LATE QUATERNARY PALEOHYDROLOGY OF THE EASTERN MOJAVE RIVER DRAINAGE, SOUTHERN CALIFORNIA: QUANTITATIVE ASSESSMENT OF THE LATE QUATERNARY HYDROLOGIC CYCLE IN LARGE ARID WATERSHEDS

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ABSTRACT

The combination of historic climatic/hydrologic records and the latest Quaternary record from a climatically sensitive lake basin provides a unique opportunity for determining the variability of climatic regimes and hydrologic responses over the past 20,000 years within the Mojave River watershed, a large arid drainage basin in southern California. During the twentieth century, several short-term lakes formed in the playas at the terminus of the Mojave River in response to precipitation/flood runoff thresholds in the Transverse Ranges, 200 km away from the terminal lakes. Climatic forcing during lake-forming years, especially 1916, 1938, 1969, and 1978, approximate some of the climatic conditions between 22,000 and 8,700 years ago. Climatic conditions of historical lake-building flood events occurred when the position of the subtropical jet stream poured warm moisture-laden air mass, originating from the Pacific Ocean near the Hawaiian Islands, over the Transverse Ranges. Modeling results of these conditions suggests that (1) significant increases in storm frequency and related moisture in the Transverse Ranges, and (2) an order of magnitude increase in frequency of lake-building flood events along the Mojave River are required to maintain lake levels observed in the geologic record in the terminal basins.

Analyses of thirteen cores from pluvial Lake Mojave reveal prolonged latest Pleistocene and short-duration Holocene lake events in response to the increased frequency of large-volume flood events. Data from these cores reveal strong millennia climatic oscillations, expressed as high and low lake stands, which developed in response to large scale, oceanic-atmospheric phenomenon during the latest Quaternary. The last two climatic cycles represent the transition from Pleistocene to Holocene climatic conditions, lasting from 13,700 to 8,700 years ago, and appear to correlate with significant changes in vegetation throughout the Mojave Desert. Shorter-term cycles representing climatic oscillations over centuries occurred approximately 390 and 3,620 years ago, during known times of glacial advances throughout the world. Both of these short- and long-term cycles also appear to correlate to increased oceanic sedimentation rates, landslide failures, erosion and sediment yield, fill-terrace formation and alluvial-fan building within southern California. Future changes in climate and fluctuations in the hydrologic cycle that result in lake-building flood conditions could adversely impact human activity and man-made features within and outside the Mojave River watershed. Enhanced understanding of oceanic-atmospheric conditions producing these hydrologic events will enhance the future performance of the Mojave River hydrologic system.

Key words: floods, paleohydrology, paleoclimatology, lake basins, geology, Mojave River, climatic data

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INTRODUCTION

Statement of Problem and Objectives

Hydrologic forecasting requires the reconstruction of past climatic variations and documentation of the present-day climatic regime (Kutzbach 1983). Climatic variations and their hydrologic responses in the southwestern United States during the late Quaternary (less than 25,000 years) are recorded by numerous features in the physical environment, including lake sediments, landforms, and biotic remains (Barry 1983). Establishing quantitative relations between climate changes and responses of the hydrologic system requires (1) a comprehensive study of as many paleoenvironmental parameters of the system as possible and (2) the occurrence of several paleohydrologic indicators within a limited geographic area and within a relatively closed hydrologic system (Dohrenwend, Wells and McFadden 1986).

One of the most detailed and climatically sensitive records is preserved in ancient Lake Mojave which covered Silver and Soda playas in southern California (figures 1, 2). Currently, the Mojave River drainage basin is a closed hydrologic system covering approximately 9,500 km^2. The Mojave River flows eastward from the Transverse Ranges and terminates at the playas of Soda and Silver Lake over 200 km away from the mountainous source area (figure 2). The terminal area of the Mojave River contains several geologic features which record variations in the hydrologic cycle during the past 20,000 years, including (1) radiocarbon-dated shore features from late Pleistocene and Holocene lakes, (2) lacustrine sediments of pluvial Lake Mojave which contain evidence for large-volume flood events, and (3) flood deposits on adjacent alluvial fan surfaces (Ore and Warren 1971; Wells and Dohrenwend 1985; Wells et al. 1987b; Enzel et al. 1988).

The Mojave River watershed has several well-documented, historic

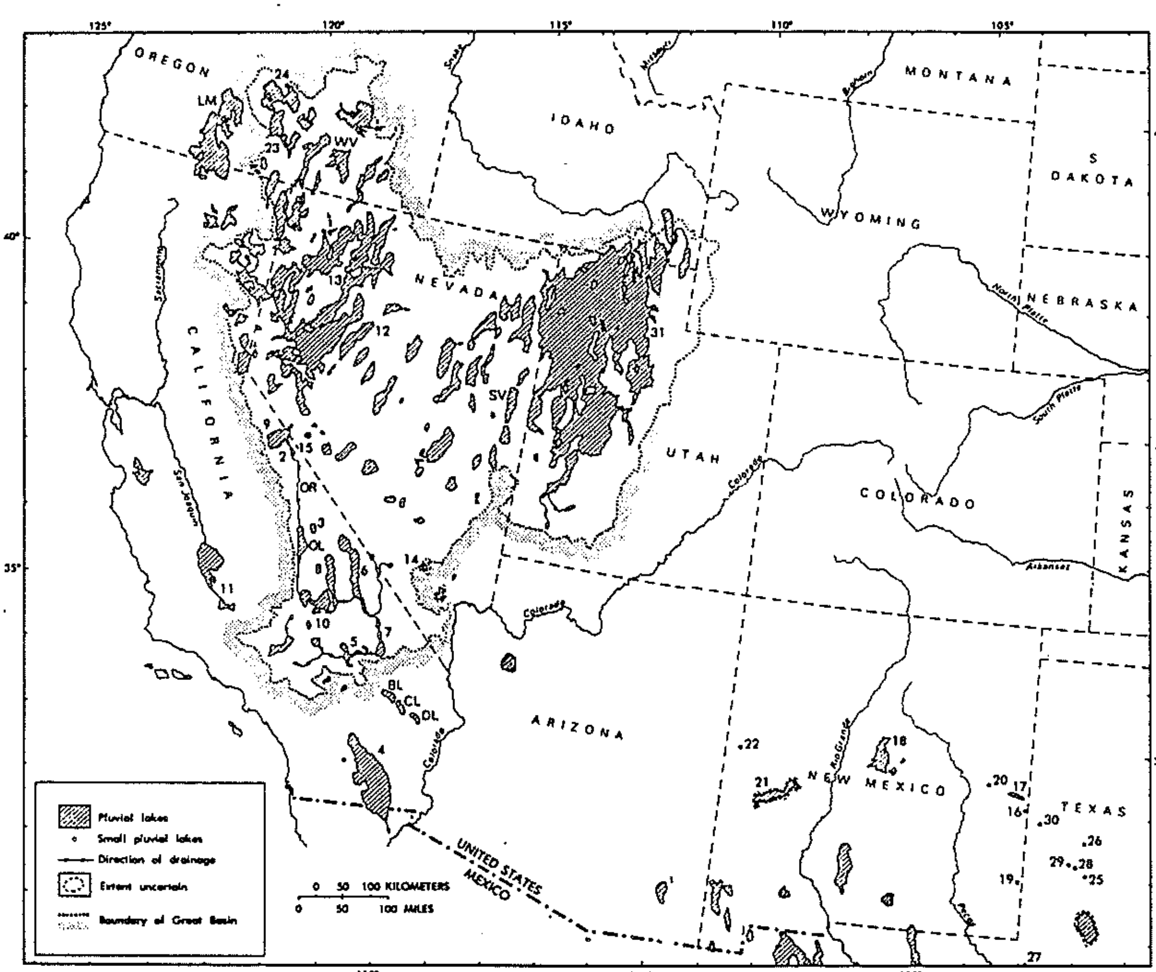


Figure 1. Pleistocene Lakes of the Western United States (modified from Benson and Thompson 1987 and Hawley, pres. com. 1989). Lake Mojave and Lake Manix are indicated by the numbers 7 and 5, respectively.

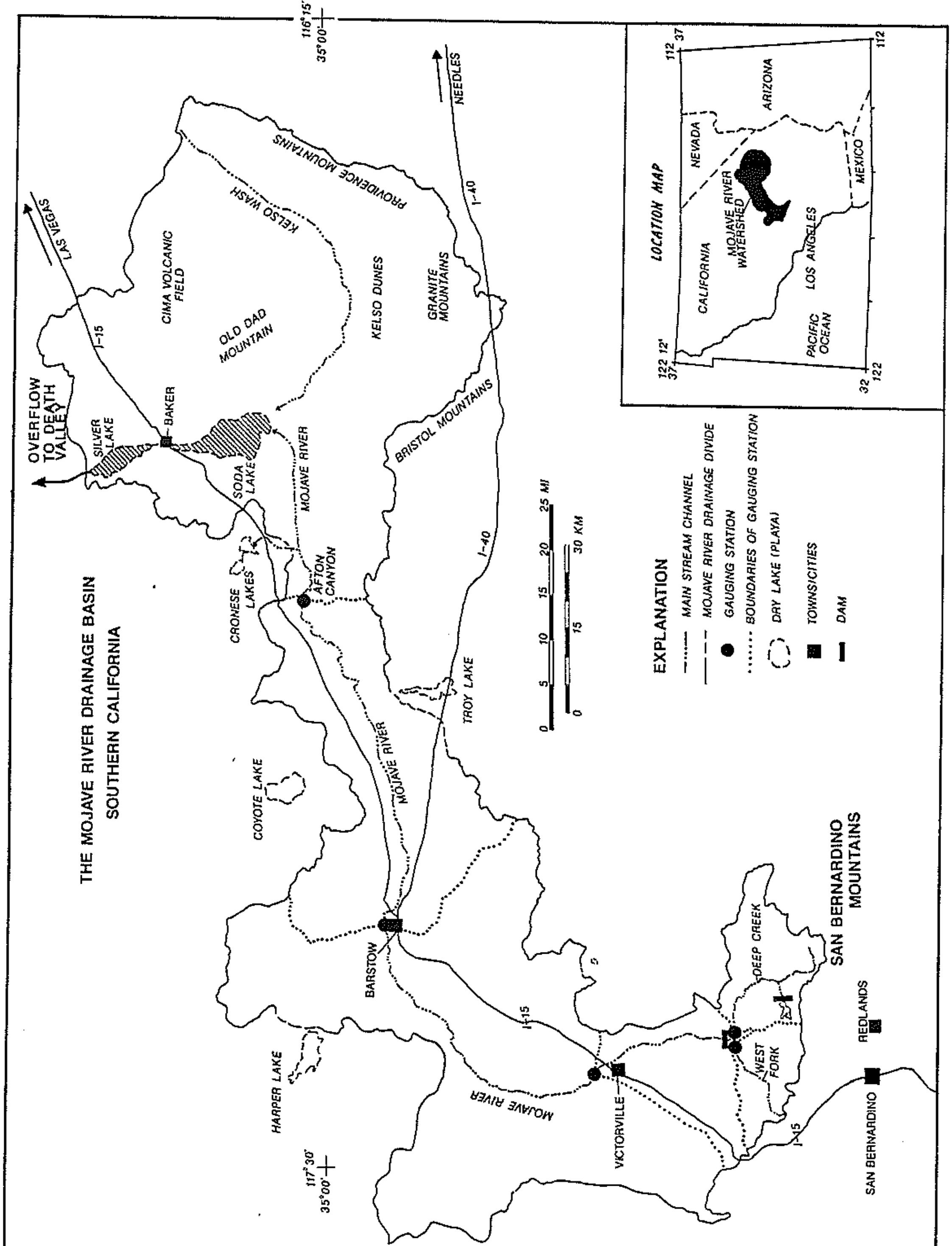


Figure 2. The Mojave River drainage basin, southern California.

hydrologic and climatic data for flood events and associated ephemeral lake-building at the terminus of the Mojave River. During the 20th century, several shallow lakes formed briefly in the terminal playas in response to prolonged precipitation events in the Transverse Ranges. Analyses of cores from Lake Mojave sediments and associated shore features reveal prolonged late Quaternary high- and low-lake stands occurred in response to changes in the frequency of similar large-volume flood events which were associated with climatic conditions in the Transverse Ranges. Only a very small portion of the Transverse Ranges was glaciated during this time (Sharp, Allen and Meier 1959). Glacial meltwaters thus provided only a small fraction, if any, of the discharge into pluvial Lake Mojave relative to rain and snow. This study shows that over a 20,000+ year history, the Mojave River terminus responded directly to variations in precipitation and runoff from a mountainous area which represents only 5% of the total drainage basin area. These responses reveal fluctuations in climate on the scale of centuries to millennia that apparently affected sedimentation and geomorphic processes outside the Mojave River drainage basin. The combination of historic hydrologic record and the climatically sensitive record covering the past 20,000+ years provide a unique setting for elucidating the climatic and hydrologic history of a large arid drainage basin in the southwestern United States and developing a unified model of climatic variability during the latest Quaternary.

This report provides a qualitative and quantitative assessment of the variations in hydrologic regimes (precipitation, evaporation, runoff, and soil-leaching conditions) of a large arid drainage basin in response to climatic changes during the past 20,000+ years. The specific goals of this research are summarized below.

1. The project's primary goal involves the paleohydrologic and

paleolimnologic interpretations of latest Quaternary deposits at selected locations in the terminal regions of the Mojave River drainage basin. These interpretations are based upon sedimentologic, stratigraphic, and paleohydrologic analyses of flood sediments along the Mojave River within Afton Canyon; subsurface lacustrine sediments of Lake Mojave and middle and late Holocene lakes within Silver Lake playa; and shore, alluvial fan, and eolian deposits along the margins surrounding Silver Lake and Soda Lake playas. Interpretations of relative aridity are expressed in terms of loess deposition, dune-building phases, and leaching regimes recorded in soil profiles.

2. The secondary goal is a quantitative assessment of the historic hydrologic responses reacting to short-term climatic fluctuations through the analyses of historic flooding, lake development at Silver Lake playa, and climatic trends within the Mojave River drainage basin. The assessment is based upon archive literature and photography searches, flood hydraulics data, historic recharge by Mojave River runoff, instrumented climatic station data, and global atmospheric circulation patterns.

3. The third goal is the development of a unified hydroclimatic model of which will be used to quantify the magnitude and timing of hydrologic events in response to long- and short-term climatic fluctuations over historic and geologic time scales.

Physical Setting of Study Site

Geologic Setting. The Mojave River drainage basin lies within the Mojave Desert of southern California between latitudes 34°N and 35°30'N and longitude 115°30W and 119°W (figure 3). Ninety-five percent of the Mojave River drainage basin is situated in the Basin and Range Province of southern

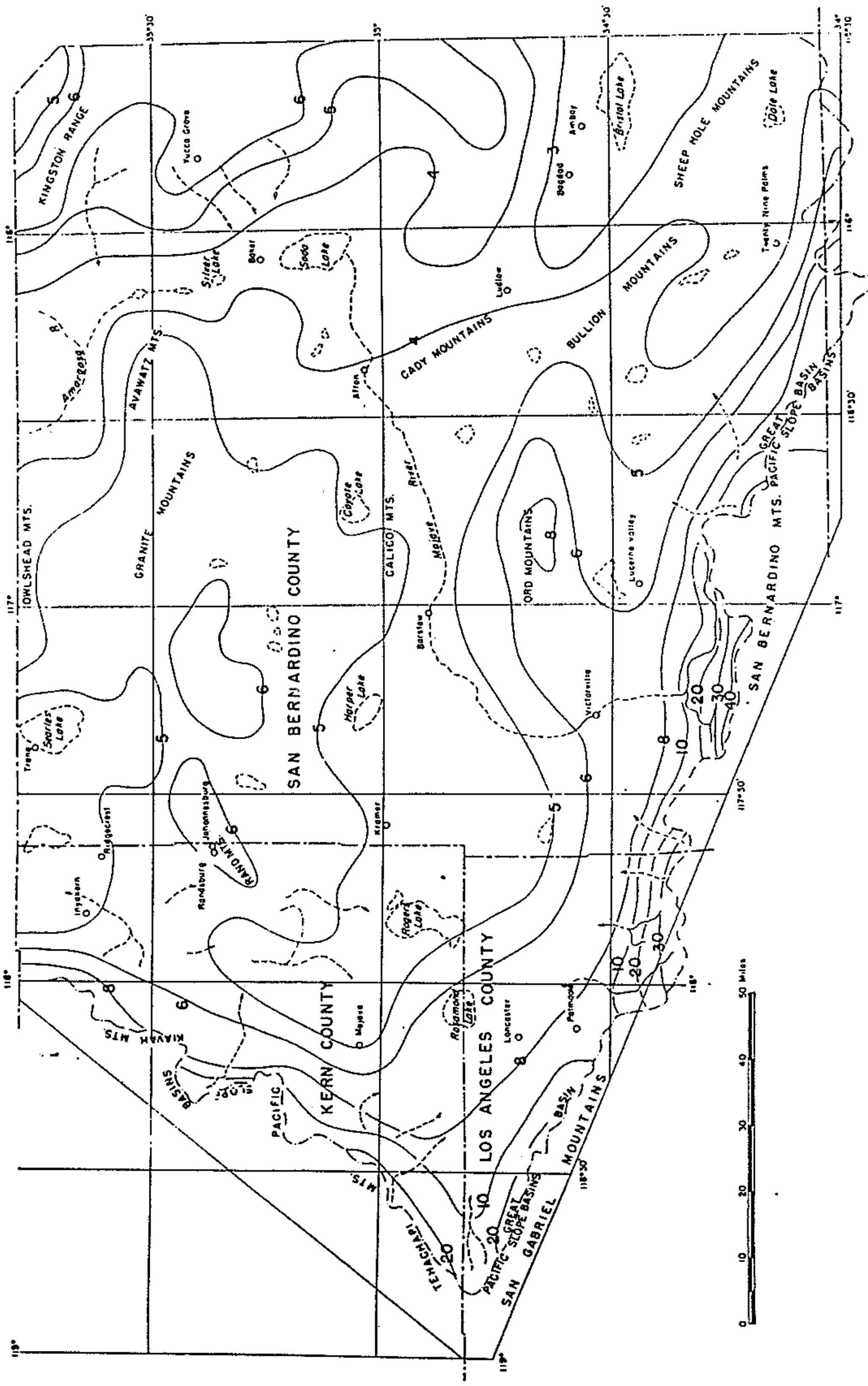


Figure 3. Spatial variations in annual precipitation over the Mojave River drainage basin (from Troxel and Hoffman 1954).

California and is bounded on the north by the Great Basin and Avawatz mountains, on the west and northwest by the Sierra Nevadas, on the south by the San Bernardino and San Gabriel mountains of the Transverse Ranges, and on the south and southeast by the Ord, Bullion, Bristol, and Providence mountains. The Basin and Range Province trends is characterized by fault-block mountains and valleys (Hunt 1974; Dokka et al. 1988). The headwaters of the Mojave River, the remaining 5% of the drainage basin, is situated within the Transverse Ranges of the Pacific Border Province (Hunt 1974). These structurally controlled ranges trend eastward to southeastward and include the San Gabriel and San Bernardino mountains which reach altitudes exceeding 3,048 m. The main stem of the Mojave River drains the San Bernardino mountains, and drainage from the San Gabriel mountains is internal and does not contribute to main stem flow on the Mojave River.

The Mojave River traverses the tectonic region known at the Mojave Desert Block which is characterized by northwest-southeast oriented right-lateral strike slip faults (figure 4). The Mojave Desert Block is structurally higher than the Great Basin and is separated from it by the Garlock fault, a left-lateral transverse fault, forming a boundary of more than 161 km between the two regions (Hunt 1974; Dokka et al. 1988). The western boundary of the Mojave Desert Block is the San Andreas fault which truncates the Garlock fault and separates the San Gabriel and San Bernardino mountains with a sense of right-lateral slip movement. The eastern boundary of the Mojave Desert Block is less well defined. Skirvin and Wells (1989) have suggested that the right-lateral faults of the Old Dad mountains form the eastern boundary and this may represent the southern extension of the Death Valley fault zone (Brady 1987) (figure 4). Within the Mojave Desert Block the northwest-trending faulting has occurred as recent as the Holocene, and has produced

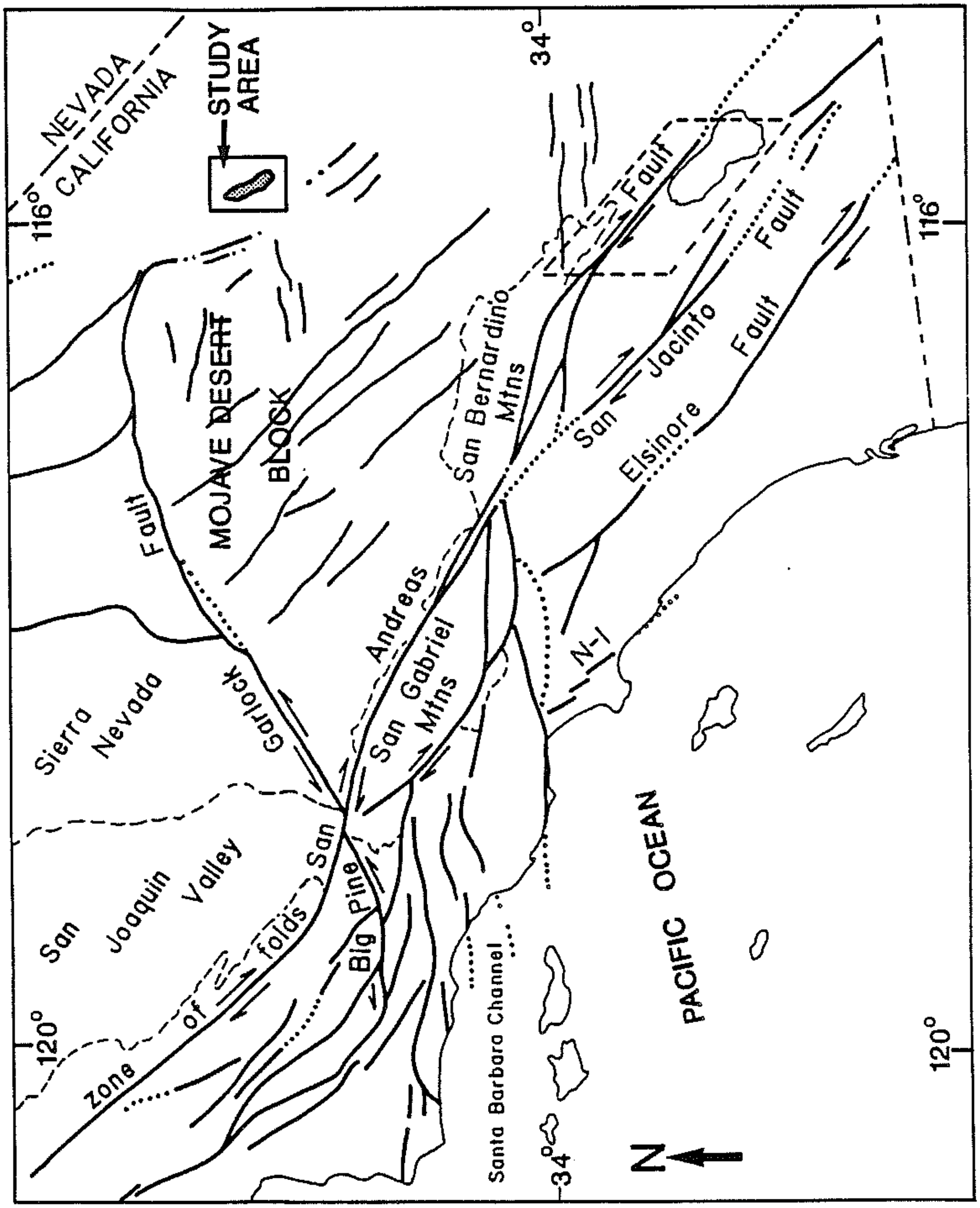


Figure 4. Generalized Tectonic map of southern California (modified from Sylvester 1988 and Garfunkel 1974).

mountains of irregular outline in the Mojave Desert region (Hunt 1974). Near the Baker, California area, the Death Valley fault zone separates the irregular metamorphic, granitic, and volcanic mountains on the west from the well-defined Paleozoic sedimentary rock of the east.

The rock types found in the Mojave Desert Range from Precambrian gneisses and other metamorphics to Mesozoic igneous rocks and Cenozoic volcanics (Sharp 1976). Early Precambrian metamorphic rocks are overlain by Late Precambrian sedimentary rocks (sandstone, shale, conglomerates, and carbonates). Coarse-grained Mesozoic granites occur extensively in the region. Warping and faulting during the Cenozoic produced local basins into which were shed thousands of feet of detritus. In addition, volcanic activity helped fill some of the basins with volcanic debris (Sharp 1976).

Climate. California experiences a warm, dry summer and a winter precipitation maximum which is 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, the San Bernardino Mountains, mean annual precipitation exceeds 1,000 mm/year (forty inches) whereas 90% of the drainage area which contributes runoff to Silver Lake playa typically receives 125 mm or less (figure 3). The steep precipitation gradient is emphasized in the headwater region, upstream of the confluence of Deep Creek and West Fork (The Forks) which receives 300 to 400 mm of precipitation (figures 2, 3). The Victorville area, which is approximately 25 km downstream from The Forks, receives 125 to 150 mm of precipitation a year. In the terminal playas, approximately 200 km away from The Forks, mean annual precipitation is less than 100 mm which is an order of magnitude less than the headwaters (U.S.

Department of Commerce different years; Troxel and Hofman 1954; Department of Water Resources 1980; Mojave River Agency 1985).

The seasonality of precipitation changes from the headwaters to the terminal playas. Within the Victorville area, the precipitation is during the winter season. From Barstow downstream, there are two seasons of precipitation; the primary season is the winter months (principally February) and a secondary one during the summer months (principally August) (Pyke 1972). Williams (1979) demonstrated that the northernmost boundary of summer dominant rainfall (i.e., areas receiving more than half the precipitation during the summer season) lies a few kilometers east of Silver and Soda playas. Precipitation during the winter season usually occurs during storms that cover larger portions of the Mojave River watershed than summer storms.

The precipitation station at Squirrel Inn within the San Bernardino Mountains received one of the largest daily intensities of precipitation recorded in the southern California region: 427 mm on January 17, 1916 (Goodridge 1986). All the extreme precipitation events (greater than 250 mm/day) recorded in southern California occurred in high elevations in the San Gabriel and San Bernardino mountains during the winter season of the following years: 1891, 1910, 1916, 1922, 1927, 1938, 1943, 1965, 1966, 1969, 1978, and 1980 (Goodridge 1986). These extreme events are responsible for the high mean annual precipitation in the Mojave River headwaters which is positively skewed (0.83 Pearson first skewness coefficient). The range of the annual precipitation in the headwater region near Squirrel Inn is 416 to 2,030 mm, and the mean annual precipitation is 1,027 mm for a sixty-six year period (standard deviation of 395 mm and median of 919 mm). Table 1 shows the monthly precipitation during two years of extreme precipitation, 1969 and 1978, at three stations in the upper Mojave River watershed. The majority of

TABLE 1

Monthly precipitation (mm) in the Mojave River watershed in water years 1969 and 1978. (Data from U.S. Environmental Services Administration, 1969; and National Oceanic and Atmospheric Administration, 1978.)

Month		Lake Arrowhead 1587 m	Victorville 871 m	Barstow 658 m
		1969		
October		10	0.1	5
November		23	7	8
December		100	6	3
January		1166	48	25
February		913	100	56
March		136	5	6
April		73	6	9
May		68	12	12
June		Trace	15	2
July		5	15	21
August		Trace	0	1
September		1	2	17
1969	Total	2495	217	167
December-April 1969	Total	2388	164	100
October		Trace	0	0.5
November		27	2	0.8
December		372	45	49
January		430	49	44
February		543	80	51
March		701	126	56
April		191	15	11

TABLE 1 (continued)

May		8	2	2
June		0	0	0
July		Trace	0	Trace
August		9	3	5
September		86	20	8
1978	Total	2363	343	226
December-April 1978	Total	2237	316	211

By using cumulative departure from mean precipitation in Squirrel Inn, Victorville, and Barstow, Hardt (1971), Ruchelwicz, Lin and Hatai (1978), and Mojave River Agency (1985) showed periods (more than one year) with a large excess of precipitation in the mid 1910s to early 1920s (1914 - 1922), late 1930 to mid 1940s (1937 - 1946), late 1960 (1965 - 1969), and late 1970s till early 1980s (1978 - 1983).

precipitation during these extreme events occurred during the winter months for all three stations.

Evaporation dominates over precipitation for the majority of the Mojave River drainage basin. Department of Water Resources (1967) estimated 200 to 250 mm/year of the annual precipitation is used by vegetation or lost by evaporation in the upper Mojave River area (between Victorville and Hesperia). Similar conditions exist downstream to the terminal playas, thus the majority of the precipitation is lost and does not contribute to stream flow and alluvial aquifer recharge along the Mojave River. The headwaters upstream from Hesperia, which receives more than 200 mm/year of precipitation, serves as the major area for contributing stream flow and ground-water recharge for the Mojave River watershed (Mojave River Agency 1985). Blaney's (1957) study of lake and pan evaporation at Silver Lake during the 1938 flood event provides critical data on the lower Mojave River watershed (figure 5). Coupled with a study of the headwater region by Crippen (1965), these data indicate the potential evapotranspiration in the lower regions of the Mojave River watershed are nearly twice the values in the headwater regions, 2,000 mm and 1,000 mm, respectively.

Vegetation. Present-day vegetation of the Mojave Desert is classified as Mojave Desert Scrub (Brown, Lowe and Pase 1980). It includes saltbush and creosote bush scrub at the lower elevations and blackbush (or black brush) scrub, shadscale scrub, and Joshua tree woodland at the higher, more northern elevations. There is a low diversity of perennial plants--the landscape is usually dominated by creosote and maybe one or two other plants (often *Larrea* or *Abrosia dumosa*). In fact, up to 70% of the Mojave is covered by this type of vegetation (Brown, Lowe and Pase 1980).

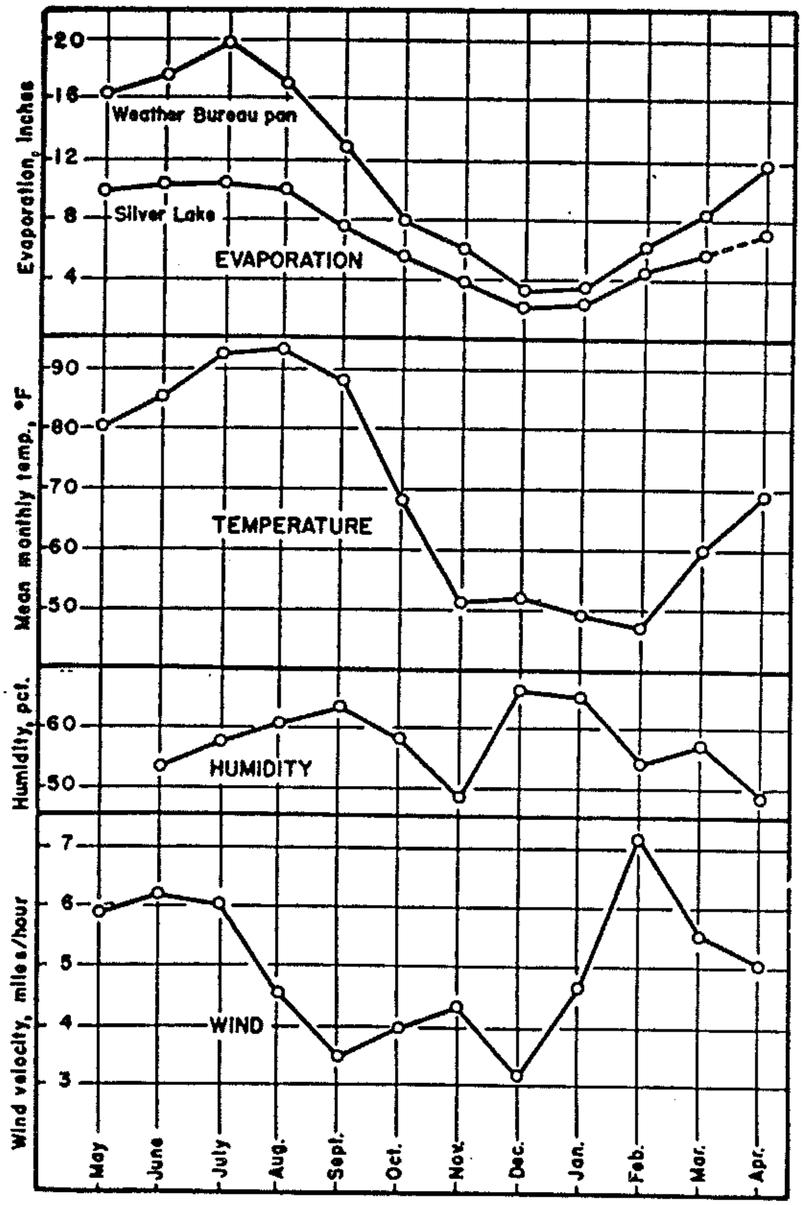


Figure 5. Monthly evaporation and meteorological data obtained from Blaney's (1957) study of the 1938 Mojave River flood and subsequent lake stand at Silver Lake.

Paleoenvironmental Conditions. Within the Mojave River drainage basin the climatic regime during the latest Pleistocene and early Holocene was considerably different from the modern Mediterranean regime and has changed significantly over longer geologic time periods. Vegetation during the Miocene (23.7 to 5.3 million years ago) included sclerophyllus oak-scrub woodland and subtropic thorn (Axelrod 1980). Seventeen million years ago, the Tehachapi flora included Arbutus, Clethra, Persea, Quercus, Sabal, and Umbellularia, members of the oak-pinyon-cypress woodland classification (Axelrod 1980). Dry tropic scrub, evidenced by the presence of Acacia, Brahea, Celtis, Dodonaea, Euphorbia, Eysenhardtia, Ficus, Pithecellobium, Prosopis, and Randia, dominated those portions of the basin that were exposed. It is postulated from this evidence that precipitation during the Miocene did not exceed 635 mm (25 inches) (Axelrod 1980). Indications that rainfall was probably about 457-508 mm (18 to 20 inches) are found in the twelve million year old Ricardo flora which includes oak, pinyon, cypress, palm (possibly Sabal), buckbush (Ceanothus), and dry tropic scrub taxa (Acacia, Lycium) Axelrod 1980). A mixed conifer forest is indicated to have existed during the Pliocene, three and half to two million years ago, north of the Mojave Desert (Axelrod 1980).

Paleoenvironmental data from analysis of plant macrofossil remains in packrat (Neotoma) middens provide perhaps the most detailed information concerning the regional timing and nature of climatic changes during the late Quaternary. These studies demonstrate that a juniper-pinyon-Joshua tree woodland was present throughout the Mojave Desert between 30,000 and 11,000 years B.P. (before present) (King 1976; Van Devender and Spaulding 1979). This woodland was present at elevations as low as 320 m where desert scrub community of xerophytic vegetation is now stable. After 11,000 to 10,000 years B.P., the pinyon and Joshua tree components of the woodland died out, but juniper persisted at elevations as low as 330 m until 8,000 years B.P. (Van Devender 1973, 1977; King 1976). Spaulding (1982) has also shown that elements of the desert scrub were present as high as 990 m after 15,000 years B.P., but most evidence indicates that this complex mosaic of woodland and desert scrub communities was not completely eliminated from elevations below 800 to 900 m until the middle Holocene.

The plant macrofossil record suggests that the latest Pleistocene climate in the desert areas south of latitude 36°N was characterized by milder, moister winters and cooler, drier summers than the present climate (Spaulding 1982; Spaulding, Leopold and Van Devender 1983; Van Devender and Spaulding 1979). Galloway (1970, 1983), however, argues that these data do not rule out a significantly cooler and drier climate in this region. From these studies it can be concluded that (1) vegetation change in this region was time transgressive, implying transitional change in climate from the latest Pleistocene to the Holocene and (2) the effective moisture of the late Pleistocene and early Holocene climatic regimes was significantly greater than the effective moisture of the modern climate.

Greater effective moisture in the latest Pleistocene and early Holocene time is supported by the pluvial-lake chronologies in the southwestern United States (Smith and Street-Perrott 1983). Several brief latest Pleistocene pluvial lake stands, lagging 4,000 to 7,000 years behind the glacial maximum, occurred in pluvial lakes fed from either glacial and/or unglaciated source areas (Smith and Street-Perrott 1983). Several lake basins fed by nonglaciated source areas also contained early-to-middle Holocene lakes (Bachhuber 1982; Fleishhauer and Stone 1982). Data collected during the present study of Lake Mojave support these observations throughout the region and are also consistent with the inferences drawn from the paleobotanical evidence which imply a time-transgressive climatic change from the Pleistocene to Holocene.

SUMMARY OF METHODOLOGY

Hydrologic Analyses

Analyses of the hydrologic records are divided into three categories: systematic, historical, and paleohydrologic. The significance of these types of studies in flood frequency analysis are shown in earlier reports (Benson 1950; Gerard and Karpuck 1979; Water Resources Council 1981). Recent studies emphasize the importance of combining historical and paleohydrological records and present new techniques to use such data (Stedinger and Cohn 1986; Baker and Pickup 1987; Hirsch and Stedinger 1987; Lane 1987; National Research Council, 1988; Stedinger, Therivel and Baker 1988; Webb, O'Connor and Baker 1988). Historical hydrologic studies of large flood events and ephemeral lake stands at the terminus of the Mojave River utilized archival records, and the relations between climatic patterns and lake stands were based on these historical documents. Drs. Peter Lagasse and James Schall of Resource Consultants, Inc. and Dr. Richard Heggen of the University of New Mexico provided critical information and discussions on the various methodologies used in the hydrologic analyses part of the study.

Historical Records. Our approach involved the use of all previous hydrologic data from numerous state and federal agencies and extensive archival documents (i.e., reports, maps, photographs, film, newspapers). The search involved both positive and negative historical evidence for flood/lake events. Positive evidence is defined as a direct observation involving written descriptions, maps, photographs, aerial photographs and films showing a flood event on the Mojave River or a lake at the terminus. Negative evidence is defined as a lack of mention of a flood/lake event in the Mojave River drainage basin by travelers, government expedition members, and early residents in the lower Mojave River valley, as summarized, for example, by Antevs (1937). Both types of evidence were rare for the period prior to the late 1890s. Searches of archives were conducted for those years when travelers reported large storms and floods in areas of California outside of the Mojave River drainage basin (Lynch 1931; Troxel et al. 1942; San Bernardino County Flood Control Distrist 1972). Archive searches were conducted for specific years when large discharges were observed along the Mojave River between Barstow and the terminal lakes. Based upon these searches, there were only three years in this century (1943, 1958, and 1966-67) century during which no evidence exists for lake development although large storms and floods existed within the Mojave River drainage basin.

Systematic Records. The systematic hydrologic records consist of average daily discharge for five U.S. Geological Survey gauging stations on the Mojave River. These stations include those listed in table 2 and shown on figure 2. Other gauging stations existed along the Mojave but for shorter time periods than those illustrated above. Monthly discharge data for Deep Creek, West Fork, and Victorville are available for the early part of the century from the Lake Arrowhead Company records (summarized in Conkling et al. 1934). Annual discharge measurements and estimations of annual discharges exist in several publications (McClure, Sourwine and Tait 1918; Blaney and Ewing 1935; Conkling et al. 1934; U.S. Army Corps of Engineers 1956; 1966, 1968; State of California 1967; Hardt 1969, 1971; Buono and Lang 1980; Ruchelwicz, Lin and Hatai 1978; Mojave River Agency 1985).

Peak discharges for the stations given in table 2 were obtained from the U.S. Geological Survey data base. A recent summary of the peak discharges in the upper Mojave River is in a report by the U.S. Army Corps of Engineers

TABLE 2

Major Gauging Stations Along the Mojave River

STATION NUMBER	STATION NAME	PERIOD OF RECORD
10260500	Deep Creek Near Hesperia	1905-22, 1930-85
10261000	West Fork of Mojave River near Hesperia	1904-22, 1929-71, 1974-85
10261500	Mojave River at Lower Narrows	1899-06, 1930-85
10262500	Mojave River at Barstow	1931-85
10263000	Mojave River at Afton near Victorville	1930-32 (partially)

(1986) which also contains estimations of the combined peak discharges a short distance downstream from the confluence of the West Fork and Deep Creek, The Forks. In 1956 the USACE estimated the largest historical peak discharges at The Forks since the late 1950s. These data were incorporated into this study.

Flood Frequency Analyses. Flood frequency analyses for the gauging stations of the Mojave River (table 2) are carried out according to procedures described in Bulletin 17B of the Water Resources Council (1981), including procedures for historical and missing data. Flood frequency analyses was not conducted for the Barstow station where more than 30% of the years had zero discharge. Various plotting position methods were compared (Cunnane 1978; Hirsch and Stedinger 1987). Log Pearson 3 distribution was applied to the data and was either visually tested or tested with the procedure described by Filliben (1975).

Climatic and Atmospheric Circulation Analyses. Atmospheric circulation and climatic data was obtained from Dr. R. Balling, Jr., Arizona State Climatologist, and from D. Cayan, Scripps Institute of Oceanography. Dr. Balling and Mr. Cayan provided critical information and discussions concerning these data bases and associated interpretations.

Atmospheric circulation patterns associated with the years of large flood and lake events at the terminus of the Mojave River were analyzed according to procedures given by D. Cayan. The data base for this study is available for the period 1899 to present from the National Ocean and Atmosphere Administration and Scripps Institute of Oceanography. The dates for documented lake-building events at the terminus of the Mojave River were taken from the archive study and classified as an "event." A case is defined as the average monthly North Pacific sea level pressure for the month in which an "event" occurred. These conditions were plotted for the intersection point of every five degrees on a grid of 60°-20°N and 130°-110°W. A composite of cases is the average monthly North Pacific sea level pressure at the grid for all cases. An anomaly is defined as the departure from the mean sea level pressure in millibars at each of the grid point. In addition, the 700 mb height maps were modified for specific cases from the literature, and satellite radar imagery was used to locate the high cloud patterns during the "events." These cloud patterns approximate the location of the subtropical jet stream.

