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Late Quaternary geology and paleohydrology of pluvial Lake Mojave, southern California

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ABSTRACT

A complex history of lake-level fluctuations is recorded in subsurface, cored lake deposits and shoreline features of Silver Lake and Soda Lake depositional basins of southeastern California. These basins are the location of former pluvial Lake Mojave and the present terminus of the Mojave River. The Silver Lake depositional basin is relatively shallow and has minimal relief across the pre-lake basin floor, resulting in a high resolution stratigraphic sequence that can be correlated in the subsurface and to the surface features. Radiocarbon-dated lake sediments from Silver Lake indicate that episodic flooding of the basin began as early as 22 ka with prolonged highstands lasting between 2000 and 3000 yr. Two major high and persistent lake stands occurred in the Silver Lake basin, and presumably in the Soda Lake basin, between ca. 18.4 ka and 16.6 ka (Lake Mojave I) and 13.7 ka and 11.4 ka (Lake Mojave II). These pluvial periods resulted from significantly increased precipitation and annual large-scale floods. The floods originated in the upper Mojave River drainage basin and reached Afton Canyon with discharge values two to three times larger than modern extremes. Periods of intermittent lake conditions during which the Silver Lake basin experienced several desiccation events separated the higher stands and more continuous Lake Mojave phases. The most significant drying event is recorded at 15.5 ka as large desiccation cracks infilled with windblown sand.

During the earlier phases of its existence, Lake Mojave was the second of two large desert lakes sustained by the Mojave River; the other, Lake Manix, occurred upstream from Lake Mojave. Overflow from Lake Manix sustained Lake Mojave I which stabilized at the A-shoreline (elevation 287–288 m). The beginning of Lake Mojave II appears to have coincided with the incision of Afton Canyon and subsequent draining of Lake Manix, an event which significantly increased sediment loading, reducing total

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lake volume and increasing evaporative surface area. This condition resulted in significantly greater overflow of Lake Mojave into the Death Valley basin. This overflow produced controlled downcutting of the Lake Mojave outlet spillway between 12 and 11 ka and ultimately stabilized at an elevation of 285.5 m (B-shoreline). The majority of shoreline features currently found around the margins of Silver Lake and Soda Lake date to Lake Mojave II, as the shallow lake conditions resulted in modification and erosion of the older Lake Mojave I landforms. A transition to a drier climatic regime resulted in the total drying of Lake Mojave by ca. 8.7 ka, with playa conditions dominating Silver Lake and Soda Lake basins following this event.

Analysis and correlation of the surface and subsurface environments of pluvial Lake Mojave yield a detailed reconstruction of the lake level elevation history as influenced by the discharge and floods of the Mojave River. Using a simplified, precipitation-discharge–evaporation model, we infer that the late Pleistocene hydrologic conditions resulting in Lake Mojave overflow at Spillway bay in Silver Lake lie between two sets of conditions: (1) a 50% increase in precipitation in the headwater catchment resulting in annual flood events reaching Afton Canyon with discharges three times that of modern extreme floods; or (2) a 100% increase in catchment precipitation with a 50% decrease from modern evaporation combined with annual flood events reaching Afton Canyon with discharges two times that of modern extreme floods.

INTRODUCTION

Insights into the paleoclimatic and paleohydrologic nature of arid and semiarid basins can be inferred from detailed reconstructions of lake fluctuations recorded in subsurface sedimentary sequences and surrounding shoreline environments (Smith and Street-Perrott, 1983; Bradley, 1999). The terminal basins of the Mojave River in southern California contain a well-preserved record of depositional events associated with latest Quaternary pluvial Lake Mojave (Wells et al., 1989; Brown, 1989). Numerous investigators have recognized the abundance of geological and archaeological features encircling the terminal depositional basins associated with Lake Mojave: Soda Lake and Silver Lake playas (Fig. 1; e.g., Ore and Warren, 1971). Because the upper elevations of the Mojave River watershed were not glaciated, the late Pleistocene and early Holocene Mojave River watershed and its associated fluvial-lacustrine system were more sensitive to climatic variations because direct glacial storage effects neither influenced runoff nor served as a buffer to shorter-term climatic fluctuations recorded in lake sediments and shoreline features (Sharp et al., 1959).

In this paper, we elucidate the shoreline geomorphology and stratigraphy, basin-fill geometry, and subsurface stratigraphy of pluvial Lake Mojave's depositional basins, Soda Lake and Silver Lake. By establishing a high resolution subsurface stratigraphy and correlating the subsurface and shoreline stratigraphy, we provide a detailed geologic and hydrologic history of Lake Mojave during the latest Pleistocene and early Holocene. Our paper builds upon the pioneering work of Crozer-Campbell et al. (1937) and Ore and Warren (1971) who first attempted to reconstruct the chronology of Lake Mojave shoreline deposits in relation to early human occupation of this region.

The playas of Soda Lake and Silver Lake occur in the two modern depositional basins at the terminus of the Mojave River (Figs. 1, 2). The two playas are separated by a broad sill that appears to be related to pre-lake topography (i.e., local bedrock high near the town of Baker; Figures 1, 3). Remnants of shorelines of prehistoric and historic lakes occur topographically higher than the playa floors, delineating the depositional boundaries of lacustrine events associated with pluvial Lake Mojave and younger, shorter duration lake events. Remnants of the late Pleistocene to early Holocene pluvial Lake Mojave shoreline features, consisting of erosional and depositional landforms, occur between 287 and 283 m and can be traced around the margins of the modern Silver Lake and Soda Lake playas. These shorelines and their associated subsurface lacustrine deposits are the primary focus of this study. The largest and most extensively preserved shoreline features are typically found along the northern margins of both basins (e.g., Plates 1 and 2; GSA Data Repository files A and B[1]).

In addition to pluvial Lake Mojave, floodwaters of the Mojave River inundated Soda Lake and Silver Lake playas creating ephemeral, mid-to-late Holocene lakes and deep, long-lasting lakes in the latest Pleistocene and early Holocene (Wells et al., 1989; Enzel and Wells, 1997). Historic Mojave River flooding occasionally has created short-term shallow lakes. Shoreline features associated with the mid-Holocene and younger lakes only have been found at the northern end of Silver Lake playa (Fig. 2;

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[1] GSA Data Repository item 2003069—(A) detailed stratigraphic description of units at the Silver Lake quarry site shown in Figures 7 and 12 (from Brown, 1989; Wells et al., 1989); (B) lithologic description of two outcrops exposed in the Baker Dump quarry, northern Soda Lake; fence diagram of sediments exposed in the Baker Dump quarry, A-shoreline beach ridge, northern Soda Lake playa and outcrop sites of two lithologic descriptions; (C) detailed stratigraphic descriptions of cores Sil-E, Sil-F, Sil-G, Sil-H, Sil-I, Sil-J, Sil-L, and Sil-M taken from the Silver Lake depositional basin (see Figure 7 for locations; from Brown, 1989); and (D) plate summarizing major stratigraphic features and bounding surfaces in selected cores in the northern Silver Lake depositional basin and the correlation of these features (Plate 4 from Brown, 1989)—is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

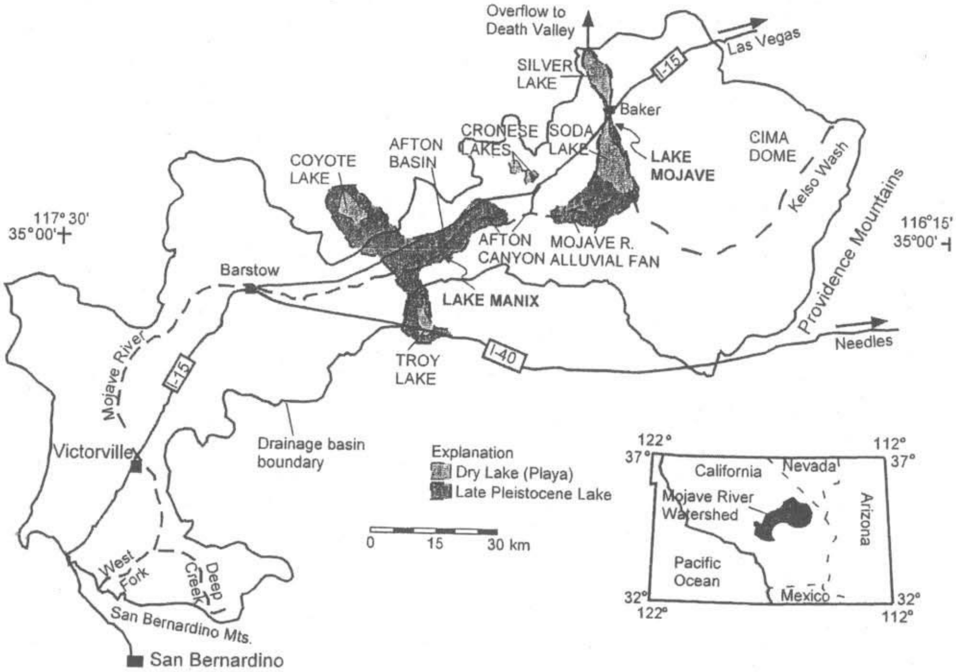


Figure 1. The Mojave River drainage basin showing maximum extent of latest Quaternary Lake Mojave and Lake Manix (now dissected), as well as key geographic features of the study; modified from Wells et al. (1989) and Meek (1989).

Wells et al., 1987, 1989; McFadden et al., 1992). These shorelines are not related temporally with pluvial Lake Mojave and are not the focus of this paper.

Mojave River watershed

The Mojave River drainage basin (Fig. 1) is ~9500 km^2 in size. The Mojave River flows from the San Bernardino Mountains (with elevations above 3000 m) 200 km eastward to a fan-delta region downstream of Afton Canyon where river discharge flows north into the Cronese Lakes basins (326 m) or east into the Silver Lake and Soda Lake basins (276 m). The mountainous headwater region that comprises <5% of the total drainage basin area accounts for >90% of the total basin precipitation (Wells et al., 1989; Enzel, 1990, 1992). During historic times (1894–2001), at least 10 temporary lakes (lasting 2–18 months) formed in the Silver Lake basin as a result of large-magnitude winter storms in the Transverse Ranges and subsequent runoff of the Mojave River (Enzel et al., 1989; Enzel and Wells, 1997). During these large flood events, the Mojave River crossed Soda Lake playa via a series of anastomosing channels. The channels terminated at the northern end of Silver Lake playa, and the floodwaters filled Silver Lake basin to produce these historic ephemeral lakes. The most extreme events resulted in back flooding into the Soda Lake basin. One historical flood and associated ephemeral lakes in the Silver Lake basin and the northern end of Soda Lake playa are shown in Figure 2.

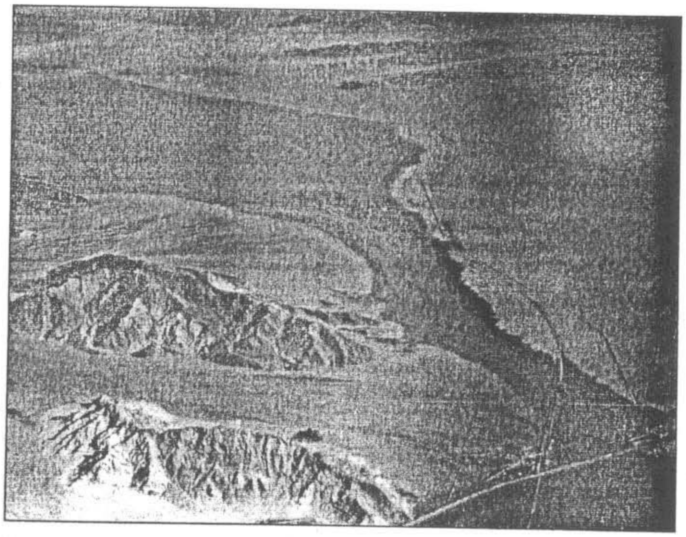


Figure 2. Oblique aerial photograph of Silver Lake playa and northern Soda Lake playa near Baker, California, after the 1938 flood. The 1938 ephemeral lake in Silver Lake playa was fed by overflow through a broad, shallow channel connecting the northern end of Soda Lake basin with Silver Lake basin. The level of these historic, ephemeral lakes did not reach the level of the prehistoric shorelines that surround the playa floors (Wells et al., 1987). Photograph by Spence Air Photos, courtesy of the Department of Geography, University of California, Los Angeles.

The Soda Lake and Silver Lake basins are surrounded by numerous mountain ranges with range-top elevations >2000 m (e.g., Providence Mountains, Figure 1). The largest ephemeral stream draining these desert mountains is Kelso Wash, originating between Cima Dome and the Providence Mountains (Fig. 1). During the highstands of pluvial Lake Mojave, Soda Lake and Silver Lake basins were not the terminus of the Mojave River because waters overflowed toward Death Valley (Fig. 1). The maximum elevation of ancient Lake Mojave was controlled by an outlet spillway (at a current elevation of 285.4 m) which developed

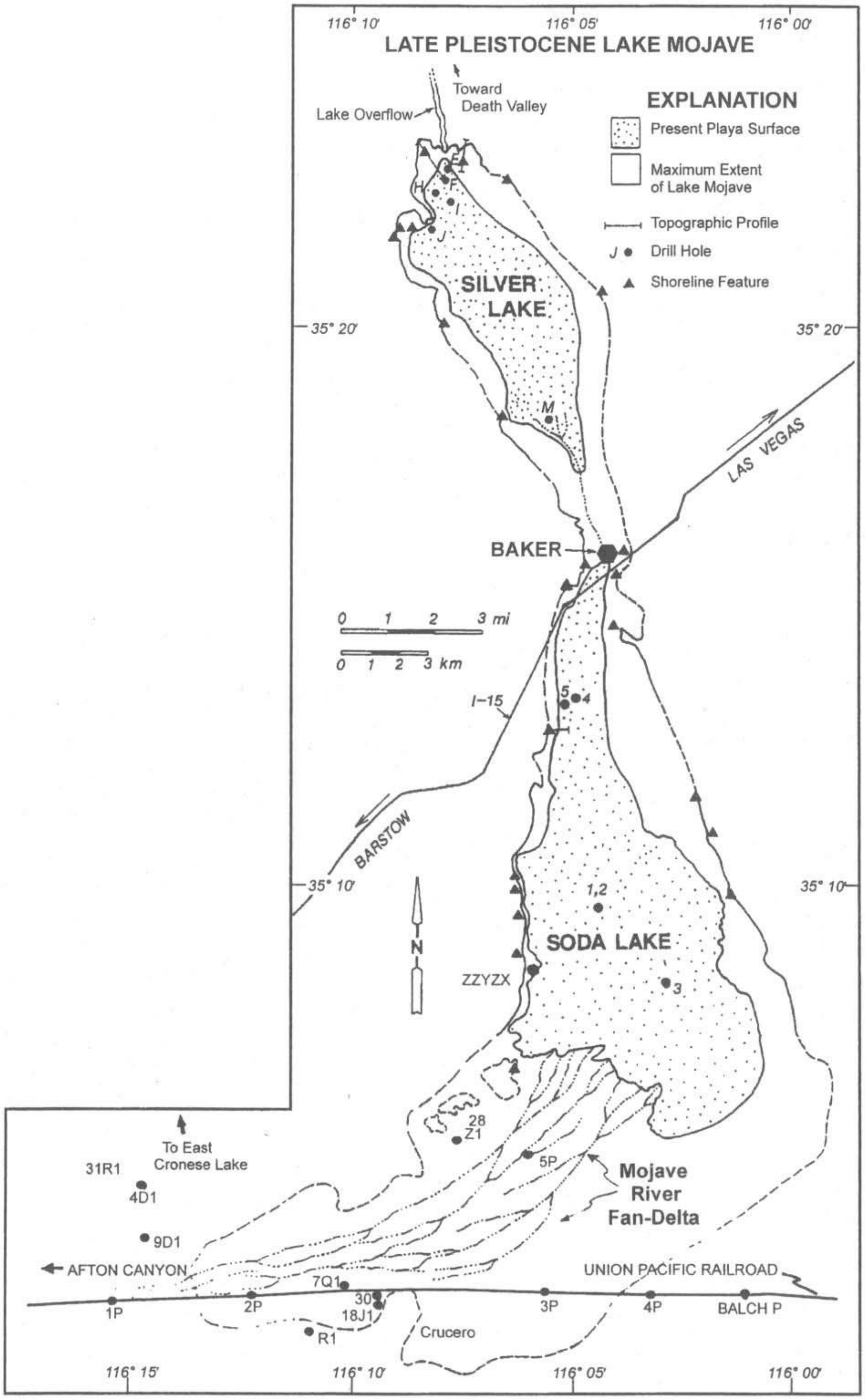
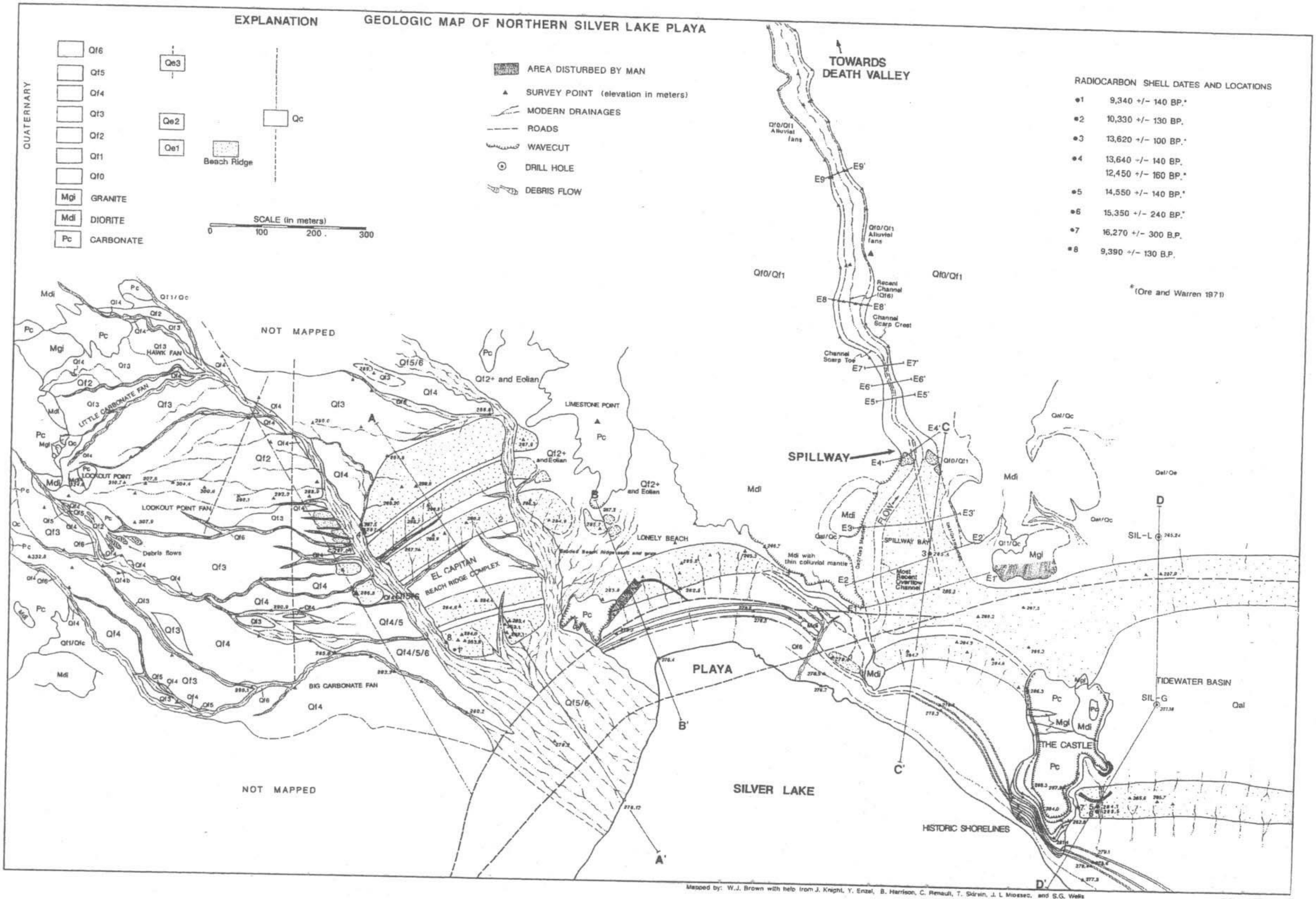


Figure 3. Map showing the maximum extent of latest Pleistocene Lake Mojave in Silver Lake playa and Soda Lake playa depositional basins. The location of the shoreline is dashed where it is buried or eroded. Major shoreline features are indicated by a solid triangle, and drill holes are indicated by a solid circle (note: (1) prefix Sil- has been omitted on figure such that Sil-J, for example, is represented by J only, and (2) numbers 3P or 4P, for example, are drill holes in the Soda Lake basin). The present-day playa surface is shown with a stippled pattern.



Mapped by: W.J. Brown with help from J. Knight, Y. Enzel, B. Harrison, C. Renault, T. Skirvin, J. L Miossec, and S.G. Wells

PLATE 1

Plate 1. Surficial geologic map of northern Silver Lake playa showing major stratigraphic and geomorphic features and elevations of shoreline features.

