Correlation of Late Cenozoic Tuffs in the Central Coast Ranges of California by Means of Trace- and Minor-Element Chemistry

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By Andrei M. Sarna-Wojcicki

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A geochemical approach to the correlation of tuffs in Pliocene and Pleistocene marine and nonmarine strata of central California

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CORRELATION OF LATE CENOZOIC TUFFS IN THE CENTRAL COAST RANGES OF CALIFORNIA BY MEANS OF TRACE- AND MINOR-ELEMENT CHEMISTRY

By Andrei M. Sarna-Wojcicki

ABSTRACT

Deformed late Cenozoic tuffs in the central Coast Ranges of California have been correlated by means of trace- and minor-element chemistry of volcanic glass, supported by potassium-argon dates, petrographic data, and stratigraphy. Cluster analysis of the chemical data indicates that four orders of chemical variability exist in the trace- and minor-element composition of volcanic glass. The greatest differences are between tephra of silicic and intermediate composition. Considering silicic tephra alone, the greatest differences are observed between tephra erupted in different volcanic provinces. Differences between samples of silicic tephra erupted within the same volcanic field are smaller, while the smallest differences are observed between samples of tephra from individual eruptions.

Five widespread tuffs and composite tephra units erupted during a period from approximately 1 to 6 million years ago have been recognized in the study area. These include the tuff in the type section of the Merced Formation, the Putah Tuff Member of the Tehama Formation, the Lawlor Tuff, the Pinole Tuff and the tuff in the Merced(?) Formation of Sonoma County. All except the first were erupted from local central Coast Range sources, probably in the Sonoma volcanic field; the tuff in the type section of the Merced Formation was derived from the southern Cascade Range, about 320 km north of the main study area.

Tuff correlations indicate that Suisun Bay and Mount Diablo, in the eastern part of the main study area, were formed less than 4 million years ago and that drainage from the Great Valley of California to the ocean in the vicinity of the San Francisco Bay was established some time between 0.6 and 3.3 million years ago.

INTRODUCTION AND SCOPE OF STUDY

Correlations between the discontinuous exposures of deformed Pliocene and lower Pleistocene strata in the central Coast Ranges of California are important to an understanding of late Cenozoic development of the region because the distribution and structure of these strata record the tempo and style of ongoing deformation in the Coast Ranges. However, late Cenozoic sedimentation has been too rapid and has occurred under environmental conditions too diverse to permit refined correlation on the basis of fossil chronology. Radiometric dating of these geologically young deposits lacks sufficient precision as a correlation tool owing to the large errors involved in correcting for atmospheric argon-40 in the potassium-argon method, the effect of detrital contamination, and the general scarcity of material suitable for dating within sedimentary sections.

Because of the problems in fossil and radiometric age correlation, many of the late Cenozoic deposits in the central Coast Ranges are lumped into a broad, ill-defined "Plio-Pleistocene" category. A more detailed regional correlation of these deposits on the basis of tephrochronology, supported by radiometric, stratigraphic, and paleontological data, can serve as one of the basic tools in the solution of several longstanding geologic problems, such as the late Cenozoic paleogeography of the Coast Ranges and the nature and rates of late Cenozoic deformation.

The principal approach to correlation discussed in this paper is that of geochemical tephrochronology—comparison of tuff beds in these deposits by means of minor- and trace-element compositions of the volcanic glass (chemical fingerprinting method of Jack and Carmichael, 1968). Other comparative methods, such as mafic-mineral frequency analysis, refractive indices of glass, and potassium-argon dating of some of the main tuff units, serve to support the correlations based on this chemical fingerprinting of the tuff units.

This paper is mainly concerned with the results of tuff correlations and their geologic implications. A more detailed discussion of methods and the relative merits of various correlation criteria can be found in the author's dissertation (Sarna-Wojcicki, 1971).

This study is limited to middle and late Pliocene and early Pleistocene deposits in the central Coast Ranges of California, between lat. 37°30′ N. and 38°45′ N. (fig. 1). Some tuff units and volcanic sources outside of this region, in the Clear Lake area and northern Great Valley, were also studied (inset map, fig. 1).

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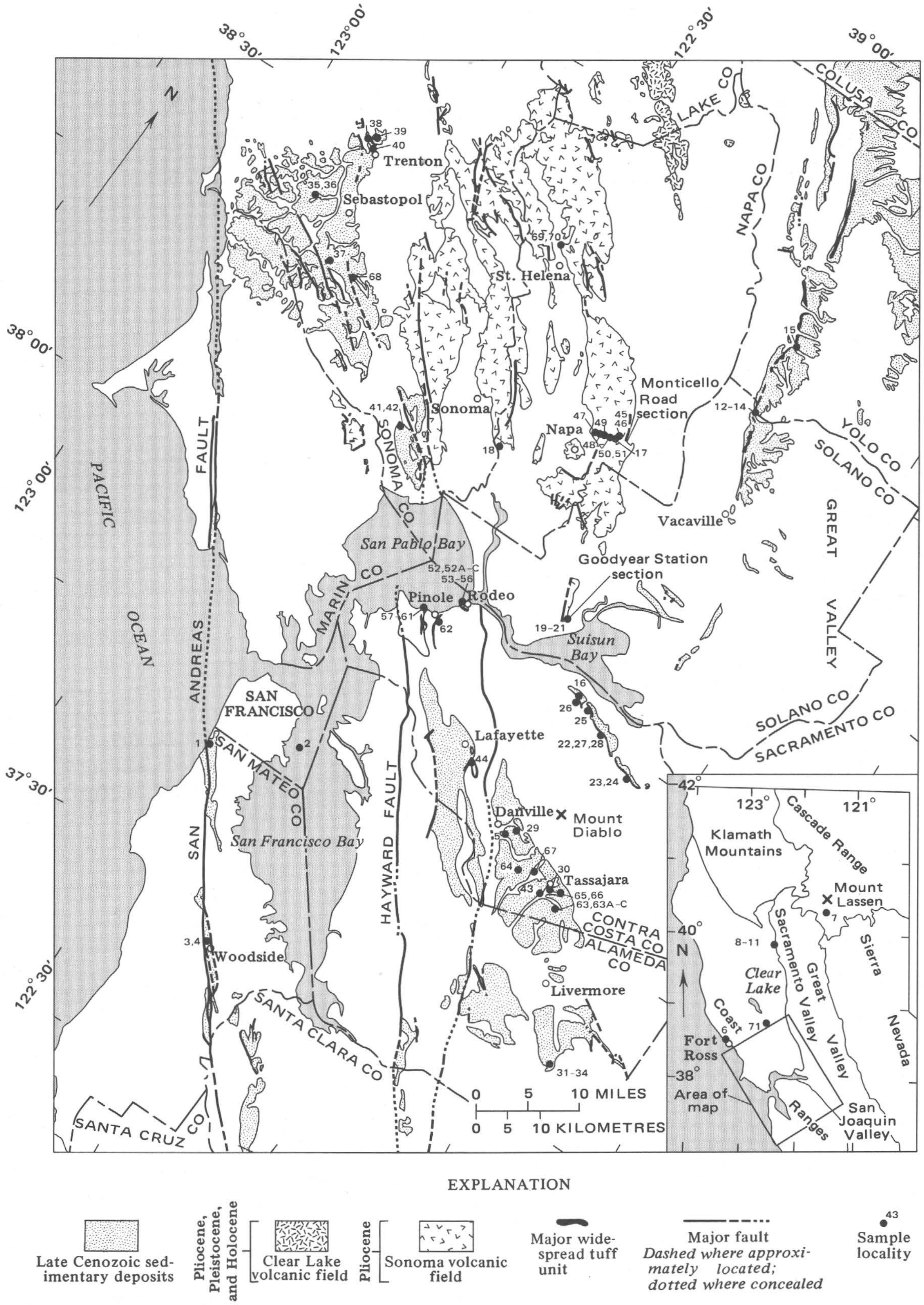

FIGURE 1.—Generalized geologic map showing location of samples, central Coast Ranges, Calif. Geology from Strand and Koenig (1965), Koenig (1966), Rogers (1966), Jennings and Burnett (1961), and Ross Wagner (written commun., 1974).

partly on research performed during 1971–72 at the U.S. Geological Survey.

I thank the following people at the Department of Geology and Geophysics at Berkeley: Robert Jack, who instructed me in XRF analytical procedures and helped in the analyses; Frank H. Brown, who did electron microprobe analyses of volcanic glass and phenocrysts; Richard L. Hay, Clyde Wahrhaftig, and Donald Savage, who advised me in this research; Garniss H. Curtis, who ran potassium-argon dates on several of the tuff samples in this study; Leonard Vigus, who helped with construction of research equipment; Leonard Leudke, who prepared and polished microprobe samples; and Katherine Condon, who helped in laboratory preparation of tuff samples.

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GEOLOGIC SETTING

Late Cenozoic deposits in the central Coast Ranges of California are discontinuous sedimentary and volcanic prisms occupying axes of northwest-trending post-Miocene basins, dissected remnants mantling uplifted northwest-trending ranges, elongate truncated edges of sedimentary prisms upwarped along zones of flexure or faulting between areas of uplift and subsidence, and elongate northwest-trending fault-bounded slivers situated along major fault zones. Throughout much of the central Coast Ranges, late Cenozoic deposits lap onto deformed rocks of Jurassic to Miocene age along major unconformities and are themselves strongly deformed.

Late Cenozoic deposits include both sedimentary and volcanic rocks. In the western part of the area, marine Pliocene and Pleistocene sediments are associated with brackish-water deposits and freshwater alluvial and lacustrine deposits of approximately the same age, though the contact relations between them in most places are concealed by younger alluvium or severed by faults. For instance, the marine Merced(?) Formation of Sonoma County probably interfingers to the east and northeast with the brackish-water and freshwater Petaluma Formation and with the freshwater alluvial Glen Ellen Formation (Bartow and others, 1973), but the transition from one formation to the other is nowhere continuously exposed. In the eastern basins, the late Cenozoic sediments are mainly alluvial, fan, and lacustrine deposits. Throughout most of the study area, the western basins are separated from the eastern by northwest-trending ranges underlain by older rocks. The volcanic rocks, restricted primarily to the northern part of the study area, form thick and extensive fields and interfinger locally with sedimentary rocks. Pyroclastic rocks in the study area are found as thick deposits interbedded with flow rocks within the volcanic fields and thinner tuff units interbedded with sedimentary deposits. Most of these thinner units were probably derived from volcanic fields within the study area. Such tuffs are fairly widespread in late Cenozoic sections throughout the central Coast Ranges, though they constitute but a small percentage of the total sediment volume. These tuffs are a useful tool in correlating stratigraphic sections between widely separated areas, especially between marine and continental sections and between sedimentary and volcanic sections for which fossil and radiometric data are often inadequate.

Tuffs interbedded in thick volcanic piles were closer to eruptive centers; consequently they contain coarser material than tuffs in the outlying areas. Two such thick volcanic piles within the study area are the Sonoma volcanic field and the Clear Lake volcanic field, but a major potential source of tuffs from outside the Coast Ranges is the area southwest of Mount Lassen, in the southern Cascade Range of northeastern California (inset map, fig. 1).

SONOMA VOLCANIC FIELD

The term Sonoma volcanic field, as used herein, refers to an area of middle and late Pliocene volcanism in the northern part of the study area. The Sonoma Volcanics, deformed and partially eroded, is the rock formation defined by Weaver (1949) which represents the present distribution of the Sonoma volcanic field. This formation is composed of pyroclastic deposits and lava flows with associated intrusive dikes. The rocks are predominantly silicic but range in composition from basalt to rhyolite. Two sections in the southeastern part of the field were studied in detail: the Monticello Road section east of Napa (fig. 1, locs. 17, 45–51) and the Goodyear Station section a few miles northwest of Suisun Bay (fig. 1, locs. 19–21). The Monticello Road section consists of more than 600 m of tuff, breccia, and flows of predominantly dacitic composition (figs. 2 and 3).

CLEAR LAKE VOLCANIC FIELD

The Clear Lake volcanic field (Becker, 1888; Anderson, 1936; Brice, 1952), northeast of the Sonoma volcanic field, was active during late Pliocene and Quaternary time (Brice, 1953; G. H. Curtis, oral commun., 1971). The volcanic rocks erupted in the Clear Lake area range in composition from basalt to rhyolite. Pyroclastic rocks are rare, suggesting that explosive volcanic activity was unimportant in the development

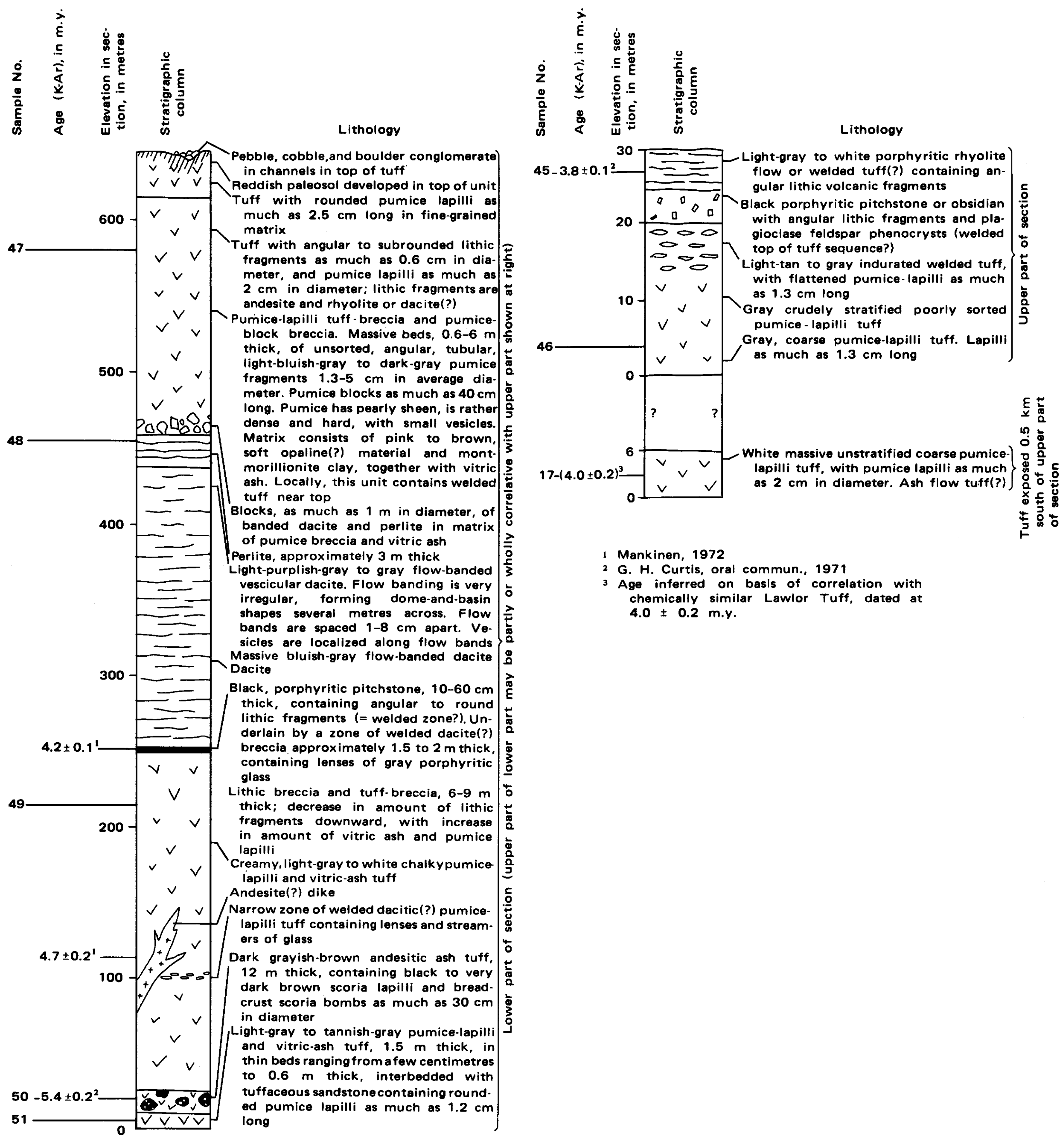


FIGURE 2.—Stratigraphic section exposed along Monticello Road, southeastern part of Sonoma volcanic field (locs. 17, 45–51).

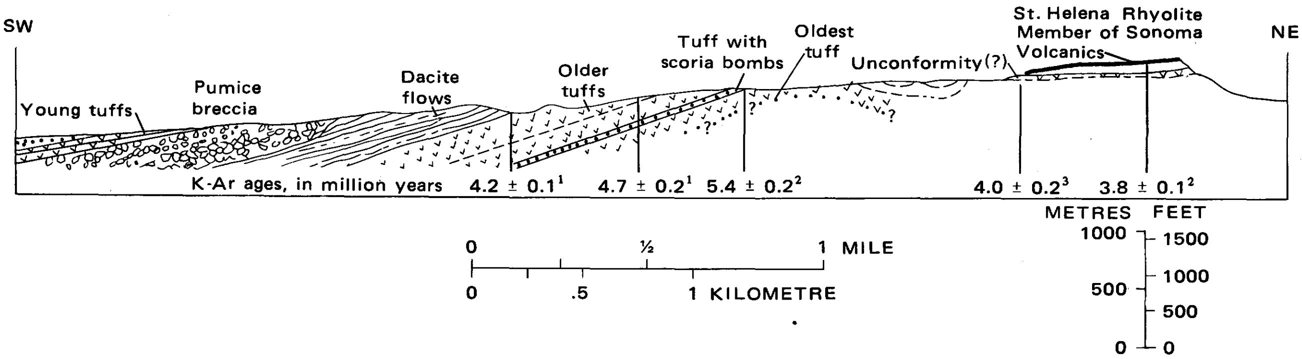


FIGURE 3.—Structure along a section roughly parallel to Monticello Road (sample locs. 17, 45–51), southeastern part of Sonoma volcanic field. Stratigraphic relations between monoclinal section in southwest and St. Helena Rhyolite Member of Sonoma Volcanics in northeast are not clear, but the St. Helena appears to be youngest unit in section.

of the field. However, a small area of tuff is exposed at Cobb Mountain and near Siegler Canyon in the Lower Lake quadrangle (Brice, 1953). At the Siegler Canyon locality, the tuff is a poorly vesiculated pumice breccia forming part of the late Pliocene Cache Formation of Anderson (1936).

