornblende--minerals that probably did not crystallize from the parent magma of the Bishop ash (Hildreth, 1977). These minerals do not have glass coatings or jackets, with the rare exception of an occasional green hornblende. Fitch and others (1978) have reported presence of older zircon crystals within cores of pumice clasts obtained from the KBS tuff in east Africa. These crystals must have been incorporated into the pumice before "consolidation of the lava froth", since no connecting vescicles were present in the clasts. The absence of glass jackets on most of the suspected xenocrysts in the Bishop ash is puzzling, and argues for detrital, rather than accidental (xenocrystic), contamination. Alternatively, perhaps glass adheres only to those crystals that are thermally equilibrated with the magma, and spalls off from xenocrysts, which are colder. These observations, considered together, suggest that the Bishop Tuff may be even younger than 0.73 m.y., but not by much, in view of the age of the early rhyolites (Bailey and others, 1976). Even among these latter flows, however, there must be some type of contamination, since the oldest age obtained on the post-Bishop Tuff early rhyolites is 0.75 m.y., and these flows clearly postdate the Bishop Tuff on the basis of field criteria (Bailey and others, 1976).

In summary, the uncertainty regarding the true ages and correlation of the Friant Pumice and the Bishop ash remains unresolved. The uncertainty in correlation of these units may be resolved by further sampling and analysis. In particular, the mineralogy and chemistry of the pumice relative to the fine ash underlying it at Friant has to be further investigated. For the present, we favor the interpretation that the Friant Pumice and Bishop ash are correlative. A possibility exists that the Friant Pumice was erupted later than the Bishop Tuff, from some as yet undiscovered vent, perhaps in the upper reaches of the San Joaquin River basin (R. A. Bailey, N. K. Huber, written communications, 1979). If this is the case, and the true ages of these units are indeed significantly different, then the correlation between the Friant Pumice and the ash in the Borrego Formation of the Salton trough on the basis of glass chemistry (samples 6 and 7) would have to be considered spurious and coincidental. Lastly, the age uncertainty associated with the uncertainty in correlation of the Friant Pumice and Bishop ash is about 0.11 m.y., not much greater than the analytical error associated with individual K-Ar age determinations on the Bishop Tuff. For purposes of temporal correlation, this

uncertainty does not seriously impair the correlation scheme proposed here (table 2).

Correlations of the Bishop ash group presented here confirm several correlations made by Merriam and Bischoff (1975) of the Bishop Tuff. Their ash sampling localities 1, 3, 4, and 6 are at or close to corresponding sample localities 6, 5, 11, and 10 of this study, all of which have been correlated here with the Bishop ash group (Friant Pumice type and the Bishop ash, IAQ type). Their samples 8, 9A, 9B, 10A, and 10B, collected from the Manix basin, and corresponding to our samples 28 through 34 (table 1) are not part of the Bishop ash group, as can be seen from the large differences in a number of trace and minor elements (fig. 4, plate 1; and figs. 3 and 5). Ashes of the Manix basin are considerably older than the Bishop ash (see below). The X-ray fluorescence rapid scan technique for rubidium, strontium, and zirconium used by Merriam and Bischoff (1975) is not sufficiently precise to resolve the small compositional differences that can be determined in tephra of the Long Valley-Mono Glass Mountain family by neutron activation or more precise X-ray fluorescence analyses. We suggest that the rapid scan technique should be used only for local correlation problems where the number of tephra units is small or their compositional contrasts high, or for initial feasibility studies.

The "ash of Mono Glass Mountain"

Several lenticular beds, 5 to 15 cm thick, of fine to medium grained, water deposited white vitric ash occur within a 2 to 2.5 m-thick zone of lacustrine tuffaceous sediments at the south end of the volcanic tableland, about 6.5 km north of the town of Bishop (samples 17, 17a-17c). The ash underlies the unwelded Bishop ash-flow tuff by about 17 m. The actual position of the Bishop ash in this section has not been located; it is either absent or covered by thick talus at the base of the Bishop Tuff. The "ash of Mono Glass Mountain" is situated 14 m below a magnetic reversal believed to be the Bruhnes-Matuyama boundary (J. C. Liddicoat, written commun., 1978). This compound depositional or eruptive unit is referred to informally as the "ash of Mono Glass Mountain" because it contains small, angular accidental fragments of black obsidian, believed to be derived from the obsidian of Mono Glass Mountain. Izett (oral commun., 1978) has dated these obsidian fragments by the fission-track method, obtaining an age of 0.9 m.y. This age agrees with the 0.9 m.y. age of obsidian at Mono Glass Mountain, some 48 km to the north, dated by the K-Ar method by Gilbert and others (1968). Because the fragments appear to be accidental rather than cogenetic, they define a maximum age for this ash. This observation is supported in part by the reversely magnetized direction of this ash (J. Liddicoat, written commun., 1978). If the ash were 0.90 to 0.97 m.y. in age, it would probably be normally magnetized, because it would have been deposited during the normal Jaramillo polarity event (Mankinen and Dalrymple, 1979).

Analyses of this ash (samples 17, 17a-17c) compare well with those of an ash in deep-water marine silts and clays of the Santa Barbara Formation exposed in the Ventura Avenue anticline west of the Ventura River (sample 18; table 1; fig. 2, plate 1; and fig. 3). The ash in the Santa Barbara Formation is 9.5 mm thick, but only the lower 6.5 mm are pure and massive, water-laid, fine air-fall(?) vitric ash. The upper 3 mm are finely laminated tuffaceous clay. This ash has been recognized by its field characteristics and

Table 4. Two-sample t-test using distribution of Student to test hypothesis that means of concentrations of selected elements in glass of Bishop ash, IAQ type (1), are the same as means of concentrations of the same elements in the "ash of Mono Glass Mountain" (2), versus the alternative hypothesis that the means are not the same. The null (first) hypothesis is rejected at significance levels (α) shown below.

Ash	Element	n	mean	st. dev.	t	α
1	La	5	19.72	0.67	-9.24	<0.0001
2		5	23.54	0.64		
1	Ce	5	45.92	1.72	-7.53	<0.0001
2		5	54.82	2.01		
1	Nd	5	18.40	1.52	-4.47	0.0029
2		5	23.00	1.73		
1	Sm	5	3.64	0.06	-5.47	0.0055
2		5	4.24	0.24		
1	Yb	5	2.64	0.06	-4.50	<0.0001
2		5	2.80	0.06		
1	Th	5	20.56	0.54	4.23	0.0054
2		5	19.40	0.29		

stratigraphic position at one other locality in the Ventura area. At that locality, it is a doublet about 4 mm thick. It overlies the gray ash (see below) by about 30-40 m. Its stratigraphic position below the Bishop ash (Friant Pumice type) at Ventura is inferred from its stratigraphic position above the gray and Bailey ashes, and lateral projection into sections where the Friant Pumice ash is locally exposed. Its relative position below the Bishop ash is also deduced from its correlation with the "ash of Mono Glass Mountain" at Bishop, which underlies the Bishop ash. Its stratigraphic position places the "ash of Mono Glass Mountain" in the Wheelerian microfaunal stage of Natland (1952). Similarity coefficients for the five analyses of this ash from both localities range from 0.96 to 0.98, and average 0.97 ± 0.01 (fig. 4, plate 1).

This ash is similar in composition to the Bishop ash group. Individual similarity coefficients between this ash and the three chemical types of the Bishop ash group range from 0.89 to 0.95, with between-group averages equal to 0.93 ± 0.02, 0.93 ± 0.01, and 0.91 ± 0.01. Student's two-sample t-tests show that despite several high individual similarity coefficients between the Bishop ash, IAQ type, and the "ash of Mono Glass Mountain", these two sample groups are significantly different with respect to lanthanum, cerium, neodymium, samarium, ytterbium, and thorium (table 4).