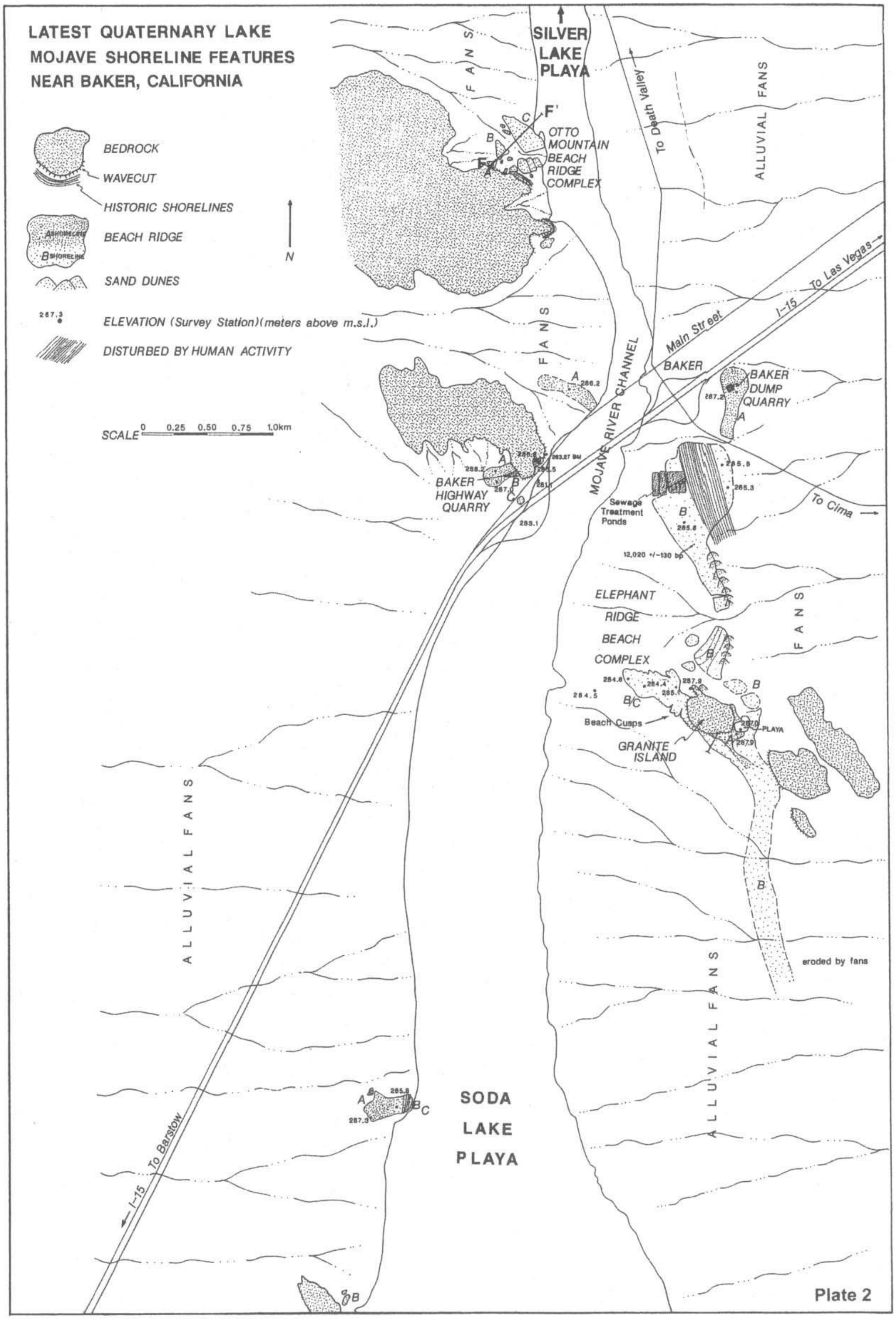


Plate 2. Geomorphic map of northern Soda Lake playa showing elevations of shoreline features.

in bedrock at the extreme north end of Silver Lake (Wells et al., 1989). During maximum lake stages, overflow from this spillway drained northward toward Dry Lake and Silurian Lake and eventually toward Death Valley (e.g., Free, 1914; Huntington, 1915; Blackwelder and Ellsworth, 1936; Blackwelder, 1954). Prominent shoreline features are found around the margins of Silver Lake and Soda Lake playas. These features indicate at least two major high and persistent lake stands at 287–288 m and 285.5 m (Ore and Warren, 1971; Wells et al., 1984, 1987, 1989; Enzel et al., 1988; and Brown et al., 1990).

No deep drilling has occurred in the Silver Lake basin, and little is known about the depth to the bedrock or configuration of the bedrock underlying the basin. This study provides the first detailed results of shallow drilling in the Silver Lake basin. Geophysical studies in the southern Soda Lake basin indicate that the depth to bedrock is >700 m (Dickey et al., 1979). Drilling information from 326 m in central Soda Lake playa and nearly as deep in southern Soda Lake playa supplement this data (Muessig et al., 1957; Dickey et al., 1979; Calzia, 1991). The Soda Lake cores indicate only one major, basin-wide, lacustrine sediment package at depths of 10–36 m (Brown and Rosen, 1995). This sediment package corresponds in age to latest Quaternary Lake Mojave shoreline features (Brown, 1989). Older basin-fill sediments composed of oxidized silts, sands, and minor clays indicate that playa and distal fan depositional environments predominated in the Soda Lake basin since at least the early Pleistocene (Brown and Rosen, 1995). Drill cores within the extreme southern portion of the Soda Lake basin and in the Cronese basins reveal blue and green lacustrine sediments at depth (Dickey et al., 1979; Brown and Rosen, 1995). No large evaporite deposits are found in any of the cores or drill holes from either the Soda Lake or Silver Lake basins suggesting that neither basin is a true hydrologically closed basin.

Climate of the watershed

California experiences a warm, dry summer and a winter precipitation maximum related to Pacific cyclonic activity, referred to as a Mediterranean regime (Barry, 1983). The precipitation distribution within the Mojave River drainage basin is highly variable. Within the headwaters of the Mojave River in the San Bernardino Mountains, mean annual precipitation exceeds 1000 mm/year. Ninety percent of the drainage area, which contributes runoff to Silver Lake playa, typically receives 125 mm or less in annual precipitation. In the terminal playas, mean annual precipitation is <100 mm, an order of magnitude less than in the Mojave River headwaters (Enzel, 1990). Furthermore, the seasonality of precipitation changes from the headwaters to the terminal playas. Within the Victorville area (Fig. 1), for example, precipitation occurs during the winter. In contrast, there are two seasons of precipitation downstream of Barstow. The primary season is during the winter months (principally February), but a secondary season occurs during the summer months (principally August) (Pyke, 1972). Precipitation during the winter season is usually during storms that cover larger portions of the Mojave River watershed, whereas precipitation during the summer season is highly variable across the eastern regions of the watershed. During the summer months, evaporation dominates over precipitation for the majority of the Mojave River drainage basin.

Previous work

Thompson (1929) examined Silver Lake and Soda Lake playas and found remnants of a pluvial lake, which he named Lake Mojave. He suggested that Lake Manix (Fig. 1) had once been the terminus of the Mojave River and that Silver Lake and Soda Lake basins became the terminus after the incision of Afton Canyon. Subsequently, researchers postulated that both lakes may have existed contemporaneously (Crozer-Campbell et al., 1937; Hubbs and Miller, 1948). Recent work by Meek (1989, 1999) and the results of this study support the latter conclusion and indicate that both lakes coexisted for a period of a few thousand years (see also Enzel et al., this volume). Studies of the Soda Lake basin by Muessig et al. (1957), Dickey et al. (1979), and Calzia (1991) revealed only one prolonged basin-wide lacustrine period in sediments from cores drilled up to 326 m. Faunal assemblages in these lacustrine clays (at depths of 10–35 m below the present playa surface of Soda Lake) have been found to correlate with similar sediments drilled in Silver Lake (Brown, 1989). Playa sediments are found above and below these lacustrine deposits.

Ore and Warren (1971) refined the Lake Mojave chronology with extensive radiocarbon dating of pelecypod shells and lithoid tufa found in shoreline features in the Silver Lake area, demonstrating that Lake Mojave existed episodically between 15 and 8 ka. Extensive work on the geomorphic history of the surrounding alluvial fans and their relations to the two prominent Lake Mojave shorelines was undertaken by Wells et al. (1984, 1987) in order to establish a dated chronology of alluvial fan deposition during the Pleistocene-Holocene transition. Soil geomorphic studies of the Silver Lake Holocene and Pleistocene shorelines and beach ridges exposed in northwestern Silver Lake allowed regional correlation of shoreline deposits, revealing a sequence of younger Holocene shoreline deposits in addition to the latest Pleistocene shorelines (McFadden et al., 1992).

RESULTS

Geometry of pluvial Lake Mojave depositional basins

In order to understand the depositional and hydrological history of pluvial Lake Mojave, the three-dimensional geometry of the ancient lake basin was defined using surface and subsurface data. Remnants of pluvial Lake Mojave shorelines surrounding the two depositional basins of Silver Lake and Soda Lake basins were used to delineate the uppermost elevations and surface boundaries of the Lake Mojave depositional system (Figs. 3, 4). The depositional system of pluvial Lake Mojave is related to the following:

- Two major shorelines—A (288–287 m) and B (285–286 m)
- One minor shoreline—C (283 m)

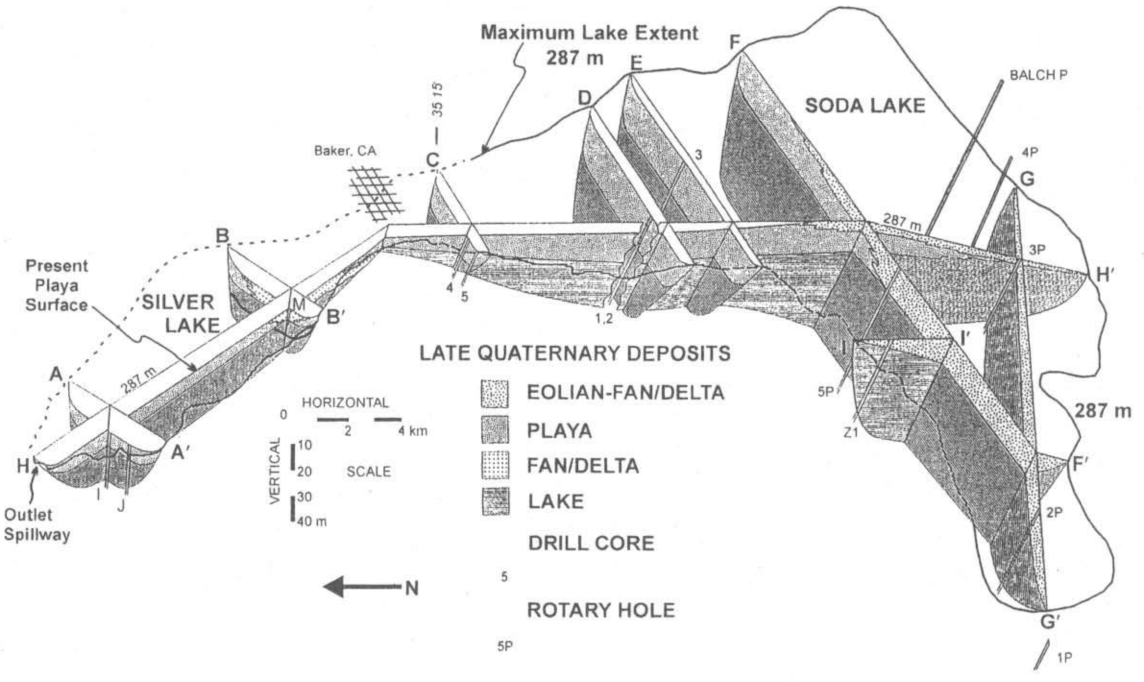
The geomorphology and stratigraphy of these shoreline features are discussed in detail later in this paper.

In order to delineate the subsurface boundaries of the Lake Mojave depositional system, we combined the data obtained from cores obtained in Silver Lake during this study with core and borehole data obtained from the Soda Lake basin (Fig. 3; Muessig et al., 1957; Moyle, 1967; Dickey et al., 1979). Cores from the Silver Lake basin were drilled utilizing a weight-driven coring rig (Cores Sil-A, Sil-B, Sil-C, Sil-D, Sil-E, Sil-G, Sil-L, Sil-M; represented as A-M in Figure 3) and a truck-mounted, continuous auger coring device using a 1.52 m split-barrel sampler (Cores Sil-F, Sil-H, Sil-I, and Sil-J; represented as F-J in Figure 3). Recovery for the above 13 cores was 95% or greater for each hole. In addition to the above coring operations, lacustrine sediments were studied in 1–2 m deep trenches. Detailed logging was undertaken on eight of the 12 cores at a 1:1 scale and later reduced to a manageable size for publication (see GSA Data Repository item C; see footnote 1). Accelerator mass spectrometry (AMS) radiocarbon ages were obtained from bulk samples taken from selected subsurface lacustrine sediments (Table 1).

Core and borehole data support that Lake Mojave was composed of two depositional basins within which lacustrine sedimentation was the thickest (Figs. 3, 4). The Soda Lake depositional basin was deeper than the Silver Lake basin during most of the lake history (Fig. 5). During the time of the deepest lacustrine deposits, ancient floodwaters filled Soda Lake basin first then overflowed the sill near Baker into Silver Lake basin (Wells et al., 1989), forming a hydrologically integrated Lake Mojave as illustrated in Figure 3. During the Holocene, greater sedimentation rates in Soda Lake basin compared to Silver Lake basin apparently resulted in a higher elevation of the Soda Lake playa surface. As a result, present-day floodwaters now pass over Soda Lake playa into the Silver Lake basin before hydrologic ponding backs into Soda Lake (Fig. 5). Figures 4 and 5 also indicate that the fan-delta, lacustrine, and playa sediments filling the two basins during the latest Quaternary reduced the lake water storage capacity dramatically. Storage capacity is the volume between the surface defined by the sloping playa (or lake) floor and the horizontal surface defined by the elevation of the overflow spillway (287 m). Total water storage capacity of pluvial Lake Mojave during the early phase of lacustrine deposition was ~7 km^3 (Fig. 6; Wells et al., 1989; Enzel, 1992). Currently, the lake basins can store only 0.15 km^3 of water and sediments before overtopping the ancient spillway at the northern end of Silver Lake playa (Fig. 6).

Geomorphology and stratigraphy of Lake Mojave shorelines

The primary goals of this part of our study are to (1) determine the timing of highstands that existed during pluvial Lake Mojave and (2) reconstruct the depositional and erosional processes



reconstruction is based on subsurface data from 14 rotary drill holes in southern Soda Lake, 19 drill cores from Silver Lake and central Soda Lake, and mapped shoreline features (Fig. 3). Pluvial Lake Mojave sediments form the base of the section, which, in turn, is overlain by playa deposits. The difference between the modern playa surface and the maximum lake extent represents the present-day storage capacity of these basins. Note that the section shown at core Sil-M (B–B′) is expanded vertically (not to scale) to illustrate stratigraphic relations; dark line at base of section at B–B′ is approximate depth of drill hole.

TABLE 1. SUMMARY OF UNCALIBRATED RADIOCARBON DATES OBTAINED FROM SAMPLES OF LAKE MOJAVE SHORELINE DEPOSITS AND LAKE SEDIMENTS

Location	Dating method	Elevation of sample (masl)	Type of material dated	Radiocarbon age (yr B.P.) and sample number	Study
Silver Lake fan delta Depth of 15–17 cm	C-14	~278	Organic carbon in sediments	390 ± 90 Beta-25634	W
Silver Lake Sil-M core Depth of 55–59 cm	AMS	~277.5	Organic carbon in sediments	3,620 ± 70 Beta-25341	W
Silver Lake Sil-M core Depth of 3.12–3.15 m	AMS	~274.9	Organic carbon in sediments	9,330 ± 95 Beta-24342	W
Silver Lake Sil-I core Depth of 6.0 m	AMS	270.65	Organic carbon in sediments	14,200 ± 145 Beta-25339	W
Silver Lake Sil-I core Depth of 9.8 m	AMS	267.75	Organic carbon in sediments	14,660 ± 260 Beta-21800	W
Silver Lake Sil-I core Depth of 15.9 m	AMS	260.70	Organic carbon in sediments	20,320 ± 740 Beta-21801	W
Beach Ridge V El Capitan complex	C-14	282.5	Whole pelecypod shells	9,390 ± 120 Beta-29552	M
Beach Ridge III El Capitan complex	C-14	286–286.5	Whole pelecypod shells	10,330 ± 120 Beta-21200	W
Beach Ridge–Soda Lake Elephant Ridge complex	C-14	~285	Whole pelecypod shells	12,020 ± 130 Beta-21199	W
Beach Ridge I El Capitan complex	C-14	287	Pelecypod shell fragments	13,640 ± 120 Beta-26456	B
Tidewater Basin Beach Ridge II–Silver Lake	C-14	282	Whole pelecypod shells	16,270 ± 310 Beta-29553	B
Top of gravel pit–Silver Lake	C-14	Unit no. 10	Tufa coats on gravel	9,160 ± 400 LJ-935	H
(See Figure 12 for stratigraphic locations.)	C-14	Unit no. 10	Tufa coats on gravel	8,350 ± 300 LJ-929	H
	C-14	Unit no. 8	Pelecypod shells	10,580 ± 100 Y-1593	O/W
	C-14	Unit no. 7	Tufa coats on gravel	9,900 ± 100 Y-1592	O/W
	C-14	Unit no. 6	Pelecypod shells	10,700 ± 100 Y-1591	O/W
	C-14	Unit nos. 6,7,8 Comb.	Tufa coats on gravel	10,870 ± 450 LJ-930	H
	C-14	Unit nos. 6,7,8 Comb.	Pelecypod shells	10,260 ± 400 LJ-932	H
	C-14	Unit nos. 6,7,8 Comb.	Pelecypod shells	10,000 ± 300 I-444	H
	C-14	Unit nos. 6,7,8 Comb.	Pelecypod shells	9,640 ± 240 LJ-200	H
	C-14	Unit no. 5	Tufa coats on gravel	11,320 ± 120 Y-1590	O/W
	C-14	Unit no. 5	Tufa coats on gravel	11,630 ± 500 LJ-934	H
	C-14	Unit no. 4	Pelecypod shells	13,150 ± 350 I-443	H
	C-14	Unit no. 4	Pelecypod shells	13,290 ± 550 Y-1589	O/W
	C-14	Unit no. 4	Pelecypod shells	13,670 ± 550 LJ-933	H
	C-14	Unit no. 1	Tufa coats on gravel	13,190 ± 500 LH-931	H

Continued on following page.

TABLE 1. SUMMARY OF UNCALIBRATED RADIOCARBON DATES OBTAINED FROM SAMPLES OF LAKE MOJAVE SHORELINE DEPOSITS AND LAKE SEDIMENTS (continued)

Bottom of gravel pit–Silver Lake	C-14	Unit no. 1	Tufa coats on gravel	13,040 ± 120 Y-1588	O/W
Beach Ridge V El Capitan complex	C-14	283.2 depth = 1	Pelecypod shells	9,340 ± 140 Y-2407	O/W
Beach Ridge I El Capitan complex	C-14	288.2 depth = 0.3	Pelecypod fragments	12,450 ± 160 Y-2408	O/W
North-central Silver Lake–Spillway Bay	C-14	Avg = 285.7 depth = 0-.6	Pelecypod fragments	13,620 ± 100 Y-1585	O/W
Tidewater Basin Beach Ridge II	C-14	284.1	Pelecypod shells	14,550 ± 140 Y-1586	O/W
Tidewater Basin Beach Ridge II	C-14	283.5	Pelecypod shells	15,350 ± 240 Y-1587	O/W
Bench Mark Bay	C-14	286.5	Tufa coats gravel	9,960 ± 200 Y-2410	O/W
Bench Mark Bay—below stone artifacts	C-14	281.9 depth = .3-.5	Pelecypod fragments	10,270 ± 160 Y-2406	O/W
Northwest Silver Lake El Capitan BR II	C-14	~287	Pelecypod shells	11,860 ± 95 DIC-2824	W
Northern Silver Lake High Shoreline El Capitan BR II	C-14	~287	Pelecypod shells	11,970 ± 160 Beta, written commun.	RW
A-Shoreline—Northwest Silver Lake	C-14	~286.5	Tufa	10,850 ± 75 DIC-2823	W

Note: Reference source for these dates (study) are coded: W—Wells et al., 1989; M—McFadden et al., 1992, B—Brown, 1989, H—Hubbs et al., 1965, O/W—Ore and Warren, 1971, and RW—Weldon, 1982.

creating the shoreline features. In order to accomplish this goal, shoreline features in Silver Lake and northern Soda Lake basins were initially mapped using aerial photographs of selected study sites (Fig. 7). Subsequently, many of the shoreline features recorded in these photographs were mapped and surveyed with an EDM-Total Station to determine exact elevations and distances. All survey measurements were tied to local U.S. Geological Survey benchmarks. Individual beach ridge units were distinguished using stratigraphic relations, height above playa surface, correlation with various wave-cut features, and lithology of beach ridge material. Conventional radiocarbon analyses were performed on lustrous pelecypod shells showing little or no recrystalization or replacement of the original aragonite structure (Table 1).

The best preserved and laterally most extensive shoreline features were formed during lake highstands, which were controlled by the elevation of the outlet spillway. Lake overflow during the A-shoreline period resulted in erosion of unconsolidated sediments at the outlet spillway and formation of the younger B-shoreline that was stabilized on bedrock (Bode, 1937; Ore and Warren, 1971; Wells et al., 1987, 1989). Therefore, these shoreline features are found around elevations of 287–288 m (A-shoreline) and 285.5 m (B-shoreline) (Figs. 4, 5). Topographically lower, less well preserved shoreline features are found below the A- and B-shorelines and formed below the elevation of the spillway control. The highest topographically of the younger shoreline features occurs at ~283 m (C-shoreline; Wells et al., 1987, 1989; McFadden et al., 1992; Enzel et al., 1992).

