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Correlation of the Rockland Ash Bed, a 400,000-Year-Old Stratigraphic Marker in Northern California and Western Nevada, and Implications for Middle Pleistocene Paleogeography of Central California

ANDREI M. SARNA-WOJCICKI,* CHARLES E. MEYER,* HARRY R. BOWMAN,† N. TIMOTHY HALL,‡ PAUL C. RUSSELL,* MARTA J. WOODWARD,‡ AND JANET L. SLATE§

*U.S. Geological Survey, Menlo Park, California 94025; †Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720; ‡Department of Geology, Stanford University, Palo Alto, California 94305; and §Department of Geology, University of Arizona, Tucson, Arizona 85721

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Outcrops of an ash bed at several localities in northern California and western Nevada belong to a single air-fall ash layer, the informally named Rockland ash bed, dated at about 400,000 yr B.P. The informal Rockland pumice tuff breccia, a thick, coarse, compound tephra deposit southwest of Lassen Peak in northeastern California, is the near-source equivalent of the Rockland ash bed. Relations between initial thickness of the Rockland ash bed and distances to eruptive source suggest that the eruption was at least as great as that of the Mazama ash from Crater Lake, Oregon. Identification of the Rockland tephra allows temporal correlation of associated middle Pleistocene strata of diverse facies in separate depositional basins. Specifically, marine, littoral, estuarine, and fluvial strata of the Hookton and type Merced formations correlate with fluvial strata of the Santa Clara Formation and unnamed alluvium of Willits Valley and the Hollister area, in northwestern and west-central California, and with lacustrine beds of Mohawk Valley, fluvial deposits of the Red Bluff Formation of the eastern Sacramento Valley, and fluvial and glaciofluvial deposits of Fales Hot Spring, Carson City, and Washoe Valley areas in northeastern California and western Nevada. Stratigraphic relations of the Rockland ash bed and older tephra layers in the Great Valley and near San Francisco suggest that the southern Great Valley emerged above sea level about 2 my ago, that its southerly outlet to the ocean was closed sometime after about 2 my ago, and that drainage from the Great Valley to the ocean was established near the present, northerly outlet in the vicinity of San Francisco Bay about 0.6 my ago.

INTRODUCTION

About 400,000 yr ago, a great volcanic eruption occurred near the present site of Lassen Peak, in the southern Cascade Range of northeastern California, producing widespread rhyolitic ash-flow sheets and wind-borne tephra. Although the location of the eruptive vent is unknown, the most likely source lies in the vicinity of Brokeoff Mountain, about 7 km southwest of Lassen Peak (M. A. Clynne, 1982, personal communication).

Fine ash from the eruption was carried downwind in all directions, and for distances of at least 400 km, forming a layer that covered much of northern California and western Nevada (Fig. 1), and probably a much wider area as well. Thus, this ash bed represents a widespread time–stratigraphic marker that permits correlation of Quaternary deposits of diverse and widely separated depositional environments: volcanic, fluvial, glaciofluvial, lacustrine, estuarine, and marine.

Our purpose is (1) to document the equivalence of this ash bed among its several outcrop and core localities, (2) to correlate the Quaternary deposits that contain this ash, and (3) to discuss the paleogeographic implications of the correlations. Coincidentally, we are able to compare the three methods of chemical identification that we have used.

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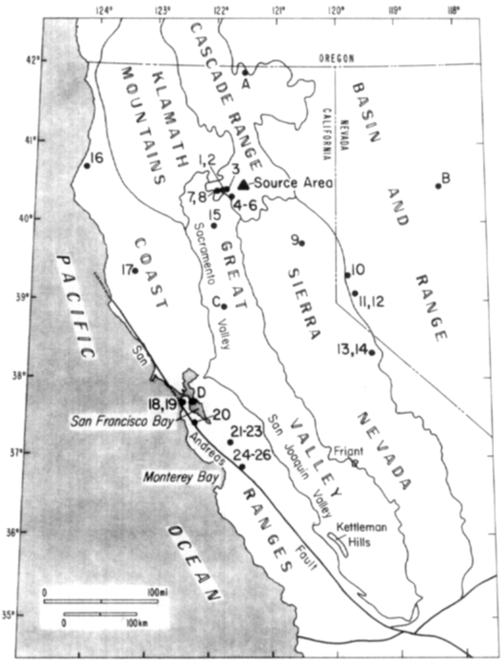

FIG. 1. Source area and sample locations of the Rockland tephra. Analytical data for samples from localities 1–26 are presented in this report. A–D, localities at which the Rockland ash has been identified; data for these localities are not presented here. A, Tulelake core sample (A. M. Sarna-Wojcicki, D. P. Adam, and C. E. Meyer, 1983, unpublished data); B, Oreana area (J. O. Davis, 1983, personal communication); C, Zemora wells area (E. J. Helley, 1982, personal communication); D, San Francisco Bay core sample (Sarna-Wojcicki, 1976).

PREVIOUS STUDIES OF THE ROCKLAND TEPHRA

The Rockland Pumice Tuff Breccia of Wilson (1961)

Wilson (1961) mapped the volcanic stratigraphy in the vicinity of the towns of Mineral and Manton southwest of Lassen Peak, in northeastern California (Fig. 2). He suggested that the valley in which the town of Mineral is situated is the eroded remnant of a volcanic caldera, and that the surrounding rugged hills and ridges, composed of volcanic flow rocks, are remnants of an ancient volcano which he named Mount Maidu. Accoring to Wilson, the climactic event in the history of Mount Maidu was an eruption that produced massive amounts of pumice ash-flow tuff and air-fall ash. Wilson informally named these deposits the Rockland pumice tuff breccia after Rockland School, located near the easternmost exposure of the ash-flow tuff about 16 km west of Brokeoff Volcano.[1]

Gilbert (1969) subdivided the Rockland pumice tuff breccia informally into the Lassen Lodge and Manton units (Fig. 2). On the basis of K–Ar analyses, Gilbert concluded that the Lassen Lodge unit was older than the Manton unit, but data presented here on the chemical composition and stratigraphy of the Rockland pumice tuff breccia and Rockland ash bed suggest that the two units are coeval.

Distal Localities of the Rockland Ash Bed

An ash layer southwest of San Francisco is interbedded with nearshore marine and nonmarine deposits in the upper part of the type section of the Merced Formation, where it was described by Hall (1965) (samples 18, 19: Figs. 1 and 3). Hall pointed out that the ash bed in the type Merced Formation was remarkably similar to the Rockland pumice tuff breccia. Based on petrographic characteristics and chemical analyses of volcanic glass, Sarna-Wojcicki (1976) supported Hall's suggestion, and also confirmed previous correlations of the ash bed in the Merced Formation with an ash bed in the Alameda Formation beneath San Francisco Bay (locality D), and with an ash exposed to the south, in the Santa Clara Formation (sample 20).

Wagner (1980) described an ash bed in

[1] In this study we use the informal name "Rockland ash bed" for the ash at distal localities because it is less cumbersome than Wilson's term. We have previously called it the "Maidu ash," following Wilson's suggestion that the ash was erupted from this volcano, but as L. J. P. Muffler and M. A. Clynne have pointed out, recent fission-track ages on the Rockland ash bed (Meyer *et al.*, 1980) are about 0.6 to 0.8 my younger than the youngest rocks erupted from Mount Maidu. We also use the informal term "Rockland tephra" to refer collectively to both the Rockland pumice tuff breccia of Wilson (1961) and the Rockland ash bed.

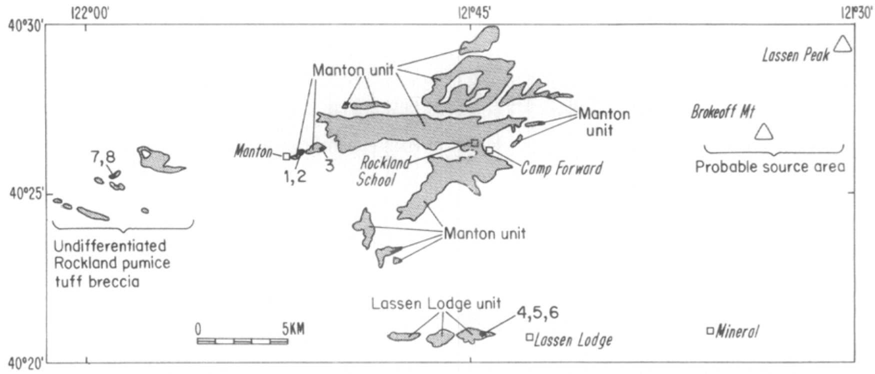

FIG. 2. Areal extent and sample locations of the near-source Rockland pumice tuff breccia. Geology from Wilson (1961), Gilbert (1969), Helley *et al.* (1981), and unpublished mapping by M. A. Clynne (1982, personal communication). The undifferentiated Rockland pumice tuff breccia of Wilson (1961) is locally divided into Manton and Lassen Lodge units of Gilbert (1969).