SOUTHERN CASCADE RANGE VOLCANIC FIELD

The large volcanic field in the vicinity of Mount Lassen, northeast of Sacramento Valley (inset map, fig. 1), has been active throughout late Cenozoic time, from at least the late Pliocene to Holocene time (Macdonald, 1966). Tephra from some of the more explosive eruptions, such as the Nomlaki Tuff Member of the Tehama Formation, was deposited in northeastern and northwestern Great Valley (Russell, 1931; Anderson and Russell, 1939). Although the southern Cascade Range in the vicinity of Mount Lassen is approximately 320 km to the northeast of the main study area, it is a potential source area for some of the water-transported tuffs in the central Coast Ranges because this area has drained through the San Francisco Bay area since at least Pleistocene time (Hall, 1966; this study).

All tuff units examined in this study are listed in table 1. A more detailed discussion of the texture, stratigraphy, and structure of the tuffs and the stratigraphic sections is given in the description of units. Basic data on radiometric age determinations for this study are given in table 2.

ANALYTICAL METHODS

Samples of tuff were collected both laterally and vertically in a stratigraphic section wherever possible to test for random and systematic variations within each unit. Between 200 and 500 grams of sample were taken for physical and chemical analysis. In addition, larger samples, up to several kilograms, were taken at several localities for radiometric dating. Laboratory work consisted of five main operations: (1) physical description of the tuffs on the basis of microscopic examination, (2) measurement of the refractive indices of glass, (3) mafic-mineral analysis, (4) X-ray fluorescence spectrometric analysis for minor and trace elements, and (5) radiometric dating of the tuffs.

REFRACTIVE INDICES OF GLASS

The range of refractive indices for several samples of each tuff were measured under the petrographic microscope after the samples were treated with 8 percent hydrofluoric acid to remove altered and hydrated surfaces. The Becke line method, a D-line filter, and Cargille immersion liquids calibrated to 0.002 R.I. intervals were used in determinations, and the ranges of refractive indices were corrected for temperature variations. Precision attained for the average refractive index of glass in the sample was ±0.001.

MAFIC-MINERAL ANALYSIS

Samples were crushed and sieved, and the 120- to 60-mesh fraction (0.125 to 0.250 mm) was separated in a Frantz magnetic separator. The magnetic fraction was separated in bromoform, the heavy separate placed in optic oils, and mafic mineral frequencies were determined by line count under a petrographic microscope fitted with a mechanical stage.

X-RAY FLUORESCENCE SPECTROMETRIC ANALYSIS

Relative and absolute concentrations of trace- and minor-element concentrations in tuff samples were determined by means of a Norelco Universal Vacuum Spectrograph using the analytical procedures described by Jack and Carmichael (1968; see table 3). Samples were analyzed for iron, titanium, barium, manganese, zirconium, rubidium, strontium, zinc, yttrium, gallium, niobium, copper, and nickel. Two types of analyses were run: (1) rapid-scan analyses of acid-treated whole-rock samples, which indicate relative proportions of the rubidium-niobium group (rubidium, strontium, yttrium, niobium) on the basis of relative peak intensities (Jack and Carmichael, 1968) and (2) "absolute" analyses of glass separated from the whole-rock sample, which indicate concentrations of all elements listed above by comparison with analyzed standards. Powdered whole-rock samples for rapid scan were treated with 10 percent hydrochloric acid in order to remove strontium in carbonate form, a common groundwater contaminant (Sarna-Wojcicki, 1971).

Rapid-scan analyses can be useful in indicating the correlation between specific units. However, when considering a large number of units within a single petrographic province, such as those erupted from the Sonoma volcanic field, chemical similarities between units often result in overlap of data for sample groups from different tuff units. Variations in ground-water and detrital contamination and in concentrations of crystals and lithic fragments may cause a spread or scatter of the data, again resulting in apparently overlapping sample groups. In either case, the results make correlation on a fine scale difficult or impossible. In such situations a procedure that has better resolution than rapid scanning of whole-rock samples is necessary. For this reason, volcanic glass of selected samples was separated and scanned to see if the spread of data for individual units could be reduced.

Selected samples were crushed and sieved, and glass from the 120- to 60-mesh fraction (0.125 to 0.250 mm) was separated using the Frantz magnetic separator. The glass was treated with 10 percent hydrochloric acid, etched with 5 percent hydrofluoric acid, and cleaned in an ultrasonic vibrator to remove adhering fine particles.

The magnetic properties of some samples prevented complete separation of the salic minerals and altered-glass fragments from the clean glass. Some of these

TABLE 1.—*Units studied*

[See figure 1 for locations of samples]

Sample locality	Material	Unit	Geologic age	Radiometric age (K-Ar), in m.y.	References
1	Water-laid tuff	Merced Formation (type section)	Late Pliocene and early Pleistocene	1.49±0.75	Hall (1966).
2	do	Alameda Formation	do		do.
3, 4	do	Santa Clara Formation	Pliocene and Pleistocene		Dibblee (1966).
5	Ash-fall(?) tuff	Tassajara Formation	Pliocene or Pleistocene		Clark (1943).
6	Water-laid tuff	Ohlson Ranch Formation	Pliocene(?)		Bartow, (oral commun., 1972).
7	Ash-flow tuff	Unnamed formation	Pleistocene	0.25±1.1±0.5	Wilson (1961); Gilbert (1969).* Curtis (oral commun., 1971).*
8–11	do	Nomlaki Tuff Member of Tehama Formation.	Late Pliocene	3.3±0.4	Anderson and Russel (1939); Evernden, Savage, Curtis, and James (1964).*
12–15	Water-laid tuff	Putah Tuff Member of Tehama Formation.	do	3.28±0.10	Miller (1966)*; Sims and Sarna-Wojcicki (1974).
16	Ash-tuff	Sonoma Volcanics	do		Present study.
17	Ash-flow tuff	Sonoma Volcanics	do		Weaver (1949).
18	do	do	do		Do.
19–21	Ash-flow tuffs	do	do		Do.
22–28	do	Lawlor Tuff	do	3.96±0.16	Patten (1947); present study.*
29, 30	do	Tassajara Formation	Pliocene or Pleistocene	4.00±1.00	Clark, (1943); present study.*
31, 32	Water-laid tuff	Livermore Gravels of Clark (1930).	Late Pliocene	4.46±0.45	Huey, (1948); present study.*
33, 34	do	do	do		Do.
35–37	do	Merced(?) Formation	Early and late Pliocene	5.68±0.68	Travis (1952); present study.*
38–40	Various types of tuff.	do	do	6.0±0.1	Travis (1952); Bartow, Sarna-Wojcicki, Addicott, and Lajoie (1973).*
41, 42	Water-laid tuff	Petaluma Formation	Early or middle and late Pliocene		Bartow, Sarna-Wojcicki, Addicott and Lajoie (1973).
43	do	Tassajara Formation or Green Valley Formation.	Pliocene or Pleistocene		Clark (1943).
44	do	Unnamed tuff	Miocene or Pliocene	8.18±2.0	Curtis (oral commun., 1971).*
45–49	Tuff	Sonoma Volcanics	Middle or Upper Pliocene	[1]3.79±0.08	Weaver (1947); Curtis (oral commun., 1971)*
50, 51	Tuff with scoria bombs	do	do	[2]5.36±0.16	Do.
52, 52A–C	Tuff	Pinole Tuff	Middle Pliocene	[3]5.2±0.1	Weaver (1947); Evernden, Savage, Curtis, and James (1964).*
53, 54	Tuff with scoria bombs	do	do		Do.
55–62, 79	Tuff	do	do		Do.
63, 63A–C	do	Tassajara or Green Valley Formation of Clark (1943).	do		Do.
64	do	do	do		Do.
65, 66	do	Green Valley Formation of Clark (1943).	Pliocene		Do.
67	do	Tassajara Formation	Pliocene or Pleistocene		Do.
68	Vent breccia	Unnamed breccia	Pliocene(?)		Travis (1952).
69	Pumice at Napa Glass Mountain.	Sonoma Volcanics	Pliocene		Weaver (1949); Jack and Carmichael (1968).
70	Obsidian at Napa Glass Mountain.	do	do		Do.
71	Pumice breccia	Cache Formation of Anderson (1936)	Upper Pliocene		Brice (1953).
77	Ash-fall(?) tuff	Unnamed tuff	Pliocene(?)		Patten (1947).
78	Ash-flow(?) tuff	Sonoma Volcanics	Pliocene		Weaver (1947).

*Reference to radiometric age date.
[1]At top of unit.
[2]At base of unit.
[3]Near base of unit.

samples were separated in bromoform-alcohol mixtures, but the use of heavy liquids was generally avoided in order to avoid contamination with bromine, which affects the rubidium analyses in the X-ray fluorescence procedure.

The separated glass was then mixed with 20 percent by weight fibrous cellulose binder and pressed into 3.2-cm-diameter discs in a hydraulic press at pressures of about 2,500 kg/cm^2 (35,000 lb/in^2). The standards were similarly prepared in order to provide uniform surfaces for both sample and standard. Glass separates were then analyzed for "absolute" concentrations of other elements that cannot be easily analyzed by the rapid-scan technique: iron, titanium, barium, manganese, zinc, copper, nickel, and gallium, as well as the rubidium-niobium group. The position for each of these elements was calibrated with pure element standards (for example, RbCl for rubidium), and element concentrations were determined by fixed-time counts at fixed 2θ positions. Additional counts were made at adjoining 2θ positions to determine the shape and intensity of the background curve. U.S. Geological Survey standards used were G–1 and G–2 for all elements except for gallium, zinc, copper, and nickel, for which W–1 was used (Fleisher, 1969; Flanagan, 1969).

METHODS OF EVALUATING CHEMICAL DATA

Trace- and minor-element analyses were compared (1) graphically, utilizing binary and ternary diagrams and histograms, (2) by calculation of similarity coefficients, using a computer program to perform analyses of similarity, and (3) by cluster analysis, using a computer program to calculate Q-mode cluster analysis on distance function, and shown on a dendrogram.

GRAPHIC METHODS

Rapid-scan analyses of whole-rock samples for the three most abundant elements in the rubidium-niobium group (rubidium, strontium, and zirconium)

TABLE 2.—*Analytical data on potassium-argon dates*

[Age determinations were made at the potassium-argon laboratory of the Department of Geology and Geophysics, University of California, Berkeley. Spectrometric analyses by N. Gilbert. Potassium analyses by J. Hempel]

Sample loc.	Sample no.	Unit	Material	K (percent)	40 Ar atm. (percent)	Age (million years)
22	KA2310	Lawlor Tuff, Contra Costa Co.	Coarse plagioclase crystals (24–48 mesh)	0.7225	75.0	3.96±0.16
30	KA2319	Tuff in Tassajara Formation, south of Mount Diablo, Contra Costa Co.	Plagioclase crystals (60–120 mesh)	0.6060	96.0	4.00±1.00
31	KA2323	Lower tuff bed in Livermore Gravels of Clark (1930) south of Livermore, Alameda Co.	Plagioclase crystals (60–120 mesh)	0.6030	89.9	4.46±0.45
37	KA2321	Tuff in the Merced(?) Formation near Roblar, Sonoma Co.	Coarse plagioclase crystals (24–48 mesh)	0.7642	92.1	5.68±0.68

TABLE 3.—*Summary of X-ray fluorescence spectrometer analytical conditions*

[Standard value of iron in percent; all other values in ppm. Modified in part from Jack and Carmichael (1968)]

Element	Analytical line	Analyzing crystal	Exciting radiation (50 kilovolts)	Primary beam filter	Detector (with pulse-height discrimination)	Path	Standard (assumed value) weight percent or parts per million
Fe	K	LiF 200	W	--------	Scintillation	Air	G–2 (1.844)
Ti	K	LiF 200	W	--------	Flow-proportional	Vacuum	G–1 (1560); G–2 (2930)
Mn	K	LiF 200	W	--------	Scintillation	Air	G–1 (200); G–2 (280)
Ba	L	LiF 200	W	--------	Flow-proportional	Vacuum	G–1 (1040); G–2 (2030)
Ni	K	LiF 200	Mo	0.001″Ti	Scintillation	Air	W–1 (78)
Cu	K	LiF 200	Mo	0.001″Ti	do	do	W–1 (110)
Zn	K	LiF 200	Mo	0.001″Ti	do	do	W–1 (82)
Ga	K	LiF 200	Mo	0.001″Ti	do	do	W–1 (16)
Rb	K	LiF 220	W	--------	do	do	G–1 (220); G–2 (175)
Sr	K	LiF 220	W	--------	do	do	G–1 (250); G–2 (465)
Y	K	LiF 220	W	--------	do	do	G–1 (13); G–2 (10)
Zr	K	LiF 220	W	--------	do	do	G–1 (210); G–2 (320)
Nb	K	LiF 220	W	--------	do	do	G–1 (20); G–2 (16)

[1]Jack and Carmichael (1968).

were recalculated to mutual percentages and plotted on a ternary diagram. Analyses of absolute concentrations of trace and minor elements in the purified glass were plotted on histograms and on binary diagrams of one element plotted against another.

SIMILARITY COEFFICIENT

A coefficient that allows all analyzed variables for a pair of samples to be compared has been derived by Borchardt, Aruscavage, and Millard (1972). This similarity coefficient, which is 1 for identical analyses, is given by:

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

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 = X_iA/X_iB if $X_iB \geq X_iA$; otherwise X_iB/X_iA,
X_iA = concentration of element i in sample A, and
X_iB = concentration of element i in sample B.

The similarity coefficient is a simple and effective way of comparing any quantitative parameters for any group of samples, and the method is readily adapted to a simple computer program. The only disadvantage to this method involves comparison of a large number of samples. For 50 samples, 1,225 comparisons must be made; for 100, 4,950, and for 200, 19,900 since the number of comparisons increases exponentially with increase of the sample population. For large sample populations, provisions must be made to extract coefficients within a selected range.

Borchardt, Aruscavage, and Millard (1972) have also introduced weighting coefficients in order to minimize the effect of the least accurately determined elements on the similarity coefficients. In this study, weighting coefficients were not used. Instead, only those elements were used that were considered reliable, both with respect to the precision of the analysis and the natural variability of the elements within the volcanic glass. The reliability of any particular element was evaluated by multiple analyses of samples from a single, extensive tuff bed (locs. 22–28). Analyses were made on samples collected both laterally and vertically in the section in order to test the internal consistency of chemical and physical properties within a single depositional unit. Analyses for only those elements that showed a high degree of consistency (iron, titanium, barium, manganese, zirconium, rubidium, strontium, and zinc) were used in calculating similarity coefficients and the cluster analysis described in the next section. Comparisons of multiple analyses of a single unit indicated that copper, nickel, gallium, and, to a lesser extent, yttrium were not reliable for correlation purposes, mainly because these elements occur in low concentrations not much above the detection limit of the X-ray fluorescence method. Consequently, the precision for analyses of these elements was low and these elements were not included in the comparison procedure. In addition, strontium, though abundant, varies greatly owing to ground-water contamination, concentration in feldspar and mafic microlites and phenocrysts, and concentration in mafic and intermediate lithic volcanic fragments. However, strontium is important in distinguishing between tuffs derived from different volcanic fields, so analyses of similarity were run both with and without strontium.

CLUSTER ANALYSIS

In addition to calculation of similarity coefficients, the chemical data were also compared by means of Q-mode cluster analysis using a computer program by Parks (1970). According to Parks, the program "computes an R-mode principal components analysis (factor analysis with unities in the principal diagonal)* * *" using the simple distance function. Factor scores are then calculated, forming a set of "new orthogonal (uncorrelated) variables."[1] The formula used for the simple distance function for R-mode analysis is

$$d_{1,2}=1.0-\left[\sum_{i=1}^{N}(X_{1i}-X_{2i})^2/N\right]^{1/2}.$$

Using the new orthogonal variables, the program "computes a Q-mode similarity matrix, comparing each sample with all other samples across all variables," using the distance function as similarity coefficient. The formula for distance function for Q-mode analysis is

$$d_{1,2}=\left[\sum_{i=1}^{M}(X_{i1}-X_{i2})^2/M\right]^{1/2}.$$

The Q-mode similarity matrix now contains the euclidian distance between all possible pairs of samples measured in a space with dimensionality equivalent to the number of factors found in the R-mode principal components analysis. This matrix is then searched for the two samples with the least distance between them, which are then combined to form a cluster and the measurements of the pair averaged. All distances be-

[1]Some of the elements analyzed in this study, for instance, iron and manganese, are not independent variables but, on the contrary, show a high degree of correlation for certain sample groups (see fig. 7).

tween either member of the pair and other samples are recalculated using the newly averaged measurements of the cluster. The process is repeated until all the samples are grouped into a number of clusters of progressively greater distance (higher values of the distance function). The program plots all the groups on a dendrogram that shows the relations of all individual samples and all groups of samples to each other, with respect to the distance function.

The advantage of this method is that several orders of chemical variability and relations between samples are readily apparent in a two-dimensional format. Since the outcome of the clustering procedure is influenced by the composition of every sample present in the sample group, the actual values of the distance function and the resulting clusters formed are affected by the range of compositional types included in the comparison. Inclusion of particularly unusual composional varieties in the cluster analysis results in tighter clustering (smaller values of the distance function) for samples of similar composition, while exclusion of such unusual varieties results in a greater spread (higher values of the distance function) between the remaining samples. Inclusion or exclusion of the unusual compositional varieties serves as a device with which to focus on compositional variations between sample groups of particular interest.

RESULTS OF ANALYSES

Before individual tuff units can be correlated by means of trace- and minor-element chemistry, the variability within and between individual eruptive units[2] and within and between individual volcanic fields must be established. Greatest differences in trace- and minor-element chemistry were observed between silicic tuffs on the one hand and intermediate pumice-lapilli tuffs on the other. These differences are illustrated by the two analyses shown in table 4. The group average similarity coefficients between silicic and intermediate tuff groups range between 0.42 and 0.61, with an overall average of 0.51, the lowest average coefficient for all sample groups considered (fig. 4). Large differences between the silicic and intermediate tephra are also indicated by the dendrogram derived from cluster analysis (fig. 5). Silicic and intermediate samples are grouped at highest values of the distance function (0.25–0.48).

Among silicic tuffs, greatest differences are observed between tuffs derived from different volcanic fields. Tuffs that are definitely known to have been erupted in

[2]An eruptive unit is defined here as a collection of all those outcrops that, on the basis of several criteria, primarily trace- and minor-element chemistry of the volcanic glass but also petrographic characteristics, radiometric age, stratigraphic position, fossil data, and other pertinent information, are considered to be products of a single eruption or of multiple eruptions closely spaced in time.