The largest, laterally most extensive, and best preserved shoreline features typically are found along the northern margins of both basins (Fig. 7; Plates 1 and 2) because (1) the maximum fetch of the lake in a north-south direction combined with prevailing southwesterly winds produced the strongest wave activity and therefore the largest features along the northern margins of each lake; and (2) the proximity of bedrock outcrops in these areas protected the shore features from erosion or burial by active alluvial fan streams. Four sites were selected for detailed studies at the northern end of the Silver Lake basin (the Tidewater basin, Spillway bay, El Capitan complex, and Silver Lake quarry), as well as several sites selected in the northern Soda Lake basin (Fig. 7).

Tidewater basin

Two large beach ridges are preserved in the northeastern portion of Silver Lake in the area known as Tidewater basin (Fig. 7 and Plate 1). Both of these ridges are composed predominantly of fine gravel to coarse, sand-sized grus. The highest ridge is 287.9 m amsl at its maximum elevation and appears to be associated with the topographically highest lacustrine depositional features associated with pluvial Lake Mojave. Detailed topographic measurements of beach deposits show that they are topographically

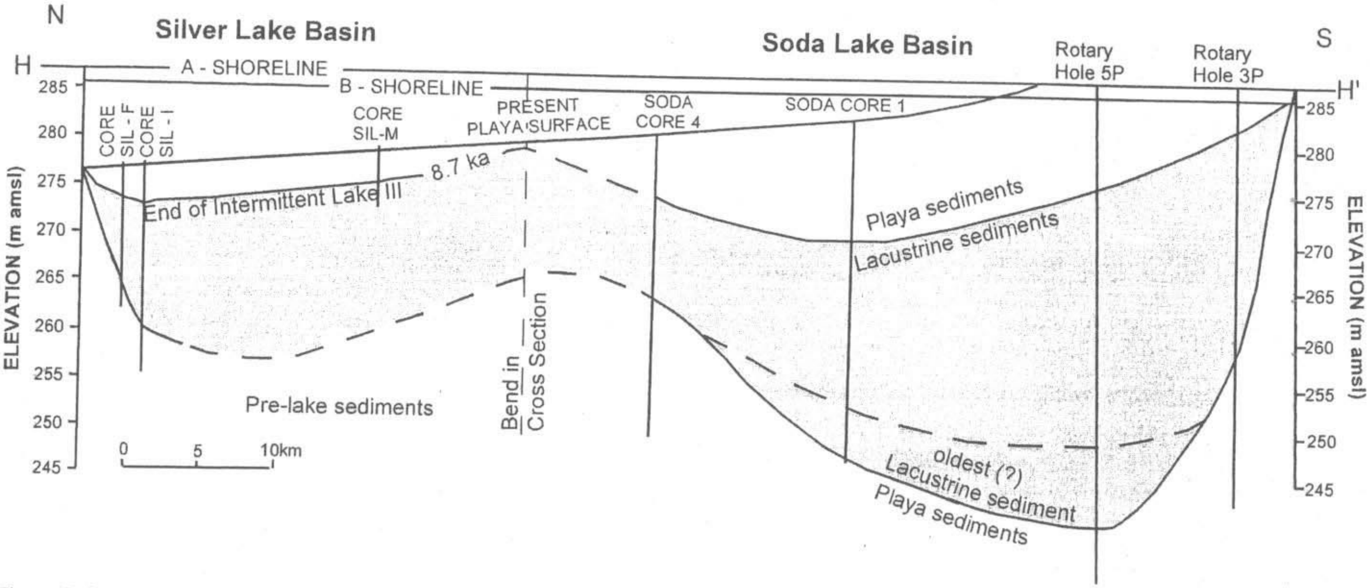


Figure 5. Cross section (H–H′ from Fig. 4) showing pluvial Lake Mojave deposits in the Silver Lake and Soda Lake depositional basins using selected core data as well as the slope of the modern playa floor and the elevation of the two highest shorelines (A and B) associated with Lake Mojave.

higher. Detailed stratigraphic studies, however, show that many of the beach deposits are mantled by younger eolian sediments (McFadden et al., 1992), which does not reflect an accurate measurement of shoreline processes.

The highest beach ridge, which merges westward into the A-shoreline features in Spillway bay (Plate 1) and eastward into a bedrock outcrop, has not been dated directly. No shell material was observed in exploratory pits excavated in the highest ridge. To the north of this ridge lies a small topographic depression that slopes gradually uphill to a broad saddle (289.5 m) that marks the drainage divide between Silver Lake basin and Dry Lake basin to the north. Core Sil-L, which was obtained from this basin (Plate 1), yielded no lacustrine sediments and indicates that bedrock is <2 m below the surface (Brown, 1989). We infer that the highest beach ridge served as a barrier to Lake Mojave at its highest stand.

A larger topographic depression (Tidewater basin) lies between the two beach ridges (Fig. 7 and Plate 1). Core Sil-G was drilled to a depth of 6.25 m in the Tidewater basin (Fig. 7 and Plate 1) and reveals several meters of green clays, interpreted as lacustrine in origin (Brown, 1989; Wells et al., 1989). The topographically lower ridge starts in an embayment of the Castle (Plate 1), a large bedrock outcrop, and trends eastward.

A complex depositional history is recorded in a stream-cut exposure at the extreme western edge of the topographically lower beach ridge (285–286 m; Figure 8). Eleven lithofacies, ranging from cobbles and pebbles to clayey silt, are exposed at this locality along the walls of the streams that dissect the beach ridge. These lithofacies indicate changing depositional environments as well as fluctuating water levels (Table 2). Several green, fine-grained clay and silt-rich lithofacies (units IV, VI, VIII, and XI) are interbedded with coarser sand and gravel units (units V,

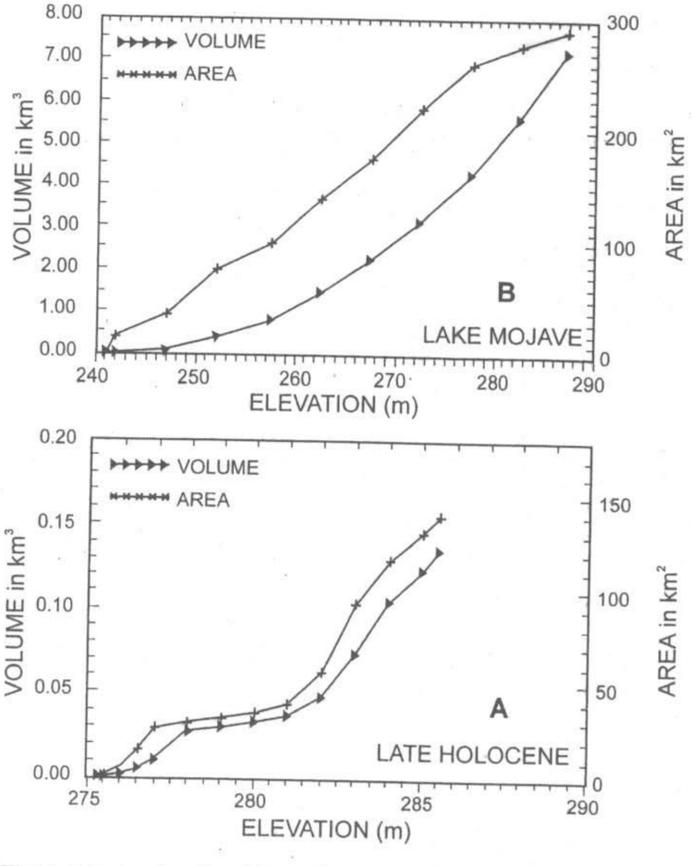


Figure 6. Lake elevation, lake volume, and lake area curves (two sets) for highstand (A-shoreline, see Fig. 5) of late Pleistocene Lake Mojave (B) and shallower and shorter-duration Holocene lakes (A, late Holocene, modified from Enzel, 1990). Note that elevation of the A-shoreline is 287 m and the B-shoreline is 285.5 m.

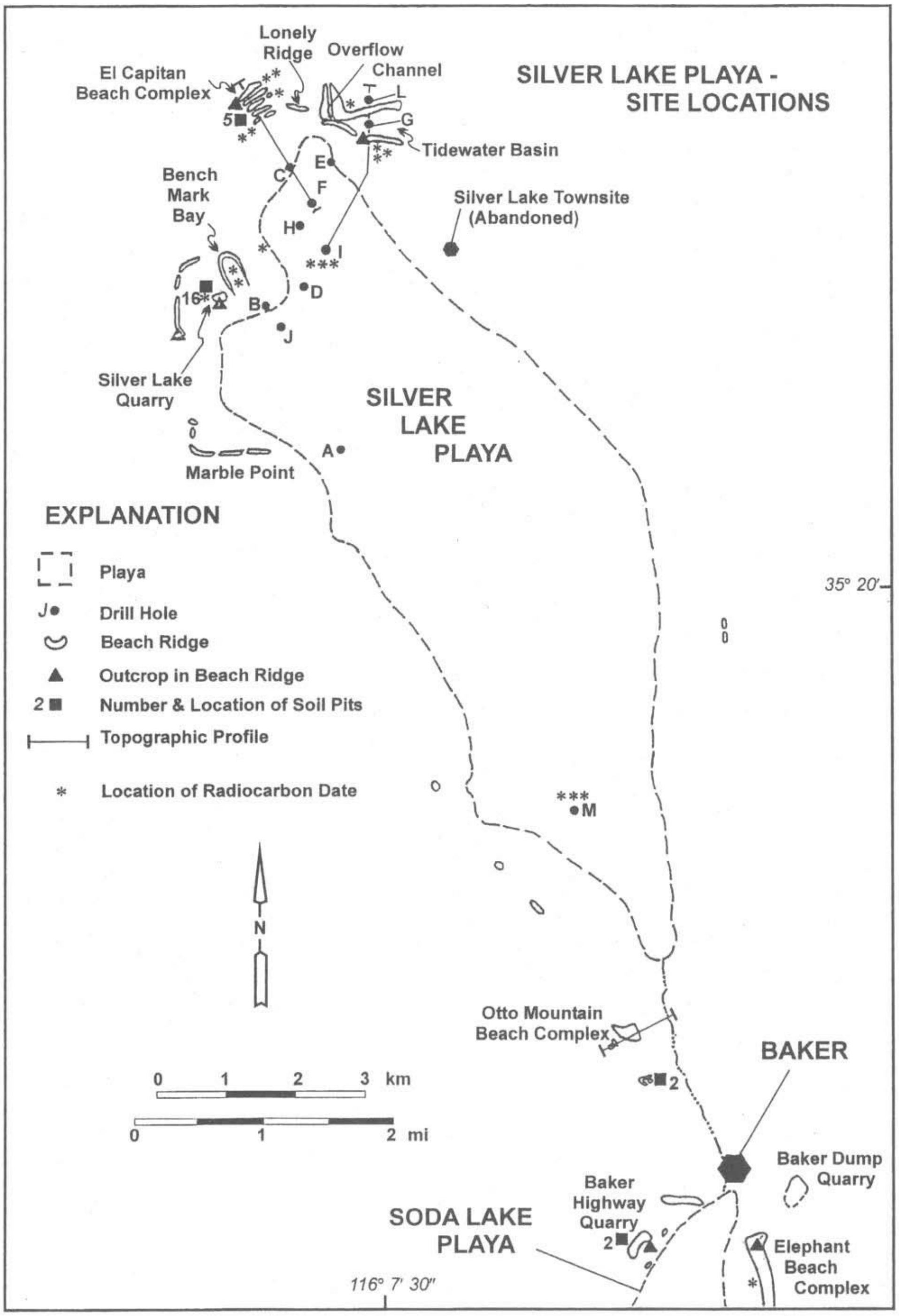


Figure 7. Map of Silver Lake playa and northern Soda Lake playa, showing major study sites (i.e., Tidewater basin, major shoreline features, location of key samples used in radiocarbon dating, and sites of cores investigated during this study. Radiocarbon ages are provided in Table 1.

VII, IX, and X) and indicate a low-energy deposition environment (e.g., offshore, backbasin, or lagoonal). At least two of these fine-grained lithofacies are truncated laterally by lakeward-dipping, one-to-two clast thick cobble lags, interpreted as erosional (ravinement) surfaces and overlying transgressive cobble lags. We believe that these lags formed during rising lake levels as the shoreface moved upward and landward (northward). Similar stratigraphic relations have been described for Quaternary marine coastal sequences (Nummedal and Swift, 1987; Kraft and Chrzastowski, 1987). One of these bounding surfaces truncates a section within unit VII immediately above sediments dated at 15,350 ± 240 yr B.P. and below sediments dated at 14,550 ± 140 yr B.P. From this stratigraphic section (Fig. 8), we infer that lake levels receeded below 283 m circa 15.4 ka before rising circa 14.5 ka.

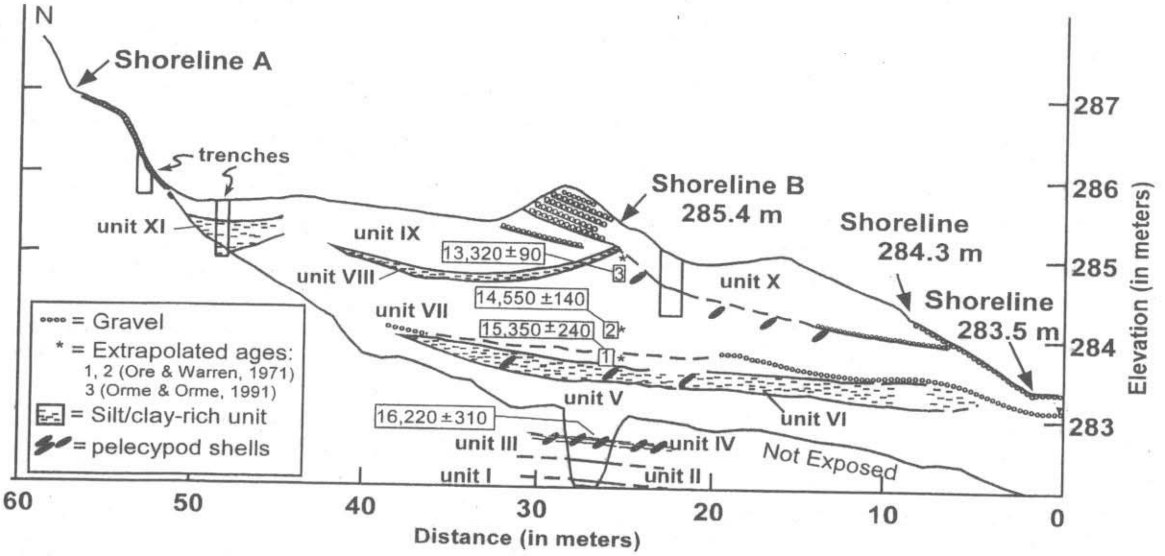


Figure 8. Stratigraphic cross section of Lake Mojave beach ridge deposits in the Tidewater basin area of northern Silver Lake playa (see Fig. 7). Eleven distinct lithofacies are present in the stream-cut exposure at the westernmost edge of the beach ridge. Four fine-grained green deposits are present in the outcrop (i.e., lithofacies IV, VI, VIII, XI), and all other units are composed of gravel and coarse sand. Prominent erosion (ravinement) surfaces preserved as gravel lags indicating at least three major transgressions and regressions are recorded at this locality. Shells collected by Ore and Warren (1971) and Orme and Orme (1991) were obtained several meters to the east of this outcrop from unit VII and were extrapolated stratigraphically into this cross section. Ages are reported in radiocarbon years B.P. (see Table 1 for details).

Abundant ostracodes were present in the fine-grained sediments of these four units (IV, VI, VIII, and XI; Figure 8), supporting our interpretation that these fine-grained lithofacies are lacustrine in origin (R. Forester, 1987, 1988, personal commun.; Steinmetz, 1988, 1989). Unit IV contains abundant *L. ceriotuberosa* and minor amounts of *L. bradburyi*. Unit VI contains abundant *L. ceriotuberosa* and common *L. bradburyi*. Units VIII and XI contain only one *L. ceriotuberosa*. Steinmetz (1989) correlates an abundance of *L. ceriotuberosa* in stratigraphic sections of Lake Manix sediments (Fig. 1) with an increase in the trophic state of the lake and lake filling. He has found peak abundances at times of high lake levels within a stratigraphic section that correlates with the beginning of the Wisconsin glaciation. *L. bradburyi* occurs in lakes that are relatively shallow, turbid, and isothermal with ambient air (Forester, 1987; Steinmetz, 1988). The co-occurrence of *L. bradburyi* and *L. ceriotuberosa* within sediments of the Coyote subbasin of Lake Manix suggests that climatic seasonality was not extreme and that the lake was relatively shallow during that period (Steinmetz, 1989). Based upon a comparison with Steinmetz's study, we infer that unit IV formed under relatively deep water conditions and that unit VI was deposited under relatively shallow water conditions. The later inference is consistent with our interpretation of the ravinement surface in unit VII that truncates unit VI; this relation reflects lake shallowing and shoreline recession after the deposition of unit VI and then shoreline transgression that formed the ravinement surface and lake filling to form unit VII.

Whole pelecypod shells, in growth position and in an excellent state of preservation, were collected from unit IV of this exposure (Fig. 8) and yielded a radiocarbon age of 16,270 ± 310 yr B.P. (Beta-29553, Table 1). This is the oldest known radiocarbon age obtained from deposits associated with any of the shoreline landforms related to pluvial Lake Mojave. The preservation of the pelecypod shells in growth position supports the inference that unit IV formed under deeper water conditions (below wave base/offshore).

Ore and Warren (1971; Table 1) dated shells from two superimposed sets of cross strata located ~20 m west of the above location. These units are composed of coarse-sand-sized to granule-sized clasts that dip ~26° toward N10°W. These two shell-bearing horizons are located at elevations of 283.5 m and 284.1 m and yield age dates of 15,350 ± 240 and 14,550 ± 140 yr B.P., respectively (Fig. 8). At the same location as the Orr and Warren site, Orme and Orme (1991) generated a radiocarbon age of 13,320 ± 90 yr B.P. (Beta-36305) from shells obtained at 285.2 m, clearly below unit X but stratigraphically above the shells found by Ore and Warren (1971). Based upon detailed topographic measurements and numerous stream-cut exposures, we extrapolated the stratigraphic position of these three radiocarbon ages westward to the outcrop illustrated in Figure 8, suggesting the dates are from lithofacies that are no older than unit VI and younger than unit VIII.

The Tidewater basin site is critical to understanding the complex history of Lake Mojave and reconstructing the formation

TABLE 2. LITHOLOGIC DESCRIPTION OF AN EXPOSURE IN THE LOWER BEACH RIDGE, TIDEWATER BASIN SITE, NORTHERN SILVER LAKE BASIN, FAUNAL INFORMATION

Unit no.	Description of Outcrop-Tidewater Basin Beach Ridge II
XI	**66 cm thick Gravelly, Silty Clay.** (Not the same location as Units I–X.) Unit is irregularly laminated to massive in nature. Bottom not reached. Lower portion of unit is very strongly indurated and contains abundant disseminated $CaCO_3$. Occasional shell fragments found throughout. Top of unit is moderately sorted with subangular to subrounded granitic grus and marble clasts. Bottom of unit is poorly sorted with angular to subrounded granitic grus and marble clasts. Boundary between these subunits is gradational. Color 2.5Y 6/4. Unit contains ostracodes *(L. ceriotuberosa).*
X	**0–45 cm Gravel.** This unit includes crest and youngest beach deposits. Cobbles to pebbles (gravel–90%) with a coarse sand matrix composed almost entirely of grus. 7/5YR 6/4. Alternating laminations of coarse sand averaging about 15–20 cm thick. Each layer coarsens upward. Reddening at base of unit (5YR 7/4) 4–5 cm above unit 4. Coarse sand laminae dip about 5° to the south.
IX	**45–66 cm Gravel Cobbles to Pebbles with Minor Sand Matrix.** Unit is composed almost entirely of grus. Coarse sand-gravel laminations dip gently (3°–5°) lakeward and exhibits moderate sorting within individual laminar. Minor scattered shell fragments. Color 7.5YR 5/4 (dry).
VIII	**66–72 cm Fine Sand and Silt with Evaporite Minerals.** Unit is variable in thickness (4–8 cm). Pinches out about 1 m south of described outcrop locality. Abundant disseminated $CaCO_3$. Irregular patches of clay-silt with abundant carbonate. Locally preserved seeds. Overall moderately to well sorted and moderately stratified. Sharp upper boundary. Color 5Y 6/2 (dry), 5Y 5/2 (moist). Sample collected from the most clayey part of this unit contain abundant ostracodes (*L. ceriotuberosia*) as well as *L. heterocypris* sp.
VII	**72–187 cm Gravel Granules to Cobbles Composed Almost Entirely of Grus.** Occasional bedding or laminations dipping almost horizontal. Overall, unit is about 70% subrounded to subangular granules. Laminar units are well sorted and usually about 2–3 cm thick. Sharp upper boundary. Color 10YR 4/4 (moist).
VI	**187–207 cm Gravelly, Silty Sand.** Moderately well sorted fine-medium sand matrix with varying amounts of granules that increase in percentage near boundaries. Moderate amounts of silt and clay near middle. Upper 4–5 cm contain cobbles to pebbles and pelecypod shells. Possible bioturbation in upper 10 cm of unit. Color 5Y 7/2. Locally abundant evaporate minerals $CaCO_3$ and mirabilite in thin horizontal laminations. Lower boundary gradational, upper boundary sharp. Entire unit effervesces strongly. Abundant ostracodes (*L. bradburyi and L. ceriotuberosia*).
V	**207–255 cm Silty, Sandy Gravel.** Pebbles and granules in basal 8–10 cm grading upwards to finer-grained granules and sand with a silt-rich component that increases in abundance near the top of the unit. Overall the unit is composed of grus and displays mottled oxidized (7.5YR 6/6 dry) and reduced (5Y 5.5/3 dry), roughly horizontal zones. Stratification dips gently north (3°) away from the lake. Lower boundary is irregular and slightly wavy. Upper boundary is gradational.
IV	**255–269 cm Sand–Gravel.** Basal coarser zone in lower 5–8 cm with angular clasts up to 2.5 cm in size. Finer-grained alternating thin bands of reddened, oxidized (7.5YR 5/6 dry) granules and reduced gray-green (5Y 6.5/3 dry) sand-sized material overlie the coarser zone. The sandy zones contain abundant whole pelecypod and gastropod shells preserved in growth position. Strong disseminated $CaCO_3$ is present in the lower portion of this unit, extending from the base of the shell horizon to a depth of 33 cm. Sorting is moderate within individual lamination zones. Lower boundary shows evidence of scour. Moderately abundant ostracodes present (*L. cariotuberosa* with minor *L. bradburyi*).
III	**269–282 cm Gravel.** Subrounded to subangular clasts (up to 4 cm in size) of granite and lesser amount of limestone. The unit coarsens upward. Fine-grained matrix composed of sand- to granule-sized grus. Overall gray-green, reduced color (5Y 6/4 dry). Unit is strongly cemented by disseminated $CaCO_3$.
II	**282–312 cm Granule-sized Gravel.** Moderately well sorted with thinly stratified bends dipping gently lakeward. Locally horizontal aligned oxidized zones, although unit is an overall gray, reduced color (5Y 6/4 dry). Lower gradational boundary unit is composed almost entirely of grus.
I	**312–327+ cm Gravel, Pebbles to Cobbles.** Subrounded angular, composed of limestone and granite. Matrix is composed of sand-sized material of grus and limestone. Overall unit is a reduced, green-gray color (5Y 6/6 moist, 5Y 6/4 dry).