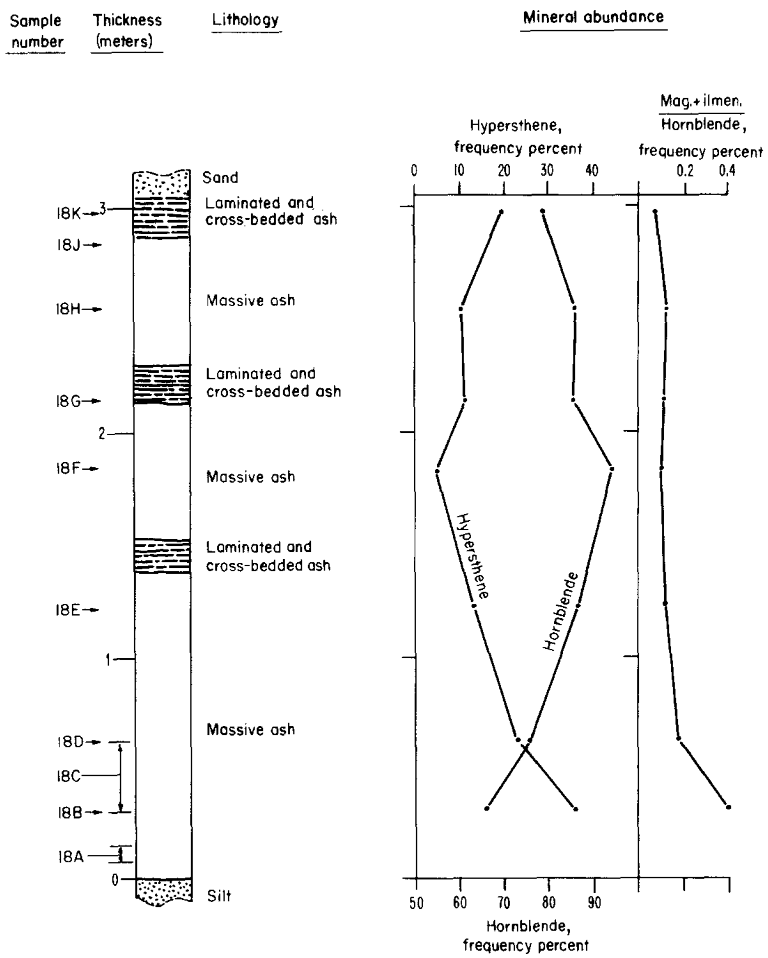

FIG. 3. Stratigraphy of the Rockland ash bed at locality 18 south of San Francisco and relative abundances of magnetic heavy minerals. Samples 18 A, C, and J collected for K–Ar and fission-track age analyses; remaining samples, for petrographic analysis.

the Hookton Formation of Ogle (1953), in the Humboldt basin of northwestern California (sample 16). He correlated this ash bed with the ash in the type Merced Formation south of San Francisco on the basis of chemical composition of the volcanic glass.

NEW LOCALITIES OF THE ROCKLAND ASH BED

We and other workers have found ash at several new distal exposures that we identify as the Rockland ash bed (Figs. 1 and 12; Table 1): (1) in the Mohawk Lake Beds of Turner (1891), northeastern California (sample 9; Fig. 1; Mathieson and Sarna-Wojcicki, 1982); (2) in outwash gravels of the Mount Rose fan, western Nevada (sample 10; Tabor and Ellen, 1975); (3) in alluvium south of Carson City, western Nevada (samples 11 and 12; Davis, 1978); (4) in outwash gravels of the Fales Hot Spring area, east-central California (samples 13, and 14; M. M. Clark, 1975, personal communication); (5) an ash bed overlying the Red Bluff Formation in the vicinity of the town of Vina, in north-central California (sample 15; Harwood *et al.*, 1981); (6) in alluvium of Willits Valley, northwestern California (sample 17; R. J. Janda, 1976, personal communication); (7) in the Santa Clara Formation southeast of the city of San Jose, west-central California (samples 21–23; this report); and (8) in alluvium west of the town of Hollister, west-central California (samples 24–26; D. Oberste-Lehn, 1974, personal communication).[2]

EXTENT AND VOLUME OF TEPHRA

About 400,000 yr of erosion have stripped the ash from most of the area where it was once deposited and concentrated it in depositional basins where it is now buried. It is exposed only at sites where rates of crustal uplift and recent erosion are sufficiently rapid to expose it. These factors make it difficult to estimate the original areal extent and volume of the ash deposited downwind from this eruption.

The proximal air-fall tephra layer of the Rockland ash bed at the locality of samples 1 and 2 is at least 6 m thick and possibly as much as 12 m (Fig. 4). This locality is probably no farther than 15 to 40 km away from the vent, judging by the coarseness of the pumice lapilli in the air-fall deposit and the coarseness of pumice clasts in the associated ash-flow tuff. The initial air-fall thickness of the distal Rockland ash bed can be determined at only a few sites. For instance, in the Hookton Formation of the Humboldt basin, about 220 km from the source area, the total thickness of the Rockland ash bed is as much as 40–50 cm, and the massive, basal air-fall layer is about 23 cm thick (sample 16, Fig. 1; M. E. Perkins, 1982, personal communication). This locality is at the margin of the presently known ash distribution (Fig. 1), and thus was probably not situated along the thickest part of the air-fall lobe.

At comparable distances from the source area the Rockland ash bed is about as thick or thicker than the Mazama ash bed (Fig. 5), a widespread tephra layer from an eruption in the vicinity of Crater Lake, Oregon (Williams and Goles, 1968; Bacon, 1983) about 6800–7000 yr ago. Thus, the eruption that produced the Rockland tephra was probably as great as, or greater than, that of Mount Mazama, estimated to have produced 50–70 km^3 of tephra (Williams and Goles, 1968; Bacon, 1983).

Because the eruption of Mount Mazama covered at least 1,700,000 km^2 with ash (Sarna-Wojcicki *et al.*, 1984b) we expect that the extent of the Rockland ash bed is much greater than the approximately 200,000-km^2 minimum area shown in Figure

[2] New data indicate the Rockland ash bed is present in core samples obtained from Tulelake, northern California, 160 km north of the eruptive source area (A. M. Sarna-Wojcicki, C. E. Meyer, and D. P. Adam, 1983, unpublished data); locality A, Fig. 1), and in surface outcrops near Oreana in northern Nevada, about 280 km east of the eruptive source area (J. O. Davis, 1983, personal communication; locality B, Fig. 1).

TABLE 1. Locations of Ash Samples Correlated with the Rockland Tephra, and Methods by Which Glass of Each Sample Has Been Analyzed

Sample No.	Tephra unit	County, state	Quadrangle	Township and range
	Proximal tephra: Rockland Pumice Tuff Breccia of Wilson (1961)			
1	Manton unit; air-fall ash	Tehama, Calif.	Manton 15′	30N, 1E
2	Same loc. as 1; strat. below 1; air-fall ash	Tehama, Calif.	Manton 15′	30N, 1E
3	Manton unit; ash-flow tuff	Tehama, Calif.	Manton 15′	30N, 1E
4	Lassen Lodge unit; ash-flow tuff	Tehama, Calif.	Lassen Peak 15′	29N, 2E
5	Same loc. as 4; strat. below 4; ash-flow tuff	Tehama, Calif.	Lassen Peak 15′	29N, 2E
6	Same loc. as 4; strat. below 5; ash-flow tuff	Tehama, Calif.	Lassen Peak 15′	29N, 2E
7	Undifferentiated, reworked air-fall ash	Shasta, Calif.	Manton 15′	30N, 1W
8	Undifferentiated, reworked air-fall ash	Shasta, Calif.	Manton 15′	30N, 1W
	Distal Tephra: Rockland Ash Bed, Air-Fall, and Reworked Air-Fall Ash			
9	Ash bed in Mohawk Lake Beds	Plumas, Calif.	Blairsden 7.5′	22N,13E
10	Ash bed in alluvium of Mount Rose fan	Washoe, Nev.	Washoe City 7.5′	17N,19E
11	Ash bed in unnamed alluvium near Carson City	Carson City, Nev.	Dayton 15′	15N,20E
12	Duplicate of 11; same stratigraphic interval	Carson City, Nev.	Dayton 15′	15N,20E
13	Ash bed in unnamed glacio(?)fluvial outwash	Mono, Calif.	Fales Hot Sprgs 7.5′	6N,23E
14	Duplicate of 13; same stratigraphic interval	Mono, Calif.	Fales Hot Sprgs 7.5′	6N,23E
15	Ash bed overlying Red Bluff Formation	Tehama, Calif.	Vina 7.5′	25N, 1W
16	Ash bed in Hookton Formation (Railroad Gulch ash bed)	Humboldt, Calif.	Fields Landing 7.5′	4N, 1W
17	Ash bed in unnamed alluvium, near Willits	Mendocino, Calif.	Willits 15′	18N,13W
18	Ash bed in Merced Formation, Olympic Golf Course	San Mateo, Calif.	San Francisco S. 7.5′	3S, 6W
19	Ash bed in Merced Formation, coast, storm sewer outlet	San Francisco, Calif.	San Francisco S. 7.5′	2S, 6W
20	Ash bed in Santa Clara Formation, near Woodside	San Francisco, Calif.	Woodside 7.5′	6S, 4W
21	Ash bed in Santa Clara Formation, near San Jose	Santa Clara, Calif.	Morgan Hill 7.5	8S, 2E
22	Same loc. as 21, stratigraphically below 21	Santa Clara, Calif.	Morgan Hill 7.5	8S, 2E
23	Same loc. as 21, stratigraphically below 22	Santa Clara, Calif.	Morgan Hill 7.5	8S, 2E
24	Ash bed in unnamed alluvium, Lomerias Muertas	San Benito, Calif.	Chittenden 7.5	12S, 4E
25	Same loc. as 24, same stratigraphic interval	San Benito, Calif.	Chittenden 7.5	12S, 4E
26	Same loc. as 24, same stratigraphic interval	San Benito, Calif.	Chittenden 7.5	12S, 4E

[a] INAA, instrumental neutron activation analysis (Table 2); EMA, electron-microprobe analysis (Table 3); XES, energy-dispersive X-ray fluorescence spectrometric analysis (Table 4).

[b] Spanish-Mexican land grants. Locations are given in geographic coordinates of degrees, minutes, and hundredths of minutes.