TABLE 4.—Comparison of glass compositions of a silicic and an intermediate tuff

[Concentrations of iron and silica, in percent; all other concentrations in parts million]

	SiO_2	$FeO+Fe_2O_3$	Ti	Ba	Mn	Zr	Rb
Sample 50[1]	62.70	6.86	7362	423	1596	207	54
Sample 37[2]	71.43	1.62	803	698	237	247	181

[1]Intermediate tuff with scoria bombs.
[2]Silicic tuff.

the southern Cascade Range, such as the Nomlaki Tuff Member of the Tehama Formation (Anderson and Russell, 1939; Lydon, 1967) and a pumiceous tuff near Mineral (Wilson, 1961; Gilbert, 1969), have higher concentrations of strontium and lower concentrations of iron, zirconium, zinc, and yttrium than tuffs erupted in the Sonoma volcanic field (table 5). The samples of pumice tuff near Mineral (fig. 1, loc. 7) and the Nomlaki Tuff Member (fig. 1, locs. 8–11) have low similarity coefficients when compared with silicic tuffs erupted from the Sonoma volcanic field (fig. 4). Group average similarity coefficients comparing tuffs from the southern Cascade Range and the Sonoma volcanic field range from 0.48 to 0.64, with an overall average of 0.60. Tuffs from different volcanic provinces have distance function values of between 0.135 and 0.210 (fig. 5). Differences between tuffs derived from the Sonoma volcanic field, those from the southern Cascade Range, and those of inferred southern Cascade Range provenance are graphically illustrated in figures 6 and 7.

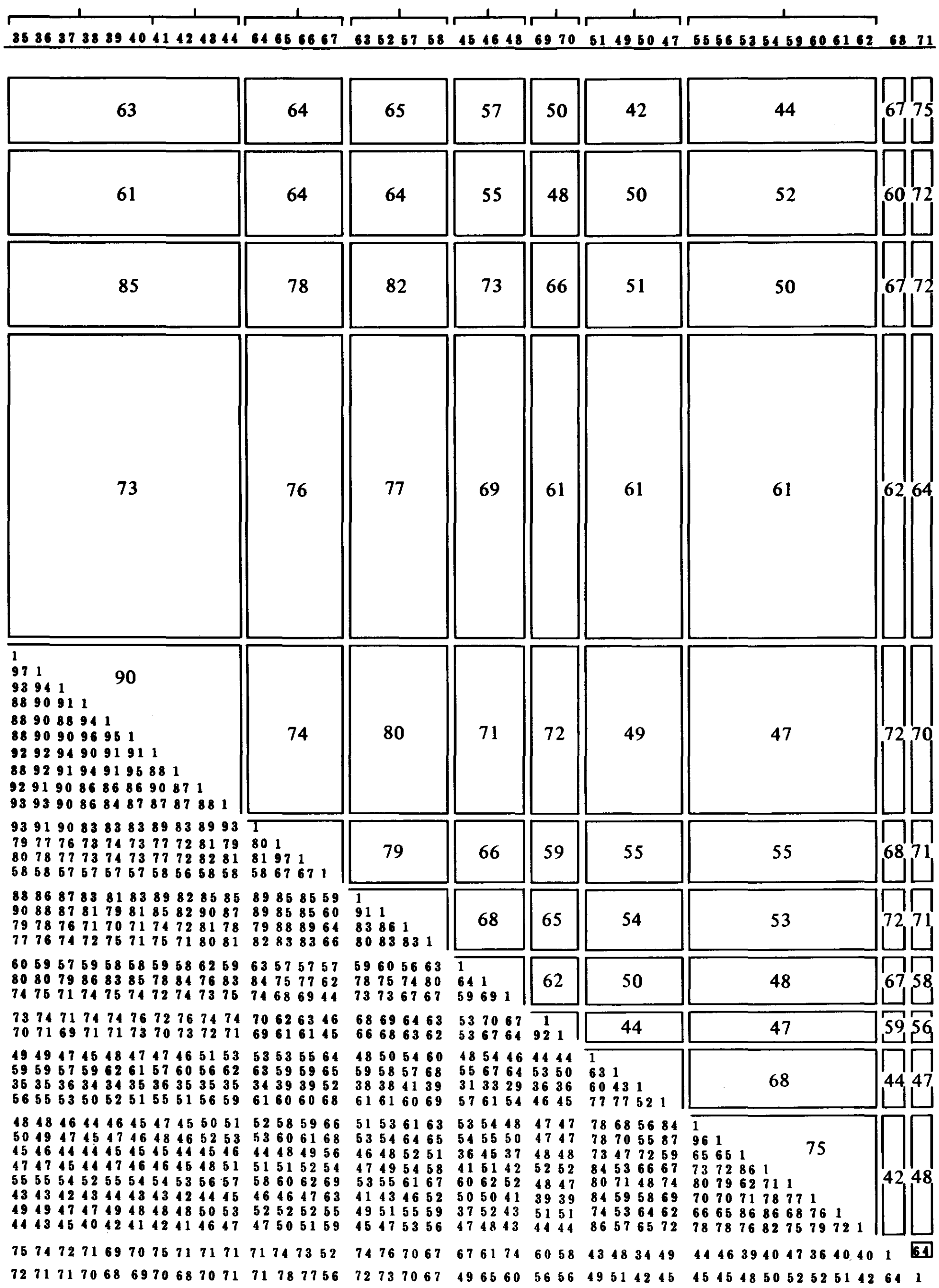
Silicic tuffs of different ages that are known to have been erupted from the same volcanic field show smaller compositional differences than those erupted from different volcanic fields. Age and source criteria independent of chemical analyses are available to test the validity of this assertion. Relative and absolute ages of many of the units studied are known from stratigraphic position and radiometric dates. With respect to source, it is possible to identify those tuffs that were erupted, for example, from the Sonoma volcanic field by several criteria. First, coarse tuffs, tuff-breccias, and agglomerates are interbedded with flow rocks in the Sonoma volcanic field itself, indicating proximity of the tuffs to vents. For instance, north of Suisun Bay (fig. 1, locs. 19–21) pumice bombs as much as 30 cm in diameter were found in coarse ash flow tuffs. Second, in outlying areas beyond the Sonoma volcanic field, the source of the more widespread silicic tuffs is indicated by coarseness of the tuffs and by size gradients that increase towards the Sonoma volcanic field. Independent confirmation of the source of these tuffs is obtained from the trace- and minor-element analyses of the volcanic glass. Most analyses of tuffs in the central Coast Ranges show strong chemical similarities between tuffs of the Sonoma volcanic field and those of the out-

		Sample Loc.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Widespread silicic tuffs erupted in southern Cascade Range	Tuffs in central Coast Ranges derived from southern Cascade Range	1	1																																	
		2	93	1																																
		3	85	81	1			86																												
		4	85	83	97	1					75					66														57								
		5	81	78	87	85	1																													
		6	76	73	84	83	80	1																												
		7	67	64	75	74	66	81	1																											
	Nomlaki Tuff Member of Tehama Formation	8	80	78	76	77	75	72	65	1		82																								
		9	81	83	76	77	75	72	64	93	1					63														63								
		10	81	79	80	81	78	76	69	92	93	1																								
		11	82	83	74	75	73	71	65	91	94	90	1																							
Widespread silicic tuffs erupted in central Coast Ranges	Putah Tuff Member of Tehama Formation (12–15) and correlative tuff (16)	12	54	61	63	63	66	61	54	62	67	66	65	1																						
		13	58	59	64	65	68	64	56	60	65	66	64	91	1		90																			
		14	58	60	65	67	67	65	55	60	65	66	64	89	95	1												78									
		15	65	68	69	71	72	66	54	66	71	71	70	83	86	89	1																			
		16	60	59	64	66	68	64	54	59	64	64	63	88	93	96	88	1																		
	Lawlor Tuff correlatives in Sonoma volcanic field	17	61	63	61	61	62	61	54	60	65	66	64	82	82	82	82	82	1																	
		18	63	63	61	61	61	58	53	63	67	67	66	78	78	77	82	77	91	1																
		19	62	62	58	58	62	58	51	63	66	66	65	80	78	77	81	77	93	91	1															
		20	63	63	56	58	62	58	50	64	68	65	67	81	78	78	81	78	93	90	96	1														
		21	66	66	58	57	60	55	50	64	68	65	69	77	74	73	79	73	88	92	93	93	1													
	Lawlor Tuff	22	63	63	59	59	62	58	52	63	67	67	66	81	80	78	81	78	91	93	96	94	92	1					93							
		23	63	63	58	58	61	57	52	63	68	66	65	82	80	71	80	79	93	91	95	94	92	96	1											
		24	60	61	59	59	59	58	53	61	65	65	64	80	81	80	79	81	94	93	93	91	90	95	96	1										
		25	62	62	58	58	61	57	51	63	66	65	65	79	77	76	80	76	91	92	96	92	92	95	96	92	1									
		26	63	64	59	59	63	58	51	64	67	67	66	80	77	77	82	77	91	91	97	96	94	95	95	91	96	1								
		27	63	63	59	59	61	57	52	63	67	67	66	80	78	78	79	78	94	91	97	95	94	95	96	94	94	96	1							
		28	62	62	59	59	60	57	52	63	66	66	65	79	79	77	80	77	92	93	97	95	92	97	95	96	95	96	96	1						
		29	65	65	60	60	63	58	50	66	69	67	68	77	74	73	81	74	89	91	93	92	93	91	91	89	93	93	92	92	1					
	Lawlor Tuff correlatives south of Mount Diablo	30	62	62	58	58	61	57	51	63	66	66	65	80	78	78	80	78	93	91	96	94	91	95	94	95	96	95	97	95	92	1				
		31	64	64	61	61	63	59	53	63	68	68	67	80	78	77	83	77	92	94	95	92	94	95	94	94	95	94	94	95	94	94	1			
		32	63	63	59	58	61	56	52	63	68	66	66	80	78	76	80	76	90	94	95	93	93	97	96	94	95	95	95	96	92	94	95	1		
		33	62	62	59	59	60	55	51	64	65	65	64	74	73	72	78	72	87	94	91	87	90	91	89	89	93	90	90	92	91	91	93	92	1	
		34	64	64	61	60	62	56	52	66	67	67	65	76	75	73	79	73	85	92	89	86	88	91	89	88	91	90	89	91	88	89	92	92	96	1
	Tuff in Merced (?) Formation of Sonoma County	35	55	57	62	64	66	64	57	59	63	63	63	82	90	91	82	90	77	75	72	72	68	75	74	77	71	71	72	74	68	72	72	74	71	70
		36	53	56	61	61	64	63	55	58	62	62	62	83	90	90	80	90	76	74	72	72	68	74	74	76	71	71	72	73	68	72	72	73	70	70
		37	56	58	63	64	66	64	57	60	64	64	64	81	90	89	80	88	75	72	71	72	68	74	73	76	70	70	71	73	67	71	71	72	67	68
		38	54	56	62	64	67	64	57	59	64	64	63	87	89	86	77	86	74	69	70	70	66	71	72	72	68	69	70	70	64	70	70	69	65	66
		39	55	57	63	62	67	62	55	63	68	66	69	87	87	84	75	83	76	73	71	71	68	74	73	75	70	71	71	73	67	71	71	72	68	69
		40	52	55	61	62	65	63	56	58	62	62	62	86	87	84	75	84	74	71	70	70	67	73	72	74	69	69	70	71	66	70	70	71	67	68
	Southern correlatives of tuff in the Merced(?) Formation	41	56	59	64	64	69	66	58	61	66	66	65	80	86	85	78	85	76	73	71	72	68	74	74	76	70	71	72	73	67	72	71	73	68	69
		42	52	54	60	61	63	62	52	57	62	62	61	84	87	85	76	84	74	71	70	70	67	72	72	74	69	69	70	71	66	70	70	70	66	68
		43	55	58	63	64	67	63	55	59	63	63	63	78	84	86	85	85	76	76	75	74	71	77	73	75	74	74	73	75	70	73	74	76	72	72
		44	53	55	61	62	62	62	55	56	61	61	60	87	90	90	82	90	80	78	76	76	72	78	78	81	75	75	76	77	71	76	76	77	74	74
	Uncorrelated tuffs of central Coast Range provenance south of Mount Diablo	64	56	58	65	64	66	63	55	58	63	63	62	84	90	92	84	91	83	78	78	78	73	80	79	83	77	77	78	79	73	78	78	78	76	75
		65	70	65	71	70	75	66	57	69	71	72	70	80	80	79	84	76	74	77	74	75	75	76	74	73	74	75	73	74	75	73	77	76	76	76
		66	69	67	70	70	74	65	56	70	72	72	71	81	81	80	85	77	75	77	74	75	76	76	74	73	74	75	73	74	75	73	77	77	76	78
		67	58	58	54	53	56	49	48	64	64	62	64	63	62	61	68	62	70	74	74	74	76	73	74	70	77	75	73	73	80	76	76	74	77	78
	Silicic Pinole tuffs (52, 57, 58) and correlative tuff (63)	63	60	63	66	67	71	65	56	64	70	70	69	81	87	86	82	83	76	73	73	73	68	75	75	76	72	72	73	74	68	73	72	74	71	70
		52	59	61	66	68	68	64	55	62	67	67	66	80	85	87	87	84	78	77	75	76	71	78	75	77	74	74	75	77	71	75	75	76	73	73
		57	66	67	62	64	66	59	50	63	67	65	68	77	78	80	87	78	74	77	73	74	77	76	73	73	74	74	72	74	74	72	76	76	74	74
		58	63	65	63	62	65	59	54	62	67	67	66	82	80	78	84	79	85	86	85	85	85	87	84	83	84	87	86	86	83	83	85	87	85	83
Silicic tuffs and flows of Sonoma volcanic field	Silicic tuffs exposed along Monticello Road	45	46	46	55	55	59	55	46	50	52	54	49	59	62	62	65	64	68	66	69	68	66	66	65	65	68	69	67	67	69	67	68	66	65	63
		46	56	57	58	59	65	58	51	59	63	61	62	91	89	86	79	87	82	75	80	83	79	79	80	79	77	80	80	79	76	78	78	78	73	73
		48	47	49	55	56	55	55	50	54	58	57	57	72	70	71	64	69	64	63	62	62	60	63	62	65	61	62	62	63	58	61	61	62	61	60
	Napa Glass Mountain	69	40	42	48	49	54	50	48	46	50	50	50	68	69	68	63	59	64	64	61	61	59	62	63	64	60	61	61	62	58	61	62	62	61	61
		70	39	41	47	48	53	49	43	46	49	49	49	65	66	66	61	67	63	63	61	60	58	61	61	63	60	59	60	60	58	60	62	62	60	60
Heterogeneous tephra of intermediate composition of Pinole Tuff and Sonoma volcanic field (Monticello Road section)	Intermediate tuffs exposed along Monticello Road	51	54	57	46	47	42	43	43	58	57	57	59	52	50	49	51	49	59	63	62	62	65	61	61	61	63	62	62	62	64	62	62	63	67	66
		49	51	50	47	47	47	47	44	54	54	54	53	68	64	62	60	61	69	72	73	71	71	72	72	72	74	72	73	73	71	73	71	73	76	74
		50	38	40	32	33	31	36	35	44	44	43	44	35	37	34	35	33	37	41	39	38	40	39	39	39	40	38	38	39	40	39	40	40	43	43
		47	50	50	46	45	44	40	43	55	54	52	55	59	51	51	57	57	68	67	70	70	70	69	71	70	70	69	71	70	68	71	67	70	71	68
	Intermediate Pinole tuffs	55	54	57	47	46	45	39	39	53	53	51	54	52	50	49	54	49	60	64	64	63	68	63	62	61	65	64	63	63	66	63	64	64	69	69
		56	55	55	47	47	46	40	39	55	54	52	55	53	51	50	56	50	61	65	65	64	69	64	63	62	66	65	64	64	68	64	66	66	70	70
		53	45	48	38	39	37	40	45	51	51	49	51	46	46	44	45	44	51	55	53	51	54	53	53	53	54	52	52	53	52	53	54	55	57	57
		54	50	53	42	43	40	44	42	57	56	54	57	51	48	47	49	48	57	61	60	59	61	60	60	60	61	60	60	60	60	60	61	62	65	64
		59	62	65	55	54	53	47	45	61	61	59	62	60	58	56	60	56	68	73	73	72	76	72	71	71	74	72	72	73	75	72	73	73	77	77
		60	58	61	48	49	46	45	42	60	60	57	60	48	46	46	51	47	57	57	59	59	61	57	57	56	60	60	59	58	63	59	59	58	61	61
		61	49	52	42	42	39	43	48	56	55	53	56	53	51	49	51	50	55	60	58	57	59	60	59	58	59	59	58	59	58	58	59	60	63	64
		62	50	52	44	44	41	37	38	49	49	48	50	46	44	44	47	44	53	57	56	55	59	55	54	54	57	56	56	56	58	55	56	56	60	60
	Volcanic vent, Sonoma County	68	56	52	66	66	70	66	58	60	60	64	57	61	67	68	69	68	62	66	62	61	60	64	61	62	63	62	60	64	59	60	63	64	62	62
	Tuff-breccia, Cache Formation of Anderson (1936), Clear Lake area	71	71	69	74	74	73	78	65	72	74	75	72	70	72	73	75	71	66	66	62	62	62	64	64	64	63	63	63	63	64	63	65	64	63	65

FIGURE 4.—Similarity coefficient matrix. Similarity coefficients are calculated for each sample pair in study group. Individual values of similarity coefficients are given in lower left half of matrix, while average values for main sample groups are given in symmetric positions across the identity diagonal in upper right half of matrix. Calculations were made by comparison of following eight elements: Fe, Ti, Ba, Mn, Zr, Sr, Rb and Zn. No iron analyses were available for samples 1 and 2; consequently these samples were compared with other samples using remaining seven elements. Values of similarity coefficient are given in hundredths, with decimal point omitted.

lying areas, including specific correlatives (fig. 1, locs. 17–34, 47, and 55). Similarity coefficients for silicic tuffs erupted in the Sonoma volcanic field range from 0.66 to 0.85, with an average of 0.75, and values of the distance function are between 0.05 and 0.135.

Smaller differences in chemical composition of volcanic glass are observed between samples of the same tuff unit. The similarity coefficient for seven samples of



the Lawlor Tuff, for example, range from 0.91 to 0.97 with an average of 0.95. Values of the distance function for samples within the Lawlor Tuff range between 0.015 and 0.050. Values of the distance function for duplicate analyses of single samples and on replicate analyses of samples from single exposures are in the lower part of this range (for example, locs. 3 and 4, 33 and 34, 65 and 66, fig. 1).

Graphic analysis of the chemical data was usually sufficient to distinguish between most eruptive units because variations in chemical composition within units were considerably smaller than variations between units. However, in a few instances, for example, the Putah Tuff Member of the Tehama Formation and the tuff in the Merced(?) Formation of Sonoma County, differences between tuffs erupted from a single volcanic province were rather subtle and could be resolved only by statistical comparison of analyses.