Geologic Field Methods

Surficial Mapping. Shoreline features in Silver and Soda Lake playas were mapped initially using aerial photographs (scale = 1:24,000 and 1:11,300). Many of these shoreline features were then mapped in the field using a Wild brand laser theodolite and distomat surveying instrument tied into local U.S. Geological Survey benchmarks to determine exact elevations and distances. Because of the excellent preservation of lacustrine-geomorphic interrelationships in the northern end of Silver Lake playa detailed mapping of the beach ridge complexes, alluvial fan units, wavecut features, and spillway characteristics was undertaken (scale of 1 in = 50 m) in this location (plate 1 and 2). Alluvial fan units were mapped based on their relative soil development, preservation of original bar and swale topography, pavement characteristics, varnish characteristics and stratigraphic relationships as described earlier by Wells and others (1987) (table 3). Individual beach ridge units were distinguished based upon stratigraphic relationships, height above playa surface, correlation with various wave-cut

TABLE 3

Summary of alluvial fan soil-geomorphic characteristics in the Silver Lake piedmont (after Wells, McFadden and Dohrenwend 1987).

Alluvial Unit	Inferred Age	Mean Particle Size[1]	Depositional Bar Relief[2]		Maximum[3] Diameter of Largest Surface Clast (cm)	Varnish on Clasts[4] %	Reddening of clast undersides	
			mean	range			% Reddened	Maximum red color
Qf6	modern channel	2.4 ± 1.2	n.m.[5]	n.m.	14.3 ± 9.8	3 ± 10	30.0	7.5YR 6/8
Qf5	latest Holocene	5.8 ± 3.4	0.25	0.11 - 0.41	13.0 ± 5.3	12 ± 18	32.0	7.5YR 6/8
Qf4	middle to late Holocene	4.4 ± 3.8	0.22	0.11 - 0.37	11.4 ± 3.2	22 ± 19	68.0	5YR 5/8
Qf3	early to middle Holocene	2.6 ± 1.1	n.m.	n.m.	8.5 ± 1.9	38 ± 28	97.8	5YR 5/8
Qf2	early Holocene	2.7 ± 1.8	0.12	0.06 - 0.27	12.2 ± 3.5	35 ± 22	76.0	5YR 6/8
Qf1	Late Pleistocene	2.8 ± 2.5	0.08	0.06 - 0.09	5.9 ± 1.7	60 ± 30	60.3	5YR 6/8

1 Value determined on basis of measurement of the intermediate diameter of the clasts (minimum diameter considered = 8 mm) collected every 1 m over 50 m linear transect (Qf6, Qf5) or in square grides on walls of trenches excavated in deposits (Qf4, Qf3, Qf2, Qf1).

2 Constructional relief measured between top of depositional (longitudinal) bar and adjacent swale (∿ 10 measurements/unit).

3 Value determined on basis of measurement of the intermediate diameter of the largest clasts collected every meter over 50 m surface transects.

4 Visual estimate if percentage of clast covered by sufficient varnish to obscure clast lithology.

5 Not measured.

features and lithology of beach ridge material. In addition, radiocarbon dating of pelecypod shells (Anadonta Californiesis) and lithoid tufa (table 4) combined with relative degree of soil development (McFadden et al. 1988) and microfaunal distributions Forrester and Bradbury, pers. com. 1987 and 1988) provided useful information on dating and correlating individual beach ridges with subsurface lacustrine units.

Drilling Procedures. Drilling of the lake sediments was undertaken using two methods. Cores Sil-A, Sil-B, Sil-C, Sil-D, Sil-E, Sil-G, Sil-L, Sil-M, and Sil-N were drilled using the piston coring rig of the University of New Mexico. Core Sil-M was drilled using a 2.0 in core barrel, all other piston cores were drilled using a 1.5 in core barrel. Cores Sil-F, Sil-H, Sil-I, and Sil-J were drilled by Kleinfelder and Associates of Sacramento, California with a truck-mounted, continuous auger coring device using a 5 ft. long split-spoon sampler. The core barrel diameter was 2.25 in. Recovery for the above thirteen cores was 95% or greater for each hole. Occasional problems arose in the auger drilled holes from highly plastic lacustrine clays adhering to the sides of the core barrel. Some disturbance of cores occurred in these instances. In addition to the above coring operations, lacustrine sediments were studied in three excavated trenches: two in East Cronese Lake and a third near drilling site Sil-M in Silver Lake (figure 2, 6).

Laboratory Methods

Core logging. Preliminary logging of hole Sil-I (figure 6) indicated three distinct types of sedimentological features preserved in sublaminated to very locally laminated green, clay-sized lacustrine sediments of pluvial Lake Mojave. Thin, horizons of coarser silt-rich material, thin carbonate and

TABLE 4

Summary of radiocarbon dates of Lake Mojave shoreline features and lake sediments.

Location	Dating Method	Elevation of Sample	Type of Material Dated	Radiocarbon Age (yrs. B.P.) and Sample Number	Study
Silver Lake fan-delta Depth of 15-17 cm	C-14	~278 msl	organic carbon in sediments	390 ± 90 Beta-25634	W
Silver Lake Sil-M core Depth of 55-59 cm	AMS	~277.5 msl	organic carbon in sediments	3,620 ± 70 Beta-25341	W
Silver Lake Sil-M core Depth of 3.06-3.09 m	AMS	~274.9 msl	organic carbon in sediments	9,330 ± 95 Beta-24342	W
Silver Lake Sil-I core Depth of 6.0 m	AMS	270.65 msl	organic carbon in sediments	14,200 ± 145 Beta-25339	W
Silver Lake Sil-I core Depth of 8.9 m	AMS	267.75 msl	organic carbon in sediments	14,660 ± 260 Beta-21800	W
Silver Lake Sil-I core Depth of 15.95 m	AMS	260.70 msl	organic carbon in sediments	20,320 ± 740 Beta-21801	W
Beach Ridge V El Capitan Complex	C-14	282.5 msl	whole pelecypod shells	9,390 ± 140 Beta-29552	M
Beach Ridge III El Capitan Complex	C-14	286-286.5 msl	whole pelecypod shells	10,330 ± 120 Beta-21200	W
Beach Ridge-Soda Lake Elephant Ridge Complex	C-14	~285 msl	whole pelecypod shells	12,020 ± 130 Beta-21199	W
Beach Ridge I El Capitan Complex	C-14	287 msl	pelecypod shell fragments	13,640 ± 120 Beta-26456	B
Tidewater Basin Beach Ridge II-Silver Lake	C-14	282 msl	whole pelecypod shells	16,270 ± 310 Beta-29553	B
Top of Gravel Pit-Silver Lake	C-14	Unit No. 10	tufa coated gravel	9,160 ± 400 LJ-935	H
"	C-14	Unit No. 10	tufa coated gravel	8,350 ± 300 LJ-929	H
"	C-14	Unit No. 8	pelecypod shells	10,580 ± 100 Y-1593	O/W

TABLE 4 (continued)

"	C-14	Unit No. 7	tufa coated gravel	9,990 ± 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 coated 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 1-444	H
"	C-14	Unit Nos. 6,7,8 Comb.	pelecypod shells	9,640 ± 240 LJ-200	H
"	C-14	Unit No. 5	tufa coated gravel	11,320 ± 120 Y-1590	O/W
"	C-14	Unit No. 5	tufa coated 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 coated gravel	13,190 ± 500 LJ-931	H
Bottom of Gravel Pit-Silver Lake	C-14	Unit No. 1	tufa coated gravel	13,040 ± 120 Y-1588	O/W
Beach Ridge V (?) El Capitan Complex	C-14	283.2 m depth=1 m?	pelecypod shells	9,340 ± 140 Y-2407	O/W
Beach Ridge I El Capitan Complex	C-14	288.2 m depth=0.3 m	pelecypod fragments	12,450 ± 160 Y-2408	O/W
North-Central Silver Lake-Spillway Bay	C-14	avg=285.7 m depth=0-.6 m	pelecypod fragments	13,620 ± 100 Y-1585	O/W
Tidewater Basin Beach Ridge II	C-14	284.1 m	pelecypod shells	14,550 ± 140 Y-1586	O/W

TABLE 4 (continued)

Tidewater Basin Beach Ridge II	C-14	283.5 m	pelecypod shells	15,350 ± 240 Y-1587	O/W
Bench Mark Bay	C-14	286.5 m	tufa coated gravel	9,960 ± 200 Y-2410	O/W
Bench Mark Bay-Below Stone Artifacts	C-14	281.9 m depth=.3-.5 m	pelecypod fragments	10,270 ± 160 Y-2406	O/W
Northwest Silver Lake El Capitan BR II?	C-14	~287 m	pelecypod shells	11,860 ± 95 DIC-2824	W
Northern Silver Lake High Shoreline El Capitan BR II ?	C-14	~287 m	pelecypod shells	11,970 ± 160 Beta-written comm.	RW
A-Shoreline-Northwest Silver Lake	C-14	~286.5 m	tufa	10,850 ± 75 DIC-2823	W

W = Wells et al. 1989

O/W = Ore and Warren 1971

M = McFadden et al. (in preparation)

B = Brown, M.S. (in preparation)

H = Hubbs et al. 1965

RW = Weldon 1982

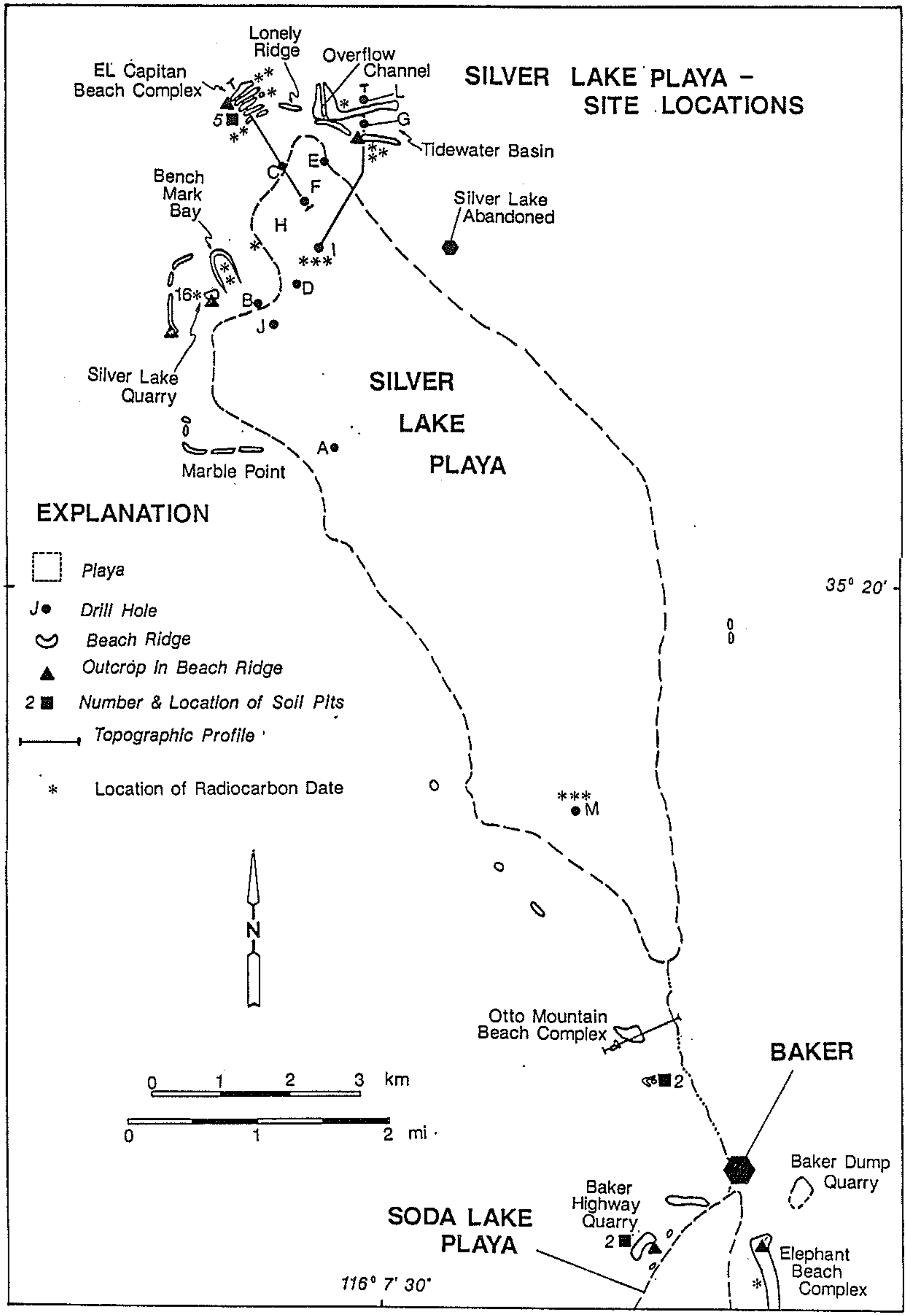


Figure 6. Simplified diagram of Silver Lake, California showing major shoreline features and core location sites investigated during this study. Number and location of radiocarbon dates is indicated by an *.

sulphate-rich evaporite bands and desiccation cracks indicate relative lake fluctuations (i.e., drying events). Based on this preliminary core logging, a systematic program was developed to characterize and describe in detail these events (table 5). Detailed core logging was completed on a scale of 1:1 for each of the thirteen cores except for Sil-M, which was logged at a scale of 2:1. Microscopic examination of many of the core segments was also undertaken to characterize various faunal distributions and the mineralogy of coarser grained sediment units.

Faunal Analysis. Twelve samples were collected from various locations in the Sil-H and Sil-1 cores (figure 6). These samples were treated with a dispersing agent and then agitated on a shaker table to deflocculate clay sediments. The samples were then sieved using Tyler screens, and the greater than 150 mm size fraction was analyzed. Each of the samples contained ostracodes and other organic residue. Based on this observation, a more extensive sampling program was undertaken. Over 100 samples were collected from the four auger holes and several of the piston drilled cores (Sil-E, Sil-G, Sil-M). In addition, about twenty additional samples were collected from Soda Lake Core 1 drilled by Meussig et al. (1957). These samples were then sent to the U.S. Geological Survey in Denver for faunal analysis of ostracodes, diatoms and pollen by R. Forrester, J. Platt Bradbury, and R. Thompson, respectively.

Isotopic Dating Techniques. A total of six samples were collected from lacustrine subsurface units in cores and trenches for isotopic age dating (table 4). Initially, five samples were analyzed for organic carbon content using standard laboratory techniques in the Chemistry Lab within the Geology

TABLE 5

EVENTS RECORDED IN LAKE MOJAVE CORES

Event Number	Type of flooding, partial lowering, or total drying event recorded in Silver Lake Cores
1	Darker 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 silt
5	Fine sand overlying clay
6A	Horizontal laminations of $CaCO_3$
6B	Horizontally aligned blebs or discontinuous laminations of $CaCO_3$
6C	Disseminated $CaCO_3$
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	Event consisting of diorite, carbonate, and granite find sand- to silt-sized clasts (interpreted as being local runoff/ turbidite event)
(D)	The letter (D) when used as a postscript to any of the above numbers indicates a drying event (mudcrack) preserved directly below the given flooding event
(S?)	The letter (S?) when used as a postscript to any of the above numbers indicates a mudcrack possibly caused by syneresis processes

Department at the University of New Mexico. Due to the very low organic carbon content of the sediments accelerator mass spectrometry (AMS), radiocarbon dating procedures were required for five of the six samples. Dating was conducted by Beta Analytic, Inc. of Coral Gables, Florida. Approximately 50 grams of lake sediments were collected and dated from each of these localities (table 4).

Pelecypod shells (Anadonta californiesis) were collected from five separate locations around the lake margins (table 4). Shell material showing little or no recrystallization or replacement of the original $CaCO_3$-aragonite structure were collected from three separate beach ridge deposits along the northwestern margin of Silver Lake playa, from a trench excavated in a beach deposit in northeastern Silver Lake and from a beach complex along the northeastern margin of Soda Lake playa near Baker (plate 3). These shells were submitted to Beta Analytic, Inc. for standard radiocarbon dating (table 4).

Soil Procedures

The basis of the use of soils for geochronological purposes and for the study of landform development was provided primarily by the research of Jenny (1941), who developed the state-factor approach for evaluating pedologic data. This approach is used by many geologists and has been used in a large number of studies for age determination of Quaternary surficial deposits and study of landscape evolution (Birkeland 1984). For the purposes of this study, we described and sampled soils exposed in pits excavated on the most geomorphologically stable part of landforms. Soils were described on beach ridges and alluvial fans flanking Silver Lake and Soda Lake playas; however, most of the soils studied were associated with the well-preserved beach ridge sequence north of Silver Lake playa (plate 1, figure 6) and on numerous alluvial fan surfaces on the western flank of Silver Lake and Soda Lake playas (figure 2).

Field Procedures. The soils were described according to methods and nomenclature of the Soil Survey Staff (1951, 1975, 1981). Bulk samples were collected from all subhorizons from selected profiles for subsequent textural, morphological, and chemical analyses. Because the degree of development of many field properties of soils is strongly time dependent (Bockheim 1980; Birkeland 1984), soil field data was quantified by determining the soil profile development index (PDI) of Harden (1982). Calculation of the index facilitates comparison of soils described in this study with soils described in other areas of the Mojave Desert.

Laboratory Procedures. Soil samples were air-dried and subdivided into fine (less than 2 mm) and coarse (greater than 2 mm) fractions. Sample splits of the fine fractions were made for determination of pH, gypsum and soluble salts, particle-size distribution, and Fe-oxide composition. Soil pH was determined with a 1:10 soil-to-water ratio. Soil carbonate content was determined using the method described by Machette (1985). Soil gypsum and soluble salt content was determined using the method described by Reheis (1985). Electroconductivity values were measured using a Sybron/Barnstead PM-70CB conductivity bridge. Soil particle-size distribution was determined (after carbonates and soluble salts were removed using the method of Rabenhorst and Wilding 1984) by dispersal of clays using sodium pyrophosphate, wet-sieve analysis to determine sand content, and pipette extraction to determine silt and clay content. A split of the fine fraction was crushed to

80 mesh for determination of Fe oxide content.

Wet-chemical extraction techniques were used to determine the content and nature of Fe oxides present in soil samples. The dithionite-citrate-bicarbonate method of Mehra and Jackson (1960) and the oxalate extraction of procedure Schwertmann (1973) and McKeague and Day (1966) were used to estimate the total ferric oxide (Fed) and poorly crystalline oxide contents (Feo), respectively. Magnetite was removed from samples prior to Fe oxides extraction due to magnetite solubility under the conditions of the oxalate extraction (Rhoton et al. 1981; Walker 1983). Extracted Fe was measured using a Perkins-Elmer 303 atomic absorption spectrophotometer.

QUATERNARY GEOLOGY AND PALEOHYDROLOGY OF LAKE MOJAVE

Introduction

Background. Important insights into the paleoclimatic and paleohydrologic nature of arid and semi-arid basins can be inferred from detailed reconstructions of lake fluctuations recorded in lake sediments and surficial geomorphic features (Bradley 1985). In the western United States, almost 100 closed basins supported lakes during the Pleistocene (figure 1). Only a few of these pluvial lakes have been studied in detail, including Lake Bonneville (Gilbert 1890; Broecker and Kaufman 1965; Currey 1980; Currey and Oviatt 1985), Searles Lake (Smith 1962, 1968, 1976; Stuvier and Smith 1979; Smith et al. 1983; Smith and Street-Perrott 1983; Smith 1984), Lake Lahontan (Morrison 1964; Benson, 1978, 1981; Thompson, Benson and Hattori 1986; Benson and Thompson 1987) and Lake Russell (Mono Lake) (Lajoie 1968). Unfortunately, smaller-scale paleoclimatic and paleohydrologic fluctuations recorded in these lacustrine systems were probably affected by glacial storage or annual precipitation in the mountainous headwaters of these basins (Porter, Pierce and Hamilton 1983). The presence of glacial meltwaters within these lake basins impacted the size of the fluvial and lacustrine systems and acted as a buffer to shorter-term climatic fluctuations recorded in lake sediments and shorelines features. This study focuses on a smaller, more sensitive fluvial-lacustrine system in which direct glacial storage effects were not a major factor influencing runoff.

Purpose. The primary purpose of this chapter is three-fold: (1) to determine the lacustrine-geomorphic history of the Silver and Soda Lake basins (pluvial Lake Mojave) during the latest Pleistocene and Holocene by examining and correlating cored lake deposits with surficial shoreline features; (2) to develop a precipitation-evaporation mass-balance lake model to characterize the paleoclimate and paleohydrology responsible for Lake Mojave; and (3) to further refine the timing of alluvial fan deposition in the Mojave River terminal area as previously described by Wells et al. (1987).

Study Site Description. The maximum elevation of ancient Lake Mojave was controlled by an outlet spillway developed in bedrock at the extreme north end of Silver Lake (current elevation = 285.5 m.) (figure 6). During maximum lake stages, overflow from this spillway drained north towards Dry Lake and Silurian Lake and eventually toward Death Valley (Blackwelder 1954). Prominent shoreline features are found around the margins of Silver Lake and Soda Lake playa which indicate at least two major high and persistent stands of the lake (figures 7, 8, and 9) (Ore and Warren 1971; Wells et al. 1984, 1987; Enzel et al. 1988; and Brown et al. 1988). The most extensive sequence of these shoreline features, the El Capitan beach ridge complex, is preserved in the extreme northwestern margin of Silver Lake playa where deposits of five beach ridges interfinger with alluvial fan and eolian deposits (plate 1). The majority of shoreline features in the southern third of pluvial Lake Mojave have been buried by progradation of the Mojave river fan-delta complex and a series of dune fields derived from fan- delta fine grained sediment.

Previous work. Thompson (1929) was the first worker to examine Silver and Soda Lake playas as remnants of a pluvial lake which he named "Lake Mojave." His early work suggested Manix Lake (figure 1) had once been the terminus of the Mojave river and it was not until after the incision of Afton Canyon that Silver and Soda Lake basins became the terminus of the Mojave River. However, recent work (this study; Meek 1989) suggests that both lakes

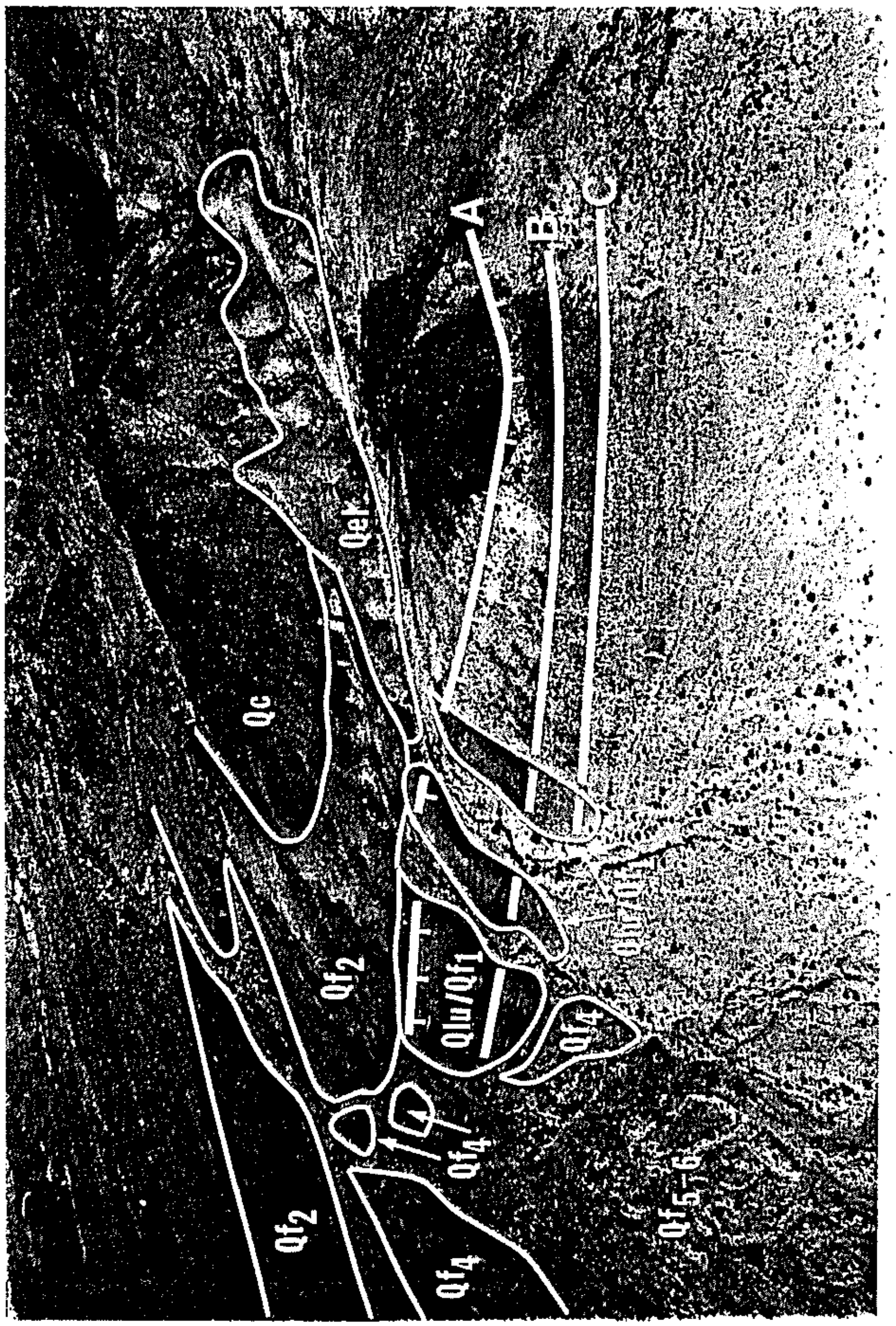


Figure 7. Photograph showing wavecut shorelines in bedrock and alluvium, northern Silver Lake playa. Several historic shorelines are present near the playa surface. The A-shoreline is visible as a distinct scarp cut into dioritic bedrock in the upper right. The Soda Mountains are visible in the background.

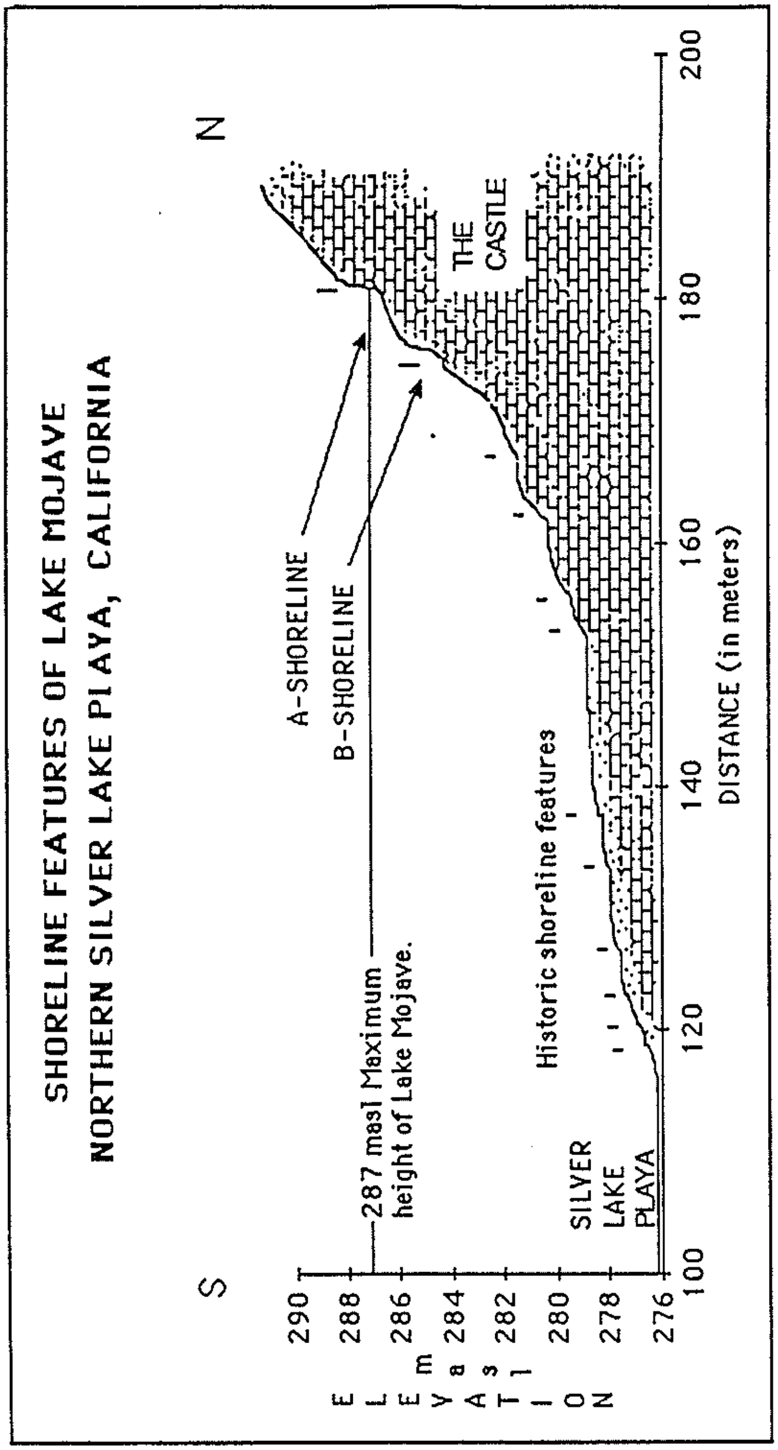


Figure 8. Topographic profile of historic and pre-historic shorelines and wavecuts of pluvial Lake Mojave, "The Castle," Northern Silver Lake playa. The distinct A- and B-shoreline wavecut scarps were produced during high stands of the lake controlled by the elevation of the overflow spillway. The lower shoreline features were formed at elevations below spillway control and are much less prominent. The lowest shoreline features consist of stone alignments paralleling topography that were formed during historic lake stands.

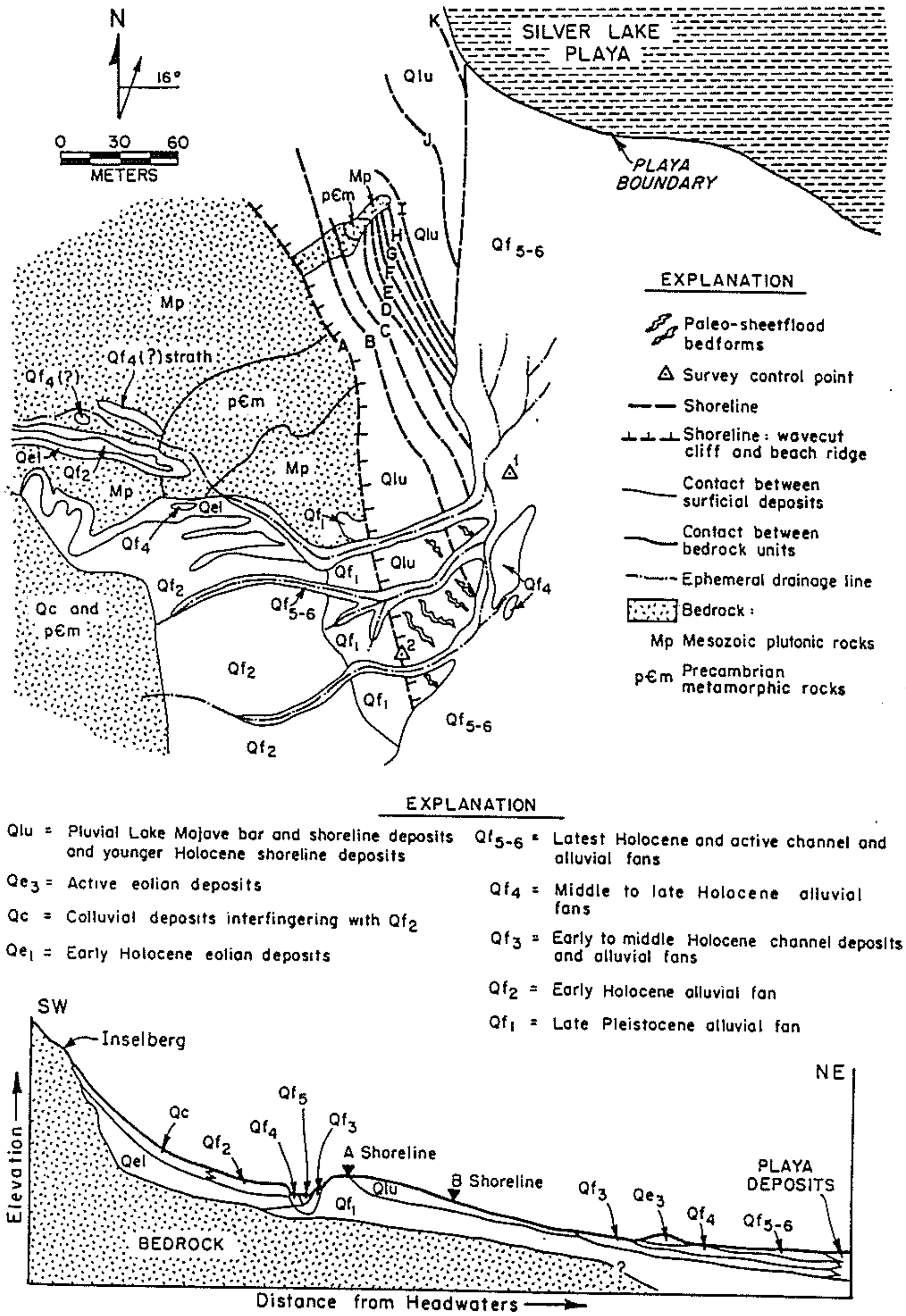


Figure 9. Shoreline-geomorphic relationships in north Silver Lake playa (Wells, McFadden and Dohrenwend 1987).

coexisted for a period of over 6 ka. Drilling of the Soda Lake basin by Meussig, White and Byers (1957) revealed only one prolonged lacustrine period in sediments from cores drilled up to 326 m deep. These lacustrine clays which occur at depths of 10 to 35 m below the present playa surface of Soda Lake, have been shown to correlate with similar sediments drilled in Silver Lake (this study) based on faunal information (Thompson 1988, pers. com.).

The importance of the Lake Mojave area as an early man site was investigated by Crozer-Campbell and Campbell (1937) during which several shoreline features and the outlet spillway were mapped in some detail. Blackwelder (1954) proposed that overflow from the Lake Mojave spillway would have eventually reached pluvial Lake Manly in Death Valley during the late Pleistocene. The first major attempt at reconstructing the Lake Mojave chronology was undertaken by Ore and Warren (1971) and involved extensive radiocarbon dating of <u>Anadonta</u> <u>californiesis</u> pelecypod shells and lithoid tufa found in shoreline features in the Silver Lake area. These isotopic dates ranged from 15,350 ± 240 years B.P. (Y-1587) to 8,350 ± 300 years B.P. (LJ-929) (table 4) indicating major lacustrine events during this interval. 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 and 1987). The most recent work has involved mapping shorelines around the lake in detail (Enzel et al. 1988; Brown et al. 1988) and examining soil-profile development in beach ridges exposed in northwestern Silver Lake (McFadden et al. 1988). This chapter will concentrate on correlating cored lake deposits with shoreline features in order to reconstruct lake fluctuations during the latest Quaternary.

Geomorphology of Lake Mojave Basins and Shorelines

Regional Setting. Core and borehole data obtained from Soda Lake playa (Meussig, White and Byers 1957; Moyle Jr. 1967; Dickey, Neimeyer and Sholes 1979) combined with the cores obtained during our drilling of Silver Lake playa in 1987-88 are used to construct the configuration of the depositional basins of pluvial Lake Mojave (figure 10). Lake Mojave was composed of two depositional basins where lacustrine sedimentation was the greatest; each basin was centered in the areas of the present-day Silver Lake and Soda Lake playas (figure 10). The two basins are separated by a broad sill that appears to be related to pre-lake alluvial fan surfaces and a local bedrock topographic high near the town of Baker. The Soda Lake depositional basin was deeper than that of the Silver Lake basin during most of the lake history. Thus, ancient floodwaters filled Soda Lake basin first, then overflowed into Silver Lake basin. Effective water storage of both lakes was reduced by filling the basins with lacustrine and playa sediments during the latest Quaternary. Because greater sedimentation rates in Soda Lake basin resulted in a higher elevation of the playa surface in recent times, historic flood waters pass over Soda Lake playa into the Silver Lake basin before hydrologic ponding backfills into Soda Lake basin.

Extensive shoreline features are found around the margins of modern day Silver and Soda Lake playas. These consist of erosional wavecut scarps, depositional beach ridges, and offshore bars (figure 6). The maximum height of pluvial Lake Mojave was controlled by an outlet spillway cut into bedrock in Spillway Bay at the extreme northern end of Silver Lake playa (plate 1 and 2). The most extensive shoreline features are found around elevations of 287 m (A-shoreline) and 285 m (B-shoreline) (figures 8 and 9). These features formed during prolonged lake stands at elevations controlled by the stability

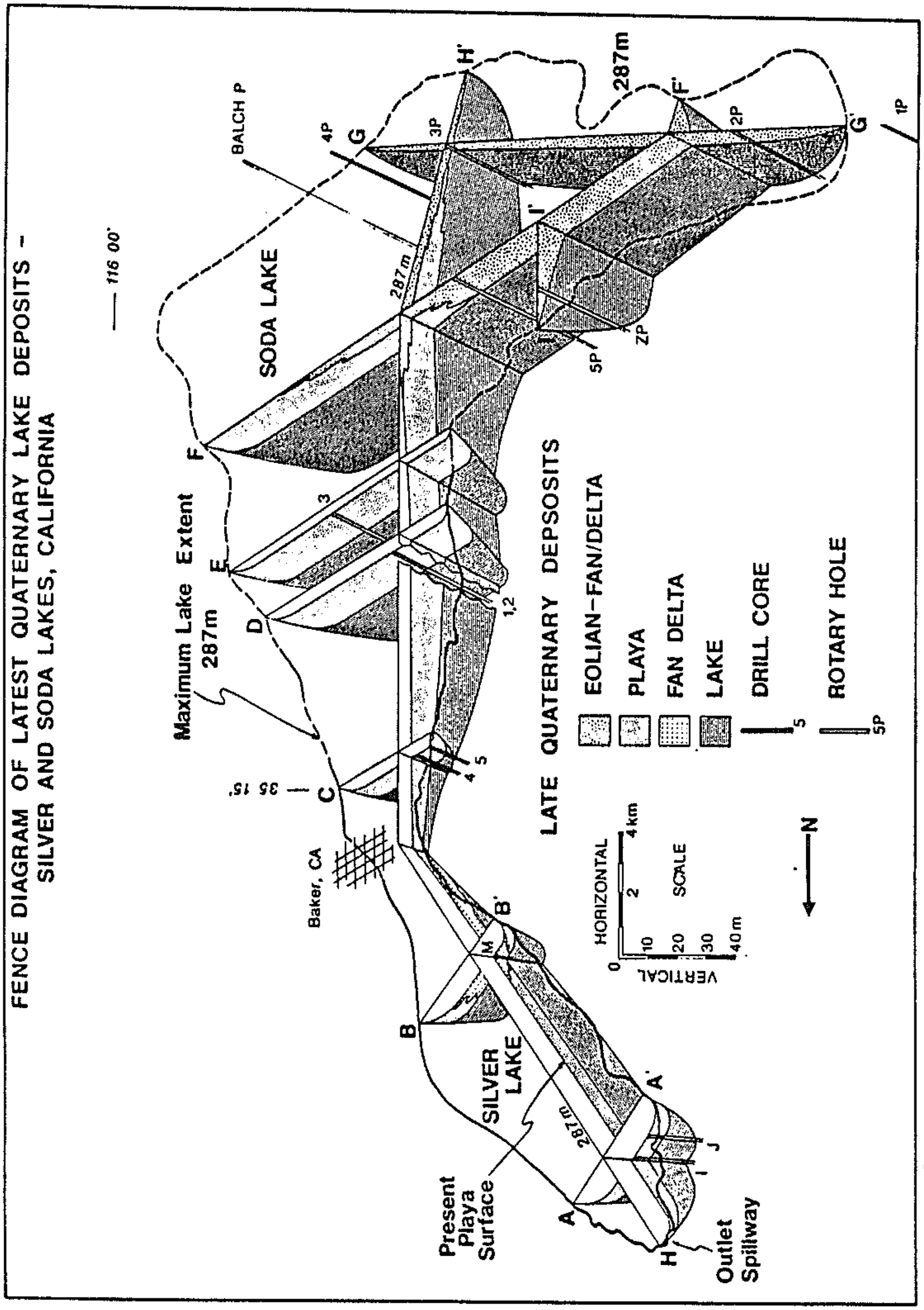


Figure 10. Fence diagram of Latest Quaternary Lake deposits - Silver and Soda Lakes, California. This reconstruction is based on subsurface data from 14 rotary drill holes in southern Soda Lake, 18 drill cores from Silver Lake and central Soda Lake and mapped shoreline features.

of the outlet spillway between a period of downcutting. Lower, less extensive shoreline features are found below the A and B shorelines and formed below the elevation of spillway control. The most extensive of the younger shoreline features occur at elevations of approximately 283 m (C-shoreline) (Figure 8). Historic large-scale floods of the Mojave River have produced small beach features at elevations below these three prehistoric shorelines (Wells et al. 1887) (plate 1, figure 9).

The largest and most extensively preserved shoreline features are found typically along the northern margins of both Silver and Soda Lake playas (plate 1 and 3) because: (1) the maximum fetch of the lake and prevailing wind directions (southwesterlies) produce the strongest wave activity and therefore the largest features in the northern margins of each lake, and (2) the proximal location of these features to bedrock-defended areas protect the shore features from erosion or burial by active alluvial fan streams.

Shorelines Surrounding Silver Lake Basin. Results of extensive mapping of the northern margin of Silver Lake and the lacustrine/piedmont relationships are shown in plate 1. Four separate beach complexes are present and have formed distinctly different profiles due to local slope and morphological differences in the piedmont/shore interface.