The gray ash

A gray ash (sample 19), about 0.8 m thick, underlies the "ash of Mono Glass Mountain" (sample 17) by about 6 m, at the south end of the volcanic tableland (Chalk Bluffs), north of the town of Bishop. This ash is also a compound depositional (and eruptive ?) unit. This ash is correlated on the basis of its glass chemistry with a gray ash which crops out in the Ventura Avenue anticline near the town of Ventura (samples 20, 21, 21a-21d). Similarity coefficients for this ash range from 0.92 to 0.97, with an average of 0.95 ± 0.02. The lower average value of the similarity coefficient, and the somewhat greater spread of these values indicate that, like the Bishop ash group, the gray ash may also be a compound unit and represent several closely-spaced eruptions, although there is not a sufficient number of analyses of this ash to determine whether this is the case.

The gray ash in the Ventura area is about 2.5 cm thick, fine, vitric, and generally uniform in thickness. Stratigraphic separation between the gray and the Bailey ash near the central portion of the doubly-plunging Ventura Avenue anticline is about 120 m (samples 20, 21), but farther west, on the northwestern, plunging flank of the anticline, it is only about 17 m, indicating that this stratigraphic interval thins to the northwest. The gray ash is situated within the Wheelerian microfaunal stage of Natland (1952). The age of the gray ash is unknown, but its paleomagnetic orientation is reversed (written commun., J. Liddicoat, 1978). Because the gray ash underlies the "ash of Mono Glass Mountain" by only 6 m near Bishop, and overlies the Bailey ash (see below) by as little as 17 m, its age probably lies somewhere between 0.96 (the end of the Jaramillo normal magnetic event) and 1.2 m.y., the age of the Bailey ash. An alternative interpretation is that the age of both the "ash of Mono Glass Mountain" and the gray ash lie within the reversed polarity period between 0.73 and 0.91 m.y. This seems less likely because within the Ventura Avenue anticline, the gray ash is situated stratigraphically much closer to the Bailey ash, dated at 1.2 m.y.

(see below), than it is to the "ash of Mono Glass Mountain", which near Bishop is situated closely below the Bishop Tuff. Thus, it is more likely that the gray ash was deposited before, while the "ash of Mono Glass Mountain" was deposited after, the Jaramillo normal polarity event. According to Liddicoat (written communication, 1979), however, the entire section exposed at Chalk Bluffs near Bishop is reversely magnetized below the Bruhnes-Matuyama boundary, including the "ash of Mono Glass Mountain" and the gray ash below it. The Jaramillo event has not been found there, although it may be situated within a sandy interval within this section, or has been eroded away. Pending further paleomagnetic work and direct age determination by the fission-track method, we will consider this ash to be about 1 m.y. old ($1.0^{+0.2}_{-0.1}$ m.y.).

Bailey ash

The informally named Bailey ash (Yeats and others, 1967; Izett and others, 1974), has been recognized to date only within the South Mountain-Balcom Canyon and Ventura areas of coastal southern California (samples 22 through 26a). Its glass chemistry strongly indicates that it belongs to the Long Valley-Mono Glass Mountain family of ashes erupted from sources east of the central Sierra Nevada (table 1; figs. 1, and 3; fig. 2, plate 1). The Bailey ash may be covered at its inferred source area by younger volcanic rocks, such as the Bishop Tuff. The Bailey ash is the thickest of six ashes presently recognized in the Balcom Canyon-South Mountain-Ventura area, and consequently represents a sizeable eruption. In some exposures, such as the one west of the Ventura River, the ash is about 20 cm thick, but only the basal 3 cm looks like possible pure air-fall ash (fig. 7). The basal part consists of chalky white to porcellaneous, fine vitric ash. The upper part consists of fine layers and laminae of silty to clayey ash, alternating with partings of silt and clay.

The Bailey ash has been mapped discontinuously in the Balcom Canyon-South Mountain area, where it is situated wholly within the Pico Formation, as mapped locally by Weber and others (1973), and to the west, in the foothills north of the town of Ventura, where it is situated near the contact of the Santa Barbara and the underlying Pico Formations. The ash has been mapped both above and below this formation contact. The ash has also been mapped on both the southern and northern flanks of the Ventura Avenue anticline over a distance of about 23 km, and is a good stratigraphic marker bed. No exposures exist between the Ventura and Balcom Canyon-South Mountain areas, since the section between these two areas is down-dropped between two antithetical, high angle-reverse faults, the Oak Ridge and the Ventura-Pitas Point faults. Presence of this ash in the intervening area is inferred from subsurface information by Blackie and Yeats (1976).

When the seven analyses of the Bailey ash from the Balcom Canyon-South Mountain area are compared with seven analyses of the ash from the Ventura area (table 5), the similarity coefficient comparing averages of the two groups is 0.98, demonstrating quite convincingly that this ash can be correlated across the intervening structures between the areas of exposure.

Figure 7. Generalized stratigraphic section of Bailey ash west of the Ventura River (sample locality 24).

Figure 7

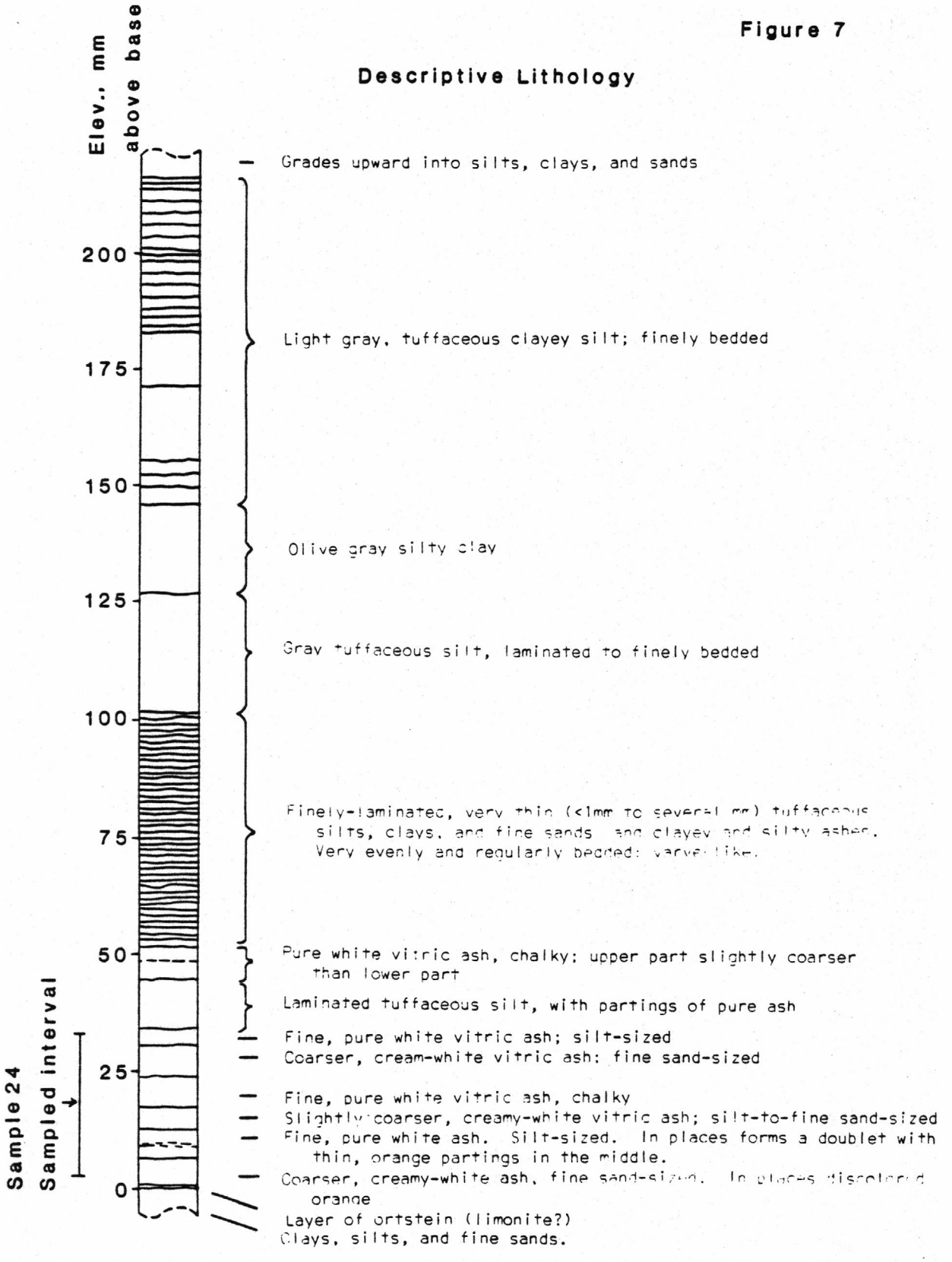
Descriptive Lithology
Elev., mm above base
200
175
150
125
100
75
50
25
0
Sample 24
Sampled interval
Grades upward into silts, clays, and sands
Light gray, tuffaceous clayey silt; finely bedded
Olive gray silty clay
Gray tuffaceous silt, laminated to finely bedded
Finely-laminated, very thin (<1mm to several mm) tuffaceous silts, clays, and fine sands and clayey and silty ashes. Very evenly and regularly bedded; varve-like.
Pure white vitric ash, chalky; upper part slightly coarser than lower part
Laminated tuffaceous silt, with partings of pure ash
Fine, pure white vitric ash; silt-sized
Coarser, cream-white vitric ash; fine sand-sized
Fine, pure white vitric ash, chalky
Slightly coarser, creamy-white vitric ash; silt-to-fine sand-sized
Fine, pure white ash. Silt-sized. In places forms a doublet with thin, orange partings in the middle.
Coarser, creamy-white ash, fine sand-sized. In places discolored orange
Layer of ortstein (limonite?)
Clays, silts, and fine sands.

