AN EARLY PLEISTOCENE PLUVIAL LAKE IN FISH LAKE VALLEY, NEVADA-CALIFORNIA: RINGSIDE RESORT FOR THE ERUPTION OF THE BISHOP TUFF

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ABSTRACT

The question of whether a pluvial lake existed in Fish Lake Valley, Nevada and California, has been debated for over 100 years. We have obtained stratigraphic evidence that a lake did exist in this valley at intervals during late Pliocene to middle Pleistocene time. This lake may have overflowed northward, or it may have been periodically contiguous with a pluvial lake to the north in Columbus Salt Marsh.

Proof of the existence of this lake, informally named Pluvial Lake Rennie, rests primarily on four outcrops of shallow-water lacustrine sediments, two outcrops of deep-water sediments, and drilling logs of sediments. The exposed and buried sediments contain beds of silicic tephra, which provide age control. Based on thickness, grain size, and major-oxide chemistry of glass shards, three of the shallow-water deposits consist mainly of tephra that was most likely derived from the 0.74-Ma eruption of the Bishop Tuff. These three deposits include deltaic, beach, and siliceous hot-spring sediments. One outcrop of beach sand is underlain by lacustrine (?) sediments believed to be about 1 Ma. The exposed deep-water sediments consist of green claystone, siltstone, and fine-grained sandstone containing tephra derived from the eruptions of the ~2.1-Ma tuff of Taylor Canyon and, provisionally, of the ~2.0-Ma Huckleberry Ridge Tuff. The drilling logs record numerous thick beds of clay and sandy clay, some containing beds interpreted to be volcanic ash; these clay beds are inferred to be deep-water lacustrine sediments.

From the outcrops and drilling logs, the history of Pluvial Lake Rennie is as follows: (1) At around 2 Ma, the lake was deep enough in its northeastern part that clay was deposited. The lake level in early Pleistocene time is not known, but a lake probably existed around 1 Ma. (2) At about 0.74 Ma, the lake had a high stand at an elevation of about 1440 m. The lake level must have dropped during or just after the eruption of the Bishop ash. (3) The lake may have persisted sporadically at a lower level until about 0.5 Ma, but no long-lived lake existed in Fish Lake Valley in late Pleistocene time. The late Pliocene and Pleistocene record of Pluvial Lake Rennie is reasonably parallel to that of Lake Tecopa, 200 km to the southeast.

INTRODUCTION

The existence of a pluvial lake in Fish Lake Valley, Nevada and California, and its relation to other nearby pluvial lakes such as Columbus Salt Marsh (fig. 1), have been topics of debate in Quaternary studies of the Great Basin for over a century. For example, Russell (1885) showed a very small pluvial lake confined to the valley; Hubbs and Miller (1948) proposed that a pluvial lake of uncertain size and age overflowed to Lake Lahontan; Mifflin and Wheat (1979) thought that there was no late Pleistocene lake, but that there may have been an early Pleistocene lake connected to Lake Lahontan. Most of the published studies included Fish Lake Valley in compilations of the pluvial lakes of large regions, and little work beyond interpretation of aerial photographs and limited field checking was done.

We have obtained stratigraphic evidence that substantiates the existence of a pluvial lake in Fish Lake Valley and that bears on its age during recent mapping of late Cenozoic deposits and faults of Fish Lake Valley (Reheis, in press a; J.L. Slate, thesis in progress). The purpose of this paper is to present the stratigraphic evidence for the existence

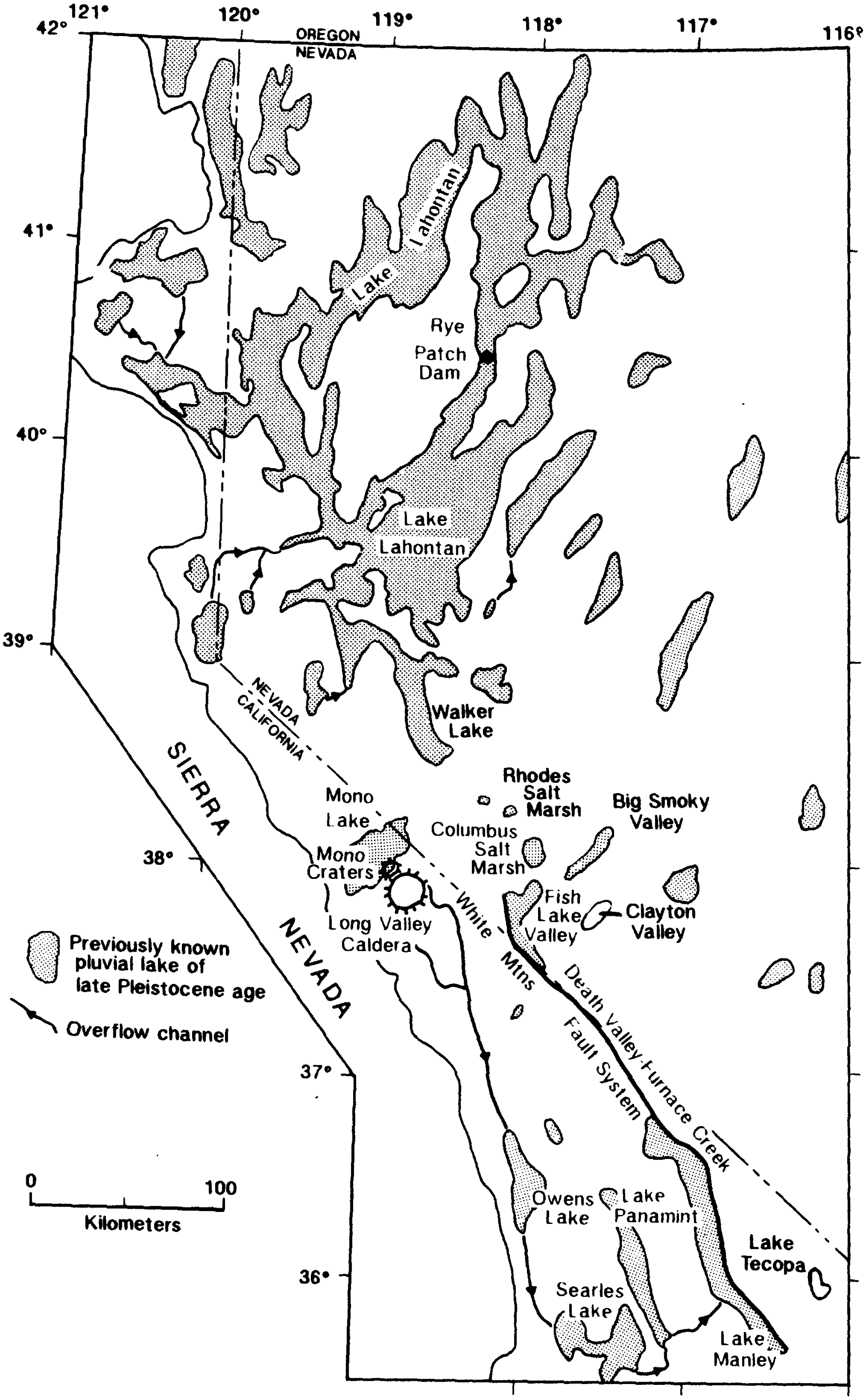


Figure 1. Regional location map showing selected late Pleistocene pluvial lakes and their connections in the western Great Basin, sources of silicic tephra in the Long Valley area, and the Death Valley-Furnace Creek fault system (modified from Morrison, 1965).

of this pluvial lake, to present tephrochronologic data on its age, and to infer its depth, its extent, and the nature of its connection to other lakes. We emphasize that some of the tephrochronologic correlations are preliminary, in particular the discrimination of the Bishop ash from the chemically similar Glass Mountain tephra layers. Other analyses that permit more confident identification of the Bishop ash are in progress.

We informally name this lake Pluvial Lake Rennie in honor of Douglas P. Rennie, who unstintingly gave his help and companionship in the field during 1987 and 1988 before his untimely death in a car accident. He must be excited to know where the early discoveries of mysteriously thick tephra layers in Fish Lake Valley have led us.

BACKGROUND AND METHODS

Geographic, Geologic, and Climatic Setting

Fish Lake Valley is a nearly closed basin about 70 km east of the Long Valley caldera and about 80 km east of the Mono Craters (fig. 1). The valley lies between the glaciated White Mountains (elevations as high as 4340 m) on the west and the lower, unglaciated Silver Peak Range on the east. Drainage from the valley is partly blocked on the north by the low Volcanic Hills (fig. 2), but overflows intermittently from the playa in the northeast corner northward through "The Gap" into Columbus Salt Marsh (Beaty, 1968).

Fish Lake Valley owes its existence and its remarkably well-exposed stratigraphy to right-oblique faulting along the Fish Lake Valley fault zone (Sawyer, 1990), which forms the northern end of the Death Valley-Furnace Creek fault system (fig. 1). Vertical offset along the faults that bound the east side of the White Mountains and the northwest side of the Silver Peak Range (fig. 2) expose coarse alluvial-fan and finer-grained sediments that blanket most of the valley floor and margins. These sediments are well preserved due to the arid climate of Fish Lake Valley, which lies in the rain shadow of the Sierra Nevada and the White Mountains. The sediments contain numerous beds of silicic volcanic tephra that were largely derived from the nearby Long Valley caldera and the Mono Glass Mountain area (fig. 1; Reheis, in press a,b). The tephra layers provide the chronologic framework for the alluvium and other sediments.

The magnitude and extent of glaciation in the White Mountains is a topic of debate. These mountains contained small valley glaciers of Tahoe and Tioga age (LaMarche, 1965; Elliott-Fisk, 1987). LaMarche (1965) suggested that the northern valleys of Indian and Chiatovich Creeks may have had glaciers extending to the range front in pre-Tahoe time. Elliott-Fisk (1987) defined the "Dyer Glaciation" of possible Sherwin age (>740 ka) based on "Glacial till...preserved as uplifted fans at canyon mouths..." of Perry Aiken and McAfee Creeks near Dyer (fig. 2). These deposits, however, are indistinguishable from alluvial-fan deposits elsewhere along the range (J.L. Slate, unpub. data).

Fish Lake Valley contains abundant groundwater, which is largely recharged by surface and subsurface flow from the White Mountains and discharged at springs and other areas of high water table in the northeastern part of the valley (fig. 2; Rush and Katzer, 1973). The only perennial standing water is Fish Lake, a spring-fed pond. Recharge to the valley sediments was probably greater during recent glaciations than at present, but little or no evidence supports surface flow northward into Columbus Salt Marsh during those times (discussed below).

Mean annual temperature on the valley floor is about 10.5 ^{o}C (National Climatic Data Center, 1986). Mean annual precipitation on the valley floor is about 12 cm, whereas on the White Mountain crest it is at least 40 cm (Rush and Katzer, 1973). Until now, little evidence was available regarding climatic conditions in the valley in Pleistocene time.