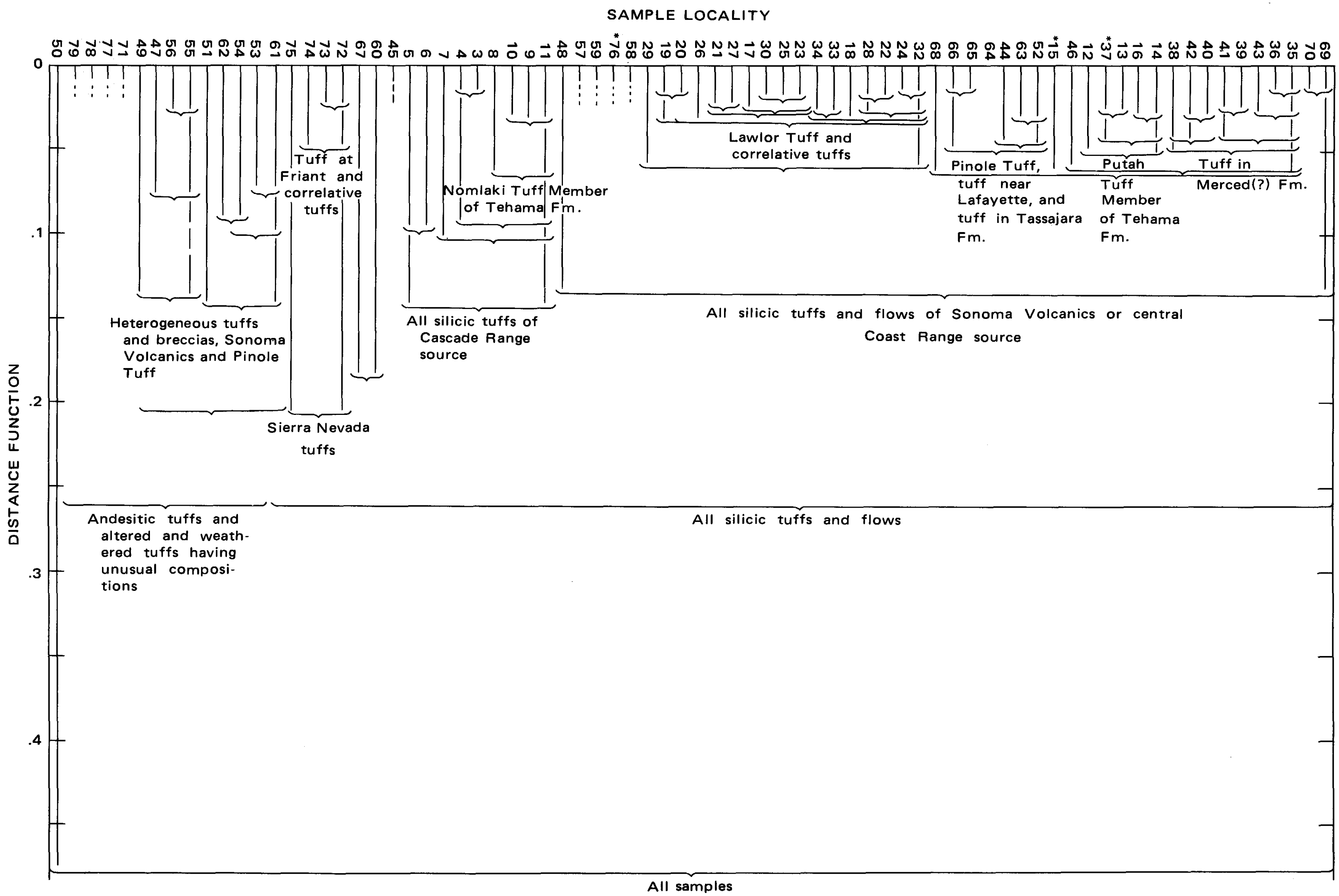


FIGURE 5.—Dendrogram from printout of cluster analysis program. Samples are grouped against distance function for 79 samples analyzed for Fe, Ti, Ba, Mn, Zr, Rb, Sr and Zn. Five samples from the Sierra Nevada (72–76) have been included for comparison but are not part of present study. Starred (*) samples are probably misgrouped because of high variability of some of eight elements analyzed (fig.17). Sample 15 is a weathered sample from Putah Tuff Member of Tehama Formation; sample 37 is from a tuff in Merced(?) Formation of Sonoma Co.; sample 76 is Holocene surface pumice from Red's Meadow in south-central Sierra Nevada.

TABLE 5.—*Chemical analyses and petrographic data*

[Sample numbers are same as locality numbers shown in figure 1. ND, not determined. Concentration of iron in precent; all other concentrations in parts per million. P, mineral present but not abundant]

Sample No.	Concentrations of minor and trace elements in volcanic glass													Main refractive Index of glass	Principal mafic mineral frequencies (percent)				Rock type
	Fe	Ti	Ba	Mn	Zr	Rb	Sr	Zn	Y	Ga	Nb	Cu	Ni		Gr. hblde	Br. hblde	Hypersth.	Augite	
Fine-grained tuffs in Coast Ranges derived from the southern Cascade Range																			
1	ND	1,628	1,166	395	107	125	130	26	ND	13	4	35	7	1.499±0.001	[1]72	[1]0	[1]28	[1]0	Tuff
2	ND	1,867	1,130	377	111	120	131	34	ND	12	9	21	40	1.499±0.001	80	0	20	0	Do.
3	.71	1,010	1,061	281	102	115	113	25	9	13	13	39	13	ND	77	0	21	2	Do.
4	.71	1,014	1,045	260	105	123	131	27	9	12	12	15	7	ND	ND	ND	ND	ND	Do.
5	.82	1,205	1,132	287	125	199	106	25	12	13	7	22	11	1.499±0.001	90	2	0	8	Do.
6	.62	918	948	305	109	166	201	23	15	8	36	15	15	ND	96	0	3	1	Do.
Ash-flow tuffs near Mount Lassen and northern Great Valley, erupted from the southern Cascade Range (Nomlaki Tuff, 8–11)																			
7	.61	885	790	327	104	79	414	18	9	14	33	6	1	1.496–1.500±0.001	[1]48	[1]0	[1]52	[1]0	Tuff.
8	.90	1,372	1,052	518	169	102	177	28	9	12	30	9	10	1.500–1.501±0.001	24	0	68	8	Do.
9	.94	1,332	1,055	419	182	107	169	33	12	14	35	43	12	1.501±0.001	15	13	60	13	Do.
10	.87	1,168	965	387	181	103	162	28	14	13	4	10	7	1.501±0.001	26	8	55	10	Do.
11	1.08	1,453	1,003	420	161	99	168	32	9	13	20	11	12	1.501–1.502±0.001	30	6	51	13	Do.
Tuffs erupted in the Sonoma volcanic field, or of inferred Sonoma volcanic provenance, central Coast Ranges (Putah Tuff Member, 12–15, and correlative, 16)																			
12	1.36	1,251	814	278	276	153	27	45	28	13	3	14	15	1.503±0.001	0	3	91	6	Tuff.
13	1.34	1,088	794	262	256	174	35	43	27	13	14	20	14	1.502±0.001	0	3	93	4	Do.
14	1.39	1,018	838	244	261	170	37	39	21	14	0	15	9	1.501±0.001	0	1	93	6	Do.
15	1.40	1,131	981	244	263	158	68	37	24	13	0	12	8	1.503±0.001	0	1	98	1	Do.
16	1.44	1,006	875	247	274	186	38	41	17	16	7	17	10	1.502–1.503±0.001	1	4	85	10	Do.
Tuff erupted in the Sonoma volcanic field, or of inferred Sonoma volcanic provenance, central Coast Ranges (Lawlor Tuff, 22–28, and correlative tuffs, 17–21, 29–34)																			
17	1.62	1,074	836	366	312	154	51	60	47	17	24	27	15	1.506±0.001	ND	ND	ND	ND	Tuff.
18	1.60	1,064	711	441	301	140	64	60	34	15	13	0	10	ND	0	98	2	0	Do.
19	1.73	1,174	817	459	326	154	59	58	26	19	18	12	11	1.504±0.001	ND	ND	ND	ND	Do.
20	1.62	1,283	840	448	336	157	56	57	24	18	20	5	10	1.505±0.001	[2]0	[2]11	[2]78	[2]11	Do
															[3]0	[3]50	[3]47	[3]3	
21	1.75	1,473	801	436	339	143	68	59	27	18	15	9	11	1.508; 1.512±0.001	ND	ND	ND	ND	Do.
22	1.72	1,174	758	433	301	148	58	54	26	16	25	8	9	ND	ND	ND	ND	ND	Do.
23	1.72	1,211	812	440	297	145	50	57	24	17	13	9	10	1.505±0.001	3	64	4	29	Do.
24	1.68	1,048	755	428	303	147	48	59	25	17	15	14	11	1.505±0.001	0	52	8	40	Do.
25	1.81	1,180	796	470	304	149	62	63	25	20	16	16	12	1.505±0.001	ND	ND	ND	ND	Do.
26	1.78	1,203	845	447	326	152	62	56	25	17	23	2	9	1.505±0.001	7	49	6	39	Do.
27	1.73	1,173	830	437	329	143	54	59	18	18	18	7	15	ND	ND	ND	ND	ND	Do.
28	1.72	1,129	768	454	319	146	57	56	18	17	15	4	8	ND	0	73	6	21	Do.
29	1.68	1,258	913	456	313	144	71	67	32	22	3	18	11	[4]1.504; 1.506±0.001	28	22	0	50	Do.
30	1.83	1,183	849	449	304	148	53	61	24	17	14	4	10	[4]1.500; 1.506±0.001	[5]0	[5]35	[5]27	[5]38	Do.
															[3]4	[3]59	[3]21	[3]16	Do.
31	1.70	1,134	809	422	305	148	71	59	29	17	14	9	12	[4]1.503; 1.505±0.001	0	23	56	21	Do.
32	1.75	1,213	733	431	297	143	60	58	25	17	16	11	13	[4]1.499; 1.505±0.001	0	39	29	32	Do.
33	1.82	1,136	684	502	306	135	74	60	23	14	21	13	11	1.505±.001 (33–34)	0	23	52	24	Do.
34	1.82	1,137	718	517	290	137	82	56	24	13	9	8	8						
Tuffs erupted in the Sonoma volcanic field, or of inferred Sonoma volcanic provenance, central Coast Ranges (tuff in the Merced(?) Formation of Sonoma County, 35–40, and correlatives, 41–44)																			
35	1.18	876	686	237	247	181	41	40	24	17	17	11	12	1.498; 1.501±0.001	2	96	1	0	Tuff.
36	1.18	803	698	233	242	176	39	43	21	19	7	11	14	1.498; 1.501±0.001	ND	ND	ND	ND	Do.
37	1.21	710	759	250	216	174	40	40	19	15	3	13	12	1.502±0.001	[6]0 [7]1 [5]0	[6]1 [7]12 [5]29	[6]70 [7]57 [5]30	[6]29 [7]66 [5]13	Do.
38	1.13	766	817	259	225	190	28	44	28	18	9	43	20	ND	ND	ND	ND	ND	Do.
39	1.09	750	751	310	249	179	27	44	24	19	4	11	8	ND	ND	ND	ND	ND	Do.
40	1.11	755	755	285	228	183	27	48	28	18	9	6	6	ND	ND	ND	ND	ND	Do.
41	1.07	729	724	278	221	181	44	41	23	15	17	34	13	ND	[5]1	[5]3	[5]36	[5]60	Do.
42	1.16	775	767	215	219	177	29	48	29	14	9	23	10	ND	[8]0	[8]1	[8]95	[8]4	Do.
43	1.16	738	667	240	261	179	59	39	20	14	10	1	11	1.503±0.001	10	11	36	43	Do.
44	1.27	857	654	250	279	163	39	46	41	18	8	15	14	1.501; 1.503±0.001	7	17	57	18	Do.
Tuffs and flows of the Sonoma Volcanics, Monticello Road section																			
45	0.58	1,105	897	26	402	214	64	75	46	17	51	30	12	ND	[9]P	0	0	0	Welded tuff(?).
46	1.36	1,348	817	266	333	190	29	51	35	14	46	15	17	ND	[9]0	0	0	0	Tuff.
47	2.70	1,369	585	751	447	94	50	107	24	25	79	16	16	1.515±0.001	[9]P	P	P	0	Pumice breccia.
48	1.05	818	625	97	418	152	22	33	24	22	73	18	6	1.507±0.001	[9]P	0	0	0	Dacite flow.
49	2.08	1,178	694	576	530	132	20	113	46	23	49	23	10	1.513±0.001	[9]P	0	0	P	Tuff.
50	5.12	7,362	423	1,596	207	54	208	114	22	22	33	34	14	1.565±0.005	[9]1	0	3	96	Do.
51	2.78	3,299	657	784	342	93	151	88	31	24	42	26	18	1.511±0.001	[9,10]3	3	86	7	Do.

In summary, graphic and statistical evaluation of the chemical data indicates that four orders of variability exist in trace- and minor-element compositions of volcanic glass. The greatest variability exists between

TABLE 5.—*Chemical analyses and petrographic data*—Continued

Sample No.	Concentrations of minor and trace elements in volcanic glass													Main refractive Index of glass	Principal mafic mineral frequencies (percent)				Rock type
	Fe	Ti	Ba	Mn	Zr	Rb	Sr	Zn	Y	Ga	Nb	Cu	Ni		Gr. hblde	Br. hblde	Hypersth.	Augite	
Tuffs erupted in the Sonoma volcanic field or of inferred Sonoma volcanic provenance, central Coast Ranges (tuffs of the Pinole Tuff and correlative sample, 63)																			
52	1.20	1,014	584	236	230	160	55	37	26	16	17	9	11	1.501±0.001	[11]7	77	12	4	Tuff.
53	3.48	4,596	444	855	238	69	262	60	30	16	14	5	4	1.533±0.001	[11]0	4	34	62	Agglomerate tuff.
54	3.15	3,935	435	781	307	90	191	58	26	16	21	9	15	[3]1.509; 1.513; 1.528±0.001	[11]0	0	31	70	Tuff.
55	2.70	1,798	413	814	444	107	87	95	61	22	20	17	17	1.509±0.001	0	77	0	23	Do.
															1	48	6	46	
56	2.74	1,621	470	826	456	104	84	97	65	20	21	3	8	1.501±0.001	0	25	15	60	Do.
57	1.47	1,615	529	232	244	151	69	33	16	17	12	5	5	1.501±0.001	0	16	73	11	Do.
58	1.50	1,206	587	330	328	136	64	44	19	18	7	11	11	1.502±0.001	ND	ND	ND	ND	Do.
59	2.30	2,308	743	616	405	108	107	70	54	18	17	8	3	1.506±0.001	[10,12]0	P	0	P	Do.
60	2.99	4,663	1,135	643	381	87	156	83	25	17	23	10	8	1.509±0.001	[10]0	0	P	P	Do.
61	2.82	4,890	439	598	272	82	266	49	16	15	15	10	8	ND	[13]0	0	3	97	Do.
															0	5	30	64	
62	3.63	3,624	498	983	371	88	118	89	20	20	14	9	15	[3]1.509; 1.512; 1.517±0.001	0	0	46	55	Do.
63	1.12	1,146	582	267	218	171	44	34	28	13	14	22	12	ND	4	7	6	83	Do.
															[14]0	[14]5	[14]8	[14]87	
															[15]7	[15]9	[15]5	[15]79	
Uncorrelated tuffs of the Tassajara area, south of Mount Diablo																			
64	1.25	989	686	250	306	172	44	40	32	16	23	6	10	[3]1.501; 1.502±0.001	1	21	22	57	Do.
65[16]	1.28	1,316	601	276	247	152	78	26	15	14	8	4	7	1.501±0.001	0	0	2	98	Do.
66[17]	1.30	1,355	622	270	251	154	82	29	14	15	4	6	13		ND	ND	ND	ND	Do.
67	1.95	1,360	908	498	235	40	79	90	26	17	17	7	8	1.501±0.001	1	32	36	32	Do.
Vent tuff-breccia, 68; associated pumice and obsidian of Napa Glass Mountain, Sonoma County, 69, 70																			
68	0.75	851	651	79	221	192	64	26	22	15	10	18	9	ND	ND	ND	ND	ND	Vent breccia.
69	1.08	555	447	202	283	199	11	57	30	16	26	8	12	ND	[18]0	0	P	0	Pumice.
70	1.08	555	443	211	291	207	6	59	34	16	24	9	14	ND	[18]0	0	P	0	Obsidian.
Tuff in the Cache Formation of the Clear Lake area, north-central Coast Ranges																			
71	1.28	919	1,368	269	235	138	209	50	23	15	4	11	8	1.503±0.001	0	0	P	0	Tuff-breccia.
Altered and chemically contaminated tuff south of Suisun Bay																			
77	1.07	831	808	844	189	148	109	37	14	16	10	18	17						
Hydrothermally altered tuff in the Sonoma Volcanics north of St. Helena																			
78	0.21	5,400	682	20	526	142	57	3	35	8	44	12	8						
Tuffaceous lake clays in the Pinole Tuff																			
79	1.97	1,167	1,375	1,037	166	83	54	124	14	15	8	11	8						

[1]Data from Hall (1965).
[2]48–120 mesh.
[3]120 mesh.
[4]More than one glass type in sample.
[5]60–120 mesh.
[6]28–48 mesh.
[7]35–100 mesh.
[8]28–32 mesh.
[9]Separate consists mostly of magnetite and ilmenite plus a few grains of pink zircon.
[10]Very few transparent mafic minerals present.
[11]Separate contains mostly biotite and ilmenite.
[12]Mafic mineral separate contains mostly magnetite or ilmenite.
[13]Mafic mineral separate from scoria lapillus in tuff.
[14]Angular mafic mineral grains.
[15]Rounded mafic mineral grains.
[16]Coarse glass separate, 60–120 mesh.
[17]Fine glass separate, 120–200 mesh.
[18]Dark-green to bluish-green amphibole (arfedsonite?).

tephra of silicic and intermediate compositions. Considering silicic tephra alone, the greatest chemical variability exists between units erupted from different volcanic fields. Smaller chemical differences are observed between silicic tuffs erupted at different times from a single volcanic field, while the smallest variability is observed within a tuff layer representing a single eruption. Of the silicic tuffs analyzed, variations in the trace- and minor-element compositions of the glass are discontinuous from one order to the next, making it possible in most instances to identify tephra of individual eruptions, as well as the volcanic field from which the tephra was erupted.