Table 5. Comparison of average compositions of seven glass samples of the Bailey ash from the South Mountain-Balcom Canyon area with seven samples from the Ventura area. Similarity coefficient comparing the averages of the two groups is 0.98. [Concentrations in parts per million except for iron, which is in percent]

		Sc	Mn	Fe	Zn	Rb	Cs	La	Ce	Nd	Sm	Eu	Tb	Dy	Yb	Lu	Hf	Ta	Th	U
South Mountain-Balcom Canyon area (Avr. 7)		2.73	(432)	0.52	31	240	8.2	18.5	43.8	19	4.2	0.05	0.77	(5.14)	3.91	0.55	4.14	3.05	27.2	9.00
	s[1]	±0.06		±0.04	±3	±11	±0.4	±1.3	±3.0	±1	±0.2	±0.02	±0.03		±0.13	±0.02	±0.12	±0.13	±0.8	±0.83
Ventura area (Avr. 7)		2.70	(436)	0.53	31	231	8.3	19.2	45.7	20	4.3	0.05	0.80	(5.18)	3.81	0.54	4.16	3.08	26.9	9.22
	s	±0.04		±0.02	±3	±7	±0.4	±1.4	±2.5	±1	±0.1	±0.01	±0.03		±0.04	±0.02	±0.04	±0.16	±0.7	±0.60

[1]Sample standard deviation

Figure 8

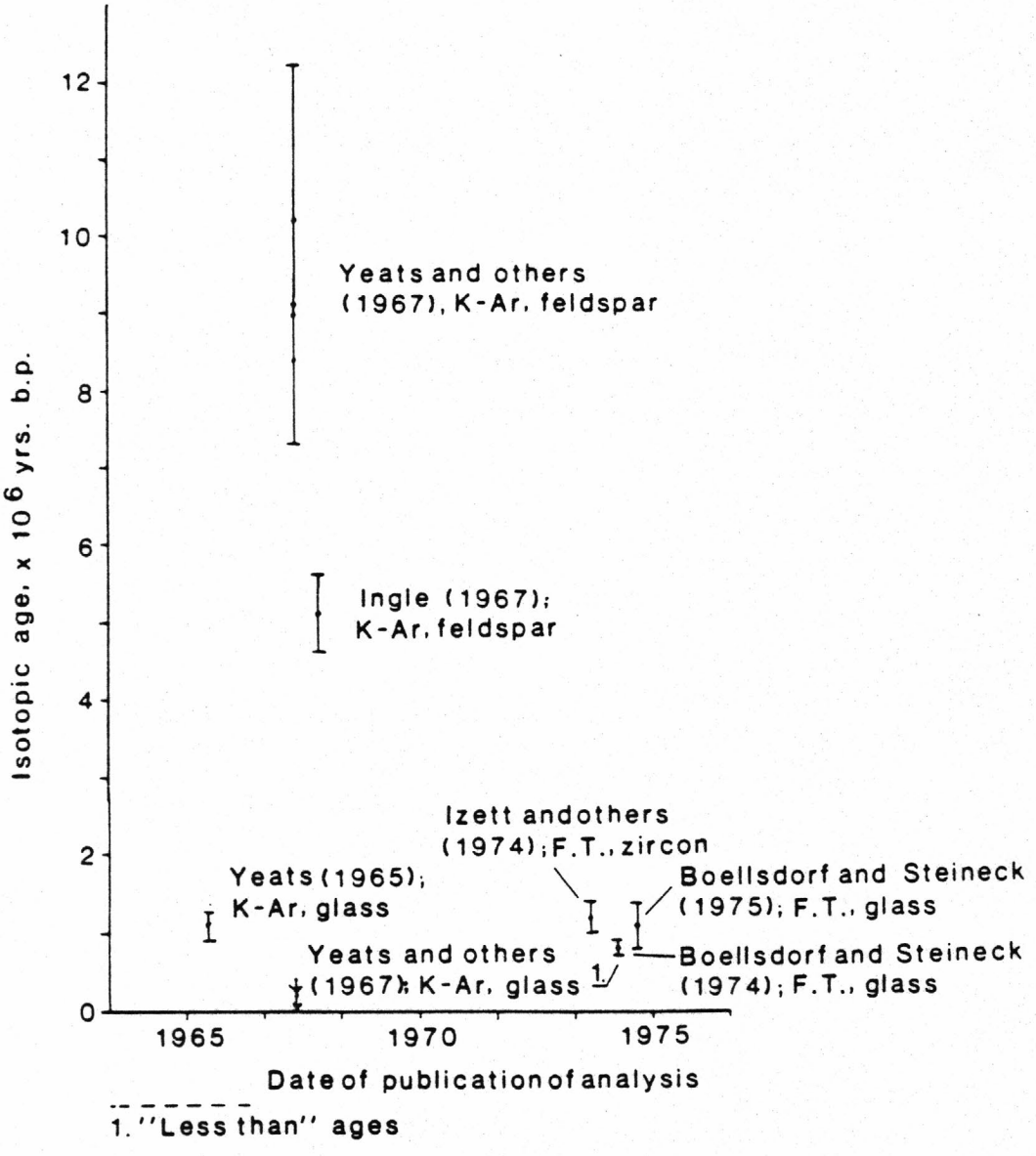

Figure 8. Isotopic ages of the Bailey ash plotted against publication dates of analyses. Analytical method and material analyzed are shown adjacent to reference in which date is given. K-Ar:potassium-argon method. F.T.:fission-track method.

Similarity coefficients for all 14 analyses of this ash range from 0.91 to 0.98, and average 0.95 ± 0.01. If analyses of sample 23a are not included (this analysis, a replicate of sample 23, is suspect; it deviates sharply from the average of the four other replicates, samples 23, 23b, c, and d) the similarity coefficients range from 0.93 to 0.98, and average 0.96 ± 0.01.

The Bailey ash has been dated by both the K-Ar and fission-track methods (fig. 8), but only the latter method appears reliable in view of the fine grained and water deposited nature of the ash. Early K-Ar ages (fig. 8) are too old to be consistent with stratigraphic evidence and ages of other ashes, such as the overlying gray ash and "ash of Mono Glass Mountain", and the underlying lowermost gray ash (see below). The older ages would also be inconsistent with the Wheelerian microfaunal stage assigned to the stratigraphic interval within which this ash is situated (Natland, 1952; Van Eysinga, 1975). According to Izett and others (1974), some of the earlier age analyses are probably too old owing to detrital contamination. The age of 1.2 ± 0.2 m.y. on a sample of this ash collected from the Balcom Canyon locality (Izett and others, 1974; our sample locality 22) and an age of about 1.2 ± 0.3 m.y. obtained by the fission-track method on glass (Boellsdorf and Steineck, 1975), are most compatible with other available ages, and stratigraphic and biostratigraphic information.