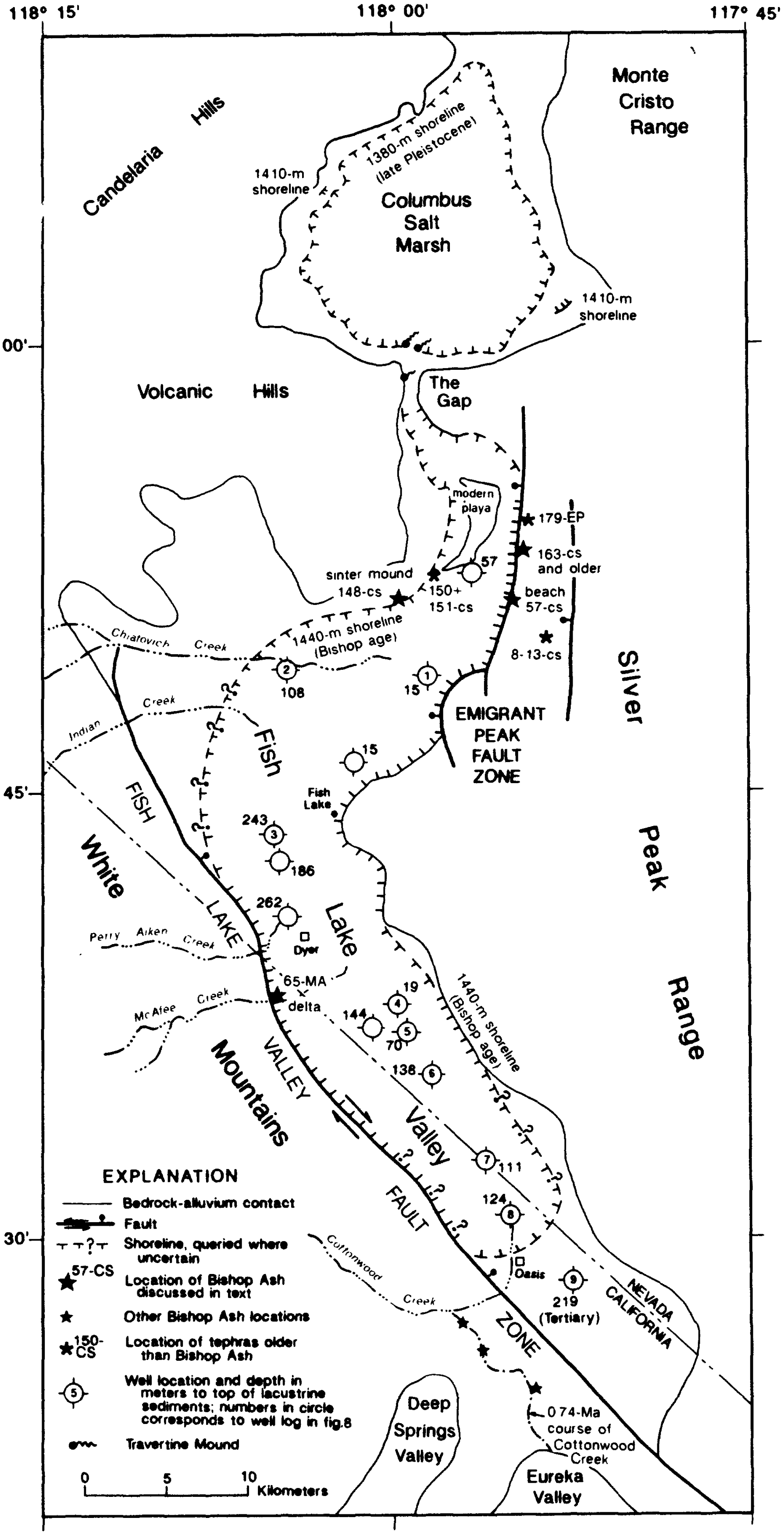


Figure 2. Sketch map of Fish Lake Valley and vicinity, showing locations discussed in text, selected well locations, and reconstructed pluvial-lake shorelines.

Packrat middens indicate a cooler late Pleistocene climate from the presence of juniper-shadscale woodland as late as 10,700 B.P. at the southern end of Fish Lake Valley, which is the present northern boundary of creosote bush (Spaulding, 1980). Mifflin and Wheat (1979) inferred a last-glacial climate for Nevada that was about 2.8°C lower in mean annual temperature and about 70% higher in precipitations than the modern climate. Clearly, these conditions were not sufficient to produce a large, long-lived, late Pleistocene lake in Fish Lake Valley, because it has no shorelines of this age (Mifflin and Wheat, 1979; this study). In late Pliocene and early Pleistocene time, however, the entire region may have been much wetter because the White Mountains (dePolo, 1989; Reheis and McKee, this volume) and to a lesser extent the Sierra Nevada (Huber, 1981) were lower in elevation, and the rain-shadow effect of these ranges was consequently weaker.

Previous Studies

Fish Lake Valley was identified as a site that might have had a pluvial lake as early as the late 1800's, and a connection between it and other pluvial lakes was suggested early in the 1900's. Russell (1885) and Meinzer (1922) mapped a small pluvial lake about the same size as the modern playa in northeastern Fish Lake Valley (fig. 2). Free (1914) proposed that a pluvial lake discharged northward through The Gap to a pluvial lake in Columbus Salt Marsh. Hubbs and Miller (1948) suggested that the pluvial lake may have had an early (pre-Lahontan, or pre-Illinoian; Morrison and Davis, 1984) or very temporary late Pleistocene pluvial connection to Lake Lahontan (fig. 1), based on the resemblance of a now-extinct fish (Siphateles sp.) in modern Fish Lake (fig. 2) to Lahontan fish. However, they discounted Free's (1914) suggestion of discharge through The Gap based on their observations of terraces.

Later in this century, the postulated lake grew in size. Snyder and others (1964), in a map of Pleistocene lakes of the Great Basin based on identification of shoreline features on aerial photographs and on limited field reconnaissance, showed a large (480 km^2) pluvial Fish Lake of unspecified age that overflowed northward into a pluvial lake in Columbus Salt Marsh. Late Pleistocene shorelines are prominent in Columbus Salt Marsh, but do not exist in Fish Lake Valley (Mifflin and Wheat, 1979; Reheis, in press a). We infer that their lake reconstruction in Fish Lake Valley was based on an incorrect identification of a curvilinear fault scarp east of the modern playa as a shoreline. This same inference was made by Mifflin and Wheat (1979, and M.D. Mifflin, oral commun., 1990), who omitted Fish Lake Valley from their detailed investigation of late Pleistocene pluvial lakes and pluvial climates of Nevada. These authors did, however, suggest that ancient Lake Lahontan may have extended as far south as Clayton Valley (fig. 1), including Fish Lake Valley, in pre-Lahontan time. They based their suggestion mainly on: (1) the presence of extensive evaporite deposits in valleys below 1500 m elevation that connect Clayton Valley with Walker Lake, the southernmost arm of Lake Lahontan in late Pleistocene time; and (2) the presence of lacustrine gravels at elevations well above that of the late Pleistocene Lahontan shoreline at Walker Lake.

Methods

Many beds of silicic volcanic tephra were found and sampled in the course of detailed mapping in the northern part of Fish Lake Valley. Of these, several were suspected to be ash derived from the eruption of the Bishop Tuff in the area of Long Valley, Calif. (fig. 1), based on the thickness and coarse grain size of the deposits. The stratigraphy and sedimentology of these outcrops of suspected Bishop ash, including measured sections at three well-exposed sites, were described.

Table 1. Electron-microprobe analyses of volcanic glass shards from middle Pleistocene and upper Pliocene tephra layers of Fish Lake Valley, California and Nevada, and comparative compositions of shards from near-source and distal tephra layers of the Long Valley--Mono Glass Mountain source area of California. Values given are in weight-percent oxide, recalculated to 100 percent fluid-free basis. Original oxide totals before recalculation are given to indicate approximate degree of hydration of volcanic glass. Approximately 15 individual glass shards were analyzed for each sample. [e] - glass shards of a sample are heterogenous with respect to this element. Homogeneity data are not available for some samples; these samples were analyzed with a MAC[1] three-channel electron microprobe. Other samples were analyzed with a nine-channel SEMQ[1] electron-microprobe. Multiple analyses of a homogenous natural glass standard, RLS 132, are given below (39) and provide a close estimate of the analytical error for each oxide in electron-probe analysis. Comparative values based on wet-chemical analysis of the same sample are also given (40). C. E. Meyer, U.S.G.S., Menlo Park, electron-probe analyst.

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total
Thick, coarse, water-deposited tephra in fan alluvium (1, 2), and thick, reworked ash and tuff in nearshore sands of Pluvial Lake Rennie (3-6); sample 6, bydrothermally altered and leached ash from sinter mound (see text); Bishop ash from Gilbert Summit, CA (7)										
1. FLV-65-MA	77.6	13.0	0.70	0.02	0.02	0.43	0.06	3.7	4.5[e]	92.6
2. FLV-66-MA	77.7	12.7	0.75	0.02	0.04	0.43	0.07	3.8	4.5[e]	94.1
3. FLV-57-CS	77.6	12.7	0.69	0.02	0.04	0.44	0.07	3.7	5.0[e]	93.3
4. FLV-163-CS	77.6	12.9	0.79	0.02	0.05	0.41	0.06	3.5	4.8	93.4
5. FLV-148A-CS	77.8	12.6	0.72	0.03	0.03	0.43	0.07	3.7	4.7[e]	94.9
6. FLV-148-CS	77.5	13.8[e]	0.43[e]	0.11[e]	0.00	0.51[e]	0.05	3.5[e]	4.2[e]	88.0
7. FLV-4-WP	77.9	12.5	0.74	0.05	0.04	0.44	0.06	3.7	4.5[e]	94.0
Mean (1-5, 7):	77.7	12.7	0.72	0.03	0.03	0.43	0.07	3.7	4.6	93.8
± standard dev.:	0.1	0.2	0.03	0.01	0.01	0.01	0.01	0.05	0.2	0.9
Proximal Bishop airfall ash bed at south end of tableland, southeast of Long Valley Caldera, north of Bishop, CA, at Owens River (8, 9), and at Insulating Aggregates Quarry (10); distal Bishop ash bed from Lake Tecopa, CA (11), Arches National Park, Utah (12), and Onion Creek, Utah (13)										
8. BT-11A1	77.6	12.7	0.69	0.03	0.04	0.43	0.06	3.7	4.8	94.4
9. BT-11C1	77.7	12.6	0.72	0.03	0.04	0.42	0.06	3.7	4.8	93.9
10. BT-8	77.8	12.5	0.73	0.03	0.05	0.44	0.05	3.8	4.7	94.3
11. TECO-28B	77.0	12.9	0.75	0.04	0.03	0.43	0.06	3.8	5.0	93.9
12. ARCH-88-1	77.4	12.7	0.74	0.04	0.03	0.43	0.07	4.2	4.4	92.2
13. 66W5	77.6	12.7	0.74	0.03	0.05	0.45	0.07	3.9	4.4	93.1
Mean (8-13):	77.5	12.7	0.73	0.03	0.04	0.43	0.06	3.8	4.7	93.6
± standard dev.:	0.3	0.1	0.02	0.01	0.01	0.01	0.01	0.2	0.2	0.9
Finer, thinner-bedded tephra layers at locality FLV-163-CS, stratigraphically below coarse beach sand of samples 3 and 4, above										
14. FLV-162-CS	77.4	12.9	0.77	0.03	0.07	0.46	0.07	3.4	5.0	93.5
15. FLV-161-CS	77.5	12.8	0.71	0.03	0.06	0.45	0.06	3.5	5.0	94.0
16. FLV-160-CS	77.4	12.8	0.73	0.01	0.06	0.50	0.07	3.5	4.9	93.8
17. FLV-147-CS	76.8	12.6	0.71	0.04	0.05	0.45	0.03	3.2	6.2	93.7
Glass Mountain D (18; ca. 0.9 Ma) and G (19, 20, 22, ca. 1.0 Ma) ash beds, stratigraphically below airfall Bishop ash bed at locality of samples 8, 9 above										
18. BT-2	78.0	12.3	0.71	0.03	0.05	0.41	0.06	3.5	5.0	95.4
19. BT-1	77.3	12.9	0.80	0.03	0.03	0.43	0.05	3.9	4.6	94.6
20. BT-1C	77.8	12.7	0.77	0.03	0.05	0.42	0.06	3.5	4.6	94.6
Volcanic ash beds in upper Pliocene alluvial-fan gravels underlying fan alluvium containing sample 3, 4, and 14 -17 (above) in northeastern Fish Lake Valley (21-28)										
21. FLV-8-CS	77.8	12.4	0.58	0.05	0.11	0.31	0.06	3.8[e]	5.0[e]	94.1
22. FLV-9-CS	77.4	12.3	0.56	0.05	0.10	0.32	0.06	2.8[e]	6.5[e]	93.7
23. FLV-10-CS	77.1	12.6	0.57	0.05	0.08	0.34	0.07	2.8[e]	6.4[e]	94.3
24. FLV-11-CS	77.1[e]	12.7	0.57	0.05	0.09	0.34	0.07	2.8[e]	6.4[e]	93.7
25. FLV-12-CS	77.2	12.8	0.60	0.04	0.09	0.33	0.05	3.2[e]	5.8[e]	94.4
26. FLV-13-CS	77.5	12.8	0.60	0.04	0.08	0.33	0.04	3.9[e]	4.8[e]	95.2
27. FLV-150-CS	77.3	12.7	0.61	0.03	0.09	0.34	0.05	4.0[e]	5.0[e]	94.9
28. FLV-151-CS	77.3	12.7	0.60	0.04	0.09	0.34	0.05	4.1[e]	4.7[e]	95.2
Mean (21-28):	77.3	12.6	0.59	0.04	0.09	0.33	0.06	3.4	5.6	94.4
±standard dev.:	0.2	0.2	0.02	0.01	0.01	0.01	0.01	0.6	0.8	0.6
Proximal Tuff of Taylor Canyon, near Mono Glass Mountain (29-32; ca. 1.9-2.1 Ma); distal Waucoba ash beds (33, 34) in Owens Valley, east of Big Pine, CA., and distal ash (35) stratigraphically below Huckleberry Ridge ash bed (ca. 2.0 Ma) in Pico Fm., Ventura, southwestern CA.										
29. TTC-6	77.2	12.9	0.58	0.05	0.09	0.33	0.09	4.1	4.6[e]	94.6
30. TTC-9A	77.6	12.7	0.58	0.04	0.10	0.34	0.07	3.7	4.9[e]	93.2
31. TTC-18	77.9	12.5	0.59	0.05	0.10	0.35	0.07	3.5	5.1[e]	93.7
32. TTC-19	77.5	12.6	0.59	0.05	0.07	0.33	0.06	3.9	4.9[e]	93.2
33. WAC-6	77.2	12.7	0.60	0.04	0.06	0.34	0.09	4.0	4.9	95.2
34. W2A	77.4	12.5	0.60	0.03	0.08	0.34	0.08	3.3	5.7	93.0
35. P-169Q	77.6	12.6	0.58	0.04	0.10	0.33	0.06	3.9	4.9	92.8
Average (29-35):	77.5	12.6	0.59	0.04	0.09	0.34	0.07	3.7	5.0	93.7
± standard dev.:	0.2	0.2	0.01	0.01	0.02	0.01	0.01	0.3	0.3	0.9