Five separate beach ridges are present in the El Capitan ridge complex, more than in any other in the Lake Mojave area (plate 1). A topographic profile A-A' constructed normal to the long axis of the ridges indicates that these ridges formed on a long, gently inclined slope (plate 2). The highest three beach ridges (BRI, BRII, BRIII) have well-developed stone pavements overlying an eolian unit which is approximately one meter thick and contains a soil correlative to unit Qe2 (Wells, McFadden and Dohrenwend 1987; McFadden et al. 1988). Below this eolian unit, imbricated gravels dip gently lakeward. Lithology of the beach material is dominantly mafic metamorphic rocks, diorite, and granodiorite with minor amounts of limestone/marble. A significant amount of grus (rock fragments of chemically or physically weathered granite) is observed in deposits of BRIII. A detailed outcrop description of beach ridge I is shown in table 6. Abraided carbonate coatings on many of the gravels in the upper 3 ridges suggest reworking of the nearby fan units. Tufa is common on many of the larger clasts, and pelecypod shells (Anadonta californiesis) are present in beach ridges I, II, III, and V. Shells in the highest of these ridges have been dates isotopically at 13,640 ± 120 years B.P. (Brown, M.S. thesis, in prep.) and 12,450 ± 160 years B.P. (Ore and Warren 1971) (table 4). A shell horizon in B.R. III has been dated at 10,330 ± 130 years B.P. (this study), (table 4). Approximate locations for these dated samples are shown in cross section A-A' (plate 2). The lowest two beach ridges lack the eolian mantle of unit Qe2 and appear to be composed almost entirely of granules-to-coarse sand-sized grus. Beach ridge IV shows a distinct erosional surface between two groups of southward dipping foresets. The erosional surface also dips southward toward the playa and displays no evidence of a soil development between the upper and lower units. The lowest beach ridge contains a buried soil overlain by a thin gravel cover containing another weakly developed soil (see following section). Whole pelecypod shells collected from 5-10 cm below the top of the burid soil yielded a radiocarbon date of 9,390 ± 140 B.P. (table 4). The western flanks of all five beaches have been eroded by alluvial-fan channels with inset fan durdeposits. The gentle topographic gradient of this area is probably responsible for the extensive beach ridge development. Small changes in elevation of the lake surface resulted in regressions across a broader area, thus producing a new

TABLE 6

LITHOLOGIC DESCRIPTION OF HIGHEST BEACH RIDGE I IN EL CAPITAN COMPLEX - NORTHWEST SILVER LAKE

Unit Number	Description of outcrop
4	EOLIAN 272 - 278 cm. Thinly stratified reddened fine to medium sand correlative to Qe3 of Wells, McFadden and Dohrenrend (1987)
3	EOLIAN 182 - 272 cm. Massive fine to medium sand. Moderately well sorted. Approximately 10% gravel fraction with clasts found in random orientations to locally thin discontinuous small lenses with imbrication almost horizontal (dipping slightly lakeward). Gravels composed of mafics, diorite and granodiorite, many of which have abraided $CaCO_3$ coatings. Angular to subrounded. 10YR 6/4.
2	BEACH RIDGE 150 - 182 cm. Imbricated Gravels (70 - 80%) with coarse sand matrix. Pebbles to cobbles are subangular to subrounded. Dominantly composed of diorite and granodiorite; some clasts have TUFA coatings. Most clasts are platy and imbricated and dip to the south. Relatively sharp upper and lower boundaries.
1	BEACH RIDGE 0+ - 150 cm. Gravelly sand. Fine to coarse sand with 10 - 15% gravel (mostly granule to pebble sized). Unit shows moderate to strong stratification with moderate to moderately well sorted nature within each bed. Coarser clasts are usually platy and subrounded and are imbricated similar to unit 2. Pelecypod SHELL fragments from 10 - 20 cm below top of horizon yielded 13,640 ± 120 (Brown, M.S. thesis, in prep.). Pedogenic $CaCO_3$ found concentrated along upper boundary with unit 2 (stage I+). Color 2.5Y 5.5/2 (D) 2.5Y 4.5/2 (M). Unit contains ostracodes (*L. Ceriotuberosa*).

beach ridge during subsequent lake level stability.

In contrast to the gently inclining slope present in El Capitan ridge, Lonely beach ridge has formed on a relatively short, steeply inclined surface (plate 1), resulting in a series of stacked ridges as shown in cross section B-B' (plate 1). This beach ridge has greater relief than any other investigated in this study. The dominant particle size is granule-to-coarse sand composed almost entirely of grus. No shells were found in this ridge although there was a lack of adequate subsurface exposures present. The western margin of the ridge truncates against a limestone outcrop. Reconstructions suggest that this ridge originally continued beyond the limestone outcrop and graded into the lower two ridges in the El Capitan complex. Post-lake erosion and recent alluvial fan deposition have modified this area. The upper three beach ridges in El Capitan complex merge together and grade eastward above and under Lonely ridge (plate 1). The A shoreline is represented by an extensive wavecut notch in dioritic bedrock outcrops north of the former beach zone. Recent fan deposition and an eolian sand ramp mantle along the dioritic bedrock outcrop to the north have removed or covered all depositional remnants of the highest shoreline. To the east, the beach ridge ends at several wavecut notches in bedrock. At this site water from pluvial Lake Mojave overtopped bedrock and prevented deposition during the lower more recent stands of the Silver Lake basin. Several minor historic shorelines have been recognized in this locality also.

Overflow during high stages of the lake exited the basin through the overflow channel in the Spillway bay beach ridge complex, and detailed surveying of spillway area is shown in plates 1 and 2. The overflow channel has no visible terraces present and is cut into alluvial fan deposits inferred to be equivalent in age to that of units Qf0/Qf1. These deposits slope away from the low relief marble, dioritic, and mafic metamorphic hillslopes. Channel walls are very steep (cross-sections E4, E5, E6, E7, E8, and E9, plate 2) and expose stage III+ to IV pedogenic carbonate horizons in fan units. Field observations suggest that these deposits and petrocalcic soils have probably been altered extensively by ground water movement or streamflow during the high stand of the lake. Historic overflow of the Silver Lake basin has not occurred, and the channel has acted as a sediment trap for eolian material, which has blanketed the floor to depths of over one meter. During abandonment of the spillway channel, minor locally derived runoff has carved a small channel in the upper reaches of the spillway channel. The spillway channel has been truncated just over a km downstream of Spillway bay by alluvial-fan deposits of units Qf5 and Qf6. Field observations and air photo analysis suggest that the channel previously continued northward several km to Dry Lake.

A small embayment, Spillway bay, is present just lakeward of the outflow channel and contains evidence for three different lake stands. Three small beach/lacustrine reworked fan remnants are found just south of the outflow constriction (plate 1). These remnants, in addition to wavecut notches developed in bedrock and older fan surfaces (units QfQ/Qf1), correspond in height to the A shoreline. An eolian mantle over 60 cm deep is present along the margins of the bay but thins toward the main north-south axis (cross-section C-C', plate 2). Three cross sections (E1, E2, E3, plate 2) through the Spillway Bay indicate an average level of 286 m. which also corresponds to the A shoreline. The Anadonta californiesis shells collected 30 cm to 70 cm below the surface (location 3, plate 1) by Ore and Warren (1971) gave an isotopic age of 13,620 ± 100 years B.P. (table 4). This age range corresponds to dated of shells in the highest beach in the El Capitan complex. A broad channel cut into the western margin of the bay represents the B shoreline overflow (altitude = 285.4 m) (plate 2). A man-made linear channel was cut into the bay in an attempt to protect the now-abandoned town of Silver Lake during the 1916 flood. A large continuous beach ridge (altitude = 284.8 m), which occurs directly south of the bay, corresponds to the lake stand elevation observed at Lonely ridge and the lower two El Capitan ridges. This elevation apparently represents the final high stand of the Lake Mojave. The beach ridge trends east-west between bedrock outcrops and lacks the eolian mantle found on many of the higher ridges around the lake. Overflow of the lake apparently did not occur at the lake level represented by this shoreline because the geomorphic features correlated with this ridge are over half a meter below the elevation of the spillway channel. The ridges discussed are composed almost entirely of granule-to-coarse sand-sized grus, except near the large bedrock outcrop referred to as "The Castle," where the ridges are composed of limestone and marble predominantly (plate 1).

Three well-preserved wavecut scarps are cut into The Castle at altitudes of 286-287, 284-285, and 283 m., respectively (figure 8, plate 1). The highest wavecut scarp extends around the majority of The Castle and eventually disappears near the extreme northern exposure of bedrock where the scarp merges into the highest beach ridge. The wavecut notch of the B shoreline terminates at the lowest beach ridge in Spillway bay and Tidewater basin (plate 1). The scarp of the C shoreline is less well developed than the wavecuts of the A and B shorelines and disappears at the base of two major beach ridges in Tidewater basin. Ten shorelines lower than the C shoreline are preserved as linear gravel deposits in the extreme southern flank of The Castle. These shorelines are inferred to be historic in age (Wells, McFadden and Dohrenwend 1987).

Two large beach ridges are preserved in the northeastern portion of Silver Lake in the area referred to as Tidewater basin (plate 1). Both of these ridges are composed predominantly of fine gravel-to-coarse sand sized grus. The highest ridge is 287.9 m in elevation at its maximum height and merges westward into the A shoreline features in Spillway bay and eastward into a bedrock outcrop on the eastern side of highway 127 (figure 6). No shell material was observed in exploratory trenches excavated in the highest ridge; however, eolian deposits were present to a depth of 80+ cm. To the north of this ridge lies a small depression which slopes gradually uphill to a broad saddle (altitude = 289.5 m) that marks the drainage divide between Silver Lake basin and Dry Lake basin. Core Sil-L, which was obtained from this basin (plate 1, appendix A), yielded no lacustrine sediments and indicated that bedrock is less than 2 meters below the surface. A larger basin (Tidewater basin) is preserved between two beach ridges. Core Sil-G was drilled to a depth of 6.25 m in the Tidewater basin and revealed several meters of green lacustrine clays. The topographically lower of the two ridge starts in an embayment of The Castle and trends eastward and eventually southward after crossing the highway (figure 6). A complex depositional history is recorded in a stream-cut exposure at the extreme western edge of this beach ridge (figure 11, table 7). Eleven distinct units ranging from cobbles and pebbles to clayey silt are exposed at this locality and indicate fluctuating water levels as well as differing environments of deposition. Several green, fine-grained clay and silt-rich units, containing laterally continuous thin bands of calcite and other exaporite minerals are interbedded with coarser sand and gravel units (table 7, figure 11) and suggest a low-energy depositional environment. Abundant ostracodes were present in the fine-grained sediments from Units IV, VI, VIII, and XI and were analyzed by

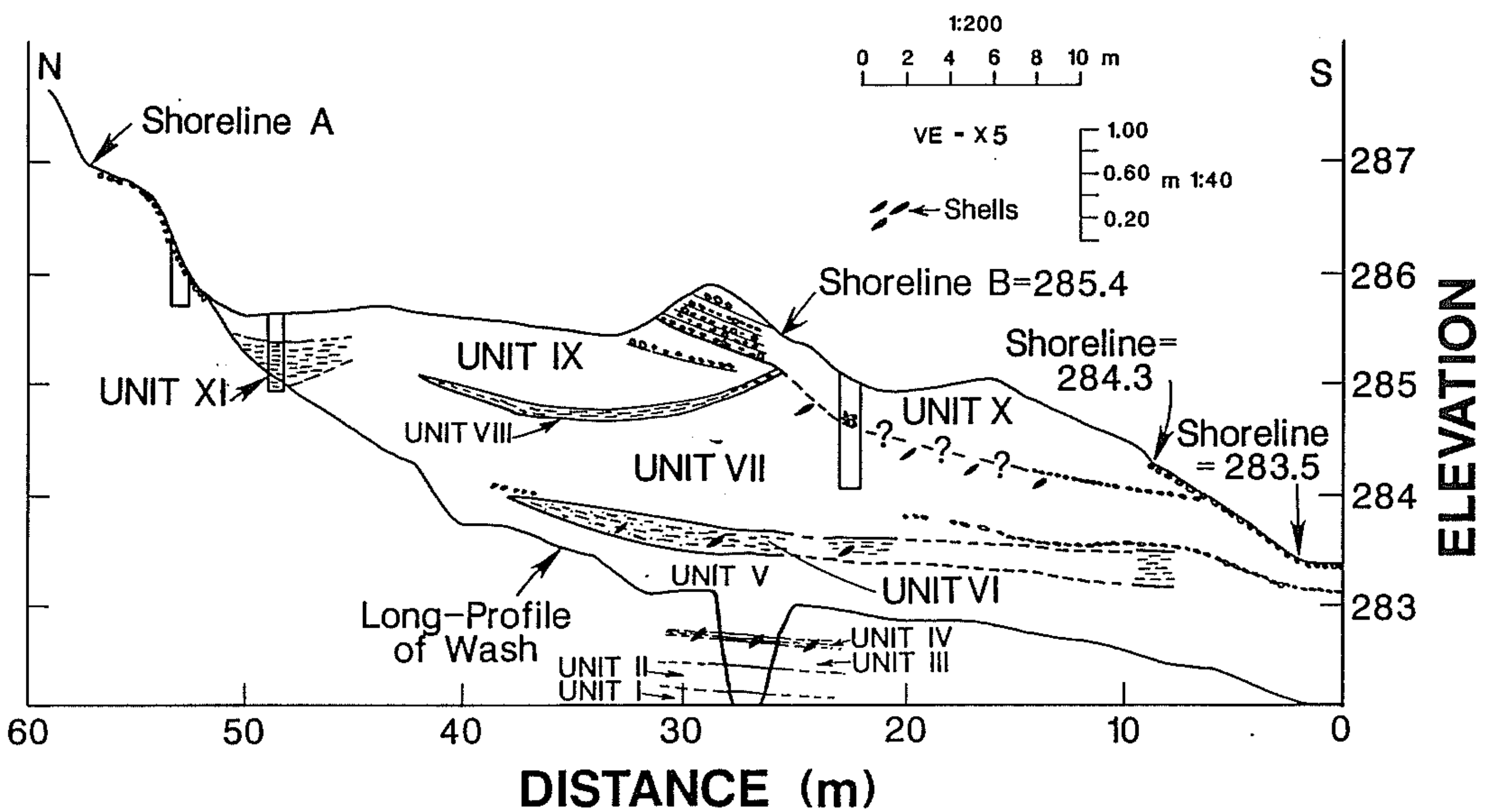


Figure 11. Stratigraphic cross section of Lake Mojave beach ridge deposits - Tidewater Basin, Northern Silver Lake playa. Four fine-grained green units are shown in the outcrop (units IV, VI, VIII, and XI) and indicate this beach feature was overridden by the lake at least four times during its existence. The two lower fine-grained units contain ostracodes found only in lake sediments of the Lake Mojave I phase or older. Pelecypod shells from unit IV dates at 16,270 ± 310 years B.P. Shells collected by Ore and Warren (1971) 15 meters to the east of this outcrop from unit VII dated at 14,550 ± 140 and 15,350 ± 240 years B.P. This is the oldest known shoreline feature related to latest Quaternary Lake Mojave. See table 7 for a detailed sedimentological description of this outcrop.

Table 7

LITHOLOGIC DESCRIPTION OF TIDEWATER BASIN BEACH RIDGE II

Unit Number	Description of outcrop - SiL-0-3
11	66 cm thick. (Not the same location as Units 1-10) GRAVELLY, SILTY, CLAY. Unit is irregularly laminated to massive in nature with laminations fading towards top. Bottom not reached. Lower portion of unit is very strongly indurated and contains abundant disseminated $CaCO_3$. Occassional shell fragments found throughout. Top of unit is moderately sorted with subangular to subrounded grus and marble. Bottom of unit is poorly sorted with angular to subrounded grus and marble. Boundary between these subunits is gradational. Color 2.5YR 6/4. Unit contains ostracodes (<u>L. ceriotuberosa</u>). Possibly modified by human activity.
10	0 - 45 cm GRAVEL. This unit includes crest and most recent 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 abourt 15 - 20 cm thick. Coarsening upwards in each layer. Reddening at base of unit (5YR 7/4) 4 - 5 cm above unit 4. Coarse sand laminae dip about 5 degrees to the south.
9	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 degrees) lakeward and exhibit moderate sorting within individual laminae. Minor scattered shell fragments. Color 7.5YR 5/4 (D).
8	66 - 72 cm. FINE SAND AND SILT with evaporite minerals. Unit is quite variable in thickness (4 - 8 cm). Pinches out about one meter 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 5YR 6/2 (D), 5Y 5/2 (M). Samples collected from the most clayey part of this unit contain abundant ostracodes (<u>L. ceriotuberosia</u>) as well as <u>Heterocypris sp</u>.
7	72 - 187 cm GRAVEL. Granules to cobbles composed almost entirely of grus. Occasional bedding or laminations dipping almost horizontal (same as unit 6). Overall unit is about 70% granules, subrounded to subangular in nature. Laminar units are well sorted and usually about 2 - 3 cm thick. Sharp upper boundary. Color 10YR 4/4 (M).

TABLE 7 (continued)

6 187 - 207 cm Gravelly, Silty SAND moderatley 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 contains cobbles to pebbles and Pelecypod SHELLS. Possible bioturbation in upper 10 cm of unit. Color 5Y 7/2. Locally abundant evaporite 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).

5 207 - 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 (D) and reduced 5Y 5.5/3) (D) zones of a roughly horizontal nature. Stratification dips gently north (3 degrees) away from the lake. Lower boundary is irregular and slightly wavy. Upper boundary is somewhat gradational.

4 255 - 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) (D) granules and reduced gray-green (5YR 6.5/3) (D) sand-sized material overly the coarser zone. The sandy zones contain ABUNDANT whole pelecypod and gastropod SHELLS preserved in growth position (dated at 16,220 ± 310 years B.P.). 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 laminations/zones. Lower boundary shows evidence of scour. Moderately abundant ostracodes present (L. ceriotuberosa with minor L. bradburyi).

3 269 - 282 cm GRAVEL. Subrounded to subangular clasts (up to 4 cm in size) of granite and lesser amounts of limestone. The unit coarsens upward. Fine-grained matrix composed of sand-to granule-sized grus. Overall gray-green, reduced color (5Y6/4) (D). Unit is strongly cemented by disseminated $CaCO_3$.

2 282 - 312 cm GRANULE-sozed gravel. Moderately well-sorted with thinly stratified beds dipping bently lakeward. Locally horizontally aligned oxidized zones, although unit is an overall gray, reduced color (5Y 6/4) (D). Lower boundary is gradational in nature. Unit is composed almost entirely of grus.

1 312 - 327+ cm GRAVEL, pebbles to cobbles. Subrounded to subangular, composed of limestone and granite. Matrix is composed of sand-sized material of grus and limestone. Overall unit is a reduced, green-gray color (5Y6/6) (M) (5Y6/4) (D).

Faunal information from R. Forrester, pers. com. 1987, 1988.

R. Forrester (pers. com. 1987, 1988). 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 species of ostracode: _L. ceriotuberosa_. Whole pelecypod shells, in growth position and in excellent state of preservation were collected from Unit IV and yielded a radiocarbon age of 16,270 ± 310 years B.P. (Beta-29553). The lower units in this beach ridge therefore represent the oldest known shoreline feature related to Lake Mojave. Ore and Warren (1971) (table 4) dated shells from two superimposed sets of cross strata located approximately 20 meters west of the location described in figure 11 and table 7. These units are composed of coarse-sand to granule-sized clasts that dip approximately 26° toward N10W. The shell horizons are located at 283.5 m and 284.1 m and yielded age dates of 15,350 ± 240 and 14,550 ± 140 years B.P., respectively. Projecting these locations westward to the outcrop in figure 11 places them at the same elevation as unit VII. Ore and Warren (1971) were unable to find these shell-bearing units in several pits excavated to the east.

A small gravel quarry excavated in an embayment in northwestern Silver Lake (figure 6) has exposed a series of interbedded gravels, sands and silty clays deposited during pluvial Lake Mojave. The top of the quarry is approximately 8 m below the A shoreline which is preserved as a wavecut cliff in dioritic bedrock. The top of the deposits form the land surface and slope away from the bedrock cliffs to the southwest. The deposits exposed in the quarry are described in table 8. A cross section of the exposure is given in figure 12. Gravel units in the quarry contain tufa coated clasts and in some areas strata with pelecypod-shell fragments. Sandy and clayey units often contain abundant pelecypod shells as well. A detailed chronology of these deposits has been reconstructed from radiocarbon dates obtained from _Anadonta_

TABLE 8

LITHOLOGIC DESCRIPTION OF SILVER LAKE QUARRY

Unit Number	Description of outcrop - SiL-0-1.
	0 - 14 cm DISTURBED SURFACE - loose unconsolidated material
7	14 - 64 cm GRAVEL - very thinly bedded; granules to pebbles. Angular. Some fragments of TUFA. More than 80% gravel. Local thin sandy beds unconsolidated and soft. Soil developed on this unit. 14 - 19 cm has an Av horizon. 19 - 37 cm is a Bw horizon with a loose coarse sand matrix (7.5YR 5.5/4 (D)). 19 - 37 cm Cox horizon 10YR 5/6 (D) 10YR 5/6 (M).
6	64 - 130 cm SAND, medium to coarse. Locally angular granule to pebble lenses. No $CaCO_3$. Entire unit is soft and friable. Sharp upper boundary.
5	130 - 155 cm. Fining upwards unit with COBBLES at base grading to PEBBLES at top. Angular and coated with thick TUFA rinds more than 95% gravel; very little fines. Medium to well sorted (high energy environment) with loose consistency. Composed of mafic, granodiorite, and diorite clasts.
4	155 - 190 cm SAND, medium to coarse. Non-effervescent, soft and friable; very finely laminated and well sorted. Contains less than 5% angular gravels. Upper boundary is very sharp. 10YR 6/5.
3	190 - 209 cm GRAVEL, angular pebbles to granules. TUFA coatings. Sandy matrix is strongly effervescent. Overall 25 - 30% gravel comprised predominantly of diorite and other mafics. Sand 7.5YR 5/3.
2	209 - 265 cm SAND, fine to coarse. Very finely bedded to laminated. Each layer is well-sorted. Locally, very thinly bedded well-sorted gravels. Gravels have TUFA coatings. Upper boundary is gradational and clast size increases to subangular-subrounded coarse quartzose sand. Overall unit is grain supported with silt matrix.
1	265 - 325 cm CLAY LOAM-LOAM, indurated, medium effervescent with lamination ranging from 1 mm to 1 cm thick. Root remnants common. Mudcracks infilled with well-sorted sand that strongly reacts with HCL. Pelecypod and gastropod SHELLS common. Upper boundary sharp. Silt-clay 5Y 5/3 (D). Sand 10YR 6/4 (D).

TABLE 8 (continued)

LITHOLOGIC DESCRIPTION OF SILVER LAKE QUARRY

Unit Number	Description of outcrop - SiL-0-2
I	0 - 20 cm SOIL HORIZON, coarse sand with cobbles and pebbles. Fragments of TUFA. Overall unit is friable. Unit color changes from 5/6YR (M) at bottom to 4/4YR (M) at top.
H	20 - 37 cm COARSE SAND WITH COBBLES AND PEBBLES. Coarse material is strongly weathered and can be cut with a knife. Minor $CaCO_3$ disseminated (sand). Fragments of TUFA. Friable nature. 5/6 7.5YR (M). Sharp lower boundary.
G	37 - 74 cm GRAVEL, cobbles to pebbles with broken TUFA fragments in addition to coatings on clasts. Coarse sand matrix 5/6 10YR. Reddens upward and shows some evidence of weathering.
F	74 - 84 cm SILTY CLAY, indurated. Minor Pelecypod and Gastropod SHELLS.
E	84 - 96 cm GRAVEL. Same as unit 3, except for smaller size clasts (fewer cobble sized clasts and more pebble sized clasts).
D	96 - 102 cm SAND, coarse with approximately 5% fine gravel. 7/2 5Y color. Moderately indurated. Contains abundant Pelecypod and Gastropod SHELLS.
C	102 - 150 cm GRAVEL, cobbles to pebbles with coarse sand matrix. Subangular to subrounded, moderately to strongly weathered clasts (cannot cut with a knife). ALL clasts have TUFA coating. Unit is approximately 90% gravel. Lower boundary sharp.
B	150 - 167 cm SAND, well sorted and moderately indurated. Contains abundant Pelecypod and gastropod SHELLS.
A	167 - 241 cm GRAVEL, angular to subrounded pebbles to cobbles. Clasts are strongly weathered (can be cut with a knife). Coarse sand matrix with Pelecypod SHELL fragments. Many gravels have TUFA coatings. Sand content increases towards top of unit. Upper boundary with unit B is sharp.

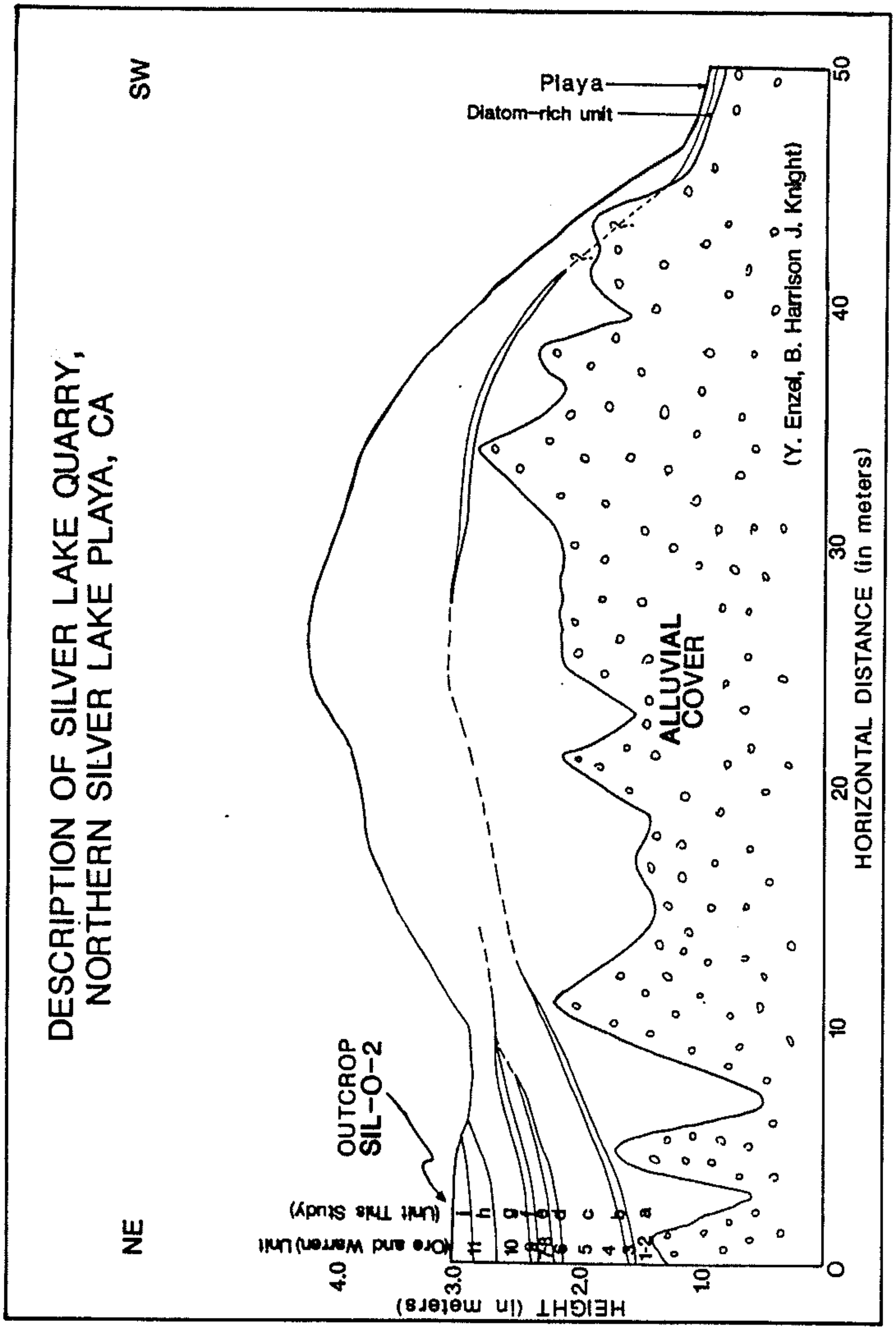
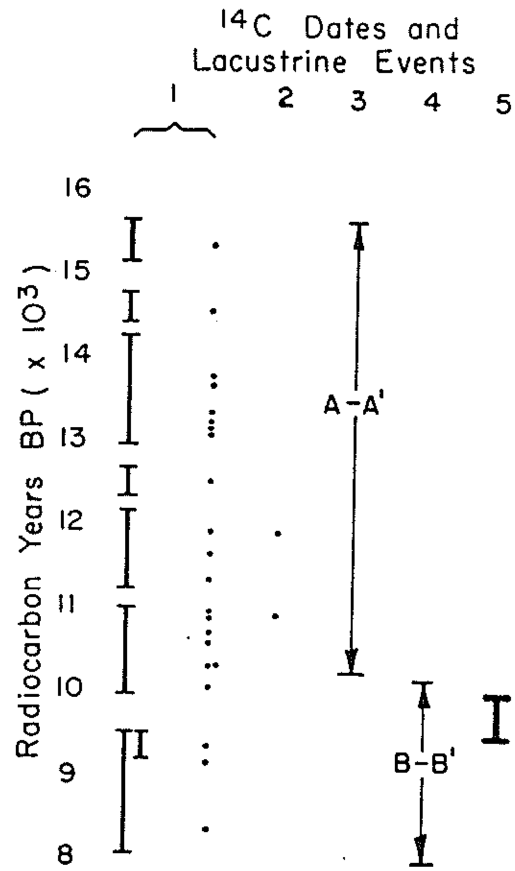


Figure 12. Stratigraphic cross section of the Silver Lake quarry. Outcrop description Sil-O-2 (table 8) is located in the northeastern margin of this outcrop. The extensive radiocarbon dating of pelecypod shells and tufa dating of Ore and Warren (1971) (table 4) was done at this locality also. Unit numbers from their original study and Unit letters from this study are indicated.

californiesis shells and tufa-coated gravels by Ore and Warren (1971) (figure 13, table 4). These dates show a regular progression from the oldest on the bottom (13,670 ± 550 B.P.) to the youngest dates at the top of the outcrop 8,350 ± 300 and 9,160 ± 400 B.P.) and correspond with the range of dates (table 4) from other shoreline features in Silver and Soda Lake basins. Field observations of the sediments also suggest the absence of any protracted drying events in the quarry location. An exposed clay-rich, diatomaceous unit southwest of the quarry outcrop contains abundant Campylodiscus clypeus.

A series of beach ridges are preserved at the Otto Mountain beach ridge complex near the fan-delta area of southern Silver Lake on the western flank of the Soda Mountains (cross section F-F', plate 2 and plate 3). A well-developed stone pavement mantles all the beach ridge surfaces; however, the highest two ridges have slightly better developed pavements. Clast size is dominantly gravel with abundant subangular-to-subrounded mafic metamorphic, diorite, and minor limestone clasts. Tufa coatings are found on some clasts in the highest beaches. The A-shoreline wavecut scarp is present behind the ridges where local alluvial fan deposition has not mantled bedrock. Immediately below this wavecut is a small remnant of a beach ridge which is interpreted as being related genetically to the A shoreline. A much larger ridge is present just below this ridge and corresponds to the B shoreline (altitude = 285.5 m). The third and topographically lowest ridge apparently corresponds to the C shoreline (altitude = 283 m) and contains several local breaks in slope. These local topographic features indicate either several prograding ridges piled on top of one another or several recessional wavecuts preserved in a single ridge. The land surface below the lowermost ridge grades to the level of the present-day fan-delta channels.

Numerous shoreline features are present along the western flank of Silver



1 = Radiocarbon dates reported by Ore and Warren (1971) showing cumulative error bars

2 = Radiocarbon dates reported in this paper

3 = Range in age of those deposits associated with shoreline A-A' (below the elevation of A-A' and above shoreline B-B')

4 = Range in age of those deposits associated with shoreline B-B' (shoreface below B-B' and above C-C')

5 = Inferred interlacustrine event between stands at shorelines A-A' and B-B'

Figure 13. Summary of previous Lake Mojave rabiocarbon dates - Silver Lake playa.

Lake playa. Bedrock outcrops near the present playa level show well-developed wavecut cliffs, which typically have associated beach ridges and bars. The most extensive features are found at an elevation of 287 m (i.e., A shoreline height). The absence of bedrock-defended areas and the presence of very large active fan channels along the eastern margin of the playa has resulted in little preservation of geomorphic features related to Lake Mojave lake stands. Local exposures of beach deposits are present near the now deserted town of Silver Lake. A few beach remnants occur approximately one km north of Baker at an elevation of 287 m.

Soda Lake Shoreline Features. Extensive shoreline features are found preserved in the northern margins of Soda Lake basin (plate 3). Field investigations were focused at three separate locations: Elephant beach ridge complex in northeastern Soda Lake, which is the largest depositional shoreline feature preserved in either lake; the Baker Highway quarry; and shoreline and wavecut features developed on alluvial fan deposits and bedrock outcrops on the west-central margin of Soda Lake, north of Soda Springs. No prominent shoreline features have been found in southern Soda Lake basin due to extensive modification by eolian processes and by fluvial processes of the broad fan complex related to the terminus of the Mojave River.

Slightly west of the town of Baker, a large beach ridge was quarried for sand and gravel (plate 3) and provides an excellent 3-dimensional view of the subsurface stratigraphy of the A and B shoreline beach ridges. During this study several additional backhoe trenches were excavated in the quarry. Four outcrops were described in detail (table 9) and the stratigraphy of the ridge is reconstructed in figure 14. Although many units were described in each outcrop, they are grouped into four major units. The basal deposits (unit 1)

TABLE 9

LITHOLOGIC DESCRIPTION OF BAKER HIGHWAY QUARRY

Unit Number	Description of outcrop - SOD-0-2
6	0 - 145 cm BEACH RIDGE. (Top of outcrop has been reconstructed due to interference by man.) Medium to well-sorted coarse sand to pebbles. Rounded to subrounded. Very thinly bedded in places with low angle cross-beds. Pelecypod shell fragments common throughout unit. Color 5YR 4/2. Minor $CaCO_3$ on bottoms of clasts.
5	145 - 325 cm BEACH RIDGE (High energy). Coarse sandy gravel. Mostly pebble-sized material; subrounded to locally subangular. Sorting is moderate within individual bedding horizons. Low angle cross beds. Upper boundary is erosional and planar in nature. Abundant disseminated $CaCO_3$. Alternating gravelly beds with coarse sand to granules. Very small pelecypod shell fragments. Locally contains thin beds of well-sorted sand. Color 5YR 4/2.
4	325 - 455 cm BEACH RIDGE. Sandy gravel to pebbly gravels. Thin to medium bedded with subrounded, medium to well-sorted clasts within beds. Alternating beds of gravel to coarse-fine sand with finer grained material concentrated in thinner beds. Small amounts of disseminated $CaCO_3$. Locally contains thin beds of well sorted sand with small pelecypod shell fragments. Top of unit contains shells. Most bedding dipping S20E. Color 5Y 4/1.
3	455 - 492 cm BEACH RIDGE to near shore environment. Thinly cross-laminated fine to coarse sand. Well-sorted, subrounded to rounded. Less than 1% gravel which is locally found as small lenses. Pelecypod shells and abundant ostracodes (5 - 10%) which are probably _L. Ceriotuberosa_. Lower boundary sharp but wavy due to bioturbation. Upper boundary sharp and smooth. Color 2.5Y 7/2.
2	492 - 541 cm NEAR SHORE ENVIRONMENT. Fine sand. Thinly bedded and very well sorted. Gravel content less than 1%. Overall unit is soft in nature. Well rounded clasts. Bedding is wavy parallel to parallel in nature. Extensively burrowed especially near top of unit which also contains many pelecypod shells, some of which are in growth positions. Bedding dips at 3 - 4 degrees to the SE. Overall unit contains up to 30% ostracodes which have been positively identified as _L. Ceriotuberosa_ (R. Forrester, pers. com. 1987). Upper beds are slightly more indurated due to disseminated $CaCO_3$. Color 5Y 7/2.

TABLE 9 (continued)

LITHOLOGIC DESCRIPTION OF BAKER HIGHWAY QUARRY

Unit Number	Description of outcrop - SOD-0-2
1	541 - 591 cm. Sandy gravel which is 50 - 60% gravel. Gravels are angular to subangular and composed of pebble to cobble sized metamorphic marble, quartzite, and volcanic lithologies. Overall grain supported, medium sorted. Matrix is composed of coarse to fine sand sized, subrounded to subangular material. Unit is strongly cemented with carbonate which increases with depth. $CaCO_3$ often nodular, especially at depth. Color 2.5Y 5/2. Upper boundary very sharp. Bedding is parallel to subparallel in nature and dips S80E at 5°.

Outcrop description by J. Knight, F-L. Miosssec and Y. Enzel

TABLE 9 (continued)

LITHOLOGIC DESCRIPTION OF BAKER HIGHWAY QUARRY

Unit Number	Description of outcrop - SOD-0-3
7	0 - 35 cm ARTIFICIAL FILL (disturbed by man).
6	35 - 65 cm BEACH RIDGE. Sandy gravel. Fine to coarse sand to cobbles. Low angle cross-bedding(?). Gravel fraction about 60%. Predominantly mafic metamorphics and quartzite. Lower boundary is sharp and planar subhorizontal in nature with a concentration of pebbles to cobbles in lower few cm. Also near the base is a thin layer concentrated Pelecypod shell fragments. Unit contains lesser amounts of shell fragments throughout. Color 5Y 6/4 (D).
5	65 - 98 cm CHANNEL FILL UNIT (24 - 33 cm thick). Upper boundary is horizontal and sharp. Lower boundary is irregular due to channelization and burrowing. Channel area is stacked upon channels of unit 3. Basal lag of rounded to subangular granules and pebbles with a few cobbles. An overall fining upwards sequence exists throughout the unit and culminates in a pelecypod shells layer about 10 cm thick at top (shells are oriented nearly vertical). Entire unit contains some shell fragments. Matrix is composed of granules to medium sand which fines upward to silty fine sand. Larger clasts composed of mafic metamorphics. Color at base 5Y 7/3; at top 5Y 6/3.
4	98 - 138 cm NEAR SHORE. Ostracode-rich sand with trace of granule-sized material. Granules are subangular to subrounded. Sand is well sorted and more mature than unit 2. Discontinuous laminae which have been disturbed by burrowing. Ostracodes are L. Ceriotuberosa (R. Forrester, pers. com. 1987) and are concentrated in the laminations. Complete pelecypod shells throughout unit. Upper boundary is truncated by channel scouring. More biogenic activity than lower sand. Internal scours are present. Color 5Y 6/3.
3	138 - 154 cm CHANNEL SCOUR (0 - 22 cm thick). Overall, poorly sorted gravelly sand. Sand fraction is fine grained and well-sorted, subangular. Gravel fraction composed of pebbles to granules composed predominantly of mafic metamorphics with lesser amounts of volcanics and marble. Discrete, well defined pebble layers with granules intermixed. Horizontal bedding. Upper boundary sharp, planar and horizontal in nature. Lower boundary variable and scoured into unit 2. Matrix color 5Y 6/3.

TABLE 9 (continued)

LITHOLOGIC DESCRIPTION OF BAKER HIGHWAY QUARRY

Unit Number	Description of outcrop - SOD-0-3
2	138 - 180 cm NEAR SHORE. Fine to very fine sand. Well-sorted with continuous laminations which have been disturbed by burrowing. Ostracodes and shell fragments present. Laminations are individual fining upwards sequences. Entire unit effervesces strongly. Lower boundary is sharp and planar. Upper boundary is irregular due to channelization. Color 5Y 6/3 (D).
1	180 - 270 cm ALLUVIAL FAN. Sandy gravel, very poorly sorted. Gravels are pebbles to granules of subangular nature. Massive to poorly bedded. Finer fraction composed of very fine sand which effervesces strongly in acid. Gravels occur in small horizontal lenses which show poorly developed laminations. No shells present. Upper boundary sharp and marked by a textural change from coarse to fine. Color 5Y 6/1 (D).

TABLE 9 (continued)

LITHOLOGIC DESCRIPTION OF BAKER HIGHWAY QUARRY

Unit Number	Description of outcrop - SOD-0-4
4	0 - 35 cm ARTIFICIAL FILL
3	35 - 53 cm. Similar to unit 2. Contains the same matrix as unit 2 but contains about 40% granules.
2	53 - 75 cm BEACH RIDGE-NEARSHORE. Laminated very coarse sand to granules alternating with very fine moderately sorted sand in base of unit. Grades upward to finer moderately sorted silty sand that eventually grades to sand without silt in highest part of unit. Top of unit is heavily burrowed.
1	75 - 100 cm BEACH RIDGE. Gravelly, sand, poorly sorted. Gravels are granules to pebbles with carbonate coatings and are angular to subangular. Unit is about 30% gravel. Poorly sorted sand matrix, fine to coarse, subangular to subrounded. Metamorhpic rocks are the dominant lithology. Unit effervesces strongly and contains no shells. Gradational upper boundary. Lower boundary not exposed. Color 2.5Y 7/2.