Thin ash below the Bailey ash

A very thin, fine-grained, white vitric ash, about 6 mm thick (sample 27), crops out in silty, tuffaceous beds of the Pico Formation, where this formation is buttressed-up against strongly deformed beds of the Modelo Formation, west of South Mountain (the "sea knoll" of Yeats, 1965). This ash is about 245 m below the stratigraphic level of the Bailey ash (R. Yeats, written commun., 1974). It is chemically similar to the Long Valley-Mono Glass Mountain family of ashes and probably represents a minor eruption from that source, although the ash has been found only in the South Mountain area. No direct isotopic age has been determined for this ash but it must be older than the 1.2 m.y. age of the overlying Bailey ash, and probably younger than about 2 m.y., an age estimated for the underlying lowermost gray ash (see below). If we take the age of the Bishop ash (0.7 m.y.), the age of the Bailey ash (1.2 m.y.), the thickness of the stratigraphic interval between them, and assume uniform sedimentation rates within the basin, we can make a rough estimate of the age of this thin ash by using the 245 m separation between it and the Bailey ash and extrapolation of the sedimentation rate down the section. This calculation gives us about 1.5 m.y. Interpolating the age of this ash from the Bailey ash, above, and the lowermost gray ash, below, again on the basis of stratigraphic position of the three, and assuming a 2 m.y. age for the lowermost ash, we again get about 1.5 m.y. for the thin ash below the Bailey ash. Obviously, such estimates are subject to considerable error because sedimentation rates most likely have not been constant during these time intervals, and also must have differed considerably from site to site. An independent age estimate, made on the basis of systematic compositional trends discussed below gives us an age of between 1.3 and 1.4 m.y.

This ash is chemically most similar to the Bailey ash (samples 22 through 26a; similarity coefficients of 0.86 ± 0.01 between this ash and the Bailey), and to the upper, white ash in the Manix basin of the Mojave Desert (samples 28, 29; similarity coefficient of 0.86).

Lowermost, gray ash, South Mountain area

A 2.5 cm thick, fine, gray, vitric ash is interbedded with sand and silt beds of the Pico Formation, buttressed against deformed Modelo Formation, a few meters above the Pico-Modelo contact, west of South Mountain (sample 43). This ash is about 670 m below the stratigraphic level of the Bailey ash.

In chemical composition of its glass, this ash contrasts sharply with ashes of the Long Valley-Mono Glass Mountain family, but is very similar to tephra erupted from the Yellowstone area (Pearlette tephra family). The ash correlates well with a gray, 40 cm thick ash interbedded with lake beds of Pleistocene Lake Tecopa (ash C of Sheppard and Gude, 1968; samples 44, 44a, and 45). The similarity coefficient between these samples ranges from 0.96 to 0.98, and averages 0.97 ± 0.01.

The age of this ash has not been determined. Again, assuming uniform sedimentation rates, the ages of the Bishop and Bailey ash, and the stratigraphic separation between them in the Ventura Avenue anticline section north of the town of Ventura, we can estimate the age of the lowermost gray ash using the stratigraphic separation between it and the position of the Bailey ash. This estimate gives us 2 to 2.1 m.y. Again, the same cautions apply regarding uniformity of sedimentation rates and variation in rates from site to site in the basin.

The lowermost gray ash, and its correlative in lake beds of Pleistocene Lake Tecopa, however, are chemically quite similar to the Pearlette type B ash (see below), which has been dated at about 2 m.y. (Naeser and others, 1971; Christiansen and Blank, 1972), although not similar enough to be considered correlative on the basis of chemical analyses alone (similarity coefficients of 0.92 to 0.94, with an average of 0.93 ± 0.01). Christiansen and Blank (1972) report that the Huckleberry Ridge Tuff, the near-source ash-flow tuff correlated with the Pearlette type B ash (Naeser and others, 1973), is a composite sheet. Perhaps here again we see the effect of multiple eruptions where sequential products of an eruptive episode of short duration account for chemical differences in samples of this tephra type. Further work on this problem is currently under way.

Ashes of the Manix basin, Mojave Desert

Four ash beds crop out in pluvial lake beds and deformed older alluvium of the Manix basin in the Mojave Desert, about 40 km east of Barstow. The upper ash, in pluvial lake beds, was not analyzed because glass in the sample was devitrified. The three other ashes, interbedded with older fluvial deposits in the basin, and separated from the overlying pluvial lake beds by an angular unconformity, had fresh glass and were analyzed.

Upper white ash, Manix basin

A fine, white, vitric ash, about 8 cm thick, crops out in low cliffs on the south side of the Mojave River (samples 28, 29). Only the basal 2 to 2.5 cm is massive, pure, airfall(?) ash, the upper part being finely bedded, water laid tephra, probably locally reworked. This ash does not correlate with any other ash analyzed to date. It is most similar to ashes of Long Valley-Mono Glass Mountain provenance, and was probably erupted from that volcanic province. Although correlated with the Bishop Tuff on the basis of rapid-scan X-ray fluorescence analysis for rubidium, strontium, and zirconium by Merriam and Bischoff (1975), this ash is chemically different from the Bishop ash group, particularly with respect to scandium, manganese, samarium, hafnium, tantalum, and thorium (table 1).

Middle white ash, Manix basin

A fine, white, vitric ash, about 3 to 4 cm thick (samples 30-33) underlies the upper white ash by about 12 to 15 m. Pure, white ash, about 1.3 cm thick near the base, rests with sharp contact on alluvial silts and sands, grading upward into pinkish tuffaceous silts. The upper 2 to 3 cm consists of well bedded or laminated, water-laid ash. Samples 30 and 31 were collected on the south side of the Mojave River; samples 32 and 33, on the north side, about 0.8 km north of localities 30 and 31, correlating the ash over this short distance. This ash also correlates well with an ash, the second from the top of a sequence of four ashes interbedded with late Cenozoic Waucoba lake beds in eastern Owens Valley, about 270 km to the north of the Manix basin (sample 34). Range of similarity coefficients for ashes of these two localities is from 0.95 to 0.96, with an average of 0.96 ± 0.01. Range of similarity coefficients for the entire group of five samples is from 0.95 to 0.98, with an average of 0.97 ± 0.01.

There is no direct isotopic age available for this ash at the Manix basin localities, but a K-Ar age of 2.3 m.y. has been obtained on the ash in the Waucoba lake beds of Owens Valley (Hay, 1966; our sample locality 34). This age appears to be somewhat too old, if the correlation of an ash which underlies the middle white ash at Manix basin is correct (see below).

Although Merriam and Bischoff (1975) correlated this ash with the Bishop Tuff on the basis of rapid-scan X-ray fluorescence analysis for rubidium, strontium, and zirconium, neutron activation analyses for trace and minor elements reveal large differences between these tephra units, particularly for scandium, manganese, iron, rubidium, cesium, samarium, terbium, dysprosium, ytterbium, lutecium, hafnium, tantalum, thorium, and uranium (table 1; fig. 3). Furthermore, the ash correlates well with an older, late Cenozoic ash in the Waucoba beds (see above), and is underlain by an ash correlated with the Pearlette type B ash, dated by others at about 2 m.y. (see below).

Despite the large differences in glass chemistry between the middle white ash at Manix basin and the Bishop ash group, the middle white ash belongs to the Long Valley-Mono Glass Mountain family of ashes, as can be seen in gross chemical similarities to other tephra units belonging to this group, as well as in systematic, age related depletion trends which are a characteristic of this tephra family (table 1; figs. 3 and 5; fig. 4, plate 1).

Lower gray ash, Manix basin, and Pearlette type B ash

A fine, gray, vitric ash, 3 cm thick (sample 41) underlies the middle white ash (sample 32) by about 2 to 3 m in low hills on the north side of the Mojave River in the Manix basin. This ash correlates very well on the basis of its glass composition with a sample of the Pearlette type B ash (sample 42) from the Borchers faunal locality, Meade County, Kansas, obtained from G. Izett (written commun., 1977). The similarity coefficient between these two samples is 0.97. Furthermore, this thin gray ash in the Manix basin contains crystals of green to brown hornblende, clinopyroxene, allanite, zircon, apatite, ilmenite, and magnetite, minerals typical of the Pearlette ash family (Izett and others, 1970). This represents a correlation of a single tephra unit over a distance of about 1500 km between sample localities and over a distance of about 1200 km between the putative source area in Yellowstone National Park and the Manix basin.