Note: from R. Forester (personal commun., 1987, 1988).

and age of the highest shoreline. Although no age is available for the older and higher beach ridge (287.9 m) complex at Tidewater basin, this site appears to provide the oldest radiocarbon date of lacustrine sediments within any of the studied Lake Mojave shoreline environments (Figs. 8 and 9; Table 1). The existence of this older, undated beach ridge (Fig. 9) suggests that (1) prior to 16.2 ka, and probably during the last glacial maximum, Lake Mojave was a higher and deeper lake than later in its history; and (2) during this highstand period, the lake reached the elevation of 287–288 m that is controlled by a spillway and overflow channel (see profile E4–E4′; Plates 1 and 3). During this time period, Lake Mojave overflowed toward Death Valley (Fig. 3).

Based upon these stratigraphic and geomorphic relations, the higher (287.9 m) beach ridge appears to represent a distinctly different (older) lake stand than that represented by the lower (285.6 m) beach ridge. We hypothesized that an older (at least 16.2 ka and older) stand of Lake Mojave produced the higher beach ridge at the level of shoreline A (287–288 m) during this time and under conditions in which the lower beach ridge either did not exist or was not emergent (e.g., a spit). Under this environment, lacustrine clays (such as those in unit IV) would be deposited in relatively deeper waters at the present site of the Tidewater basin topographic depression. We tested this hypothesis by drilling Core Sil-G in the topographic depression between the two ridges (GSA Data Repository item C; Figure 9; Plate 1).

This hypothesis is supported by the recovery of 3 m of green clays from Core Sil-G. Thus, we infer that the clays were deposited during the same time (at least 16.2 ka and older) and under conditions similar to unit IV (GSA Data Repository item C; Plate 3). In order to determine if these clays were lacustrine and not playette, groundwater discharge, or lagoonal in origin, the paleontology of the sediments was examined by J.P. Bradbury (1988, personal commun.). He determined that the basal part of these green clays contained diatoms (*Fraglilaria constuens v. subsaline*), which are found in abundance within the stratigraphic top of an older phase of deep-lake deposits (dated ca. 16 ka and defined as Lake Mojave I later in this paper). These paleontologic data support the hypothesis that a lacustrine environment existed within the Tidewater basin topographic depression prior to ca. 16.0 ka, and that an older and higher lake existed within the Tidewater basin prior to formation of the 285.6 m beach ridge starting at ca. 14.6 ka. During this older Lake Mojave highstand, the green clays were deposited in water up to, but not exceeding, 10–12 m (Plate 3, Figure 9). In that there is no evidence for younger lacustrine sediments in the Tidewater basin, we infer that the highest beach ridge formed at the time of this older highstand and that this site was not modified significantly by younger highstands reaching approximately the same elevation in other sites along the Silver Lake basin. The lack of lacustrine or lagoonal deposits north of the highest beach ridge (288 m; Plate 3) indicates that this ridge was the barrier to Lake Mojave in this area and that water did not overtop the ridge. The only other course for water to overflow during the older highstand is the overflow channel at Spillway bay that drains toward Death Valley (Fig. 7).

We believe that the data above support the hypothesis that the ~288 m beach ridge is older than the ~285 m beach ridge, and this interpretation allows us to reconstruct a simplified geomorphic evolution of the shoreline environment of Tidewater basin (Fig. 10). Based upon radiocarbon data obtained from cores discussed later in this paper, we infer that the geomorphic history starts at ca. 18 ka and, based upon radiocarbon data from the northern Silver Lake sites, continues through 10 ka. Between 18 ka and 16 ka, the following conditions prevailed: Lake Mojave extended into the Tidewater basin; the beach ridge at ~288 m (A-shoreline) formed and stabilized; spits prograded laterally from local bedrock and alluvial fan topographic highs at the current site of the lower beach ridge; and any highstands of Lake Mojave overflowed through Spillway bay and the overflow

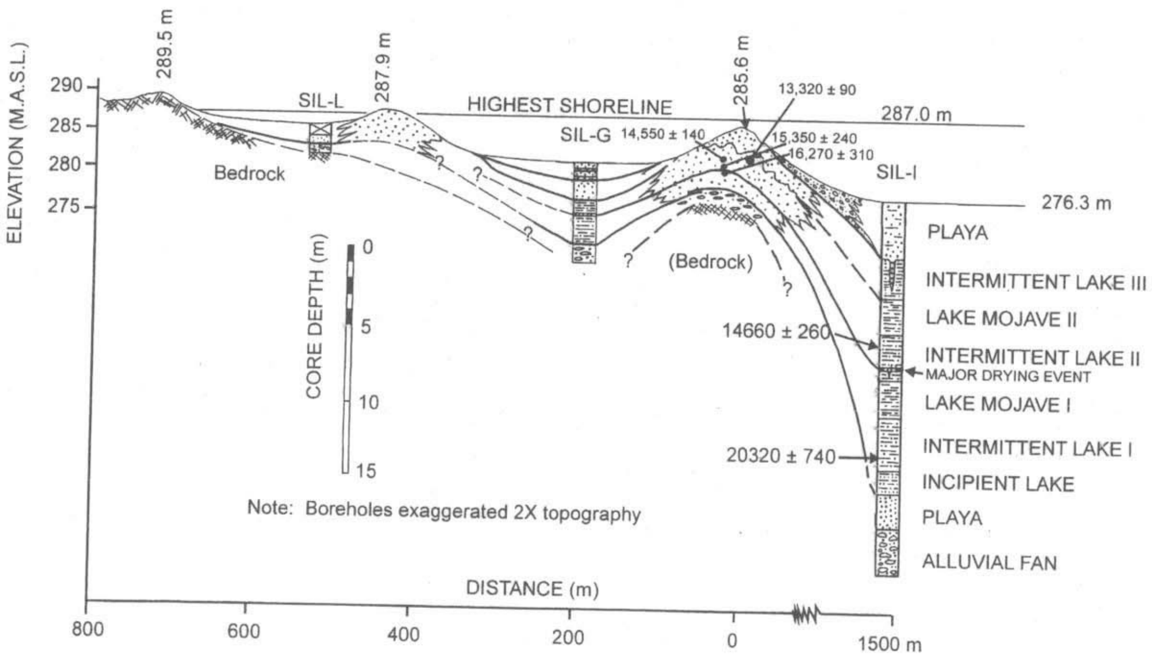
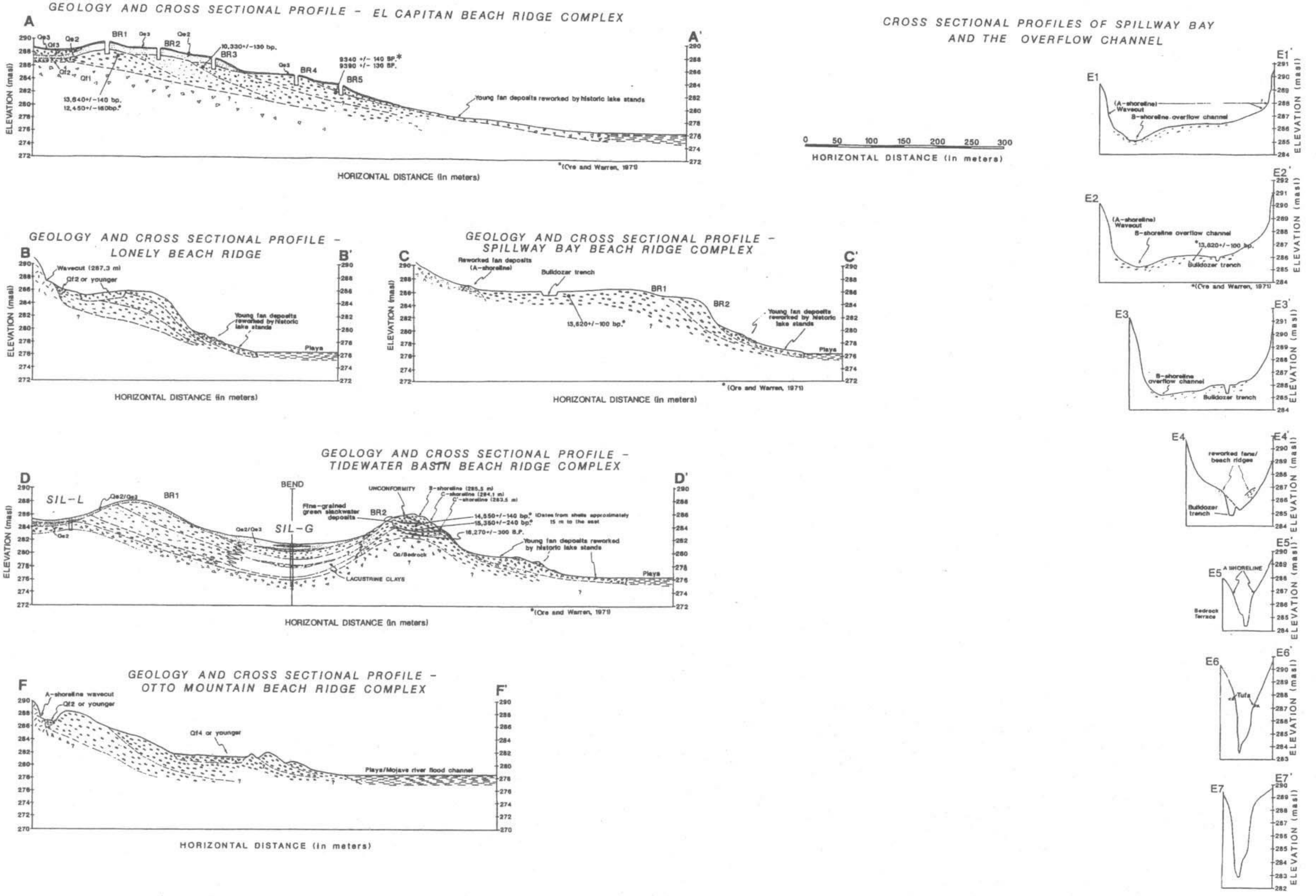


Figure 9. Cross section showing correlation of shoreline features and cored-lake deposits in northern Silver Lake deposition basin. Correlations are based on biostratigraphy, lithostratigraphy, and radiocarbon dating of pelecypod shells in shoreline sediments and lacustrine sediments in cores Sil-I, Sil-G and Sil-L (see Fig. 7 for location). Bold solid and dashed lines represent isochrones in near-shore and subaqueous environments, and dots are locations of radiocarbon-dated samples.

GEOLOGIC AND TOPOGRAPHIC PROFILES OF SELECTED SITES IN THE SILVER LAKE BASIN, CA



GEOLOGY AND CROSS SECTIONAL PROFILE - EL CAPITAN BEACH RIDGE COMPLEX

GEOLOGY AND CROSS SECTIONAL PROFILE - LONELY BEACH RIDGE

GEOLOGY AND CROSS SECTIONAL PROFILE - SPILLWAY BAY BEACH RIDGE COMPLEX

GEOLOGY AND CROSS SECTIONAL PROFILE - TIDEWATER BASTN BEACH RIDGE COMPLEX

GEOLOGY AND CROSS SECTIONAL PROFILE - OTTO MOUNTAIN BEACH RIDGE COMPLEX

CROSS SECTIONAL PROFILES OF SPILLWAY BAY AND THE OVERFLOW CHANNEL

*(Ore and Warren, 1971)

Plate 3. Geologic and topographic profiles of selected sites in Silver Lake depositional basin (see Plate 1 for locations).

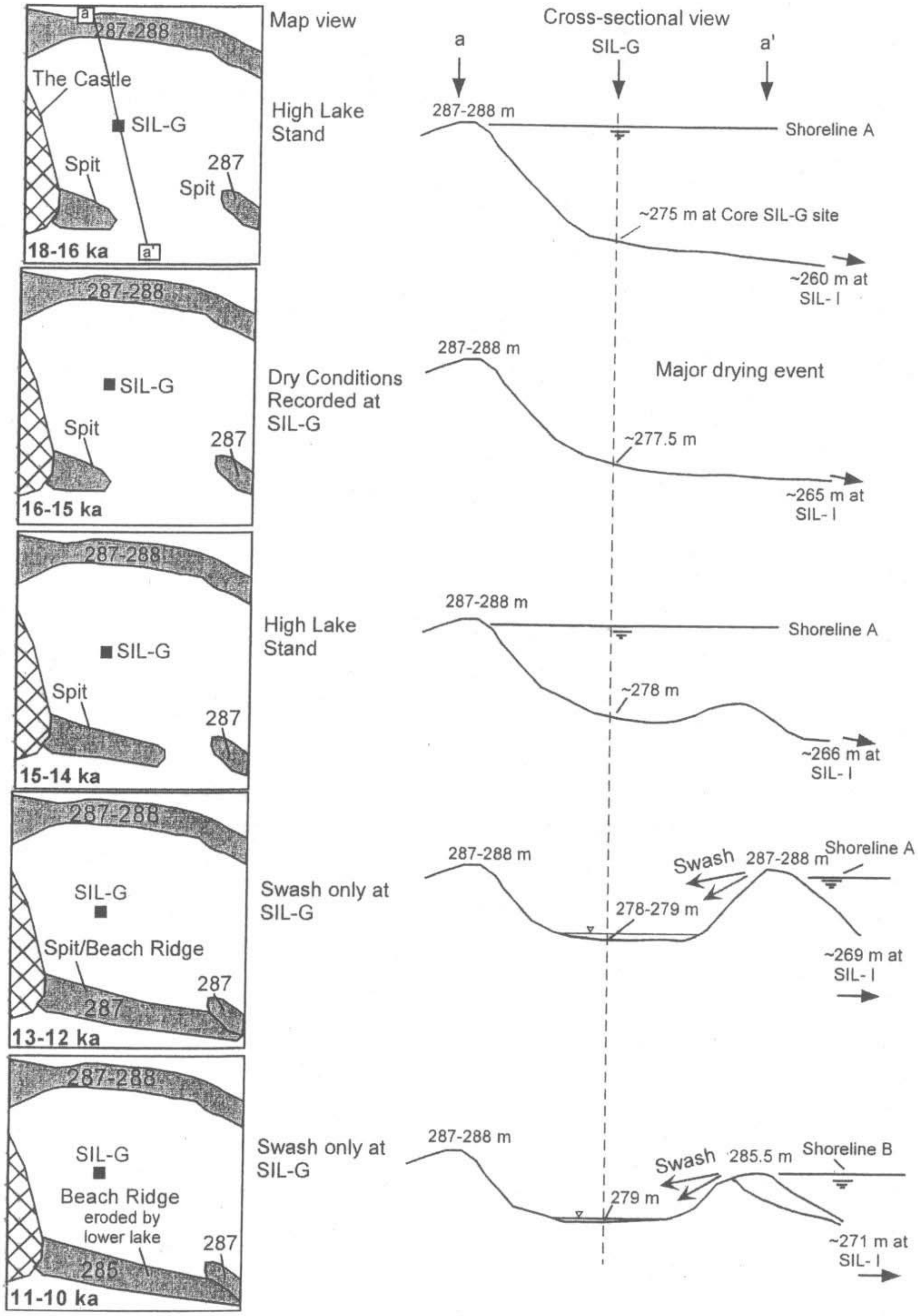


Figure 10. Schematic map and cross sections showing interpretation of spit and beach ridge evolution in the Tidewater basin (see Fig. 7) between 18 ka and 10 ka.

channel toward Death Valley (Fig. 10). Circa 15.4 ka, a major drying event occurred with total lake drying in the Silver Lake basin evidenced by eolian sediments found in cores Sil-G and Sil-I (see GSA Data Repository item C for detailed stratigraphy; Figures 9, 10). After 15 ka and before 14.6 ka, lake levels rose forming a major bar/spit complex that emerged between 14 ka and 13 ka, blocking lake access to the Tidewater basin and ending lacustrine deposition within the basin. Lacustrine processes apparently modified the emergent bar (287 m) until circa 11–10 ka when Lake Mojave overflow resulted in downcutting of the spillway to an elevation of 285.5 m. Episodic transgressions eroded the upper parts of the beach ridge complex attached to the bedrock high west of the Tidewater basin, resulting in an elevation of 285–286 m (Fig. 10).

Spillway bay

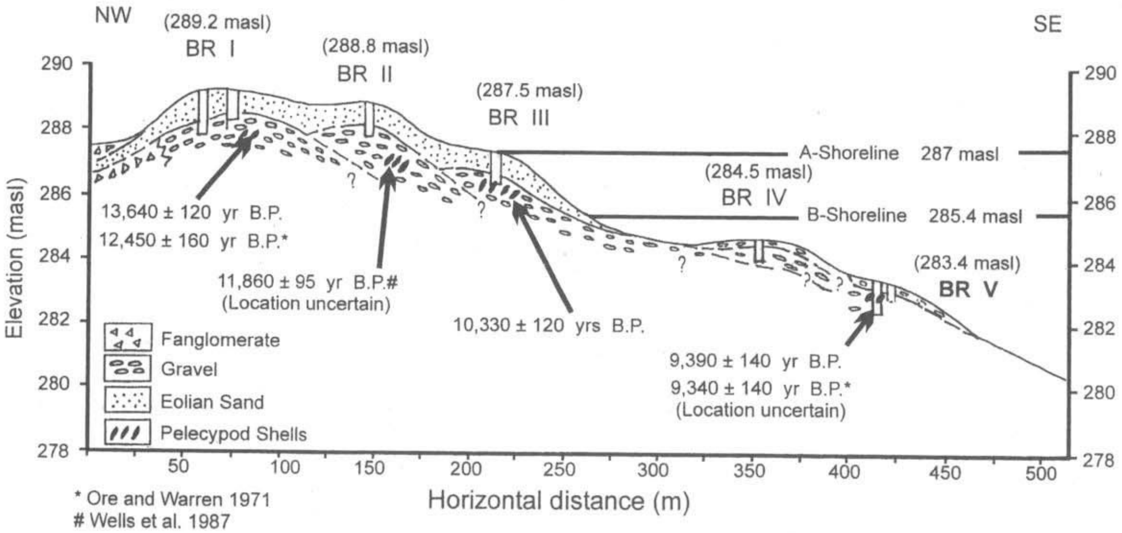
Topographic profiles at the northern end of the bay (Spillway site; E-4 in Plate 3) show two distinct spillway levels at 287 and 285.5 m that we correlate with the A- and B-shorelines, respectively. This correlation indicates that overflow occurred during both stands of pluvial Lake Mojave. There are no natural exposures of the shore-margin deposits in the Spillway bay area (outlet channel bay of Ore and Warren, 1971) (Plates 1, 3), but two key observations can be made from the geomorphology of the Spillway bay: (1) weakly developed wavecut cliffs present on both sides of the bay are most pronounced at 287–288 m in elevation; and (2) a broad, shallow paleochannel is cut into the bay's deposits with its thalwag at 285.5 m, exactly at the elevation of the B-shoreline.

Small pits excavated along the shallow walls of a trench (Plate 3) indicate that bay sediments consist of granular grus deposited in both beach and fluvial environments. The fluvial deposits suggest fluvial reworking by channels that formed during overflow discharge and migrated laterally across the entire width of the bay. Ore and Warren (1971) collected reworked pelecypod shells from fluvial sediments 30–70 cm below the surface and at an elevation of ~285 m (i.e., B-shoreline elevation; see Plates 1, 3). The radiocarbon age of these reworked shells is 13,620 ± 160 yr B.P. These shells suggest that the Spillway bay site was last occupied by Lake Mojave stands at the B-shoreline elevation and that fluvial channels during overflow reworked these shoreline sediments after ca. 13.6 ka.