Table 1 (continued)

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total
Fine-grained, bluish-gray, 0.5-m-thick tephra layer (36) in tuffaceous lake beds stratigraphically below dissected fan alluvium containing samples 3, 4 and 14 - 17 (above); Huckleberry Ridge ash bed in lake beds of Pleistocene Lake Tecopa (37) and in Pico Fm., Ventura County, CA (38)										
36. FLV-179-EP	76.61	12.14	1.72	0.01	0.04	0.59	0.11	2.8	6.0	93.86
37. TECO-12B	76.30	12.36	1.75	0.03	0.05	0.61	0.14	3.5	5.3	94.86
38. PICO-157	76.61	12.25	1.73	0.03	0.04	0.59	0.13	3.7	4.9	94.64
39. RLS 132 (Av. 18)	75.4	11.3	2.12^2	0.06	0.16	0.11	0.19	4.9	4.4	98.6
standard dev.:	0.1	0.2	0.04	0.01	0.01	0.01	0.01	0.1	0.1	
percent st.d.:	0.2	1.4	1.9	17	6.3	9	5.3	2.7	1.4	
40. RLS 132 (wet chemical	75.7	11.4	2.12^2	0.05	0.15	0.12	0.21	5.3	4.5	99.6

[1]Use of trade names by the U.S. Geological Survey does not represent an endorsement of the product.
[2]Iron reported as FeO for the standard.

Table 2. Comparison of the average of volcanic glass shard compositions of five unaltered samples of the Bishop ash bed in Fish Lake Valley (1) with the glass shard compositions of a hydrothermally altered sample, FLV-148-CS (2). Note that the original analysed values are given below, not values normalized to 100 percent, in order to estimate the amounts of elements lost or gained in the altered sample during alteration. A-U - difference for each oxide between the altered and average of the unaltered samples. %A-U - the percentage difference between the altered and average of the unaltered samples. Other comments as in Table 1.

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total
1. Bishop ash bed	72.9	11.9	0.67	0.03	0.03	0.41	0.06	3.5	4.4	93.8
2. FLV-148-CS	68.1	12.1	0.38	0.10	0.00	0.45	0.04	3.1	3.7	88.0
A-U	-4.8	+0.2	-0.29	+0.07	-0.03	+0.04	-0.02	-0.4	-0.7	-5.9
%A-U	-6.5	+2	-43	+233	-100	+10	-33	-12	-16	

Tephra samples were examined under the petrographic microscope. Glass shards of samples that contained glass were separated from other components and analyzed by electron microprobe for major-oxide composition (tables 1 and 2) using methods described by Sarna-Wojcicki and others (1984). Sample compositions were compared against compositions in a data base of previously analyzed tephra layers using numerical programs, and the best matches were identified. Correlations were made on the basis of similarity in chemical composition, petrographic characteristics (for example, shard morphology, mineralogy; data not shown), and other stratigraphic and numerical-age data.

Values for glass compositions in Table 1 are normalized to 100 percent to correct for the variable amounts of hydration of the volcanic glass. Original totals, all significantly lower than 100 percent, are approximate guides to the degree of hydration of each sample. In addition to hydration, some post-depositional alkali exchange has occurred in many of the samples. Variability in sodium and potassium contents are particularly apparent for the older tephra layers, those correlative with the tuff of Taylor Canyon (table 1). One sample (FLV-148-CS), collected from a sinter mound where the pluvial shoreline deposits are particularly well preserved by silica and carbonate cementation, has been hydrothermally altered (Table 2).

Samples from the cemented strata of the sinter mound were examined in thin section. These samples were also ground and analyzed in powder mounts for whole-rock mineralogy by X-ray diffraction.

Over 100 driller's logs of irrigation and domestic wells deeper than 60 m in Fish Lake Valley were examined for evidence of lacustrine sediments. The sedimentology in these logs was plotted with depth and compared to more detailed logs of boreholes drilled in the area south of the modern playa during lithium investigations by the U.S. Geological Survey (fig. 2; Pantea and others, 1981).

EVIDENCE FOR AN EARLY PLEISTOCENE LAKE

The geologic evidence supporting an early Pleistocene lake in Fish Lake Valley derives from five outcrops, three of which represent deposition in shallow water and two in deeper water, and on sediments reported in water-well logs and cores. The five areas of outcrop are described in order from south to north, followed by description of the nature of the overflow or connecting channel.

The Delta at McAfee Creek

A dissected remnant of alluvial-fan gravel overlies, is channeled into, and is interbedded with, a thick (>30 m) deposit of fluvially deposited tephra on the north side of the mouth of McAfee Creek (figs. 2 and 3; map of area is in fig. 3, road log, this volume). The tephra and overlying gravel are in fault contact on the west with bedrock along an inactive strand of the Fish Lake Valley fault zone. A second inactive group of small faults cuts the tephra deposit but dies out in the overlying gravel in the area where the gravel channels most deeply into the tephra (fig. 3); hence, these faults were active during deposition of the tephra. A third fault, the presently active strand, bounds the tephra deposit and overlying gravel on the east.

<u>Stratigraphy and sedimentology</u>

A 71-m-thick section of gravel and tephra, divided into six subsections based on composition and bedding (fig. 3), was measured in the middle of the exposure on the north side of McAfee Creek. West of the measured section, the sediments consist mainly of tephra; east of the section, the sediments are chiefly coarse gravel. Gravel in most of the section consists mainly of granodiorite and quartz monzonite, whereas gravel in the uppermost 11 m consists mainly of dolomite, marble, and limestone. Normal faults with offsets ranging from 0.5 to 2 m are well exposed in the lower 35 m of the section but were not observed in higher beds.

The base of the measured section consists of at least 6.4 m (base not exposed) of nearly pure tephra, with pumice clasts 1-3 cm long, reworked into beds ranging from 10-30 cm thick. Above the tephra beds is 9.8 m of interbedded tephra and gravel with beds ranging from 10 cm to 2 m thick. Gravel beds are fairly well sorted and clast-supported. Rip-up clasts of pebbles and cobbles in a mud matrix are interbedded with tephra and gravel at the base, and crossbedded layers of tephra and gravel are scoured into massive beds of tephra near the top of this subsection.

The base of the subsection containing foreset tephra beds is marked by an abrupt, smooth contact at the base of a poorly sorted, matrix-supported deposit containing pebble- to boulder-size clasts. Two erosional scarps about 0.5 and 1.5 m high in this deposit are overlain by a total of 3.5 m of steeply dipping (N75^{o}E at 38^{o}SE) tephra beds that are truncated at the top by 70 cm of planar-bedded tephra. Such a configuration is typical of deltaic deposits of pluvial lakes elsewhere in the Basin and Range province