TABLE 1—*Continued*

Section, 1/4, 1/16 section	Collector	Field No.	Type of analysis[a] INAA	EMA	XES
Proximal tephra: Rockland Pumice Tuff Breccia of Wilson (1961)					
21, NE1/4 of SE1/4	A. M. Sarna-Wojcicki	RPT(M)6A	x	x	x
21, NE1/4 of SE1/4	A. M. Sarna-Wojcicki	RPT(M)7	x	x	
22, E1/2 center	A. M. Sarna-Wojcicki	RPT(M)8	x	x	x
22, SW1/4 of SW1/4	A. M. Sarna-Wojcicki	RPT(L)3	x		x
22, SW1/4 of SW1/4	A. M. Sarna-Wojcicki	RPT(L)4	x		x
22, SW1/4 of SW1/4	A. M. Sarna-Wojcicki	RPT(L)5	x	x	x
28, W1/2 center	A. M. Sarna-Wojcicki	RPT-11	x		x
28, W1/2 center	A. M. Sarna-Wojcicki	RPT-12	x		
Distal Tephra: Rockland Ash Bed, Air-Fall, and Reworked Air-Fall Ash					
19, SW1/4 of NW1/4	S. A. Mathiesen	SAM-38		x	x
13, NE1/4 of NW1/4	R. W. Tabor	RWT-102-74	x	x	
35, NW1/4 of SE1/4	J. O. Davis	LAH-3		x	x
34, NW1/4 of SE1/4	J. O. Davis	LD-67			x
23, SE1/4 of NW1/4	M. M. Clark	MMC-1	x		x
23, SE1/4 of NW1/4	M. M. Clark	MMC-2	x	x	
31, center of W1/2	E. J. Helley	VINA-1	x	x	
35, NW1/4 of NW1/4	M. E. Perkins	RRG-1		x	x
32, SW1/4 of NE1/4	A. M. Sarna-Wojcicki	WILL-2	x	x	x
N37°42.35′W122°29.47′[b]	A. M. Sarna-Wojcicki	KA-1	x		
N37°42.85′W122°30.17′	A. M. Sarna-Wojcicki	KA-4	x		
N37°26.15′W122°16.70′	A. M. Sarna-Wojcicki	WO-1	x	x	x
N37°12.23′W121°42.73′	A. M. Sarna-Wojcicki	SC-5		x	x
N37°12.23′W121°42.73′	A. M. Sarna-Wojcicki	SC-6		x	x
N37°12.23′W121°42.73′	A. M. Sarna-Wojcicki	SC-7		x	
N36°53.35′W122°16.70′	D. Oberste-Lehn	LMT-1	x		x
N36°53.35′W122°16.70′	D. Oberste-Lehn	LMT-2	x		
N36°53.35′W122°16.70′	D. Oberste-Lehn	LMT-3	x	x	x

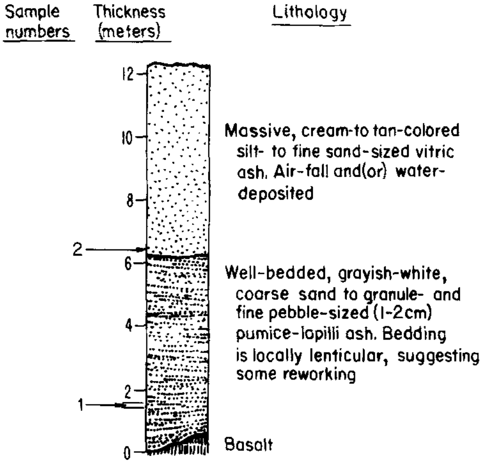

FIG. 4. Stratigraphy of the Rockland ash bed = Manton unit (of Gilbert, 1969) of the Rockland pumice tuff breccia of Wilson (1961) showing locations of samples 1 and 2.

1. One reason why the ash may not have been found in areas further to the north and east than shown on Figure 1 is that rates of uplift, and consequently of erosion and exposure, are slower in this region compared to those in western Nevada and California. Alternatively, directions of prevailing winds at the time of the eruption of the Rockland ash bed may have been different than those at the present.

METHODS

We disaggregated and sieved tephra samples and separated glass and phenocrysts using methylene iodide–acetone solutions and a magnetic separator (Sarna-Wojcicki, 1976; Sarna-Wojcicki *et al.*, 1979, 1984a). We analyzed glass separates by instrumental neutron-activation (INAA) for 20 elements, electron microprobe (EMA) for 12 elements, and energy-dispersive X-ray fluorescence (XES) for 13 elements. In XES analysis, we determined spectral characteristics in the form of peak intensity ratios rather than actual concentrations to avoid the extra steps required to run standards, and the associated errors. Sarna-Wojcicki *et al.*, (1984a) have given the details of XES and EMA analytical methods

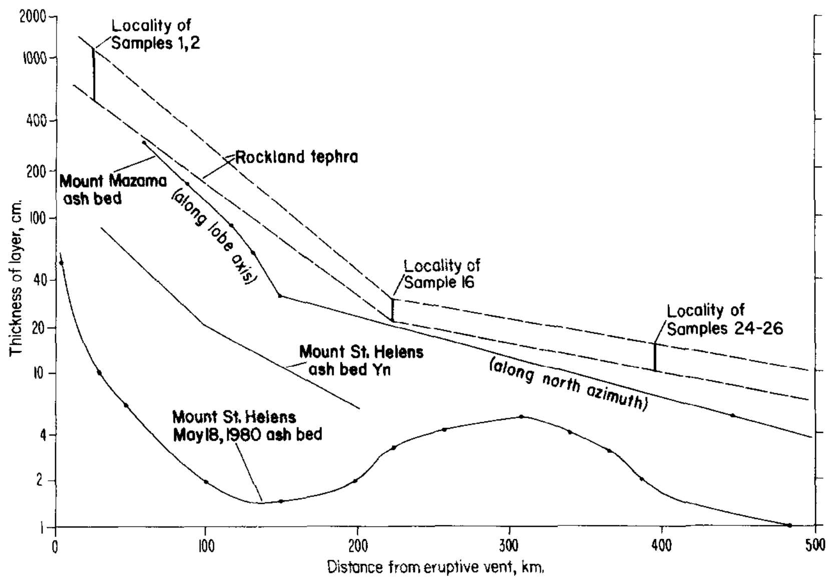

FIG. 5. Variation in thickness of several air-fall tephra layers with distance from the source, compared to the thickness of the Rockland (air-fall) tephra. Dashed lines represent our minimum and maximum estimates of the thickness of air-fall tephra, based on thickness data from three exposures. Note that the two distal localities of the Rockland ash bed (loc. 16 and 24–26) are near the margins of the known area of distribution (Fig. 1) and, consequently, probably do not represent the maximum thicknesses of the air-fall ash bed at those distances. Figure is modified from Shipley and Sarna-Wojcicki (1982).

used, and Sarna-Wojcicki *et al.* (1979) have discussed the INAA analytical methods used.

For purposes of correlation, we selected elements on the basis of their natural variability, both within individual tephra units and among units of different age, as well as according to precisions attainable for each element in silicic glasses by the three analytical methods (Sarna-Wojcicki *et al.*, 1979, 1984a). Chemical compositions of volcanic glass samples were matched using the similarity coefficient (SIMANAL) (Borchardt *et al.*, 1972; Sarna-Wojcicki, 1976; Sarna-Wojcicki *et al.*, 1979) and standard deviations of averages of ratios of element concentrations (RATIONAL) (Sarna-Wojcicki *et al.*, 1984a) (Fig. 6). We compared the chemical composition of glass of the Rockland ash bed with compositions of tephra layers of different ages—layers that are stratigraphically above or below the Rockland ash bed, or are of demonstrably different age on the basis of other criteria (Fig. 7).

PETROGRAPHIC CHARACTERISTICS OF THE ROCKLAND TEPHRA

The ash-flow phase of the Rockland pumice tuff breccia is composed of sparse pumice clasts in an abundant matrix of vitric-crystal ash. The air-fall ash and fluvially reworked tephra are composed of pumic lapilli and vitric-crystal ash. The dominant constituent of both proximal and distal air-fall ash is glass shards of several types: elongate pumice shards with tubular or elongate, spindle-shaped vesicles, and subordinate frothy, irregularly shaped pumice shards with spherical or ovoid vesicles (Fig. 8). Irregular, curved solid-glass or poorly vesiculated bubble-wall junction and ribbed bubble-wall shards predominate in the finer ash, with pumiceous shards subordinate. Refractive index of the volcanic glass ranges from 1.499 to 1.501, with 1.499 and 1.500 being the most common.

Near the source, the ash (both air-fall and ash-flow phases) contains about 10% lithic fragments and about an equal amount of plagioclase feldspar (Wilson, 1961). In addition, minor glass coated dark-green to brown hornblende, and hypersthene, augite, magnetite, ilmenite, apatite, and zircon are present. At proximal sites, hornblende and hypersthene are nearly equal in abundance, but hornblende increases with distance relative to hypersthene (Fig. 9), possibly because the more equant and denser hypersthene falls out closer to the volcanic source, or because of preeruption zoning in the magma chamber.

CHEMICAL COMPOSITION OF THE ROCKLAND TEPHRA

The Rockland pumice tuff breccia is rhyolithic in bulk composition, containing about 71% silica (Table 2). It is similar in silica content and predominance of sodium over potassium to widespread silicic tephra erupted from the high Cascade Range, and most similar to tephra erupted from the southern part of that range; it differs markedly from widespread silicic tephra erupted from other major Quaternary volcanic source areas of the western United States (Fig. 10).