Detailed field studies indicate that overflow during lake high stages only exited the basin through the overflow channel north of the Spillway bay beach-ridge complex. The overflow channel has no visible terraces (Plate 3) and is cut into alluvial fan deposits inferred by Wells et al. (1987) to be correlative with either unit Qf0 or Qf1 (mid- or late-Pleistocene, respectively) based on the degree of soil development. The alluvial fan deposits slope away from the local, low relief hillslopes composed of marble, dioritic, and mafic lithologies. The channel walls are very steep and expose stage III+ to IV pedogenic carbonate horizons in fan units. Field observations suggest that these deposits and petrocalcic soils probably were altered extensively by groundwater movement or streamflow (i.e., dissolution and recementation features) during lake highstands. After the last overflow event, the channel acted as a sediment trap for eolian material that blankets the floor to depths >1 m. Field observations and interpretation of aerial photographs suggest that the channel previously continued several kilometers north toward Lake Dumont (K. Anderson and Wells, this volume). Overflow of the Silver Lake basin has not occurred during historic times (past ~150 yr; McFadden et al., 1992).

El Capitan beach ridge complex

Five separate beach ridges are present in the El Capitan complex (formerly the northern beach ridge sequence of Bode [1937] and northwest beaches of Ore and Warren [1971]), more than in any other beach ridge sequence in the Lake Mojave area (Figs. 7, 11). Topographic profile A–A′ constructed perpendicular to the long axis of the ridges indicates that these ridges formed on a long, gentle slope (Plate 1). The highest ridges—BR I, BR II, and BR III—have well-developed stone pavements overlying an eolian unit ~1 m thick. This unit contains a soil similar to that described on unit Qe2 (Wells et al., 1987; McFadden et al., 1992). Below this eolian unit, imbricated beach gravels dip gently toward the former lake basin floor.



* Ore and Warren 1971
\# Wells et al. 1987

Figure 11. Stratigraphic cross section of the El Capitan beach ridge complex, northern Silver Lake playa (see Fig. 7) emphasizing beach ridge stratigraphy, location of radiocarbon dates on pelecypod shells, and shoreline elevations (modified from McFadden et al., 1992).

The lithology of the beach material is predominately mafic metamorphic rock, diorite, and granodiorite with minor amounts of limestone/marble. A significant increase in the amount of grus is observed in the BR III deposits. Abraded carbonate coatings on many of the gravel clasts in the upper three ridges suggest reworking of the nearby fan units. Tufa is common on many of the larger clasts, and all five ridges contain pelecypod shells. Shells from seven locations in the El Capitan complex have been radiocarbon dated (Table 1; Figure 11) making this one of the most well-dated series of beach ridges in southern California. The El Capitan complex shells become progressively older with increasing elevation and distance from the playa (Fig. 11). Shell ages from the upper three ridges are (1) 13,640 ± 120 yr B.P. (this study) and 12,450 ± 160 yr B.P. (Ore and Warren, 1971) from BR I (Fig. 11); (2) 11,970 ± 160 yr B.P. (Weldon, 1982) and 11,860 ± 95 yr B.P. (Wells et al., 1987; location uncertain) from BR II (Fig. 11); and (3) 10,330 ± 120 yr B.P. (this study) from BR III (Fig. 11). The lowest two beach ridges are Holocene in age (Orr and Warren, 1971; McFadden et al., 1992). Radiocarbon dating of the soil carbonates on the beach ridges supports the above ages and is summarized in McFadden et al. (1994) and Amundson et al. (1994).

It is important to note that surface elevations of the three highest beach ridges at the El Capitan site do not reflect the actual shoreline elevations due to an early Holocene eolian accretionary mantle overlying the beach deposits (Fig. 11; McFadden et al., 1992). We infer that the two highest beach ridges (BR I and BR II, elevation 288 m; dated between ca. 13.6 and 11.8 ka) formed during Lake Mojave stands at the A-shoreline. Based upon data from the El Capitan beach ridges and our observations at Tidewater basin, we believe that the A-shoreline has been occupied episodically from >16 ka through ca. 12 ka. Thus, shoreline deposits at the A-shoreline elevation (287–288 m) may be of differing geologic ages at different geographic locations, but all are older than ca. 12 ka. The El Capitan and Spillway bay data together indicate that the B-shoreline (285.5 m) is no older than ca. 12 ka, and one radiocarbon age in a beach ridge associated with the elevation of the B-shoreline is 10.3 ka. We infer from the study sites along the northern Silver Lake basin that the B-shoreline is no older than 12 ka and was stabilized by ca. 10.3 ka to allow beach ridge formation.

These observations demonstrate that deposits of significantly different ages can occur at the same elevation along a shoreline as well as within a single landform along the shoreline margin. Clearly, the results derived from age dating must be carefully combined with detailed stratigraphic and geomorphic analyses when reconstructing paleolake histories.

Silver Lake quarry

A small gravel quarry was excavated in a spit composed of coarse-to-fine grained deposits at the northwestern corner of the Silver Lake playa (Figs. 7, 12). The quarry exposes a series of interbedded gravel, sand, and silty clay beds deposited by pluvial Lake Mojave (Ore and Warren, 1971). The top of the quarry is ~8 m below the A-shoreline, which is preserved as a wave-cut cliff in dioritic bedrock flanking the quarry. The top of the spit slopes southwest from the bedrock. A detailed chronology of these deposits has been reconstructed from radiocarbon ages obtained from tufa-coated gravels and locally abundant pelecypod shells (Fig. 12) (Ore and Warren, 1971; also discussed by Wells et al., 1987). These ages show a regular progression from the oldest in unit 1 (13,670 ± 550 yr B.P.) to the youngest at the top of the outcrop (8350 ± 300 yr B.P.).

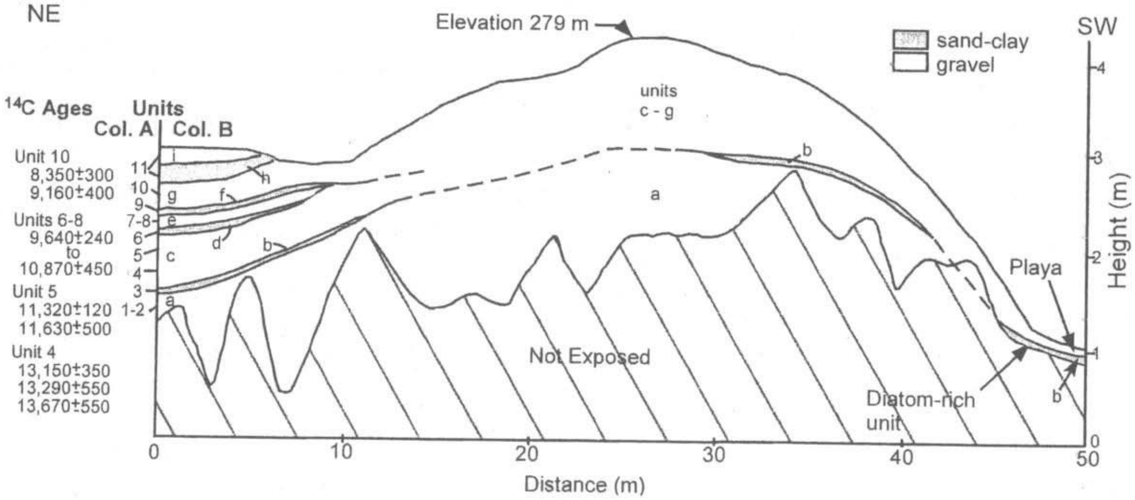


Figure 12. Simplified stratigraphic cross section of the Silver Lake quarry site (see Fig. 7) at the northern end of Silver Lake Playa highlighting stratigraphic positions of radiocarbon dates obtained by Ore and Warren (1971) and this study (Table 1). Green sandy clay rich in pelecypod shells indicated by shading.

We observe two stratigraphic packages (unit a and units b–i; Figure 12) of sediments within the spit separated by a sharp bounding surface (see GSA Data Repository item A for stratigraphic description). Unit a (undated) forms the lower stratigraphic package and is composed predominately of weathered angular to subrounded pebbles and cobbles. The upper package (units b–i) consists of alternating layers of silty clay, sand, and unweathered gravels along the flanks of the spit and ranges in age from ca. 13.7 ka to 8.3 ka (Fig. 12). The difference in weathering of the two packages of sediment indicates a significant hiatus in the deposition of the two units; this contrasts with the conclusion first proposed by Wells et al. (1987) suggesting that no major diastem exists in this sequence. The core of the spit, represented by unit a, clearly predates 13.7 ka; and these deposits were exposed subaerially during lake-lowering events to allow the weathering of the clasts, which was probably enhanced by salts derived from the lake. We infer that these lower lake levels and period of subaerial weathering most likely occurred between the older (>16.2 ka) and younger (<14.6 ka) stands of Lake Mojave observed at Tidewater basin.

Northern Soda Lake basin

Extensive shoreline landforms are preserved along the northern margin of Soda Lake basin near Baker, California (Plate 2). Field investigations focused on three separate beach ridges, corresponding in height to the A-shoreline stands of Lake Mojave (287 m). Sand and gravel quarries at each of these sites provide an excellent three-dimensional view of the shore-margin stratigraphy (Wells et al., 1989). The Baker Highway quarry site (Plate 2) contains sediments that can be divided into four units. The upper three units contain abundant pelecypod shells (or shell fragments, depending on the outcrop) and are of lacustrine origin. These units unconformably overlie sediments composed of angular, poorly sorted, gravel-to-sand sized clasts that are interpreted to be of alluvial fan origin. Ostracodes collected from sediments directly above the lacustrine–alluvial fan unconformity have been identified as *L. ceriotuberosa* and are common to lacustrine deposits of pluvial Lake Mojave (R. Forester, 1988, personal commun.).

The Baker dump quarry, which was excavated in a broad beach ridge deposit southeast of the town of Baker, exposes beach sediments unconformably overlying alluvial fan and eolian deposits (GSA Data Repository item B). This beach ridge extends as high as 287 m, forms part of the A-shoreline, and is undated. A soil developed on topographically lower ridge deposits exhibits stage I+ pedogenic carbonate and displays oxidized horizons (color = 7.5YR 5/8, dry). Ostracodes identified as *L. ceriotuberosa* (R. Forester, 1988, personal commun.) were found throughout the beach sediments in addition to locally abundant pelecypod shells. A very large, almost continuous sand ridge extends from the beach ridge at the Baker dump quarry southward in an arc toward a bedrock outcrop (Elephant Ridge beach complex; Plate 2). This beach ridge has a maximum elevation of ~285.5 m, corresponding to the elevation of the B-shoreline. Locally, the ridge has been eroded by alluvial fan channels, covered by small eolian dunes, and extensively modified by human activity. Pelecypod shells from 40 cm below the land surface of this beach ridge were radiocarbon dated at 12,020 ± 130 yr B.P., representing the oldest ages obtained from the B-shoreline complex at this site (Plate 2). Surrounding Granite Island are several higher beach ridges and locally preserved wavecut scarps that correspond in elevation to the A-shoreline (287–288 m).

On the western side of Soda Lake, wavecuts are found on bedrock headlands and older alluvial fan segments that extend several km north of Zzyzx (Fig. 3; Harvey and Wells, this volume). The absence of major bedrock outcrops south of the Zzyzx area combined with the prograding fan delta of the Mojave River from Afton Canyon and extensive eolian deposition have resulted in little preservation of latest Quaternary Lake Mojave shoreline features in the southern Soda Lake basin (Fig. 3). Core data discussed in the section below, however, indicates that Lake Mojave extended south all the way to Crucero and west toward Afton Canyon (Fig. 3).

Geologic and chronologic relationships of shoreline deposits at the north end of Soda Lake basin are similar to those observed in the northern Silver Lake basin (Plate 2; GSA Data Repository item B). The A-shoreline is at the same elevation in the Soda Lake basin as it is in the Silver Lake basin, demonstrating a lack of regional tilting. In addition, the Soda Lake basin A-shoreline is older than 12 ka based on the radiocarbon age from the topographically lower and stratigraphically younger B-shoreline (consistently at ~285 m elevation in the Soda Lake basin). Also, deposits associated with the Soda Lake basin A-shoreline, exposed in the Baker dump quarry, unconformably overlie a buried soil developed in alluvial fan sediments resting upon eolian deposits. This stratigraphic sequence is very similar to that observed throughout the Cronese basins, which were part of pluvial Lake Mojave during the late Quaternary (Fig. 1; Clarke et al., 1996; Wells and Anderson, 1998; Lancaster and Tchakerian, this volume). In the Cronese basins (Fig. 1), these eolian deposits range in age from 30 ka to 15 ka, with three deposits dating from 22 ka to 23 ka (Lancaster and Tchakerian, this volume).

Subsurface sedimentology and stratigraphy within the Silver Lake depositional basin

We located the sites of drill cores within the northern Silver Lake basin to document geographic variations with the sediments and stratigraphy from the lake axis to the lake margin and in order to better understand variations in lake levels during pluvial Lake Mojave. Cores Sil-I and Sil-H were drilled near a north-south axis of the playa and show evidence of deeper water conditions (greatest thickness of lacustrine clays) than any of the other core sites (Fig. 7). Cores Sil-J, Sil-F, and Sil-E were drilled in areas farther from the axis and closer to the margins of pluvial Lake Mojave, where the thickness of lacustrine sediments should be less. Sediments in Core Sil-E, which was drilled near the present playa-fan interface, indicate the shallowest, most lake-margin conditions of any core site drilled in Silver Lake basin. Core Sil-M was drilled in the fan-delta area at the southern end of Silver Lake basin (Fig. 7).

Sediments observed in the Silver Lake and Soda Lake basin cores are grouped into three chronostratigraphic units (see Table 3 for definition; see GSA Data Repository item C for core descriptions) based upon radiocarbon ages from Silver Lake basin (Table 1) and regional correlation of sediments between Silver Lake and Soda Lake basins (Figs. 4 and 5). The three units are as follows: (1) a pre-Lake Mojave chronostratigraphic unit, the oldest characterized by sand and gravel deposited as alluvial fan and eolian sediments; (2) the Lake Mojave chronostratigraphic unit dominated by clastic lacustrine sediments composed mainly of reduced green-to-blue, clay-size particles indicating persistent standing water; and (3) a post-Lake Mojave chronostratigraphic unit characterized by oxidized, massive, silt-to-clay-size sediments indicating playa conditions with episodic wetting and drying events (Enzel et al., 1992). Although the sedimentary character and stratigraphic properties (facies) vary laterally across the Silver Lake basin, the boundaries between these units are defined in terms of the formation and timing of late-Pleistocene, early-Holocene Lake Mojave.

Pre-Lake Mojave paleogeography in northern Silver Lake basin

Seven cores are utilized to define basal contact of the Lake Mojave chronostratigraphic unit (i.e., pre-lake topography) and sedimentary environments underlying the pre-lake surface in the northern Silver Lake basin (Fig. 13). These cores show that the pre-Lake Mojave sediments immediately below the Lake Mojave package are predominantly alluvial fan and playa in origin. Fine-grained, playa-like deposits occur at the base of core Sil-H and Sil-I but are not observed in cores Sil-J, Sil-F, or Sil-E (Fig. 13). Thus, the areal extent of the pre-lake playa was smaller than the current playa in the northern part of the Silver Lake basin. Within the subsurface, pre-lake environment, alluvial fans flank the playa and consist of angular-to-subrounded, gravel-to-sand sized clasts that are moderately to strongly stratified and sorted. Pedogenic carbonate (stage I to II and stage IV) is present on clast surfaces and is disseminated in the matrix, indicating that the pre-lake surface was subaerially exposed with sufficient time to allow soil development. Based upon the two stages of pedogenic carbonate observed in the subsurface fan sediments, we infer that two different ages of alluvial fan units formed in this basin prior to Lake Mojave. The oldest, with stage IV pedogenic carbonate, is interpreted to be an alluvial fan deposit that correlates with unit Qf0 of Wells et al. (1987). The alluvial fan unit with stage I–II pedogenic carbonate may be equivalent to unit Qf1 of Wells et al. (1987) and is inferred to be inset within and/or overlie the older alluvial fan unit (Fig. 13).

The maximum relief of the playa deposits forming the pre-lake topography between cores J and E near the basin axis (Fig. 13) is ~1 m. The relief between the paleo-playa floor and the flanking alluvial fan deposits is >5 m. These cores suggest that the pre-lake landscape of northern Silver Lake basin was similar to the current playa/alluvial fan landscapes of Silver Lake basin: low relief and shallow gradients except near topographic highs created by bedrock or older alluvial fan units (Fig. 13).

Sedimentology and stratigraphy of Lake Mojave chronostratigraphic unit

Detailed stratigraphic and sedimentologic studies of the Lake Mojave chronostratigraphic unit, including the nature of internal bounding surfaces, provide data for a high resolution geologic and hydrologic reconstruction of the Mojave River terminal basin (Silver Lake) during the late Pleistocene. We refer to our reconstructions as high resolution because core measurements were made at a scale of 1:1, allowing us to record variations in strata at the millimeter scale and correlate these strata from one core to another (GSA Data Repository items C and D, see footnote 1). The primary sedimentary features within the strata of the Lake Mojave

TABLE 3. DEFINITION OF SEDIMENTOLOGIC AND HYDROLOGIC TERMINOLOGY USED TO DESCRIBE DIFFERENT SCALES OF SEDIMENTARY FEATURES AND ASSOCIATED HYDROLOGIC EVENTS WITHIN THE SILVER LAKE BASIN, CALIFORNIA

Term	Definition
Bounding surface	A bedding plane or surface, classified into 12 types (see Table 4), separating sediments of differing properties
Sedimentary layer	Fundamental and discrete body of sediment with specific characteristics and separated by bounding surfaces
Banding	Thin zone of chemical precipitates within sediments and/or along the margin of a bounding surface
Sedimentary package	Grouping of lithofacies sedimentary layers in cores or surface exposures according to common, major attributes
Hydrologic condition (basin-wide)	Five relative lake levels reconstructed from the correlation of bounding surfaces and stratigraphic features among cores that vary geographically from the depocenter of pluvial Lake Mojave
Lake phase	Hydrologic condition interpreted from the lithologic and geographic variation of a chronozone identified in cores from the northern Silver Lake depositional basin

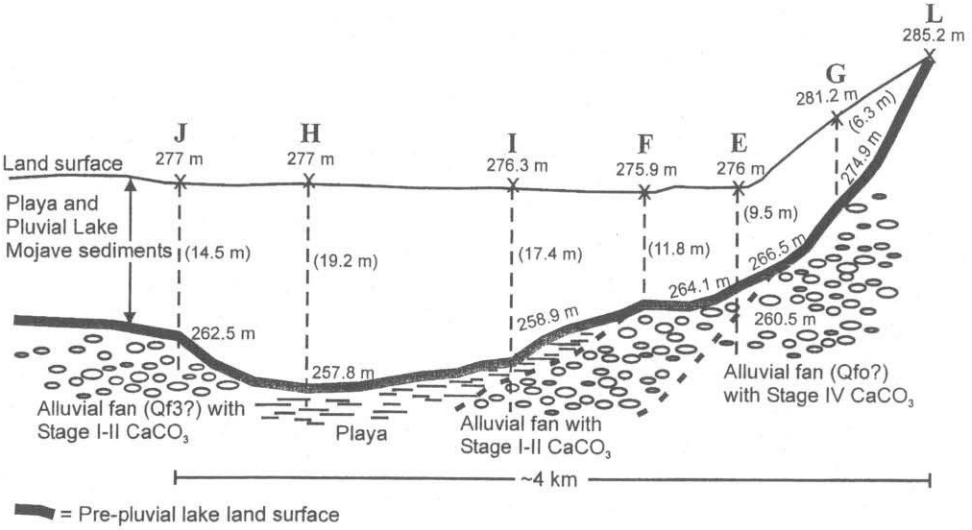


Figure 13. Schematic cross section reconstructed from selected cores (Sil-E through Sil-J, and Sil L) at the northwestern edge of the Silver Lake playa (see Fig. 7), showing the paleogeography of the pre-Lake Mojave depositional surface (bold line). Depth from the playa floor to the base of the pluvial Lake Mojave sediments is given in parentheses, and includes both Holocene playa and Lake Mojave sediments. Note the low relief and shallow gradient in the basin center.

unit include layers and bounding surfaces between these layers (see Table 3 for definitions). We distinguish layers within these strata from bedding and laminae because we focus on changes in key properties from layer to layer and less on the significance of individual layer properties (e.g., thickness).

Sediments recovered from the cores of the Lake Mojave chronostratigraphic unit include both detrital sediment and chemical precipitates. These sediments are dominated by detrital sediments from the Mojave River and are predominantly clay and silt-sized. Within the detrital lacustrine sediments, the following two types of layers (see Table 3 for definitions) dominate: (1) upward-fining sequences of very fine sand and silt grading to fine silt and clay, and (2) laminated-to-sublaminated clay beds varying in thickness from one to several centimeters (GSA Data Repository item C). In addition to these two types of layers, cores contain a third type of thin layer that consists of nonlaminated silt to very fine sand, which appears to be slightly coarser-grained relative to the two types discussed above. This third type of layer occurs at irregular intervals within the laminated-to-sublaminated, clay-sized sediments (Table 4). This third type of nonlaminated layer typically is accompanied by color changes, is almost always rich in silt, and contains a distinct lithologic fingerprint of phlogopite-rich sediments. The source of the phlogopite is within the upper Mojave River drainage basin (Brown, 1989).

We interpret that the phlogopite-rich layers were deposited during large-scale flooding of the Mojave River into pluvial Lake Mojave (see GSA Data Repository item C). This interpretation is supported by observations of exceptionally high proportions of phlogopite in Mojave River flood sediments near the mouth of Afton Canyon and the present-day Silver Lake and East Cronese Lake fan. Several stream sediment samples collected near Victorville, California (Fig. 1) also contained abundant phlogopite particles. In contrast, local floods from precipitation in the mountains surrounding Silver Lake and Soda Lake basins carry sediments that reflect local lithologies with little or no phlogopite.