TUFF CORRELATIONS

Correlations were made on the basis of chemical fin-

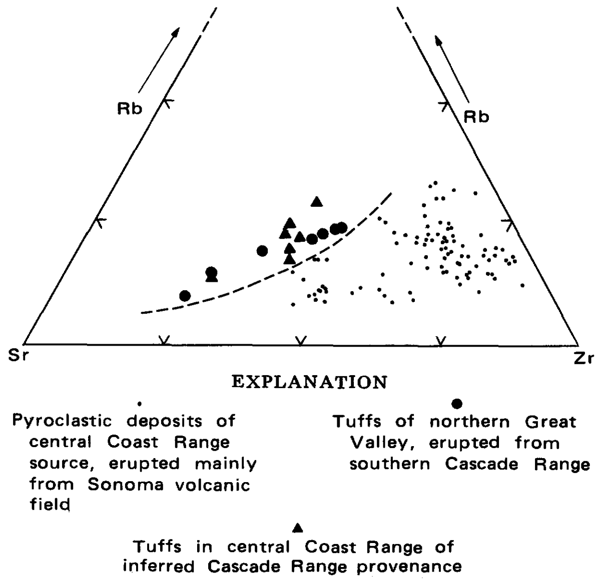


FIGURE 6.—Provincial differences between tuffs in central Coast Ranges and southern Cascade Range. Mutual percentages of net intensity peaks for Rb, Sr, and Zr. Intensity peaks were obtained by using rapid X-ray fluorescence scans on powdered whole-rock samples treated with 10 percent HCl. Dashed line separates tuffs of Cascade Range provenance from those of central Coast Ranges provenance.

gerprinting of the volcanic glass, supported by additional evidence such as tuff petrography, stratigraphic position and sequence, potassium-argon ages, and available fossil data. Five widespread tuff units have been recognized within the central Coast Ranges. Figure 8 shows the known maximum areal distribution of these units. In order of decreasing age, the tuffs and their chemical correlatives are: (1) the tuff in the Merced(?) Formation of Sonoma County (fig. 9, locs. 35–44), (2) the Pinole Tuff and tuffs in the lower part of the Monticello Road section in the Sonoma volcanic field (fig. 9, locs. 47, 50–56, 59–63), (3) the Lawlor Tuff (fig. 9, locs. 17–34), (4) the Putah Tuff Member of the Tehama Formation (fig. 9, locs. 12–16), and (5) the tuff in the type section of the Merced Formation of western San Francisco peninsula (fig. 9, locs. 1–4). In addition to the above tuff units, there are approximately twelve more known tuff units within the central Coast Ranges that at this time have not been correlated with any widespread eruptive unit.

TUFF IN THE MERCED(?) FORMATION OF SONOMA COUNTY

Exposures of correlative tuff have been found in the marine Merced(?) Formation of Sonoma County (fig. 1, locs. 35–40), in the fresh- or brackish-water Petaluma Formation north of San Pablo Bay (fig. 1, locs. 41 and 42), and near the base of the continental Tassajara Formation or the upper part of Clark's (1943) Green Valley Formation south of Mount Diablo (fig. 1, loc. 43). A tuff that overlies the Neroly Formation and underlies

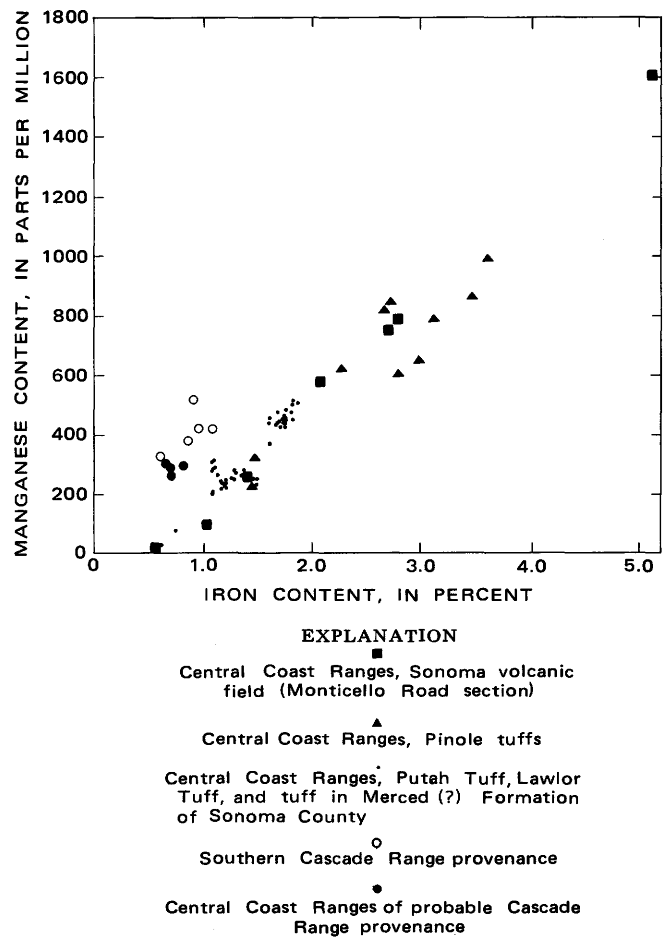


FIGURE 7.—Provincial differences between tuffs from the central Coast Ranges and from the southern Cascade Range, as illustrated by variations in concentrations of iron and manganese in volcanic glass.

Ham's (1952) Mulholland Formation in the eastern Berkeley Hills (fig. 1, loc. 44) is a tentative correlative. The tuff in the Merced(?) Formation of Sonoma County has been dated at 6.1±0.1 m.y. (fig. 1, loc. 40, Bartow and others, 1973) and at 5.7±0.5 m.y. (fig. 1, loc. 37; table 2), while the tuff in the eastern Berkeley Hills (fig. 1, loc. 44) has been dated at 8.2±2.0 m.y. (G. H. Curtis, oral commun., 1971); consequently, its correlation with the tuff in the Merced(?) Formation is uncertain.

Although the refractive indices of the glass are very similar for those samples examined, the mafic-mineral frequencies between fine and coarse facies are particularly obvious. For instance, sample 35 (table 5), a fine water-laid ash tuff, is considerably enriched in hornblende with respect to sample 37, from a coarser facies of the same tuff containing pumice lapilli and cobbles. Presumably, the differences in mafic-mineral frequencies vary considerably (table 5). Differences in mafic-mineral frequencies between these samples are due to hydraulic sorting. Frequency counts of mafic minerals on three size fractions of the coarser facies of this tuff indicate that the hornblende is finer grained than augite and therefore would tend to be concentrated in the finer grained facies (fig. 10).

PINOLE TUFF

The Pinole Tuff, a 275-m-thick sequence of tuffs, contains both silicic tuffs (fig. 1, locs. 52, 57 and 58) as well as pumice-lapilli tuffs of intermediate composition (table 1, locs. 53–56, 59–62). Glass composition of the intermediate tuffs is heterogeneous. Pumice lapilli of several different compositions may be present within a single sample, as indicated by presence of several glass types with different refractive indices (table 5, locs. 54, 62). This heterogeneity introduces considerable scatter into the analytical data owing to sampling errors and makes it difficult to make specific correlations on the basis of glass chemistry.

The Pinole Tuff can be correlated in a general way with the lower part of the Sonoma volcanic field in the Monticello Road section east of Napa. At both localities, andesitic tuffs containing scoria lapilli and bombs (fig. 9, locs. 50, 51, 53, 54, 60, 61, and 62) are exposed near the base of the sections. At both sections, volcanic de-

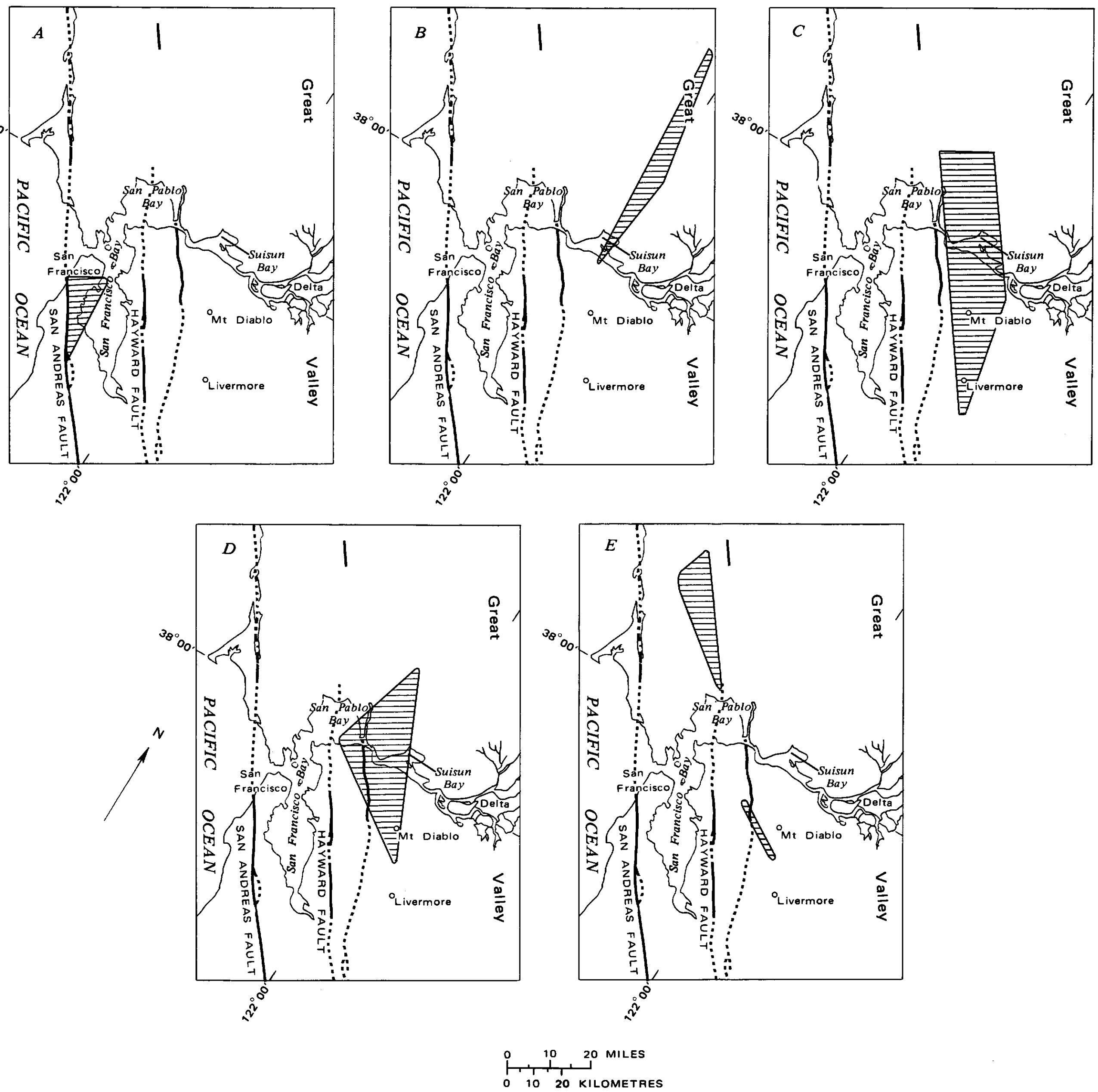


FIGURE 8.—Maximum known areal distribution of five major eruptive tuff units (horizontal lined areas) identified in present study. *A*, Tuff at type locality of Merced Formation. *B*, Putah Tuff Member of Tehema Formation. *C*, Lawlor Tuff. *D*, Pinole Tuff. *E*, Tuff in the Merced(?) Formation of Sonoma County.

posits grade upwards into more silicic types. Figure 11 shows rapid-scan analyses on whole-rock samples from both sections. Similarity coefficients for heterogeneous intermediate tephra from the two localities are low, probably for the reasons mentioned above. The highest similarity coefficients for sample pairs from the two sections range from 80 to 87 (locs. 47, 53, 56, 59–62), about the same as the highest internal coefficients for the Pinole Tuff, except for samples from localities 55 and 56, which have a coefficient of 0.96. Intermediate tuffs from the Pinole and Monticello Road sections of the Sonoma volcanic field are more similar to each other than they are to any other analyzed tuff (fig. 4). In addition, radiometric ages support the correlation of these tuffs. A potassium-argon date of 5.2±0.1 m.y. was obtained on a sample from the Pinole Tuff near the base of the section (loc. 61) (Evernden and others, 1964), whereas a 5.4±0.2-m.y. date was obtained on a sample of tuff with scoria bombs near the base of the Monticello Road section (loc. 50) in the Sonoma volcanic field (G. H. Curtis, oral commun., 1971).

Since the pyroclastic rocks in the Monticello Road section are thicker and generally coarser and contain interbedded flow rocks and intrusive dikes, we might suspect that they are closer to the eruptive source than are the Pinole Tuff (fig. 1, locs. 52–62). The tuff containing the scoria bombs in the Pinole Tuff, however, is coarser at locality 53 than at the Monticello Road locality 50, suggesting that for this unit at least the eruptive vent was closer to the Pinole localities.

Similarities in stratigraphic sequence and glass chemistry at the Pinole and Monticello Road localities, as well as radiometric dates, suggest that the sections are contemporaneous and had a common source. However, because niobium content in volcanic glass of the Monticello Road volcanic rocks is systematically higher (table 5, samples 45–62), it is still possible that tephra was erupted from a series of separate but related vents and need not have had a common source.

The Pinole Tuff is correlated in a general way with a 60-m-thick sequence of tuffs and tuffaceous sediments south of Mount Diablo. Rapid-scan analyses again show vertically systematic changes in chemical composition in both sections (figs. 12 and 13). The similarity coefficient between the only complete "absolute" analysis made on a sample from the locality south of Mount Diablo and a tuff in the Pinole Tuff section is 0.91 (locs. 52 and 63). The sample at locality 52, however, was obtained from near the top of the Pinole Tuff at Rodeo, while the sample at locality 63 was obtained from near the base of the section south of Mount Diablo; consequently these tuffs may not be correlative. Nevertheless, since the tuff at locality 63 is massive, while that at locality 52 is composed of rounded pumice lapilli in a tuffaceous matrix, it is possible that the tuff at locality 52 was reworked from a more massive unit lower in the Rodeo section.

LAWLOR TUFF

The known extent of the Lawlor Tuff (fig. 1, locs. 22–30) and its correlatives (fig. 1, locs. 17–21, 29–34) is shown in figure 8. The Lawlor is an ash flow tuff, the distant end of which has been found as far south as the southwestern flank of Mount Diablo (fig. 1, locs. 29, 30), interbedded with the uppermost(?) part of the Tassajara Formation; a reworked, water-laid correlative has been found even further south on the north flank of the Diablo Range, south of the town of Livermore, where it is interbedded with the Livermore Gravels of Clark (1930) (fig. 1, locs. 31–34). Three outcrops of ash flow tuff correlative with the Lawlor have also been found within the upper part of the Sonoma Volcanics (fig. 1, loc. 17–21).

The average similarity coefficient for analyses of the Lawlor Tuff and its correlatives is 0.93, while values of the distance function in cluster analysis range from 0.015 to 0.035 for all but one sample (29) and from 0.015 to 0.060 for all samples (fig. 5). The similarity of the chemical analyses can be easily visualized when histograms of the analyses are compared (fig. 14). The similarity of the analyses becomes even more remarkable when average values of samples from the physically continuous Lawlor Tuff are compared with average values of samples from all other known correlative but physically separate localities (table 6). Comparisons of average values indicate greater consistency in concentrations even for some of those elements (yttrium, gallium, niobium, copper, and nickel) that show considerable scatter in individual sample comparisons.

Radiometric ages support correlations made on the basis of chemical fingerprints (fig. 9). A potassium-argon date of 3.96±0.16 m.y. has been obtained for the Lawlor Tuff at its type locality in Lawlor Ravine in the hills south of Suisun Bay, north of Mount Diablo (fig. 9, locs. 22, 27, 28), a date of 4.0±1.0 m.y. on an exposure in the Tassajara area, south of Mount Diablo (fig. 9, table 2, loc. 30), and a date of about 4.46±0.45 m.y. from its southernmost correlative in the Livermore Gravels of Clark (1930) (fig. 9, table 2, locs. 31, 32). The tuff exposure correlative with the Lawlor Tuff near the top of the Monticello Road section (fig. 9, loc. 17) is overlain by the St. Helena Rhyolite Member of the Sonoma Volcanics, dated at 3.8±0.1 m.y. (G. H. Curtis, commun., 1971), and, if my interpretation of the structure in this area (fig. 3) is correct, is underlain by dacite dated at 4.2±0.1 m.y. (Mankinen, 1972).

