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

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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. Clyrne, 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.
MIDDLE PLEISTOCENE TEPHRA

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. According 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...
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).

| Sample number | Thickness (meters) | Lithology                        | Mineral abundance |
|               |                   |                                  |                   |
| IBK           | 3                 | Sand                             | Hypersthene,      |
| IBJ           | 1                 | Laminated and cross-bedded ash    | frequency percent |
| IBH           | 1                 | Massive ash                      |                   |
| IBG           | 2                 | Laminated and cross-bedded ash    | Mag.+ilmen.,      |
| IBF           | 1                 | Massive ash                      | Hornblende,       |
| IBE           | 1                 | Laminated and cross-bedded ash    | frequency percent |
| IBD           | 1                 | Massive ash                      |                   |
| IBC           | 1                 | Laminated and cross-bedded ash    |                   |
| IBB           | 1                 | Massive ash                      |                   |
| IBA           | 0                 | Silt                             |                   |

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 Gales, 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 km³ of tephra (Williams and Gales, 1968; Bacon, 1983).

Because the eruption of Mount Mazama covered at least 1,700,000 km² 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-km² minimum area shown in Figure 1.

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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 |
|------------|-------------|---------------|------------|--------------------|
| 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          | Lassen Lodge unit; ash-flow tuff | Tehama, Calif. | Manton 15' | 30N, 1E |
| 4          | Same loc. as 4; strat. below 4; ash-flow tuff | Tehama, Calif. | Lassen Peak 15' | 29N, 2E |
| 5          | Same loc. as 4; strat. below 5; ash-flow tuff | Tehama, Calif. | Lassen Peak 15' | 29N, 2E |
| 6          | Undifferentiated, reworked air-fall ash | Shasta, Calif. | Manton 15' | 30N, 1W |
| 7          | Undifferentiated, reworked air-fall ash | Shasta, Calif. | Manton 15' | 30N, 1W |
| 8          | Ash bed in Mohawk Lake Beds | Plumas, Calif. | Blairsden 7.5' | 22N,13E |
| 9          | Ash bed in alluvium of Mount Rose fan | Washoe, Nev. | Washoe City 7.5' | 17N,19E |
| 10         | Ash bed in unnamed alluvium near Carson City | Carson City, Nev. | Dayton 15' | 15N,20E |
| 11         | Duplicate of 11; same stratigraphic interval | Carson City, Nev. | Dayton 15' | 15N,20E |
| 12         | Ash bed in unnamed glacio(?)fluvial outwash | Mono, Calif. | Fales Hot Sprgs 7.5' | 6N,23E |
| 13         | Duplicate of 13; same stratigraphic interval | Mono, Calif. | Fales Hot Sprgs 7.5' | 6N,23E |
| 14         | Ash bed overlying Red Bluff Formation | Tehama, Calif. | Vina 7.5' | 25N, 1W |
| 15         | Ash bed in Hookton Formation (Railroad Gulch ash bed) | Humboldt, Calif. | Fields Landing 7.5' | 4N, 1W |
| 16         | Ash bed in unnamed alluvium, near Willits | Mendocino, Calif. | Willits 15' | 18N,13W |
| 17         | Ash bed in Merced Formation, Olympic Golf Course | San Mateo, Calif. | San Francisco S. 7.5' | 3S, 6W |
| 18         | Ash bed in Merced Formation, coast, storm sewer outlet | San Francisco, Calif. | San Francisco S. 7.5' | 2S, 6W |
| 19         | Ash bed in Santa Clara Formation, near Woodside | San Francisco, Calif. | Woodside 7.5' | 6S, 4W |
| 20         | Ash bed in Santa Clara Formation, near San Jose | Santa Clara, Calif. | Morgan Hill 7.5 | 8S, 2E |
| 21         | Same loc. as 21, stratigraphically below 21 | Santa Clara, Calif. | Morgan Hill 7.5 | 8S, 2E |
| 22         | Same loc. as 21, stratigraphically below 22 | Santa Clara, Calif. | Morgan Hill 7.5 | 8S, 2E |
| 23         | Ash bed in unnamed alluvium, Lomerías Muertas | San Benito, Calif. | Chittenden 7.5 | 12S, 4E |
| 24         | Same loc. as 24, same stratigraphic interval | 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 |