TABLE 9 (continued)

LITHOLOGIC DESCRIPTION OF BAKER HIGHWAY QUARRY

Unit Number	Description of outcrop - SOD-0-5a
5	0 - 61 cm BEACH RIDGE. Unit contains 5 fining-upwards sequences with subrounded pebbles and subangular cobbles at base of sequences grading upwards to granule or pebble to very fine sand with cross-bedded laminae which have low angle dips to the southwest. Lowest sequences shows the greatest range of grain sizes (cobbles to very fine sand) with cross-bedding restricted to finer fraction. Upper sequences are more homogeneous in nature and have steeper, better exposed cross-bedding.
4	61 - 106 cm NEAR SHORE. Sand. Thin basal granule layer grading to very fine to fine sand which appears bioturbated. Sand is well-rounded and well-sorted and contains abundant ostracodes. Minor pebbles from above unit via root casts. Many cycles in unit expressed as color changing from reddish to gray (2.5Y 7/3) (gleying in upper part of sequences). Top of unit is 283.58 masl.
3	106 - 152 cm NEAR SHORE TO BEACH RIDGE. Laminated to massive(?) fine sand. Overlain by granule sized stone layer. Overlain by gently-dipping cross bedded fine sand unit a few cm thick. Sharp boundary with stone layer which is overlain by a fine sand layer displaying well developed planar lamination. Upper boundary slightly wavy. Upper part of this layer has broken ostracodes and concave down pelecypod shells (horizontal). Color 2.5Y 7.3
2	152 - 180 cm BEACH RIDGE TO FLUVIAL. Thinly bedded sandy gravels that internally show scoured surfaces infilled with sand. Softly indurated Fe-oxide and carbonate on reworked clasts. Gravels are poorly sorted, subangular to subrounded granules with minor pebbles. Composed mainly of volcanics and metamorphics, with stripped $CaCO_3$ coatings. Sands are 2.5Y 7/2 in color, coarser fraction is redder. Lower boundary is sharp and wavy (was produced by ripple structures?).
1	180 - 215+ cm BEACH RIDGE. Sandy gravel. Pebbles, cobbles and granules comprise about 50% of unit which is poorly sorted and poorly bedded. Clasts are subangular to subrounded and are composed of mafic metamorphics. Some clasts show evidence of reworking of $CaCO_3$ coatings. 2.5Y 7/2

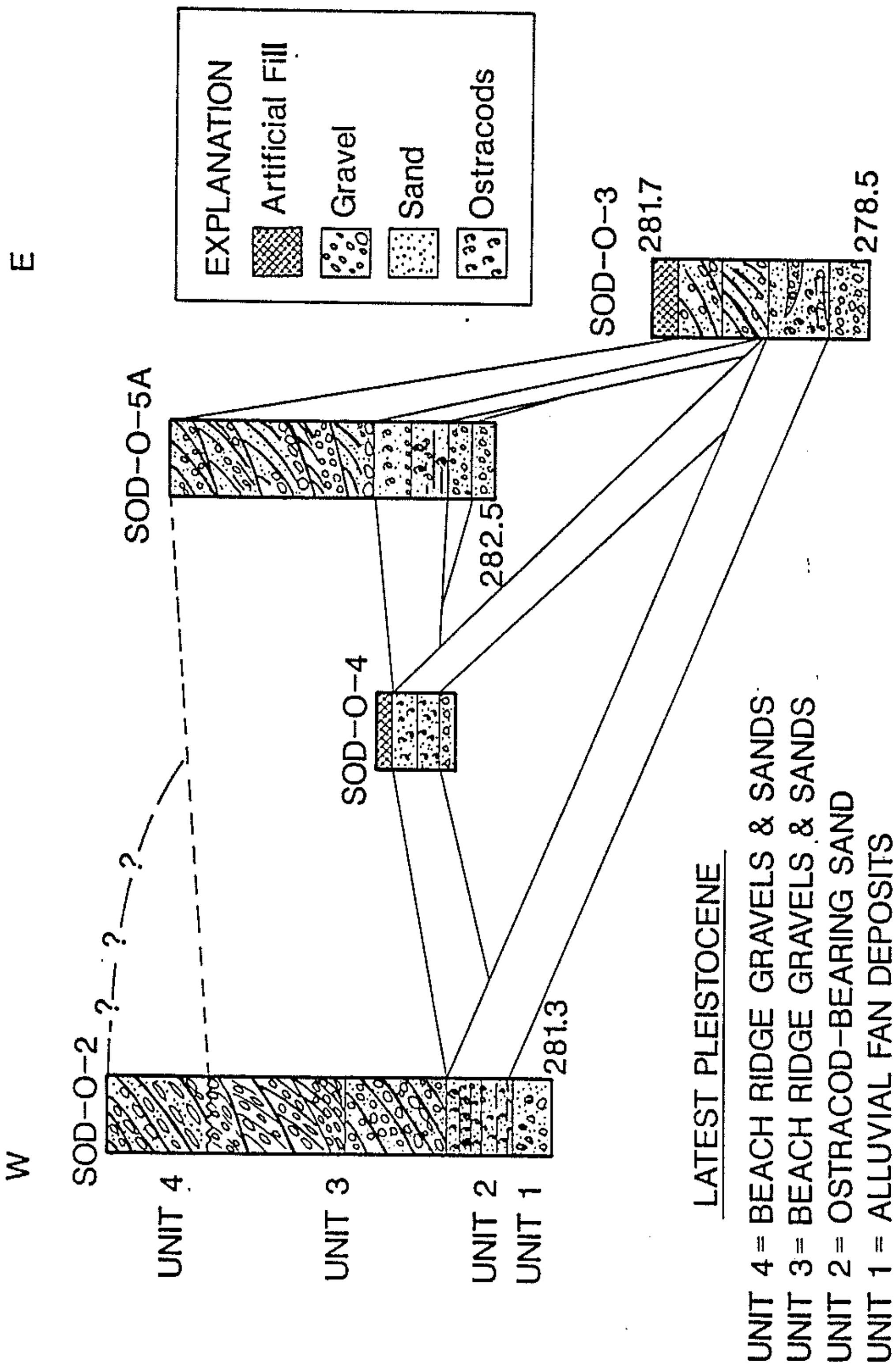


Figure 14. Fence diagram of beach sediments exposed in the Baker Highway quarry, northern Soda Lake playa, based on exposed stratigraphy and four detailed outcrop descriptions at the site (table 9).

are composed of angular, poorly sorted gravel-to-sand sized clasts of mafic metamorphic rocks, volcanics and minor quartzite. Bedding is poorly developed to massive in nature. Unit 1 is interpreted to be an alluvial fan. Unconformably overlying the alluvial fan is a fine to coarse sand deposit (unit II) containing abundant ostracodes identified as Limnocythera ceriotuberosa (R. Forrester, pers. com. 1987). Unit II is laminated to stratified in nature and has been bioturbated extensively. Abundant pelecypod shells (or shell fragments depending on the outcrop) are found throughout the unit. Evidence for channel scouring is found in the southernmost outcrop (SOD-3, table 9). This unit is overlain by a well-stratified gravel-rich deposit (unit III) with beds dipping gently toward the south. Pelecypod shell fragments are present locally in unit III, and these deposits are inferred to represent a southwardly prograding beach ridge. Outcrop SOD-2 contains another set of beach ridge deposits (unit IV) not widely observed at this locality due to removal during quarrying. Unit IV unconformably overlies unit III and contains medium to well-sorted pebbles and coarse sand. Unit IV appears to exhibit low-angle cross stratification that dips southward. This unit has been modified by human activity and has been partially reconstructed on disturbed outcrops.

A large shallow quarry, excavated in broad beach ridge deposit southeast of the town of Baker and used as the town's sanitary landfill, provides excellent exposures of Lake Mojave sediments (plate 3). Detailed descriptions of two quarry exposures reveal a complex history (table 10), and correlation among the exposures is illustrated in figure 15. The basal unit in the quarry is an eolian unit containing fine-to-medium grained quartz sand. Unconformably overlying this unit are alluvial fan sediments containing angular pebble-to-cobble sized clasts in a northern exposure and eolian

TABLE 10

LITHOLOGIC DESCRIPTION OF BAKER DUMP QUARRY

Unit Number	Description of outcrop - SOD-0-5
5	0 - 160 cm BEACH RIDGE (INNER) UNIT. Medium to coarse sand. Moderate to moderately well-sorted quartz rich material showing poorly stratified to non-stratified nature. Locally unit contains well-stratified lenses of well sorted, moderately well rounded sand. Trace pelecypod shell fragments. 5Y 6.5 (D) 5Y 6.5/3 (M). Several thin near horizontal beds of green sand containing secondary carbonate and possible evaporite minerals (thenardite?).
4	160 - 237 cm BEACH RIDGE/BAR (OUTER) UNIT. Very fine sand to coarse sand/granules. Moderate sorting with moderate to strong stratification. Dominantly grus with locally abundant well-preserved whole pelecypod shell and shell fragments. Locally the unit contains subrounded pebbles in lenses.
3	237 - 250 cm TRANSITIONAL UNIT. Poorly sorted sandy clay to pebble sized gravel. The finer fraction is composed almost totally of grus and quartz. The coarse fraction contains clasts of diorite, limestone and minor amounts of subrounded volcanics (Cima?). Overall, this unit fines upward. Some pelecypod shell fragments and locally abundant ostracodes near top of unit. Sand-sized fraction gives unit its color 5Y 5/3 (W or D). Beginning of Lake. Sharp lower boundary; gradational upper boundary.
2	250 - 285 cm ALLUVIAL FAN UNIT. Fine sand to pebbles. Poorly-sorted, moderately stratified nature with bedding about 4 - 5 cm thick. Composed dominantly of grus. Localized lenses of limestone and diorite pebbles. Some eolian fine-medium sand layers at top of sets. Most of unit 7/5YR 5/8 (D) 8.75YR 5/4 (W). Stage 1 to 1+ $CaCO_3$ development (same as unit 1).
1	285 - 350+ cm EOLIAN UNIT. Medium-poorly sorted sand. Moderately poor to poorly laminated. Less than 5% silt in matrix. Two distinct horizons. 320 - 350+ cm - 10YR 7/4 (D) 10YR 3/3 (M) 285 - 320 cm - 10YR 5/5 (D) 10YR 3.3.5(M). Both horizons have a 1 cm thick $CaCO_3$ lamination (non-continuous) and $CaCO_3$ nodules as well. Upper contact sharp and very slightly wavy (erosional).

TABLE 10 (continued)

LITHOLOGIC DESCRIPTION OF BAKER HIGHWAY QUARRY

Unit Number	Description of outcrop - SOD-O-6
5	0 - 60 cm BEACH RIDGE (INNER UNIT). Medium to coarse sand. Moderate to moderately well-sorted quartz-rich material showing poorly stratified to non-stratified nature. Locally unit contains well-stratified lenses of well-sorted, moderately well rounded sand. Trace pelecypod shell fragments. 5Y 5/3.5 (D) and 5Y 6.5/3 (M). Several thin, near horizontal beds of green sand/silt containing secondary carbonate and possible evaporite minerals (thenardite?). Same as unit 5 in Outcrop SOD-O-5.
4	60 - 150 cm BEACH RIDGE. Cross bedded coarse sand with lesser amounts of granules to pebbles. Moderately well sorted. Very minor amounts of pelecypod shell fragments.
3	150 - 250 cm BEACH RIDGE/BAR (OUTER) UNIT. Fine sand to coarse sand, granules and pebbles. Moderate sorting with moderate to strong stratification. Predominantly grus with locally abundant well-preserved pelecypod shell fragments. Locally the unit contains subrounded pebbles in lenses. Many thin horizontally continuous green fine sand/silt layers with $CaCO_3$ and thenardite(?). Same as unit 4 in outcrop SOD-O-5, except overall coarser in nature.
2	250 - 275 cm ALLUVIAL FAN UNIT. Fine sand to granules and minor pebbles. Poorly sorted, moderate stratified nature with bedding about 4 - 5 cm thick. Composed mainly of grus. Localized lenses of limestone and diorite pebbles. Some eolian fine-medium sand layers at top of sets. Most of unit 7.5YR 5/8 (D) 8.75YR 5/4 (M). Stage 1 to 1+ $CaCO_3$ development. Soil development in this unit penetrates into lower eolian unit. Same as unit 2 in SOD-O-5.
1	275 - 360+ cm EOLIAN UNIT. Fine to medium well-sorted sand. Moderately poor to poorly laminated. Less than 5% silt in matrix. Two distinct horizons. Both horizons have a 1 cm thick $CaCO_3$ lamination (non-continuous) and $CaCO_3$ nodules as well. Upper contact sharp and very slightly wavy (erosional). Same as unit 1 in SOD-O-5.

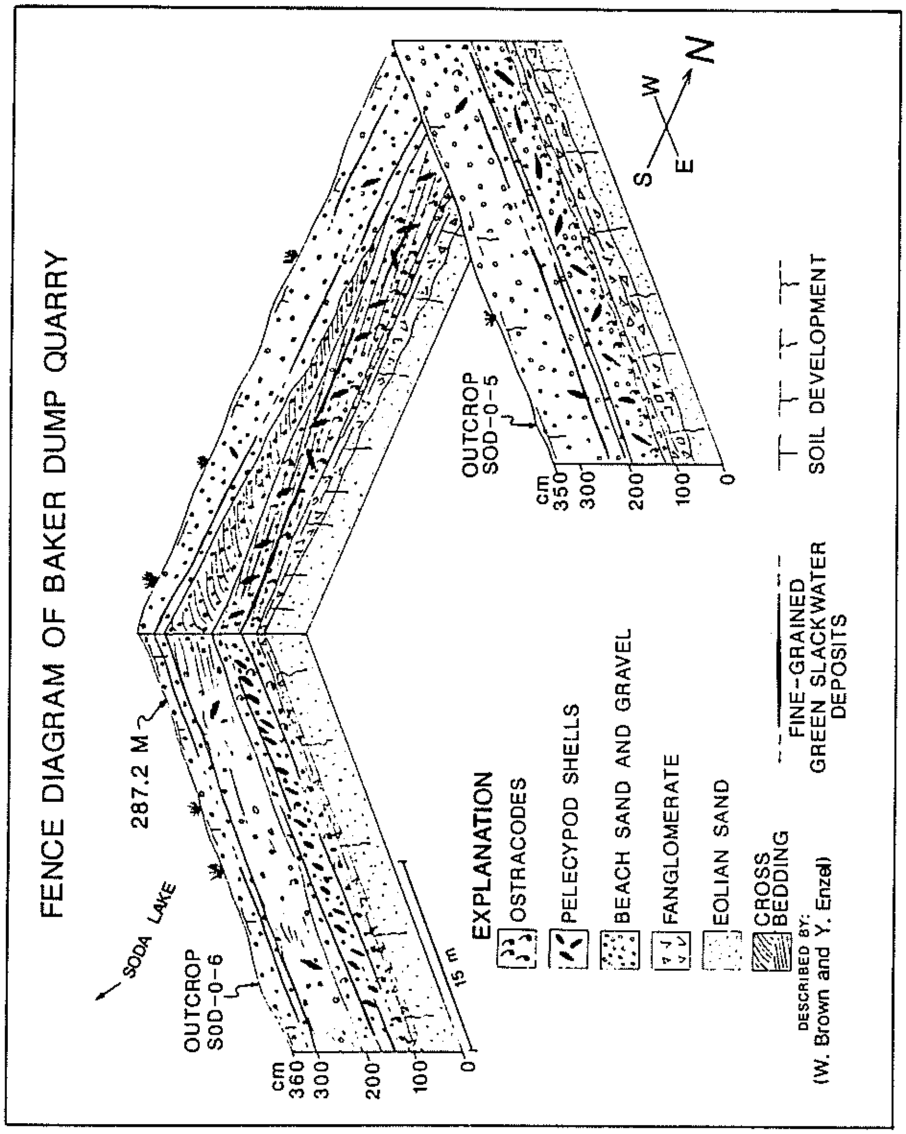


Figure 15. Fence diagram of sediments exposed in the Baker Dump quarry, A-shoreline beach ridge, northern Soda Lake playa, based on exposed stratigraphy and two detailed outcrop descriptions (see table 10) at the site.

sediment mixed with granule-to-pebble sized clasts in the southern exposure. A soil is developed in these two units containing stage 1+ pedogenic carbonate in the lower portion of the alluvial unit and in the upper portion of the eolian unit. Both units display reddened horizons (color = 7.5YR 5/8, dry). Sediments overlying these units are lacustrine in origin.

A thin irregular transitional unit is present in the northern outcrop and is composed of poorly sorted sandy green clay to pebble-sized gravel. The deposits are upward fining and contain shell fragments with locally abundant ostracodes (Limmocythere ceriotuberosa) (R. Forrester, pers. com. 1988) near the top. This unit pinches out laterally toward the south and grades vertically into an overlying unit composed of quartz-rich, very fine to coarse sand. The sediments are moderately sorted and strongly to moderately stratified in nature. The southern outcrop contains several horizontally continuous, thin, green silt-rich/carbonate-rich bands. Foresets dip gently toward the south-southwest and indicate a beach ridge/bar prograding in that direction. Abundant pelecypod shells are present throughout this unit. Overlying the shell-rich unit are two more beach ridge units. The older of these deposits is approximately one meter thick and composed of southward dipping cross-bedded coarse sand with very minor amounts of shell fragments. These deposits pinch out to the north and are overlain by the youngest sediments which are composed of poorly stratified to locally well-stratified, medium-to-fine sand, containing several thin green fine-sand/silt bands rich in $CaCO_3$. The entire sequence exposed at the dump quarry represents a prograding beach ridge complex and marks a transition from outer ridge/bar/offshore to inner ridge backbeach deposits. The top of the sequence has an elevation of 287.2 m, indicating the ridge formed during the Lake Mojave stand at the A shoreline.

Extending from the beach ridge at the Baker dump quarry is a very large, almost continuous sand ridge that trends southward in a crescentic arc toward Granite Island, a bedrock outcrop that was isolated from the mainland during the highest lake stand (plate 3). This beach ridge has a maximum elevation of about 285.5 m at its crest and, therefore, corresponds to the elevation of the B shoreline. Locally, the ridge has been eroded by alluvial-fan channels, covered by small eolian dunes and modified extensively by human activity. *Anadonta californiesis* (pelecypod) shells from 40 cm below the ridge surface at location SOD-1-1 (plate 3) were radiocarbon dated at 12,020 ± 130 years B.P. (table 4). The shells are found stratigraphically about 15 cm. below a thin, magnetite and basaltic sand-rich horizon possibly related to basaltic volcanism at the A cone of the Cima volcanic field (figure 2). Surrounding Granite Island are several higher beach ridges and locally preserved wavecut scarps that correspond in elevation to the A shoreline (287 m). The southwestern margin of Granite Island has three separate beach ridge levels in which recessional shoreline wavecuts are preserved (figure 16). It is possible that these wavecut/shorelines represent the yearly drops in the lake and record annual evaporation rates. These features correspond with similar recessional wavecuts preserved in an isolated beach ridge along the northwestern flank of Soda Lake basin (plate 3). Directly west of Granite Island is a well-preserved series of beach cusps cut into the B- shoreline ridge, suggesting that Lake Mojave wave activity was striking the shoreline head with little or no longshore current. The B-shoreline ridge continues south of Granite Island approximately 0.3 km before the ridge terminates at the margin of active alluvial fans. Many of the bedrock areas that outcrop near the present playa surface along the eastern margin of Soda Lake and south of Granite Island have wavecut notches corresponding to the 287 m high A

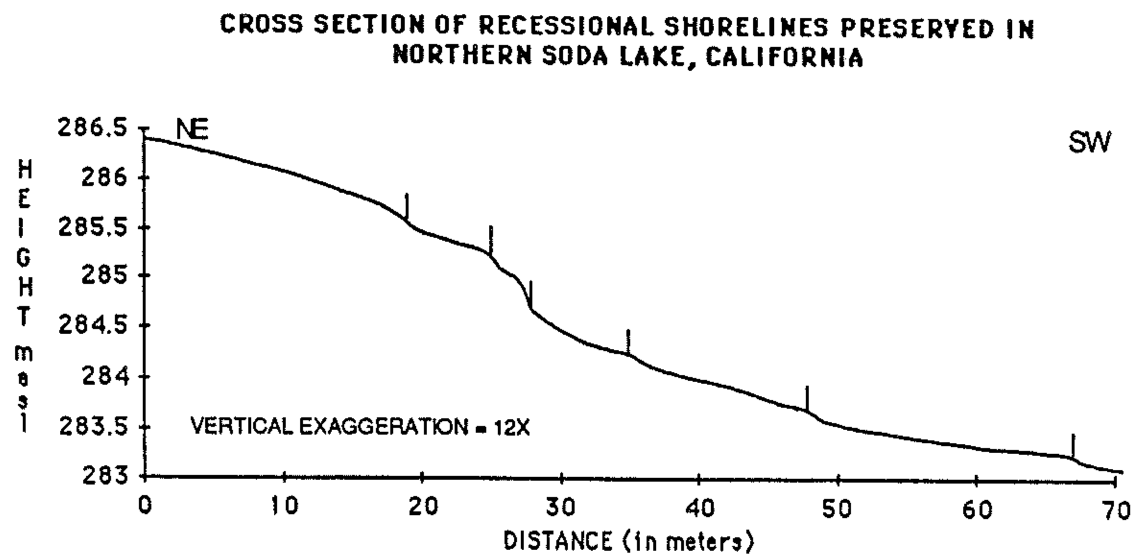


Figure 16. Cross section of recessional shorelines preserved in the Elephant Ridge beach complex, Granite Island, northeastern Soda Lake playa.

shoreline. In addition, several small beach surfaces are preserved in this area, the most extensive found near an abandoned mine at the extreme southern end of Little Cowhole Mountain.

Several other locations along the northern flanks of Soda Lake basin show evidence of beach ridges and/or wavecut features. A large beach ridge on the northwestern margin of Soda Lake playa has features corresponding to 287 m, 285 m and 283 m shorelines. In addition, a series of recessional berms cut into these surfaces appear to represent annual lowering of the lake/yearly evaporation, suggesting incremental lowering of 0.5 m between wavecuts. Similar features are found on the other side of Soda Lake southwest of Granite Island (figure 16).

A much smaller pair of beach surfaces has been preserved along the western flank of Soda Lake playa near the edge of the Soda Mountains (plate 3). A small bedrock outcrop has shielded these surfaces from fluvial erosion. The height of a moderate- to poorly-defined wavecut scarp (A shoreline?) developed in bedrock near these beaches suggests these deposits are related to the B-shoreline of Lake Mojave. The Soda Springs area, which is the site of the Desert Studies Consortium, contains a very large beach ridge extensively modified by human activity.

On the western side of Soda Lake, wavecuts are found in exposed bedrock extend several km north of Soda Springs. The absence of major bedrock outcrops south of the Soda Springs area, the prograding fan-delta of the Mojave River from Afton Canyon, and extensive eolian deposition of have resulted in little preservation of latest Quaternary Lake Mojave shoreline features in the southern Soda Lake basin. Core data discussed in the section below indicates that Lake Mojave extended south all the way to Crucero and west towards Afton Canyon (figures 10 and 17).

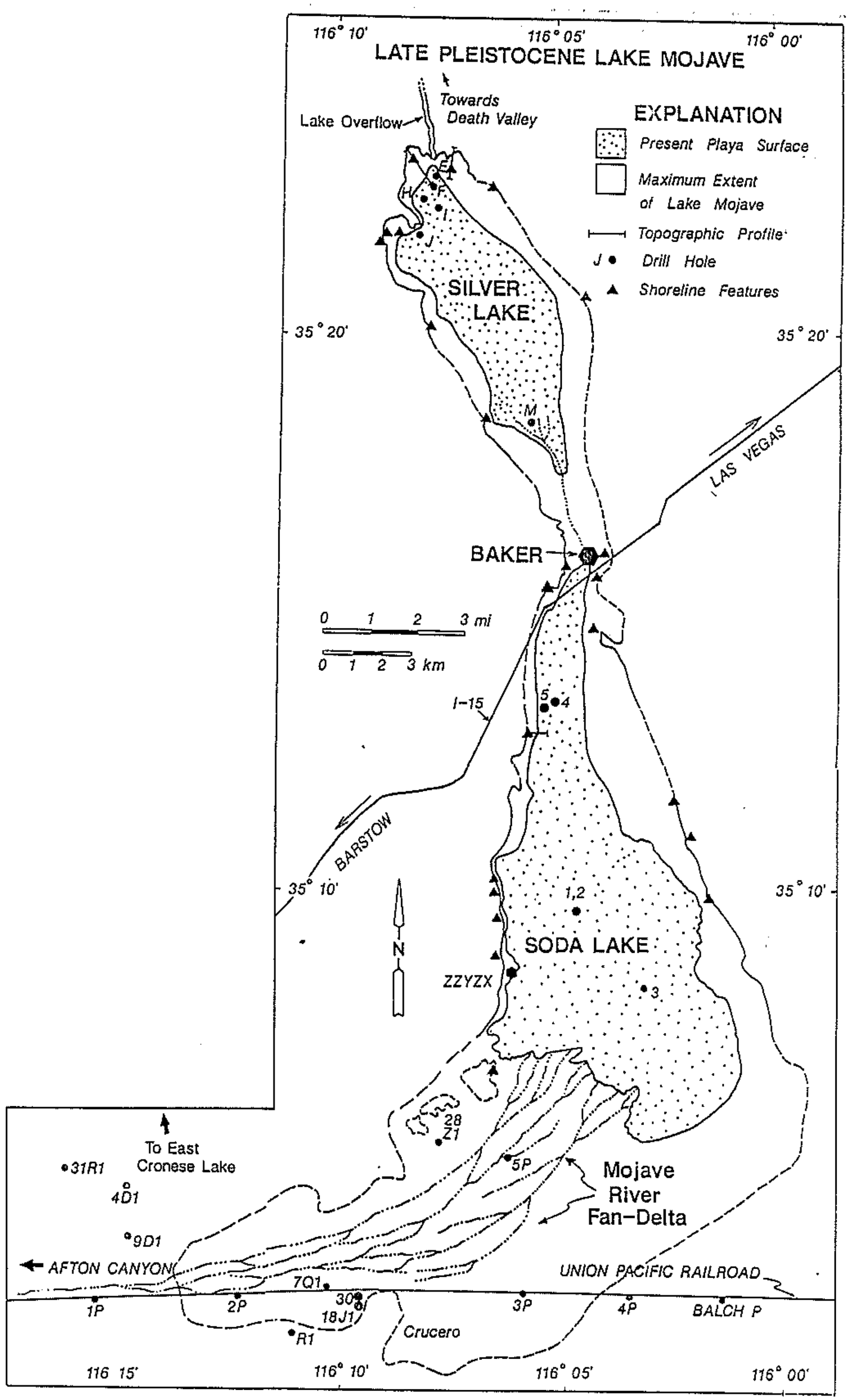


Figure 17. Map showing the maximum area extent of Latest Pleistocene Lake Mojave. Shoreline features are indicated by a Δ, drill holes are indicated by a •. The modern playa surface is shown with a stipled pattern.

Subsurface Stratigraphy of Lake Mojave Deposits

Overview. A total of thirteen cores were drilled in Silver Lake basin during this project; eight of these cores were studied in detail (figure 16). Cores Sil-I and Sil-H were drilled in the center of northern Silver Lake playa and show evidence of water conditions deeper than any of the other cores, in addition to having the greatest thicknesses of lacustrine clays. Cores Sil-J and Sil-F were drilled in more marginal settings, maximum depth to lacustrine sediments in these areas is substantially less than cores Sil-I or Sil-H. Sediments in core Sil-E, drilled near the present playa/fan interface, indicate the shallowest, most marginal conditions of any core site drilled in Silver Lake basin. Cores Sil-G and Sil-L were drilled in Tidewater basin and the small topographic depression behind the highest beach ridge in Tidewater basin, respectively (plate 1). Sil-G contains interbedded lacustrine clay and sand to gravel-sized sediment units. Sil-L contains no lacustrine sediments and is composed of alluvium/colluvium and bedrock. Two cores were drilled in the fan-delta area of Silver Lake basin, Sil-M and Sil-N (figure 16) and contained the best preserved record of Holocene conditions in the basin.

Detailed descriptions of the above cores were found in Brown (M.S. thesis, in preparation) and are plotted at a scale of either 1:10 or 1:20, depending on the complexity and relative spacing of events in each core. Sediments in the core can be grouped into three categories: (1) pre-Lake Mojave sediments characterized by coarse-grained sand and gravel deposits as alluvial fans; (2) lacustrine sediments composed mainly of reduced green to blue, clay-sized particles indicating persistent standing water; and (3) stratigraphically youngest playa sediments composed of oxidized brown, disturbed and non-laminated mixtures of silt, sand, and clay indicating dry conditions punctuated by occasional wetting events. The stratigraphy of these sediments provided critical paleohydrologic information for the first time about Lake Mojave and younger sediments. Within the lacustrine sediments, paleoflood events are recognized as thin layers of larger particle size interspersed within laminated-to-sublaminated clays or as drying events or partial drying/lake lowering events overlain by clay-sized lacustrine sediment. Within the playa sediments, paleoflood events are recorded as thin clay-rich lacustrine sediments. These features provide the critical data base for interpreting latest Quaternary hydrologic resources of the Mojave River and its terminal Lake Mojave.

Hydrologic Events Recorded in the Subsurface Stratigraphy of Lake Mojave Sedimentologic Events for Paleoflood Events. Initial logging of the cores revealed thin bands of relatively coarser non-laminated sediments occurring at irregular intervals within fine-grained, laminated to sublaminated clay-sized sediments. These relatively coarser layers are accentuated typically by an accompanying color change and are almost always rich in silt-sized clasts. These coarser bands of sediment are composed of a distinct lithologic "fingerprint" of phlogopite-rich sediments whose source is somewhere in the Mojave River drainage basin and are, therefore, interpreted as being transported during large-scale flooding events sourced in the upper basin of the Mojave River. Field investigation of recent Mojave River overbank and flood- discharge sediments near the mouth of Afton Canyon and in the present-day Silver Lake and East Cronese Lake fan-deltas indicates an exceptionally high proportion of phlogopite in these flood sediments. Bedrock geology within the local Soda and Silver Lake basins exhibits no major formation containing large amounts of phlogopite (Grosse 1959), rather the source of the phlogopite is in the headwater region of the Mojave River.

Several stream sediment samples collected near Victorville, California contained abundant phlogopite particles.

Local high-discharge events, resulting from precipitation in the mountains surrounding the two lake basins, deposit sediments with a characteristic "fingerprint" representing some aspect of their source rock geology. Several thin coarser units containing abundant diorite clasts (rich in amphiboles) and locally rich marble clasts are found sporadically in the Silver Lake cores, especially those in the center or western margin of the lake where many of the bedrock outcrops are composed of diorite and marble. The basal portion of these bands is usually non-laminated and consists of poorly sorted medium sand-to-clay sized particles. These sediments grade abruptly to an increasingly well-laminated, upward-fining sequence eventually becoming indistinguishable from the more common lacustrine laminated to sublaminated clays. These vertical sequences are inferred to be sediment derived from localized runoff/flooding, possibly producing turbidity currents or subaqueous flows. The eastern margin of the lake, as represented by the Sil-E core, contains many sand-to-granule sized intervals produced during lake lowering and/or progradation of the fan surfaces into the basin during a local storm or high-magnitude runoff event. These sediments are composed almost entirely of grus and quartz which have been transported from granitic outcrops to the east.

Different types of paleoflood events are defined by comparing the clast size of the flood deposits with the grain size of the underlying lacustrine sediments and assigned a relative number based on this comparison (table 5). These events ranged from well-defined to relatively indistinct in nature. The most common types of flooding events are (1) dark coarse (?) clay with minor silt-sized phogopite overlying clay and (2) silt containing phlogopite and some clay overlying clay.

Lake Lowering Events/Partial Drying Events. Sediments found in the drill cores are separated into two types: (1) chemical precipitates and (2) detrital. Lake Mojave sediments are dominated by an influx of detrital sediments from the Mojave River and are dominantly clay and silt-sized. Chemical precipitates are found in selected localities throughout the core as thin bands of $CaCO_3$ and/or Na_2SO_4 (thenardite) and $Na_2SO_4 \cdot 10H_2O$ (mirabilite). Halite is present throughout most of the younger lake sediments but is disseminated in nature. No gypsum has been found in any surface or subsurface samples obtained from the Silver Lake basin. Occasionally, as many as nine bands of precipitates (alternating with detrital clays and silt) are found adjacent to each other. However, generally only one to four couplets are found in any one section of core. Frequency of these bands in individual cores increases with increasing proximity to the paleo-shoreline (shallower conditions). Core Sil-H, which represents the deepest water conditions of any core in the lake, has the fewest; whereas, core Sil-E has individual $CaCO_3/NaSO_4$-rich bands or layers up to 12 cm thick. Relative abundance of these bands in other cores falls somewhere between the above two extremes. Stratigraphically, these bands are often found directly below mudcracks, suggesting they are somehow related to drying episodes of the lake. If both minerals are present in a core, the $CaCO_3$ (less soluble mineral) is always found stratigraphically below the $Na_2SO_4/Na_2SO_4 \cdot 10H_2O$ (more soluble mineral) bands. Microscopic analysis of the $CaCO_3$ bands indicates they are composed of non-organic microcrystalline calcite. Ostracode concentrations are often found below or above these bands, indicating possible shallow water/near shore conditions at that locality. Thenardite/mirabilite bands are also composed of crystalline $Na_2SO_4/Na_2SO_4 \cdot 10H_2O$. This sequence is typical for evaporative conditions and forms when evaporation and lowering of the lake waters produced supersaturated conditions for a given mineral species. During the summer months, evaporation rates, biogenic activity, and water temperatures increased to maximum values ($CaCO_3$ solubility decreases with increasing temperature), conditions ideal for production of supersaturated solutions of $CaCO_3$ (Dahm, pers. com. 1988; Hardie, Smoot and Eugster 1978) and Na_2SO_4. The presence of Na_2SO_4 and $Na_2SO_4 \cdot 10H_2O$ along with $CaCO_3$ suggests that even though biotic activity was present it probably played a subordinate role in the precipitation of these evaporite minerals.

These precipitate bands are correlated among the individual cores (see section below) and typically change in composition from $CaCO_3$ in the deeper cores to $Na_2SO_4/Na_2SO_4 \cdot 10H_2O$ in the more proximally located cores (plate 4). Analysis of ostracode species present in the the Mojave Lake sediments indicate the alkalinity was dominated by Na and Cl (R. Forrester, pers. com. 1987). Analysis of two samples of water taken from East Cronese Lake after a winter flood in 1978 indicates the most common ionic species in solution currently entering the Mojave sump to be HCO_3^-, SiO_2, Cl^-, SO_4^{2-}, Na^+ and Ca^{2+} in order of abundance (Drover 1979).

Laminations. Several cores contain localized thin laminations or couplets. These couplets differ from the above partial drying/lake lowering events in that these laminations are thinner and more regular in nature. Two couplet types have been identified in the sediments. Core Sil-J contains several zones in the sediments of the Lake Mojave II phase that have alternating dark gray/black fine laminations interbedded with green clays. These laminations show no visible grain-size differences and appear to be caused by some type of "staining" of the typically green clays, possibly due to concentration and reduction of some metallic species. When present these laminations appear to have an seasonal (?) cycle (based on couplet thickness compared to average sedimentation rates) and a longer cycle in which every eight-to-ten couplets contain a thicker black bano. Evidence of these black stains/laminations is found in many of the cores representing deeper water conditions (Sil-F, Sil-H, Sil-I and Sil-J) and appear as subhorizontal blebs and sublaminae often disturbed by soft sediment deformation during compaction, bioturbation, and possibly during core drillings. The other couplet type found in Silver Lake cores is best recorded in core Sil-E (lake margin environment). Couplets, from 1.5 to 0.9 mm in thickness depending on the location in the core, are composed of very fine laminae of $CaCO_3$ (less than 0.1 mm thick) interlayered with thicker green clay bands. These laminations could be either biologically or chemically precipitated or both and are interpreted as being annual varves (deposited seasonally).

Drying Events and Desiccation Cracks. Mudcracks are preserved in selected localities in cores drilled in Silver Lake basin. Mudcracks or shrinkage cracks as they are sometimes called can form by two processes in a saline lacustrine environment: by desiccation (subaerial conditions) and by syneresis (subaqueous conditions) processes (Plummer and Gostin 1981). Numerous factors control formation of shrinkage cracks. Variations in salinity of the depositing medium, percentage and composition of mud (amount of clay-sized particles), temperature and persistence of alternating wetting-drying cycles all play a role in the formation of shrinkage cracks (Kindle 1917; Kindle and Cole 1938; Dow 1964; Baria 1977; summarized in Plummer and Gostin 1981). Ideal conditions for the formation of large desiccation cracks are low salinity, high temperature, high percentage of swelling clay, and long exposure. These cracks tend to intersect, forming triple junctions in plan view and forming "V" shaped cross-sectional profiles.

Syneresis cracks can form in a fresh-saline water environment if the substrata is composed of swelling clays. Under experimental conditions muds containing as little as 2% smectite clays formed syneresis cracks when salinity and temperature changes were induced to the depositing water (Dangeard et al. 1964; Burst 1965). These cracks were formed by shrinkage of clay lattices in response to salinity changes or by dewatering of clay minerals/muds upon compaction. Syneresis cracks can form at the sediment water interface or along bedding planes below but near the sediment water interface. These cracks are "V" shaped in cross-sectional view and generally form spindle shapes in plan view that rarely intersect to form polygonal patterns (Glaessner 1969; Plummer and Gostin 1981).

Identification of processes which formed a given episode of shrinkage cracks; desiccation/subaerial or syneresis/subaqueous can be difficult in cross-sectional profiles such as lake cores. Examining the basal sections of these shrinkage events can provide clues. Syneresis cracks rarely form polygonal cracks-they are almost always spindle shaped in plan view. The number of generations of syneresis cracks in any one locality rarely exceeds one; whereas, desiccation cracks commonly are formed over multi-generations (Plummer and Gostin 1981). Features associated with each type of crack can lead to positive identification of their origin. Many of the shrinkage cracks preserved in the cores contain coarser (eolian-fluvial) sediment infilling (often oxidized) and/or are associated with partial drying/lake lowering evaporite-rich banding, indicating a desiccation origin. Based on the above information, the majority of shrinkage cracks found in Silver Lake cores apparently were formed during desiccation of the lake. A few of these shrinkage cracks have unknown origins.

Lacustrine and Playa Phases in Silver Lake Basin

Based on the sediment characteristics and distribution of partial and total drying events recorded in the cores, the sedimentary history of pluvial Lake Mojave is divided into six major phases: Incipient Lake, Intermittent Lake I, Lake Mojave I, Intermittent Lake II, Lake Mojave II, and Intermittent Lake III. Each phase contains a package of sediments interpreted to represent specific types of hydrologic conditions of Lake Mojave (figure 18). These sedimentary packages are correlative among the numerous cores within the Silver lake basin (figure 18). The other major depositional units found within the cores include older playa and alluvial-fan sediments and younger playa sediments.

Stratigraphic Sequence. Underlying Lake Mojave lacustrine sediments are angular-to-subrounded, gravel-to-sand sized clasts that display moderate to strong stratification and sorting. Pedogenic carbonate ranging from stage I to II is present on clast surfaces and as disseminated matrix. This unit is interpreted to be an alluvial-fan deposit correlative with units Qf1 and QfO fan surfaces discussed by Wells, McFadden and Dohrenwend (1987). Overlying the fan sediments is a deposit composed of sand to coarse silt that exhibits upward fining sequences and is found in both the I and H cores (figure 18). This represents a combination of eolian material and reworked playa deposits possibly correlative with unit Qel of Wells, McFadden and Dohrenwend (1987). This unit grades vertically into the Incipient Lake phase which is characterized by many upward-fining sequences (10-20 cm thick), consisting of

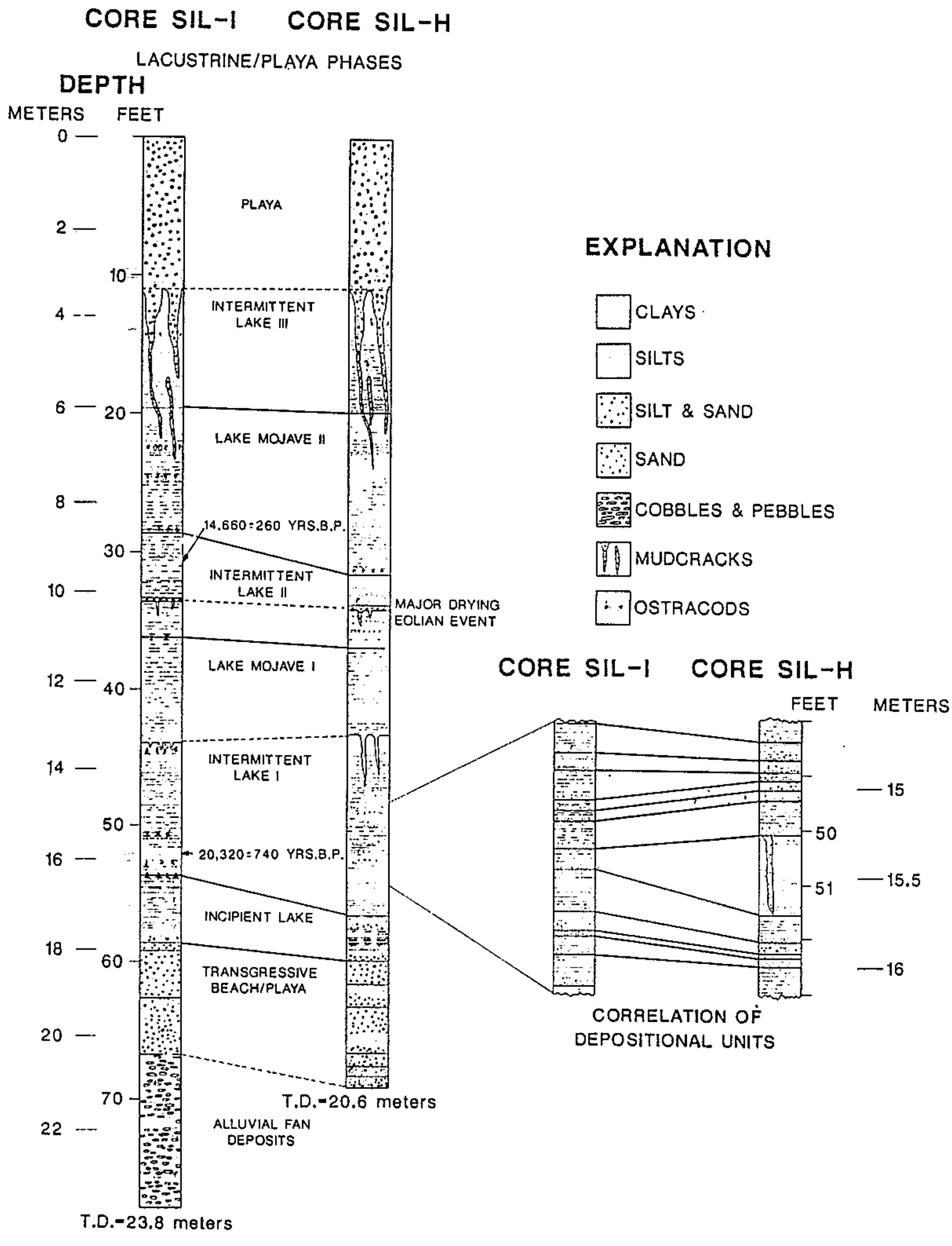


Figure 18. Simplified core descriptions of drill holes Sil-I and Sil-H, northern Silver Lake playa. Major lake phases are indicated based on lacustrine conditions represented by sediment in cores. An expanded view of the zone between 14 and 16 m depth is shown to emphasize the detailed nature of event correlations between the two core locations. The location of AMS radiocarbon dates are also shown.

sand-coarse silt-sized particles at the base grading to generally non-laminated, fine silt-clay sized particles at the top. These sediments are characteristically gray-to-pale green in color. The Incipient Lake phase grades vertically into the overlying Intermittent Lake I phase which is characterized by non-laminated to laminated clay-sized sediments that contain types (1) (2) and (5) flooding events (see table 3). Ostracodes and locally preserved diatoms are common throughout this sedimentary package, indicating long-term sustained water levels. These long-term lake stands are separated by drying events indicated by desiccation cracks. An absence of drying events distinguishes the overlying Lake Mojave I phase from underlying and overlying phases. Continuous water existed in Silver Lake basin in the areas of cores Sil-I and Sil-H during the Lake Mojave I phase. Ostracodes and diatoms are present throughout sublaminated olive green-to-blue clay-sized sediments. Numerous flooding events are found in this phase with types (2) and (1) being the most common (see table 5).