At the southernmost locality correlative with the Lawlor Tuff, two thin tuffs in the Livermore Gravels of

Clark (1930) are exposed; the lower bed is approximately 3 m thick (fig. 9, locs. 31 and 32), and the upper bed is approximately 1.8 m thick (fig. 9, locs. 33 and 34). Both tuffs are water laid, well bedded, laminated, and, locally, crossbedded. The two tuffs are separated by 7.6 m of tuffaceous sediments and were probably erupted within a short period of time of each other from a common vent in the Sonoma volcanic field. Samples of the glass separated from the two tuffs have very similar minor- and trace-element concentrations and

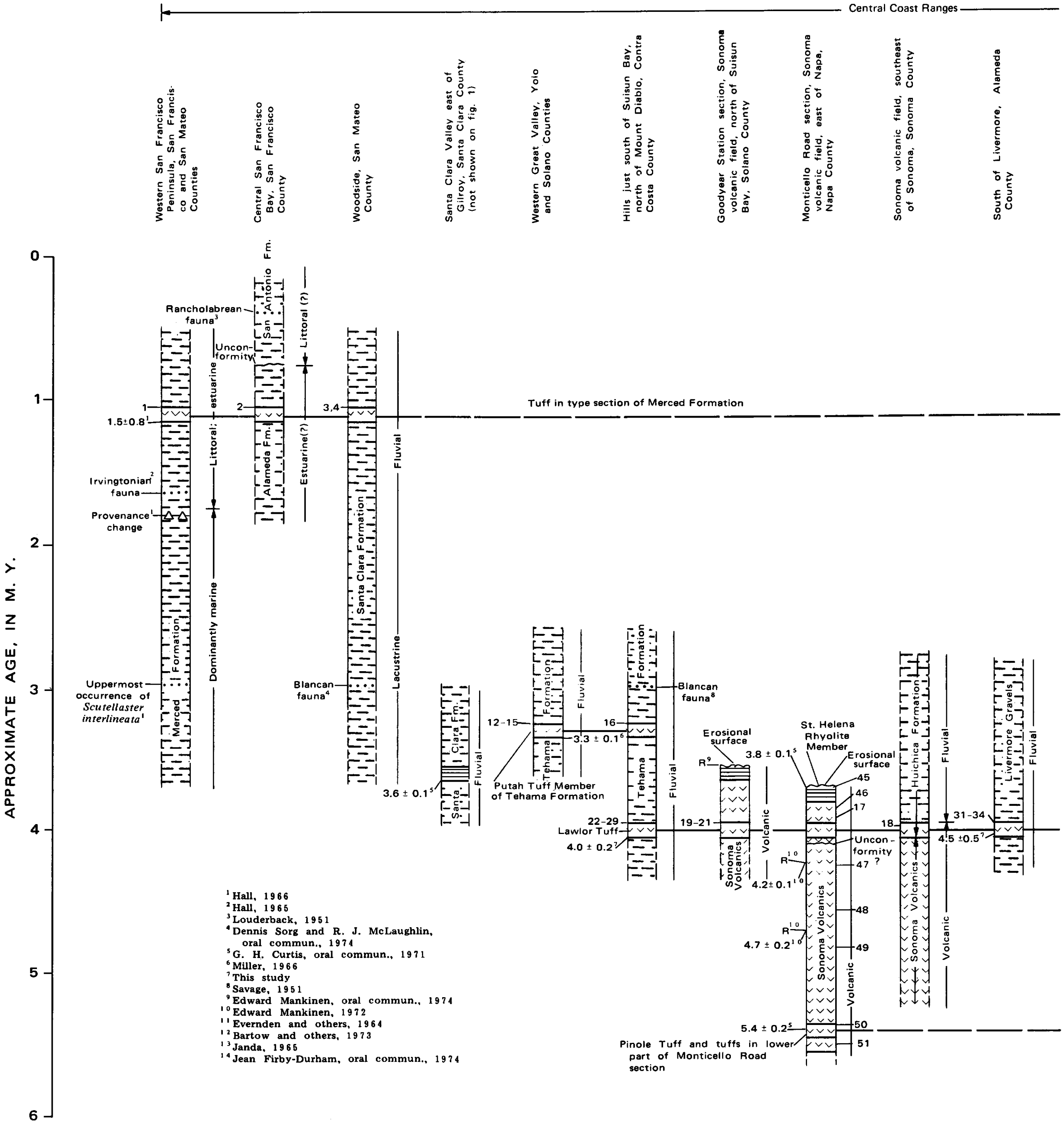


FIGURE 9.—Summary of correlations of late Cenozoic tuffs based on chemical fingerprinting and petrographic characteristics of tuffs, stratigraphic position and sequence, potassium-argon ages, and fossil evidence. Solid horizontal lines indicate correlation certain; dashed horizontal lines indicate correlation probable; and queries indicate correlation uncertain. Location of sections shown in figure 1.

are hard to distinguish by these analyses (table 7). Neutron activation analyses, however, indicate that the glass composition of the two tuffs is distinct (H. R. Bowman and Sarna-Wojcicki, unpub. data). Similarity coefficients comparing these two tuffs with tuffs at other localities correlative with the Lawlor show greater similarity in every instance between the lower bed and the Lawlor eruptive unit (table 8).

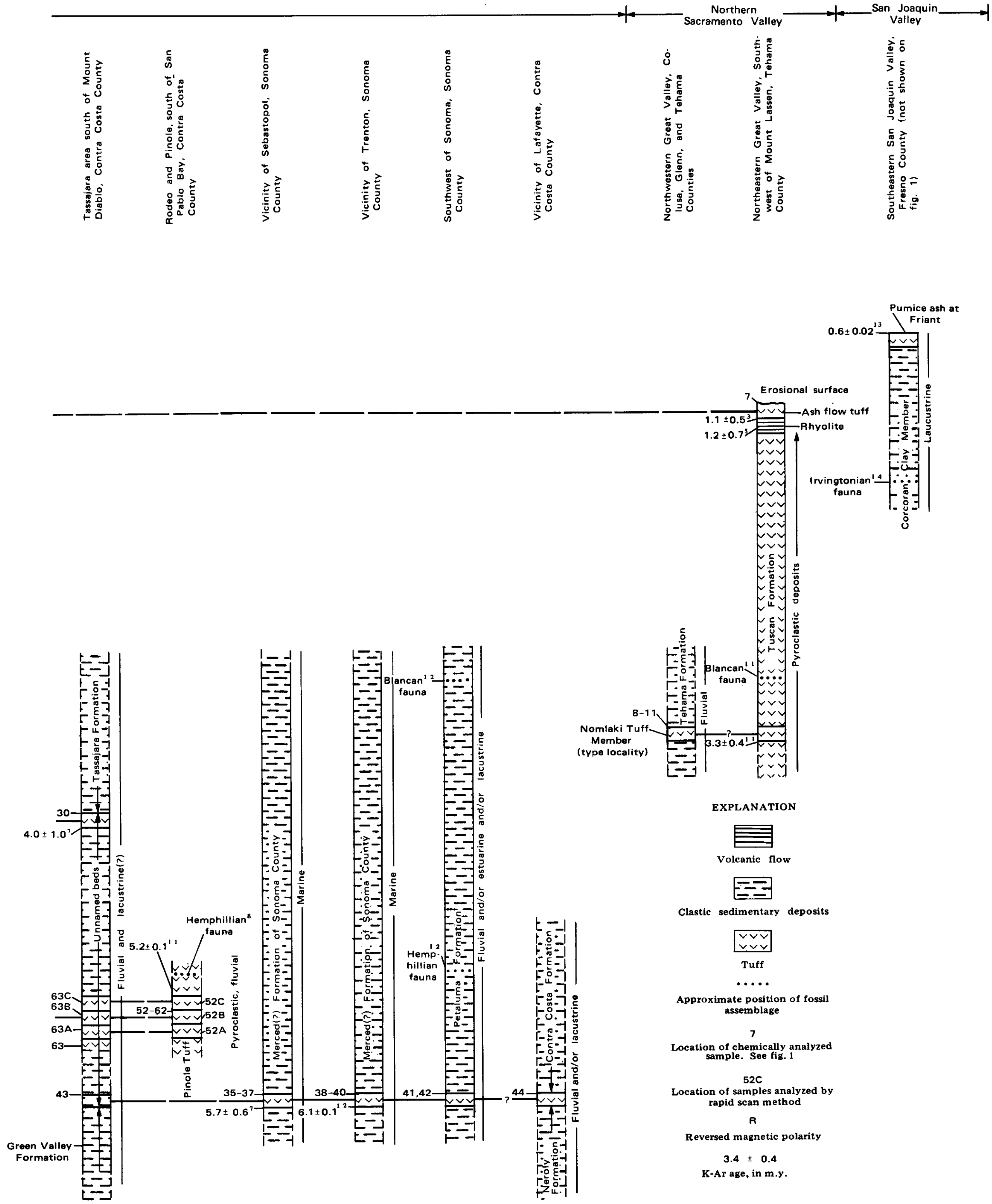


FIGURE 9.—Continued.

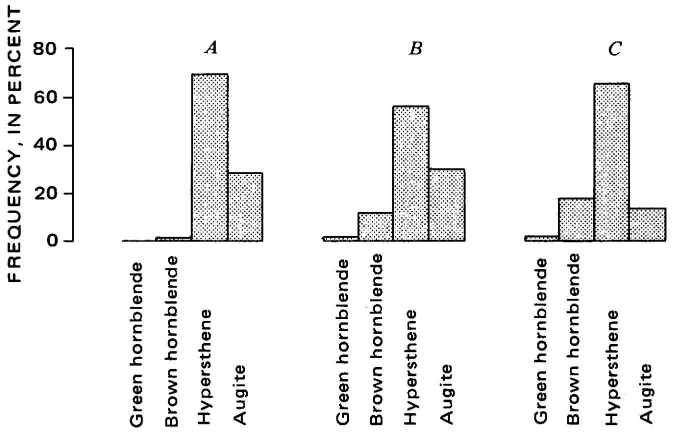


FIGURE 10.—Principal mafic mineral frequencies of three size fractions of tuff in Merced(?) Formation of Sonoma County. Frequency counts were made on coarse pumice-lapilli tuff (loc. 37, table 5). *A*, 28–48 mesh. *B*, 35–100 mesh. *C*, 60–120 mesh.

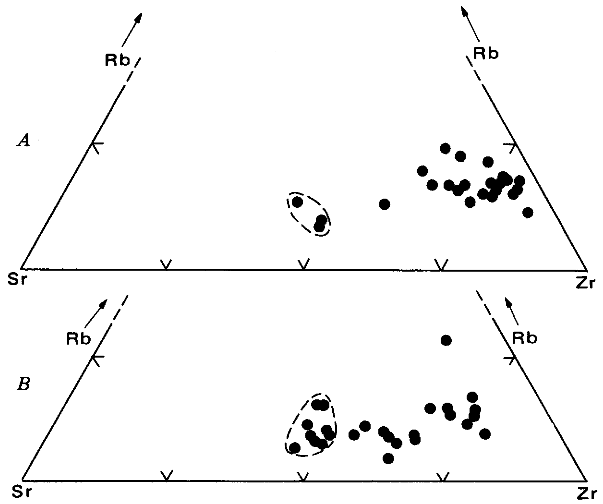


FIGURE 11.—Correlation of the Pinole Tuff with the Sonoma Volcanics. Mutual percentages of net intensity peaks for Rb, Sr and Zr. Intensity rapid peaks obtained by using rapid X-ray fluorescence scans on powdered whole-rock samples treated with 10 percent HCl. *A*, Tuffs in the Pinole Tuff at Rodeo, Wilson Point and south of town of Pinole. *B*, Tuffs and flows of Sonoma Volcanics, Monticello Road, east of Napa. Tuffs of intermediate composition containing bread crust scoria bombs are included within dashed lines.

Although the refractive indices of glass for the Lawlor eruptive unit are virtually the same for all samples, the mafic-mineral abundances vary considerably (table 5). These differences cannot be explained by eolian or hydraulic sorting since the tuff at all but one of the localities correlative with the Lawlor appears to be an ash flow. Variations in mafic-mineral frequencies may be due to inhomogeneous distribution of crystals in the magma prior to eruption. Alternatively, the Lawlor

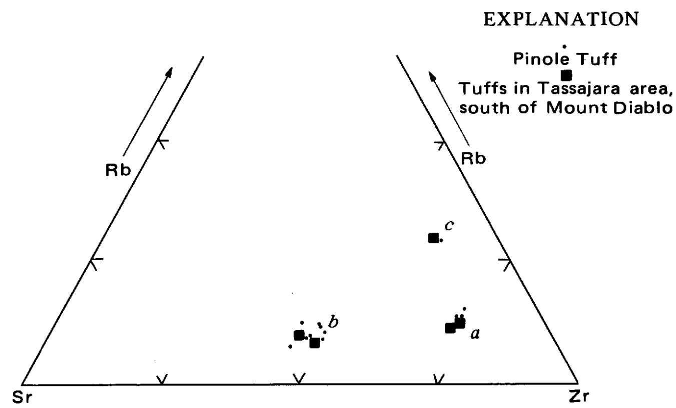


FIGURE 12.—Correlation of the Pinole Tuff (loc. 52A, B, and C) with tuffs south of Mount Diablo (loc. 63A, B, and C). Mutual percentages of net intensity peaks for Rb, Sr and Zr. Intensity peaks obtained by using rapid X-ray fluorescence scans on powdered whole-rock samples treated with 10 percent HCl. Samples from *a*, gray pumice-lapilli tuff near the base of the Pinole Tuff (loc. 52A), and basal tuff south of Mount Diablo (loc. 63A); *b*, intermediate tuff with scoria bombs in the Pinole Tuff (loc. 52B), and similar finer grained tuff south of Mount Diablo (loc. 63B); *c*, silky silvery pumice lapilli from tuffaceous matrix near top of Pinole Tuff (loc. 52A), and from near top of tuff sequence south of Mount Diablo (loc. 63C).

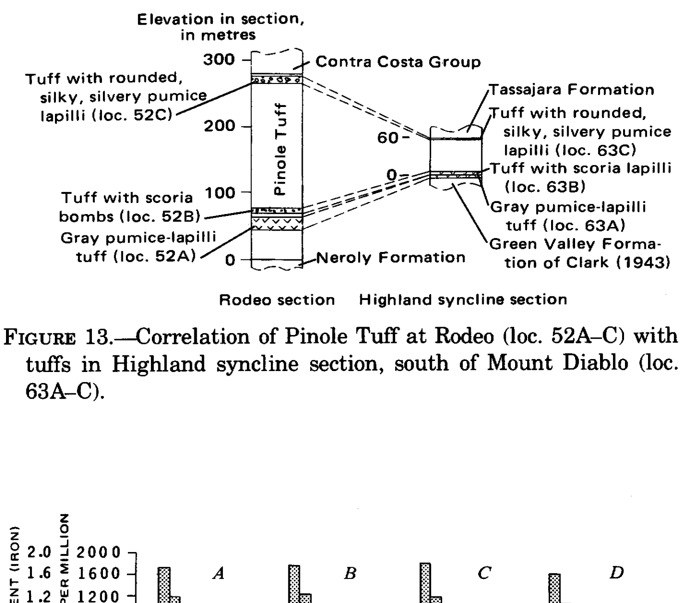


FIGURE 13.—Correlation of Pinole Tuff at Rodeo (loc. 52A–C) with tuffs in Highland syncline section, south of Mount Diablo (loc. 63A–C).

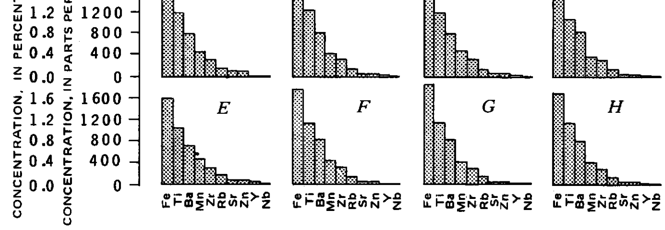


FIGURE 14.—Concentrations of minor and trace elements in volcanic glass of Lawlor Tuff and its correlatives. *A–C*, Lawlor Tuff (fig. 5, locs. 22, 23, 25). *D–H*, Lawlor correlatives (fig. 5, locs. 17–19, 30, 31). Iron in percent; remaining elements in parts per million.

Tuff and its correlatives may actually represent several separate eruptions closely spaced in time.

The Lawlor Tuff and its correlatives form an eruptive unit extending over 112 km, interbedded with the upper part of the Sonoma Volcanics, the base of the Tehama Formation, the uppermost(?) part of the Tassajara Formation, and the Livermore Gravels of Clark (1930).

PUTAH AND NOMLAKI TUFF MEMBERS OF THE TEHAMA FORMATION

A thin tuff bed (fig. 9, loc. 16) correlative with the Putah Tuff Member of the Tehama Formation of the western Great Valley (fig. 9, locs. 12–15) has been found south of Suisun Bay, stratigraphically above the Lawlor Tuff. This thin tuff bed is interbedded with sediments which have been referred to as the Los Medanos Formation (Clark, 1943) or the Wolfskill Formation (Weaver, 1949) but have been recently designated as the Tehama Formation (Sims and Sarna-Wojcicki, 1975) on the basis of lithologic correlation with the type Putah Tuff Member. This correlation extends the maximum distance between correlative localities (locs. 15, 16, fig. 1; fig. 9) of the Putah Tuff Member to approximately 97 km.

The Putah Tuff Member is a composite unit of water-laid tuffs and probably represents several eruptions closely associated in time. Similarity coefficients for unweathered samples within the Putah (fig. 4, locs. 12, 13, and 14) are 0.91, 0.89, and 0.95. Coefficients between these samples and a weathered sample (fig. 4, loc. 15) are lower (0.83, 0.86, and 0.89) possibly owing to higher concentrations of barium and strontium in the form of insoluble authigenic sulfate in the weathered sample. The southernmost correlative sample (fig. 4, loc. 16) is most similar (similarity coefficient of 0.96) to the sample (fig. 4, loc. 14) obtained from the lowermost emplacement unit at its type locality.

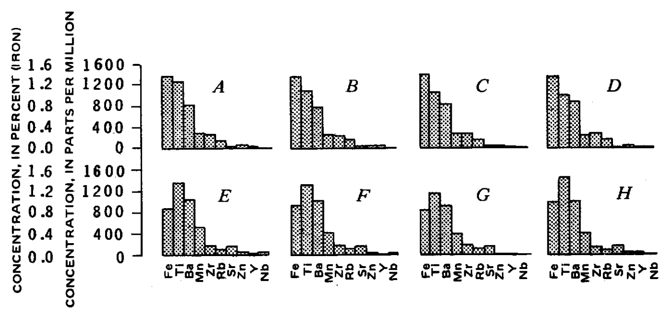


FIGURE 15.—Concentrations of minor and trace elements in volcanic glass of the Putah Tuff Member, a Putah correlative south of Suisun Bay, and the Nomlaki Tuff Member (locs. 8–11) from its type locality. *A–C*, Putah Tuff member of Tehama Formation (locs. 12–14). *D*, Putah correlative, south of Suisun Bay (loc. 16). *E–H*, Nomlaki Tuff Member of Tehama Formation (locs. 8–11).

Miller (1966) has shown that the Nomlaki Tuff Member (fig. 1, locs. 8–11), exposed within and near the base of the Tehama Formation in northern Sacramento Valley, is not correlative with the Putah (locs. 12–16) although both tuffs are about the same age[3] and in similar stratigraphic position. Miller's conclusions were confirmed during this study by chemical fingerprinting of glasses from the two tuffs (fig. 15).

Average within-unit similarity coefficients for the Putah and Nomlaki Tuff Members of the Tehama Formation are 0.90 and 0.92, respectively, while the average similarity coefficients between the units is 0.63 (fig. 4). Samples of the Putah (locs. 12–15) and its correlative (loc. 16) are clustered at distance function values of about 0.050; the samples from both the Putah and Nomlaki Tuff Members are grouped at values of 0.260 (fig. 5).

[3]The Nomlaki has been dated by potassium-argon methods at 3.3±0.4 m.y. (Evernden and others, 1964); the Putah at 3.3±0.1 m.y. (Miller, 1966; G. H. Curtis, oral commun., 1971).