The similarity coefficient comparing analyses of the lowermost gray ash in the Manix basin (sample 41) with an analysis of the upper part of the Pearlette type O ash at the Lake Tecopa locality (sample 38) is also high (0.95), but not as high as the coefficient comparing the former ash with the Pearlette type B ash (0.97). Furthermore, isotopic age and stratigraphic control (fig. 2) independent of glass chemistry supports correlation of the lower gray ash with the Pearlette type B ash. As previously mentioned, the lower gray ash at Manix basin (sample 41), the lower gray ash in the South Mountain area (sample 43), the gray ash (ash C of Sheppard and Gude, 1968) in the Lake Tecopa area (samples 44, 45), and the Pearlette type B ash from the Meade County locality in Kansas (sample 42) may all be part of a single eruptive episode of short duration, and correlate with near source tephra in the Yellowstone area represented by the compound Huckleberry Ridge Tuff, dated at 2 m.y. (Christiansen and Blank, 1972).

Other tephra units of limited areal extent or recognition

A number of tephra units the glass of which has been analyzed in the present study are found at single localities only, or are exposed over small areas. These units may have been produced by minor local eruptions, or they may be products of larger eruptions that have not yet been widely recognized. Alternatively, some of these samples may also be tephra whose original composition has been somewhat masked or altered by post-depositional, diagenetic processes, but the glass of which is still optically isotropic.

Ash in late Cenozoic lake beds of Searles Lake

A sample of a fine, white vitric ash interbedded with late Cenozoic (upper Pliocene) lake beds, has been obtained from a bore hole in Searles Lake (sample 35; Smith, 1978). This ash does not match well with any other ash we have analyzed, although it is most similar to ashes of the Long Valley-Mono Glass Mountain family (similarity coefficients of 0.65 to 0.95). The ash is most similar to the "ash of Mono Glass Mountain" (average similarity coefficient of 0.94 $\pm$ 0.01), but is most likely much older than that, probably about 3 m.y., according to stratigraphic and paleomagnetic data (Liddicoat and Smith, 1979). Although glass separated from this ash was optically clear for the most part, there is a possibility that deposition in a saline lake may have changed the glass chemistry of this ash so that it can no longer be matched with unaltered glass of the same tephra unit.

Tuffs of the Coso area

Glass from an unwelded, pumiceous ash-flow collected by W. Duffield (oral commun., 1977) in the Coso area east of the southern Sierra Nevada (sample 36) does not correlate with any other analyzed tephra unit on the basis of glass chemistry (table 1; fig. 4, plate 1), not even with the other analyzed tuffs of the Coso area. This ash has an unusual composition, compared to other tephra samples, with very low concentrations of iron, as well as of the rare earth elements lanthanum, cerium, neodymium, samarium, terbium, dysprosium, ytterbium, and lutecium (table 1). Perhaps this ash also has been affected by post-depositional processes.

Pumice from a distinctive air-fall pyroclastic unit of the Coso volcanic field (Duffield and Bacon, 1977), has been analyzed in this study (samples 46-48, and 48A). This unit yields a weighted mean K-Ar age of 2.99 $\pm$ 0.20 m.y. (Duffield and others, in press), and 2.98 $\pm$ 0.28 and 2.91 $\pm$ 0.20, according to fission-track ages determined in this study (table 6). Sample 46 overlies sample 47 at the locality where they were collected but exact stratigraphic relations of sample 48, from another locality, are unknown. Analyses of samples 48 and 48A were run on coarse-grained and fine-grained glass, resepctively, separated from the same sample. These two separates were run to determine the effect of grain size on composition of this phenocryst and microlite-rich pumice tuff. As can be seen from table 1, there is very little if any difference between the two analyses within the limits of analytical precision of the neutron activation method, consequently there is little or no error in the analyses due to differences in degree of separation of these two samples.

Ash in Searles Valley

An ash collected from late Cenozoic lacustrine deposits exposed on the southeast side of Searles Valley by G. I. Smith (oral commun., 1976; sample 49) does not correlate with any tephra unit analyzed in this study, nor is it similar to any tephra family recognized at the present time. It is possible that tephra erupted from the Coso area has a very large compositional spectrum, and that samples 36, 46-48, and 49 have all been erupted from the Coso area. Not enough information is available in this study to test this hypothesis.

Pumice overlying the Cahuilla beds, Salton trough

Large pumice cobbles up to 20 cm in diameter overlie the Cahuilla beds of the Salton trough. The Cahuilla beds, in turn, overlie the strongly deformed Borrego Formation with marked angular unconformity. The pumices were most likely derived by erosion from young pumice domes (dated at about 16,000 years b.p. by the K-Ar method, Muffler and White, 1969) situated at the south shore of the Salton Sea, and floated northward along the shore of the lake. The highest extent of these cobbles probably defines a former high stand of the lake in this area. Glass from one of these cobbles (sample 50) was analyzed. The chemical composition of this glass is quite distinct from that of the Bishop ash group tephra in the Borrego Formation, especially with respect to iron, rubidium, cesium, the RE elements, and hafnium, and supports our contention that there is no genetic relationship between the ashes in the Borrego Formation and the local pumice domes. This pumice is also easily

Table 6. Analytical data on fission-track age of zircon crystals from an ash-flow tuff in the Coso area (sample 48)

Analyst	Spontaneous tracks No. counted	Spontaneous tracks Density[1]	Induced tracks No. counted	Induced tracks Density[1]	Neutron flux[2]	Age (m.y.±2)
C. Meyer	217	7.1×10^5	2088	1.4×10^7	9.59×10^{14}	2.98±0.28
M. Woodward	390	5.3×10^5	3754	1.1×10^7	9.59×10^{14}	2.91±0.20

[1]Tracks per cm^2.

[2]Neutrons per cm^2.

distinguished from other tephra families on the basis of its chemical composition (table 1; fig. 4, plate 1; and fig. 5).

Provincial relationships of tephra of the Long Valley-Mono Glass Mountain family

The Long Valley-Mono Glass Mountain family of tephra is defined on the basis of gross chemical similarities that distinguish these tephra units from tephra of other families. The Bishop ash group, the "ash of Mono Glass Mountain", and the gray ash beneath it have all been erupted from sources just east of the central Sierra Nevada, as indicated by thickness and clast size gradients of these units. Because of chemical similarities (fig. 3), the Bailey ash and the thin white ash below it are also presumed to have been erupted from this general area, although no near-source outcrops of these ashes have been found. The younger, voluminous deposits of the Bishop Tuff may cover near-source correlatives of the older ashes. Likewise, the upper, white ash, and middle white ash of the Manix basin, and the subsurface ash obtained from lake beds of Searles Lake, are also considered to belong to this family (fig. 4, plate 1).

In general, greatest similarity is observed between tephra units that are close in age or stratigraphic proximity to each other, while larger differences are observed between units that are further separated (fig. 3). These relationships suggests that there are some systematic compositional variations in this tephra suite that are time related. Isotopic or relative ages of six of these units are known. These are the Bishop ash group, the "ash of Mono Glass Mountain", the gray ash beneath the latter ash, the Bailey ash, the thin ash beneath the Bailey, and the middle white ash of the Manix basin. These six units show systematic depletion trends with time for a number of elements (fig. 3). Five elements, manganese, rubidium, tantalum, hafnium, and uranium show the most consistent depletion trends with decreasing age (fig. 9). Isotopic ages of three of these ashes, the Bishop, Bailey, and Waucoba (equivalent to the middle, white ash of the Manix basin) have been determined, while ages of two others, the "ash of Mono Glass Mountain" and the gray ash below it, can be fairly closely bracketed at about 0.8 ± 0.1 and 1.0 ± 0.2 m.y., respectively, based on stratigraphic relations to the other ashes and magnetic polarity (fig. 9). As mentioned above, the 2.3 m.y. age of the ash in the Waucoba beds is considered to be somewhat too old, since this ash closely overlies the 2 m.y. old Pearlette type B ash, based on our chemical correlations. A straight-line extrapolation of the age-composition trend between the Bishop and the Bailey ash (fig. 9) would intersect the normalized composition of the middle, white ash of Manix basin (equivalent to the ash in the Waucoba beds) at about 2 m.y. Normalized values of the five elements plotted against their ages have a more-or-less linear relationship. Using this relationship, we can predict the age of the thin ash below the Bailey ash at between about 1.3 and 1.4 m.y. (fig. 9).