During logging of cores taken from Silver Lake basin, we recognized that both the layers and nature of the bounding surfaces within the cores were critical in constructing the vertical sequence of geologic events. We observed that layers composed of different sediment types are separated by bounding surfaces (see Table 3 for definition) with well-defined properties. The properties of the bounding surfaces are used to classify them into 12 distinct types (Table 4). These bounding surface types reflect subtle but significant changes in depositional conditions (Brown, 1989, p. 24–25; Wells et al., 1989, p. 76–82; see GSA Data Repository items C and D). We infer that thin horizons of coarser silt-rich material, thin carbonate and sulfate-rich evaporite bands, and desiccation cracks reflect lake fluctuations such as lake lowering or drying events (see below; Table 4; see Smoot and Lowenstein, 1991, for example). These bounding surfaces are, in turn, overlain by lacustrine sediments representing deeper water conditions. The vertical sequence of these layers and boundary types has been correlated from core to core in the Silver Lake basin (Fig. 14; GSA Data Repository item D). Some of the higher-order bounding surfaces maintain their general character among the cores, whereas some of the lower-order bounding surfaces show significant variations. These variations are systematic from the center of the ancient lake to its margin and are critical to interpretation of the latest Quaternary hydrologic responses of Lake Mojave and the ancestral Mojave River. Successful correlation of the lake deposits are due, in part, to low relief of the pre-lake topography (Fig. 13). For example, the elevation difference of the pre-lake surface between cores Sil-H and Sil-I (which show the best correlation as illustrated in Figure 14 and GSA Data Repository item D) appears to be <1 m and >600 m. Correlations become slightly more difficult for those cores near the lake margin that suggest a 9 m elevation change in pre-lake topography over a distance of ~1000 m.

At some of the bounding surfaces, we infer drying, partial drying, or lake lowering from the presence of evaporites and mud cracks. Within a clastic matrix, primary chemical precipitates are

TABLE 4. TYPES AND PROPERTIES OF BOUNDING SURFACES OBSERVED IN PLUVIAL LAKE MOJAVE SEDIMENTS AND USED IN THE STRATIGRAPHIC ANALYSIS OF CORES OBTAINED FROM SILVER LAKE BASIN

Bounding surface type	Description
1	Dark coarser clay with minor silt-sized phlogopite overlying lighter colored finer grained clay
2	Silt containing phlogopite overlying clay
3	Sandy silt overlying silty clay
4	Fine sand overlying silty clay
5	Fine sand overlying clay
6A	Horizontal laminations of $CaCO_3$
6B	Horizontally aligned blebs of $CaCO_3$
7A	Horizontal laminations of thenardite and/or mirabilite
7B	Horizontally aligned blebs of thenardite and/or mirabilite
7C	Disseminated thenardite and/or mirabilite
8	Gravel overlying sand
9	Sediment (interpreted as being locally derived sediment from runoff/turbidite processes) consisting of diorite, carbonate, and/or granitic clasts overlying sediment of any size

Note: The letter D is used in conjunction with the bounding surface types to indicate a mudcrack associated with a drying event related to a boundary surface, and the letter S is used with these types to indicate a mud crack possibly caused by syneresis (i.e., nondrying) processes.

found at or just below bounding surfaces throughout the core as millimeter-to-centimeter thick bands of nonorganic carbonate, Na_2SO_4 (thenardite) and $Na_2SO_4 \cdot 10H_2O$ (mirabilite), including combinations of these precipitates (Tables 3 and 4; GSA Data Repository items C and D). Microscopic analysis of selected carbonate bands indicates that they are composed of microcrystalline calcite (Brown, 1989). In addition, displacive halite (Li et al., 1997) is widely disseminated throughout most of the upper parts of the cores. The frequency of the carbonate, thenardite, and mirabilite bands in individual cores increases with increasing proximity of the core to the paleo-shoreline (shallower conditions). For example, core Sil-H, which represents the deepest water conditions of any core in the lake, has the fewest bands of precipitates. In contrast, core Sil-E near the lake margin (Fig. 13) has individual carbonate, thenardite, and mirabilite bands up to 12 cm thick (GSA Data Repository item C).

Stratigraphically, these bands of chemical precipitates often are found directly below a bounding surface associated with mud cracks, suggesting that they are caused by lake drying episodes. If thenardite and mirabilite appear together, the carbonate is always found stratigraphically below them within the same band. This sequence within a band is typical when evaporation and lowering of lake waters produce supersaturated conditions of these mineral species. During the summer months, for example, evaporation rate, biogenic activity, and water temperature in a lacustrine environment increase greatly, thus decreasing values of carbonate solubility. These conditions are ideal for producing supersaturated solutions of $CaCO_3$ and Na_2SO_4; $CaCO_3$ will precipitate first because it is less soluble than Na_2SO_4. The precipitate bands are correlated from core to core (GSA Data Repository item D) and typically change in composition from carbonate in the cores associated with the deeper lake environment to thenardite in the cores associated with lake margins, thus suggesting the characteristic "bulls eye" pattern of evaporite facies changes found in many dry lake basins (Hunt et al., 1966; Hardie et al., 1978; Eugster and Hardie, 1975).

Mud cracks are observed commonly in subsurface sediments from Silver Lake basin (Fig. 14; GSA Data Repository item C). Mud cracks or shrinkage cracks form by the following two processes in a saline lacustrine environment: desiccation (subaerial conditions) and syneresis (subaqueous conditions) (Plummer and Gostin, 1981). Determining which processes (subaerial or subaqueous) formed a given set of shrinkage cracks can be difficult in cross-sectional profiles such as lake cores (Glaessner, 1969; Plummer and Gostin, 1981). In order to address this difficulty, we carefully examined the sediments infilling the lowest part of the mud cracks. Many of the shrinkage cracks preserved in the cores are filled with coarser, often oxidized (eolian and fluvial) sediment or are associated with evaporite bands. These features indicate a subaerial origin rather than a subaqueous origin. The above observations suggest that the majority of shrinkage cracks found in Silver Lake cores formed during desiccation of the lake.

Chronozones of the Lake Mojave chronostratigraphic unit, Silver Lake basin

Core data for the Lake Mojave chronostratigraphic unit (GSA Data Repository items C and D) yield a high resolution stratigraphy that is primarily based on the identification of the three types of sedimentary layers and the 12 types of boundary surfaces. Our goal is to use this high resolution stratigraphy and its systematic geographic variations to define correlative, basin-wide, relative

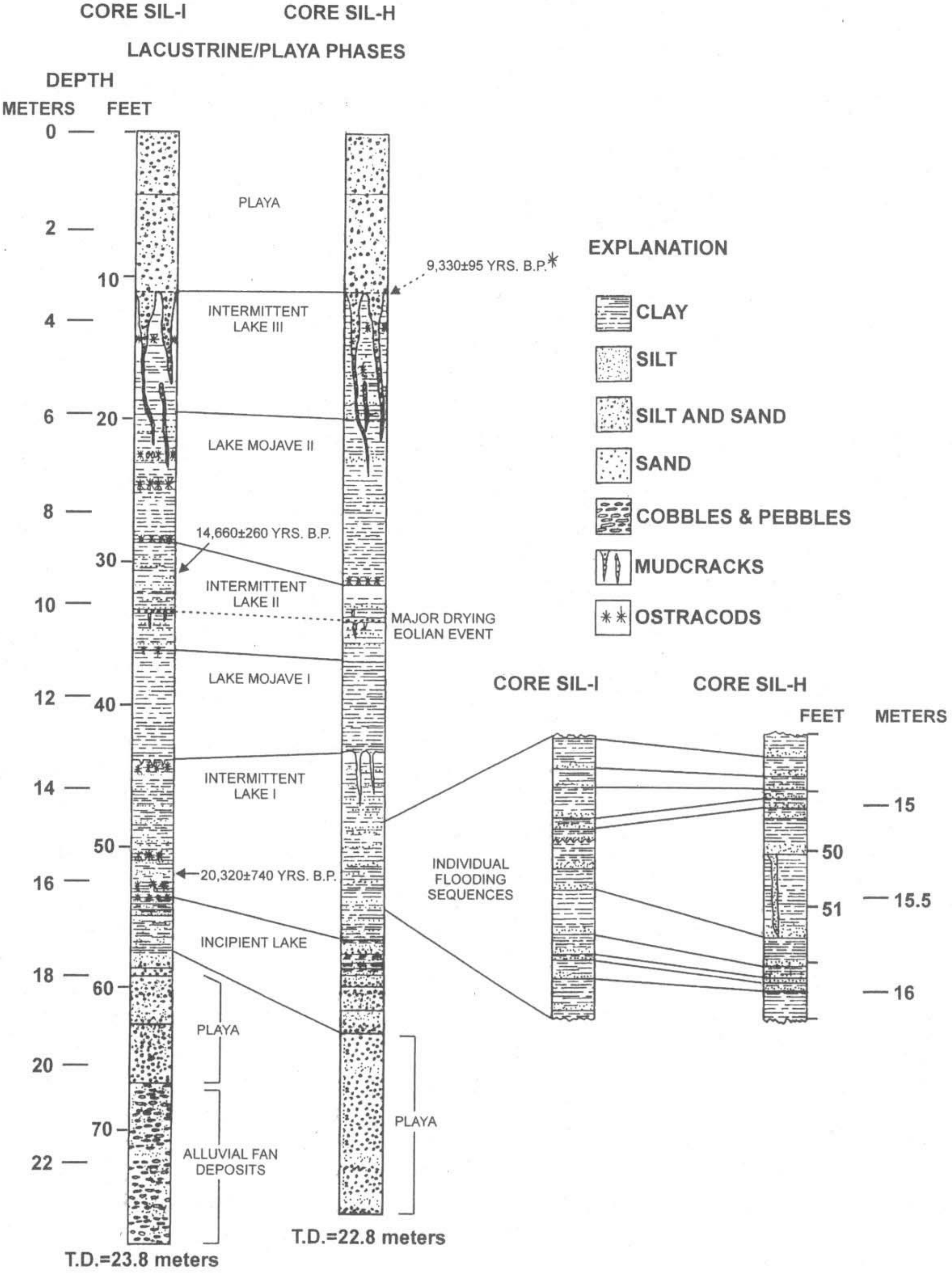


Figure 14. Simplified stratigraphy of cores Sil-I and Sil-H in the northern Silver Lake depositional basin, showing major lake chronozones (phases) and an expanded view of the zone between 14 and 16 m depth to emphasize the detailed nature of event correlations between the two core locations. The location of radiocarbon dates also are shown in core Sil-I (see Table 1 for details).

hydrologic conditions within the Silver Lake depositional basin (Fig. 3). Using the vertical sequences of these layers and bounding surfaces, we define five primary and one secondary informal chronozones on the basis of physical features that we interpret to reflect general synchronicity, including the frequency or absence of bounding surfaces with mud cracks and evaporites (Table 4; GSA Data Repository items C and D). Three chronozones are dominated by features indicating lake-drying events, and two lack such sedimentary features. Cores Sil-I and Sil-H exhibit the five primary chronozones (herein defined as Intermittent Lake I, Lake Mojave I, Intermittent Lake II, Lake Mojave II, and Intermittent Lake III from oldest to youngest) and the secondary chronozone (defined as Incipient Lake) that is stratigraphically below Intermittent Lake I and the oldest chronozone (Fig. 14). Those chronozones that show no signs of drying are Lake Mojave I and Lake Mojave II (Fig. 15); in contrast, Intermittent Lakes I, II, and III show frequent signs of drying and lake lowering conditions (Fig. 15).

The five primary chronozones of pluvial Lake Mojave overlie deposits collectively defined as Incipient Lake (Fig. 14). The Incipient Lake deposits are characterized by many upward-fining sequences (10–20 cm thick), consisting of sand to coarse, silt-sized particles at the base grading to generally nonlaminated, fine, silt- and clay-sized particles at the top. We interpret these upward-fining sequences to represent individual flooding sequences within the Silver Lake depositional basin. These sediments are characteristically gray to pale green in color indicating reducing depositional conditions. The top of the Incipient Lake I chronozone is the least distinguishable boundary; these deposits grade upward into the overlying Intermittent Lake I chronozone. Thus, we classify the Incipient Lake I chronozone as secondary because it may not be distinguishable from the overlying chronozone. The Intermittent Lake I chronozone is characterized by nonlaminated to laminated, clay-sized sediments. Less frequent desiccation cracks suggest relatively longer-term lake stands interrupted by short-term drying events. An absence of drying events distinguishes the Lake Mojave I chronozone from the underlying and overlying Intermittent Lake chronozones (Figs. 14 and 15). Diatoms from the Lake Mojave I chronozone suggest generally deeper, less saline water conditions than lake conditions in the younger chronozones (J.P. Bradbury, 1988, personal commun.). Therefore, we conclude that continuous water existed in Silver Lake basin in the areas of Cores Sil-I and Sil-H during the period of Lake Mojave I.

Sediments of the Intermittent Lake II chronozone rest conformably on the Lake Mojave I sediments and exhibit sediment and faunal characteristics similar to those of the Intermittent Lake I chronozone. More mud cracks are found in the sediments of the Intermittent Lake II chronozone than in any other lake phase. One of most extensive drying periods during the history of pluvial Lake Mojave occurred during the deposition of this chrono-

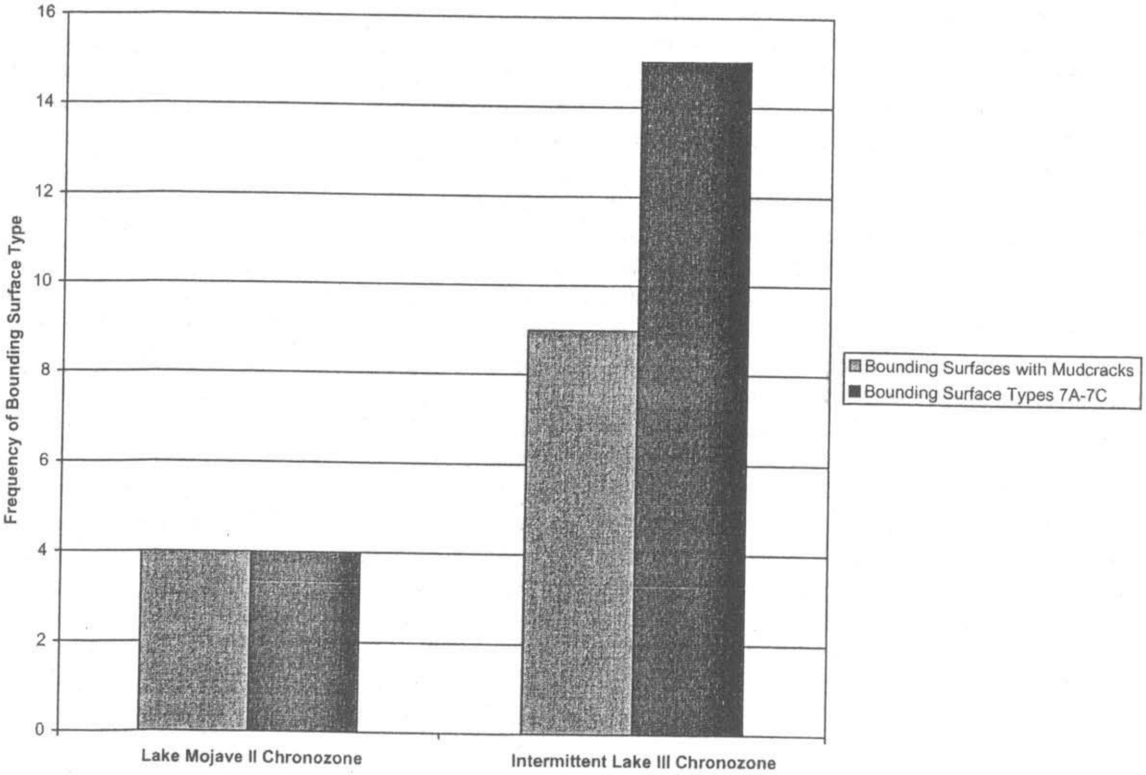


Figure 15. Comparison of bounding surface types in two different phases of pluvial Lake Mojave (Lake Mojave II and Intermittent Lake Phase III). Note significantly lower frequency of bounding surface types which indicates drying or partial drying during Lake Mojave II.

zone. This drying event produced large, distinctive desiccation cracks infilled and overlain with several centimeters of well-sorted, fine-medium eolian sand in most cores from the northern Silver Lake area (e.g., Figure 14).

Overlying the Intermittent Lake II chronozone is the Lake Mojave II chronozone. Major drying events are absent from the Lake Mojave II chronozone, indicating long-term stands of water; however, evidence of numerous partial drying or lake lowering events are found, especially in the lake-marginal cores (Brown, 1989).

Overlying the sediments of Lake Mojave II is the last major lacustrine chronozone, Intermittent Lake III. Sediments of the Intermittent Lake III chronozone are similar in nature to the sediments of Lake Mojave II but contain mud-crack and other desiccation features. Numerous desiccation cracks infilled with eolian and fluvial sands mark the end of pluvial Lake Mojave and the Intermittent Lake III chronozone as well as establish the beginning of the playa conditions, which have persisted to the present.

Thermophilic ostracodes and diatoms in the sediments from these cores and in shoreline features indicate that lake water during the Lake Mojave I and Intermittent Lake I chronozones was generally warmer (especially during the winter months) and less turbid or less saline than lake waters of the three younger lacustrine chronozones (R. Forester and J.P. Bradbury, 1987, personal commun.). The presence of these ostracodes in the Lake Mojave I and Intermittent Lake I phases does not necessarily indicate warmer climatic conditions but may reflect the greater buffering effect on seasonal water temperature fluctuations in a larger, deeper lake system.

Radiocarbon dates were obtained from three of the chronozones (Fig. 14; Table 1). The oldest date (20,320 ± 740 yr B.P.) comes from a depth of ~15.9 m below the playa surface in core Sil-I within the basal part of the Intermittent Lake I chronozone. Also from core Sil-I and at a depth of 9.8 m is a radiocarbon date of 14,660 ± 260 yr B.P. from the upper section of the Intermittent Lake II chronozone. We obtained a radiocarbon date of 9330 ± 95 yr B.P. from core Sil-M at a depth of slightly >3 m below the playa surface (Fig. 7). This age was obtained from sediment in that core that is just below the boundary of the Intermittent Lake III chronozone and the overlying, post-Lake Mojave chronostratigraphic unit; the relative stratigraphic position of this age is illustrated in core Sil-H in Figure 14 although the dated sample was not taken from this core. This date closely limits the end of pluvial Lake Mojave (Fig. 14). Radiocarbon dates from the cores in northern Silver Lake basin indicate that the five primary chronozones forming the Lake Mojave chronostratigraphic unit were deposited during a period lasting at least 11,000–12,000 yr.

DISCUSSION

Age estimates and sedimentation rates of pluvial Lake Mojave

Radiocarbon dating of shell material and tufa from shoreline features and paleoenvironmental reconstructions suggest that pluvial Lake Mojave existed in the Silver Lake basin prior to ca. 16 ka and ended between ca. 8.3 and 9.1 ka. Radiocarbon dates from core samples allow us to refine this timing. Organic materials from Core Sil-I at depths of 9.8 m and 15.9 m below the playa floor were dated at 14,660 ± 260 yr B.P. and 20,320 ± 740 yr B.P., respectively (Fig. 14; GSA Data Repository item C). A radiocarbon age of 9330 ± 95 yr B.P. was obtained from samples at a depth of 3 m in Core Sil-M (its relative stratigraphic position is illustrated in Core Sil-H, Figure 14). These ages are consistent with an independently developed chronology of pluvial Lake Mojave determined from the various beach ridges and wavecut shorelines around the lake (Figs. 7, 8, 11, and 12). The validity of a third radiocarbon date (14,200 ± 145 yr B.P.), taken from core Sil-I at a depth of ~6 m, is considered suspect because its stratigraphic position is very close to the final desiccation of pluvial Lake Mojave, which has been independently dated from samples in the shoreline environments at ca. 8.7 ka and in the subsurface at ca. 9.3 ka. Thus, the radiocarbon age from core Sil-I contradicts a chronology of other dates obtained from the lake margins and subsurface, and we have chosen not to incorporate this radiocarbon date into our studies.

Using the stratigraphic separation between the two radiocarbon ages obtained from a single core (core Sil-I, a vertical column of sediment), we calculate an average, long-term sedimentation rate of 1.08 m/1000 yr. We acknowledge the limitations of our age estimates derived from this method (e.g., uncalibrated versus calibrated radiocarbon dates; boundaries between layers reflecting a hiatus in the sedimentation rate; and variable processes over time such as flooding, lake lowering, and total drying events). The average sedimentation rate, however, is based on data derived from core Sil-I near the deepest part of Silver Lake basin (Figs. 13, 14). During this study, Sil-I has been used as a baseline to relate all other cores drilled in the lake, and core recovery during drilling of Sil-I was nearly 100%.

Application of the 1.08 m/1000 yr rate to the sediment column above these dates yields an estimated age of 8.7 ka for termination of pluvial Lake Mojave. When this age is compared to the Lake Mojave termination based on the radiocarbon age of tufa (a deposit that does not always yield reliable radiocarbon ages) from the Silver Lake quarry (Fig. 12; Table 1; Ore and Warren, 1971; Wells et al., 1987), these two ages differ by only 0.2%.