Sediments of the Intermittent Lake phase II rest conformably on the Mojave I phase sediments and exhibit sediment and faunal characteristics similar to the Intermittent Lake I phase. More mudcracks are found in the sediments of this period than any other lake phase, several of which could have been formed by syneresis processes. The most extensive drying period during the history of pluvial Lake Mojave occurred during this phrase and is indicated by large, distinctive desiccation cracks infilled with sand-sized material (and overlain by several centimeters of well-sorted fine sand in most cores). This unit represents a tie-line/positive correlation between all cores drilled in Silver Lake playa (see plate 4). Several smaller drying events occur stratigraphically above and below the larger event. Sediments of the Intermittent Lake II and older phases rarely contain partial drying/lake lowering evaporite bands. Diatoms from these lake phases indicate generally deeper, less saline water conditions than in the younger lake phases (J.P. Bradbury, pers. com. 1988). Overlying the Intermittent Lake II phase is the Lake Mojave II phase characterized by numerous partial drying/lake lowering events found in laminated to sublaminated clay-sized sediments. Total drying events are absent from this phase, indicating long-term stands of water. Ostracodes are common; however, diatoms are absent (J.P. Bradbury, pers. com. 1988). Very large desiccation cracks, containing oxidized silt- and sand-sized material, extend vertically from the top of the Intermittent Lake III/Playa boundaries and penetrate the upper sediments of Lake Mojave II (figure 18). These desiccation cracks have extensively disturbed original structures in the Sil-I and Sil-H cores. Overlying the sediments of Lake Mojave II is the last major lacustrine sediment package, Intermittent Lake III, which is very similar to the Lake Mojave II sediments. The major difference being total drying events recorded in the Intermittent Lake III sediments. Preservation of original structures is poor due to the extensive desiccation cracks formed during the transition into the overlying Holocene playa sediments. Cores Sil-J, Sil-F, and Sil-E contain the most complete record of lake fluctuations during the Intermittent Lake III phase and will be discussed in a following section.

Playa conditions have prevailed in the Silver Lake basin since the end of the Intermittent Lake III phase. The playa sediments are composed of relatively featureless sand, silt, and clay which were physically disrupted during repeated wetting, drying, and desiccation cracking. This disruption resulted in a mixture of sediments with original depositional structures obliterated. Four thin packages of lacustrine sediments occur within 2.0 meters below the playa surface and indicate that during the Holocene at least four short-lived "wet" periods produced temporary lakes in the Silver Lake basin (figure 19).

Isotopic and Geomorphic Dating of Lacustrine and Playa Phases. Pluvial Lake Mojave existed from approximately 22,000 to 8,500 years ago based upon radiocarbon dating of shell material and tufa on shoreline features (Wells et al. 1987; Ore and Warren 1971; Brown, M.S. thesis, in prep.) and from recently obtained radiocarbon dates of organic matter in the Silver Lake cores (table 4). Two dates on organic material from core Sil-I at approximate depths of 9 and 16 m below the playa floor are 14,660 ± 260 years B.P. (Beta-21,800) and 20,320 ± 740 years B.P. (Beta-21,801), respectively (figure 18). The oldest isotopic date from the shore features of Lake Mojave is 16,270 ± 310 years B.P. (Beta 29553). Thus, the oldest date from the core demonstrates that Lake Mojave reached Silver Lake basin as early as 22,000 years ago. The thicker pluvial sediments from Soda Lake basin may contain even older lacustrine units (figure 10).

Using the distance between two age dates obtained from core Sil-I, a long-term sedimentation rate of 1.08 m/1,000 years is estimated (figure 18). Application of this rate to the sediment column above the youngest date yields an estimated age of 8,730 years B.P. for the top of the Intermittent Lake III phase/end of pluvial Lake Mojave. When compared to the average age of the youngest two shore dates (table 4; Ore and Warren 1971), the age estimated by the sedimentation rate differs by only 0.2% from the radiocarbon dates on tufa from the youngest unit in the Silver Lake quarry (table 4). The remarkable similarity between surface and subsurface ages suggests the use of an average sedimentation rate for age estimations is reasonable. The concordance of different dating methods is presented in figure 20. This is a summary figure

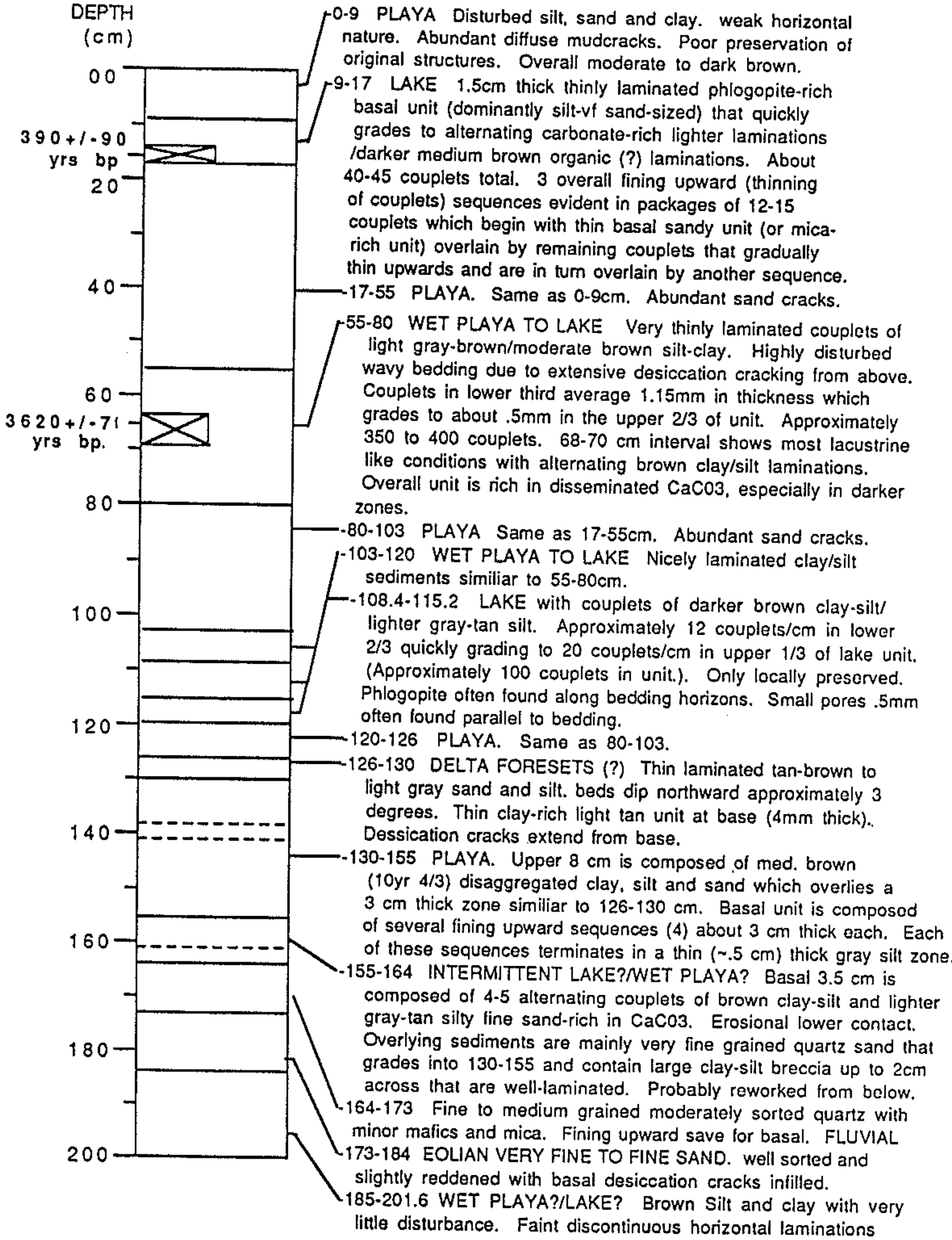


Figure 19. Detailed description of sediments preserved at site M in the fan-delta complex of Silver Lake playa. This information is from two cores, Sil-M and Sil-N drilled to a depth of 6.4 m and from a trench excavated to a depth of 1.6 m. A total of four lacustrine intervals are present in the upper 2.2 meters of sediment. The upper two have been dated at 390 ± 90 and 3620 ± 70 years B.P., respectively and coincide with the worldwide periods of greater effective moisture during the "Little Ice Age" and the "Neoglacial" (see text for further explanation).

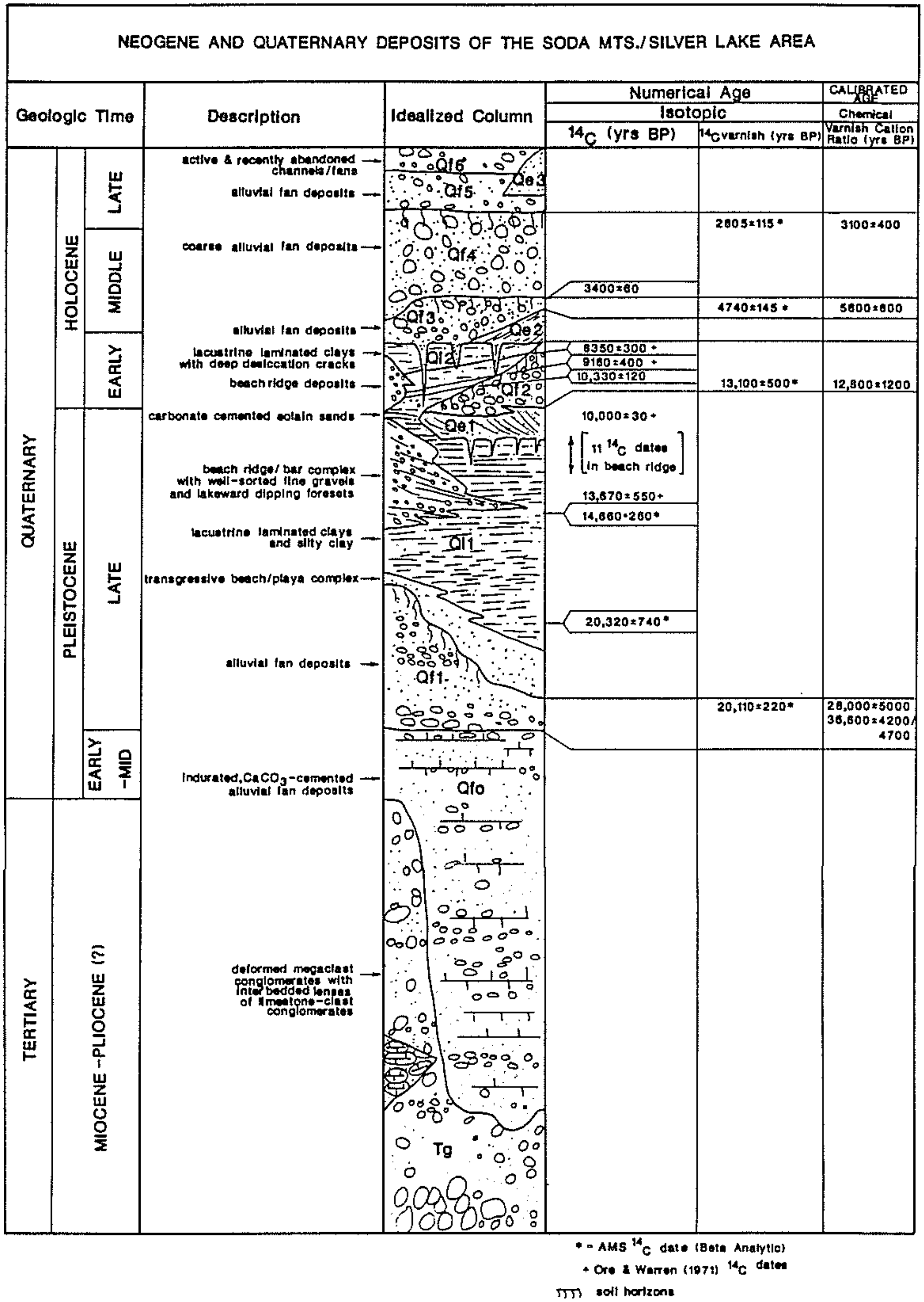


Figure 20. Summary of the relationship between piedmont and lacustrine geomorphic units - Silve Lake, California. Based on stratigraphy and various age dating techniques.

of major alluvial fan, eolian, and lacustrine stratigraphic units and their associated numerical and calibrated ages for Silver Lake basin. Several independent dating procedures support the dates obtained from the cores in Silver Lake.

Using this geomorphic dating method, the earliest lake sediments in the Intermittent Lake I phase are approximately 22,000 years old. The Lake Mojave I phase apparently existed for approximately 1,800 years, from about 18,400 to 16,600 years B.P. The Lake Mojave II phase persisted as a continuous lake for about 2,300 years from about 13,700 to 11,400 years B.P. Shells dated at 16,270 ± 310 years B.P. in sediments from Tidewater Basin beach ridge II contain L. bradburyi, an ostracode found only in sediments of the Lake Mojave I or older lake phases. The excellent preservation of these shells, combined with the detailed stratigraphy and additional shell dates from this beach ridge (table 7, figure 11) suggest that the age estimates of 18,400 to 16,660 years B.P. for Lake Mojave I (calculated from average sedimentation rates) may be a few hundred years too old. This could be the result of one or more of the following factors: 1) the oldest core date 20,320 years B.P. has a possible error of ± 710 years and the shell date has a possible error of 310 years; when combined a maximum possible error of up to 1,020 years is possible between the two dates; 2) sedimentation rates in the Lake Mojave basins have varied with time; and 3) the age dates are incorrect. The later seems unlikely due to the otherwise exceptional correlation between surface and subsurface dates and well-developed stratigraphy. A combination of one or both of the remaining factors is most likely. The age discrepancy is well within the possible error associated with the above two age dates and although the average sedimentation rate works exceptionally well when analyzing pluvial Lake Mojave as a whole, there were undoubtedly periods in the lake history during which sedimentation rates varied from the average. The majority of shore features dated, correlate in age with the Mojave II phase and Intermittent Lake III, suggesting that the earlier Mojave I lake features were reworked and obliterated during the later high stands in the Silver Lake basin.

Silver Lake Basin Core Descriptions

Detailed core descriptions are not provided in this report due to the volume and size of each description. The data presented below are based upon data given in the appendices of a Master's of Science thesis being prepared by W. Brown.

Core Sil-I and Sil-H. Core Sil-I is the deepest of the cores drilled in Silver Lake (figure 18). During this study, Sil-I has been used as a baseline to tie in all other cores drilled in the Lake. AMS dating of organic material in whole lake sediments was conducted on three locations in the core (figure 18). The two radiocarbon dates of 20,320 ± 740 years B.P. and 14,660 ± 260 years B.P. appear to correlate well with surficial dating of shells and tufa in various beach ridges and wavecuts around the lake. A third radiocarbon date (14,200 ± 145 years B.P., Beta-25,339) taken from sediments near the top of Lake Mojave II sediments does not fit the chronology of other dates obtained from the lake margins and dates obtained from subsurface sedimentation rates, thus, its validity is suspect.

Core recovery during drilling of Sil-I was nearly 100%. This complete record shows that flooding, lake lowering, and total drying events are numerous and well-preserved and indicates that the basin had a complex history of lake fluctuations at this locality.

Sil-H was drilled to a depth of 20.6 m below the playa surface (figures 10 and 18). This core displays features similar in nature to Sil-I; however, fewer partial drying and total drying events are present and more of the lacustrine clays are bioturbated than in core Sil-I. These observations suggest core Sil-H was the site of deeper water during most of the history of pluvial Lake Mojave.

Faunal analysis of samples collected from the lake clays in core Sil-I was conducted by J.P. Bradbury and R. Forrester of the USGS. No diatoms are found above 8.7 m depth or below 14.0 m in core Sil-I, indicating either high alkalinity, significantly turbid water, or both. *Stephanodiscus* and *Campylodiscus clypeus* are the most common diatoms found in between these two depths. A distinctive *Campylodiscus*-rich zone is present at a depth of 9.8 m. A sample from 15.0 m depth contains abundant *Limnocythere bradburyi* and minor *Limnocythere ceriotuberosa*. *Campylodiscus* and minor *Stephanodiscus* are present at 12.78 m depth, indicating water of low salinity. Ostracodes in this zone are mostly *L. Bradburyi* with possible *L. ceriotuberosa*. *Stephanodiscus* and *Chaetoceros* are found at 12.15 m depth. Samples from 11.75 m. just below the transition between Lake Mojave I and Intermittent Lake II contain only *L. ceriotuberosa* ostracodes and *Stephanodiscus*. Samples between 8.80 and 10.50 m depth contain *L. ceriotuberosa*, *Candona sp*. and *Potapolypris*. Ostracodes are found throughout the core above these localities as high as 4.0 m depth and are identified as *L. ceriotuberosa*. *Phacotus*, a freshwater algae, has been positively identified in the core from depths of 15.37 to 4.78 m.

Cores Sil-J and Sil-F. These two cores contain sediments similar in nature to Sil-I and Sil-H; however, significantly more drying events (desiccation cracks) and partial drying/lake lowering events are present, suggesting these cores are located proximal to the paleo-shoreline and shallower conditions. Such hydrologic settings record smaller-scale fluctuations in the lake system. Core Sil-J contains the best preserved laminated (varved?) sediments found in the cores. The core was obtained from a large embayment south of the Silver Lake gravel quarry (figure 6). Unfortunately, drilling recovery in this core was poor in many of the lower segments making identification of events impossible in these zones. Core Sil-F has the best record of lake fluctuations of pluvial Lake Mojave of any drilled in Silver Lake. Exceptional preservation of $Na_2SO_4/Na_2SO_4 \cdot 10H_2O$ (partial drying/lake lowering) bands in the Intermittent Lake III phase indicate rapid and significant fluctuations in lake levels. Drying events are well-preserved with some core sections showing evidence of three stages of overlapping mudcracks. Reconstruction of the later half of the Intermittent Lake III phase is based mainly on this core. Flooding events are recorded with slightly higher frequency in core Sil-F than in the other cores, indicating a more sensitive recording mechanism at this locality. An ostracode-rich zone at 11.45 m depth contained abundant _L. ceriotuberosa_ and common _L. bradbury_ (R. Forrester, pers. com. 1987).

Core Sil-E. This core was drilled less than 100 m away from the present playa/fan interface in the northeastern margin of Silver Lake (figure 6). Numerous sustained lake lowering events are recorded as thick bands (up to 12 cm thick) of $CaCO_3/Na_2SO_4/Na_2SO_4 \cdot 10H_2O$-rich sediments. Clay sediments often contain very thin laminae of $CaCO_3$ (less than 0.2 mm thick) forming couplets with thicker bands of clay-sized sediments. The average thickness of these couplets varies from 0.9 to 1.5 mm in thickness, which tends to be smaller than the range in most other locations. Drier periods and/or active alluvial fan deposition during the history of the lake are often represented by granule to sand-sized upward-fining beds of grus deposited during minor progradation of the eastern fans into the lake basin. Generally, less total drying events are preserved as mudcracks, possibly due to the overall coarser nature of sediments at this location. Evidence of a Holocene lake stand correlative to a Holocene lake in Sil-M (discussed below) is present as highly disturbed finely laminated sediments 80 cm below the playa surface. An ostracode-rich zone at a depth of 8.65 m contain poorly preserved specimens of *L. ceriotuberosa*.

Core Sil-M. Late in 1987, permission was given by the Bureau of Land Management to drill the southern portion of Silver Lake playa. Core Sil-M obtained from a site near the present fan-delta/playa margin was drilled to a depth of 6.4 m. (figures 6 and 21). The lowest units are composed of laminated, green lacustrine clays containing many partial lake lowering events. Overlying these units are over 250 couplets of alternating green clays and tan fine sand (composed dominantly of quartz with minor phlogopite). Thicknesses of these couplets are highly variable ranging from 6.5 mm to 1.3 mm. In thinner couplets the clay band is usually thicker. Thicker couplets are dominated by the sand layer. Thickness variability seems to vary in a quasi-cyclic nature with thin layers dominating for two to ten couplets stratigraphically overlain by thicker layers which dominate for two to ten couplets. Occasionally, sand-rich units are interspersed among these couplets at irregular intervals and possibly relate to large-scale flooding events of the Mojave River. Overall, these couplets become thinner and maximum sediment size decreases upward through the core, and eventually the couplets become indistinguishable. At these locations, the sediments consist of a

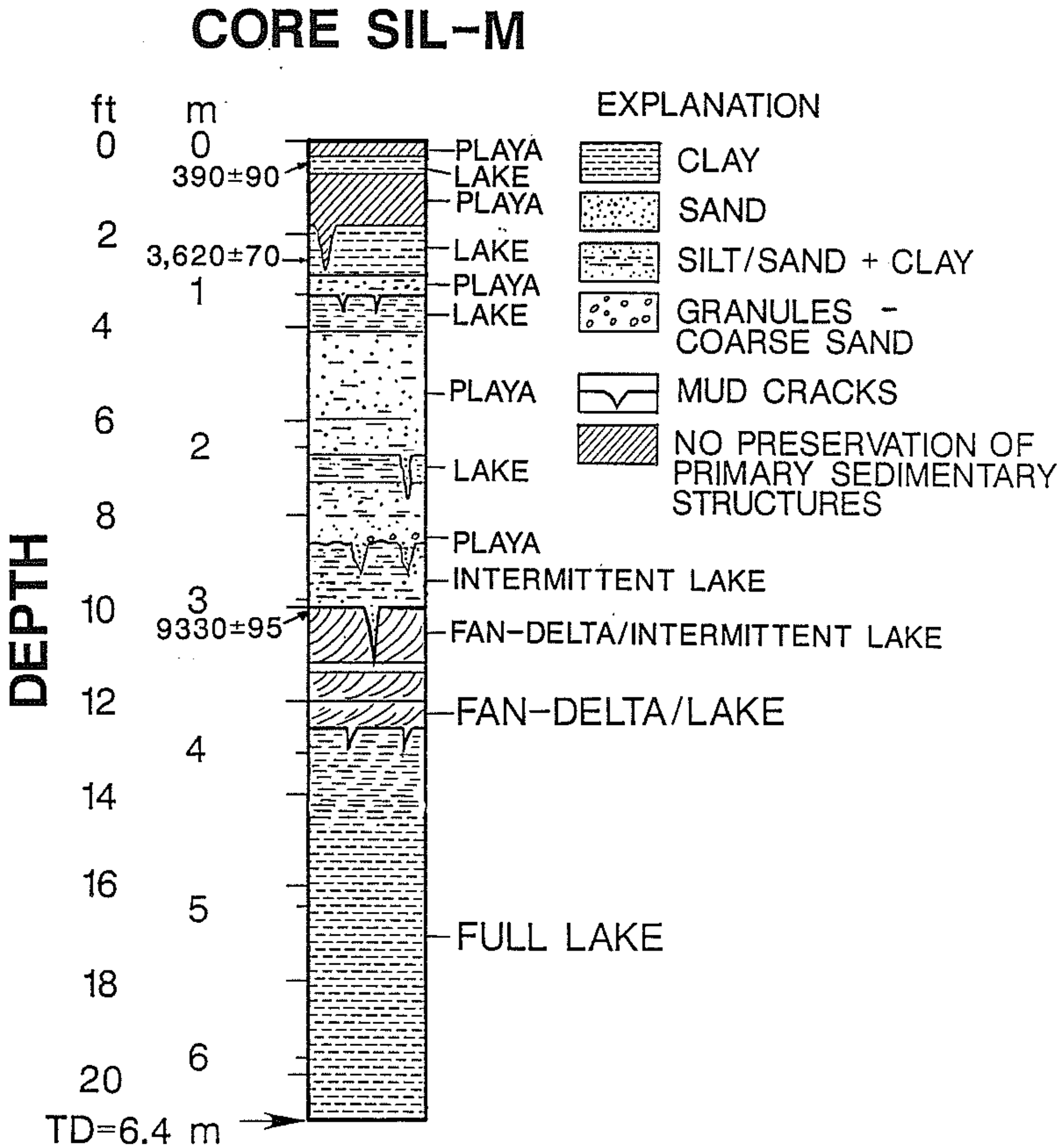


Figure 21. Simplified description of sediments preserved at site-M in the fan-delta complex of Silver Lake playa. The information is from two cores, Sil-M and Sil-N drilled to a depth of 6.4 m and from a trench excavated to a depth of 1.6 m. Laminated sediments from four short-lived lacustrine periods that postdate the end of pluvial Lake Mojave (younger than 9330 ± 95 years B.P.) are present. The upper two have been dated at 390 ± 90 and 3620 ± 70 years B.P.

non-segregated, poorly sorted clay sand. Overlying deposits take on an increasingly oxidized, brown color that eventually dominates all sediments up core. This sequence is interpreted to represent a delta with foresets composed of coarser sand layers produced during seasonal(?) discharge of the Mojave River with the clay layers deposited during quiet-water settling of fine-grained sediments from suspension. As the delta prograded into the lake these foresets became indistinguishable. Two Accelerator Mass Spectrometry (AMS) radiocarbon dates and a single standard radiocarbon date were obtained from whole sediment samples taken from core Sil-M (table 1) during this study. The oldest date of 9,330 ± 95 years B.P. (table 4) was obtained on material collected at the top of the last continuous lacustrine sediments which occur at a depth of 3.15 to 3.17 m. Overlying these sediments are oxidized, brown silts with lesser amounts of clay and sand which locally dominant this interval. Many episodes of desiccation overlain by flooding events are present, indicating highly fluctuating lake levels. These oxidized silts grade vertically into an interval about 35 cm thick containing laminated brown clay and silt layers representative of wetter lacustrine conditions. Overlying the 35-cm. thick lacustrine sediments are oxidized, brown, coarse sands and silts, suggesting drier conditions than the lower oxidized layer. Large sand-filled mudcracks and eolian sand layers are present in the core from this unit to the top of the core.

Four relatively wet periods are recorded in the playa-sediment dominated sequence observed in cores Sil-M and Sil-N and pit #1 (figures 16, 19, and 21). Sediments in these four zones indicate wet playa/marshy and lacustrine conditions. Pit #1 was excavated to a depth of 1.6 m approximately 10 m southwest of the Sil-M drill site. A stratigraphic description is given in figure 19. The youngest lake deposits are found between depths of 9 to 17 cm below the present playa surface and have been dated isotopically at 390 ± 90 years B.P. (table 4). The next oldest lake sediments occur between depths of 55-80 cm and have been dated isotopically at 3,620 ± 70 years B.P. (table 4). These youngest Holocene lake stands occur during time periods of known advances in glacial activity, referred to as neoglaciation (figure 22). Two zones below these late Holocene lake stands are observed in core Sil-M and represent periods of standing water in the Silver Lake basin. These sediments, however, have not been dated isotopically, and the ages of these older lake stands are inferred to be mid-early Holocene based upon the bracketing dates of 3,620 ± 9,330 ± 90 years B.P. (figure 21).

The youngest three lacustrine units are composed of finely laminated brown to light gray-tan, silt and clay-sized sediments that could represent annual varves. The 390-year old lake contains about 40 to 45 couplets with a thin basal unit composed of over 50% phlogopite clasts and very fine sand- to silt-sized material. The 3,620-year old lake and next oldest lake sediments are very similar in character, containing very thinly laminated couplets of light gray to brown silt/clay laminations. Approximately 100-105 couplets are found in the 3,620-year old lake with the relatively "wettest" period occurring in the center of the interval. The next oldest Holocene lacustrine unit contains about 100 couplets with phlogopite found along lamination surfaces. The oldest interval of wet playa-to-lacustrine sediment in core Sil-M is composed of dark brown clay-silt and lighter bands of carbonate that do not appear to be annual laminations due to thickness of banding. All four of these Holocene units are rich in disseminated $CaCO_3$, especially in the darker, finer grained zones.

Phacotus, a freshwater algae, is present in sediments of the 390-year old lake and the third oldest lake sediments (J.P. Bradbury, pers. com. 1988).

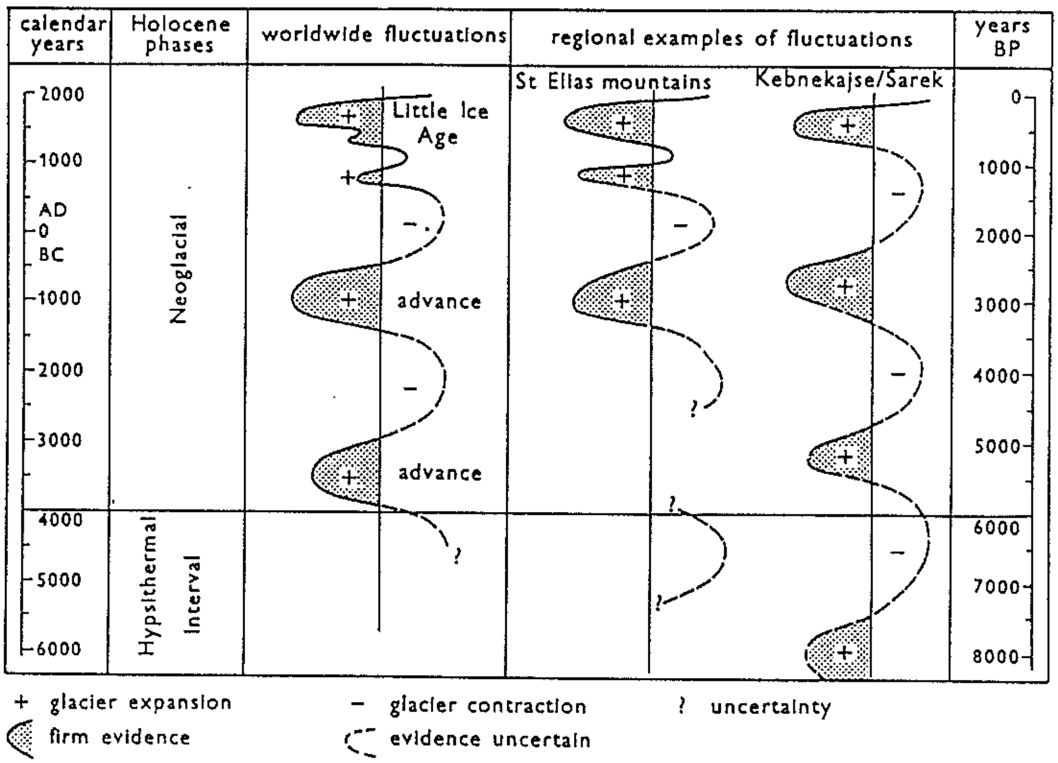


Figure 22. Neoglacial periods during the last 8,000 years (from Denton and Karlen 1972).

The other two Holocene lakes have not been analyzed for faunal remains. Phacotus is the most common biological constituent in the sediments of Sil-M and is found in both lacustrine clays and delta foresets with the exception of the sample collected at 5.76 m depth which is barren of all diatoms and algae. The lacustrine clays at the very base of the core (6.40 m) contain a rare diatom species indicative of slightly saline water conditions (J.P. Bradbury, pers. com. 1988).

Cores Sil-G and Sil-L. Two cores were drilled in the Tidewater basin area (plate 1) in an attempt to characterize lake level fluctuations. Sil-L was obtained from a hole drilled in a basin behind the highest beach ridge and contained no lacustrine units, indicating the lake probably never reached this locality and that lake overflow never occurred in this area. Core Sil-G was drilled to a depth of 6.25 m in Tidewater basin and is composed of two thick green clay units near the base separated by a thin sandy unit. These are overlain by oxidized and alternating layers of sand, clay, and gravel indicative of drier conditions punctuated by brief wetter intervals. The base of the core is composed of gray to green, angular coarse gravel overlain by several sandy units with a single 4-cm thick sandy clay horizon.

Samples collected from the clay units are several of the upper sandy units in core Sil-G have been analyzed by J. Bradbury for diatoms and other microfauna. Clays at 5.15 m contain abundant Fragilaria construens v. subsalina, a diatom also found in the core Sil-I at the top of the Lake Mojave I phase and in Soda Lake core no. 1 at depths of 24.4 m and 28.3 m. Overlying sediments contained the following diatoms: Fragilaria construens v. subsalina is not found in any samples collected above this zone. Campylodiscus clypeus, Epithemia turgida, E. adnata, E. muelleri and rarely, *Surirella striatula*, *S. peisonis*, *Cymbella mexicana* and *Ropalodia gibba*. *Phacotus* is found throughout the clays. *Campylodiscus clypeus* is common in the clays above 4.65 m. Ostracodes are present in many locations but have not been analyzed.

Correlation Among Hydrologic, Stratigraphic, and Geomorphic Features

Correlation of Events Recorded in Silver and Soda Cores. Correlations among individual flooding, partial drying/lake lowering, and total drying events are illustrated in plate 4 for selected cores. Several characteristic features are observed in all core logs and are used to correlate hydrologic events over Silver Lake and Soda Lake basins. These correlation lines are illustrated as relatively thicker tie-lines on plate 4. The two most distinctive of these are 1) the major drying event that occurred during the Intermittent Lake II phase and 2) the presence of a 2-6 cm thick darkened (organic?), clay-rich silty sand horizon occurring at about 3.35 m in core Sil-I and similar depths in the other auger cores.

Under any given lake condition, a single event may be recorded differently depending on the location. Because sediments from individual core locations in Silver lake playa represented different environments in the lake at a single instance in time, hydrologic events (i.e., flooding, partial drying/lake lowering, and total drying) have been recorded differently. In addition, fluctuating lake conditions will be more easily recorded in a more sensitive environment. For instance, a total drying event in a marginal setting (core Sil-E) might be recorded as a partial drying/lake lowering event basinward (cores Sil-F and Sil-J) and not at all in the deeper basin areas (cores Sil-I and Sil-H) (figure 6). More sensitive environments proximal to the shore will, therefore, record a greater number of events and/or lake fluctuations during the same period of time. Flooding events are inferred to overlie total or partial drying/lake lowering events because a substantial increase in water in the basin would be necessary to return the system to "full lake" conditions. Sedimentation rates also differ to some extent among the cores depending on the location in the basin. Cores drilled in the deeper portions of the basins (cores Sil-I and Sil-H) indicate higher sedimentation rates than those drilled along the margins (cores Sil-E and Sil-F). The estimated sedimentation rate of 1.08 m/1,000 years is based upon data from core Sil-I during the lacustrine phases of pluvial Lake Mojave and probably represents a relatively higher rate due to its geographic position.

Correlation of the Intermittent Lake I phase among cores is more difficult than the overlying units probably because the basin apparently had more topographic irregularity. Thus, many local environments existing during initial lacustrine stages, later "smoothed out" as basin sedimentation proceeded. Correlations among the lower parts of cores Sil-F and Sil-J and cores Sil-I and Sil-H have proved unsuccessful and no attempt is made to show any of these. Correlations between cores Sil-F and Sil-I/Sil-H have been successful to the top of the Lake Mojave I sediments. Core Sil-J has been correlated with core Sil-F to the base of the Intermittent Lake II phase. Core preservation in Sil-J is very poor below this depth making correlations difficult and unreliable. Core Sil-E correlates well with the Sil-F, but a large segment of missing core precludes correlation of events between Sil-E and the other cores below the end of Lake Mojave II phase. Correlation of cores Sil-M and Sil-G with the other cores except on a very general level is not possible due to the distinctly different environments represented in each when compared to the others.

Correlations between the above Silver Lake cores and those drilled in

Soda Lake (Meussig, White and Byers 1957) are general and based on the distribution of ostracode and diatom species. Samples collected from Soda Core no. 1 at depths of 24.4, 25.3, and 33.5 m contain *L. bradburyi* and minor *L. ceriotuberosa* (R. Forrester, pers. com. 1987) (figure 10). These are only found in Silver Lake in the Intermittent Lake I and the Lake Mojave I phases. Younger units in Silver Lake contain only *L. ceriotuberosa*. In addition, *Fragilaria construens v. subsalina*, a diatom found in abundance in lake clays in the base of core Sil-G and at the top of Mojave Lake I phase in core Sil-I is also found in Soda Lake Core no. 1 at 24.4, 25.3 and 28.3 m suggesting these sediments were deposited during the same period (J.P. Bradbury, pers. com. 1987). No correlations can be made with rotary cores in southern Soda Lake due to the lack of preserved samples.

Correlation of Shoreline Features with Lacustrine Sediments. Correlation of subsurface features in cores and shoreline features in Silver and Soda Lake basins is based on stratigraphy, faunal distribution, isotopic dating, and soil- geomorphic relationships of shoreline features.

Faunal data and radiocarbon dating of shoreline features (table 4) indicate that the majority of the A shoreline features were formed during the Lake Mojave II phase. Topographically lower shoreline features centered around 285.4 m (B-shoreline) correspond to the end of the Lake Mojave II and Intermittent Lake III phases (table 4). *Limnocythere ceriotuberosa* is found at the base of the A shoreline beach ridge and just above an alluvial fan deposit in the Baker Highway Quarry, indicating the ridge was formed after the Lake Mojave II phase (table 9). Only one surficial deposit shows evidence of the earlier lacustrine phases in the basin, the lower beach ridge in Tidewater basin.

The most complete, and complex history of shoreline fluctuations is preserved in the extreme northern margins of Silver Lake basin (plate 1). Figure 23 shows a correlation among lacustrine sediments of Sil-I and Sil-G and the two beach ridges preserved in Tidewater basin (plate 1). The basal green clays in Tidewater basin (core Sil-G) are correlative to the top of the Lake Mojave I phase in core Sil-I based on diatom distributions (J.P. Bradbury, pers. com. 1988). The upper ridge (altitude = 287.2 m) corresponds to the level of the A shoreline and the top of the second ridge (altitude = 285.4 m) corresponds to the height of the B shoreline. Although no faunal samples have been examined and no shells have been dated from the upper ridge at this locality, numerous radiocarbon dates on tufa and shell samples from other A-shoreline features support this interpretation. Correlative beach ridges to the west of this area are dated at 13,640 ± 100 years B.P. (Spillway bay) and 13,620 ± 120 years B.P. (El Capitan complex). These dates indicate that the Lake Mojave II phase is primarily responsible for the extensively preserved A-shoreline features at elevations of approximately 287 m. Shell dates of 14,550 ± 140 and 15,350 ± 240 years B.P. (Ore and Warren 1971) and 16,270 ± 310 years B.P. (Brown, M.S. thesis, in prep.) from buried sediments in the 285.4 m beach ridge indicate these are correlative to the Intermittent Lake II and Lake Mojave I phases. In addition, ostracode samples from units IV and VI in the lower portion of the 285.4 m beach ridge (figure 11) indicate the presence of abundant _L. ceriotuberosa_ and common _L. bradburyi_ (table 7). _L. bradburyi_ is only found in sediments relating to Lake Mojave I or older phases in both Sil-I and SODA Core 1 (R. Forrester, pers. com. 1987). Therefore, the lower portions of this beach ridge were formed during the Intermittent Lake II phase and the end of the Lake Mojave I phase. Units VI, VII, and XI in the 285.4 m ridge show evidence of three episodes of high water

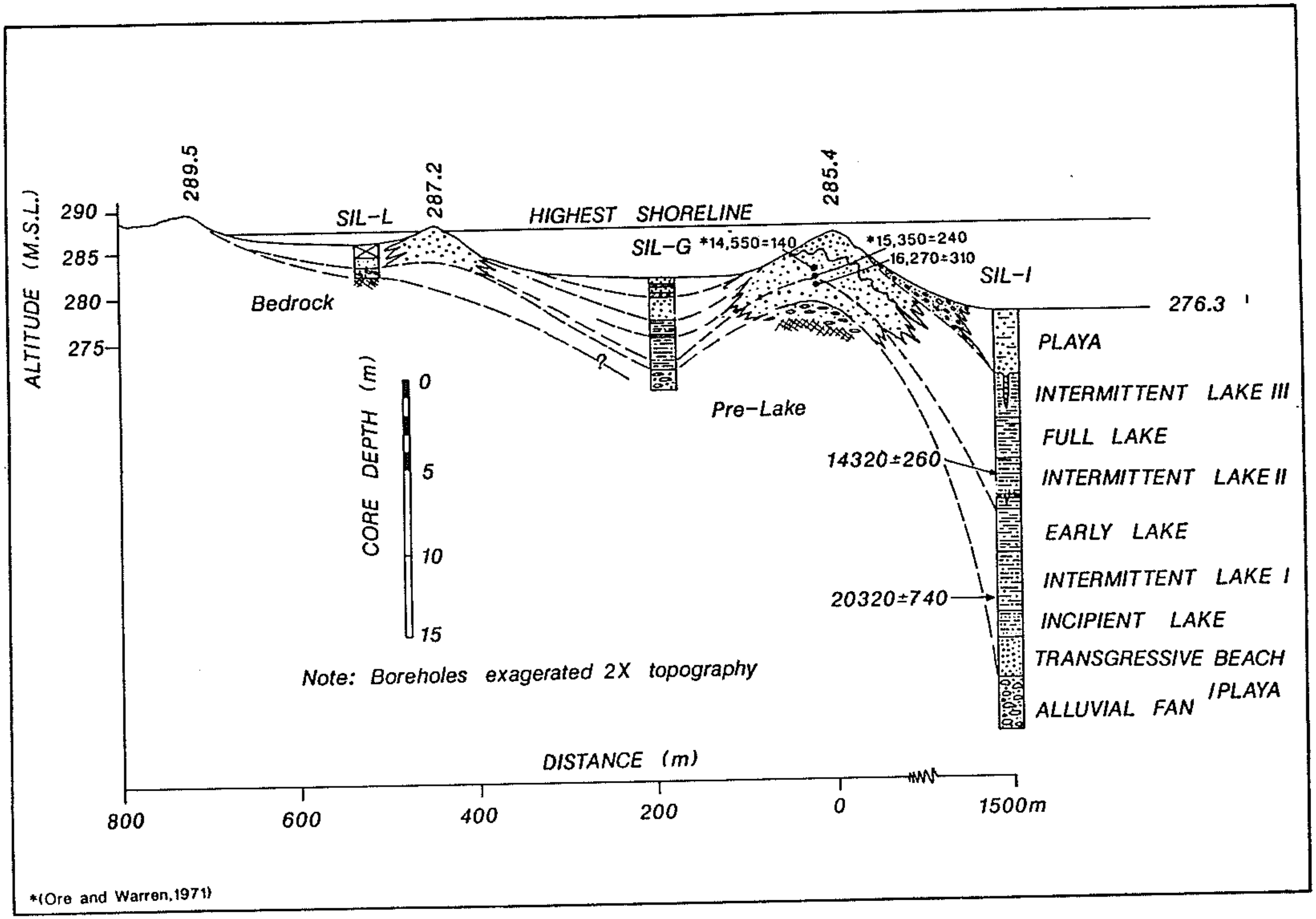


Figure 23. Cross-section correlating beach features and cored lake deposits in northern Silver Lake, based on: biostratigraphy, stratigraphy, and radiocarbon dating of pelecypod shells in shoreline features and AMS dating of bulk lacustrine sediments in Core Sil-I.

conditions indicating the beach ridge/bar was overridden during the period these units were being deposited. A coarser grained gravel-rich unit truncates the lower units and contains no shells. It is, therefore, younger than the above units. The stratigraphy shown in figure 23 indicates a younger beach ridge at higher elevations than the older features.