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*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, \( \frac{1}{4} \), \( \frac{1}{16} \) section | Collector | Field No. | Type of analysis* |
|-------------------------------------------------|-----------|-----------|------------------|
| Proximal tephra: Rockland Pumice Tuff Breccia of Wilson (1961) |           |           |                  |
| 21, NE\( \frac{1}{4} \) of SE\( \frac{1}{4} \) | A. M. Sarna-Wojcicki | RPT(M)6A | x     x     x    |
| 22, E\( \frac{1}{2} \) center | A. M. Sarna-Wojcicki | RPT(M)8   | x     x     x    |
| 22, SW\( \frac{1}{4} \) of SW\( \frac{1}{4} \) | A. M. Sarna-Wojcicki | RPT(L)4   | x     x     x    |
| 28, W\( \frac{1}{2} \) center | A. M. Sarna-Wojcicki | RPT-11   | x     x     x    |
| Distal Tephra: Rockland Ash Bed, Air-Fall, and Reworked Air-Fall Ash |           |           |                  |
| 19, SW\( \frac{1}{4} \) of NW\( \frac{1}{4} \) | S. A. Mathiesen | SAM-38 | x     x     x    |
| 13, NE\( \frac{1}{4} \) of NW\( \frac{1}{4} \) | R. W. Tabor | RWT-102-74 | x     x     x    |
| 35, NW\( \frac{1}{4} \) of SE\( \frac{1}{4} \) | J. O. Davis | LAH-3 | x     x     x    |
| 34, NW\( \frac{1}{4} \) of SE\( \frac{1}{4} \) | J. O. Davis | LD-67 | x     x     x    |
| 23, SE\( \frac{1}{4} \) of NW\( \frac{1}{4} \) | M. M. Clark | MMC-1 | x     x     x    |
| 31, center of W\( \frac{1}{2} \) | E. J. Helley | VINA-1 | x     x     x    |
| 35, NW\( \frac{1}{4} \) of NW\( \frac{1}{4} \) | M. E. Perkins | RRG-1 | x     x     x    |
| 32, SW\( \frac{1}{4} \) of NE\( \frac{1}{4} \) | A. M. Sarna-Wojcicki | WILL-2 | x     x     x    |
| N37°42.35'W122°29.47" | 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     x    |
| N37°12.23'W121°42.73" | A. M. Sarna-Wojcicki | SC-6 | x     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     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    |
Sample numbers | Thickness (meters) | Lithology
--- | --- | ---
1 | 12 | Massive, cream-to tan-colored silt- to fine sand-sized vitric ash. Air-fall and/or water-deposited
2 | 6 | Well-bedded, grayish-white, coarse sand to granule- and fine pebble-sized (1–2 cm) pumice-lapilli ash. Bedding is locally lenticular, suggesting some reworking

**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 fluviolavially 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 pumiceous 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 preruptation zoning in the magma chamber.

CHEMICAL COMPOSITION OF THE ROCKLAND TEPHRA

The Rockland pumice tuff breccia is rhyolitic 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,
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 Meyers 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 pumice tuff breccia suggest a younger age of about 400,000 yr for this unit (C. F. 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.