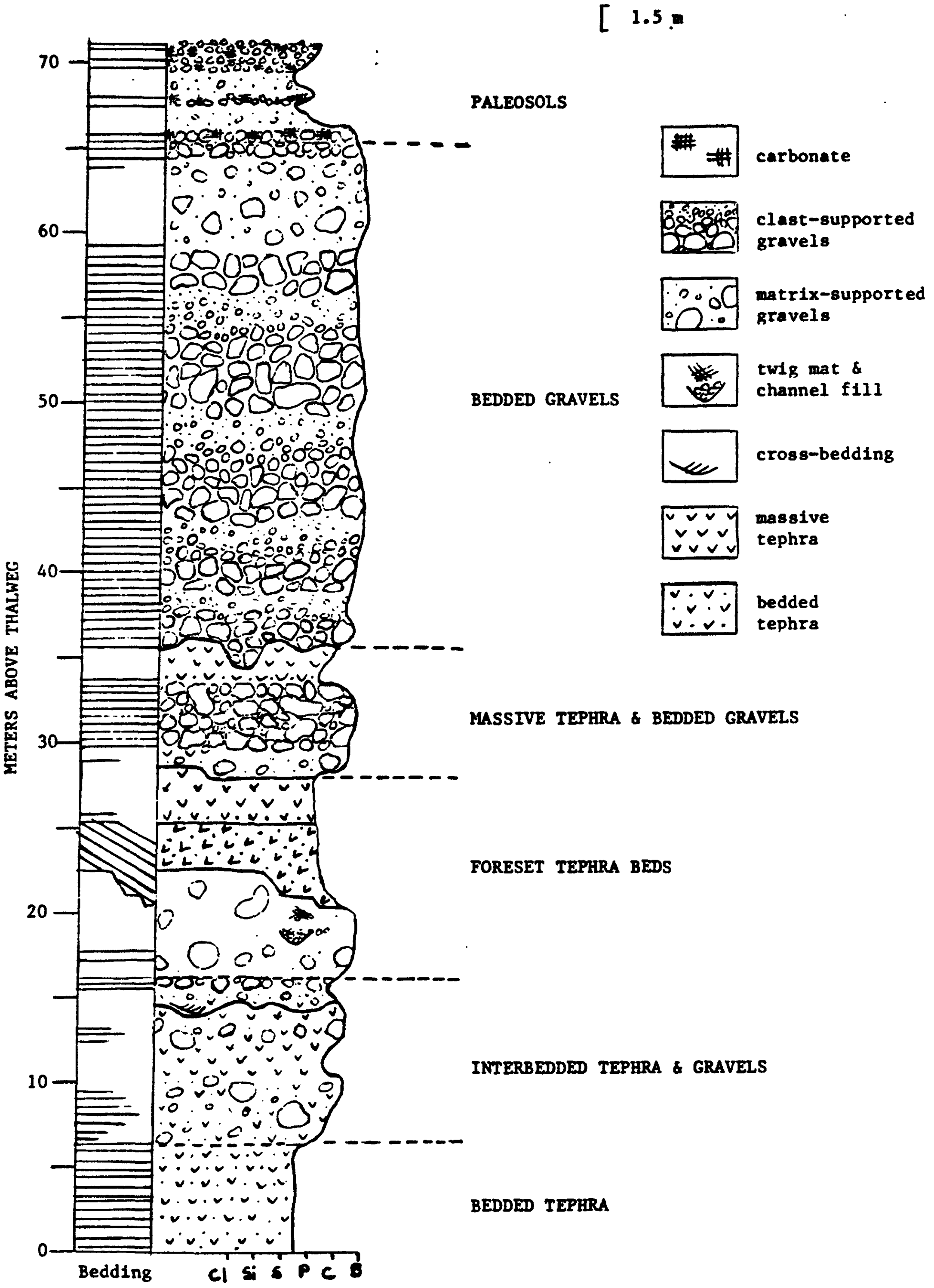


Figure 3. Stratigraphic section of deltaic and alluvial-fan deposits at the mouth of McAfee Creek (fig. 2), measured by Abney level and tape. Horizontal scale indicates range of clast size within a given bed (cl, clay; si, silt; s, sand; p, pebble; c, cobble; b, boulder).

(Russell, 1885; Gilbert, 1890). A poorly bedded, matrix-supported deposit containing cobbles and boulders overlies the topset and foreset tephra beds, and cuts off the tephra beds on the down-dip end.

The topset beds grade upward into massive tephra that is overlain and channeled into by matrix-supported and clast-supported gravel; this section is cut by at least four faults that do not penetrate the overlying 30-m-thick section of poorly bedded, mostly clast-supported, cobble-to-boulder gravel.

The uppermost 6 m of the section contains two buried soils and a stripped relict soil. The soils are marked by prominent carbonate-cemented horizons; horizons between these carbonate-rich horizons are poorly exposed but appear slightly reddened. The lowest buried soil is formed in poorly sorted gravel of granodiorite and quartz monzonite, whereas the upper buried soil and the surface relict soil are formed in fairly well-sorted gravel of carbonate rocks.

Dating

The major-oxide composition of glass from the tephra deposit at McAfee Creek (FLV-65- and 66-MA, table 1) matches with other Bishop ash samples (0.74 Ma; Izett and others, 1970, 1988), although correlation with older rhyolitic ashes from Glass Mountain (0.9-1.0 Ma; Sarna-Wojcicki and others, 1984; Izett and others, 1988), on the northeast rim of the Long Valley caldera (fig. 1), is not precluded. However, the great thickness (>30 m) and coarse grain size (pumice clasts as much as 7 cm long) of the tephra deposit favor a Bishop correlation, for the Bishop eruption was far larger volumetrically than those at Glass Mountain (Bailey and others, 1976). In comparison, maximum pumice clasts from the large eruption of Mount Mazama ash from Crater Lake, about 6,850 yrs B.P., at a comparable distance of 60 to 70 km from the source, are 4.5 to 6 cm in diameter (Fisher, 1964).

Interpretation

Based on the thickness, grain size, sorting, and locally steep bedding of the tephra deposit, we infer that it was deposited as a delta of McAfee Creek at the margin of a pluvial lake. Although the tephra deposit is reworked, its thickness and purity suggest that deposition occurred close to or at the time of the ash eruption. The major-oxide chemistry, coarse grain size, and thickness of the deposit suggest that this tephra is most likely the Bishop ash. This tephra deposit was first described, but not identified, by Elliott-Fisk (1987) as underlying "glacial outwash and till" correlated with the Sherwin Till of the eastern Sierra Nevada. Based on sorting and stratification, however, this gravel consists of alluvial-fan deposits like those elsewhere along the White Mountains (J.L. Slate, unpub. data). Nor can the gravel be correlative with outwash of Sherwin age, because Sherwin till underlies the Bishop Tuff at the type locality (Sharp, 1968). There is, however, a younger till that overlies the Bishop Tuff at Reds Meadow and at other sites near the Long Valley Caldera (Huber and Rinehart, 1967; Sarna-Wojcicki and others, 1984).

Beach Sands Along the Emigrant Peak Fault Zone

Normal faults that bound and lie west of the northern Silver Peak Range (fig. 2) expose a thick (at least 400 m) sequence of alluvial-fan gravel, derived from the Silver Peak Range, that locally contains interbeds of well-sorted sand and fine gravel in exposures along the westernmost fault (Reheis, in press a). The basal deposits are moderately indurated and cemented with carbonate, but the upper deposits are only slightly indurated. As a result, exposures are poor because lag gravel from the upper deposits blankets most slopes.

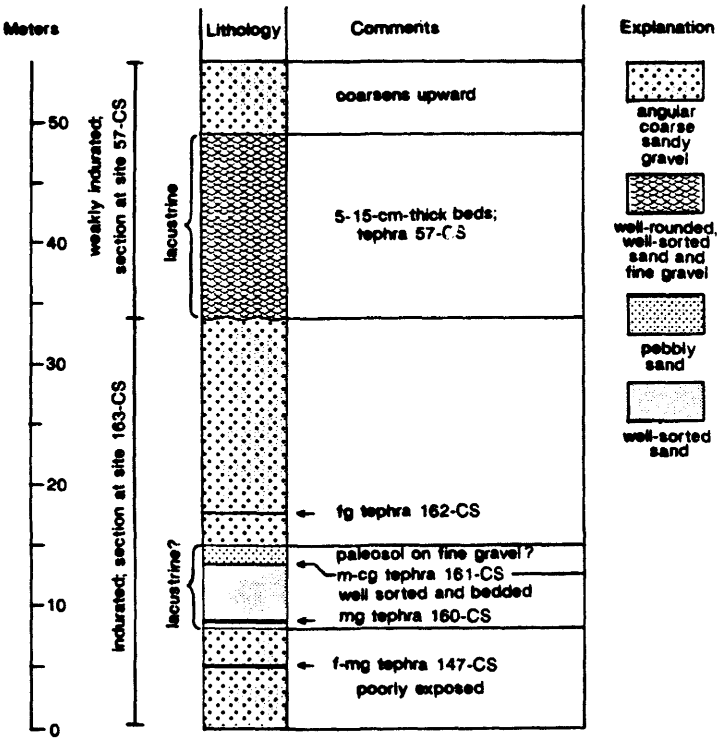


Figure 4. Composite stratigraphic section of beach and alluvial-fan deposits at sites 57-CS and 163-CS (fig. 2), measured using a Brunton compass.

Stratigraphy and sedimentology

At site 57-CS (fig. 2), hand-dug excavations revealed a stratum of loose, well-rounded sand and fine gravel about 15 m thick (fig. 4). This sandy unit lies in sharp contact above indurated, very gravelly, angular, cobble-sized fan gravel and is interbedded upward with moderately sorted, angular to subangular, granule- to cobble-sized fan gravel in a matrix of sand and silt. The sandy unit consists mainly of glass and pumice with grains of volcanic and sedimentary rocks like those in the fan gravel; the lithic grains are few at the base of the unit and increase upward. The sandy unit consists of alternating layers, 5-15 cm thick, of well-sorted, crossbedded, lenticular, medium to coarse sand and coarse sand to fine gravel. Pumice clasts up to 0.5 cm long are better rounded than the lithic grains. Crossbedding within the individual layers is flat to gently dipping and the layers have thin laminae of heavier lithic grains alternating with laminae of lighter pumice and glass; such laminations are characteristic of beach sands (Pettijohn and others, 1973).

Dating

The major-oxide composition of glass from near the base of the sandy unit (FLV-57-CS, table 1) is most like that of the Bishop ash, although it is also similar to the older ashes from Glass Mountain. Based on the size of pumice clasts and the thickness of the sandy unit, the unit was most likely deposited during and shortly following the Bishop eruption, which was much larger than eruptions from the Glass Mountain area. Pumice clasts are not as large as those in the deltaic deposit at McAfee Creek, but the sandy unit southeast of the playa was deposited in a lower-energy environment and lies 25 km farther from Long Valley.

Stratigraphic relations (fig. 4; discussed below) with probable ~1-Ma Glass Mountain tephra beds in underlying dissected fan deposits, which are in turn underlain by tephra beds of the tuff of Taylor Canyon and, provisionally, the Huckleberry Ridge Tuff

Ma) in lacustrine deposits, support the identification of the tephra at site 57-CS as the Bishop ash.

Interpretation

From the grain size, sorting, and roundness of the grains and the nature of bedding and stratification, we believe that the sandy unit represents deposition in shallow water at the shoreline of a lake (Reheis, in press a). The sharp lower contact of the sandy unit with fan gravel suggests either (1) an abrupt change in lake level at or just before the eruption of the Bishop Tuff, or (2) a motion on one of the strands of the Emigrant Peak fault zone east of the outcrop (fig. 2) at about the time of the ash eruption that dropped the former fan surface below lake level. In either case, the lake level must have dropped shortly after the eruption, because the sandy unit is buried by as much as 50 m of fan gravel.