Chemical analyses by the three different methods (INAA, EMA, and XES; Tables 3–5; Figs. 6 and 7) indicate that glass of the Rockland tephra is homogeneous and identical within analytical error for all samples analyzed. These analyses confirm equivalence of the Manton and Lassen Lodge units of the Rockland pumice tuff breccia and of proximal and distal samples. There is no chemical difference between glass of the air-fall and ash-flow facies of the proximal tephra.

Concentrations of elements in glass of other late Cenozoic ash beds differ significantly from the Rockland ash bed (Figs. 6 and 7). For example, the samarium content of glass in the Rockland tephra has a narrow range of 0.17 ppm (Table 3) and does not overlap with that of the Nomlaki Tuff Member of the Tehama and Tuscan formations, chemically the most similar tephra unit to the Rockland ash bed (Fig. 11).

Of the three analytical methods used,

INAA

	1	2	3	4	5	6	7	8	10	13	14	15	17	18	19	20	24	25	26	DB	LC	BP	RD	NM
1	0	98	98	97	97	97	98	97	97	97	97	95	96	96	97	96	95	95	96	69	42	58	52	80
2	2	0	98	97	97	98	98	98	97	97	98	96	96	97	98	97	95	96	96	69	43	58	52	79
3	3	3	0	96	96	97	97	98	96	97	97	95	96	97	97	96	95	95	96	68	42	58	51	78
4	5	4	6	0	96	97	96	97	97	96	98	96	96	96	97	97	95	95	97	69	43	57	52	79
5	4	3	5	4	0	96	97	96	95	95	97	94	94	95	96	95	93	94	95	71	43	58	52	80
6	4	3	4	4	5	0	98	98	98	98	98	96	97	97	97	97	96	96	97	69	42	58	51	78
7	3	2	3	5	5	3	0	97	97	97	97	95	96	96	96	96	95	95	95	70	42	59	52	79
8	4	3	4	3	3	2	3	0	98	97	99	96	97	97	98	97	96	96	97	69	43	57	51	78
10	4	4	5	4	5	3	3	3	0	97	97	96	97	97	98	97	96	96	97	69	42	58	51	78
13	3	3	4	5	4	3	3	3	4	0	98	96	98	98	98	97	96	97	98	68	42	57	51	78
14	4	4	5	3	4	3	4	2	4	3	0	97	97	98	98	98	96	97	98	69	42	57	51	78
15	5	5	6	4	5	4	5	4	5	4	4	0	98	97	97	97	97	97	97	67	42	56	51	78
17	4	3	4	4	4	2	3	2	4	3	3	3	0	98	97	97	97	97	98	67	42	57	51	77
18	4	4	5	4	4	3	4	3	4	4	3	4	3	0	98	98	97	97	98	67	42	57	51	78
19	4	3	5	4	3	3	4	2	3	3	2	4	3	2	0	98	97	97	98	68	42	57	51	78
20	4	4	5	4	5	3	4	3	3	3	3	4	4	3	4	0	97	97	97	67	42	56	51	78
24	6	6	7	6	6	4	6	4	5	5	4	4	4	3	4	4	0	97	98	67	41	56	50	77
25	6	6	7	6	6	4	6	4	6	5	4	5	5	3	5	5	4	0	97	68	41	57	51	78
26	5	4	6	4	4	3	5	3	5	3	2	4	3	3	2	4	3	4	0	68	42	56	51	78
DB	29	28	28	29	28	29	29	28	28	27	28	29	27	29	28	28	30	28	29	0	52	72	50	71
LC	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0	50	29	42
BP	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0	47	61
RD	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0	65
NM	23	23	24	22	24	24	24	24	23	24	24	23	24	23	24	23	24	24	24	64	31	93	60	0

EMA

	1	2	3	6	9	10	11	12	14	15	16	17	18	20	21	22	23	26	LT	DB	LC	BP	RD	NM
1	0	97	97	97	96	95	95	95	96	97	94	96	96	95	98	98	96	96	77	75	72	69	69	93
2	4	0	97	98	96	96	98	98	99	99	97	99	96	96	97	97	97	96	78	74	71	69	70	93
3	3	4	0	97	96	97	97	95	96	96	95	96	97	96	97	98	97	96	77	75	72	69	68	91
6	4	2	4	0	97	96	97	96	97	98	95	97	96	95	96	96	95	97	78	75	71	68	71	95
9	6	6	7	5	0	94	95	94	95	96	93	95	96	95	96	96	95	97	77	75	71	68	71	93
10	6	6	4	7	12	0	97	95	95	95	95	95	95	95	94	96	96	93	79	75	72	69	68	90
11	6	2	4	4	9	5	0	97	99	97	98	98	97	98	95	97	98	95	79	75	71	70	69	92
12	8	4	7	6	10	7	4	0	97	97	98	99	95	95	95	95	96	94	79	74	70	69	71	94
14	6	2	5	3	7	6	2	5	0	98	97	98	97	98	96	96	97	97	79	75	70	69	70	93
15	5	2	5	3	5	7	5	5	4	0	95	98	95	95	96	97	97	96	77	74	71	70	70	93
16	9	5	7	7	12	6	4	3	5	7	0	97	96	97	94	96	97	95	80	74	70	69	71	93
17	6	2	6	4	8	6	3	2	4	3	4	0	95	96	96	96	97	95	79	74	71	69	70	93
18	6	5	5	5	9	6	4	9	4	7	8	7	0	98	96	98	97	98	80	76	71	68	70	93
20	7	5	5	5	9	6	3	8	3	7	7	6	3	0	95	97	98	96	80	76	71	69	69	92
21	3	5	4	5	7	7	6	9	6	5	10	7	6	7	0	98	97	96	77	74	71	68	70	93
22	3	4	2	5	9	5	4	8	5	5	8	6	5	6	3	0	99	96	78	75	72	70	69	92
23	4	3	3	4	8	5	3	7	4	4	7	5	5	5	4	2	0	96	78	75	72	70	68	91
26	6	5	7	4	5	9	6	9	4	5	9	7	4	5	5	6	5	0	79	74	70	68	71	93
LT	37	37	35	39	45	32	34	37	36	40	34	37	33	33	38	35	34	39	0	74	71	61	79	78
DB	89	91	83	96	•	78	84	93	90	97	87	92	83	83	90	83	84	96	48	0	80	80	61	75
LC	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	58	0	77	60	68
BP	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	84	32	56	0	50	65
RD	36	34	36	34	33	36	34	34	33	34	33	34	32	34	32	34	34	30	31	49	63	68	0	75
NM	9	7	9	7	10	8	7	6	7	8	5	6	8	9	9	9	8	9	42	36	48	41	39	0

XES

	1	3	4	5	6	7	9	11	13	16	17	20	21	22	24	26	LT	DB	LC	BP	RD	NM	G1
1	0	96	97	97	98	95	97	95	98	98	98	99	97	95	98	97	70	76	63	65	69	90	84
3	5	0	94	93	95	94	95	93	95	95	94	95	95	93	94	93	68	73	61	65	69	89	83
4	3	7	0	98	97	94	95	96	97	97	97	97	96	95	96	96	70	74	63	63	70	89	84
5	3	6	3	0	96	93	96	97	97	97	98	98	96	96	96	97	70	75	63	64	70	90	85
6	2	6	4	4	0	93	97	95	97	97	97	98	97	94	97	96	70	75	63	64	70	90	84
7	7	8	8	7	9	0	93	94	94	94	94	95	94	94	95	93	68	74	61	67	67	88	80
9	4	6	6	5	4	10	0	95	97	97	97	96	97	94	95	96	69	76	64	65	69	90	84
11	6	8	5	5	6	8	6	0	97	96	96	95	97	98	94	95	69	74	62	64	70	89	85
13	3	6	4	3	4	8	4	3	0	98	97	97	98	96	96	96	69	75	63	64	70	89	85
16	2	6	4	3	4	8	5	5	3	0	98	98	97	95	97	96	70	76	64	64	70	89	85
17	2	6	4	3	4	7	4	6	4	3	0	98	98	95	97	97	70	76	64	64	69	90	83
20	1	5	3	3	3	7	5	5	3	2	3	0	97	95	97	97	70	75	63	64	70	90	84
21	4	6	5	4	4	8	3	4	3	3	3	4	0	96	95	96	69	75	63	65	69	89	84
22	6	8	7	5	8	7	7	4	5	6	6	6	6	0	94	95	68	74	62	66	70	88	85
24	4	8	5	4	5	9	7	8	7	5	4	4	7	9	0	97	70	75	64	64	69	91	82
26	4	8	5	3	5	10	5	7	5	4	4	5	6	7	4	0	70	76	65	64	70	91	84
LT	63	69	64	60	63	63	62	61	64	62	61	62	62	61	61	59	0	77	72	64	71	73	61
DB	60	67	62	59	60	60	60	57	61	59	59	60	59	57	60	59	36	0	79	79	59	71	69
LC	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	60	59	0	77	56	65	61
BP	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	69	52	40	0	54	62	58
RD	77	82	72	76	76	81	80	79	80	78	75	77	79	82	74	76	47	•	98	•	0	74	72
NM	14	15	14	14	13	18	13	15	15	14	14	14	14	17	14	13	32	41	55	59	32	0	81
G1	28	29	26	26	27	33	25	25	24	26	27	28	24	26	29	26	55	49	67	69	47	35	0