Allowing a test of the value of the average sedimentation rate derived from core Sil-I and supporting the concordance of these two independently derived age estimates is a radiocarbon age derived from bulk sediments between 3.1 and 3.2 m below the playa surface in Core Sil-M (Figs. 3, 14) (Enzel et al., 1992; Enzel and Wells, 1997). The age of 9330 ± 95 yr B.P. was obtained just below the bounding surface that reflects the end of pluvial Lake Mojave (Table 1; GSA Data Repository item C). Combining this radiocarbon date and its associated depth below the surface with the two radiocarbon dates from core Sil-I (14,660 ± 260 yr B.P. and 20,320 ± 740 yr B.P.) at depths of 9.8 m and 15.9 m, an estimated sedimentation rate of 1.16 m/1000 yr is calculated. This value, calculated from three radiocarbon samples in two different cores, is similar to the rate of 1.08 m/1000 yr calculated using two dates from the same core. In addition, the radiocarbon age from core Sil-M is similar to the ages derived from shells (9390 ± 140 yr B.P.; 9340 ± 140 yr B.P.) in the topographically lower portions of the El Capitan beach ridge and tufa in Silver Lake quarry (9160 ± 400 yr B.P.; Figure 11).

Radiocarbon ages within the youngest shoreline deposits of pluvial Lake Mojave (some ages on tufa are as young as 8350 ± 300 yr B.P. and others on shells are 9340 ± 140 yr B.P.) vary with the type of sample and from depositional site to depositional site in response to natural variations in lacustrine processes and sediment preservation. The radiocarbon date from the youngest deposits in one core is 9330 ± 95 yr B.P., which may differ from another core similar to shoreline environments and thus explain the 600 year difference estimated by the average sedimentation rate. We infer that the subsurface environment provides the most reliable estimate of when pluvial Lake Mojave ended, which we estimate to have occurred between 8.7 ka and 9.3 ka.

The similarity between surface and subsurface ages as well as tufa and shell radiocarbon dates suggests that use of an average sedimentation rate for age estimations of lacustrine phases is reasonable. Using age estimation by sedimentation rates, the earliest lake sediments in the Silver Lake basin are inferred to be ca. 22 ka. This age is consistent with the stratigraphic relations observed in the Baker Dump quarry (Wells et al., 1989; GSA Data Repository item B). The earliest deposits of pluvial Lake Mojave at this site cover a sequence of alluvial fan deposits overlying eolian deposits; the eolian deposits are inferred to be 22–23 ka based upon correlation with results from Lancaster and Tchakerian (this volume).

We use the average sedimentation rate to estimate the age of the Lake Mojave sedimentary package and to provide a more refined estimate of the hydrologic conditions leading to the layering and bounding surfaces in the cores. We recognize, however, that both of these sedimentary properties as well as the sedimentation rates will vary with (1) the pre-Lake Mojave topographic conditions, (2) the core location within the depositional basin that impacts drying events (Fig. 13; GSA Data Repository items C and D), and (3) climatic conditions and erosion rates in the Mojave River headwaters. Because cores Sil-H and Sil-I are near the basin axis and had little topographic relief (Fig. 13), their sedimentation rates were probably very similar (GSA Data Repository items C and D). Thus, we infer that the entire depositional history of Lake Mojave in the Silver Lake basin is recorded within cores Sil-H and Sil-I. As the Silver Lake basin progressively filled with sediment, gradients between high and low topography became subdued and geographic variations in sedimentation rate probably became comparable for the later stages of basin filling (Fig. 13).

Figure 16 is a time-series plot of sedimentation processes including thickness between bounding surfaces, frequency of bounding surfaces, and cumulative sediment thickness during the formation of Lake Mojave's five chronozones. In Figure 16, cumulative sediment thickness is plotted on the y-axis, and time in radiocarbon years is plotted on the x-axis. The time scale is based upon the average sedimentation rate calculated from core

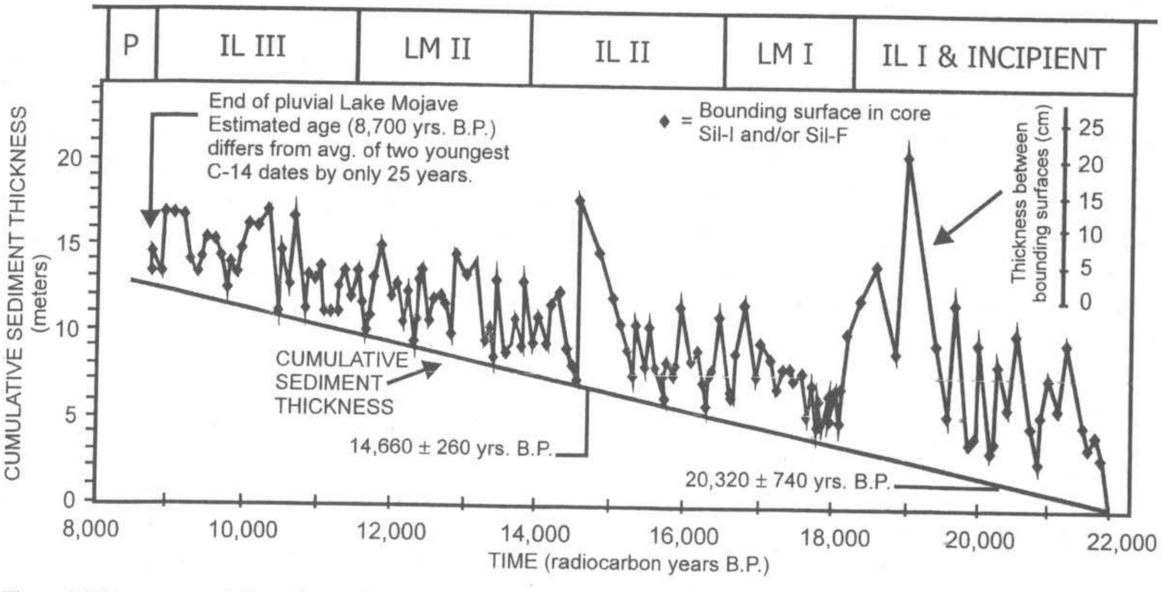


Figure 16. Reconstructed chronology of Lake Mojave sedimentation based on sediment characteristics from Silver Lake cores Sil-I, Sil-F and Sil-H (see Fig. 7 for locations) showing cumulative thickness over time, major bounding surfaces, and thickness of sediments between bounding surfaces. Chronology based on average sedimentation rates calculated from accelerator mass spectrometry core dates and correlations of subsurface stratigraphy with dated shoreline features (see text for further description). Timing of lake phases are shown above the cumulative thickness plot. IL I—Intermittent Lake I; LM I—Lake Mojave I; IL II—Intermittent Lake II; LM II—Lake Mojave II; IL III—Intermittent Lake III; P—Holocene playa.

Sil-I. The average accumulation rate of sediment within Silver Lake basin at the core Sil-I location is shown by the straight line increasing from 0 m at the base of the Intermittent Lake I (and Incipient Lake) chronozone to ~13 m at the top of the Intermittent Lake III chronozone. The frequency of boundary surfaces preserved in the combined records of cores Sil-I and Sil-F are shown by the black diamond symbols (Fig. 16). The frequency of these surfaces illustrates the number of times that significant sedimentologic changes occurred within the record. These changes include (1) change from low or dry conditions to standing water; (2) change in the depositional process during standing water conditions; and (3) flooding events. The thicknesses of sediment accumulation between bounding surfaces was measured vertically from the cumulative sediment line, using the scale in the upper right-hand portion of Figure 16. That is, the time-series plot has been "tilted" to parallel the accumulation of sediment.

The Lake Mojave I and Lake Mojave II chronozones display more frequent, more regularly spaced bounding surfaces whereas the Intermittent Lakes I, II, and III chronozones show fewer surfaces and greater variability in the stratigraphic distance between the surfaces. These patterns suggest that the processes producing the two types of Lake Mojave chronozones were more consistent in frequency and amount of water and sediment input into the Silver Lake basin. Figure 16 also graphically shows that the average sedimentation rate does not fully explain the episodic nature and variability of sedimentation processes in Silver Lake basin during its occupation by pluvial Lake Mojave.

Latest Pleistocene Mojave River floods and sedimentation in the Silver Lake basin

Pluvial Lake Mojave consisted of two major depositional basins the configuration of which influenced sedimentary processes at the terminus of the ancestral Mojave River and consequently the sedimentologic record of these basins during the late Pleistocene (Figs. 3, 4, 5). During the deposition of the Lake Mojave chronostratigraphic unit, the latest Pleistocene Mojave River fan delta prograded eastward from the mouth of Afton Canyon (Fig. 1). Lake Mojave extended ~40 km northward from the terminal reaches of the fan delta to the spillway at the northern end of Silver Lake basin.

The boundary surfaces identified in the cores represent a sedimentologic change. We interpret these changes to indicate either (1) flooding of this basin to produce standing water after low or dry conditions or (2) flooding into a body of standing water that created a silt-rich plume containing phlogopite. In both cases, we infer that large floods of the Mojave River produced these sedimentologic changes. The northernmost location of the cores within Silver Lake basin is the most geographically distant point from the fan-delta complex of the Mojave River where water and sediment first entered Lake Mojave within Soda Lake basin. Consequently, when pluvial Lake Mojave was low (e.g., Intermittent Lake I, II, and III chronozones), thicker accumulation of sediment without any significant sedimentologic change occurred in the most northern, or distal, portions of Silver Lake basin (Fig. 16) because the effects of flood discharge and sedimentation were mostly confined to Soda Lake basin. During higher stands of pluvial Lake Mojave, accumulation of sediment between bounding surfaces in northern Silver Lake basin was thinner, and bounding surfaces reflect frequent flood input (Fig. 16). The sequence of these floods as recorded in the stratigraphic record are illustrated in cores Sil-I and Sil-H of Figure 14.

Variations in hydrologic conditions and lake levels in Silver Lake basin during the latest Pleistocene

Comparison of the sedimentology of individual cores also was used to reconstruct basin-wide depositional environments and, in turn, to infer the major hydrologic conditions during pluvial Lake Mojave. Several characteristic features that record hydrologic conditions, varying from floods to desiccation, are observed in all cores and were used to reconstruct lake levels in Silver Lake basin. Because correlated sedimentary layers from individual core locations in Silver Lake basin represent different environments in the lake at a single point in time, hydrologic conditions (i.e., flooding, partial drying or lake lowering, and total drying) have been recorded differently in the various core locations. For example, a total drying event in core Sil-E may be recorded as a partial drying or lake lowering event in core Sil-F and not at all in core Sil-I, respectively located from the shore margin to the basin axis (see Figures 7 and 13 for geographic locations). Thus, environments proximal to the shore record a greater number of lake fluctuations than environments proximal to the basin center during the same period of time (GSA Data Repository item D).

In order to quantify hydrologic conditions across Silver lake basin during the latest Pleistocene, we defined five relative lake levels based upon a comparison of hydrologic conditions (as interpreted from sediments and bounding surfaces) at core sites Sil-I and Sil-F (Fig. 17). The chronology of these relative lake-level types is based upon age estimates calculated from average sedimentation rates (Fig. 17). Lake-level type 5 represents high lake water conditions throughout Silver Lake basin, and most likely the Soda Lake basin lacks any evidence of drying or partial drying. Such conditions probably resulted in spillway overflow. Quantitative constraints on the water levels, however, are not available on this scale other than maximums represented by high shorelines. Lake-level type 4 indicates partial drying or other lake lowering events near the lake margin within the Silver Lake basin (i.e., reduction of lake volume). Type 3 represents partial drying or other lake lowering conditions near the center of pluvial Lake Mojave in Silver Lake basin. Type 2 involves total drying along the lake margin in Silver Lake basin, whereas Type 1 represents total drying of Silver Lake basin. Because Soda Lake basin is deeper than Silver Lake basin and the two are separated by a sill (Fig. 4), the paleohydrologic conditions associated with Types 1–4 may not necessarily apply to the southern part of pluvial Lake Mojave in Soda Lake basin.

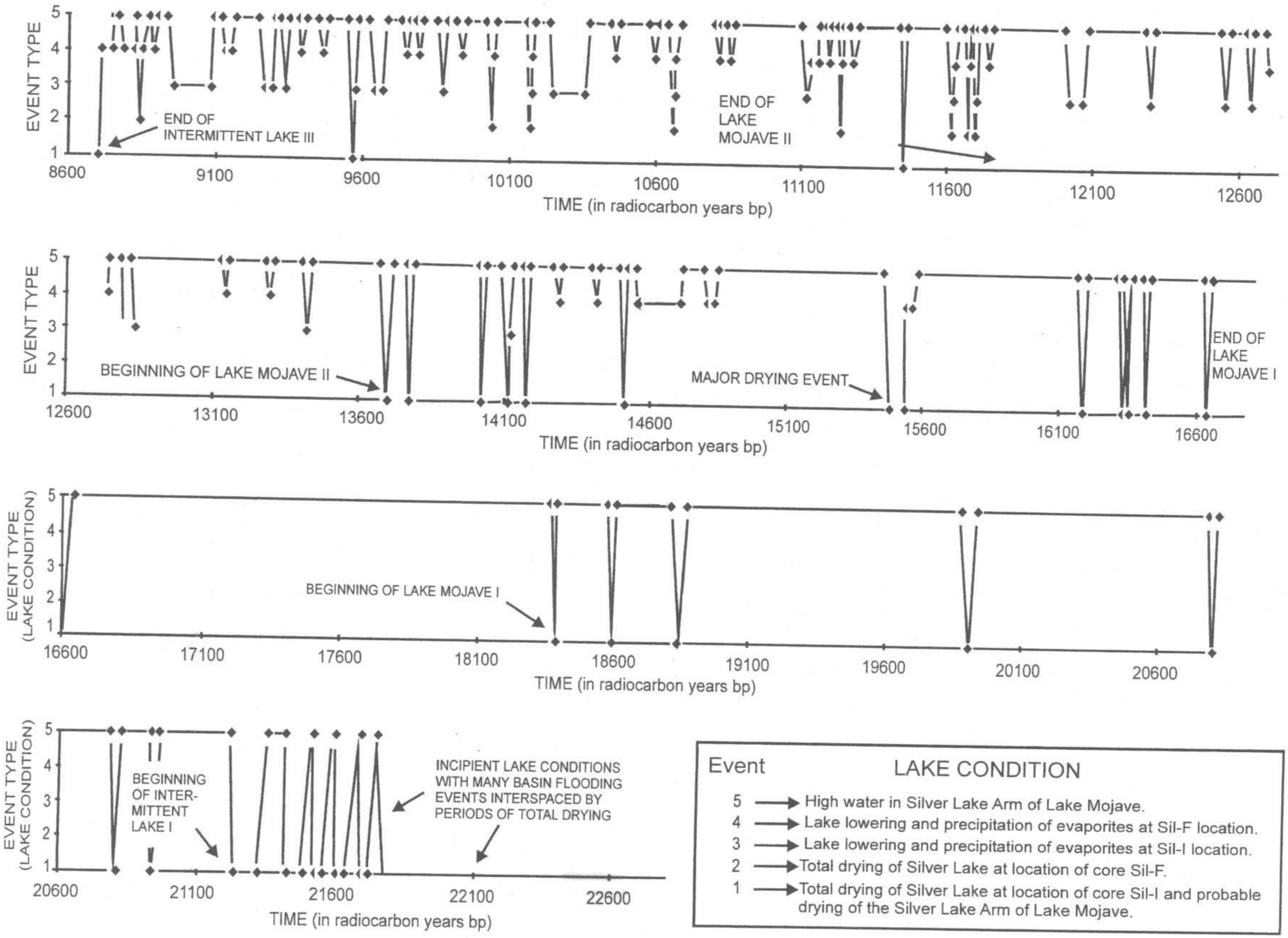


Figure 17. Reconstructed hydrology of Lake Mojave based on five types of lake levels inferred from comparison of stratigraphy of cores Sil-I and Sil-F located at the northern end of Silver Lake depositional basin (modified from Brown, 1989).

Based on the variation and timing of lake levels, pluvial Lake Mojave can be divided into the following six major lacustrine phases: Incipient Lake, Intermittent Lake I, Lake Mojave I, Intermittent Lake II, Lake Mojave II, and Intermittent Lake III (Fig. 14). Five of these lacustrine phases correlate with the chronozones discussed above. The sedimentology of the Incipient Lake phase suggests that waters from the Mojave River inundated Silver Lake basin in an episodic yet progressive style. There is no evidence in the subsurface that catastrophic processes rapidly inundated the basin. Thus, there is no subsurface evidence to support the hypothesis that Lake Manix drained catastrophically into Lake Mojave (Meek, 1989).

Cores Sil-J and Sil-F (Fig. 7) contain sediments similar in nature to those found in Sil-I and Sil-H (GSA Data Repository items C and D). Significantly more drying events (desiccation cracks) and partial-drying lake-lowering events, however, are evident in cores Sil-J and Sil-F, supporting the interpretation that these cores are proximal to the paleo-shoreline and represent shallower conditions than indicated by Sil-I or Sil-H (Fig. 13). Cores near the paleo-shoreline record smaller but more frequent fluctuations in this lake system. Core Sil-F, when compared to core Sil-I, shows the most detailed record of pluvial Lake Mojave fluctuations of any core drilled in Silver Lake. Exceptional preservation of $Na_2SO_4/Na_2SO_4 \cdot 10\ H_2O$ (partial drying or lake lowering) bands and desiccation cracks in Core Sil-F indicate significant and rapid fluctuations in lake levels during the Intermittent Lake III phase.

Using the chronology established by the average sedimentation rate and the variations in sedimentologic and hydrologic process (Figs. 16 and 17), the approximate ages of the lake phases (or chronozones) are estimated as follows:

- Incipient and Intermittent Lake I = ca. 22.6 ka to 18.4 ka
- Mojave I = 18.4 ka to 16.6 ka
- Intermittent Lake II = 16.6 ka to 13.7 ka
- Mojave II = 13.7 ka to 11.4 ka
- Intermittent III = 11.4 ka to 8.7 ka

Changes in lake volume and storage capacity of Lake Mojave

The sediment accumulated in Silver Lake and Soda Lake basins during the history of pluvial Lake Mojave reduced the storage capacity and impacted the hydrology of both basins (Figs. 4, 5, and 6). Estimates of potential lake volume and storage capacity in the basins are based on spatial relationships identified in drill cores and rotary holes. These data indicate that at the beginning of pluvial Lake Mojave, both Silver Lake and Soda Lake basins would have held >7 km^3 of water before overflowing the spillway in northern Silver Lake basin. Also, the Soda Lake basin could have contained an incipient Lake Mojave for a substantial period of time before the rising lake level deposited the first lacustrine clays in Silver Lake basin (Figs. 4, 5). By the end of the Intermittent Lake III phase, Silver Lake and Soda Lake basins contained <40% of their original volume. The loss of storage capacity in response to sedimentation, combined with downcutting of the spillway, apparently enhanced the sensitivity of the lake system during the latter phases of its existence. Therefore, the Intermittent Lake III and Lake Mojave II phases were more sensitive to temporarily drier conditions in the upper Mojave basin. This hydrologic phenomenon, and internal response, can explain the increase in partial-drying lake-lowering events observed in the latter phases of Lake Mojave (Fig. 17), as well as the accumulation of salts observed in the younger lake sediments (GSA Data Repository items C and D), without requiring change in an external forcing factor such as regional climate.

The decrease in water storage capacity with time also implies that if climatic (temperature and evaporative) conditions were relatively constant in the terminal basins during the latest Quaternary, then (1) significantly larger volumes of Mojave River discharge would have been required to fill the Lake Mojave I phase to the overflow elevation and (2) larger quantities of lake water would have exited the basin via the spillway during the Lake Mojave II phase.

The location and incised nature of the outflow spillway channel (Plates 1 and 3) imply sustained periods of overflow during which discharge was confined to the overflow channel; field observations support that lake outflow did not occur at any other site forming the northern boundary of Silver Lake basin. It would appear that "typical" lake overflow could easily produce this channel without requiring large-scale, catastrophic flood volumes. We infer that downcutting of the spillway from the A-shoreline (287–288 m) to the B-shoreline (285.5 m) occurred during Lake Mojave II (after 12 ka but prior to 10 ka) when overflow conditions were more easily produced because of decreased lake storage. The timing of the downcutting also is supported by the ages of the different shorelines preserved in the El Capitan complex (Fig. 11).

Correlation of pluvial Lake Mojave shoreline and lacustrine deposits

Within the subsurface environment, the basin axis typically yields a well-preserved and relatively continuous record of depositional history but generates limited data on the absolute magnitude of lake-level fluctuations. Shoreline sediments and landforms, however, yield the best data for reconstructing lake area and lake-level elevations but only produce a discontinuous record. The use of both types of data to correlate between the surface and subsurface environments of paleolakes yields the most complete history (Wohl and Enzel, 1995). In our reconstruction of the detailed geologic history of pluvial Lake Mojave, we correlate the shoreline deposits and core stratigraphy along northern Silver Lake basin. We base our correlations on stratigraphic relations, faunal distribution, radiocarbon dating, and soil geomorphic data. These data indicate that Lake Mojave I sediments were deposited earlier than previously recognized and that during this time, lake levels were at or near the spillway elevation (288–287 m), although little erosion of the spillway occurred. During the subsequent highstand of Lake Mojave II, most of the deposits and faunal remains associated with the older lake phase were eroded. Of the known outcrops of beach deposits around the Lake Mojave basin, only those deposits within Tidewater basin (Figs. 8, 9, 10) appear to record the shoreline levels associated with Lake Mojave I.