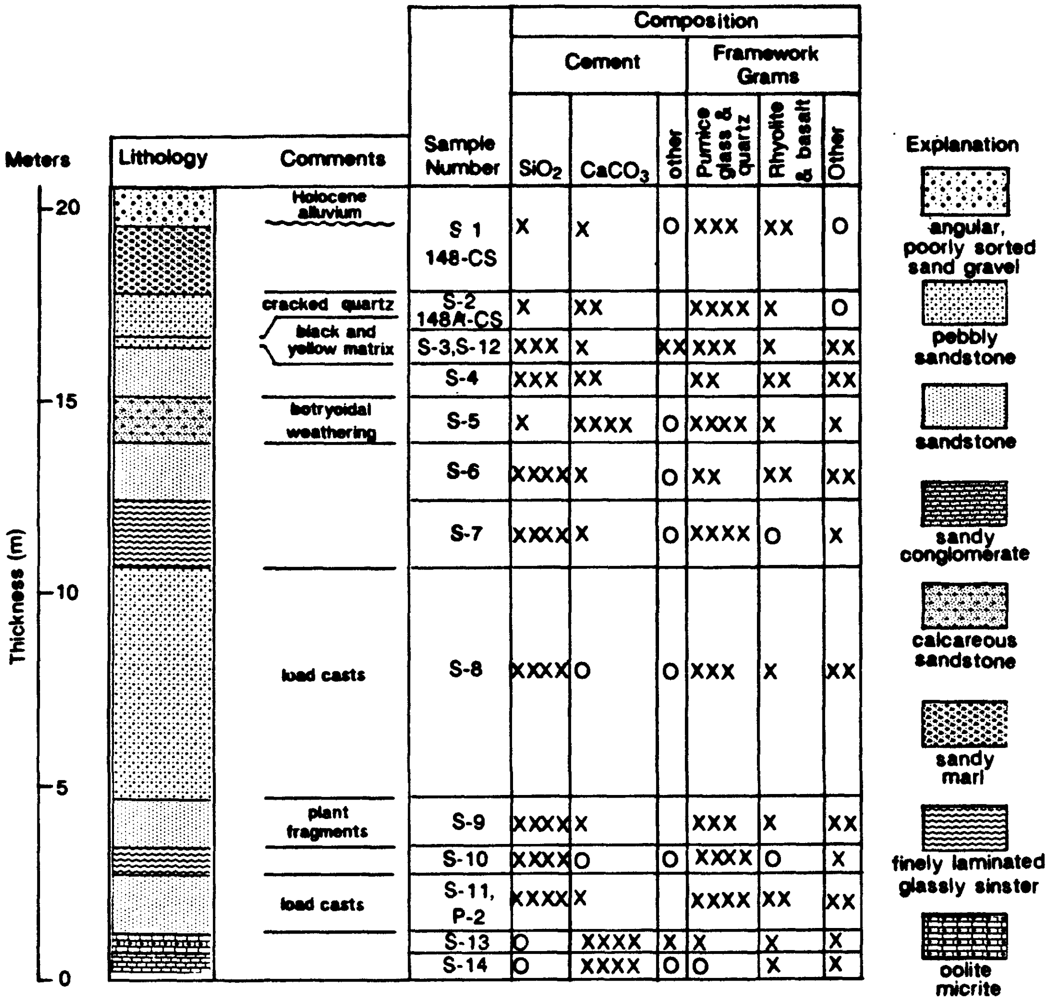
Older deposits nearby

West and north of site 57-CS, the elevation of the pumiceous beach sand rises from about 1500 m to about 1560 m (Reheis, in press a) due to tectonic tilting. At site 163-CS, about 50 m of deposits are exposed below the beach sand (fig. 4), including 10 m of loose sandy fan gravel underlying the beach sand. Below this gravel the sediments are indurated, suggesting either an unconformity at the base of the loose gravel, or cementation due to submergence beneath the Bishop-age lake. The major-oxide chemistry of sample FLV-163-CS is similar to that of the Bishop and Glass Mountain ash beds (table 1), and the layer from which this tephra was sampled can be traced almost continuously from site 163-CS to site 57-CS.

The indurated sediments that lie below the pumiceous, loose sandy unit at site 163-CS contain four lenticular tephra beds (FLV-147-, 160-, 161- and 162-CS, table 1). Two of these beds (FLV-160- and 161-CS), finer-grained than the tephra in the sandy unit, bracket a fine- to medium-grained, well-sorted, pumiceous sandstone about 5 m thick (fig. 4). The major-oxide chemistry of the four tephra beds is similar to that of glass from the Bishop and Glass Mountain eruptions (table 1). We currently think that these beds are correlative with tephra of Glass Mountain (0.9-1.0 Ma; Izett, 1981; Sarna-Wojcicki and others, 1984; Metz and Mahood, 1985; Izett and others, 1988) because they underlie the loose sandy unit believed to be of Bishop age, and because they are in turn underlain by lacustrine deposits containing ~2-Ma tephra correlated to the tuff of Taylor Canyon and, provisionally, the Huckleberry Ridge Tuff (discussed below). Hence, the pumiceous sandstone in the indurated sediments may represent deposition by a lake at about 1 Ma.

The Sinter Mound

Half-buried under gently sloping late Pleistocene and Holocene fan gravel southwest of the playa (fig. 2) is a small (<0.5 km^2) apron-shaped outcrop of rock mapped as Tertiary sedimentary rocks by Robinson and others (1976) and as Quaternary/Tertiary tuffaceous sandstone and siltstone and freshwater limestone by Robinson and Crowder (1973). The outcrop extends from about 1425 to 1443 m in elevation, and appears to be cut on the southeast by a low fault scarp (Reheis, in press a); the height of this scarp is about 5 m. The fault may be active, for springs occur along it and a 1-m-high scarp offsets Holocene (?) deposits about 2 km southwest of the outcrop along the fault. However, the fault appears to have had relatively little cumulative vertical offset in Pleistocene time.



Sample Number	Composition: Cement: SiO_2	$CaCO_3$	other	Framework Grams: Pumice glass & quartz	Rhyolite & basalt	Other
S 1 148-CS	X	X	O	XXX	XX	O
S-2 148A-CS	X	XX		XXXX	X	O
S-3,S-12	XXX	X	XX	XXX	X	XX
S-4	XXX	XX		XX	XX	XX
S-5	X	XXXX	O	XXXX	X	X
S-6	XXXX	X	O	XX	XX	XX
S-7	XXXX	X	O	XXXX	O	X
S-8	XXXX	O	O	XXX	X	XX
S-9	XXXX	X		XXX	X	XX
S-10	XXXX	O	O	XXXX	O	X
S-11, P-2	XXXX	X		XXXX	XX	XX
S-13	O	XXXX	X	X	X	X
S-14	O	XXXX	O	O	X	X

Figure 5. Stratigraphic section at sinter mound, measured by Abney level and tape (fig. 2). Relative abundances of cement and framework grains are visually estimated from hand samples, thin sections, and XRD data: 0, absent; X, minor; XX, common; XXX, abundant; XXXX, dominant. S-, rock sample; 148-CS, tephra sample; P-, paleomagnetic sample.

Stratigraphy and sedimentology

The outcrop consists mainly of interbedded sandstone, amorphous and opaline silica, and minor conglomerate (fig. 5). The beds are well sorted and stratified but thin (0.3-2 m) and very lenticular; individual beds cannot be traced across the outcrop. At the base of the outcrop, oolite micrite and weakly indurated marl are locally exposed. The rocks grade southwest along the fault into weakly to moderately indurated sandy travertine and calcareous sand around active springs.

Sandstone beds are fine- to medium-grained, thinly bedded, and pumiceous (Reheis, in press a). Their glass and pumice content increases upward at the expense of locally derived lithic grains of rhyolite, basalt, quartz, feldspar, and minor amounts of other minerals. The sand grains are subangular to subrounded and cemented by light-gray opaque silica and some carbonate. Plant fragments, including root casts, are observed in some samples, and load casts are common in some beds. Near the top of the outcrop, the pumiceous sandstone is in part cemented by black and yellow microcrystalline minerals.

Silica deposits are finely laminated, but the laminations are highly irregular in detail, and consist of light-gray, amorphous to opaline silica that breaks conchoidally. The siliceous beds contain abundant fine- to medium-grained, subangular to subrounded, volcanic glass shards and pumice grains.

The uppermost part of the outcrop is silica- and carbonate-cemented, poorly sorted sandy conglomerate consisting of granule- to pebble-size subangular pumice clasts, large sand-size grains of cracked euhedral quartz, and smaller bubble-wall glass shards, admixed with subangular to subrounded rhyolite and basalt clasts derived from the Volcanic Hills to the north (fig. 2). Throughout most of the outcrop, the pumice grains have flattened vesicles. In the upper part, however, the pumice grains have open round vesicles partly filled with secondary carbonate.

Microscopic and XRD examination of secondary minerals

Thin sections and x-ray diffraction data (fig. 6) indicate that the dominant cementing agent throughout the section is silica, but carbonate is locally dominant, and minor amounts of other secondary minerals occur in some beds. A sharp-crested but broad peak centered at 22^{o} 2O is considered characteristic of opal-CT (Jones and Segnit, 1971) and occurs in most of the XRD traces (fig. 6). The less crystalline form, opal-A, is probably also present. Thin sections show some small areas of chalcedony. In the uppermost beds, some quartz grains have been dissolved, but this process appears to have been minor and could not have provided the amount of secondary silica present in the lower beds. In samples where opaline cement dominates, small amounts of carbonate appear to have precipitated in void spaces following cementation by opal, but in other samples, carbonate cement dominates and apparently preceded opal cementation. Small rosette-like crystals that are seen rarely in thin section may be alunite.

Tephra sample FLV-148-CS is from the uppermost pumiceous layer (fig. 5). Based on major-oxide composition of the glass, this sample appears to have been hydrothermally altered (table 2). Sample FLV-148A-CS, also from the upper part of the sinter mound, has a composition like that of the Bishop ash (table 1). If the altered sample had an initial composition like that of the average of five unaltered samples of probable Bishop ash from Fish Lake Valley, then the net total deficit of oxides leached from the altered sample is 5.86 percent by weight (table 2). The remaining 6 percent deficit from 100 percent represents the approximate amount of gas and water of hydration present in the glass, plus very small amounts of several oxides and anions that were not analyzed by the electron microprobe (F, P, S, Cl, Rb_2O, SrO, ZrO_2, and BaO; 0.5 percent or less). Note that all of the manganese has been leached from the altered sample, as well as significant amounts of silica, iron, sodium, and potassium. Conversely, magnesium and calcium are considerably enriched, probably from reaction of the glass with hot water that contained these elements.

Just below the uppermost layers, a black, opaque, botryoidal mineral is interlayered with opal. Based on its appearance and XRD character, it is probably a form of pyrolusite. A yellowish microcrystalline mineral is laterally associated with the pyrolusite along the outcrop, but has not yet been identified. The layer containing these black and yellow secondary minerals underlies the layer from which the leached sample of ash was collected (fig. 5).

At the base of the outcrop, calcareous marl and oolitic rocks are locally exposed (fig. 5). Thin sections and XRD analyses (fig. 6) of the oolitic rocks indicate that most of the oolites have cores of micrite, but some have cores of micrite-cemented sand-size grains of quartz, feldspar, glass, and (or) lithics. These cores were probably derived from the micritic marl, which contains many non-carbonate grains. The concentric layers of the

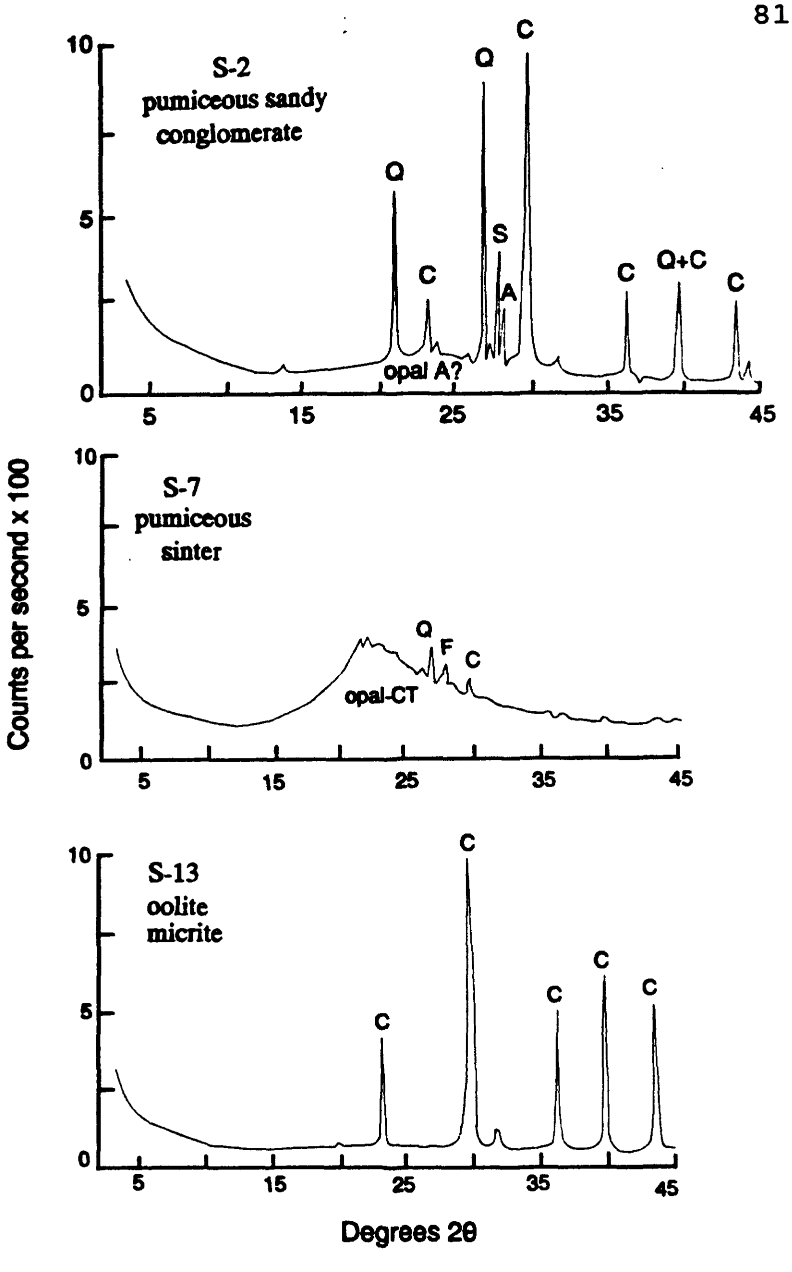


Figure 6. Representative XRD traces of rocks (powder mounts) from sinter mound (figs. 2 and 5). Opal identification follows Jones and Segnit (1971). Q, quartz; C, calcite; F, feldspar; S, sanidine; A, high-temperature albite.