Fluctuations of Pluvial Lake Mojave. Figure 24 is a reconstruction of fluctuations in Lake Mojave from the beginning of the Intermittent Lake I phase to the end of the Intermittent Lake III phase. This reconstruction is based on correlation of individual events between cores Sil-I, Sil-H and Sil-F (plate 4). Relative age is based on average sedimentation rates as calculated from data given in core and radiocarbon dates, and all events have been normalized to core Sil-I (figure 18). Fluctuations of the lake are recorded differently between the cores Sil-I/Sil-H and the Sil-F core. Lake lowering/partial drying and total drying events are recorded with greater frequency in Sil-F due to its more proximal location to the paleoshoreline (shallower conditions). Flooding events are recorded with greater frequency in Sil-I and Sil-H because of their deeper location and proximity to the main axis of the basin (figure 10 and 17). Constraints on the maximum level of the water is not available on this scale, however, minimum levels can be inferred from the presence of partial drying/lake lowering and total drying events. Based on these relations, five lake "levels" are inferred and assigned a relative number which is plotted on the y-axis of figure 24. Lake clays lacking drying or partial drying events have been assigned the number 5 indicating higher water conditions. A partial drying/lake lowering event in Sil-F has been assigned the number 4. The number 3 represents partial drying/lake lowering conditions in core Sil-I. The number 2 represents total drying in the lake at

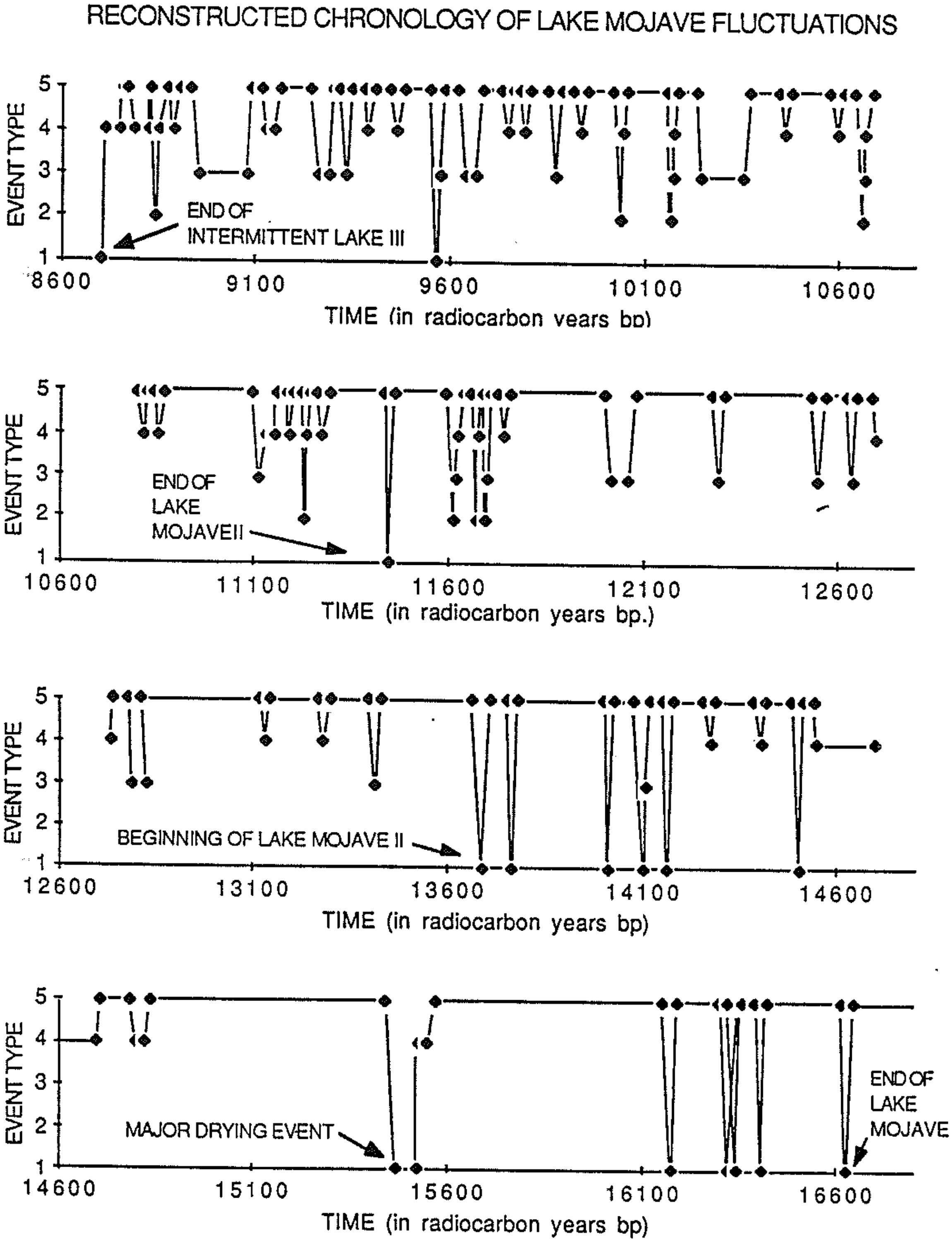
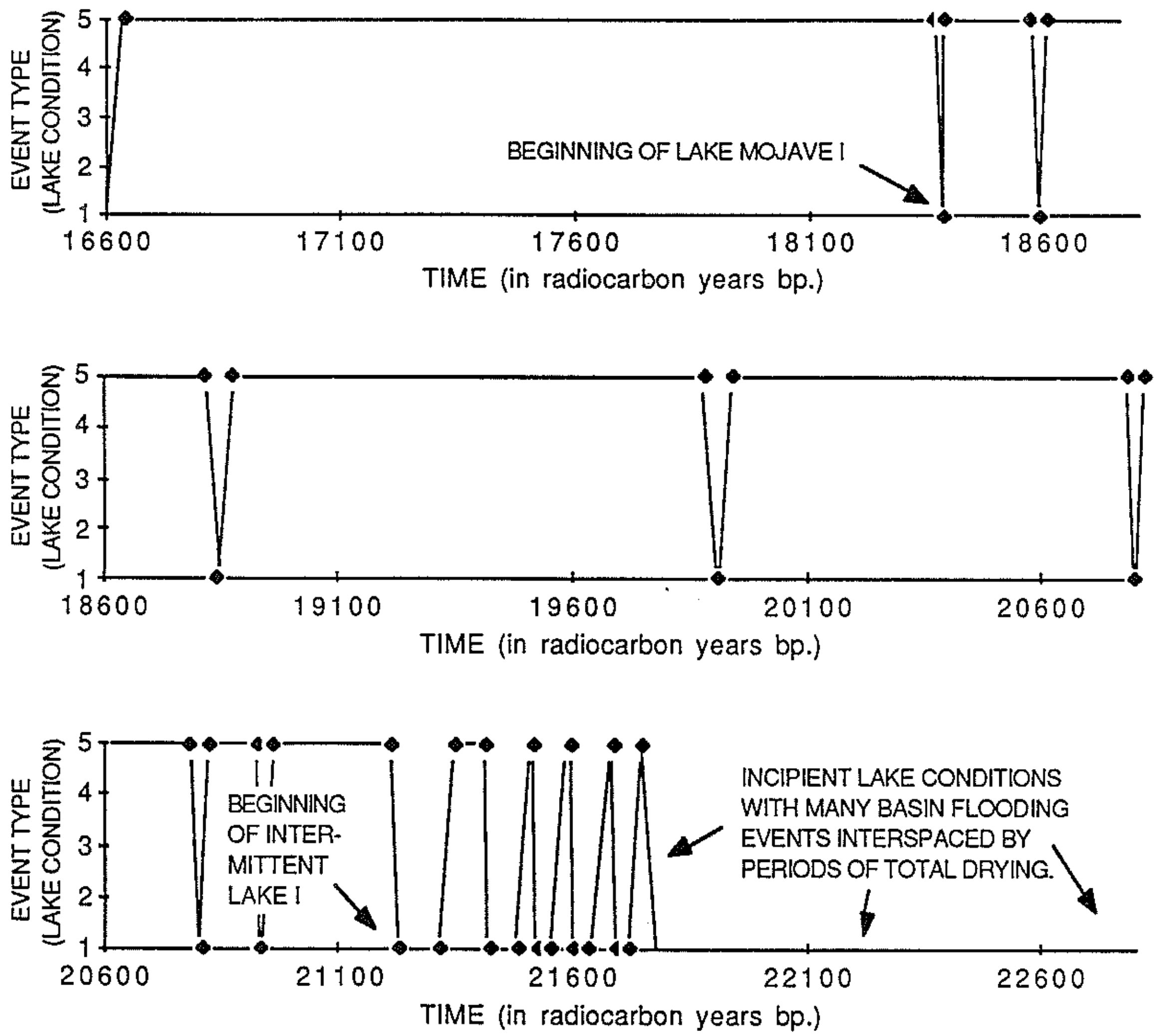


Figure 24. Reconstructed chronology of Lake Mojave fluctuations based on sediment characteristics from Silver Lake cores Sil-I, Sil-F and Sil-H (see plate IV). Chronology based on average sedimentation rates calculated from AMS core dates and stratigraphic correlations of subsurface sediments with dated shoreline features (see text for further description).



Event	LAKE CONDITION
5 →	High water in Silver Lake Arm of Lake Mojave.
4 →	Lake Lowering and precipitation of evaporites at Sil-F location.
3 →	Lake Lowering and precipitation of evaporites at Sil-I location.
2 →	Total Drying of Silver Lake at location of core Sil-F.
1 →	Total Drying of Silver Lake at location of core Sil-I and probable drying of the Silver Lake Arm of Lake Mojave.

Figure 24. (continued)

the location of Sil-F, and the number 1 has been assigned to total drying in the Sil-I location which is inferred to represent total drying of the Silver Lake basin of pluvial Lake Mojave. Correlations between Sil-F and Sil-I are absent below the top of the Lake Mojave I phase sediments, and therefore, lake conditions at the Sil-F site cannot be reconstructed. Stratigraphically below the Lake Mojave I phase deposits, core Sil-I is correlated with core Sil-H. Both cores represent similar lake settings; however, poor recovery in selected areas of Sil-I can be offset by information from Sil-H and vice-versa.

Frequency of Events Recorded in Lake Mojave Cores. To characterize the hydrologic and climatic conditions responsible for the existence of pluvial Lake Mojave, the frequency of flooding and drying events observed in the cores from Silver Lake basin is reconstructed for different lake phases. This reconstruction is based primarily on information from cores Sil-I and Sil-F. After each total drying and partial drying/lake lowering event, Lake Mojave experienced large influxes of water returning the lake environment back to high-water conditions. Flooding events are inferred to be the primary factors responsible for increased lake levels.

Figure 25 summarized a time-series plot of basin sedimentation and the frequency of flooding events during Lake Mojave's existence, 22,000 to 8,700 years ago. Individual flood event thicknesses and cumulative sediment thickness in the Silver lake basin are plotted on the y-axis in figure 25; the vertical distance between events indicates the thickness of sediment accumulation between events. Time in years B.P. is plotted on the x-axis and is based on average sedimentation rates calculated from radiocarbon dates obtained from the cores. The sedimentation rate of the basin at the Sil-I core locality is shown by the straight line increasing from 0 m at the oldest

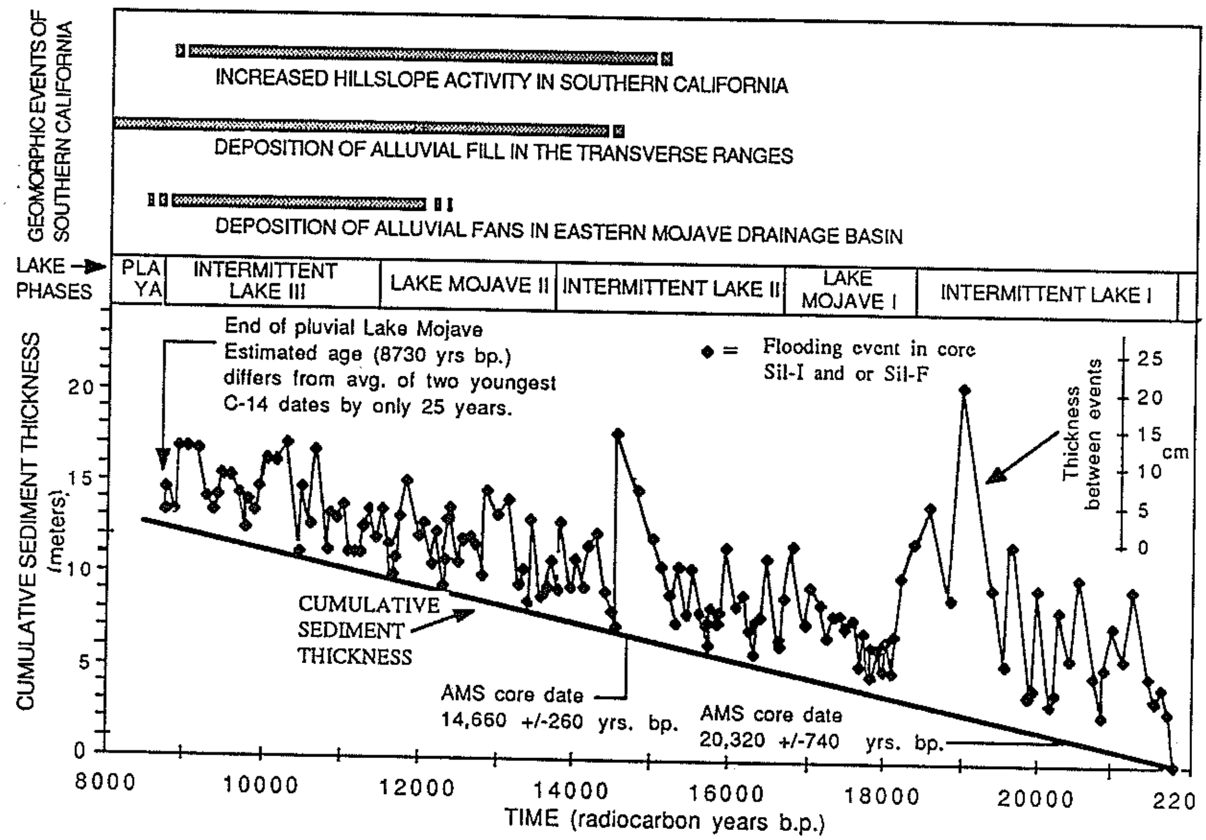


Figure 25. Relationship between the frequency of recorded flooding events and lake stage pluvial Lake Mojave, based on sediment characteristics from Silver Lake cores Sil-I, Sil-F and Sil-H (see plate IV). Chronology based on average sedimentation rates calculated from AMS core dates and stratigraphic correlation of subsurface sediments with dated shoreline features (see text for further description). Time in radiocarbon years is plotted on the X-axis. Cumulative sediment thickness at the Sil-I location is represented by the sloping solid black line and the scale in meters is shown on the left hand Y-axis. Flooding events recorded in cored lake deposits are represented by a •. The thickness of sediments between each event is represented by the vertical distance between events and the scale in cm is located on the right hand Y-axis. Lake stage is shown in the horizontal bar in the upper middle of the diagram. Note: estimates of 8730 years B.P. for the end of the Intermittent Lake III phase based on average sedimentation rates differ by only 25 years from the average of the youngest two C-14 dates (see text).

event to 16.00 m at the youngest event. A distinct pattern is evident, with the Mojave I and II lake phases having generally more frequent, more regularly spaced flooding events; whereas, the Intermittent Lake I and II and III phases contain less frequent, more sporadic flooding events.

Discussion

Flooding Events Recorded in Lake Mojave Sediments. Present-day analogs support the conclusion that coarser silty, micaceous bands are paleoflooding events. Laterally continuous, thin sediment layers are present in both Silver Lake and East Cronese Lake playas near the fan-delta areas. Each layer displays upward-fining sequences of very fine sand/silt grading to fine silt and clay. These layers or events are generally 1-3 cm thick and were deposited during historical floods sourced in the upper Mojave River drainage basin. The frequency of flooding events recorded in pluvial Lake Mojave sediments depended on the magnitude of the flooding event and the depositional environment, such as the dispersal patterns of transported sediment and the level and salinity of the lake water in relation to the inflowing river flood discharge. Conditions of low water and high salinity in the lake will favor a surface plume (hypopycnal flow) of less dense river water laden with sediment overriding the more dense lake water and carrying coarser particles further into the distal end of the system (figure 26). A flooding event of the same magnitude may not show up in the depositional record during higher water, less saline lake conditions (homopycnal flow) because coarser sediments were not transported to the distal end of the system (figure 26). Therefore the magnitudes of the flooding events are not readily inferred from the events recorded in the cores of Silver Lake basin. The record of flood frequency, however, is greater during the continuous lake stands. The lake levels were

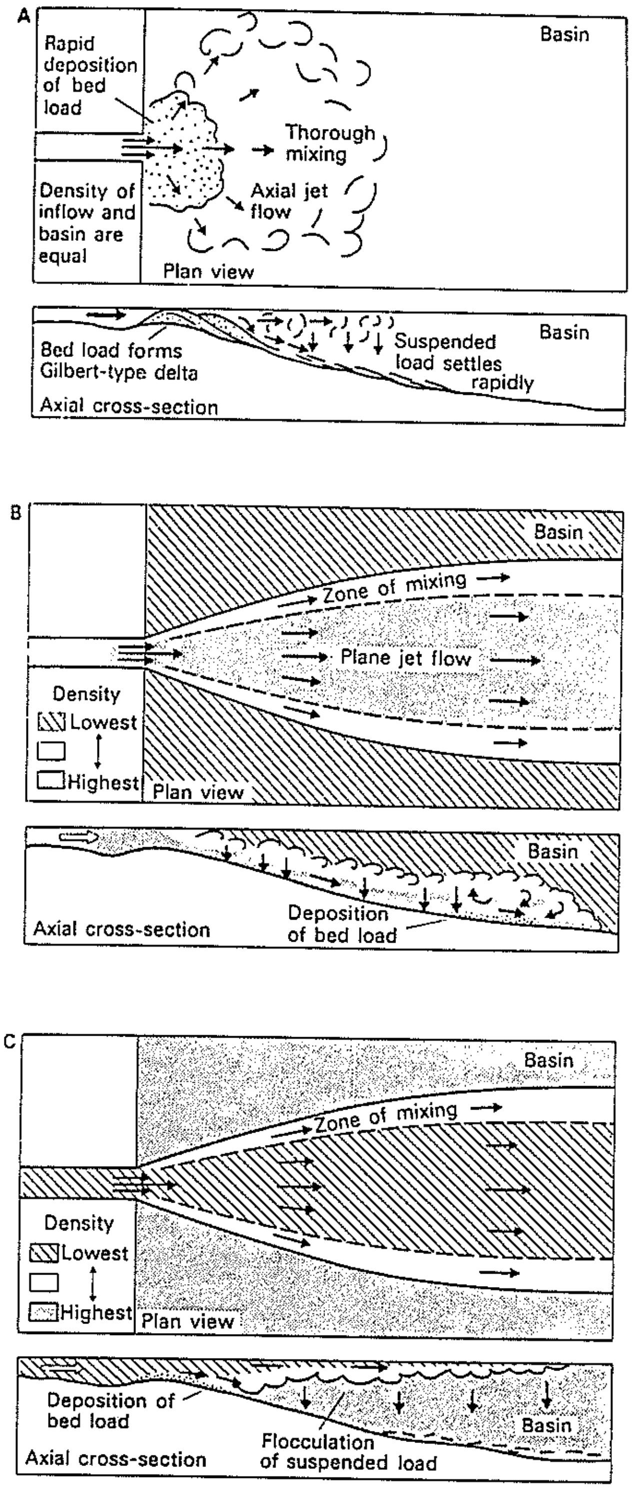


Figure 26. Diagram illustrating the different modes of interaction between sediment-laden river waters and basin waters, determined by the relative density of the water bodies. (A) homopycynal flow; (B) hyperpycnal flow; (C) hypopycnal flow (from Reading et al. 1986; modified from Fisher 1969 and Bates 1953).

generally higher during the Lake Mojave I and II phases. Under these conditions, it would have been more difficult for the basin to record a similar magnitude event than during the lower lake levels that predominated in the Intermittent Lakes I, II, and III phases. Thus, a greater frequency of higher magnitude flood events is inferred during the Lake Mojave I and II phases.

Drying Events-Magnitude and Size. The size of mudcracks preserved in the cores can be used as a relative measure of the length and severity of conditions that produced drying of the Lake. Most mudcracks in the cores are fairly small (less than 5 cm long) and are infilled with only minor amounts of silt and sand. These conditions are inferred as representing only minor, short-lived drying episodes in Silver Lake basin. The two exceptions to this are the large mudcracks and associated eolian sediments preserved in sediments of the Intermittent Lake II phase and the huge sand-filled desiccation cracks produced after the end of the Intermittent Lake III phase and the drying of pluvial Lake Mojave (figure 18). It is possible that during the entire history of lacustrine sediment deposition in the Silver Lake basin, the much deeper Soda Lake basin did not dry out except for the above two major events (figure 10).

Impact of Long-term Sedimentation in the Lake Mojave Basin During the Latest Quaternary. The excessive amount of sedimentation experienced by the Silver and Soda Lake basins during the history of pluvial Lake Mojave impacted the storage capacity and the hydrology of both basins (figures 25 and 27). Estimates of the potential lake volumes and storage in the basins are based on drill cores and rotary holes (Brown M.S. thesis, in prep.). These data

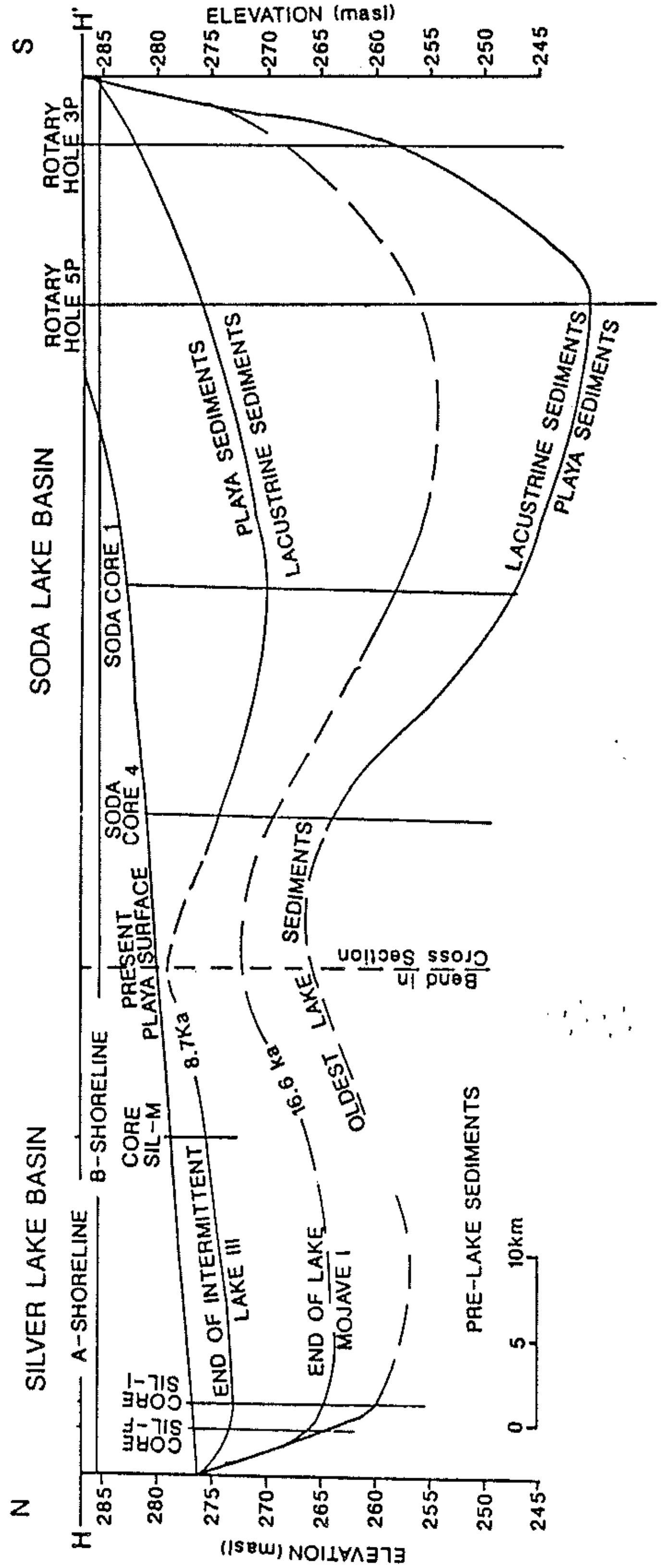
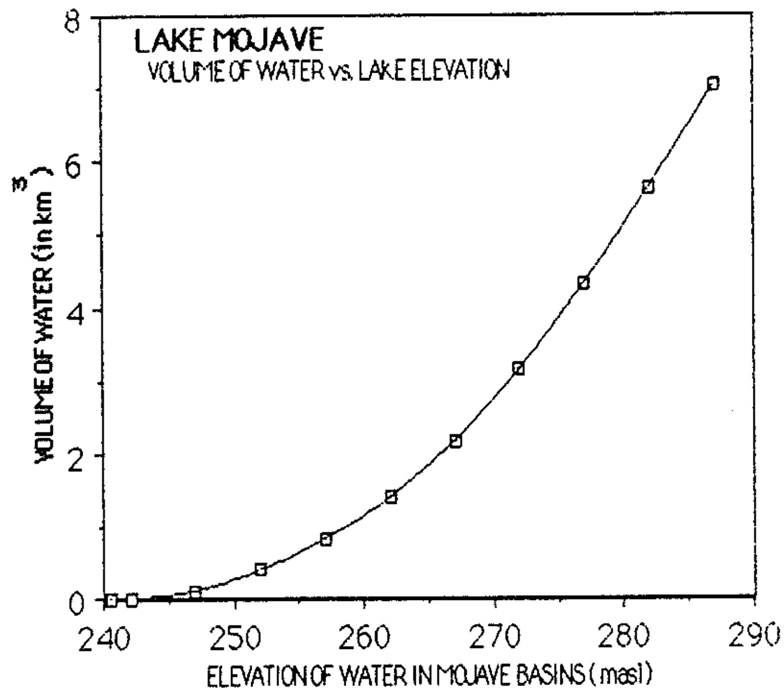


Figure 27. Cross section of pluvial Lake Mojave, illustrating the decrease in basin storage over time due to basin sedimentation and downcutting of the overflow spillway in northern Silver Lake. This section is the same as cross section H-H' in figure 10 and is based on AMS dating of shoreline features and cored lake deposits and biostratigraphic and stratigraphic correlations between surface and subsurface features.

indicate prior to lacustrine deposition, Silver Lake and Soda Lake basins would have held over 7 km^3 of water before overflowing the spillway in northern Silver Lake basin (Brown, M.S. thesis, in prep.) (figures 10 and 28). These data also suggest the Soda Lake basin could have contained an incipient Lake Mojave for a substantial period of time before overflow deposited the first lacustrine clays in the Silver Lake basin (figure 27). By the end of the Intermittent Lake III phase, the Silver and Soda Lake basins contained less than 50% of their original volume (figures 10 and 27). The loss of storage volume in response to sedimentation, and that caused by downcutting of the spillway, enhanced the sensitivity of the lake system during the latter phases of its existence. The Intermittent III and Lake Mojave II phases were therefore more sensitive to temporary drier conditions in the upper Mojave basin. This hydrologic phenomenon explains the increase in partial drying/lake lowering events observed in the latter phases of Lake Mojave, as well as the accumulation of salts observed in the cores. This phenomenon also implies that, if temperature and evaporation conditions were relatively constant in the terminal basins during the latest Quaternary, (1) significantly larger volumes of Mojave River discharge would have been required to fill the Mojave I lake to the overflow elevation, and (2) larger quantities of lake water would have exited the basin via the spillway during the Mojave II lake phase. The abundance of A- and B-shoreline features that correlate to deposits of the Lake Mojave II and Intermittent Lake III phases supports the inference of significantly increased volumes of water supplied to the lake basin via the Mojave River. The frequency and regularity of flooding events recorded in the sediments of Lake Mojave II and Intermittent Lake III phases are relatively similar for both lakes. We infer that the discharge conditions of the ancestral Mojave River feeding Mojave I and II lakes may



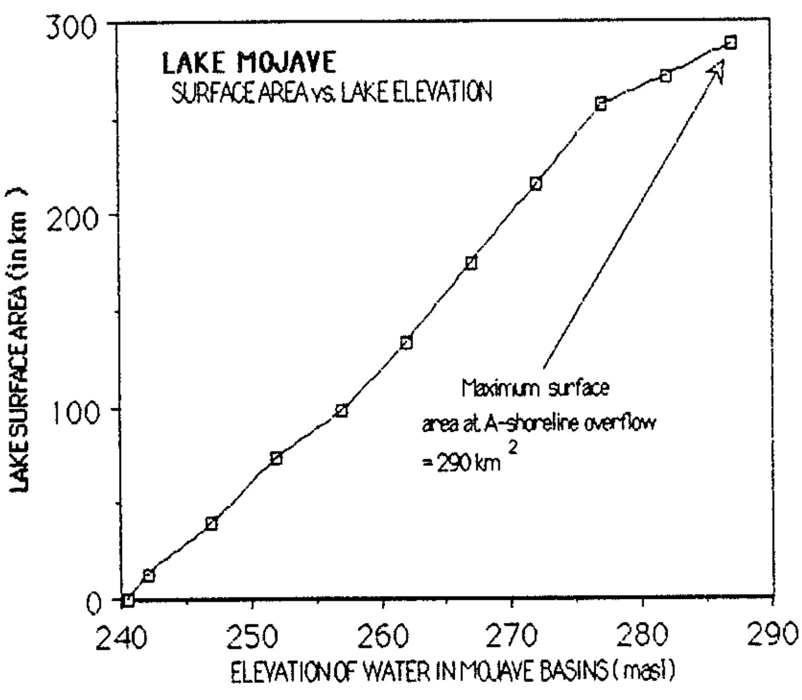


Figure 28. Estimates of basin size and shape at the beginning of pluvial Lake Mojave, based on shoreline features and drill hole and drill core information in Silver Lake and Soda Lake. A) Volume of water in the Lake Mojave basin relative to lake elevation. B) Surface area of Lake Mojave relative to lake elevation.

have been similar but that loss of water storage resulted in a lake more susceptible to short-term drying and overflow. This resulted in the similarity in the frequency of flood events recorded in both the Mojave II and Intermittent III phases (figure 25).

The nature of the outflow spillway channel implies that during periods of sustained overflow the discharge was confined to the overflow channel (plate 1). The lake outflow did not apparently erode broad areas of the alluvial fan complexes adjacent to the overflow channel. Channel walls are very steep, almost vertical in places and are often cut into bedrock (plate 2). Typical lake overflow could easily produce this channel; however, large-scale catastrophic flood volumes probably would have eroded the fan complexes which form the present-day divides at the north end of Silver Lake basin (plate 1). We interpret the overflow discharge to reflect a combination of large, but not catastrophic, flood discharges as well as discharge provided to the lake via ancestral Mojave River base flow.

Downcutting of the spillway occurred during the Lake Mojave II and possibly during the Intermittent Lake III phases when overflow conditions were more easily produced because of decreased lake storage. Numerous dates of tufa and *Anadonta* shells associated with the A and B shorelines range between 13,640 to 9,330 years B.P. (table 4) and support the conclusion that downcutting occurred during the Lake Mojave II and Intermittent Lake III phases.

Annual Discharge of the Mojave River. Core Sil-M contains over 250 alternating laminations or layers of green lacustrine clay and interbedded fine sand. The nature and regularity of these couplets argues for an alternating or cyclic phenomenon responsible for their formation. The strongest cycle in a lacustrine environment occurs annually (Anderson 1986). The clay bands formed as fine-grained material settled from suspension during quiet water conditions. The coarser bands, which contain sand, indicate much more energetic environments of transportation and deposition. The two processes which appear to be the cause for these couplets are: (1) seasonal influx of eolian material and (2) some type of seasonal (base-flow?) discharge of water from the Mojave River. Eolian material, however, would not only be preserved in deltaic sediments but should occur in other areas of the lake; however, these alternating sand/clay couplets have not been found in any of the other eleven cores drilled in Silver Lake playa, many of which represent quieter water environments (better preservation) than a deltaic region. The most likely explanation for the regularity of these sedimentary structures is that they were formed by 1) seasonal runoff as base flow and/or snowmelt from the upper Mojave River drainage basin; or 2) seasonal large-scale storm generated floods of the Mojave River.

Under present-day conditions, almost no runoff reaches the Mojave River sump due to surface water losses to the alluvial aquifer (see chapter 5). Mojave River flood waters reach the terminal playas when frequent floods of moderate magnitude fill the alluvial aquifer along the river, allowing flood waters to reach the playa floors. Large-scale winter floods also are apparently able to overwhelm infiltration processes, resulting in mountain-derived runoff reaching Silver Lake playa. An increase in ground water storage in the modern Mojave River plays an important role in regulating the routing of flood waters.

During the latest Pleistocene, additional runoff from the Transverse Ranges would raise ground water levels in the alluvial aquifers of the Mojave River, thus allowing several weeks or months of river discharge into Lake

Mojave during the spring runoff. In addition, the southern margin of Lake Mojave was significantly closer to Afton Canyon before progradation of the Mojave fan-delta complex. This late Pleistocene setting would have permitted a larger portion of the Mojave River discharge to enter directly into the lake rather than infiltrate into the broad fan-delta complex. Annual discharge coupled with frequent large-scale floods apparently supplied pluvial Lake Mojave with water from about 22,000 to 8,700 years B.P. A major change in climate between 10,000 and 8,700 years ago resulted in significantly reduced discharge and lowering of the water table along the course of the Mojave. After approximately 8,700 years ago, annual discharge ceased to reach the lake basin, and the frequency of large flood events decreased significantly. This is demonstrated by the low frequency of lacustrine deposits and flood events observed in Holocene sediments (figure 19 and 21).

Currently, Mojave River floodwaters exiting Afton Canyon can either flow northward into the Cronese Lake basins or eastward into the Soda and Silver Lake basins (figure 2). During the 20th century a diversion dam was constructed to divert flood waters into East Cronese Lake. Major floods have breached this barrier, and flood waters have continued on into Silver and Soda basins. Examination of shoreline features around the Cronese Lake basins, in addition to pits and trenches excavated in the eastern lake, suggests relatively wetter conditions existed during the mid-late Holocene when compared to Silver Lake. Also during the Holocene, a large proportion of Mojave River discharge entered the Cronese Lake basins. It is possible that before the progradation of the Mojave River fan-delta complex, which has raised the land surface over 40 m locally, that a bedrock sill at the entrance to East Cronese lake prevented significant portions of the Mojave River discharge from entering the basin. Ground-water levels reported by Thompson

(1929) indicate a major change in the water-table surface occurring at about the sill area with a steepening of gradient north of the bedrock highs. It is possible that pluvial Lake Mojave may have been the sole terminus of the Mojave River through the latest Pleistocene.

Conclusions

Late Quaternary Geologic and Hydrologic History of the Silver Lake-Soda Lake Basins. A history of fluctuations of Lake Mojave water levels and geomorphic processes along the margin of the lake are illustrated in figure 29. The earliest lacustrine sediments, which correspond to the incipient Lake phase, indicate periodic flooding of the basin, possibly from occasional overflow from an already established lake in the Soda Basin as well as reworking of playa and eolian sediments. These eolian sediments may represent unit Qel of Wells, McFadden and Dohrenwend (1987) or an older eolian deposition event prior to 22,000 years B.P. These eolian deposits rest on an alluvial fan deposit that corresponds to unit Qf1 (figure 20). Experimental rock varnish dates on exposed unit Qf1 surfaces (Dorn 1984) limits the period of deposition of unit Qf1 to between 36,000 and 22,000 years B.P.

A combination of basin sedimentation and/or increased effective discharge resulted in higher and more continuous lake stands during the Intermittent Lake I phase. Continuous lakes existed in the Silver Lake basin of pluvial Lake Mojave for a few hundred years during the mid-latter half of this phase. Soda Lake basin probably never completely dried out during the Intermittent Lake I phase. At approximately 18,400 years B.P., increased frequency and magnitude of large-scale events produced a continuous lake in the Silver Lake basin of Lake Mojave. This lake phase, Mojave I, persisted until approximately 16,600 years ago. The presence of only one shoreline feature

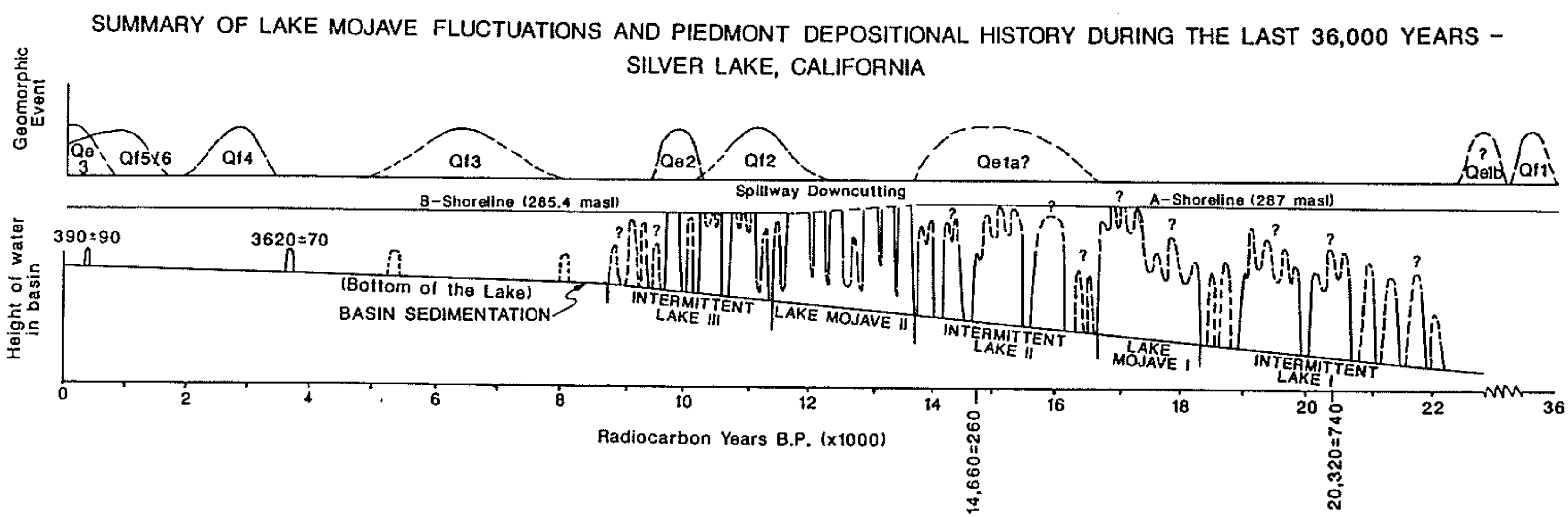


Figure 29. Summary of Lake Mojave fluctuations and piedmont depositional history during the last 36,000 years.

(Tidewater Basin Beach Ridge II) corresponding to the Lake Mojave I phase suggests that the lake level rarely reached the spillway elevation of 287 m. If any shoreline features were produced at the spillway elevation (A-shoreline height) during Lake Mojave I, than these features have been eroded, reworked, or buried by the later more persistent high lake phases of Lake Mojave II. Ostracodes and diatoms in the Lake Mojave I sediments indicate that the lake water was generally warmer (especially during the winter months) and was less turbid and/or less saline than lake waters of the overlying lacustrine phases (Forrester and Bradbury, pers. com. 1987). The presence of thermophilic ostracodes in the Lake Mojave I and Intermittent Lake I phases does not necessarily indicate warmer climatic conditions but may simply represent the greater buffering effect on seasonal water temperature fluctuations in a larger, deeper lake system.