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**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.
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 volcanioclastic 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 aluvial fan in western Nevada (sample 10), and unnamed glaciofluvial outwash or al-
TABLE 2. BULK CHEMICAL COMPOSITION OF PUMICE OF THE ROCKLAND PUMICE TUFF BRECCIA OF WILSON (1961), LASSEN LODGE UNIT OF GILBERT (1969)

| Oxide   | Analysis¹ |
|---------|-----------|
|        | 1         | 2         |
| SiO₂    | 69.44     | 71.32     |
| Al₂O₃   | 14.46     | 14.85     |
| FeO     | 1.81      | 1.86      |
| Fe₂O₃   | 0.98      | 1.01      |
| CaO     | 2.62      | 2.69      |
| MgO     | 1.32      | 1.36      |
| Na₂O    | 3.44      | 3.53      |
| K₂O     | 2.73      | 2.80      |
| MnO     | 0.04      | 0.04      |
| TiO₂    | 0.30      | 0.31      |
| P₂O₅    | 0.07      | 0.07      |
| H₂O + 105 | 0.15    | 0.15      |
| H₂O - 105 | 2.76    | —         |
| CO₂     | Nil       | —         |

¹ 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.

The Rockland ash bed also provides a...
### 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| 1.41| 1.28| 0.21| 3.09| 0.78| 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|
| 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| 224 | 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| 213 | 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| 2.73| 0.73| 13.1| 4.17|
|   | 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    | 0.3 | 0.1  | 0.03 | 0.01 | 0.02 | 0.06 | 0.02 | 0.01 | 0.08 | 0.01 | 0.2  | 0.08 |

|   | 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 |

|   |    |    |  0.02 | 2   | 0.01 | 2   | 3   | 0.1 | 21  | 0.5  | 0.5  | 0.1  | 0.01 | 0.01 | 0.02 | 0.10 | 0.02 | 0.01 | 0.06 | 0.01 | 0.1  | 0.04 |

**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.

|   |   | 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 | 1.48 | 13.8 | 4.42 |
|---|---|------|------|------|-----|------|-----|-----|------|------|-----|------|------|------|------|------|------|------|------|------|------|------|
| Dibekulewe (Ash) Bed |   | 1.32 | 264  | 1.06 | 94  | 222  | 4.2 | 48  | 79.6 | 158  | 65  | 12.30 | 0.37 | 2.12 | 14.27 | 8.35 | 1.10 | 8.50 | 4.29 | 29.9 | 6.53 |
| Bishop Ash Bed |   | 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 |   | 3.67 | 571  | 1.65 | 48  | 36  | 0.8 | 570 | 19.8 | 41  | 18  | 3.20 | 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 |   | 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 |

|   |   | 2.37 | 266  | 0.60 | 34  | 102  | 5.8 | 906 | 36.9 | 66.6 | 24  | 4.49 | 0.39 | 0.67 | 4.42 | 2.79 | 0.38 | 3.74 | 1.48 | 13.8 | 4.42 |
|---|---|------|------|------|-----|------|-----|-----|------|------|-----|------|------|------|------|------|------|------|------|------|------|------|
| Ash Bed in the Rio Dell Formation |   | 3.67 | 571  | 1.65 | 48  | 36  | 0.8 | 570 | 19.8 | 41  | 18  | 3.20 | 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 |   | 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.

|   |   | 3.47 | 267  | 0.60 | 34  | 102  | 5.8 | 906 | 36.9 | 66.6 | 24  | 4.49 | 0.39 | 0.67 | 4.42 | 2.79 | 0.38 | 3.74 | 1.48 | 13.8 | 4.42 |
|---|---|------|------|------|-----|------|-----|-----|------|------|-----|------|------|------|------|------|------|------|------|------|------|------|
| Ash Bed in the Rio Dell Formation |   | 3.67 | 571  | 1.65 | 48  | 36  | 0.8 | 570 | 19.8 | 41  | 18  | 3.20 | 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 |   | 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 |
TABLE 4  Electron Microprobe Analyses of Volcanic Glass of the Rockland Tephra Compared to Several Tephra Units of Different Age

| Sample No. | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | MnO | CaO | BaO | TiO₂ | Na₂O | K₂O | Cl | P₂O₅ | Totals |
|------------|------|-------|-------|-----|-----|-----|-----|------|------|-----|----|-----|--------|
| 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 | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | MnO | CaO | BaO | TiO₂ | Na₂O | K₂O | Cl | P₂O₅ | Totals |
|---|------|-------|-------|-----|-----|-----|-----|------|------|-----|----|-----|--------|
| 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   |