ooids consist of alternating light and dark bands, mostly micrite but locally microsparite. Voids are commonly lined with micrite layers, but some contain a late-phase authigenic mineral that may be alunite.

Dating

Two samples were analyzed for major oxides of the volcanic glass (table 1). Sample FLV-148-CS is from the uppermost bed (fig. 5) where the pumice clasts are largest. The major-oxide composition of this sample matched no known widespread tephra layers in the western United States. As discussed above, the upper layers of the outcrop have been hydrothermally altered (table 2). Sample FLV-148A-CS is from layer S-2 of the outcrop (fig. 5). The major-oxide composition of this sample is a good match for that of the Bishop ash, but it is also close to that of the Glass Mountain D ash bed. The size of the pumice clasts (up to 2 cm in diameter) in the uppermost bed favors, but does not prove, a correlation to the Bishop ash.

In summary, we believe that the pumice and bubble-wall shards were derived from the Bishop eruption. It is possible that pumice from more than one eruption, especially from the chemically similar Glass Mountain tuffs, could be present in the mound. However, there are no unconformities or discontinuites in the stratigraphic section (fig. 5) as might be expected if the mound had been deposited over a span of 300,000 years (1.0-0.7 Ma).

Interpretation

The abundance of opal as discrete layers and as cement in this outcrop strongly suggests a hot-spring origin. The presence of opal layers in Fish Lake Valley is unique to this and nearby outcrops to the northeast, discussed below. Modern spring water in northeastern Fish Lake Valley is nearly saturated with dissolved silica, in contrast to springs in other parts of the valley (Macke and others, 1990). Several other associations and characteristics, discussed by White and others (1989), support a hot-spring origin for these rocks: (1) They form an apron-shaped outcrop that is conformable with the Quaternary land surface. (2) They are spatially associated with relatively young volcanic rocks and lie on a fault active in Quaternary time. (3) They crop out only 1.5 km southwest of a deep drill hole near a Quaternary fault subparallel to the one that bounds the outcrop; this drill hole intersected artesian hot water. (4) The opal layers contain highly irregular bedding laminations. The thin layers are similar to thin-bedded opaline sinter formed by primary discharge on broad aprons at Steamboat Springs, Nevada (White and others, 1964). Some textures reported to be common in hot-spring sinters, such as columnar structures perpendicular to bedding laminations (White and others, 1989) were not observed in the rocks in Fish Lake Valley.

We infer that the sinter mound was formed in shallow water at the edge of a lake, and that the majority of the mound was constructed just after the eruption of the Bishop Tuff, based on the following observations: (1) The mound contains numerous beds of well-sorted sandstone. The sandstone beds do not exhibit trough crossbedding or other structures indicative of fluvial deposition, and they are too well sorted and bedded to represent alluvial-fan deposition. (2) The majority of the grains in the sandstone beds and throughout the mound consist of pumice and bubble-wall shards. Near the top, there are some euhedral, cracked quartz grains, some of which are contained within large pumice grains and hence must have come from the same source as the pumice. (3) There are no unconformities or apparent breaks in depositional style or composition throughout the mound. (4) The siliceous deposits overlie lacustrine marl and oolitic rocks. Oolites must have formed in carbonate-enriched, shallow water, and have been reported from both ancient and modern sediments of lakes in the Great Basin (Russell, 1885; Gilbert, 1890). (5) The pumice grains in most of the mound contain flattened vesicles, but near the top of the mound, vesicles are spherical. This suggests a sort of grading in which the lighter, air-filled pumices floated whereas heavier pumices with flattened vesicles sank.

The elevation of the uppermost beds of the sinter mound probably represents the paleo-shoreline of the lake, because this bed contains large, air-filled pumice clasts intermixed with pebbles of rhyolite and basalt derived from the Volcanic Hills to the north. The shoreline elevation may be slightly higher now due to uplift along the small fault that bounds the outcrop, but major changes in elevation are unlikely. The elevation of the uppermost bed is presently 1,443 m; hence, the paleo-shoreline is inferred to have been at about 1,440 m.

Tertiary Sediments East and West of the Playa

Fine-grained Tertiary sediments crop out east and west of the playa in northeastern Fish Lake Valley (fig. 2). East of the playa, these sediments are conformable with, and grade upward into, indurated gravel of late Tertiary-early Quaternary age (Reheis, in press a). Both outcrops were previously inferred to represent deposition in an alkaline lake on the west side of the Silver Peak Range (Robinson, 1964, and Robinson and others, 1976). The Tertiary rocks consist of green and grayish-green, weakly indurated claystones, tan, fine-grained sandstones, and tephra beds up to 50 cm thick. Southwest of the playa, lenses of siliceous sinter crop out that are similar to those in the sinter mound.

Two beds of tephra (table 1) were sampled in the southwestern area of Tertiary sediments. The lower bed, 15 cm thick (FLV-150-CS), overlies green claystones and consists of very well sorted, medium-sand-sized pumice grains. The lower bed is overlain by 1 m of well-sorted tan pumiceous sandstone grading upward into green pumiceous mudstone. The mudstone is in turn overlain by 50 cm of fine-sand-sized tephra (FLV-151-CS). This tephra is capped by 4.5 m of sediments like those between the tephra beds. Both tephras are similar to tephras of the tuff of Taylor Canyon, based on major-oxide chemistry of the glass, and hence are inferred to be about 2.1-2.2 Ma (Izett, 1981; Izett and others, 1988; Sarna-Wojcicki and others, 1984, and in press).

The Tertiary lacustrine beds on the east side of the playa are particularly well exposed at site 179-EP, just recently discovered. These beds contain multiple layers of fine-grained, white pumiceous tephra that have not yet been sampled or analyzed. Above these layers, near the top of the lacustrine beds, is a 0.5-m-thick layer of reworked, fine-grained, bluish-gray tephra (FLV-179-EP). Based on major-oxide chemistry (table 1), we provisionally correlate this layer with the Huckleberry Ridge ash bed, erupted from the area of Yellowstone National Park about 2.01 Ma (Christiansen, 1979; Izett, 1981).

The upper Tertiary sediments east and west of the modern playa indicate the presence of a lake in northeastern Fish Lake Valley at about 2 Ma. The extent of this lake is unknown, but based on the presence of claystones it must have been deeper in this area than the lake represented by shoreline deposits of the Bishop ash. Robinson (1964) inferred that it did not extend far westward into the Volcanic Hills, because these sediments lap at gentle dips onto more steeply dipping older tuffs in these hills. Similar sediments crop out as far north as The Gap (fig. 2), but apparently do not crop out north of The Gap in Columbus Salt Marsh (Robinson and others, 1976). The 2-Ma lake could not have extended as far east as site 8-13-CS (fig. 2), because tephra beds correlated to the tuff of Taylor Canyon (table 1) are there contained within alluvial-fan gravel (Reheis, in press a). Tertiary lacustrine sediments, if present, are buried beneath Quaternary sediment south of the playa. Gypsiferous green claystones occur at the southern end of Fish Lake Valley but are slightly older than those at the northern end; the southern claystones range in age from about 3.2 to more than 2.0 Ma (Reheis and others, this volume; ages based on tephrochronology by A. Sarna-Wojcicki). The upper Tertiary claystones are so weakly indurated that they probably could not be differentiated from Quaternary sediments in drill holes.

The Connection to Columbus Salt Marsh

A narrow valley about 8 km long connects the modern playa of Fish Lake Valley with Columbus Salt Marsh (fig. 2). The valley narrows to the north; the flat alluvial floor of the valley is less than 0.5 km wide at the north end. Gently sloping alluvial fans broken by small, low-standing outcrops of Tertiary and Paleozoic rocks (Robinson and others, 1976) extend up to bedrock valley walls at elevations of about 1,440 m, extending the width of the valley to as much as 1.3 km. Despite a continuous gentle gradient of about 3.8 m/km, there is no surface drainage in most years (Beaty, 1968) and no channel exists; however, there are numerous springs and wet marshes.

The valley is floored mainly by fine-grained marsh deposits of unknown thickness that grade upslope into Holocene fan deposits (Reheis, in press a). At the northern end of the valley are several active springs, three of which emerge from spring mounds constructed mostly of well sorted calcareous sand, probably eolian sand trapped by the vegetation around the springs. A few late Pleistocene fan deposits occur on the fan slopes, and they are composed of locally derived clasts.

Late Pleistocene shorelines and beach deposits of a lake in Columbus Salt Marsh stand at an elevation of about 1,380 m at the mouth of the valley, coincident with two active spring mounds. Beneath the loose sand of the mounds, and locally exposed in arroyos that cut the Holocene fan deposits blanketing the shoreline, are massive, well-cemented beds of sandy travertine (Reheis, in press a). The travertine has not been dated, but judging from its relations to the spring mounds, the shoreline, and the younger fan deposits, it was probably deposited by voluminous groundwater discharge from Fish Lake Valley into the pluvial lake in Columbus Salt Marsh in late Pleistocene time.

Interpretation

The narrow, gently sloping valley of The Gap presently serves as a shallow groundwater conduit and probably had the same role in late Pleistocene time. The buried travertine suggests that the late Pleistocene groundwater discharge was greater than that today. No distinct drainage channel exists, but it is possible that one is buried under Holocene marsh deposits.

An older (early Pleistocene?) channel that carried overflow from Pluvial Fish Lake at 1,440 m elevation into Columbus Salt Marsh is possible, but if so the evidence to document the channel has been obscured. No lag gravel of exotic composition is found on slopes below that elevation in the valley of The Gap, nor are there distinct benches cut at appropriate elevations (one low bench, possibly that mentioned by Free, 1914, is blanketed by Holocene deposits). A deep channel buried by Holocene and older deposits is unlikely, because Tertiary rocks crop out randomly on the valley floor (Reheis, in press a) and hence the alluvial fill is probably thin. However, the valley could have been a shallow sill connecting two lakes at the same shoreline elevation.