A reduction in large-magnitude flooding events and possibly in annual discharge of the Mojave River resulted in several drying events in the Silver Lake basin during the next 3,000 years, or during Intermittent Lake II phase. An extensive drying period, circa 15,500 years ago, probably resulted in total drying of both basins of Lake Mojave and a short period of eolian dominance. This drying event may be responsible for deposition of unit Qel of Wells, McFadden and Dohrenwend (1987) (figure 20). Renewed pluvial conditions during the Intermittent Lake II phase brought a return of the lake in the Silver Lake arm of Lake Mojave which reached elevations at least as high as the Lower Beach Ridge in Tidewater Basin. The fluctuating water levels of the Intermittent Lake II phase prevailed until approximately 13,700 years B.P. when increased effective discharge in the form of higher magnitude, more frequent large-scale flooding events and increased seasonal discharge of the Mojave River produced the longest, most continuous lake stand in the basin, the Lake Mojave II phase. Ostracodes and diatoms from sediments of the Intermittent Lake II and younger phases indicate seasonally cold to very cold water conditions. Relatively greater turbidity and salinity coupled with shallower conditions existed during Lake Mojave II and younger phases (Forrester and Bradbury, pers. com. 1987). This does not necessarily indicate cooler climatic conditions but may simply reflect shallowing of the lake basin. During the Lake Mojave II phase, more frequent overflow of the lake produced downcutting of the spillway from 287.0 to 285.4 m, producing the extensive A and B-shoreline features found ringing the Silver and Soda lake playas (figure 8). Increasing loss of lake volume due to increased sediment storage was apparently combined with decreasing inflow of Mojave River discharge, resulting in a more sensitive hydrologic system during the Intermittent Lake III phase which began about 11,700 years ago. This phase lasted until approximately 8,700 years B.P., during which several drying episodes occurred in the Silver Lake basin of Lake Mojave (possibly also in the Soda Lake basin too). Continued changes in the climate after 8,700 years ago greatly reduced effective discharge into Lake Mojave basin, resulting in the termination of pluvial Lake Mojave. After 8,700 years B.P., at least four brief (tens to hundreds of years?) intervals of increased effective runoff from the Mojave River into the Silver and Soda Lake basins resulted in deposition of laminated fine-grained sediments. Two of these lakes are inferred to be early to mid-Holocene in age. The youngest two Holocene lakes formed during the cooler, wetter periods of the "Little Ice Age" and the "Neoglacial" (390 ± 90 and 3,620 ± 70 years B.P., respectively). The discovery and isotopic dating of these two late Holocene lakes are the first verification of Little Ice age and Neoglacial climatic influences in desert environments. These climatic periods have only been recognized in the glaciated mountains flanking the southwestern deserts. The third and fourth Holocene lakes are thought to represent similar climatic conditions during the early- to mid-Holocene.

GENESIS OF SOILS ON BEACH RIDGES OF PLUVIAL LAKE MOJAVE, SOUTHERN CALIFORNIA: GEOMORPHIC CONTROLS AND IMPLICATIONS FOR LACUSTRINE AND EOLIAN EVENTS DURING THE HOLOCENE

Introduction

Silver Lake (figures 1 and 2) has been the location of several studies focusing on the nature of late Quaternary climatic change and landscape evolution in a desert environment (Ore and Warren 1971; Wells et al. 1987; McFadden 1988; Reheis et al. in press). Radiocarbon dating of pelecypod shells from beach ridge deposits of pluvial Lake Mojave, of which Silver Lake playa is the northern remnant, indicate that Lake Mojave persisted episodically until about 8,700 years B.P. After this time the lake disappeared, presumably in response to the glacial-to-interglacial climatic change that occurred at the end of the Pleistocene Epoch (Ore and Warren 1971). In subsequent studies (Wells, McFadden and Dohrenwend 1987; this report; McFadden et al. 1988; Reheis et al. in press; Brown, M.S. thesis, in prep.), additional geochronologic data has enabled a more detailed understanding of pluvial Lake Mojave's history of during the latest Pleistocene and Holocene. The data also has elucided the impact of climatic changes on geomorphic and pedologic processes on the evolution of desert piedmonts in the Mojave Desert. Lake-stand events are recorded by remnants of beach ridges and other shoreline features located around the margin of Silver Lake playa (plate 1). Beach ridges are common geomorphic landforms associated with pluvial lakes in the western United States; however, there have been relatively few studies focussing on the processes of soil development on this landform. Most studies of soils associated with deposits of pluvial lakes have concentrated on using the degree of soil development observed on these or other lacustrine deposits to correlate the deposits with past lake stands (Morrison 1965; Fleishhauer and Stone 1982; Scott et al. 1982). During this study, shoreline features were topographically surveyed and mapped using aerial photography; in addition, the stratigraphy, sedimentology, and relationship with associated piedmont deposits of the beach ridges were studied (Wells, McFadden and Dohrenwend,1987; this report). Also, shell materials were collected from deposits associated with a well preserved suite of beach ridges located at the northwestern part of Silver Lake playa (table 4 and plate 1). Because of the availability of these new dates and the abundant ages published in past studies, the beach ridges in the Silver Lake area are the most well-dated sequence of latest Pleistocene and early Holocene beach ridge deposits associated with pluvial lakes of southern California. The purposes of this chapter are to evaluate major processes influencing the development of soils on beach ridge landforms during the Pleistocene and Holocene and to compare and contrast soil evolution on these landforms with soil evolution on piedmont deposits of the adjacent alluvial fans.

Beach Ridges of Pluvial Lake Mojave and Silver Lake Playa-El Capitan Beach Complex

The elevation of the sequence of beach ridges preserved in the El Capitan Beach complex along the northern part of Silver Lake Playa relative to the overflow level and the modern playa floor is shown in figure 30 and plate 2. As shown in the cross section, the beach ridges at this location are designated as, from topographically highest to lowest, BRI, BRII, BRIII, BRIV, and BRV. Topographic surveys of the spillway indicate the elevation of BRIII was controlled by the present spillway elevation; however, the higher elevations of the older two beach ridges indicate that the spillway elevation

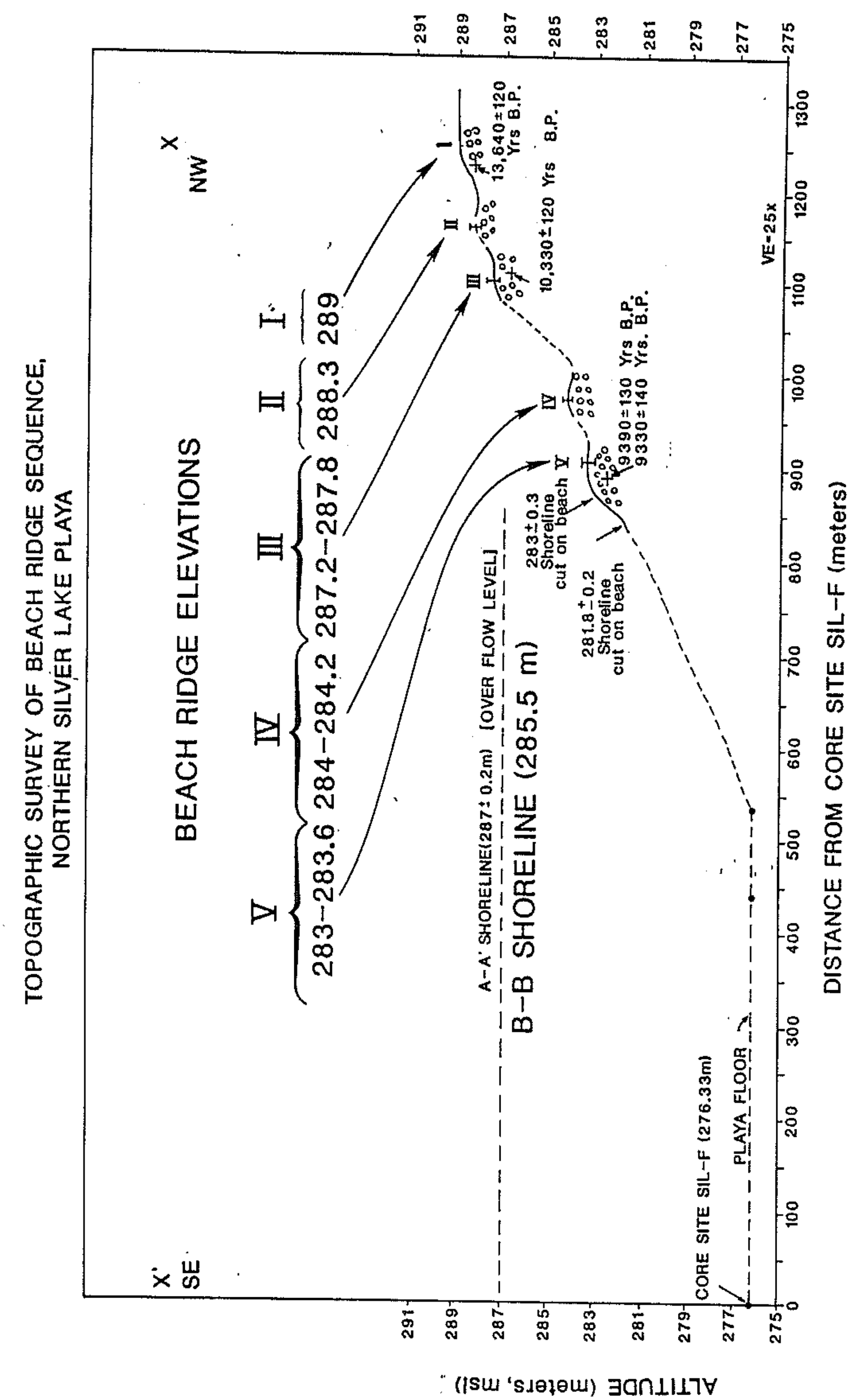


Figure 30. Topographic profile of the sequence of El Capitan beach ridge complex located at the northernmost part of Silver Lake playa.

had been as much as two meters higher than its current elevation. Presumably, overflow during high stands of pluvial Lake Mojave caused incision of the spillway. The beach ridge deposits have been exposed locally by incision of ephemeral streams. These exposures have been described and are discussed in detail in the previous section, but in general, the deposits of the upper three beach ridges typically consist of prograde foreset gravels and less commonly, gravelly sand. The gravels are usually rounded to subrounded, platy, and composed of lithologies exposed in the nearby Soda Mountains derived via reworking of gravelly piedmont deposits.

Occasionally, the beach ridge gravels contain numerous fragments of moderately to well preserved shells of the pelecypod, Anadonta californiesis. The uppermost 50 to 100 cm consists of increasingly sandy, massive materials (figure 31). The surfaces of beach ridges are characterized by a moderately well developed, varnished pavement consisting largely of pebble and cobble-sized clasts of local origin and reworked tufa.

Samples of the most well preserved shell fragments obtained from deposits associated with BRI, BRIII, and BRV were dated using radiocarbon methods, and yielded ages of 13,640 ± 120 years B.P. and 10,330 ± 120 years B.P., and 9,390 ± 140 years B.P., respectively (table 4; Beta-26,456; Beta-21,200; Beta-29,552). These ages are consistent with ages from shell and tufa materials reported in previous studies as well as ages from organic materials obtained from lacustrine sediments exposed in cores of Silver Lake playa (see section 3). These age data indicate, however, that a lake stand associated with shoreline B-B' (described by Wells, McFadden and Dohrenwend 1987), may have persisted until about 8,700 years B.P., as now indicated by data from the cored deposits and radiocarbon dates from subaerially exposed, tufa-coated gravels from shoreline deposits (see section 3).

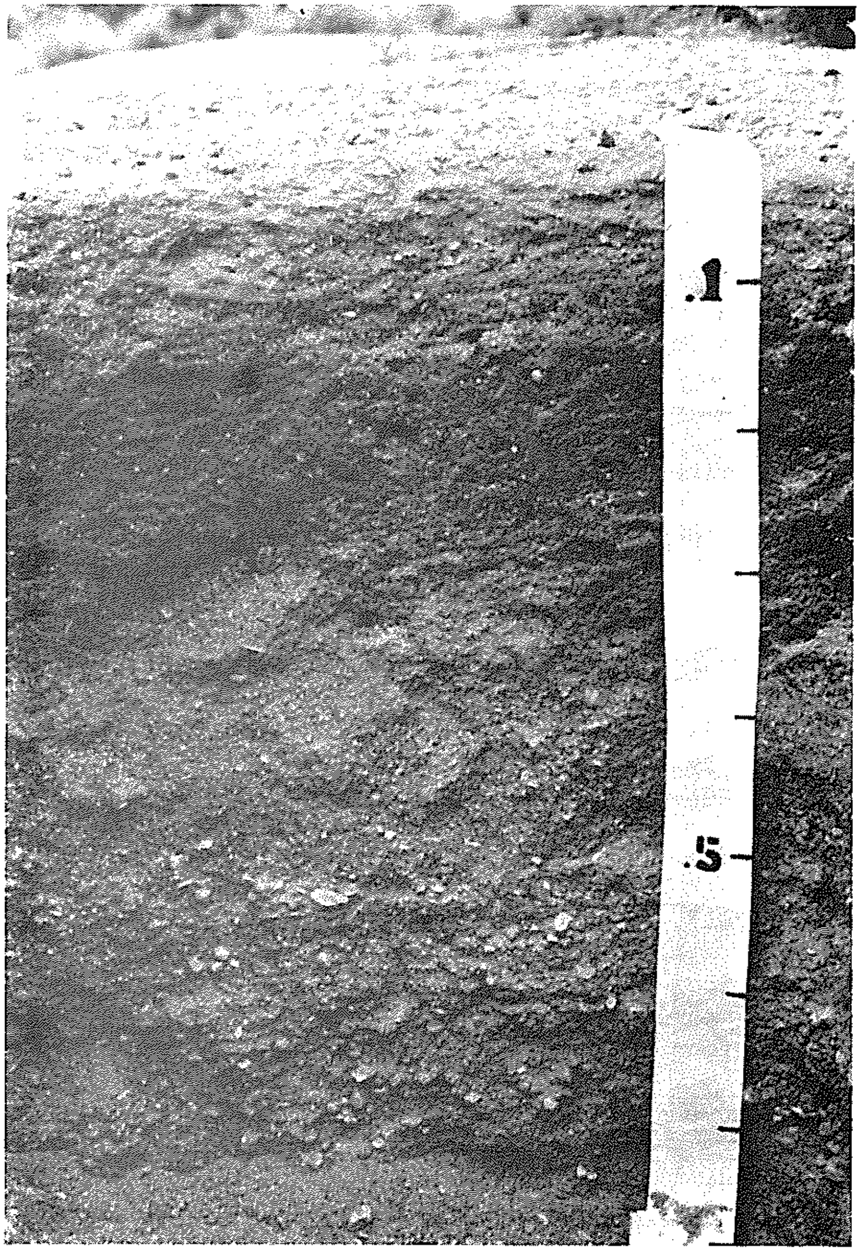


Figure 31. Weakly developed soil exposed in pit excavated on BRI in the El Capitan beach complex northern Silver Lake playa. Note moderately developed stone pavement weakly developed, thin vesicular A horizon and textural B horizon, and increase in gravel content below 35 cm.

Exposures of deposits associated with BRIV and V are finer grained than deposits of the older El Capitan beach ridges (figure 32). A weakly developed pavement composed of very weakly varnished pebbles and granules occurs on these beach ridges. Mapping of shoreline features in this area and in other areas flanking Silver Lake playa show that these beach ridges are located topographically higher than the faint shoreline features associated with historic flood events described by Wells, McFadden and Dohrenwend (1987). BRIV and BRV represent either recessional shorelines or perhaps brief periods of reoccupation of Silver Lake Playa following the major lake-level decline that occurred during the earliest Holocene.

Morphology, Texture, and Chemical Properties of Beach Ridge Soils. The soils developed on BRI, BRII, and BRIII exhibit relatively similar morphological, textural, and chemical characteristics (tables 11 and 12, figures 31, 33, and 34). This similarity is shown by values of the Profile Development Index (PDI), which range from 4.1 to 9.6. These soils have a vesicular A (Av) horizon ranging in thickness from 1 to 4 cm in thickness that occurs beneath the stone pavement described above. In most respects, the Av horizon resembles those described in other studies of soils in the Mojave Desert (McFadden 1982, 1988; McFadden, Ritter and Wells 1986; Wells, McFadden and Dohrenwend 1987), possessing primarily platy structure with subordinate prismatic structure and relatively high silt content. The horizon does not have, however, as much clay as do Av horizons described in these previous studies. The soils have a weak Bt horizon or a Bw horizon that ranges in thickness from 17 to 31 cm and exhibits weak subangular blocky or massive structure and slight reddening compared to initial parent material color (table 11). Where present, translocated clay occurs as thin bridges, although

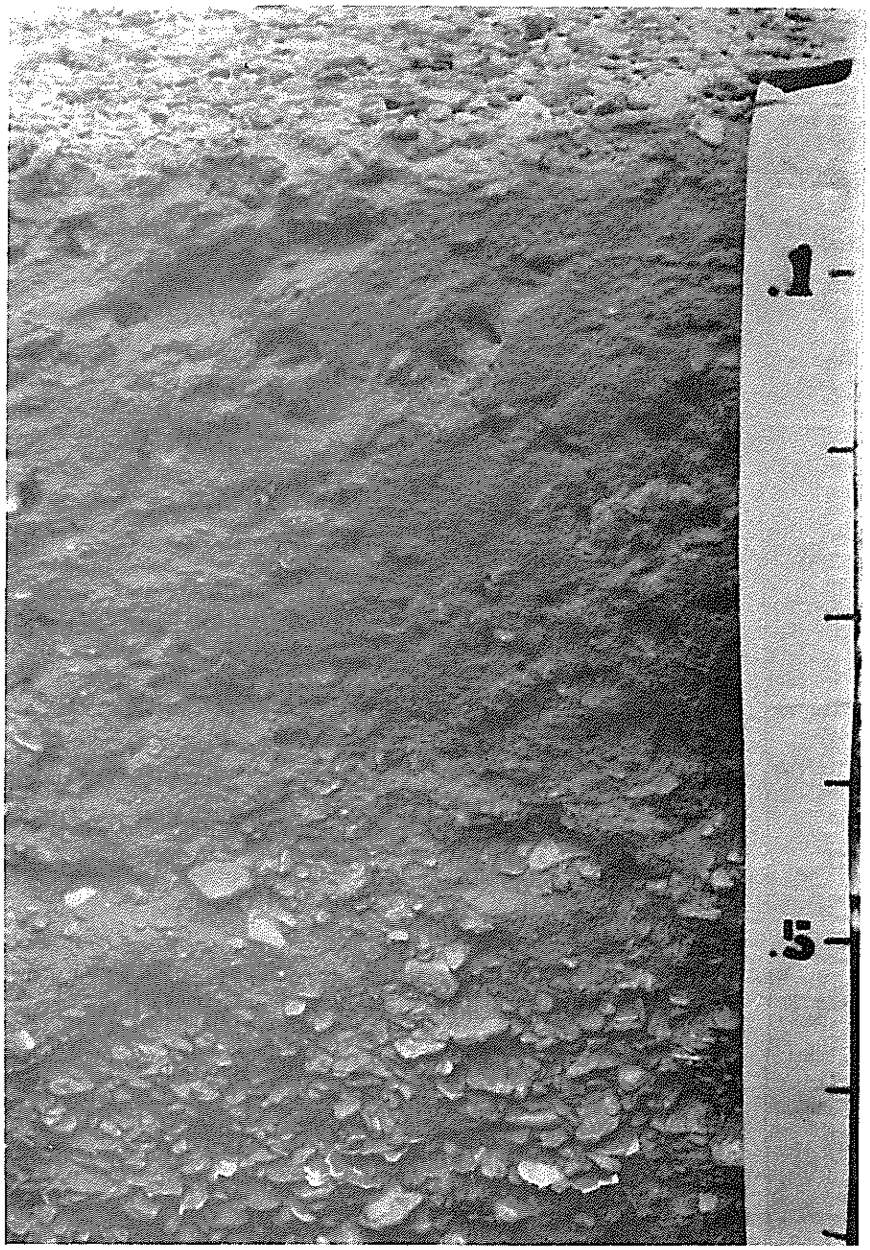


Figure 32. Very weakly developed soil exposed in pit excavated in cross-bedded, sandy gravel of BRV in the El Capitan beach complex northern Silver Lake playa. Note weakly developed, stone pavement and thin color-B horizons.

TABLE 11

SUMMARY OF MORPHOLOGICAL DATA FOR SOILS ON BEACH RIDGES IN THE STUDY AREA: see Figure 6 for location

Profile Horizon	Thickness (cm)	Color* Dry	Color* Wet	Texture %G	Texture <2mm	Structure	Consistence Dry	Consistence Wet	$CaCO_3$ stage, effer., occurrence	Clay Films	Pores	Roots	Salts	Comments
NMSIL-1														
Av	0-4	10YR7/4.5	5/4	10	LS	pl	so	ss,po	es,d	1npf	3vf&f&mdy	n.o.	n.o.	
Bw	4-27	10YR7/4.5	5/4.5	10	coS	m;2sbk	so	so,po	n.o.	n.o.	1vfdv	1vf	n.o.	
Bk	27-42	10YR7/4.5	5/4	30	coS	m	h-vh	so,po	II;ev,d	n.o.	1vf&fdv	n.o.	n.o.	
2Bk	42-84+	10YR7/3.5	5/3	60	coS	m	lo	so,po	I;es,d	n.o.	inter	n.o.	n.o.	
NMSIL-2														
A	0-0.3													
Av	0.3-4	top:10YR7/3	5/3**	<5	SiL	3vcpl&pr	vh	s,p	I;e,d	4np&co	3vf&fdv	1vf&f	n.o.	
		bt:7.5YR7/4	5/3***	<5										
Bt	4-7	7.5YR7/4	5/4	<5	LS	2f&msbk	h	vss,po	I;e,d	br&co	1fd&t	2vf&f	n.o.	
Bwk	7-12	8.75YR7/4	10YR5/4	<5	mS	m	sh	so,po	I;e,d	n.o.	inter	2vf&f	n.o.	
Bt/Bk	12-34	10YR7/4	5/4	<5	S	m	sh	so,po	e,d	n.o.	inter	1vf&f	n.o.	
(Bt)		7.5YR6/4	8.75YR5/4		LS	m	vh	ss,vps	e,d	br&co	2fdt	n.o.	n.o.	
Bky	34-60	10YR7/4	5/4	<5	S	m	vh	so,po	I;e,d	n.o.	inter;1fdt	n.o.	vf Xtals	
Bk1	60-83	10YR7/4	15/6	15	mS	m	so	so,po	I-;e,d	n.o.	inter	n.o.	n.o.	
Bk2	83-90+	10YR7/3	5/4	45	mS	sg	lo	so,po	I;e,d	n.o.	inter	n.o.	n.o.	
NMSIL-3														
Av	0-2	top:10YR7/3	5/3	<5	SiL	1cpl	h	ss,p	top;e,d	n.o.	3vf&fdv	1vf&f	n.o.	
		bt:7.5YR7/4	10YR5/4						bt:ev,d					
Bt1	2-10	7.5YR7/4	10YR5/4	10	LS	1m&csbk	sh	so,po	e,d	v1nbr	1vfdv	1vf	n.o.	
Btk2	10-27	10YR7/4	4/4	15	SL	1-2f&msbk	so-sh	ss,ps	es,d	v1nbr&co	1vft	1f&m	n.o.	
2Bky1	27-50	10YR7/4	5/4	35	m-coS	1m&cgr	so	so,po	I;es,d	n.o.	n.o.	1vf&f	Xtals on bot	
2Bky2	50-80+	10YR7/3	5/4	50	m-coS	sg	lo	so,po	I;ev,d	n.o.	n.o.	1vf&f	Xtals on bot	
NMSIL-4														
Av	0-3	10YR7/4	5/4	5	SiL	2pl	sh	ss,po	es,d	2npf	3vf&f&mv	n.o.	n.o.	
Bt	3-6	10YR7/4	5/5	50	LS	1sbk	h	.so,po	es,d	2npf	2vf&f&mdv	n.o.	n.o.	large root traces
By	6-13	10YR7/6	6/6	30	coS	m	lo	so,po	e,d	n.o.	no.o	n.o.	gyp	shells
Avb	13-16	10YR7/4	7/6	20	LS	2pl	h	ss,po	es,d	2kpf&br	2vf	n.o.	n.o.	burrows
Btb	16-23	10YR7/4	5/6	40	LS	1sbk	sh	ss,po	es,d	2nbr	1f&mdv	n.o.	n.o.	
Bkb1	23-40	10YR7/4	6/6	10	S	m;sg	lo	so,po	e,d	n.o.	inter	n.o.	gyp	shells
Bkb2	40-66+	10YR7/4	5/3	20	coS	m;sg	lo	so,po	I;es,d	n.o.	inter	n.o.	n.o.	

TABLE 11 (continued)

NMSIL-5													
Av	0-0.5	top:10YR7/4;5/4 bt:7.5YR7/4;5/4	20	SL	1npl	h	ss,po	ev,d	vinco	2-3vf&fdv	1vf	n.o.	
Bw/Bt	0.5-9	7.5YR7/4;5/6	50	LS	1fsbk	so-sh	so,po	es,d	1nbr	1vfdv	1vf	n.o.	banded Bt layers
By	9-15	7.5YR7/4;5.4	30	m-coS	sg	lo	so,po	es,d	n.o.	inter	1vf	gyp	
Cu	15-60+	10YR7/4;5/4	30	m-coS	sg	lo	so,po	es,d	n.o.	inter	1vf	n.o.	
NMSIL-6													
Av	0-2.5	10YR6/3;4/3	1	SL	2c&vcpl	h&vh	p,s	ev,d	1nbr&co	3vf&fdv	n.o.	n.o.	
Btk1	2.5-9	10YR7/3;4/3	20	m-cS	2f&msbk	h&vh	so,po	ev,d	1nbr	2vfdv	1vf	n.o.	
Btk2	9-19	7.5YR7/4;5/4	15	LS	1-2f&csbk	h&vh	so,po	I-;ev,d	1npo	1vf&fdv	1vf	n.o.	
Bky1	19-36	10YR5/3;4/3	15	LS	1m&cgr	so	so,po	I;ev,d	n.o.	inter	n.o.	gyp	
2Bky2	36-55	10YR5/3;4/3	25	LS	1mgr	lo	so,po	II;ev,d	n.o.	inter	n.o.	gyp	
Cox	55+	10YR6/3;5/3	--	S	sg	lo	so,po	I;ev,d	n.o.	inter	n.o.	n.o.	
NMSIL-7													
Av	0-6	10YR7/3;5/3	10	SiL	3vcpl	sh	ss,ps	se,d	n.o.	3vf&fdv	n.o.	n.o.	
Btk	6-17	10YR6/4;5/4	20	SL	2f-fgr	so&sh	ss,ps s,p	se,d	vlnbr	3vfdv	n.o.	n.o.	
2Bky1	17-24	10YR6/4;5/3	60	LS	1f&msbk		ss,po	se,d	n.o.	1fi	n.o.	gyp	soft nods; grain coats
2Bky2	24-35	10YR6/4;5/3	60	LmS	1fgr;1fsbk	so&sh	ss,po	se,d	n.o.	1fi	n.o.	gyp	nod
2Bky3	35-40	10YR7/3;5/3	70	Lm,cS	1f&msbk; 1f&mgr	so-sh	ss,po	I;se,d	n.o.	3vfi	n.o.		nods; clast bot
2Bky4	40-58	10YR7/4;5/3	80	LmS	sg	so	ss,po	I;se,d	n.o.	n.o.	n.o.	gyp on clast bots	
2Bky5	58-90+	10YR6/4;5/3		1m,cS	sg	sh	ss,po	II;ev,d	n.o.	3vfi	n.o.	grain coats	
NMSIL-8													
Av	0-1	top:10YR7/3;5/4 bt:10YR6/6;4/4	2	fSL	3mpl	sh	s,p	es,d	4npo	3f&mdv	n.o.	n.o.	
Btk	1-10	7.5YR6/5;4/4	5	LfS	2msbk	sh	ss,po	e-es,d	1nco&films	3vfd&mi	n.o.	n.o.	
Bk	10-30	7.5YR6/5;4/6	5	S	m	sh	vss,po	I,es,d	1nco	inter	n.o.	n.o.	lenses of carb
Bk2	30-47	8.75YR7/4;5/5	10	S	m	h	so,po	ev,d	n.o.	inter	n.o.	n.o.	
Bk3	47-75	10YR6/4;5/4	20	S	m	lo	so,po	I;es,d	n.o.	inter	n.o.	n.o.	
Bk4	75-110	10YR6/4;4/4	25	coS	m	lo	so,po	I+;ev,d	n.o.	inter	n.o.	n.o.	
Bk5	110-120+	10YR7/3;7/5	50	S	sg	lo	sokpo	I;e,d	n.o.	inter	n.o.	n.o.	
NMSOL-1													
Av	0-2	10YR7/3;4/3 ped:7.5YR6/4;4/6	<5	SiL	3mpl&pr	h	s,p	I;se,d	4npo	3f&mdv	n.o.	n.o.	
Btk	2-25	7.5YR4/4;5/4 5YR6.25/4 ped:7.5YR4/4;5/4	30	LS	2msbk	sh&h	ss,ps	I;e,d	1nbr&co	local v	n.o.	no.o	cracks with fine sand tonges mottled

TABLE 11 (continued)

Bkyx1	25-45	10YR7/4;4/3	65	LS	1f&mgr	lo	so,po	I;se,d	n.o.	inter	n.o.		bitter taste and salt splitting
Bkyx2	45-73	10YR6/3.5;4/4	50	S	sg	lo	so,po	I;e,d	n.o.	inter	n.o.		salt splitting
Bky	73-85+	10YR5.5/3;4/3	60	S	sg	lo	so,po	I;e,d	n.o.	inter	n.o.	gyp	coats clast
NMSOL-2													
Avk	0-2	10YR7/3;4/3	60	cSL	1cgr	sh	ss,ps	I-;e,d	n.o.	3vf&fdv	1f&vf	n.o.	
A/Bky	2-4.5	7.5YR7/4;4/4	60	LS	m	so	so,ps	e,d	n.o.	1f&vfdv	1vf&f	gyp coat	
Bky	4.5-34+											gyp Xtals	
NMSOL-3													
Av	0-2.5	7.5YR7/4;4/6	10	SL	2cpl	do&sh	s,p	ev,d	v1npo&co	2-3vfdv	n.o.	n.o.	
Btk1	2.5-8	7.5YR7/4;5/6	30	LS	1f&csbk	sh&h	ss,ps	es,d	vinpo	1vfdv	1vf	n.o.	
Btk2	8-24	10YR7/4;5/4	25	f-cLS	1-2f&msbk	sh&h	ss,ps	I;se-ev,d	vinpo	1vfdv	n.o.	n.o.	
Bk1	23-38	10YR6.5/3.5;5/4	40	f-vcLS	1f&csbk	h	ss,po	I;se,d	n.o.	1vf&mdv	n.o.	n.o.	
Bk2	38-50	10YR7/3;5/3.5	25	m-cLS	1f-vcgr;sg	lo&so	so,po	I;ev,d	n.o.	1vfi	n.o.	n.o.	
Cox	50-75+	10YR5/3.5;6/2	50	f-cS	sg	lo	so,po	se,d	n.o.	1vf&md	n.o.	n.o.	

*Colors are determined by the Munsell Soil Color Chart.
**top: refers to the top of a soil pad
***bt: refers to the underside of the ped

TABLE 12

SUMMARY OF TEXTURAL, CHEMICAL, AND MINERALOGICAL DATA FOR SELECTED SOILS IN THE STUDY AREA

Horizon	Depth (cm)	Particle Size % Sand	% Silt	% Clay	Wt. % $CaCO_3$	%Sol. Salts	% Gypsum	pH ($CaCl_2$)	% Fed	$\%Fe_2O_3$
NMSIL-1										
Av	0-4	63.1	3.0	3.90	6.4	ND*	ND	7.9	0.80	0.23
BW	4-27	87.6	8.6	3.7	5.1	ND	ND	8.0	0.56	0.14
Bk	27-42	83.4	11.5	5.2	7.8	0.8	ND	8.1	0.60	0.19
2Bk	42-84+	90.8	8.0	1.2	14.3	0.3	ND	8.4	0.29	0.15
NMSIL-2										
A	0-.3	78.7	16.4	4.9	5.9	0.3	ND	8.3	0.54	0.17
Avk	.3-4	64.9	25.3	9.8	10.3	0.3	ND	8.3	0.72	0.18
Bt	4-7	75.8	11.5	9.3	7.3	0.3	ND	8.1	0.60	0.15
Bwk	7-12	87.8	10.6	1.7	3.5	0.1	ND	8.1	0.50	0.24
Bt/Bk	12-34	89.5	9.0	1.6	4.5	0.3	ND	8.3	0.61	0.16
Bky	34-60	88.7	10.0	1.3	5.1	0.4	ND	8.3	0.58	0.23
Bk1	60-83	88.6	11.0	0.4	7.0	0.3	ND	8.3	0.44	0.15
Bk2	83-90+	91.5	7.5	1.0	12.5	0.3	ND	8.3	0.24	0.16
NMSIL-3										
Av	0-2	63.6	26.1	10.4	10.2	TR*	ND	7.9	0.70	0.18
Btk1	2-10	80.6	15.1	4.3	8.0	ND	ND	7.9	0.54	0.16
Btk2	10-27	83.1	11.1	5.7	8.3	ND	ND	8.0	0.46	0.17
2Bky1	27-50	90.8	7.7	1.5	13.2	TR	ND	8.2	0.32	0.16
2Bky2	50-80+	94.1	5.4	0.5	17.5	TR	ND	8.3	0.30	0.16
NMSIL-4										
Av	0-3	65.8	24.6	9.6	8.2	TR	ND	8.0	0.47	0.15
Bt	3-6	84.8	10.4	4.9	9.3	TR	ND	8.1	0.26	0.15
Cox	6-13	91.1	6.7	2.2	8.0	ND	ND	8.2	0.23	0.15
2Avb	13-16	73.6	18.8	7.6	12.2	ND	ND	8.0	0.37	0.15
2Btb	16-23	72.5	16.5	11.0	12.7	ND	ND	8.1	0.28	0.15
2Bkb1	23-40	91.9	6.8	1.4	9.1	ND	ND	8.2	0.11	0.13
2Bk	40-66+	93.7	6.1	0.2	8.5	ND	ND	8.2	0.22	0.15
NMSIL-5										
Av	0-.5	64.6	24.3	11.1	9.2	ND	ND	8.1	0.44	0.18
Bw-Bt	.5-9	89.5	8.7	1.9	8.1	ND	ND	8.1	0.39	0.19
By	9-15	91.6	7.5	0.9	7.5	ND	ND	8.2	0.17	0.09
Cu	15-60	93.2	5.2	1.7	7.5	ND	ND	8.2	0.12	0.06
NMSIL-6										
Av	0-2.5	60.4	23.7	15.9	11.2	5.0	ND	7.8		
Btk1	2.5-9	77.8	11.7	10.5	9.3	0.9	ND	8.3		
Btk2	9-19	87.4	8.9	3.7	6.9	0.8	ND	8.2		
Bky1	19-36	90.3	7.3	2.4	6.6	1.6	ND	8.2		
2Bky2	36-55	91.5	6.5	2.0	8.3	1.4	ND	8.2		
Cox	55+	92.3	5.0	2.7	8.8	1.3	ND	8.2		

TABLE 12 (continued)

NMSIL-7								
Av	0-6	40.8	42.0	17.3	10.3	1.1	ND	8.8
Btk	6-17	63.1	27.6	9.3	9.5	2.7	ND	8.1
2Bky1	17-24	74.4	21.6	4.0	5.2	3.5	TR	8.1
2Bky2	24-35	76.1	20.4	3.5	6.5	2.8	TR	8.1
2Bky3	35-40	72.2	23.8	4.0	9.9	2.7	ND	8.1
2Bky4	40-58	72.1	23.6	4.3	12.6	2.9	ND	8.1
2Bky5	58-90+	50.0	41.4	8.6	20.6	4.8	ND	8.0
NMSOL-1								
Av	0-2	33.7	46.9	19.4	14.8	0.8	ND	8.3
Btk	2-25	62.8	27.7	9.5	7.8	1.1	ND	8.2
Bkyx1	25-45	82.3	14.7	3.0	6.9	1.7	ND	8.1
Bkyx2	45-73	94.6	3.7	1.7	7.3	0.8	ND	8.2
Bky	73-85+	86.0	12.2	1.9	7.2	1.3	ND	8.2
NMSOL-3								
Av	0-2.5	52.1	38.4	9.5	11.1	0.4	ND	8.3
Btk1	2.5-8	69.4	19.9	10.7	12.8	0.8	ND	8.3
Btk2	8-24	73.0	19.9	7.1	6.4	0.2	ND	8.1
Bk1	24-38	75.2	13.9	10.9	5.9	0.3	ND	8.0
Bk2	38-50	90.9	6.7	2.4	6.7	0.3	ND	8.1
Bx	50-75+	95.8	2.2	2.0	6.4	0.4	ND	8.2

*ND+ = values <0.05
**WTR = values <0.10

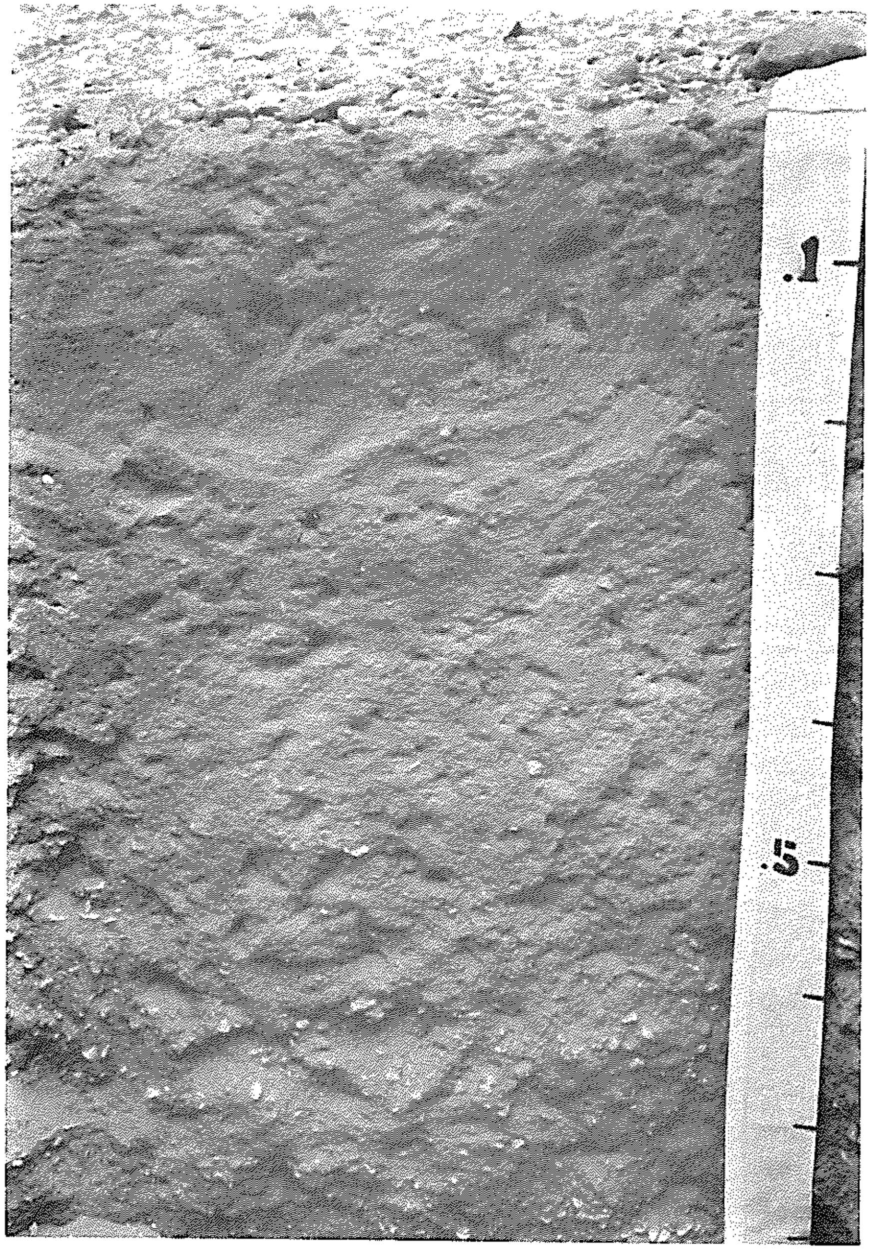


Figure 33. Weakly developed soil exposed in pit excavated on BRII in the El Capitan beach complex northern Silver Lake playa. Note moderately developed stone pavement, weakly developed, thin vesicular A horizon and textural B horizon, and increase in gravel content below a depth of 50 cm.