TABLE 6.—*Average minor- and trace-element composition of volcanic glass of the physically continuous Lawlor Tuff unit compared with average compositions of correlative but physically separate outcrop localities*

[Sample localities shown in figure 1. Concentrations of iron in percent; all other concentrations in parts per million]

	Fe	Ti	Ba	Mn	Zr	Rb	Sr	Zn	Y	Nb	Ga	Cu	Ni
Lawlor Tuff, average of seven analyses (locs. 22–29)	1.73	1160	795	444	311	147	56	58	23	19	17	9	11
Lawlor correlatives, average of eleven analyses (locs. 17–21, 29–34)	1.72	1193	791	448	311	146	64	60	29	15	17	11	11

TABLE 7.—*Trace- and minor-element analyses of volcanic glass of two thin water-laid tuffs in the Livermore Gravels of Clark (1930)*

[Concentrations of iron in percent; all other concentrations in parts per million]

	Sample loc.	Fe	Ti	Ba	Mn	Zr	Rb	Sr	Zn	Y	Ga	Nb	Cu	Ni
Upper bed	34	1.82	1137	718	517	290	137	82	56	24	13	9	8	8
do	33	1.82	1136	684	502	306	135	74	60	23	14	21	13	11
Lower bed	32	1.75	1213	733	431	297	143	60	58	25	17	16	11	13
do	31	1.70	1134	809	422	305	148	71	59	29	17	14	9	12

TABLE 8.—*Average similarity coefficients comparing trace- and minor-element analyses of volcanic glass of two thin water-laid tuffs in the Livermore Gravels of Clark (1930) with all other outcrop localities of the Lawlor Tuff*

	Tuffs in Livermore Gravels	
	Upper bed (locs. 33, 34)	Lower bed (locs. 31, 32)
Upper bed	[1]0.95	0.92
Lower bed	.92	[2].96
South of Mount Diablo (sample 30)	.90	.94
South of Mount Diablo (sample 29)	.90	.93
Lawlor Tuff (samples 22–28)	.90	.95
Southeast of Sonoma Volcanics (samples 19–21)	.89	.94
Sonoma Volcanics Monticello Road (sample 17)	.86	.91
Sonoma Volcanics near Schellville (sample 18)	.93	.94

[1]Sample from locality 33 compared with sample from locality 34.
[2]Sample from locality 31 compared with sample from locality 32.

Mafic-mineral frequencies of samples of the Putah Tuff Member (table 3) are similar, as are the refractive indices of glass (table 5); the same is true for the Nomlaki Tuff Member. There are significant differences in mafic-mineral frequencies between the two tuffs; however, differences in refractive indices of glass between the Putah and Nomlaki are very slight (table 5).

Trace- and minor-element composition of the volcanic glass in the Putah Tuff Member is very similar to that of the tuff in the Merced(?) Formation of Sonoma County. Although the average similarity coefficient between the Putah and the tuff in the Merced(?) Formation of Sonoma County is 0.85, individual sample pairs from the two tuffs may have similarity coefficients as high as 0.91 (fig. 4) for the eight-element comparison used. It was not possible to distinguish clearly between the two tuffs using cluster analysis on the main group of eight elements or on a second run using seven elements, omitting strontium. This is due both to the chemical similarity of the glass of the two tuffs and to a rather high variability for manganese, rubidium, and strontium. It appears that chemical variability of the glass for some elements can differ for different eruptive units. Elements with consistent concentrations in one unit may be more variable in another. For instance, amounts of rubidium in the Lawlor Tuff are very consistent, while those in the Putah and the tuff in the Merced(?) Formation of Sonoma County are more variable. The two last tuffs are known from independent evidence to be of different age: the Putah was dated by potassium-argon analysis at 3.3±0.1 m.y. (fig. 9, locs. 12–15; G. H. Curtis, oral commun., 1971), while the tuff in the Merced(?) Formation of Sonoma County was dated at 5.7±0.6 (fig. 9, locs. 35–37) and 6.1±0.1 m.y. (fig. 9, locs. 38–40). Calculations of similarity coefficients and cluster analysis were performed on samples of these tuffs using only the four most consistent variables: iron, titanium, barium, and zirconium (fig. 16). By this procedure it was possible to distinguish differences in composition between the two tuffs. On the basis of these calculations, the average similarity coefficient between samples of the Putah and the tuff in the Merced(?) Formation is 0.82, while the average internal within-unit similarity coefficient for both units was 0.93. The highest similarity coefficient for a pair of samples from the two tuffs was 0.88. By means of cluster analysis with

	Sample loc.	14	13	12	15	16	35	36	37	38	39	40	41	42	43	44
Putah Tuff Member of Tehama Formation (loc. 12–15) and a correlative tuff (loc. 16)	14	1														
	13	.96	1													
	12	.93	.94	1												
	15	.92	.91	.90	1											
	16	.97	.92	.92	.93	1										
Tuff in the Merced(?) Formation of Sonoma County	35	.87	.88	.83	.80	.84	1									
	36	.85	.86	.81	.76	.83	.97	1								
	37	.83	.84	.79	.76	.80	.89	.92	1							
	38	.85	.85	.81	.78	.83	.90	.92	.94	1						
	39	.84	.86	.81	.78	.82	.93	.94	.93	.94	1					
	40	.83	.84	.79	.76	.80	.95	.94	.95	.97	.97	1				
Tuff in the Petaluma Formation	41	.80	.81	.77	.74	.78	.90	.92	.95	.94	.95	.96	1			
	42	.84	.85	.80	.77	.81	.91	.94	.96	.97	.94	.97	.95	1		
Tuff south of Mount Diablo	43	.84	.84	.80	.78	.81	.94	.95	.91	.90	.94	.92	.92	.92	1	
Tuff near Lafayette	44	.87	.87	.85	.81	.87	.94	.92	.85	.85	.87	.86	.85	.86	.92	1

FIGURE 16.—Similarity coefficient matrix comparing trace- and minor-element analyses of glass samples of the Putah Tuff Member of Tehama Formation (locs. 12–16) and the tuff in the Merced(?) Formation of Sonoma County. Calculations of coefficients for the four most consistent elements, Fe, Ti, Ba, and Zr.

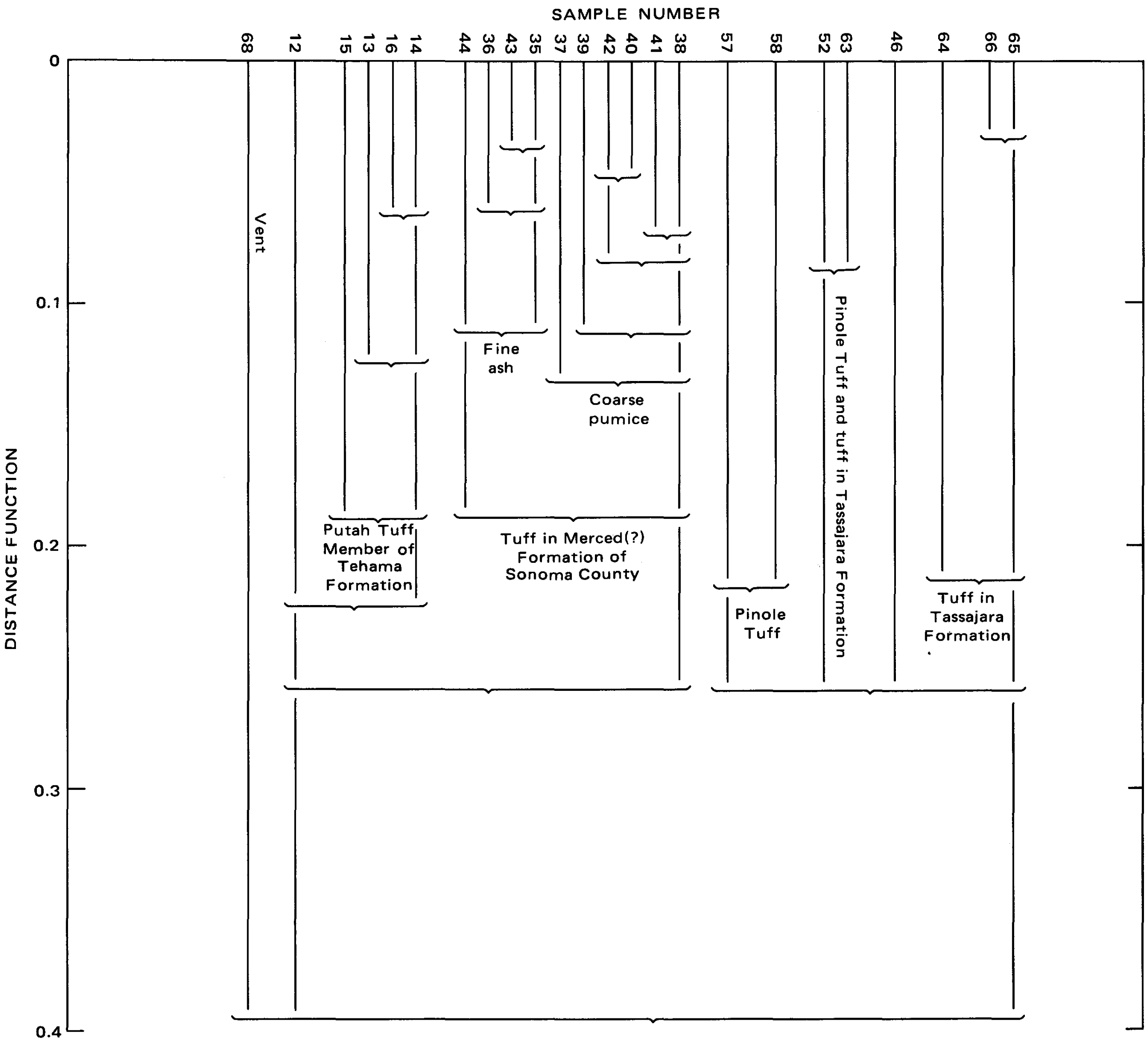


FIGURE 17.—Dendrogram from cluster analysis of trace- and minor-element data, using distance function, for Fe, Ti, Ba, and Zr. See text for explanation. Sample number is same as locality number shown in figure 1.

only these four elements, it was also possible to distinguish between the two eruptive units. To emphasize differences between samples, the cluster analysis in this instance was run only on samples of the Putah Tuff Member, the tuff in the Merced(?) Formation of Sonoma County, plus several close compositional relatives (fig. 17).

TUFF IN THE TYPE SECTION OF THE MERCED FORMATION

A correlative of the tuff in the type section of the Merced Formation of western San Francisco peninsula (fig. 1, loc. 1) has been obtained from a drill hole 10 miles to the east, in sediments of the Alameda Formation beneath San Francisco Bay (fig. 1, loc. 2). The similarity coefficient for analyses of seven elements (titanium, barium, manganese, zirconium, rubidium, strontium, and zinc) in the volcanic glass of these two tuffs is 0.93. No iron analyses have as yet been made on these two samples, so they are not included in the cluster analysis (fig. 5). A tuff similar to that in the Merced and Alameda Formations was exposed in a trench in the Santa Clara Formation, in the town of Woodside (fig. 1, locs. 3 and 4) approximately 20 miles south of the former localities. Though the tuff at the Woodside locality has the same mineralogy as the tuffs in the Merced and Alameda Formations (table 5), earlier analyses had indicated that there are considerable differences in titanium and manganese content of the glass. Similarity coefficients between samples 1 and 2 on the one hand, and 3 and 4 on the other, range between 0.81 and 0.87, with an average of 0.84. On the basis of the earlier analyses alone, the correlation of the tuff in the Santa Clara Formation with the tuff in the Merced and Alameda Formations must be considered uncertain. However, new analyses by Brent Fabbi, U.S. Geological Survey, Menlo Park, of tuff in the Santa Clara Formation and in the type Merced Formation show a high similarity coefficient of 0.97, indicating that the tuffs are correlative (Fabbi and Sarna-Wojcicki, unpub. data). The earlier analyses are probably inaccurate owing to incomplete separation of crystals and lithic fragments from the fine-grained volcanic ash.

The tuff in the Merced Formation is fine grained and probably was deposited by water. It has no coarse-grained facies within the central Coast Ranges that might indicate local eruptive sources, and it differes in glass chemistry from tuffs of local provenance. For instance, the similarity coefficients between the tuff in the Merced Formation (sample 1) and tuffs of local Coast Range provenance, such as the Putah Tuff Member (samples 12–15), the Lawlor Tuff (samples 22–28), and the tuff in the Merced(?) Formation of Sonoma County (34–40), are low (0.59, 0.62, and 0.54, respectively). The similarity coefficient between the tuff in the Merced Formation and a tuff-breccia in Anderson's (1936) Cache Formation within the Clear Lake volcanic field (sample 71) is also low (0.66). This indicates that the Merced tuff probably did not have its source in the Clear Lake area either, even though the period of volcanism in the Clear Lake area encompasses the age of the tuff in the type section of the Merced Formation (G. H. Curtis, oral commun., 1971). A 1.5±0.8 m.y.-potassium-argon date on tuff in the Merced Formation (fig. 9, loc. 1; Hall, 1966) is younger than the youngest known potassium-argon age obtained on rocks of the Sonoma Volcanics (2.9 m.y., Mankinen, 1972). These ages, if correct, further exclude the Sonoma volcanic field as a likely source of this tuff. However, the similarity coefficient between the tuff in the type section of the Merced Formation and the average for the Nomlaki Tuff Member, a unit of known Cascade Range provenance (Anderson and Russell, 1939; Lydon, 1967), is 0.81, a value typical of provincial "relatives," suggesting that the tuff in the type section of the Merced Formation was erupted in this volcanic province.

On the basis of glass chemistry and petrography, as well as radiometric ages, it seems likely that the source of the tuff in the type Merced, Alameda, and Santa Clara Formations was in the southern Cascade Range, near the town of Mineral, where two Pleistocene pumice ash-flow units crop out (Wilson, 1961). These two pumice ash-flow units yielded scattered potassium-argon ages ranging from 0.26 to 1.1 m.y. (Gilbert, 1969).[4] Though earlier analyses have indicated that the tuff in the type Merced Formation (fig. 9, loc. 1) is not correlative with one of the ash-flow units, exposed near Lassen Lodge (fig. 1, loc. 7), new analyses (Fabbi and Sarna-Wojcicki, unpub. data) indicate that the tuff in the type section of the Merced Formation is probably correlative with another ash-flow unit, exposed near Manton Lodge; the similarity coefficient for these two tuffs is 0.90.

The mafic mineralogy of the tuff in the type section of the Merced Formation (fig. 1, loc. 1) and its local correlatives (fig. 1, locs. 2–4) is the same as that of the pumice ash flows near Mineral (fig. 1, loc. 7). Both groups of tuffs have dark-green hornblende and pale pleochroic hypersthene as the principal mafic phenocrysts (table 5). The mafic mineral frequencies are different; the pumice tuff at Mineral has more hypersthene and less hornblende than the tuff in the Merced Formation. These differences can be explained by either hydraulic or eolian sorting of these minerals away from their source. Fragments of the thinner, tabular, and more cleavable hornblende would probably be carried further by wind or water than the stubbier, equant hypersthene crystals. The refractive indices of glass of the tuff in the type section of the Merced Formation and its correlatives are nearly the same as those at Mineral (table 5).

DISCUSSION

Five widespread late Cenozoic tuffs, ranging in age from approximately 1 to 6 m.y., have been identified in the central Coast Ranges of California by means of chemical analyses of volcanic glass, potassium-argon dating, and petrographic and stratigraphic evidence (fig. 9). These units provide five temporal horizons that make it possible to correlate late Cenozoic volcanic, alluvial, lacustrine, and marine deposits.

Four of the five widespread units were erupted from source areas within the central Coast Ranges, probably within the area of the Sonoma volcanic field. These tuffs include the tuff in the Merced(?) Formation of Sonoma County, the Pinole Tuff, the Lawlor Tuff, and the Putah Tuff Member of the Tehama Formation.

Several tuffs in the central Coast Ranges (fig. 1, locs. 1–6), including one of the five widespread units, the tuff in the type section of the Merced Formation (fig. 1,

[4]The 1.5±0.75-m.y.-date on the tuff in the type section of the Merced Formation is very imprecise owing to high content of atmospheric argon and possible detrital contamination. Ages on its probable chemical correlative in the southern Cascade Range are scattered, ranging from 0.26 to 1.1 m.y. (Gilbert, 1969). Consequently, the age of the tuff in the Merced Formation is not well determined but is probably about 1 m.y. or younger.

locs. 1–4), were probably erupted in the southern Cascade Range. All are fine-grained water-laid or ash-fall tuffs that, unlike tuffs of local derivation, have no coarse-grained correlatives in the central Coast Ranges. These tuffs are similar in composition to tuffs of the southern Cascade Range and differ from tuffs of the Sonoma volcanic field, the Clear Lake area, and the Sierra Nevada. For example, similarity coefficients for Coast Range tuffs of inferred Cascade Range provenance compared with tuffs of the Sonoma volcanic field range from 0.50 to 0.66, with an average of 0.61 (fig. 4). Within-province similarity coefficients for tuffs of the Sonoma volcanic field average 0.75, while coefficients for southern Cascade tuffs compared with Coast Range tuffs of suspected Cascade Range origin are also 0.75, strongly suggesting that the latter two sets of tuffs are provincial relatives.

The tuff in the type section of the Merced Formation is 15–60 cm thick wherever it is found in the bay area and contains glass-coated green hornblende laths and glass shards up to 0.5 mm long. It is unlikely that the ash was carried by air 320 km to the Merced embayment, in view of its considerable thickness and relatively coarse maximum crystal and shard size. Furthermore, prevailing wind directions must necessarily have been northerly, rather than westerly as they are at present, in order to carry the tuff southward by wind. The purity of the tuff at some of its exposures may be due to the low density of the glass shards—a drainage basin blanketed with ash of low density will probably first move that material before moving the denser normal bedload. Furthermore, if the tuff had been carried by wind to the Merced depositional basin, the tephra lens of such an eruption would be at least 320 km long and several tens of kilometres wide. The record of such an eruption would likely be preserved throughout the Pleistocene deposits of the northern Great Valley, yet no such tuff has been reported.

If this line of reasoning is correct and the tuff in the Merced Formation was erupted in the southern Cascade Range, then it seems most likely that the ash was brought to the marine Merced embayment by the ancestral Sacramento River, rather than transported by air. The presence of a water-transported tuff of Cascade Range provenance in the marine Merced Formation therefore indicates that Great Valley drainage to the Pacific Ocean in the vicinity of the bay area had been established by late Merced time, or about 1 m.y. ago.

Whether the tuff in the type section of the Merced Formation was actually transported to the Merced embayment by air or water, another line of evidence indicates that Great Valley drainage to the ocean in the vicinity of the San Francisco Bay area had been established by the time the tuff was deposited. Hall (1966) studied the mineralogy of sediments in the type section of the Merced Formation and found an abrupt mineralogical change in the upper part of the formation. Heavy-mineral grains below this change are of local provenance, while those above this change indicate a sudden influx of Great Valley sediments into the Merced embayment. The tuff in the type section of the Merced Formation lies 46 m stratigraphically above this mineral change.