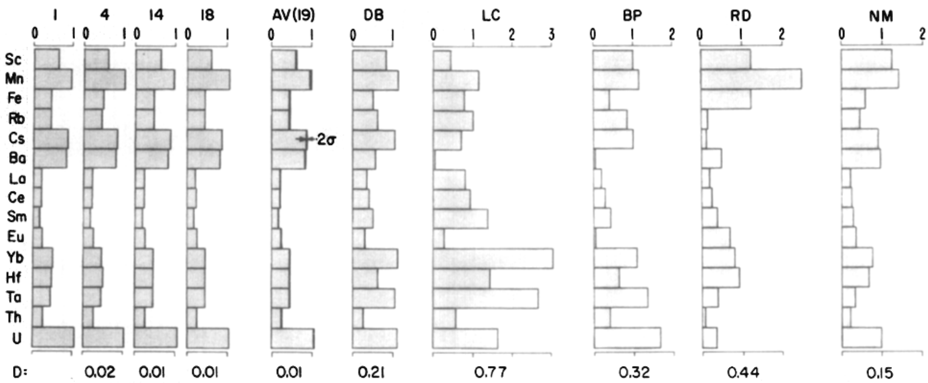

FIG. 7. Histograms from INAA analyses showing abundances of major, minor, and trace elements in volcanic glass of the Rockland tephra, and comparison to other tephra layers. Values shown are ratios of concentrations of elements in glass of tephra layers to concentrations of same elements in U.S. Geological Survey rock standard G-1. Sample 1, Manton unit (of Gilbert, 1969) and sample 4, Lassen Lodge unit (of Gilbert, 1969) of the Rockland pumice tuff breccia of Wilson (1961) (Fig. 2); samples 14 and 18, distal Rockland ash bed (fig. 1); AV (19), average of 19 samples of the Rockland tephra (an interval of 2 SD is indicated by the width of black bar on right side of shaded block for each element); DB, Dibekulewe (ash) Bed of Davis (1978); LC, Lava Creek-B ash bed; BP, Bishop ash bed; RD, ash bed in the upper part of the Rio Dell Formation; NM, Nomlaki Tuff Member of the Tehama and Tuscan formations. See Fig. 1 and Tables 1 and 4 for locations of tephra samples. D, average of absolute differences of ratios between sample 1 and, successively, each of the other samples.

compositional contrasts between the Rockland tephra and its closest relative, the Nomlaki Tuff Member, are highest in XES analysis, but there is somewhat more scatter in the data compared to INAA analyses (Fig. 6). EMA analysis shows least contrast between similar tephra layers, and it is difficult to distinguish the Rockland ash bed from the Nomlaki Tuff by this method.

CORRELATIONS AND PALEOGEOGRAPHY

Identification of the Rockland tephra at proximal and distal localities, combined with a fission-track age of about 400,000,[3]

[3] Meyer *et al.* (1980), have determined an age of 450,000 ± 0.08 yr for the Rockland ash bed using the fission-track method on zircons (localities 18 and 19), but have cautioned that the true age of this ash bed may be somewhat younger owing to the possibility of detrital or xenocrystic contamination. Recent fission-track analyses of zircons of the proximal ash-flow facies of the Rockland pumic tuff breccia suggest a younger age of about 400,000 yr for this unit (C. E. Meyer and A. M. Sarna-Wojcicki, 1984, unpublished data). Any detrital or xenocrystic zircons present in the ash-flow facies would be annealed by the heat of the flow, thus we consider the younger age more trustworthy.

FIG. 6. Similarity coefficients (SIMANAL) of Borchardt *et al.* (1972), upper right half of matrices, and standard deviations of averages of ratios of sample pairs (RATIONAL), lower left half of matrices, comparing compositions of glass samples of the Rockland tephra with each other and with samples from other tephra layers. Matrices compare data sets obtained by instrumental neutron activation (INAA), electron-microprobe (EMA), and energy-dispersive X-ray fluorescence (XES) analyses. Values in matrices are percentages. For an identical sample pair, SIMANAL values are 100% and RATIONAL values are 0%. *, RATIONAL values exceeding 99%. Samples 1–26, Rockland tephra; LT, ash bed in Hookton Formation of Ogle (1953) near town of Loleta; DB, Dibekulewe (ash) Bed on Davis (1978); LC, Lava Creek-B ash bed; BP, Bishop ash bed; RD, ash bed in upper part of the Rio Dell Formation; NM, Nomlaki Tuff Member of the Tehama and Tuscan Formations; G-1, U.S. Geological Survey Granite Standard G-1. See Figure 1 and Tables 1 and 4 for locations of tephra samples. See Figure 12 for stratigraphic relations of tephra layers.

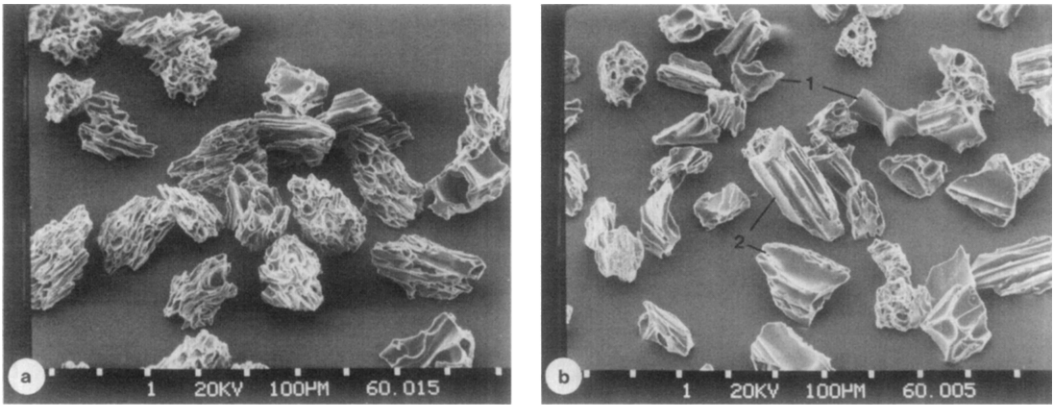

FIG. 8(a). Scanning electron micrograph of elongate pumice shards with elongate vesicles and frothy, irregularly shaped pumice shards with spherical or ovoid vesicles. Sized separately from locality of sample 4. (Photograph by R. L. Oscarson, U.S. Geological Survey.) (b) Scanning electron micrograph of solid-glass or poorly vesiculated bubble-wall junction (1) and ribbed bubble-wall shards (2). Sized separately from locality of sample 22. (Photograph by R. L. Oscarson, U.S. Geological Survey.)

allows us to correlate and date middle Pleistocene deposits of diverse facies, and to demonstrate broad synchrony of geologic events within the study region (Fig. 12). The Rockland ash bed correlates proximal volcaniclastic deposits southwest of Lassen Peak with unnamed fluvial deposits near Hollister in the southern Coast Ranges (samples 24–26), fluvial and lacustrine deposits of the Santa Clara Formation in the central Coast Ranges (samples 20 to 23), unnamed alluvium in Willits Valley in the northern Coast Ranges (sample 17), unnamed alluvium near Carson City in western Nevada (samples 11 and 12), glaciofluvial outwash of the Mount Rose alluvial fan in western Nevada (sample 10), and unnamed glaciofluvial outwash or al-

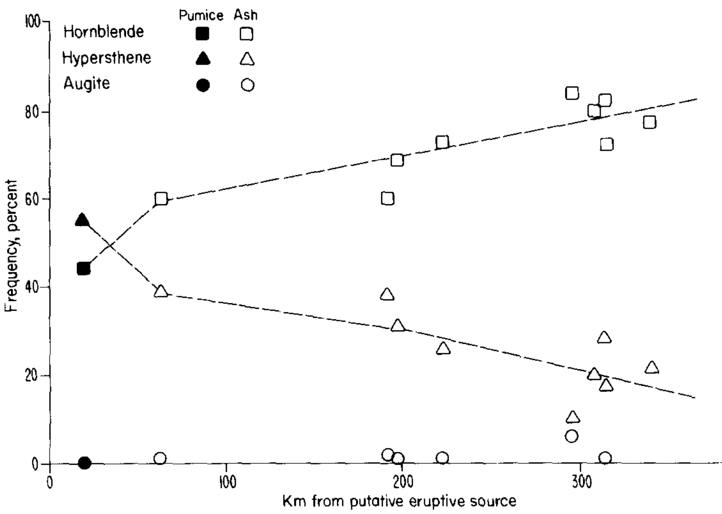

FIG. 9. Downwind variation in relative amounts of hornblende, hypersthene, and augite in the Rockland tephra, determined by line frequency counts. Distances are measured from Brokeoff Mountain, near the presumed source area. Sample at 295 km probably contains both detrital and pyrogenic augite.

TABLE 2. BULK CHEMICAL COMPOSITION OF PUMICE OF THE ROCKLAND PUMICE TUFF BRECCIA OF WILSON (1961), LASSEN LODGE UNIT OF GILBERT (1969)

Oxide	Analysis[a] 1	2
SiO_2	69.44	71.32
Al_2O_3	14.46	14.85
FeO	1.81	1.86
Fe_2O_3	0.98	1.01
CaO	2.62	2.69
MgO	1.32	1.36
Na_2O	3.44	3.53
K_2O	2.73	2.80
MnO	0.04	0.04
TiO_2	0.30	0.31
P_2O_5	0.07	0.07
H_2O +105,	0.15	0.15
H_2O −105,	2.76	—
CO_2	Nil	—

[a] Analysis 1 is cited in Wilson (1961) of "Dacite pumice, east of Ponderosa Sky Ranch, near well," in the Manton 15′ quadrangle, close to our sample localities 4–6; analysis 2 recalculated without the 2.76% absorbed water results in a rhyolitic composition. Analyses are in oxide weight percent. Analyst, W. H. Herdsman, Glasgow, Scotland.

luvium near Fales Hot Spring in east-central California (samples 13 and 14). On the basis of our correlation of the Rockland ash bed, the glaciofluvial outwash at the locality of samples 13 and 14 is younger than the Sherwin Till, which underlies the Bishop Tuff (0.7 my), is presumably roughly coeval with a post-Sherwin till, and is older than the Tahoe Till, which it underlies (M. M. Clark, 1982, personal communication; Fig. 12).