We should point out that two ashes included in this tephra family, the upper, white ash of the Manix basin, and the ash obtained from the subsurface at Searles Lake, do not fall on these trends. There are no isotopic ages of these ashes at present. The upper, white ash of the Manix basin (samples 28 and 29) is younger than the middle, white ash at that locality, but no minimum bracketing age is available, other than that the thin white ash is in unconformably overlying pluvial lake beds of Wisconsinan age (G. Jefferson,

Figure 9

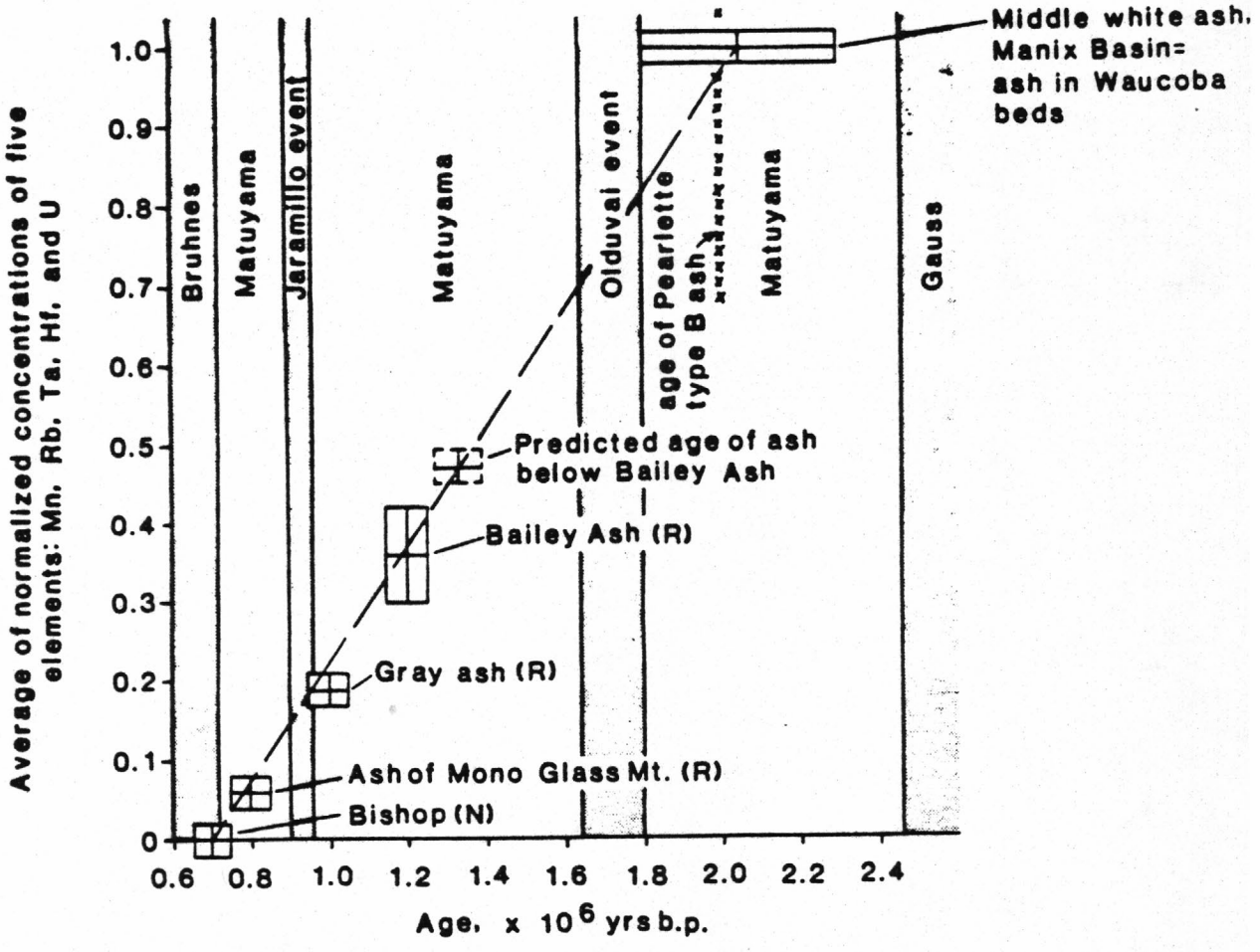

Figure 9. Average of normalized concentrations of five elements (Mn, Rb, Ta, Hf, and U) of five tephra units of the Long Valley-Mono Glass Mountain family are plotted against their ages. The age of a sixth ash, the thin white ash, situated stratigraphically below the Bailey ash, is predicted on the basis of its normalized composition and the apparent linear relationship between composition and age of this tephra family. Normalized concentrations were calculated by taking the range of average concentrations of each element in all six units, and assigning values of 0 to the element in the unit with the lowest concentration for that element, and 1 to the element in the unit with the highest concentration. The values for the remaining concentrations in each unit were calculated as proportions between 0 and 1. The normalized values for all five elements were then averaged to determine the average normalized concentration for each unit.

oral commun., 1975). The age of the ash in the subsurface from Searles Lake (sample 35) is also not know but is estimated to be about 3 m.y., based on stratigraphic and paleomagnetic data (Liddicoat and Smith, 1979). Perhaps these two ashes were not erupted from the same area as the other six, but from a closely adjacent province.

The younger ashes, such as the Bishop ash and "ash of Mono Glass Mountain", are associated with roughly coeval pyroclastic and flow rocks of widely ranging compositions. The ash-flow phases of the Bishop Tuff itself have chemical variations that are much greater than the variations in the air-fall ash (Hildreth, 1977). For this reason, we suspect that each of the six tephra units shown in fig. 9 represent climactic eruptions from about the same source area, each a culmination of a relatively shorter-term differentiation cycle. The long-term, roughly linear depletion trends may represent an envelope curve for some long-term magmatic evolution process superimposed on shorter-term cyclic eruptive episodes, such as that represented by the Bishop Tuff and associated volcanic rocks of approximately coeval age. Each climactic eruption would represent the same stage of magmatic differentiation in the shorter cycles. We do not understand the processes responsible for the systematic long-term depletion trends (if indeed they are real and systematic). For the present time, the method should be regarded as a hypothesis only--a potential, empirical method of estimating or cross-checking ages of silicic tephra belonging to this tephra family. The method needs further testing, since reversals in such compositional trends have been noted.

Recognition of provincial characteristics of tephra

Because of gross chemical similarities in trace- and minor-element glass composition, eruptive source areas of individual tephra units can be recognized. For instance, average between-unit similarity coefficients within the Long Valley-Mono Glass Mountain tephra family range from 0.62 to 0.94. Average similarity coefficients between tephra units of Pearlette-like ashes range from 0.84 to 0.93, while average similarity coefficients between these families range from 0.44 to 0.56, demonstrating the large compositional contrast between tephra from different source areas.

In this study, three main tephra families have been recognized on the basis of trace- and minor-element composition of the volcanic glass: the Long Valley-Mono Glass Mountain, the Pearlette, and the Coso. Sample 50, correlated with the pumice domes at the south shore of the Salton Sea, represents a fourth, distinct volcanic province (although no tephra unit is associated with this source), while sample 49, from Searles Valley, represents a possible fifth. In other studies (Izett and others, 1972; Sarna-Wojcicki, 1976; Sarna-Wojcicki, Mullineaux, and Waitt, unpublished data), seven other major late Cenozoic tephra families have been identified in the western conterminous United States on the basis of trace- and minor-element composition of the volcanic glass. Each of these families is associated with a specific source area. Within several tephra families, subgroups can be distinguished, while several families can be grouped into larger super-groups on the basis of gross similarities. The unique chemical characteristics associated with each eruptive source area are undoubtedly related to the parent materials from which magma was formed and the magmatic differentiation processes which operate within these source areas. These, in turn, are probably related to the tectonic setting of the source area itself. At the present time, we do not understand the specific reasons for the chemical differences observed between the different tephra families.