Figure 9 shows a correlation between the lacustrine sediments of core Sil-I and Sil-G and the two beach ridges preserved in Tidewater basin (Fig. 7). Samples collected from the clay units and several of the upper sandy units in Core Sil-G have been analyzed by J.P. Bradbury (1988, personal commun.) for diatoms and other microfauna. The lowermost clays in this core contain abundant *Fragilaria construens* v. *subsalina*; and this diatom and others found in Silver Lake cores, as well as within lower portions of lacustrine clays in Soda Lake Core 1, occur only in Lake Mojave I sediments (Wells et al., 1989). Thus, we correlate the basal green clays in Tidewater basin (core Sil-G) with the top of the Lake Mojave I phase in core Sil-I (Fig. 9). In addition, diatom distributions within the fine-grained deposits in the topographically lower beach ridge at Tidewater basin support this correlation (Fig. 8). The upper beach ridge (287.9 m) in the Tidewater basin corresponds to the level of the A-shoreline, and the lower Tidewater basin beach ridge (285.6 m) corresponds to the level of the B-shoreline. No shells have been dated from the upper ridge at this locality. Based on a detailed reconstruction of paleoenvironments in the Tidewater basin (Fig. 10), however, the 287–288 m beach ridge (A-shoreline) predated constuction of a topographically lower spit that formed the core and platform for the construction of the 285–286 m shoreline (B-shoreline) (Fig. 8). Thus, the A-shoreline marks the highest level of both Lake Mojave I and Lake Mojave II. Only during the later phases of Lake Mojave II, or during Intermittent Lake III and after downcutting of the overflow spillway, was the B-shoreline stabilized over a much older spit (Plates 1, 3). These relations support our interpretation that the A-shoreline was occupied during both Lake Mojave I and Lake Mojave II.

Shell dates of 14,550 ± 140 yr B.P. and 15,350 ± 240 yr B.P. (Ore and Warren, 1971) from buried sandy gravels in the 285.6 m beach ridge at Tidewater basin indicate that they are correlative, in part, to Intermittent Lake II. Stratigraphically below the above dated sediments are two green, finer-grained units containing *L. bradburyi* and *L. ceriotuberosa* (units IV and VI, Figure 8; Table 2). The older fine-grained unit contains shells dated at 16,270 ± 310 yr B.P., an age that is close to the age of the boundary between Lake Mojave I and Intermittent Lake II given the errors in dating and estimating based upon sedimentation rates. These data suggest that a highstand in lake level (288 m) and overflow at the spillway occurred during the latest stages of Lake Mojave I or the earliest stage of Intermittent Lake II. Because the majority of these early shoreline features at 288–287 m were eroded or buried by the later highstands of the lake, perhaps this early highstand did not last very long and therefore did not produce significant shoreline deposits. In the Tidewater basin, the youngest shoreline deposits (Intermittent Lake III phase) of the pluvial Lake Mojave complex are represented by the uppermost unit in the B-shoreline ridge (unit X, Figure 8; Table 2), which unconformably overlies older units.

An unconformity is recognized in both cores Sil-I and Sil-G by the presence of eolian sand filling and covering mud cracks at a major bounding surface (Figs. 9, 14). Based upon sedimentation rates (Fig. 17), the approximate age for this eolian deposit is 15.5 ka. These features indicate a major drying event during Intermittent Lake II (Figs. 9, 10, and 17). The presence of eolian sands on the lake basin floor strongly suggests that Lake Mojave in the Silver Lake basin was completely desiccated at this time (15.5 ka). Within the deposits of the 285–286 m beach ridge in the Tidewater basin is an unconformity within unit VII that is dated between 15.4 ka and 14.6 ka (Fig. 8). This unconformity indicates at least a lowering of the lake level below 283 m, followed by a rise in the lake level. We correlate this unconformity with the major drying event recorded in cores Sil-I and Sil-G (Fig. 9).

Water balance of pluvial Lake Mojave

Analysis and correlation of the surface and subsurface environments of pluvial Lake Mojave yield a detailed reconstruction of the lake-level elevation history as influenced by the discharge and floods of the Mojave River. In this section, we provide our interpretations of the hydrologic conditions of the Mojave River watershed that created volumes of water to sustain pluvial Lake Mojave, including overflow at the spillway in Silver Lake basin (Fig. 3).

The water balance calculation presented below is based on a simplified precipitation-discharge/evaporation model (see references in Enzel, 1992). The goal of these calculations is not to detect the climatic conditions of the past but to present several scenarios demonstrating the general changes and order of magnitude of changes that must occur in the hydrology to fill Lake Mojave I to its overflow spillway (i.e., last glacial maximum conditions). The model is as follows:

$$Ve = D + P(R) - E$$

where Ve equals equilibrium volume at a given lake elevation, D equals annual Mojave River discharge at Afton Canyon (Fig. 1), R equals runoff contribution from rainfall (P) over the basin in addition to river discharge, and E equals annual evaporation. For modern data, see Enzel (1990, 1992). Our assumptions include the following: (1) groundwater inflow, leakage out, and overflow were negligible; and (2) the calculated Ve is probably a minimal estimate. Afton Canyon was selected for the site to model the annual discharge input from the Mojave River as the river fed directly into the Soda Lake basin of Lake Mojave at the eastern end of the canyon.

The Mojave fluvial-lacustrine system is characterized by a high mountain catchment within the San Bernardino Mountains that generates high magnitude runoff events in a very different climatic zone than the desert catchments immediately surrounding the pluvial lake (Enzel, 1990). During late Pleistocene climate changes, we assumed differing types of climate and runoff changes for each area (e.g., contributing catchment and the area directly contributing into the lake). For example, in the present climatic regime, a relatively large portion of rainfall is transformed into runoff at the headwaters; whereas, the runoff from the desert catchments surrounding the two playas is very low and can be considered negligible. As a result, present-day potential lake evaporation is much greater than the local runoff entering the lake (Enzel, 1992). In the late Pleistocene, Lake Mojave reached an evaporative surface area of nearly 300 km^2. We assume that the main sources of water input to pluvial Lake Mojave were Mojave River discharge from its mountainous catchment, relatively minor local runoff from the desert catchments feeding directly into the lake basins, and direct rain over the lake. Our efforts are directed at estimating the main input source and roughly estimating the volume of river discharge into the lake. We assume several evaporation and precipitation scenarios and demonstrate the magnitude of change needed to produce Lake Mojave I at the spillway elevation.

We combined elevation-area-volume curves (Fig. 6) with assumed values for possible precipitation and evaporation to demonstrate the magnitude of change needed to produce Lake Mojave I overflow at the spillway elevation (Fig. 18; Table 5). The assumed values in the lake water budget calculations are based upon three different scenarios (Table 5). Our calculations indicate that whatever scenario is chosen to produce a significant body of water in Soda Lake and Silver Lake basins demands a significant increase in Mojave River discharge at Afton Canyon. A 50% reduction in evaporation over the lake still requires more than an order of magnitude increase in annual river discharge for the lake level to reach the spillway. This 50% evaporation reduction is larger than any values inferred for the American Southwest evaporation reductions during the latest Pleistocene (for summary of sources, see Smith and Street-Perrott, 1983).

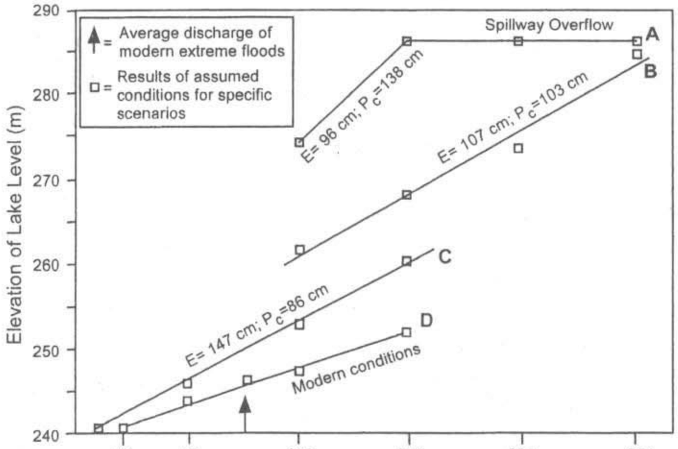


Figure 18. Modeling results of four different hydrologic conditions and associated climatic scenarios (A–D) resulting in the flooding of the terminal basins (D—modern conditions) to filling of pluvial Lake Mojave to the A-shoreline elevation (A—spillway overflow). Evaporation (E) is assumed for the topographically lower elevations of ancient Lake Mojave area, and precipitation (Pc) is assumed for the topographically higher catchment area in the San Bernardino Mountains (see Fig. 1 for locations).

We stress that even greater reductions in lake evaporation would not affect our conclusion about the required dramatic increase in Mojave River discharge. We also stress that the assumed values for the climate-related variables are only illustrative; each assumption could be challenged and the value could be refined. We believe that the values used, however, when combined with the elevation of the modern playa and shorelines as well as the bathymetry of Lake Mojave, are adequate for estimating the relative importance of climatic and hydrologic parameters in producing observed responses in the terminal basins.

Given the pre-Lake Mojave basin geometry (Fig. 5) and assuming an increase in annual discharge of the Mojave River at Afton Canyon, modern values of hydroclimatic parameters would produce only a very shallow lake (i.e., playa conditions) on the floor of Soda Lake basin at an elevation between 245 and 250 m (see scenario D, Fig. 18). We believe that a lake cannot be produced in the terminal basins of the Mojave River (with the Lake Mojave configuration [overflow, specific geometry, etc.]) without an order of magnitude increase in river discharge resulting from the mountainous catchment (see highest values for parameters in scenarios A and B, Fig. 18; Table 5). This amount of discharge can be achieved by increasing the number of storms that affect the Mojave River headwaters to produce large flow volumes at the lower Mojave River reaches.

Currently, the Mojave River experiences large transmission losses into its alluvial aquifer (Enzel et al., 1989; Enzel, 1992; Enzel and Wells, 1997), and only a small portion of the largest floods are able to reach the terminal playas. We assume that during the late Pleistocene, with increased Mojave River discharge, the transmission losses were dramatically reduced and smaller floods could have reached the lake. As shown above, the stratigraphy observed in the cores supports a flood-related sedimentology. Currently, discharge of the largest 10% of the floods in the Mojave River headwaters (Fig. 1) exceeds 250 million m^3 (Enzel, 1992). Assuming (1) no loss along the length of the Mojave River on its route to Soda Lake basin, (2) an annual occurrence of these flood discharges, and (3) a 40–50% reduction in lake evaporation, a lake will be produced with sufficient volumes to create overflow at the spillway (see scenario A, Figure 18). If we assume a tenfold increased frequency of modern extreme flood events within the San Bernardino Mountains resulting in floodwaters that reach Soda Lake and Silver Lake basins, reduced evaporation alone will result in an overflowing lake at the spillway. We believe that the most likely scenarios have been parameters that lie between A (+50% P, ~ –50% E, and about three times the value of modern extreme floods that make it annually to Afton Canyon, Figure 1) and B (+100% P, ~ –50% E, and about twice the modern values of extreme floods that make it annually to Afton Canyon) (Fig. 18).

TABLE 5. OBSERVED AND ASSUMED CLIMATIC AND HYDROLOGIC PARAMETERS FOR TWO REGIONS WITHIN THE MOJAVE RIVER WATERSHED

	Modern conditions		Assumed condition		
	Annual average	Extreme storms	Pc + 25%	Pc + 50%	Pc + 100%
A. Headwater catchment area					
Precipitation (cm)	69	86	103	138	
Runoff (%)	34	38	43	51	63
Discharge at Afton (m^3 x 10^6)	9.4	75	84	150	250
	Modern conditions		Assumed conditions*		
	Annual average				
B. Lake area					
Precipitation (cm)	10		15	20	30
Runoff (%)	0–1		0	12	8
Evaporation (cm)	203		147	107	96

Note: Modern extreme storms and/or floods are summarized in Enzel (1990, 1992) and Enzel and Wells (1997). Pc—assumed precipitation in the headwater catchment of the San Bernardino Mountains, and Pc + 25% = 25% increase in the annual average precipitation in the headwater catchment.

A. The topographically higher headwater catchment area in the San Bernardino Mountains.

B. The lake and surrounding topographically lower catchments within the Mojave River watershed.

*assumed conditions that are independently varied for each parameter (precipitation, runoff, and evaporation) in the lake area.

CONCLUSIONS

Late Quaternary geologic and hydrologic history of pluvial Lake Mojave

Our reconstruction of the late Quaternary history of Lake Mojave is derived from subsurface and surface geology within Silver Lake basin. This history is shown in Figure 19, illustrating the timing of changes in lake levels and storage capacity, formation and modification of highstand shorelines, and the geomorphic processes operating peripherally to the lake basin. Details on the late Quaternary geomorphic history of the piedmonts surrounding Lake Mojave are provided by Wells et al. (1987), Lancaster and Tchakerian (this volume), McDonald et al. (this volume), and Harvey and Wells (this volume).

From its beginning in the latest Pleistocene, Lake Mojave was the second of two large desert lakes fed by Mojave River stream discharge (Enzel et al., this volume). An abandoned spillway south of present-day Afton Canyon probably provided Lake Mojave with Lake Manix overflow during this period (Wells and Enzel, 1994). Lake Mojave, sustained by the ancestral Mojave River, experienced a significant reduction in total lake volume and surface area in response to the draining of Lake Manix. Meek (1989) estimated the surface area of Lake Manix prior to draining at 215 km^2. Estimates of the surface area and water storage volume of Lake Mojave have been based on subsurface core and drill hole data as well as surficial mapping of shoreline features. Initially, Lake Mojave would have been able to hold ~7 km^3 of water with a surface area of ~290 km^2 at the A-shoreline elevation (Brown, 1989). With the incision of Afton Canyon and draining of Lake Manix, the Mojave River flowed directly into Lake Mojave, and the total lake surface area sustained by the Mojave River may have decreased from ~500 km^2 to ~290 km^2. The decrease in storage capacity within the Silver Lake basin during the latest Quaternary is illustrated in Figure 19. The amount of lake water lost through evaporation would have been reduced drastically, and a much greater portion of water would have overflowed pluvial Lake Mojave draining north toward Death Valley (Fig. 1).

Based upon sedimentation rates, we estimate that Lake Mojave waters first reached Silver Lake basin circa 22.6 ka. In that Soda Lake basin is deeper and closer to the input point of Mojave River water, it is probable that Lake Mojave existed in Soda Lake basin long before reaching Silver Lake basin. Unfortunately, the lack of reliable core data limits our ability to estimate when Lake Mojave first occupied Soda Lake basin. Wells and Enzel (1994) infer that Lake Manix waters spilled into Soda Lake basin prior to any significant downcutting of Afton Canyon (Fig. 1). Incipient lake conditions in Silver Lake basin lasted until ca. 21 ka when the sedimentology of the cores support formation of Lake Mojave phases (and chronozones) with more variable hydrologic conditions (Intermittent Lakes I, II, and III) and those with high lake stands and a paucity of drying events (Lake Mojave I and Lake Mojave II).

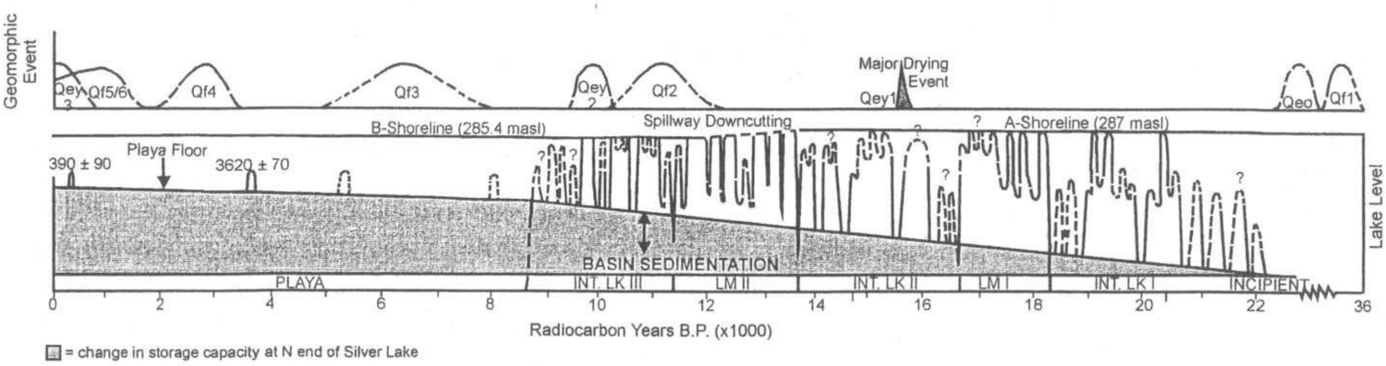


Figure 19. Simplified history of pluvial Lake Mojave fluctuations and piedmont depositional history in the Silver Lake depositional basin during the last 36,000 years showing change in storage capacity in the Silver Lake basin, periods of pluvial lake phases, and major drying events.

With the beginning of Intermittent Lake I, a series of lakes formed and lasted from a few hundred years up to thousands of years in Silver Lake basin between ca. 21.1 ka and 18.4 ka (Figs. 17, 19). During their existence, these lakes experienced no partial drying or total drying events. Circa 18.4 ka, an increased frequency and magnitude of large-scale Mojave River flooding events may have produced more frequent overflow of Lake Manix and the first prolonged lake stands with no drying events (Lake Mojave I) in Silver Lake basin. This stand persisted until ca. 16.6 ka, and only one shoreline feature at 287–288 m (A-shoreline, Tidewater basin; Figures 9, 10) may have formed during this stand.

Transition to a drier climatic regime led to decreased annual discharge of the Mojave River. Reduced frequency of large-magnitude flood events and several drying events in Silver Lake basin occurred between 16.6 ka and 13.7 ka (Intermittent Lake II). During this time, the most extensive, and perhaps prolonged, drought in the history of Lake Mojave occurred (ca. 15.5 ka). Deep subaerial mud cracks formed, and widespread eolian sedimentation occurred on the exposed lake floor and adjoining piedmonts. In addition, ostracodes and diatoms from sediments of Intermittent Lake II and younger phases indicate seasonally colder water conditions coupled with relatively greater turbidity and salinity than existed during Lake Mojave I or older phases (R.M. Forester, 1987, personal commun.; J.P. Bradbury, 1987, personal commun.).

The Lake Mojave II phase began at ca. 13.7 ka. This lake phase lasted ~2300 yr and may have coincided with the final stages of the draining of Lake Manix and increased Mojave River discharge resulting from higher magnitude, more frequent, large-scale flooding events. During this time, Lake Mojave repeatedly reached the elevation of the A-shoreline (~287 m), likely reworking shoreline sediments of Lake Mojave I. Partial drying events were more frequent in Silver Lake basin during Lake Mojave II than Lake Mojave I due to the reduction of storage capacity by sediment infilling and Mojave River delta progradation. Such conditions aided in the modification of older shoreline deposits, increased the frequency of overflow conditions at the spillway, and resulted in downcutting of the spillway to an elevation of ~285.5 m and formation of the B-shoreline. Radiocarbon dated shorelines in the El Capitan beach complex in northern Silver Lake indicate that downcutting of the outlet spillway by 1.5 m probably occurred after 12 ka and before 10 ka. The maximum expansion of shallow lakes in Death Valley occurred during this same period (D. Anderson and Wells, this volume), partially in response to Lake Mojave overflow.

Increasing loss of lake volume due to increased sediment storage combined with decreasing Mojave River discharge resulted in a more sensitive hydrologic system during Intermittent Lake III, which began ~11,400 yr ago. This final phase of Pleistocene Lake Mojave was characterized by steadily deteriorating lake conditions until the eventual transition to the prolonged playa environment of post-Lake Mojave. During the early Holocene, eolian processes reworked near-shore sediment, mantling the beach ridges and other shoreline features (Fig. 19) (McFadden et al., 1992).

SUMMARY POINTS

In summary, we offer the following points as key observations and interpretations on the research approach and results of this study:

1. Late Quaternary sedimentary sequences within the depositional basins associated with Silver Lake and Soda Lake playas can be divided into three chronostratigraphic units: pre-Lake Mojave, Lake Mojave, and post-Lake Mojave.

2. Sediments from the Silver Lake cores yield a complex, but detailed, stratigraphy from which conditions of lake flooding, lake lowering, partial drying, and total drying can be inferred. Based upon the sedimentology of the strata, including layers (three types) and bounding surfaces (12 properties) as well as the vertical and lateral changes in these features, the Lake Mojave chronostratigraphic unit contains two chronozones (Lake Mojave I and Lake Mojave II) that represent high lake stands with few drying or partial drying events and four chronozones (Intermittent Lakes I, II, and III and Incipient Lake) that represent highly variable hydrologic conditions including total lake desiccation.

3. Because the depositional basins of Lake Mojave, especially Silver Lake basin, are shallow and have minimal relief on

the pre-lake surface, sediments in these basins yield a high resolution record.

4. The high resolution record within Silver Lake basin is enhanced by our ability to correlate subsurface stratigraphy with shoreline features and deposits (Fig. 9). Radiocarbon dating is useful for such correlations, but is limited because younger lake events commonly occupied the same shoreline elevations, thus modifying or partially removing older sediments. Event stratigraphic units, such as the 15.5 ka eolian deposit, aid correlation because they were preserved in both surface and subsurface environments.

5. One of the most significant geomorphic events recorded in the cores of the Silver Lake basin indicates a major drought during the Intermittent Lake II phase, during which eolian sediments were deposited directly on the exposed lake floor at 15.5 ka.

6. Using a simplified precipitation-discharge/evaporation model, we infer that the late Pleistocene hydrologic conditions resulting in Lake Mojave overflow at Spillway bay in Silver Lake lie between the following two scenarios (Fig. 18):

- 50% increase in precipitation in the headwater catchment resulting in annual flood events reaching Afton Canyon with discharges three times that of modern extreme floods
- 100% increase in catchment precipitation with a 50% decrease from modern evaporation combined with annual flood events reaching Afton Canyon with discharges two times that of modern extreme floods.

7. The changes that have occurred in Soda Lake and Silver Lake basins due to sedimentation and loss of storage capacity are so profound that if hydrologic conditions change such that another Lake Mojave could form, we believe that the majority of water would pass through the system and flow into Death Valley.

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