Well Logs

The sediments reported in the drilling logs are dominantly sandy or clayey gravel that reflect alluvial-fan sedimentation, but there are significant thicknesses of mudstone and sandy clay interbedded with the gravel at depth (fig. 7). Fifteen of the logs (including three wells drilled by the U.S.G.S.), mainly those near the playa and along the valley axis, describe beds as much as 35 m thick of green, blue, gray, or white clay or sandy clay at depths ranging from 20 to 230 m. Such colors are believed to be characteristic of lacustrine clays, as reported by Morrison (1964) of drillers' logs in the Lahontan basin, in contrast to yellow, yellowish-red, or brown colors that typify fine-grained valley-fill sediments interbedded with alluvial-fan gravel. Significantly, two of the water-well logs report "volcanic ash" beds as much as 5 m thick at depths ranging from 100 to 150 m. Three other water-well logs in the southern part of the valley report "gypsum" beds at about the same depth as a nearby well log that reported "volcanic ash". Because gypsum beds do not crop out anywhere around Fish Lake Valley, these "gypsum" beds are inferred to be volcanic ash beds. One of the U.S.G.S. logs (#1 in fig. 7; Pantea and others, 1981) reported shell fragments at 110 m depth in a 3-m interval within a thick sequence of grayish-yellow clay and sandy clay.

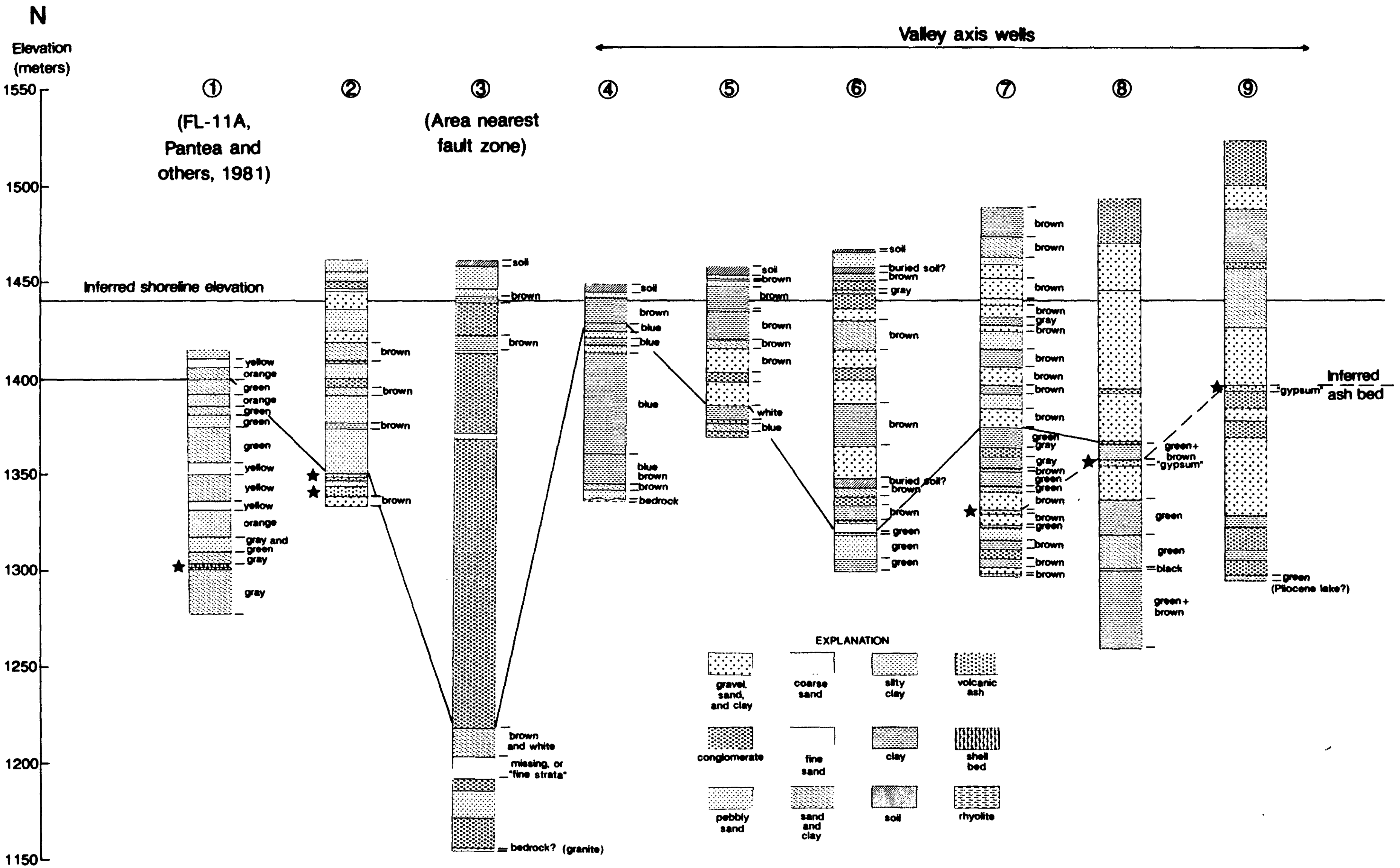


Figure 7. Representative well logs reporting lacustrine sediments and ash beds in Fish Lake Valley (fig. 2). Star, ash bed or "gypsum" bed; asterisk, bed containing shell fragments. Column to right gives sediment colors where reported (drillers often report colors only for clay beds).

Interpretation

The sequences of green, blue, gray, and white clay and sandy clay in the well logs at depth are inferred to represent intervals of lacustrine sedimentation. This inference is supported by the existence of a shell bed in one drill hole. Although drilling logs may be unreliable, the concurrence of fifteen logs made by several different drillers in the description of fine-grained sediments at depth and an abrupt change to yellow or brown sediments above is believed significant.

Three of the beds of "volcanic ash" and "gypsum" that is believed to be volcanic ash (figs. 2, 7) lie within, or are closely associated with, fine-grained sediments. In the northern well (#2, fig. 7), the two reported ash beds total about 7 m of a 13-m-thick sequence of sandy clay (no color described) that lies between beds of clayey and sandy gravel. The thickness of these ash beds suggests that their source was the eruption of the Bishop Tuff. If this correlation is correct, the thinness of the fine-grained sediments in this well may mean that the ash was deposited near the northern shoreline.

In two of the southern wells (#7 and #8, fig. 7), the 2-3-m-thick ash and "gypsum" beds lie in sequences of green and some brown clays interbedded with clayey gravel. Lacustrine sedimentation, represented by about 45 m of green and gray clay interbedded with gravel that overlie the ash and "gypsum" beds (fig. 8), must have continued episodically for some time after deposition of the ash and "gypsum" beds. Assuming that the ash in the southern wells is the Bishop ash, then the average rate of post-Bishop sedimentation indicated by these well logs is about 0.2 m/ka, and the length of post-Bishop lacustrine sedimentation in this area may have been roughly 200,000 years.

The "gypsum beds" reported in two wells south of Oasis (only one shown; #9, fig. 7) lie in thick sequences of clayey and sandy gravel at shallower depth than the ash and "gypsum" described in the two wells north of Oasis (figs. 2 and 7). None of the three well logs in this area describe green, blue, or white clay, except for one bed at the bottom of one hole, 100 m below the "gypsum" (#9, fig. 7). If these "gypsum beds" are tephra from the Bishop Tuff eruption, their occurrence in these holes suggests that the lake did not extend south of Oasis at Bishop time.

DISCUSSION AND REGIONAL IMPLICATIONS

Identification of the Bishop and Older Ash Beds

Identification of the thick, coarse-grained ash bed in Pleistocene fluvial and lacustrine deposits of Fish Lake Valley as the Bishop ash bed would date the shoreline deposits, and thus one stand of the pluvial lake in this basin, at about 0.74 Ma. Currently, the most reliable isotopic age of the Bishop Tuff is 0.738 Ma (mean age from conventional K-Ar analyses on sanidine; Izett and others, 1988, p. 23). Although our identification of this layer in Fish Lake Valley would be supported by additional analyses of the glass for trace and minor elements and by determination of magnetic polarity, its identity as the Bishop is presently indicated by sedimentologic (grain size and thickness), stratigraphic (underlain in sequence in northeastern Fish Lake Valley by fine-grained, thin beds of probable Glass Mountain tephra, fig. 4, and by ash beds of the tuff of Taylor Canyon), and chemical data (table 1), as well as by the notion that the most probable and obvious choice is likely to be the right one, as discussed below.

The eruption of the Bishop tephra from Long Valley caldera, a few tens of kilometers west of Fish Lake Valley, was one of the most explosive and largest in Pleistocene time, producing an estimated 500 km^3 of tephra (Bailey and others, 1976). Although the Bishop ash bed is present to the west and southwest of Long Valley (Sarna-Wojcicki and others, 1987), most identified sites are to the east, extending as far as south-central Nebraska (Izett and others, 1970, 1988). Consequently, the principal direction of transport was eastward, in the direction of prevailing winds.

Considering that Fish Lake Valley is only about 70-80 km due east and directly downwind of Long Valley, it is reasonable to expect that the coarsest, thickest, and most pervasive Pleistocene tephra layer there, and one with glass chemistry characteristic of the Long Valley-Mono Glass Mountain source area as well, will be the Bishop ash bed.

Tephra layers having chemical compositions similar to those of the Bishop ash bed have been erupted from the Mono-Glass Mountain source area at the east margin of Long Valley caldera. Glass Mountain is an older vent complex that was active between about 2.2 and 0.8 Ma (Metz and Mahood, 1985). Only the youngest tephra erupted from this source, such as the Glass Mountain G (about 1.0 Ma) and D (about 0.9 Ma) ash beds, can be confused with the Bishop on the basis of electron-probe shard compositions. Glass shards of the Glass Mountain G and D ash beds have the same shapes and indices of refraction as the Bishop ash bed. Furthermore, Glass Mountain G and D and the Bishop ash beds have similar mineralogy. Consequently, these ash beds cannot be distinguished from the Bishop ash bed by petrographic criteria or electron-microprobe analyses alone (Izett and others, 1988, p. 30-31).

The Glass Mountain tephra layers were produced by considerably smaller eruptions than that of the Bishop ash bed. For example, at localities at the southern end of the volcanic tableland formed by the Bishop Tuff (table 1, 7-9), about 50 km southeast of Long Valley caldera, the airfall Bishop ash bed contains coarse pumice clasts up to several centimeters in diameter, but the underlying Glass Mountain D and G ash beds consist mostly of silt- and sand-sized clasts.

Older tephra erupted from the Glass Mountain source area, such as the ~2-Ma tuff of Taylor Canyon (Krauskopf and Bateman, 1977), in addition to being thinner bedded and finer grained than the Bishop, is chemically distinguishable from the younger tephra of Glass Mountain and the Bishop ash bed (table 1). In particular, Fe, Mn, and Ca differ significantly between the 0.74-1.0-Ma tephra layers and the 2-Ma Tuff of Taylor Canyon (Izett, 1981).

Although glass of the Bishop ash bed cannot be confidently distinguished by the electron microprobe from that of the younger Glass Mountain tephra layers, these units can be distinguished by the more sensitive technique of instrumental neutron activation analysis of the glass (Sarna-Wojcicki and others, 1984), and we are currently conducting this type of analysis. In addition to chemical criteria, the Bishop ash bed can be distinguished from the Glass Mountain D and G ash beds by magnetic polarity. The former was deposited shortly before the end of the Brunhes Normal Polarity Chron, whereas the latter two were deposited during the Matuyama Reversed Polarity Chron. Sarna-Wojcicki and others (1984) suspected that the Glass Mountain G ash bed was deposited prior to the Jaramillo Normal Subchron, and the Glass Mountain D ash bed after. Paleomagnetic analysis is being performed on samples from the sandstones of the sinter mound in Fish Lake Valley; the other two shoreline deposits in the valley are too coarse-grained for this type of analysis.