The Rockland ash bed also correlates all these above-mentioned deposits with fluvioestuarine, littoral, and marine deposits of the type Merced Formation south of San Francisco (samples 18 and 19), fluvial, estuarine, and marine strata of the Hookton Formation in the Humboldt Basin, northwestern coast ranges (sample 16), and the Mohawk Lake Beds in the northern Sierra Nevada (sample 9; Fig. 12).

The Rockland ash bed overlies the Red Bluff Formation in the area east of Vina and Los Molinos, in northeastern Sacramento Valley (sample 15; Figs. 1 and 12). The olivine basalt of Deer Creek, dated at 1.08 ± 0.16 my by the K–Ar method, underlies the Red Bluff Formation in the same area (Harwood *et al.*, 1981). These two dates thus constrain the age of the Red Bluff Formation between about 0.40 and 1.1 my, and indicate that the Red Bluff Formation is broadly correlative with the Turlock Lake Formation, the upper part of the Tulare Formation, and with the Corcoran Clay Member of these two formations, in the San Joaquin Valley (Fig. 1).

The Rockland ash bed also provides a

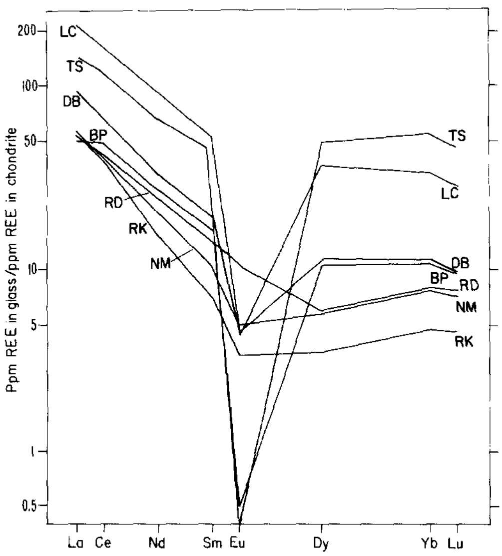

FIG. 10. Rare-earth element concentrations in volcanic glass of tephra layers erupted from different volcanic provinces, shown as ratios to Leedey's chondrite (Masuda *et al.*, 1973). LC, Lava Creek-B ash bed, erupted from the Yellowstone caldera complex, Wyoming and Idaho; TS, Tsankawi pumice bed of the Bandelier Tuff, erupted from the Valles–Toledo caldera complex in northern New Mexico (Izett *et al.*, 1972); DB, Dibekulewe (ash) bed of Davis (1978), location of eruptive vent unknown; BP, Bishop ash bed, erupted from the Long Valley caldera of east-central California; RD, ash in the upper part of the Rio Dell Formation, location of eruptive vent unknown but probably in the central Cascade Range; NM, Nomlaki Tuff Member of the Tehama and Tuscan formations; RK, Rockland tephra; the two latter units were erupted from the southern Cascade Range of northeastern California.

TABLE 3. NEUTRON ACTIVATION ANALYSIS OF VOLCANIC GLASS OF THE ROCKLAND PUMICE TUFF BRECCIA OF WILSON (1961) AND ROCKLAND ASH BED, COMPARED TO TEPHRA UNITS OF DIFFERENT AGE

Sample No.	Sc	Mn	Fe	Zn	Rb	Cs	Ba	La	Ce	Nd	Sm	Eu	Tb	Dy	Yb	Lu	Hf	Ta	Th	U
Proximal Tephra																				
1	1.88	224	0.59	24	101	5.3	1020	21.6	37.8	12	1.74	0.33	0.22	1.48	1.24	0.18	2.91	0.73	13.2	4.21
2	1.84	225	0.61	26	102	5.2	1000	21.8	38.4	11	1.68	0.32	0.22	1.48	1.20	0.17	2.97	0.73	13.2	4.18
3	1.83	218	0.54	27	101	5.2	1010	21.8	38.0	12	1.67	0.32	0.22	NA	1.18	0.17	2.91	0.74	13.4	4.26
4	1.88	238	0.66	25	102	5.1	980	21.7	37.6	10	1.64	0.33	0.23	1.38	1.13	0.19	2.92	0.71	13.0	4.06
5	1.93	229	0.66	25	102	5.4	990	21.9	39.5	11	1.68	0.34	0.22	1.41	1.28	0.21	3.09	0.78	13.3	4.18
6	1.85	228	0.60	25	106	5.4	1000	21.4	38.8	11	1.66	0.32	0.21	1.37	1.17	0.15	2.75	0.73	13.3	4.22
7	1.94	232	0.60	26	108	5.4	1020	22.1	38.3	12	1.68	0.31	0.23	1.50	1.21	0.17	2.93	0.74	13.2	4.21
8	1.88	222	0.62	23	105	5.2	980	21.8	38.6	12	1.67	0.32	0.24	1.35	1.17	0.16	2.88	0.73	13.2	4.24
Averages (*x*) and Standard Deviations (SD)																				
x	1.88	227	0.61	25	103	5.3	1000	21.8	38.4	11	1.68	0.32	0.22	1.42	1.20	0.18	2.92	0.74	13.2	4.20
SD	0.04	6	0.05	1	3	0.1	16	0.2	0.6	1	0.03	0.01	0.01	0.06	0.05	0.02	0.09	0.02	0.1	0.06
Distal Tephra																				
10	1.88	242	0.61	29	105	5.2	980	21.6	37.4	14	1.63	0.30	0.24	1.39	1.17	0.18	2.85	0.73	12.7	4.23
13	1.86	218	0.60	30	98	5.3	950	21.3	37.6	12	1.64	0.31	0.22	1.41	1.19	0.18	2.70	0.72	13.3	4.24
14	1.91	224	0.64	29	100	5.2	980	22.0	37.7	11	1.66	0.32	0.17	1.34	1.16	0.19	2.78	0.73	13.3	4.18
15	1.84	214	0.64	16	103	5.1	1020	19.6	37.3	13	1.57	0.31	0.21	1.35	1.14	0.17	2.68	0.72	12.9	3.96
17	1.78	214	0.60	17	103	5.3	950	20.6	37.2	12	1.57	0.31	0.22	1.36	1.14	0.17	2.79	0.73	13.2	4.04
18	1.84	223	0.60	26	98	5.2	1010	20.7	37.2	10	1.65	0.31	0.21	1.28	1.16	0.18	2.78	0.73	12.7	4.16
19	1.83	221	0.63	29	99	5.2	990	21.2	37.4	11	1.64	0.30	0.19	1.35	1.18	0.21	2.87	0.74	13.2	4.18
20	1.82	223	0.61	28	102	5.2	990	22.5	36.7	8	1.65	0.31	0.23	1.35	1.17	0.19	2.64	0.70	12.7	4.12
24	1.80	216	0.62	25	103	5.4	1020	21.1	36.1	11	1.61	0.29	0.19	1.24	1.12	0.18	2.65	0.70	12.9	4.18
25	1.95	215	0.61	25	100	5.6	980	20.5	37.5	11	1.67	0.31	0.21	1.23	1.18	0.17	2.64	0.72	12.8	4.10
26	1.80	217	0.64	27	97	5.4	980	21.1	37.2	12	1.63	0.31	0.22	1.30	1.14	0.20	2.75	0.73	13.1	4.17

Averages and Standard Deviations																			
$\bar{x}$	1.85	221	0.62	26	101	5.3	990	21.1	37.2	11	1.63	0.31	0.21	1.33	1.16	0.18	2.74	0.72	13.0	4.14
SD	0.05	8	0.02	5	3	0.1	21	0.8	0.6	2	0.03	0.01	0.02	0.06	0.02	0.01	0.08	0.01	0.2	0.08
Average and Standard Deviations, Proximal and Distal Tephras (1–26)																			
$\bar{x}$	1.86	223	0.62	25	102	5.3	990	21.4	37.7	11	1.65	0.31	0.22	1.37	1.18	0.18	2.82	0.73	13.1	4.16
SD	0.05	8	0.03	4	3	0.1	21	0.7	0.8	1	0.04	0.01	0.02	0.08	0.04	0.02	0.13	0.02	0.2	0.07
Average Analytical Error (1–26)																			
	0.02	2	0.01	2	3	0.1	21	0.5	0.5	1	0.01	0.01	0.02	0.10	0.02	0.01	0.06	0.01	0.1	0.04
Dibekulewe (Ash) Bed[b]																			
	2.51	262	0.68	52	134	6.3	685	35.7	66.6	24	4.45	0.39	0.67	4.42	2.79	0.38	3.74	1.68	13.8	4.42
Lava Creek-B Ash Bed[c]																			
	1.32	264	1.06	94	222	4.2	48	79.6	158.6	65	12.30	0.37	2.12	14.27	8.35	1.10	8.50	4.29	29.9	6.53
Bishop Ash Bed[d]																			
	3.06	265	0.54	30	187	6.0	20	19.4	47.1	20	3.74	0.04	0.56	4.10	2.70	0.37	3.74	2.15	21.0	6.69
Ash Bed in the Rio Dell Formation[e]																			
	3.67	571	1.65	48	36	0.8	570	19.8	41.4	18	3.30	0.90	0.43	2.34	1.99	0.30	5.37	0.61	4.2	1.36
Nomlaki Tuff Member of the Tehama Formation[f]																			
	3.69	324	0.79	36	97	5.4	1150	21.4	40.1	15	2.39	0.44	0.30	2.25	1.91	0.28	4.06	0.53	11.3	3.93

Note. Sample numbers are the same as locality numbers shown in Figs. 1 and 2. Concentrations of iron in percentage; all other concentrations in parts per million. Analysts: H. R. Bowman, Frank Asaro, and Helen Michael, Lawrence Berkeley Laboratory.