The Putah and Nomlaki Tuff Members of the Tehama Formation and the Lawlor and Pinole Tuffs (3.3, 3.4, 4.0 and 5.2 m.y. old, respectively) are restricted to the eastern part of the Coast Ranges and have not been found in coeval marine formations in the western part of the central Coast Ranges, suggesting that a north-south drainage divide existed in the central part of the Coast Ranges prior to about 1 m.y. ago and that Great Valley drainage flowed to a southerly outlet during this period. A southerly connection between the ocean and the Great Valley was in existence until late Pliocene time, as indicated by the presence of the upper Pliocene continental and marine San Joaquin Formation in the southern San Joaquin Valley (Woodring and others, 1940). Subsequently, this southerly connection was closed off, as evidenced by the presence of the extensive lacustrine Corcoran Clay Member of the Tulare Formation beneath Pleistocene alluvium in the San Joaquin Valley (Janda, 1965). The presence of this unit in the southern Great Valley indicates that Great Valley drainage was temporarily ponded. The Corcoran interfingers to the west with alluvial deposits of the Tulare Formation (Wahrhaftig and Birman, 1965), which in turn overlies the marine San Joaquin Formation. The exact age range of the Corcoran is not known, but the member is overlain at Friant by ash and pumice dated at 0.6±0.02 m.y. (Janda, 1965). The presence of Pleistocene alluvial deposits above the Corcoran suggests that drainage from the Great Valley to the ocean had been reestablished, probably via a more northerly outlet. The drainage change from a southerly outlet to one near the present site of San Francisco Bay probably took place sometime after 3.3 m.y. ago, after the eruption of the Nomlaki and Putah Tuff Members, but before about 0.6 m.y. ago.

The texture of the Lawlor Tuff at all its outcrop localities, except for the southernmost locality south of Livermore (fig. 1, locs. 31–34), is typical of an ash flow. No stratification, lamination, or vertical size gradients have been observed. The presence of the ash-flow phase of the Lawlor Tuff south of Mount Diablo suggests that neither Suisun Bay nor Mount Diablo existed at the time of the eruption, about 4 m.y. ago, and that these features were formed later. The tuff was erupted in the southeastern Sonoma volcanic field, where its coarsest facies are found, and it would have been difficult or impossible for the ash flow to cross these topographic features had they existed at the time of the eruption. A gentle topography or a slope component probably existed along the line between the southeastern margin of the Sonoma volcanic field and the southernmost exposure of the ash flow, south of Mount Diablo (fig. 1, loc. 30).

Correlative localities of the tuff in the Merced(?) Formation of Sonoma County trend diagonally across the central Coast Ranges (fig. 9) and correlative tuffs are found both in the southeast, interbedded with continental sediments, as well as in the northwest part of the study area, interbedded with marine deposits. Heavy minerals in sediments of the Merced(?) Formation of Sonoma County are of local Coast Range provenance; there is no evidence that Great Valley material was brought into the embayment during Merced(?) time (Johnson, 1934).

Correlatives of some of the tuffs examined in this study, such as the Putah Tuff Member of the Tehama Formation and the Lawlor Tuff, are undoubtedly preserved to the east under the Quaternary sediments of the Great Valley, beneath which both tuffs dip. Likewise, new correlative localities of the Putah Tuff Member of the Tehama Formation and the Lawlor and Pinole Tuffs will quite likely be found in the future in the Sonoma volcanic field, which has been only peripherally examined in the present study. The tuff in the Merced(?) Formation of Sonoma County, the oldest of the five major eruptive units, may antedate the main period of volcanism in the Sonoma volcanic field or may represent the inception of that volcanism and lie buried under the younger volcanic deposits.

Radiometric ages on the youngest tuffs and flows erupted in the Sonoma volcanic field cluster in the range 3.0 to 4.0 m.y. (2.9, 3.3, 3.3, 3.8, 4.0, 4.0, 4.2 m.y.). This cluster of dates defines a maximum age for a late Pliocene or early Pleistocene orogeny that deformed and uplifted the formations containing the volcanic units. The eastward shift of progressively younger eruptive units from the Sonoma volcanic field at the western margin of the Great Valley (fig. 8) suggests that uplift and volcanism were proceeding simultaneously. This orogeny, or perhaps displacement on the San Andreas fault, or both, closed off the sea connection between the southern Great Valley and the ocean. Sometime after this pulse of deformation and perhaps as a consequence of it, drainage in the Great Valley found an outlet to the ocean in the vicinity of the San Francisco Bay area.

DESCRIPTION OF UNITS

THICK SECTIONS OF VOLCANIC DEPOSITS

SONOMA VOLCANICS, MONTICELLO ROAD SECTION, SOUTHEASTERN PART OF SONOMA VOLCANIC FIELD, EAST OF NAPA (FIGS. 1–3, 9, LOCS. 17, 45–51)

Approximately 1 m of gray pumice lapilli tuff at the base is overlain by at least 12 m of a dark andesitic tuff containing round scoriaceous lapilli and bombs as much as 20 cm in diameter. This is overlain in turn by approximately 240 m of light-gray to cream dacitic vitric pumice-lapilli and lithic tuff, which is locally welded and intruded in at least one place by andesitic dikes.

This group of beds is overlain by approximately 215 m of massive flow-banded dacite. The uppermost 3 m of the unit consists of gray porphyritic perlite, overlain by a jumble of angular dacite and perlite boulders in a tuffaceous breccia matrix derived by infilling from the overlying unit.

The dacite flows are overlain by 150 m of coarse dacitic pumice lapilli and pumice blocks as much as 40 cm long. The pumice is gray, rather hard, and dense. Interstices between the pumice clasts are often filled with a creamy soft opaline(?) material and dark-orange-brown clay (nontronitic montmorillonite). The top of this unit is locally channeled, and the channels contain boulders of andesite, dacite, and rhyolite as much as 1 m in diameter.

The pumice-block breccia is overlain by approximately 18 m of a lithic pumice-lapilli tuff, with coarse boulders of andesite, dacite, and rhyolite at its base. This unit is overlain in turn by about 24 m of tuffaceous sediments containing rounded pumice lapilli. A reddish paleosoil(?) is developed at the top. The unit is channeled at the top; the channels contain pebbles of basalt, andesite, andesite scoria, dacite, and rhyolite.

SONOMA VOLCANICS, SOUTHERNMOST SONOMA VOLCANIC FIELD, NORTH OF SUISUN BAY (GOODYEAR STATION SECTION; FIG. 1, LOCS. 19–21)

A sequence of pumice-lapilli and pumice bomb tuffs, approximately 150 m thick, is exposed in a deep long roadcut along the frontage road of California Highway 21, just north of Suisun Bay. The entire sequence is massive and shows no stratification except for local changes in particle size and a few zones, presumably at the base of massive pumice-ash flows, where some of the larger lithic fragments have accumulated. The tuffs are overlain by a jointed andesite flow 15 m thick.

PINOLE TUFF (LOCS. 52–62)

The Pinole Tuff is a sequence of deformed layered pyroclastic deposits and tuffaceous sediments about 270 m thick, exposed northwest and south of the town of Pinole and at the town of Rodeo south of San Pablo Bay (Lawson, 1914; Vitt, 1936; Weaver, 1949). The Pinole Tuff overlies andesitic sandstone of the Neroly Formation of late Miocene age. There is no angular discordance between the two formations at Rodeo, but south and west of Pinole the tuffs rest on tuffaceous shales of the lower part of the Monterey Formation (middle Miocene). The section at Rodeo is thickest and at the time of Vitt's work (1936) was well exposed. At present much of the section has been concealed by construction.

A similar though somewhat thinner section is exposed northwest of Pinole near Wilson Point, along the south shore of San Pablo Bay and south of Pinole where, according to Vitt, the upper part of the tuff is cut off by the Pinole fault. The Pinole Tuff is actually composed of several tuffs, breccias, and tuffaceous deposits. These various units differ considerably in bedding structures, textures, mineralogy, and chemistry.

The Pinole Tuff does not contain any flow rocks or intrusive rocks. It does, however, contain scoriaceous andesite bombs as much as 1 m in diameter in the "tuffaceous breccia" unit, which suggests that at least this particular unit was deposited fairly close to source.

There are strong similarities between the Pinole section and the Monticello Road section to the north. Both sections contain fine- to medium-grained gray pumice-lapilli tuffs near the base, are overlain by darker-colored andesitic tuffs containing scoria bombs, and are overlain in turn by lighter-colored more silicic pyroclastic deposits.

WIDESPREAD TUFFS INTERBEDDED WITH DETRITAL SEDIMENTARY DEPOSITS

WESTERN PART OF THE MAIN STUDY AREA

TUFF IN THE TYPE SECTION OF THE MERCED FORMATION (LOC. 1)

On the west side of the San Francisco peninsula, a 30- to 60-cm-thick fine-grained hornblende-bearing vitric tuff is exposed in the cliffs along the beach just south of Fleishhacker Zoo, in the type section of the Merced Formation (loc. 1) (Lawson, 1914; Hall, 1966). The tuff was deposited in marine water, is crossbedded and laminated, and in places contains considerable amounts of detrital material. Another outcrop of apparently the same tuff is exposed in a steep hillside north of Westmoor School southeast of locality 1. A tuff similar to the one in the Merced Formation has been found in a drill hole at 83 m below sea level in the Alameda Formation beneath west central San Francisco Bay (Trask and Rolston, 1951; fig. 1, loc. 2). Still another tuff (locs. 3 and 4) similar to the one in the type section of the Merced Formation has been uncovered 35 km to the southeast of locality 1, in the Santa Clara Formation, in a trench cut near the San Andreas fault zone at the town of Woodside.

Louderback (1951) and Hall (1966) suggested that the tuff in the type section of the Merced Formation and the tuff in the Alameda Formation are the same on the basis of refractive indices of glass, grain size, and mineralogy. Hall further suggested that the tuff may have had its source in the southern Cascade Range, near the town of Mineral, where two extensive pumice tuff flows crop out (Wilson, 1961; Gilbert, 1969).

TUFF IN THE MERCED(?) AND PETALUMA FORMATIONS OF SONOMA COUNTY (LOCS. 35–42)

Northwest of San Francisco in Sonoma County, a tuff of variable texture and grain size is interbedded with the lower and upper Pliocene Merced(?) Formation (Johnson, 1934; Weaver, 1949; Travis, 1952; Bartow and Addicott, 1971). This tuff is exposed almost continuously for a distance of 14.5 km. The tuff, deposited by water and in places containing detritus and invertebrate marine fossils, is coarsest in the east near Trenton, where pumice bombs as much as 20 cm in diameter are found, and near Roblar, where pumice cobbles several centimetres in diameter are found. To the west it becomes progressively finer and contains more detrital contamination. Johnson (1934), Louderboack (1951), and Hall (1966) have pointed out that the tuff in the Merced(?) Formation of Sonoma County and the tuff in the type section of the Merced Formation differ in mineralogy and refractive indices of glass and are consequently not correlative. The source of the tuff in the Merced(?) Formation of Sonoma County is not known, although judging from the coarse pyroclasts it contains, the source must have been nearby.

Still another exposure of a similar tuff has been found at Sears Point, in the Petaluma Formation, just north of San Pablo Bay, approximately 43 km southeast of the Trenton locality (Bartow and others, 1973). This tuff, also deposited by water, ranges in grain size from vitric-ash tuff to pumice-lapilli tuff.

SOUTHEASTERN PART OF THE MAIN STUDY AREA

In the east and southeast part of the study area (fig. 1), there are several tuffs exposed in late Cenozoic deposits most of which have been correlated with the Pinole Tuff by Vitt (1936) on the basis of refractive indices of glass and heavy mineralogy. However, many of these correlations are not justified since the refractive indices of glass and heavy-mineral species and frequencies differ widely between many of these tuffs.

LAWLOR TUFF (LOCS. 22–28)

The Lawlor Tuff, named for its type locality in Lawlor Ravine, N½ sec. 23, T. 2 N., R. 1 W., Contra Costa County, by Weaver (1949), is well exposed in the hills northeast of Mount Diablo. It trends east-west from near Markley Canyon in the east to near Port Chicago in the west, a distance of 19 km. The tuff is exposed for much of this distance, except for a short interval near Arnold Industrial Highway where, according to Patten (1947), it is cut off from its eastern and western exposures by normal faults.

The tuff is approximately 18 m thick south of Port Chicago and thins to the east, toward Markley Canyon, where it is about 4.5 m thick. The unit is massive and contains coarse light-bluish-gray to white pumice lapilli and some angular lithic volcanic fragments that are primarily bluish gray and brown felsite. The pumice lapilli are angular and tightly interlocked. The size of the lapilli decreases from west to east, from about 5–8 cm in maximum diameter near Port Chicago to about 0.6–1.2 cm at Markley Canyon. There is no obvious sorting or stratification in the unit. Textural features indicate that the Lawlor was most probably a pumice ash flow.

The Lawlor Tuff disconformably overlies the upper Miocene Neroly Formation along much of its length except in the vicinity of Arnold Industrial Highway, where it rests unconformably on the upper Eocene Markley Sandstone Member of the Kreyenhagen Formation. The uppermost part of the Neroly Formation contains white reworked pumice-lapilli tuff.

The Lawlor Tuff is overlain by the upper Pliocene Tehama Formation (Sims and Sarna-Wojcicki, 1975), formerly the Los Medanos Formation of Clark (1943, p. 189) or Wolfskill Formation of Weaver (1949), consisting primarily of sand and gravel. A thin discontinuous tuff, approximately 0.6 to 1.2 m thick, is about 8–9 m stratigraphically above the Lawlor Tuff west of Arnold Industrial Highway (loc. 16). The tuff contains rounded pumice lapilli in a matrix of fine glass shards. On the basis of its trace- and minor-element chemistry, mafic phenocryst abundances, and index of refraction, it is correlated with the Putah Tuff.

SOUTH OF MOUNT DIABLO

In the foothills immediately south of Mount Diablo several tuffs are interbedded with tightly folded late Cenozoic continental deposits. These strata are shown on the Geologic Map of California (Rogers, 1966) as "middle and/or lower Pliocene nonmarine sedimentary rocks," but the middle and upper part of the section may be as young as late Pliocene or Pleistocene, at least partly contemporaneous with the Pliocene and Pleistocene Livermore Gravels of Clark (1930) to the south, on the basis of correlation of the Lawlor eruptive unit.

The relative stratigraphic position of at least four tuff units is known. Perhaps three or four additional tuffs have been distinguished during the present study on the basis of their chemistry and mineralogy. Most of the tuffs are discontinuous. Oestreich (1958) has attempted to use the tuffs as marker beds for the contact between the Tassajara Formation and the Green Valley Formation of Clark (1943). Vitt (1936), again without sufficient justification, has correlated all but one of these tuffs with the Pinole Tuff on the basis of refractive indices of glass and heavy-mineral evidence.

Three of the tuffs (fig. 13) are exposed along Collier Canyon Road, along the flank of Highland syncline (Oestreich, 1958) (loc. 63, 63A–C).

The tuff at the base of the Highland syncline section (loc. 63A) is unsorted and contains pumice lapilli with some angular lithic fragments. This unit, about 2 m thick at most, is probably the peripheral part of an extensive ash flow. The other two tuffs in this section (loc. 63B, C) are reworked pumice-lapilli tuffs and tuffaceous sediments. The exposed thicknesses of these tuffs and tuffaceous sediments range from about 1 to 2 m, but the units are probably thicker. These three tuffs (loc. 63A–C) are correlated with the Pinole Tuff (loc. 52A–C) on the basis of rapid-scan data. A fourth and youngest tuff is exposed farther west, about 1 mile east of Danville, stratigraphically far above the other tuffs in the area (loc. 5). It is a massive very fine grained biotite-hornblende vitric tuff, about 1 m thick, and is probably a product of direct ash fall. The minor- and trace-element composition of this tuff indicates that it was probably erupted in the southern Cascade Range.

On the south side of Livermore Valley, in the Tesla quadrangle, two tuffs are interbedded with the Livermore Gravels[5] of Clark (1930) (fig. 9, locs. 31–34). These tuffs, first mentioned by Huey (1948), are well exposed at only one locality, a roadcut in a ridge between Arroyo Mocho and Arroyo del Valle. The lower tuff is approximately 3 m thick, the upper about 2 m thick. The tuffs are separated by a zone of tuffaceous sediments approximately 8 m thick. The tuffs were deposited by water: They are well stratified and show graded bedding, laminations, and soft-sediment deformation structures. A lower, massive part of both tuffs, up to about 30 cm thick, may be directly water-

[5]The dominant clastic sediments exposed here are clay and mud, with some lenses of gravel.

laid ash-fall material. The lower bed is correlated with the Lawlor Tuff on the basis of trace-element chemistry and petrographic criteria.

NORTHEASTERN PART OF THE STUDY AREA (FIG. 9, LOCS. 8–11, 12–15)

Two extensive units, the Nomlaki and Putah Tuff Members of the Tehama Formation, are interbedded with continental deposits of the late Pliocene Tehama Formation along the foothills bordering the west side of Sacramento Valley.

PUTAH TUFF MEMBER OF THE TEHAMA FORMATION (FIGS. 1, 9, LOCS. 12–15)

The Putah Tuff Member (Sims and Sarna-Wojcicki, 1975) has been well described by Miller (1966). According to Miller, the Putah crops out almost continuously from near Vacaville in the south to a few kilometres south of the Yolo–Colusa County boundary, a distance of about 64 km. The tuff is thickest (about 15 m) south of its type locality, Putah Creek, thinning to the north and south. The tuff is well stratified and in places contains rounded hard pumice lapilli, together with detrital sedimentary material, indicating that it is water deposited or reworked.

NOMLAKI TUFF MEMBER OF THE TEHAMA FORMATION (FIGS. 1, 9, LOCS. 8–11)

The Nomlaki Tuff Member is exposed discontinuously along the western side of northern Sacramento Valley for a distance of approximately 93 km, from north of Nye Creek to Cottonwood Creek. This tuff has been described by Russell (1931), Anderson and Russell (1939), Lydon (1967), and Miller (1966).

At its type locality at the former headquarters of the old Nomlaki Indian Reservation, about 6 miles northeast of Paskenta, the tuff is approximately 4 m thick but elsewhere ranges in thickness from about 1 m to about 30 m.

On the basis of its texture, sorting, lack of bedding, and absence of any lateral gradation in particle size, Russell (1931) concluded that the Nomlaki was produced by an ash flow that had its source to the east in the Mount Lassen area, where several exposures of its presumed correlative were found interbedded with the late Pliocene Tuscan Formation.

On the Geologic Map of California (Ukiah Sheet, Jennings and Strand, 1960; Santa Rosa Sheet, Koenig, 1963, scale 1:250,000) the Putah is shown as the Nomlaki. However, Miller (1966) has concluded that the two tuffs are different on the basis of refractive index of glass and feldspar composition, conclusions that are here confirmed by trace- and minor-element chemistry of the glasses in the tuffs.

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