Table 7. Sample locations

Sample number	State	County	Quadrangle	Quarter & Section	T	R	Latitude	Longitude	Collector(s)	Field number	Lab. number (INAA)
Pumice (1), near Friant and correlative ashes											
1	Calif.	Madera	Millerton Lake 15'	NE 1/4 of NE 1/4, 1	10S	20E	N37°00'40"	W119°44'10"	R. J. Janda	63cj-26	N-ASW- 2
2	"	Tulare	Alpaugh 7.5'	NW 1/4 of NE 1/4, 16	23S	24E	N35°52'30"	W119°23'15"	Bureau of Reclamation	23-24-16B	" 4
3	"	Ventura	Ventura 7.5'	L.G.[1]			N34°17'56"	W119°16'58"	A. M. Sarna-Wojcicki	Pico-15	" 58
4	"	"	do	L.G.[1]			N34°17'57"	W119°15'48"	do	Pico-24	" 69
5	"	San Diego	Clark Lake 15'	NW 1/4 of NE 1/4, 24	9S	5E	N33°22'50"	W116°24'35"	R. V. Sharp	ST-RT3	" 125
6	"	Imperial	Durmid SE 7.5'	NW 1/4 of SW 1/4, 19	9S	12E	N33°22'29"	W115°46'07"	A. M. Sarna-Wojcicki	Salton-2	" 63
7	"	"	do	do	do	do	do	do	do	Salton-2A	" 117
Bishop ash at Insulating Aggregates Quarry (8), and correlative ashes											
8	"	Invo	Bishop 15'	NW 1/4 of NW 1/4, 4	6S	33E	N37°27'40"	W118°21'55"	A. M. Sarna-Wojcicki, J. W. Hillhouse	BT-8	" 115
9	"	Inyo	Shoshone 15'	SW 1/4 of NE 1/4, 32	22N	7E	N35°58'02"	W116°14'52"	do	Teco-5	" 183
10	"	Riverside	Murrietta 7.5'	SW 1/4 of NW 1/4, 7	7S	3W	N33°34'52"	W117°14'25"	M. Kennedy, G. Borchardt	ELSI-1	" 75
11	"	Riverside	Idylwild 15'	SE 1/4 of SW 1/4, 32	6S	3E	N33°36'00"	W116°41'44"	R. V. Sharp	ST-RT-2	" 124
12	"	Imperial	Durmid SE 7.5'	NW 1/4 of SW 1/4, 19	9S	12E	N33°22'29"	W115°46'07"	A. M. Sarna-Wojcicki	Salton-5	" 71
Bishop ash at Owens River Gorge (13), Bishop Tuff at Red's Meadow (14), and correlative ashes											
13	"	Mono	Casa Diablo 15'	W 1/2 of NE 1/4, 5	5S	31E	N37°32'47"	W118°35'26"	E. W. Hildreth	B-93	922K
14	"	Madera	Devil's Postpile 15'	N.F.[2]			N37°37'35"	W119°03'20"	R. J. Janda	J-328	N-ASW- 3
15	"	Imperial	Durmid SE 7.5'	NW 1/4 of SW 1/4, 19	9S	12E	N33°22'29"	W115°46'07"	A. M. Sarna-Wojcicki	Salton-1	" 116
16	Utah	Grand	Polar Mesa 15'	SE 1/4 of NE 1/4, 26	24S	24E	N38°41'25"	W109°14'11"	R. E. Wilcox	66W5	" 149
"Ash of Mono Glass Mountain" (17, 17a-c) and correlative ash, Ventura area (18)											
17	Calif.	Inyo	Bishop 15'	NE 1/4 of NE 1/4, 23	6S	32E	N37°27'24"	W118°40'25"	A. M. Sarna-Wojcicki	BT-2	" 55
18	"	Ventura	Ventura 7.5'	L.G.[1]			N34°19'05"	W119°20'43"	do	Pico-23	" 68
Gray ash beneath "ash of Mono Glass Mountain" (19) and correlative ashes, Ventura area (20, 21)											
19	"	Inyo	Bishop 15'	NE 1/4 of NE 1/4, 23	6S	32E	N37°27'24"	W118°40'25"	A. M. Sarna-Wojcicki	BT-1	" 101
20	"	Ventura	Ventura 7.5'	L.G.[1]			N34°18'10"	W119°16'14"	do	Pico-27	" 129
21	"	"	do	L.G.[1]			N34°18'05"	W119°18'14"	do	Pico-14	" 64

Table 7. Continued.

Sample number	State	County	Quadrangle	Quarter & Section	T	R	Latitude	Longitude	Collector(s)	Field number	Lab. number (INAA)
				Bailey ash, South Mountain (22, 23), and Ventura (24, 25, 26)							
22	Calif.	Ventura	Moorpark 7.5'	NW 1/4 of SE 1/4, 21	3N	20W	N34°19'41"	W118°58'37"	A. M. Sarna-Wojcicki	Pico-4	N-ASW- 56
23	"	"	do	NE 1/4 of SW 1/4, 20	3N	20W	N34°19'34"	W119°00'00"	do	Pico-3	" 54
24	"	"	Ventura 7.5'	L.G.[1]			N34°18'10"	W119°18'15"	do	Pico-5	" 57
25	"	"	do	L.G.[1]			N34°18'13"	W119°20'48"	do	Pico-21	" 67
26	"	"	Pitas Point 7.5'	NW 1/4 of SE 1/4, 16	3N	24W	N34°20'20"	W119°23'33"	do	Pico-18	" 65
				Ash below Bailey ash, South Mountain							
27	"	"	Santa Paula 7.5'	NE 1/4 of NW 1/4, 27	3N	21W	N34°19'00"	W119°04'24"	do	Pico-7	" 66
				Upper, white ash, Manix basin, Mojave Desert							
28	"	San Bernardino	Newberry 15'	NW 1/4 of SW 1/4, 11	10N	4E	N34°58'23"	W116°32'12"	R. Merriam, J. L. Bischoff	Manix-1	" 41
29	"	"	do	do			do	do	A. M. Sarna-Wojcicki & others	Manix-5	" 113
				Middle, white ash, Manix basin, Mojave Desert (30-33), and ash in Pleistocene (Waucoba) lake beds, E. Owens Valley (34)							
30	"	"	do	SW 1/4 of NW 1/4, 11	10N	4E	N34°58'26"	W116°32'08"	A. M. Sarna-Wojcicki & others	Manix-4	" 112
31	"	"	do	do			do	do	R. Merriam, J. L. Bischoff	Manix-2	" 42
32	"	"	do	NW 1/4 of NW 1/4, 11	10N	4E	N34°58'44"	W116°32'06"	A. M. Sarna-Wojcicki & others	Manix-7	" 120
33	"	"	do	SW 1/4 of SW 1/4, 2	10N	4E	N34°58'50"	W116°32'07"	do	Manix-8	121
34	"	Inyo	Waucoba mt. 15'	Section 18(?)	9S	34E	N37°10'	W118°12'	D. E. Marchand	W3A	" 76
				Ash from core in lake beds of Searles Lake							
35	"	San Bernardino	Searles Lake 7.5'	Cor. Sec. 22,23,26,27	25S	43E	N35°44'15"	W117°19'30"	G. I. Smith	KM3A	" 126
				Unwelded, pumiceous ash flow tuff in the Coso area							
36	"	Inyo	Haiwee Res. 15'	NE 1/4 of NW 1/4, 13	19S	37E	N36°11'55"	W117°55'17"	W. A. Duffield, C. R. Bacon	9-85	
				Uppermost ash (ash "A"), Tecopa area (37, 38), and Pearlette type "O" ash, Grand Co., Utah (39)							
37	"	Inyo	Shoshone 15'	NW 1/4 of NW 1/4, 31	21N	6E	N35°58'16"	W116°16'28"	A. M. Sarna-Wojcicki, J. W. Hillhouse	Teco-3	" 181
38	"	"	do	do			do	do	do	Teco-4	" 182
39	Utah	Grand	Polar Mesa 15'	SE 1/4 of NE 1/4, 26	24S	24E	N38°41'25"	W109°14'11"	R. E. Wilcox	67W104	" 150

Table 7. Continued.