[b] Sample from ash bed that underlies the Rockland ash bed (upper Mexican Dam Bed of Davis (1978)) at sampling localities 11 and 12. The Dibekulewe Bed overlies the Lava Creek-B ash bed near Oreana, Nevada (Davis, 1982, personal communication).

[c] Previously referred to as the Pearlette type O ash bed. Sample from Pleistocene Lake Tecopa deposits of Sheppard and Gude (1968, their ash A), southeastern California. Analysis and sample location in Sarna-Wojcicki *et al.* (1984a; their sample 37). Age of the Lava Creek-B ash is 0.6 my (Izett *et al.*, 1972).

[d] Sample from air-fall pumice-lapilli ash layer at base of unwelded ash-flow tuff of the Bishop Tuff, Insulating Aggregates Quarry, east-central California (Sarna-Wojcicki *et al.*, 1984a; their sample 8). Age of the Bishop Tuft corrected for new decay constants, is 0.73 my (Dalrymple, 1980).

[e] Sample from ash bed in the upper part of the Rio Dell Formation, Centerville Beach, Humboldt County, northwestern California. Age of this ash is about 1.2–1.3 my (Wagner, 1980).

[f] Sample from type locality at former Nomlaki Indian Reservation, northwestern Sacramento Valley, California (Sarna-Wojcicki, 1976; Sarna-Wojcicki *et al.*, 1979, their sample 6). Age of the Nomlaki Tuff Member, corrected for new decay constants, is 3.4 my (Evernden *et al.*, 1964).

TABLE 4. ELECTRON MICROPROBE ANALYSES OF VOLCANIC GLASS OF THE ROCKLAND TEPHRA COMPARED TO SEVERAL TEPHRA UNITS OF DIFFERENT AGE

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	BaO	TiO_2	Na_2O	K_2O	Cl	P_2O_5	Totals
						Proximal Tephra							
1	77.6	12.7	0.97	0.17	0.03	0.93	0.10	0.15	3.60	3.75	NA	0.04	95.4
2	77.6	12.7	0.90	0.17	0.03	0.89	0.12	0.16	3.71	3.60	0.11	NA	95.5
3	78.2	12.2	0.94	0.16	0.02	0.90	0.11	0.15	3.69	3.70	NA	0.04	94.6
6	77.3	12.7	0.95	0.18	0.03	0.90	0.10	0.16	3.83	3.67	0.10	NA	94.4
						Averages (x) and Standard Deviations (SD)							
x	77.7	12.6	0.94	0.17	0.03	0.91	0.11	0.16	3.71	3.68	0.11	0.04	95.0
SD	0.4	0.3	0.03	0.01	0.01	0.02	0.01	0.01	0.10	0.06	—	—	0.6
						Distal Tephra							
9	77.3	12.9	0.95	0.20	0.01	0.90	0.10	0.15	3.76	3.61	0.11	NA	93.5
10	78.4	11.9	0.95	0.15	0.05	0.85	0.11	0.16	3.65	3.72	NA	0.04	93.7
11	77.6	12.7	0.89	0.16	0.03	0.86	0.11	0.16	3.77	3.59	0.12	NA	92.6
12	77.4	12.9	0.89	0.17	0.03	0.87	0.12	0.18	3.66	3.63	0.12	NA	95.4
14	77.5	12.7	0.89	0.17	0.03	0.87	0.08	0.16	3.92	3.56	0.11	NA	93.9
15	77.8	12.7	0.89	0.18	0.02	0.89	0.11	0.16	3.60	3.64	0.09	NA	94.1
16	77.5	12.7	0.89	0.16	0.03	0.86	0.11	0.18	3.87	3.52	0.12	NA	92.9
17	77.7	12.7	0.89	0.17	0.01	0.88	0.09	0.17	3.66	3.60	0.10	NA	93.3
18	77.4	12.8	0.94	0.16	0.03	0.88	0.09	0.15	3.99	3.42	0.10	NA	93.1
20	77.4	12.8	0.89	0.16	0.03	0.83	0.09	0.15	3.98	3.54	0.10	NA	93.7
21	77.9	12.6	0.95	0.17	0.05	0.96	0.11	0.15	3.58	3.48	0.12	NA	94.0
22	77.8	12.7	0.93	0.16	0.03	0.90	0.14	0.15	3.55	3.57	0.13	NA	93.0

23	77.9	12.6	0.90	0.16	0.07	0.86	0.11	0.15	3.56	3.52	0.12	NA	94.1
26	77.6	12.8	0.92	0.18	0.02	0.90	0.10	0.15	3.93	3.34	0.11	NA	93.5
Averages and Standard Deviations													
x	77.7	12.7	0.91	0.17	0.03	0.88	0.11	0.16	3.75	3.55	0.11	0.04	93.6
SD	0.3	0.2	0.03	0.01	0.02	0.03	0.02	0.01	0.16	0.10	0.01	—	0.7
Averages and Standard Deviations Proximal and Distal Tephras													
x	77.7	12.7	0.92	0.17	0.03	0.89	0.11	0.16	3.74	3.58	0.11	0.04	93.9
SD	0.3	0.2	0.02	0.01	0.02	0.03	0.02	0.01	0.15	0.10	0.01	—	0.9
Ash Bed Near Town of Loleta[a]													
	74.5	13.8	1.99	0.10	0.06	0.74	0.08	0.17	5.26	3.13	0.17	NA	94.4
Dibekulewe (Ash) Bed[b]													
	76.9	12.6	1.36	0.05	0.03	0.65	0.09	0.08	4.12	4.11	NA	0.01	93.2
Lava Creek-B Ash Bed[b]													
	76.1	12.6	1.64	0.02	0.04	0.55	0.01	0.12	3.63	5.18	0.14	NA	93.9
Bishop Ash Bed[b]													
	77.4	12.7	0.75	0.04	0.04	0.45	0.00	0.06	3.34	5.22	NA	0.00	94.2
Ash Bed in the Rio Dell Formation[b]													
	73.9	14.4	1.99	0.28	0.08	1.35	0.05	0.24	5.24	2.35	0.15	NA	94.5
Nomlaki Tuff Member of the Tehama Formation[b]													
	77.0	12.8	1.03	0.18	0.05	0.95	0.10	0.20	4.06	3.60	NA	0.01	94.6

[a] Ash bed in the Hookton Formation south of the town of Loleta, Humboldt County, California (S. D. Morrison, 1980, personal communication; Wagner, 1980). This ash bed stratigraphically overlies the Rockland ash bed (sample 16).

[b] For locations of these samples, see footnotes to Table 3.

Note. Sample numbers are the same as locality numbers shown in Figs. 1 and 2. Concentrations in percentage oxide except for chlorine, which is in atomic percentage. Oxide concentrations are recalculated to 100% volatile-free basis. Totals include volatiles. NA, not analyzed. Analyst: C. E. Meyer.

TABLE 5. ENERGY-DISPERSIVE X-RAY FLUORESCENCE SPECTRAL ANALYSES OF VOLCANIC GLASS OF THE ROCKLAND TEPHRA COMPARED TO SEVERAL TEPHRA UNITS OF DIFFERENT AGES AND U.S. GEOLOGICAL SURVEY ROCK STANDARD G-1

Sample No.	Spectral region 2.96–9.01 keV (silver target)							Spectral region 12.32–17.00 keV (Ge target)				
	$K_{k\alpha}$	$Ca_{k\beta}$	$Ti_{k\alpha}$	$Mn_{k\alpha}$	$Fe_{k\beta}$	$Cu_{k\alpha}$	$Zn_{k\alpha}$	$Rb_{k\alpha}$	$Sr_{k\alpha}$	$Y_{k\alpha}$	$Zr_{k\alpha}$	$Nb_{k\alpha}$
Proximal tephra												
1	941	75	213	155	847	60	133	1391	1677	611	2030	568
3	1047	76	239	164	821	64	139	1388	1741	583	2081	560
4	907	75	211	150	855	68	122	1310	1719	605	1982	567
5	916	69	212	149	854	61	124	1371	1645	592	1958	568
6	926	76	208	154	847	62	134	1374	1692	624	2078	547
7	1044	75	222	162	829	62	132	1321	1562	597	1788	645
Average (x) and Standard Deviations (SD)												
x	964	74	218	156	842	63	131	1359	1673	602	1986	576
SD	64	3	12	6	14	3	6	35	58	15	109	35
Distal Tephra												
9	980	71	214	149	838	81	137	1401	1682	647	2053	530
11	1009	69	206	146	823	79	115	1329	1596	599	2044	563
13	992	72	214	147	848	68	126	1382	1714	606	2054	557
16	957	72	210	151	848	64	132	1395	1665	585	2070	579
17	932	72	213	148	858	69	136	1341	1656	605	1990	582
20	937	74	211	157	851	74	130	1394	1666	594	1984	559
21	1003	71	206	144	827	65	133	1337	1676	605	2000	552
22	1022	66	209	146	824	65	117	1362	1617	605	1836	575
24	848	75	215	154	860	74	134	1402	1605	610	1940	583
26	870	69	217	146	872	69	132	1425	1620	619	2004	562
Averages and Standard Deviations												
x	955	71	212	149	845	71	129	1377	1649	608	1998	564
SD	59	3	4	4	17	6	8	33	38	17	69	16
Averages and Standard Deviations Proximal and Distal Tephras												
x	958	72	214	151	844	70	130	1370	1658	605	1993	568
SD	59	3	8	6	15	9	7	33	49	16	83	24
Ash Bed Near the Town of Loleta[a]												
	522	34	106	167	965	38	129	863	726	771	3674	578
Dibekulewe (Ash) Bed[b]												
	938	40	90	126	883	106	141	1713	760	904	2057	784
Lava Creek-B Ash Bed[b]												
	808	31	95	115	957	44	188	1494	271	1074	3148	945
Bishop Ash Bed[b]												
	1429	47	89	189	797	69	173	2258	303	964	1605	883
Ash Bed in the Rio Dell Formation[b]												
	342	52	150	169	958	30	100	458	2181	446	3009	469
Nomlaki Tuff Member of the Tehama Formation[b]												
	834	67	218	175	869	65	141	1202	1474	608	2764	487
U.S. Geological Survey Standard, Granite G-1												
	943	64	198	85	741	63	105	1498	2035	516	2299	427

[a] For location of this ash bed see footnote to Table 4.