Proximal Tephra

Distal Tephra

| Sample No. | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | MnO | CaO | BaO | TiO₂ | Na₂O | K₂O | Cl | P₂O₅ | Totals |
|------------|------|-------|-------|-----|-----|-----|-----|------|------|-----|----|-----|--------|
| 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 | 3.33 | 3.57| 0.13| NA | 93.0   |
|       | 23.7 | 12.6 | 0.90 | 0.16 | 0.07 | 0.86 | 0.11 | 0.15 | 3.56 | 3.52 | 0.12 | NA | 9.41 |
|-------|------|------|------|------|------|------|------|------|------|------|------|----|------|
| SD    | 0.7  | 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**

|       | 77.7 | 12.7 | 0.91 | 0.17 | 0.03 | 0.88 | 0.11 | 0.16 | 3.75 | 3.55 | 0.11 | 0.04 | 9.36 |
|-------|------|------|------|------|------|------|------|------|------|------|------|-----|------|

**Ash Bed Near Town of Loleta**

|       | 74.5 | 13.8 | 1.99 | 0.10 | 0.06 | 0.74 | 0.08 | 0.17 | 5.26 | 3.13 | 0.17 | NA | 9.44 |
|-------|------|------|------|------|------|------|------|------|------|------|------|----|------|
|       | 76.9 | 12.6 | 1.36 | 0.05 | 0.03 | 0.65 | 0.09 | 0.08 | 4.12 | 4.11 | NA | 0.01 | 9.32 |
|       | 76.1 | 12.6 | 1.64 | 0.02 | 0.04 | 0.55 | 0.01 | 0.12 | 3.63 | 5.18 | 0.14 | NA | 9.39 |
|       | 77.4 | 12.7 | 0.75 | 0.04 | 0.04 | 0.45 | 0.00 | 0.06 | 3.34 | 5.22 | NA | 0.00 | 9.42 |
|       | 73.9 | 14.4 | 1.99 | 0.28 | 0.08 | 1.35 | 0.05 | 0.24 | 5.24 | 2.35 | 0.15 | NA | 9.45 |

**Ash Bed in the Rio Dell Formation**

|       | 77.0 | 12.8 | 1.03 | 0.18 | 0.05 | 0.95 | 0.10 | 0.20 | 4.06 | 3.60 | NA | 0.01 | 9.46 |

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*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-I

| Sample No. | Spectral region 12.32-17.00 keV (Ge target) | Spectral region 2.96-9.01 keV (silver target) |
|------------|-----------------------------------------------|-----------------------------------------------|
|            | $\text{K}_{\text{Ko}}$  $\text{Cu}_{\text{Ko}}$  $\text{T}_{\text{Ko}}$  $\text{Mn}_{\text{Ko}}$  $\text{Fe}_{\text{Ko}}$  $\text{Cu}_{\text{Ko}}$  $\text{Zn}_{\text{Ko}}$ | $\text{Rb}_{\text{Ko}}$  $\text{Sr}_{\text{Ko}}$  $\text{Y}_{\text{Ko}}$  $\text{Zr}_{\text{Ko}}$  $\text{Nb}_{\text{Ko}}$ |
| 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 |
| 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 | 553 |
| 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 | 539 |
| 21 | 1003 | 71 | 206 | 144 | 827 | 65 | 133 | 1337 | 1676 | 605 | 2000 | 552 |
| 22 | 1022 | 66 | 209 | 146 | 824 | 65 | 117 | 1362 | 1647 | 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 | 5 | 6 | 1 | 3 | 35 | 58 | 15 | 109 | 35 |
| Averages and Standard Deviations Proximal and Distal Teprhas | | |
| $x$ | 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 |

* For location of this ash bed see footnote to Table 4.

* 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.
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 northward 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, 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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