Sample number	State	County	Quadrangle	Quarter & Section	T	R	Latitude	Longitude	Collector(s)	Field number	Lab. number (INAA)
				Pearlette type "S" ash, Harlan County, Nebraska							
40	Nebr.	Harlan	Stamford 7.5'	SW 1/4 of NW 1/4,	12	2N 2W	N40°09'19"	W99°32'30"	R. E. Wilcox	66W4	N-ASW-147
40A	"	"	do	do			do	do	do	"	" 148
				Lower, gray ash, Manix basin (41), and Pearlette type "B" ash, Borchers locality, Meade County, Kansas, (42)							
41	CalifSan	Bernardino	Newberry 15'	NW 1/4 of NW 1/4,	11	10N 4E	N34°58'44"	W116°32'06"	A. M. Sarna-Wojcicki & others	Manix-6	" 114
42	Kansas	Meade	Irish Flats NE 7.5'	NW 1/4 of NE 1/4,	21	33S 28W	N37°10'08"	W100°22'08"	R. E. Wilcox	68W98	" 151
				Lowermost ash, South Mountain area (43), and ash (ash "C"), Tecopa area (44, 45)							
43	Calif.	Ventura	Santa Paula 7.5'	N 1/2,	28	3N 21W	N34°18'50"	W119°05'13"	A. M. Sarna-Wojcicki	ASW-3-23-75-1	" 70
44	"	Inyo	Tecopa 15'	SE 1/4 of SE 1/4,	23	21N 7E	N35°54'(apx)	W116°11'(apx)	M. O. Woodburne	1; Teco-1	" 73
45	"	"	do	NE 1/4 of SE 1/4,	23	21N 7E	N35°54'(apx)	W116°11'(apx)	do	2; Teco-2	" 74
				Air-fall pumice of the Coso area							
46	"	"	Haiwee Res. 15'	SE 1/4 of NE 1/4,	35	21S 38E	N36°03'57"	W117°50'22"	W. A. Duffield, C. R. Bacon	13-42-5	" 118
47	"	"	do	do			do	do	do	13-42-4	" 119
48	"	"	do	NE 1/4 of NE 1/4,	23	21S 38E	N36°05'58"	W117°50'04"	do	9-8-11; Coso-1	" 122
48A	"	"	do	do			do	do	do	do	" 123
				Ash in Searles Valley							
49	"	San Bernardino	Searles Lake 15'	N.R.[3]			N35°33'19"	W117°17'41"	G. I. Smith	AXL-30K-160-5	" 176
				Pumice overlying Cahuilla Beds, Salton trough							
50	"	Imperial	Durmid 7.5'	SE 1/4 of NE 1/4,	24	9S 11E	N33°22'50"	W115°46'05"	A. M. Sarna-Wojcicki	Salton-7	" 72

[1]Land grant,

[2]National Forest, and

[3]Naval Reserve: no township and range coordinates on available maps.

Methods

Sampling

We examined ash and tuff outcrops at collecting localities and sampled the purest or least contaminated layers or zones. For air-fall or water-deposited tephra, these layers or zones are usually situated at or near the base of the tephra units. We "high-graded" the least contaminated material from the exposures, obtaining between several hundred grams and several kilograms, depending on the thickness of the tephra unit, the ease of obtaining the purest available material, and the type of analyses planned for each sample. Samples of one-half to two kilograms were collected for chemical and petrographic analyses. At several localities, we collected larger samples of 10-20 kg for fission-track age determinations. At some outcrops, we took multiple samples vertically where presence of multiple emplacement units was suspected, or to determine vertical variability within each tephra unit. In a number of instances, we took replicate samples laterally within individual emplacement units to determine their lateral variability.

Sample preparation

Previous experience (Sarna-Wojcicki, 1971, 1976; Sarna-Wojcicki and others, 1979) indicates that purity of glass separations is reflected favorably in the quality of analytical results and facilitates data interpretation. For this reason, special care is exercised in glass separations for chemical analyses.

We disaggregated samples by hand or crushed in a mullite mortar and sieved them in plastic sieves fitted with nylon screens to avoid contamination with metals. We treated the 100-200 mesh size fraction (0.14 - 0.08 mm) with 10 percent reagent grade HCl for about one minute, rinsed several times in distilled water, etched it with 5 percent reagent grade HF for approximately 30 seconds, quenched it rapidly by dilution with a large volume of distilled water, rinsed it several times again, vibrated it in an ultrasonic cleaner, wet-sieved it again, and then dried it. We then separated the glass from other constituents in the tephra samples in a Frantz magnetic separator, and in acetone-bromoform and acetone-methylene iodide liquid solutions using a density-gradient column.

Analytical Methods

Neutron activation analysis

Bowman and others (1973), and Sarna-Wojcicki and others (1979) describe the analytical methods for neutron activation analysis. In this study, neutron activation analyses of glass samples were done by two laboratories, Lawrence Berkeley Laboratory of the University of California at Berkeley, and the Radiochemistry Laboratory of the U.S. Geological Survey at Reston, Virginia. We calculated conversion factors to correct for standardization and instrumental differences between the laboratories from least-square fits to twenty-two samples split and analyzed by each laboratory. Elemental concentrations determined by the U.S. Geological Survey laboratory (table 1[1/])

1/ Regression equations for converting USGS, Reston, analyses to those of Lawrence Berkeley Laboratory and vice-versa are given in table 8 (plate 1).

are predicted $\hat{y}$ values from regression analysis.

Electron microprobe analysis

We determined major and minor element concentrations of 12 elements in glass of tephra samples by means of an ARL-EMX[1/] electron microprobe using a 15-kilovolt excitation potential, 0.010 A specimen current and a one micron beam diameter. When possible, the beam was swept over a 10 x 10 micron area to minimize volatization of sodium and water. We used wet chemically analyzed natural glasses and silicate minerals as standards. We took X-ray counts on a total population of 60 to 80 shards per sample to evaluate homogeneity. Each area selected was evaluated visually for absence of vesicles, obvious crystalline material or abnormally fluorescent areas under the beam, to assure that only glass was being analyzed. We made corrections for background, atomic number effects, absorbtion and fluorescence using a modified on line data reduction program (Yakowitz and others, 1973). We give results of electron microprobe analyses in table 3.

Petrographic analysis

Sized separates of the 100-200 mesh (0.14-0.08 mm) fractions, and the 200-325 mesh (0.08-0.03 mm) fractions for fine tephra beds, were separated in a magnetic separator at high and low amperage settings. We further processed the intermediate magnetic fraction, containing mostly magnetic glass, for separation of volcanic glass (see above). We separated the magnetic fraction, containing the bulk of minerals rich in transition elements, in heavy liquid solutions having a specific gravity of approximately 2.85. We examined the heavy separate in optic oils under a petrographic microscope. We recorded the presence of transparent mineral species for each sample, and calculated relative frequencies of the various species present from line counts (table 2). We also noted presence of glass coatings on specific minerals. We consider glass coated minerals to be cogenetic; that is, they were probably contained in the magma chamber from which the tephra unit was erupted, and usually help distinguish such minerals from other minerals present in the tephra owing to detrital or accidental contamination.

Many of the tephra units found in the southern and southwestern parts of California were undoubtedly situated near the extreme margins of their areas of distribution, since they are very thin and fine-grained. In such units the characteristic heavy minerals are usually very small or absent owing to wind and water winnowing. Heavy mineral separates from such units are contaminated by detrital contaminants. In such instances, we have relied solely on the chemistry of volcanic glasses and refractive indices of glass, together with stratigraphic data, to establish correlations.

[1/] Any use of trade names and trademarks in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

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