Several thin, fine-grained tephra layers (table 1) are present in late Tertiary deposits in northeastern Fish Lake Valley (fig. 2). East of the Emigrant Peak fault zone, these layers are within thick gravel deposits (FLV-8- to 13-CS); west of the modern playa, the layers are within lacustrine deposits (discussed above; FLV-150- and 151-CS). These tephra layers are chemically identical to tuffs of the compound tuff of Taylor Canyon (Krauskopf and Bateman, 1977). Previously, Izett (1981) reported conventional K-Ar ages of sanidine in pumice of the tuff of Taylor Canyon as 2.1 Ma. Conventional K-Ar analyses on obsidian chunks picked from several emplacement units of this tuff, and preliminary laser-fusion $^{40}Ar/^{39}Ar$ analyses on sanidines separated from this tuff, also indicate that it ranges in age from about 2.0 to 2.1 Ma (J.K. Nakata, C.E. Meyer, and A.M. Sarna-Wojcicki, unpublished data), an age compatible with the older ages (to 2.2 Ma) obtained on the flow rocks of Glass Mountain by Metz and Mahood (1985).

Chronology, Size, and Connections of Pluvial Lake Rennie

The three thick, coarse-grained, shallow-water outcrops of tephra in northern Fish Lake Valley collectively demonstrate that a pluvial lake existed in this valley, most likely at the time of the eruption of the Bishop Tuff. This conclusion is supported by the well-log descriptions of deep-water lacustrine clays, thick shoreline beds of volcanic ash, and one bed of shell fragments. This lake, or one occupying approximately the same position (at least in the northeastern part of the valley), also existed in the late Pliocene based on lacustrine deposits east of the modern playa that contain ~2-Ma tephra. In addition, a bed of well-sorted sand below the Bishop ash and above a probable Glass Mountain tephra at site 163-CS (fig. 2) suggests the presence of a pluvial lake at about 1 Ma. Lacustrine sedimentation may have continued into the middle Pleistocene in deeper parts of the basin, but there is no evidence to support a late Pleistocene lake.

Details concerning the depth, the geographic extent, and the nature of the connection of Pluvial Lake Rennie with Columbus Salt Marsh are sparse, but some reasonable inferences can be made. Based on the elevation of the sinter mound, the shoreline elevation was at about 1,440 m. The lowest elevation of probable lacustrine sediments reported in the well logs is about 1,215 m (fig. 7). However, most of the valley floor has been significantly dropped relative to the White Mountains along the Fish Lake Valley fault zone in Quaternary time (Sawyer, 1990; Reheis and McKee, this volume). If the motion was mostly absorbed by uplift of the range, the lake may have been as much as 230 m deep. If the motion was mostly absorbed by dropping the valley floor, the lake may have been much shallower.

The geographic extent of the Bishop-aged Pluvial Lake Rennie can be approximated from the three shallow-water outcrops of probable Bishop ash and the well logs (fig. 2). The northwestern part of the lake is poorly constrained due to the lack of well logs in this area. However, the deltaic sediments at the mouth of McAfee Creek suggest that the shoreline, for an unknown distance north of the delta, was at or close to the range front. The lake probably did not extend north much past Chiatovich Creek, based on the thinness of fine-grained sediments containing volcanic ash in well log #2 (fig. 7). The lake extended about as far south as Oasis (fig. 2), based on the lack of lacustrine sediments in wells south of Oasis. This conclusion is supported by reconstructions of stream drainages and restoration of right slip along the southern part of the Fish Lake Valley fault zone (Reheis and McKee, this volume) that suggest that the depositional basin probably terminated to the south around Oasis at 0.74 Ma. For example, the course of Cottonwood Creek at the time of the Bishop eruption was southeasterly, parallel to the Fish Lake Valley fault zone and on the present drainage divide between Fish Lake Valley and Deep Springs Valley (fig. 2). Clearly, this topography could not have existed in its present form 740,000 years ago.

Given a pluvial lake in Fish Lake Valley at 1,440 m elevation, a connection must have existed to the north into Columbus Salt Marsh (fig. 2), which is at about 1,350 m elevation at its lowest point. Although a few north-dipping faults have been mapped on the north end of the Volcanic Hills and the Silver Peak Range (Dohrenwend, 1982; Robinson and others, 1976), Quaternary offset on these faults is probably not enough to account for the total elevation difference of the two basins. There are three permissible scenarios for such a connection: (1) Pluvial Lake Rennie was dammed on the northeast and drained northward primarily by groundwater discharge, as the valley does today. (2)

Pluvial Lake Rennie was dammed on the northeast and drained northward by a relatively high-energy overflow channel. (3) A contiguous lake at 1,440 m elevation was connected between Pluvial Lake Rennie and Columbus Salt Marsh via a sill in The Gap.

These scenarios are difficult to evaluate. Late Pleistocene and Holocene sediments have largely buried older deposits, if present, in The Gap and to the north. If a dam existed, it probably consisted largely of readily erodible ash-flow tuff (Robinson and others, 1976). Such a dam probably could not have maintained a lake at 1,440 m elevation for long, whether discharge occurred by groundwater or by overland flow. The 1,380-m late Pleistocene shoreline in Columbus Salt Marsh (Reheis, in press a) is not high enough to permit a lacustrine connection into Fish Lake Valley. Two remnants of older shorelines at about 1,410 m exist on the eastern and northwestern margins of Columbus Salt Marsh (J.O. Davis, written commun., 1990). This elevation is high enough to permit a lacustrine connection with the modern playa in Fish Lake Valley, but little more. If a lacustrine connection over a sill existed at Bishop Tuff time, then either or both (1) a previously undiscovered shoreline at 1,440 m elevation exists in Columbus Salt Marsh, or (2) the northern part of Pluvial Lake Rennie has been elevated by faulting or tilting about 30 m relative to Columbus Salt Marsh since 0.74 Ma.

Comparison to Other Pluvial Lake Records and the Marine Oxygen-Isotope Record

Three large pluvial lakes and lake systems were situated within 100 km of Pluvial Lake Rennie: Lake Lahontan to the north, the system of overflowing lakes to the south beginning with Owens Lake, passing through Searles Lake, and terminating in Lake Manley (Death Valley), and Lake Tecopa, about 200 km southeast of Fish Lake Valley (fig. 1). The middle and early Quaternary records from these lakes can be compared with that of Pluvial Lake Rennie. Lake Lahontan and the southern chain of lakes were fed by perennial rivers heading in the Sierra Nevada and presumably had a more secure water supply than did Lake Tecopa, fed only by streams heading in unglaciated terrain, or Pluvial Lake Rennie, in the rain shadow of both the Sierra Nevada and the White Mountains. Thus, Pluvial Lake Rennie might have a record of fluctuations more similar to that of Lake Tecopa than to those of Lake Lahontan or the upper lakes in the southern chain.

In the Lake Lahontan basin, the best record is from outcrops at Rye Patch Dam. Here, a thick deposit of the 0.63-Ma Rye Patch Dam Bed (Davis, 1978; Sarna-Wojcicki and others, in press), is overlain by lacustrine deposits (the Rye Patch Dam Alloformation, Morrison and Davis, 1984) containing the 0.62-Ma Lava Creek B ash bed (Izett, 1981). This lake apparently dried up shortly after 0.6 Ma at this location, for the lacustrine sediments are thin and are overlain by a thick sequence of terrestrial sediments and paleosols. An older, poorly dated lake cycle may be represented by sediments below the terrestrial Lovelock Alloformation, which underlies the Rye Patch Alloformation.

The record from the southern chain of lakes is derived from interpretation of cores at Searles Lake (fig. 1; Smith, 1984) dated by volcanic ash stratigraphy, paleomagnetism, and sedimentation rates. The Searles Lake record indicates fluctuating but relatively high lake level from 2.0 to 0.6 Ma, when the lake dried up for a lengthy period.

Sediments at Lake Tecopa are well exposed, even in the central part of the lake basin, due to draining of the lake in the middle Pleistocene and subsequent incision (Sheppard and Gude, 1968; Sarna-Wojcicki and others, 1984). Lake sediments with interbedded fine-grained alluvium indicate that the level of Lake Tecopa fluctuated in the late Pliocene and early Pleistocene. The lake level was relatively high at 2 Ma and at 0.6 Ma, because tephra beds of the Huckleberry Ridge Tuff, the tuff of Taylor Canyon, and the Lava Creek Tuff occur in lacustrine sediments (Sarna-Wojcicki and others, 1984, 1987). The lake drained sometime after 0.6 Ma.

Because the Bishop ash bed is stratigraphically just above the Brunhes-Matuyama Chron boundary, and because this boundary is used as an important time marker in calibrating the oxygen isotope stratigraphy in the marine record (Shackleton and Opdyke, 1973; Imbrie and others, 1984), the ash bed and associated pluvial-lake shoreline deposits in Fish Lake Valley can be correlated to the marine oxygen-isotope record. At Lake Tecopa, stratigraphic evidence indicates that the Bishop ash was erupted during a minor interstadial, oxygen-isotope stage 19, that occurred between two major stadials, stages 18 and 20 (Sarna-Wojcicki and others, in press). Alluvium that includes reworked Bishop ash prograded over pluvial lake beds of the preceding stadial, stage 20. However, a continuous sequence of lake beds containing the Bishop ash bed is found at the center of the basin. Thus, although the size of Lake Tecopa decreased during stage 19, the lake did not dry out. The same chronology applies to Pluvial Lake Rennie, where the exposed stratigraphy suggests a wide nearshore deposit overlain and preserved by alluvial fans that prograded basinward as the pluvial lake shrank. In addition, volcanic ash beds reported in well logs in the axis of Fish Lake Valley, presumably the deepest part of the pluvial lake, are apparently underlain and overlain by lacustrine deposits.

The late Pliocene to middle Pleistocene record of Pluvial Lake Rennie, though spottily preserved, appears reasonably parallel to the records of Lake Lahontan, Searles Lake, and Lake Tecopa. Pluvial Lake Rennie existed at about 2.0 Ma, as shown by the lacustrine clays and tephra beds near the modern playa (fig. 2). It probably also existed at about 1.0 Ma, based on the well sorted sands overlying probable Glass Mountain tephra (fig. 4). Pluvial Lake Rennie had a high stand at 0.74 Ma as reflected by the shallow-water deposits of probable Bishop ash, and may have retained water for some time after that, if the ash in the wells north of Oasis is the Bishop. Pluvial Fish Lake experienced many large fluctuations in water level, based on the gravelly deposits interbedded with lacustrine clays that are reported in wells.

The late middle to late Pleistocene record of Pluvial Lake Rennie diverges sharply from those of Lake Lahontan and Searles Lake, but is similar to that of Lake Tecopa. Pluvial Lake Rennie apparently did not exist during this time, whereas Lake Lahontan and Searles Lake fluctuated from low to high water levels. These relations suggest that the late middle to late Pleistocene drying of Pluvial Lake Rennie has a tectonic cause rather than regional climatic cause, analogous to the demise of Lake Tecopa sometime after 0.6 Ma. If regional climatic change were responsible, such as an overall drying trend or a shift north or south in storm tracks, then the record of Pluvial Lake Rennie should be parallel either to both Lake Lahontan and Searles Lake, or to one of these lakes. It seems more likely that the drying of Pluvial Lake Rennie was due to the increase in the rain-shadow effect on Fish Lake Valley caused by a significant increase in elevation of the White Mountains, and perhaps in part the Sierra Nevada, relative to the intervening valleys in post-Bishop time.

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