[b] For locations of these ash beds, see footnotes to Table 3.

Note. Values given are normalized peak intensity ratios obtained by dividing integrated peak intensity counts for each element by total counts (peak intensities plus background) in each of two spectral regions: 2.96 to 9.01 keV for the group of elements potassium through zinc, and 12.32 to 17.00 keV for the elements rubidium through niobium. The ratios for each element are multiplied by 10^4. Sample numbers are the same as locality numbers shown in Figs. 1 and 2. Analyst: M. J. Woodward.

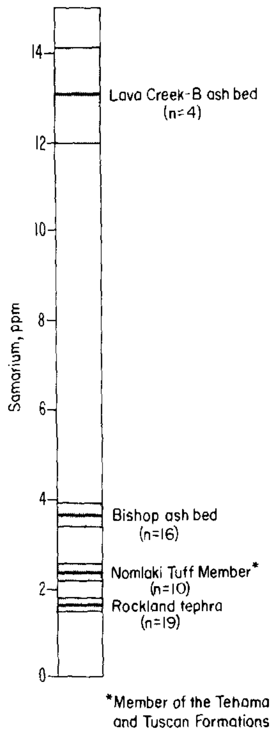

FIG. 11. Concentration of samarium in volcanic glass of the Rockland tephra and three other widespread tephra layers. Bold horizontal lines represent the average content of samarium; shaded blocks represent a range of plus or minus 3 SD from the average concentrations.

minimum age constraint on a major drainage change that occurred in the Great Valley of California. Throughout much of late Cenozoic time, the Great Valley drained south to an embayment of the ocean situated in the southeastern part of the valley (Woodring *et al.*, 1940). This embayment extended across the present southern Coast Ranges and joined the Pacific Ocean, presumably near the present site of Monterey Bay. Progressive northwestward displacement of the Coast Ranges block west of the San Andreas fault probably lengthened and narrowed this connecting seaway. We do not know precisely when or how this connection was severed, but the youngest marine beds in the southern Great Valley, the San Joaquin Formation (Woodring *et al.*, 1940), are about 2 my old, which is the age of a tuff situated near either the base of the Tulare Formation in Arroyo Doblegado, in the North Dome of the Kettleman Hills (Obradovich *et al.*, 1978), or the top of the San Joaquin Formation (Sarna-Wojcicki *et al.*, 1979; A. M. Sarna-Wojcicki, 1984 unpublished data). Since 2 my ago, the Great Valley has remained an emergent basin, because no younger marine deposits are found within it. A drainage outlet or successive outlets from the emergent Great Valley to the ocean may have existed between about 2 and 0.7 my ago, but no deposits of Great Valley provenance of this age have been found west of the San Andreas fault. It is unlikely that the Great Valley was a closed basin for this entire period of time, because no extensive body of evaporite deposits has been found in the subsurface that would support such a hypothesis (Clyde Wahrhaftig, 1984, personal communication). For a short part of the last 2 my, however, the Great Valley has been a closed basin, and has contained a large freshwater lake, as deduced from the presence of the widespread lacustrine Corcoran Clay Member of the Turlock Lake and Tulare formations (Frink and Kues, 1954) found in the subsurface and in outcrops along the margins of the southern Great Valley.

How long this lake was in existence is not known, but the end of lake deposition occurred about 0.62 my ago, which is the age of the Friant Pumice Member (of the Turlock Lake Formation), because alluvium containing abundant cobbles of that pumice overlies the Corcoran Clay Member on the east side of the San Joaquin Valley (Janda, 1965; Dalrymple, 1980). We can make a rough estimate of the life span of this lake on the basis of sedimentation rates. Rates of deposition of lacustrine clays in most large lakes are between about 0.5 and 1 mm/yr (John Sims, 1982, personal communication). The Corcoran Clay Member is as much as 30–50 m thick (Frink and Kues, 1954; Lettis, 1982). Using this range, the lake that formed the Corcoran Clay Member may have existed for a period of

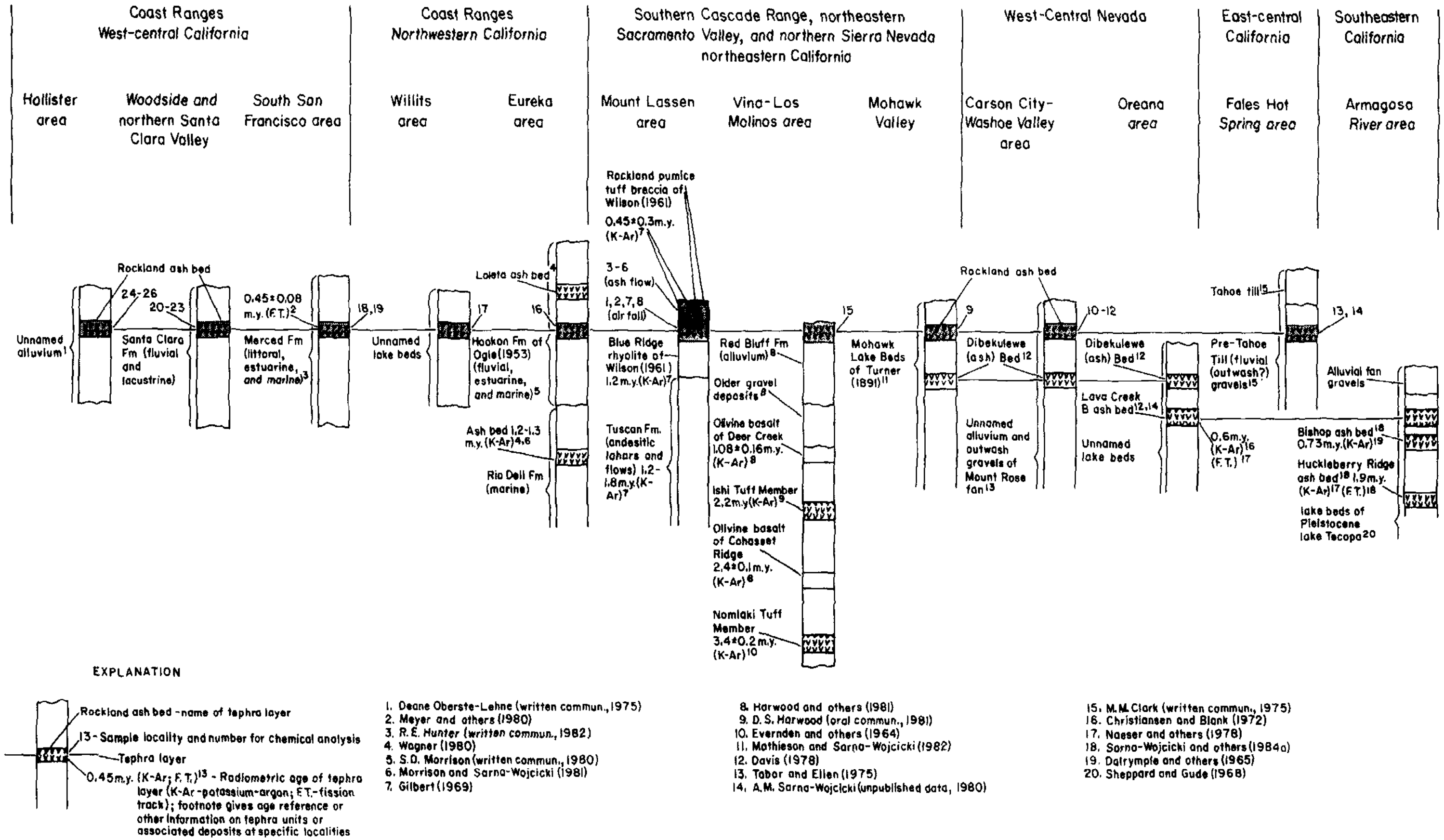

FIG. 12. Correlation chart of the Rockland tephra and stratigraphic relations to other tephra layers of similar age.

between about 50,000 and 100,000 yr. Thus, if the top of the Corcoran Clay Member is about 0.62 my old, then its base should be about 0.67–0.72 my. The Corcoran Clay Member and overlying Friant Pumice Member are overlain in turn by Pleistocene alluvial-fan deposits (Janda, 1965) that indicate a change in drainage of the Great Valley; fan alluviation, alternating with stream incision, has continued to the present and suggests a return to external drainage in the Great Valley after the end of deposition of the Corcoran Clay Member.

In the San Francisco Bay area, Hall (1965, 1966) suggested that sediments of Great Valley provenance first entered the ancestral San Francisco Bay estuary sometime before deposition of the Rockland ash bed. Mineral assemblages typical of Great Valley alluvium first appear in the type Merced Formation about 115 to 150 m stratigraphically below the Rockland ash bed. Thus, the Great Valley became emergent about 2 my ago, the southern outlet was closed sometime after about 2 my ago, and external drainage to the ocean near the present outlet appears to have been established about 0.6 my ago.

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