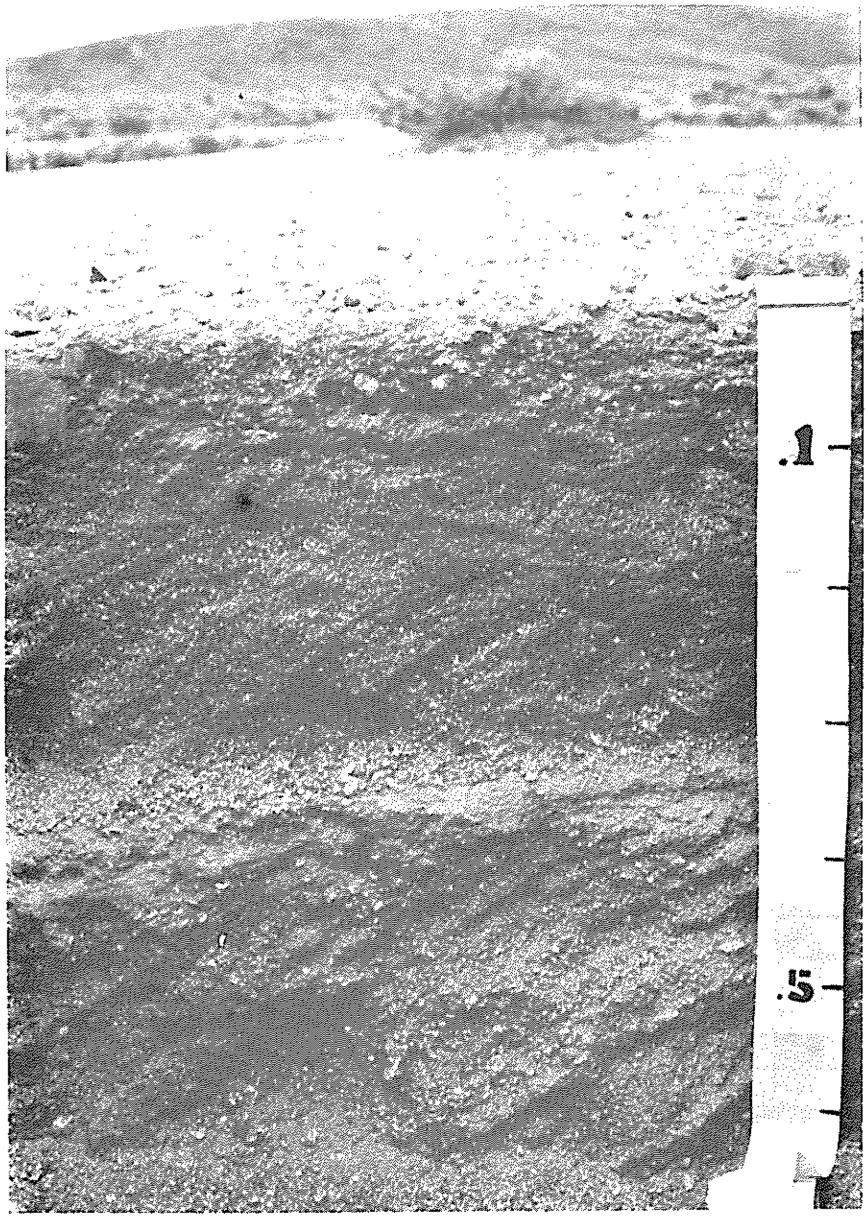


Figure 34. Weakly developed soil exposed in pit excavated in BRIII in the El Capitan beach complex Silver Lake playa. Note moderatley developed stone pavement, weakly developed, thin vesicular A horizon and textural B horizon, and rapid increase in gravel content below a depth of 45 cm. Whole pelecypod shells, which yielded a date of 10,330 ± 120 years B.P. are visible at a depth of 65 cm.

typically only colloidal stains can be discerned. Occasionally, Bt lamellae are present, associated with weakly preserved cross beds. Textural data show that most clay has accumulated in the Av horizon and that somewhat less clay has accumulated in the Bt horizon; thus, the Av horizon cannot be considered an entirely eluvial horizon. Accordingly, the depth function for clay that typifies argillic horizons is not observed. However, if the Av horizon is considered to form via continued cumulate soil development as suggested in several studies (Peterson 1980; McFadden, Ritter and Wells 1986), then the increase in clay content in the Bt horizon relative to the parent materials observed for the soil on BRIII is sufficiently large to meet the requirements of an argillic horizon.

Pedogenic carbonate exhibits stage I morphology (terminology after Gile, Peterson and Grossman 1966), having accumulated as thin, discontinuous coatings that occur primarily on the bottom sides of gravel. Pedogenic carbonate is also present as disseminated carbonate. Segregated pedogenic carbonate is not observed in parts of the Bt horizon, and laboratory data show that this horizon constitutes the zone of minimum carbonate accumulation (table 12). Because the content of locally strongly disaggregated calcareous pelecypod shells increases with depth, the measured carbonate content also increases; thus, it is not possible to determine if sufficient carbonate has accumulated to meet the requirements of a calcic horizon. The data do show, however, that a significant amount of pedogenic carbonate has accumulated throughout the profile, reflecting minimal leaching conditions in the hot, arid climate of the lower Mojave Desert. Minimal leaching also has promoted accumulation of small amounts of soluble salts and gypsum (table 11 and 12); gypsum is observed as acicular crystals located primarily below the largest gravel clasts. Textural data suggest salts and gypsum accumulate preferentially in clay- and silt-rich soils and below the most clay enriched horizons of the profile.

Depth functions show that pH is lowest in the Av horizon and tends to increase slightly with depth, suggesting that sodium-rich salts may predominate lower in the profile. However, no obvious correlation of pH with carbonate, gypsum, or soluble salt content occurs. Extractable Fe oxide data show, as was the case with carbonate, that Fed content is highest in the Av horizon and decreases slightly in the Bw or Bt horizon. In contrast to carbonate, Fed content decreases significantly in the lower Bk horizons. Feo content does not change significantly with depth, although perhaps a very minor amount of Feo has accumulated in the Bw horizon of BRII and the Av horizon of BRI.

Soils developed on the highest group of beach ridges and occurring at a similar elevation elsewhere along Silver Lake and Soda Lake playas have profiles characteristics that resemble those on BRI, BRII, and BRIII. One major distinction is observed, however: the soils contain considerably larger amounts of soluble salts. In addition, the Av horizons of the soils are more clay and silt rich.

The soils on BRIV and BRV are more weakly developed than those on the upper three beach ridges and have developed almost entirely in gravelly sand or sandy gravel (figures 31 and 35). Also, BRIV has a soil formed in a thin deposit that overlies a buried soil. The soil in the upper deposit is very slightly less well developed (PDI = 1.8) than the buried soil (PDI = 2.0), and both soils associated with BRIV are slightly less well developed than the soil of BRV. All of the soils possess thin, weakly developed Av, Bw or Bt, and Bk horizons. Small amounts of clay and silt have accumulated primarily in the Av horizon and to a lesser extent the Bw or Bt horizon. Pedogenic carbonate

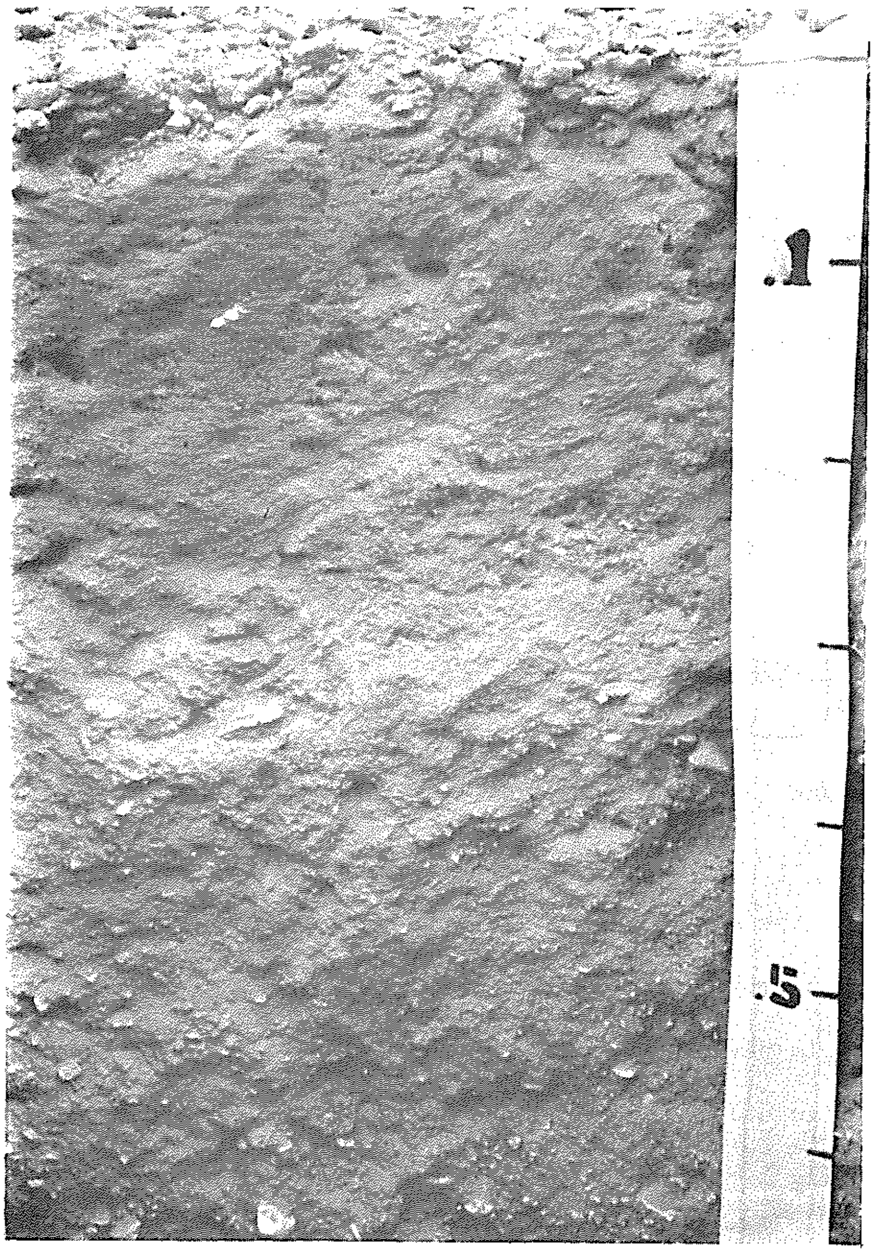


Figure 35. Very weakly developed soil exposed in pit excavated in gravelly sand of BRIV in the El Capitan beach complex northern Silver Lake playa. Note weakly developed pavement, and thin, color-B horizon. Top of buried soil occurs at a depth of 13 cm.

occurs as thin, discontinuous coatings on the bottoms of clasts in the lowest horizon of the buried soil of BRIV, but laboratory analysis suggests a minor amount of carbonate has accumulated as disseminated carbonate in the Av and Bw horizons as well. Laboratory analysis indicates that soluble salts and gypsum are not present in significant amounts in these soils, although occasionally gypsum crystals were observed in a few horizons not detectable with the analytical method used in this study. As with soils on the higher beach ridges, Fed has accumulated primarily in the Av and Bw or Bt horizons, and there is no indication of Feo accumulation.

Discussion

Genesis of Soil on Latest Pleistocene and Earliest Holocene Beach Ridges. Textural data for the uppermost 50 to 75 cm of the soil profiles associated with BRI, II, and III show that the sandy materials reflect an environment quite different from the high energy shoreline environment which favored accumulation of the well sorted, cross-bedded gravelly deposits that are observed below a depth of 1.0 to 1.5 m. Because a fluvial source for the sandy deposits is precluded owing to the topographic position of the beach ridges, an eolian origin for the sand is inferred. The sources of the sand may include sandy littoral and deltaic deposits exposed subsequent to desiccation of pluvial Lake Mojave or sandy deposits of distal fans and washes.

The lack of buried soils within the sandy deposits and the overall similarity of the soils on these beach ridges indicate that the accumulation of the sand occurred as a single event, perhaps occurring soon after desiccation of the lake or during the final stages of the Intermittent Lake III phase. Furthermore, there is no evidence for a buried soil developed in the underlying gravel deposits of BRI, II and III, also suggesting accumulation of the eolian blanket before soils could develop on BRI and II. This interpretation is consistent with stratigraphic relations discussed in previous studies of the Silver Lake area and in the Cima volcanic field. These studies evidence for periods of eolian activity during the latest Pleistocene to middle-to-early Holocene (Wells et al. 1985; Wells, McFadden and Dohrenwend 1987; Brown, M.S. thesis, in prep. and this report, section 3).

On the basis of the minimum ages for BRI discussed previously and elsewhere in this report, BRI must have been abandoned and, therefore, may have subject to soil development for as much as 4000 years prior to deposition of the eolian sand mantle. The absence of an obviously buried soil implies either erosion and removal of a previously existing soil, or that the rate of soil development prior to burial by eolian sand was quite slow or that the eolian mantle was emplaced at least partly after BRI and BRII were abandoned, but before BRIII had become established. Because there is no geomorphic evidence for significant erosion of the well-preserved beach ridge landforms, the first hypothesis is considered unreasonable. Also, as discussed previously, soil stratigraphic data and pedologic data indicate that the eolian deposits were emplaced during a single event, presumably following abandonment of BRIII, and not in two or more intervals of time. Thus, the second hypothesis seems most reasonable.

The very low rate of soil development implied by the lack of observable soil development in the gravels of the older beach ridges buried by eolian sand can be explained by two factors. (1) The open framework character of the gravels promotes rapid infiltration in the extremely permeable material and is conducive for translocation of silt, clay, carbonates, gypsum, and salts to depths of several meters. This process would preclude or drastically decrease the rate of development of textural B horizons and Av horizons, and probably would promote only accumulation of carbonate coatings on gravel clasts at depths of a meter or more. (2) A low rate of eolian dust influx in the latter part of the latest Pleistocene and the earliest Holocene prevailed during times of high stands of pluvial Lake Mojave. A low dust influx rate would limit the rate of development of soils in the currently arid, hot environment that minimizes the magnitude of chemical alteration (McFadden 1988; Reheis et al. in press).

The strong influence of eolian dust influx on soil development in deserts has been documented in a large number of studies (Birkeland 1984). The data for the soils developed on the beach ridges in the study area is in accord with these studies. For example, the lack of carbonate, soluble salts and gypsum, as well as the initially low silt and clay content of the eolian sandy deposits, strongly indicate an external, eolian origin for the silt, clay, carbonates, gypsum, and soluble salts. The nearby playa of Silver Lake provides an abundant source for such materials, as is demonstrated by analysis of cores of Silver Lake Playa discussed elsewhere in this report. Depth functions for Fed also suggest an eolian origin for much of the accumulated Fe oxides, although the slight reddening shows that at least some of the observed increases reflect formation of authigenic Fe oxides (McFadden 1982; McFadden and Weldon 1987). Other studies of the soils formed on piedmont deposits of the Soda Mountains have also demonstrated the significance of incorporation of eolian dust, based on analysis of rates of changes in profile morphology (Reheis et al. in press; McFadden unpublished data) and analysis of mineralogic and chemical data for the soils (McFadden unpublished data). In addition, as Peterson (1980) has suggested, the presence of sodium salts in eolian dust may accelerate the rate of textural B horizon development in soils by enhancing dispersal and translocation of eolian clays initially incorporated in the Av horizon.

Studies by Wells, McFadden and Dohrenwend (1987), McFadden, Ritter and Wells (1986), McFadden et al. (1988) and Brown (M.S. thesis, in prep.) have shown, however, that rates and magnitude of eolian activity have varied considerably during the Pleistocene and Holocene in the Mojave Desert. Several lines of evidence indicate the last major eolian event occurred during the early Holocene, probably triggered by increases in aridity, decreases in vegetation, and increases in sediment available for wind entrainment and transport. Presumably, the environmental characteristic of glacial or "pluvial" periods minimizes eolian activity, due to more semiarid conditions that favor greater vegetation cover and major sources of fines enriched in carbonates, clay, and salts (i.e., playas). A major implication of this hypothesis is that such periods would be characterized by comparatively slow development of noncumulate soils on relatively stable geomorphic surfaces (McFadden, Ritter and Wells 1986; McFadden et al. 1988; Reheis et al. in press). The rate of soil development would be further minimized in circumstances entailing deep translocation of eolian fines and solutes in highly permeable parent materials, such as gravels.

The rate of development of soils in beach ridge gravels may be low, however, even during periods of relatively high eolian activity. In the study area, soils on the oldest beach ridges have developed in sand, which is much less permeable than gravel. This enabled development of soils resembling soils that have developed on fluvial deposits of middle Holocene age on the piedmont of the Soda Mountains (Wells et al. 1987; McFadden 1988, Reheis in press). Beach ridge landforms in other areas of the Mojave Desert do not exhibit such soils. For example, field observations of high energy, gravelly shoreline and beach ridge deposits of pluvial lakes associated with Owens dry lake, Searles dry lake, Panamint Valley and Death Valley, located in the deserts of California, as well as pluvial lakes of the San Agustine Plains and Animas Valley located in New Mexico. In all cases, the soils exposed in pits or stream-cut exposures of the deposits were thought to represent the latest Pleistocene or earliest Holocene pluvial lakes, as suggested by studies of Smith (1975), Smith and Street-Perrot (1983), Hooke (1972), Markgraf et al. (1983) and Fleishhauer and Stone (1982), lacked reddened, clay-enriched Bt horizons, and in some cases, the entrainment and transport. In all cases, the soils exposed in pits or stream-cut exposures of the deposits thought to represent the latest Pleistocene or earliest Holocene pluvial lakes, as suggested by studies of Smith (1975), Smith and Street-Rerrot (1983), Hooke (1972), Markgraf et al. (1983) and Fleishhauer (1982). In all cases, reddened, clay-enriched Bt horizons were not present, and in some cases, the weakly developed Av or Al horizon occurred immediately above the gravels, which possessed discontinuous coatings of carbonate. Because these soils must have developed largely in the Holocene, a time during which moderately developed soils have formed in fluvial deposits of deserts of the western United States (Nettleton et al., 1975; Birkeland 1984; McFadden 1988; Reheis 1987; Gile, Hawley and Grossman 1981), the relatively low rate of accumulation of silt, clay, and other soil materials must be due to the ease of translocation of such materials through the solum.

Chadwick and Davis (1988) and Morrison (1964) report that well-developed soils have formed on latest Pleistocene shoreline deposits of Lake Lahonton. They also conclude that the development of these soils reflects very high rates of dust influx after the dessication of a pluvial lake. Presumably such soil development is related to cumulater soil development favored by unusually high rates of dust influx commensurate with the dessication of this areally extensive pluvial lake.

Although soil-geomorphic evidence indicates soils on BRI, II, and III have formed in an eolian deposit, data for the soils demonstrate the degree of profile development varies slightly, despite the presumably equal durations of soil development. The variability is attributed to two major factors: the position of the beach ridge relative to the major direction transport of suspended eolian material and the topographic form of the beach ridge. For example, BRI is farthest removed from Silver Lake Playa and is topographically somewhat more subdued than lower and younger beach ridges. This may result in a less favorable environment for eolian sedimentation compared to that associated with topographically more prominent beach ridges. These characteristics would be expected to favor slightly lower rates of dust accumulation.

Genesis and Estimated Age of Soils on the Earliest Holocene Beach Ridges

In contrast to the soils on BRI, II, and III, the soils developed on BRIV and BRV have developed directly in the sandy gravelly beach ridge deposits. Thus, formation of the lower two beach ridges apparently post-dated deposition of much of the eolian sandy mantle observed on the higher beach ridges. The development of Av horizons and weak Bw or Bt horizons in soils on the lower beach ridges, however, show that most eolian material has accumulated primarily in the upper part of the soil and was not translocated deeply below the surface. This can be attributed to the lower permeability of the parent materials, which reflects sedimentological characteristics associated with deposition in a lower energy environment favored by a shallower lake (see section 3). The nature of these deposits may also reflect reworking of fine grained deposits of distal allvuial fans similar to those now observed at the playa margin. In addition, the closer proximity of these beach ridges to the playa, and their topographic form probably favors dust accumulation, as discussed above. Also, as discussed above, the presence in these soils of silt, clay, and carbonate enriched horizons implies an eolian source for these materials.

Soil development on the lower beach ridges most closely resembles that of soils formed in middle and late Holocene deposits of the Soda Mountains piedmont. As mentioned previously, these soils and deposits have been the subject of several studies. For example, fan unit Qf3 (figure 20), which was deposited between 3,400 and 8,000 years B.P. (Wells, McFadden and Dohrenwend 1987), possesses a soil that typically exhibits a well developed Av horizon, a 15-cm thick, slightly reddened Bw horizon, pedogenic carbonate accumulation with stage I morphology, and pedogenic gypsum and soluble salt accumulation. The PDI for the soils is typically 7. Fan unit Qf4 (figures 20 and 29), deposited after 3,400 years B.P. but probably before 2,000 years B.P., possess soils that typically have a well developed Av horizon, a very thin (less than 1 cm) slightly reddened Bw horizon, and pedogenic carbonate with stage I morphology. The PDI for such a soil is 4.9. Given the generally similar textural characteristics of the piedmont deposits and lower beach ridge gravelly sand, temporal correlation solely based on soil development would suggest that the soil on BRIV and BRV has formed over a period of 2,000 to 3,400 years. The age radiocarbon dated pelecypod shells (9,390 ± 140 years B.P.) in the buried soil of BRV, however, demonstrates that the soils on the surface of BRIV must have formed during much of the Holocene. This shows that the rate of soil development on BRIV and BRV as expressed by overall soil development has been lower during the Holocene than the rates of development of soils on Holocene deposits of the piedmont.

One major factor may explain the lower rate of soil development on the earliest Holocene beach ridges compared to that associated with soils on Holocene fan deposits. The fan deposits commonly have a bar-and-swale topography that is characterized by local relief that commonly exceeds 0.25 meters, which constrasts with local relief of less than 0.05 on the surface of the beach ridge landforms. The much rougher surfaces of the fan deposits may favor entrapment of larger amounts of dust during times of eolian activity as described by Wells et al. (1985) in a study of the evolution of the surfaces of volcanic landforms in the Cima volcanic field. As has been discussed previously, numerous studies of soil development in arid regions have concluded that pedogenesis has been profoundly influenced by the incorporation of eolian dust. Thus, geomorphic surfaces in arid regions that tend to favor comparatively high rates of entrapment of eolian dust may be characterized by an associated high rate of soil development. Differences in such topographically influenced rates of soil development might be most magnified during times of increased eolian activity, which may characterize periods of hot, dry climate such as the Holocene (Wells et al. 1985; McFadden, Ritter and Wells 1986; McFadden 1988).

Formation of Gravel Pavements on the Older Beach Ridges

The moderately well developed and varnished pavement that is present on the upper three beach ridges closely resembles the pavements on late Pleistocene geomorphic surfaces on the Soda Mountains piedmont and those observed on the surfaces of late Pleistocene volcanic flows of the nearby Cima volcanic field. The development of pavements in these areas has been attributed partly to development of cumulate soils formed in silt and clay rich eolian materials. These materials accumulate below an increasingly well sorted layer of gravel which is derived from gravel-rich fluvial deposits or basalt rubble and colluvium (McFadden, Ritter and Wells 1986; McFadden, Wells and Jercinovic 1987). The gravel layer is composed largely of fine grained lithologies resistant to mechanical weathering. Soil-stratigraphic relations observed in the beach ridge deposits, however, indicate the process of initiation of pavement development is different from that proposed for piedmont and volcanic flow surfaces, given the initially low gravel content of the sandy eolian deposits.

Because the beach ridges are topographically isolated from fluvial deposition, the gravel pavement must have formed via concentration of gravel due to removal of sand. The process of sand removal is most likely deflation, which may have occurred when diminished sand supply, coupled with occasionally strong winds, favored sand entrainment and transport. Assuming an initial gravel content of about 10 to 20%, the deflation of approximately 50 to 100 cm of sand would be required to form a lag pavement. Formation of the pavement, however, should increasingly favor entrapment of eolian dust, inevitably causing development of the vesicular A horizon in the incorporated silt and clay above developing textural B and carbonate-rich subhorizons. Thus, pavement evolution and soil development currently are similar to pavement evolution and soil development observed on piedmonts and volcanic flow surfaces. Av horizon thickness, however, is as much as 8 to 10 cm on soils of the latter surfaces. As has been hypothesized previously, the presence of thin Av horizons in beach ridge soils probably reflects the topographically smooth form of the sand mantled beach ridges, which contrasts with the rougher topography of volcanic flow surfaces and the bar-and-swale form of bouldery piedmont deposits.

Conclusions

Soil studies on beach ridges associated with pluvial Lake Mojave show that the soils have formed in an eolian blanket deposited sometime after abandonment of BRI, BRII, and BRIII. The pedologic characteristics of these soils directly reflects geomorphic processes responsible for rapid pavement development and dust entrapment is probably derived primarily from Silver Lake playa. An obviously buried soil is not present in the underlying BR1 beach ridge gravels, which must have been subaerially exposed for at least several thousand years. This is attributed to the highly permeable nature of the gravels thought to promote deep translocation of eolian fines. Also, the lack of a prolonged period of playa development prior to 8,700 years B.P. may have greatly limited eolian sources during the latest Pleistocene. The presence of relatively weakly developed soils in beach ridge deposits associated with other pluvial lakes in desert regions, therefore, may not indicate the occurrence of relatively recent lakestands. The weak soil development may instead reflect geomorphic circumstances that have limited eolian activity sufficiently to minimize formation of textural B and Av horizons in relatively permeable beach ridge deposits.

The more weakly developed soils on the younger beach ridges in the study area have formed directly in somewhat less permeable beach ridge deposits, which in contrast to the older beach ridge deposits, has favored accumulation of playa-derived dust at a shallow depth. On the basis of comparable degree of soil development, the ages of the younger beach ridges and the associated lakestands are estimated to range between 2,000 and 6,000 years B.P. The period of eolian activity during which the older beach ridges were mantled by sand, therefore, is estimated to have occurred between sometime before 9,300 years, but after abandonment of BRI. This relatively small interval of time may be the age range associated with deposition of eolian unit Qe2 (figures 20 and 29), recognized by Wells, McFadden and Dohrenwend (1987) in previous studies of the Silver Lake area.

The topographically smoother form of beach-ridge landforms compared to piedmont landforms may promote a lower rate of soil development during the Holocene in beach ridge deposits when compared to the rate of soil development observed in Holocene piedmont deposits. The basis for this hypothesis is provided by (1) studies of soil development in arid regions that demonstrate the significance of incorporation of eolian dust in the development of major genetic horizons in such soils; and (2) studies of landform evolution in arid regions that demonstrate the critical role of surface roughness in the entrapment and deposition of eolian materials. The results of these studies combined with those of this study show that morphological similarity of soils in a given study area, despite relative similar climatic conditions and composition of parent materials, does not necessarily imply a similar duration of soil development. Future studies of soil development in arid regions coupled with the availability of independent numerical age data will be required in order to further develop the application of soil-geomorphic studies to the analysis of landform evolution.

HISTORICAL FLOOD AND LAKE HYDROLOGY: RESPONSES TO MODERN CLIMATIC/ ATMOSPHERIC REGIMES AND CALIBRATION FOR PALEOHYDROLOGIC AND PALEOCLIMATIC RECONSTRUCTIONS

Introduction

Documented lake-forming flood events occurred in 1903, 1910, 1916, 1921-22, 1938, 1969, 1978, 1980, and 1983 at the terminus of the Mojave River (figure 36). Lake stands approximately 3.1, 6.7(?), and 1.8 m deep occurred during the best documented and largest flood events in 1916, 1938, and 1969 (Wells et al. 1984; Daingerfield 1939). The maximum discharges recorded in the headwaters of the Mojave River and along its course at Barstow and Victorville during the 1938 flood were 1,821 and 2,000 m^3 sec, respectively (figures 2 and 37). Flood stages exceeded 6.3 m during the 1938 event. All of these floods originated in the mountainous uplands of the Transverse Ranges during the winter months of December through March, which is the primary precipitation maximum in southern California (Pyke 1972). The primary purposes of this section are (1) to present evidence for historically documented large floods and/or a lake stands within the Mojave River, (2) to establish the climatic and atmospheric regimes responsible for these lake building flood events, and (3) to discuss the implications of these conditions for hydrologic conditions and climatic changes during the latest Pleistocene and Holocene.

Hydrologic Framework for the Mojave River Watershed

Conceptual Model of the Hydrologic System. Any attempt to reconstruct hydrologic responses related to modern climatic fluctuations in a drainage basin requires a physical-based model, consisting of major input, output, and storage of the system. Such a model for the Mojave River drainage basin is

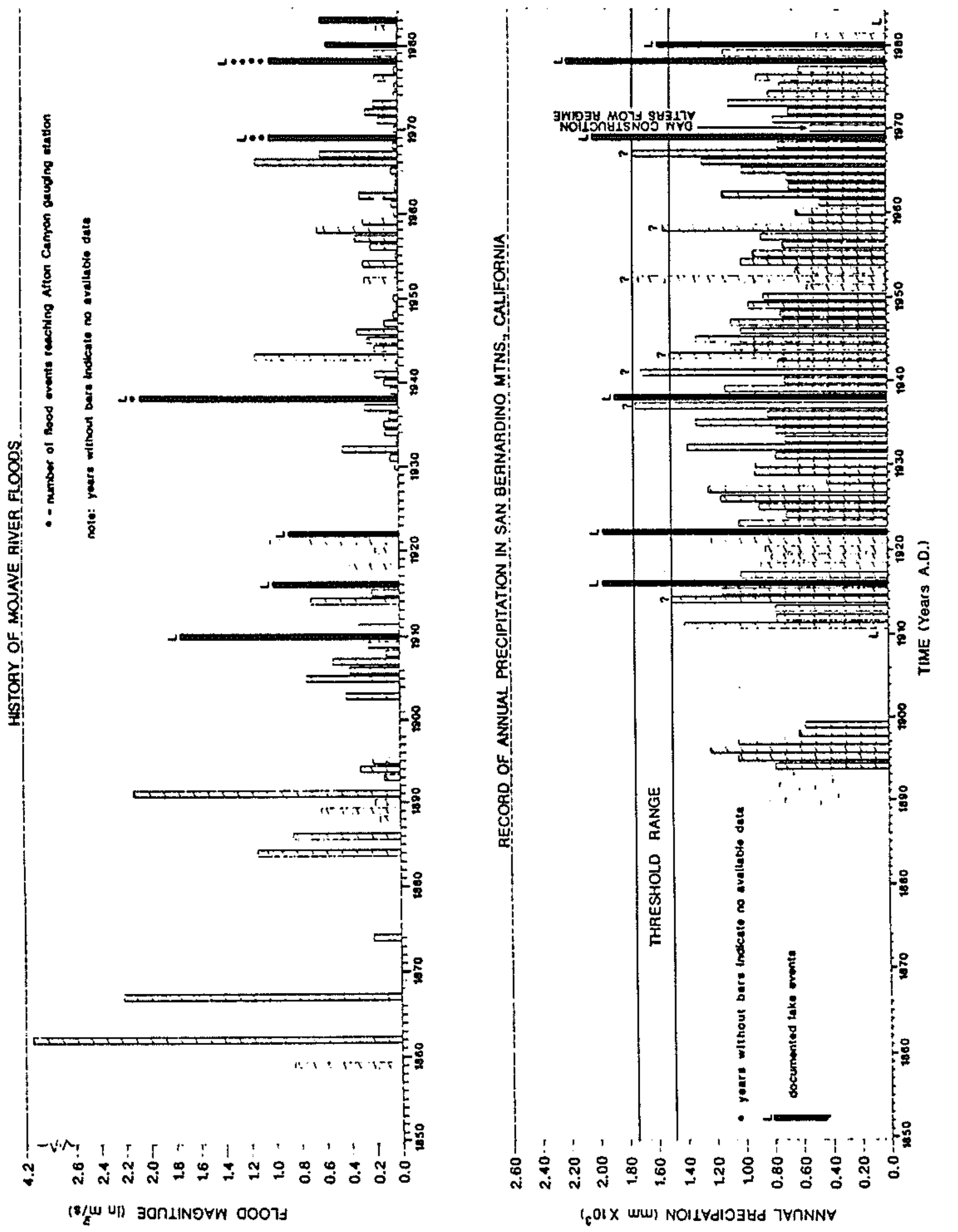


Figure 36. Historic record of Mojave River floods from 1850 to 1990. Documented lake-forming event illustrated as solid bar. Data from San Bernardino County Flood Control District. Historic record of annual precipitation in the San Bernardino Mountains. Solid bars represent well documented lake-forming event years, and dash bars represent years of possible lake events. Solid horizon lines represent upper and lower boundaries of lake-forming events.

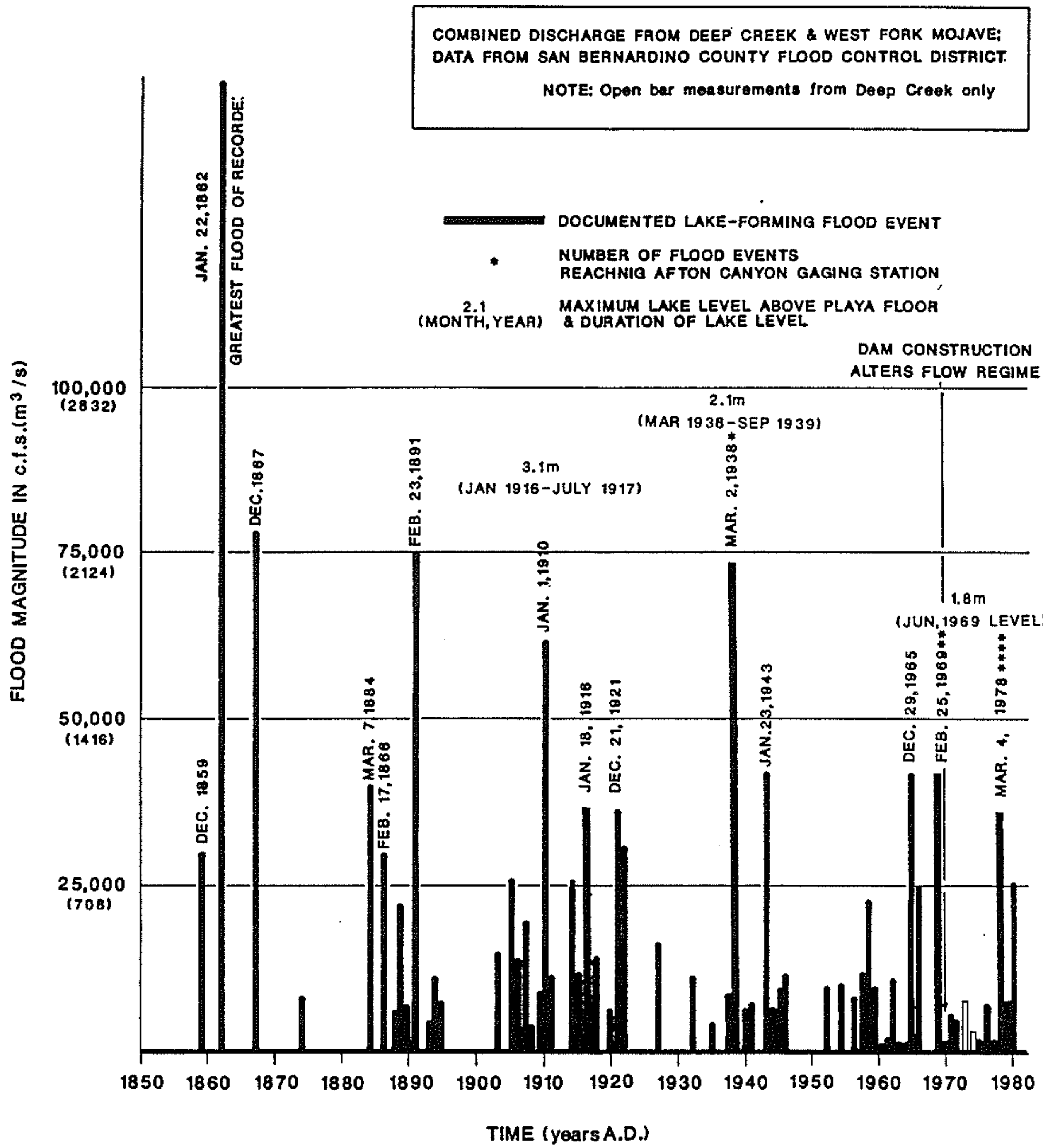


Figure 37. Historic record of Mojave River floods from 1850 to 1980. Data from San Bernardino County Flood Control District.

illustrated in Figure 38 and is critical to the discussions in this section and section 6.

A conceptual model represents an approach intermediate between empirical black-box analyses and deterministic approaches (Anderson and Burt 1985). This approach was selected for the Mojave River drainage basin on the basis of (1) a simple arrangement of selected hydrologic components which represent single process elements (i.e., input, output, storage) and (2) non-linear relations output and storage components. The non-linear character of these relations reflects the natural threshold conditions present for the Mojave River system. The source of the threshold conditions reflects processes such as ground-water storage in alluvial aquifers and sediment storage in terminal basins (figure 38).

A comparison of figure 36 with figure 2 illustrates the physical setting for the model. The major source of input into the system is precipitation in the San Bernardino Mountains where annual precipitation typically exceeds 1,000 mm. During the years of the documented flood/lake events, annual precipitation exceeded values between 1,500 and 1,750 mm in this mountain range (figure 36). Most of this precipitation accompanied Pacific storms and occurred over a period of one month or less. Climatic data from the San Bernardino Mountains suggest a threshold range in annual precipitation related to single and clusters of storms affect the volumes of runoff and episodes of lake building (figure 38).

Mojave River floods recorded at the confluence of Deep Creek and West Fork demonstrate that very large flood events originating in the Transverse Ranges, even those greater than the 1969 event, did not always produce a lake at the terminus of the river (figure 36). These data, along with a study by Hardt (1969), indicate that the character of the storm and recharge into the

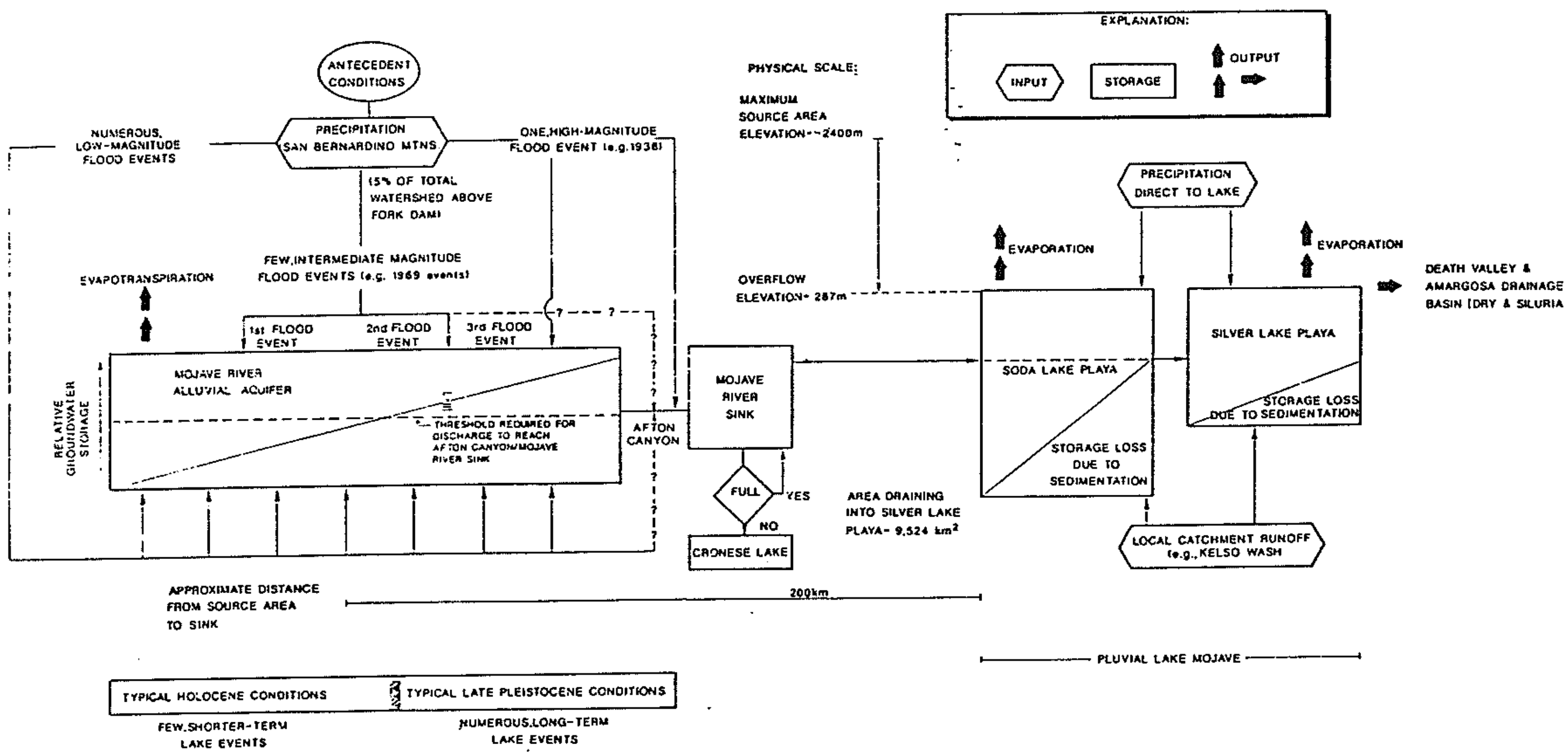


Figure 38. Conceptual model for the Mojave River Drainage basin control on lakes in its terminal basins.

alluvial of the Mojave River also affect the volume of flood waters reaching the Mojave River terminus (figure 38). Conditions that are characteristic of relatively lower-magnitude floods occurred in 1969 and 1978 and were preceded by one-to-four flood events (figure 36). Thresholds related to precipitation and to ground-water storage apparently must be exceeded before flood-water volumes sufficient to support a lake can pass through Afton Canyon and pass through Afton Canyon and into the Mojave River terminus. Under the present-day conditions, flooding of the distal playa takes place only when a single, high- magnitude flood or few, closely spaced lower-magnitude floods occur in the winter months (figures 36 and 38).

The conceptual model also incorporates a temporal component by including decreasing lake volumes in response to increasing sediment storage in the terminal lake basins during the latest Quaternary (figure 38). In addition, overflow conditions are given and show the output of lake water during the time of Lake Mojave. Physical scales are illustrated on the model to highlight the significance of these conditions on the hydrologic system.

Spatial and Temporal Distribution of Stream Flow. Although the Mojave River is the largest river in the Mojave Desert region (approximately 9,500 km^2), the runoff-generating area sustaining the river is a very small area in its headwaters (554 km^2), upstream from The Forks (figure 2). The two main tributaries are Deep Creek and West Fork that join at The Forks to form the Mojave River. No significant discharge contribution from any tributary along the Mojave River occurs downstream from The Forks. The long-term average annual stream flow is 96 million cubic meters (Mojave River Agency 1985). The total discharge is positively skewed at all gauging stations, with the highest skewness at the Barstow and Afton stations (figure 2). The standard deviation at all the stations (figure 2) is equal or larger than the mean (Ruchlewicz, Lin and Hatai 1978). These conditions reflect the great variability of Mojave River discharge (figure 39).

Along the Mojave River, stream flow only occurs during flood events. During these flood events, the alluvial aquifer associated with the river is recharged (Thompson 1929; Blaney and Ewing 1935; Conkling et al. 1934; Hardt 1969, 1971; California Department of Water Resources 1967; Ruchelwicz et al. 1978; Buono and Lange 1980; Mojave River Agency 1982, 1985; USACE 1956, 1966, 1986). However, along the river are reaches where the water table is at or near the channel floor, resulting in permanent base flow and/or relatively extensive cover of phreatophytes. These local channel conditions are related to geologic constrictions of the Mojave River alluvial aquifer, which are controlled by the northwest trending faults of the Mojave Desert block (figure 4). These reaches include: (1) Deep Creek, (2) Victorville to Helendale, (3) five kilometer reach near Hodge, (4) a few kilometers east of Yermo, (5) Camp Cady, and (6) Afton Canyon (Hardt 1971). A trend toward increased base flow and "surface wetness" at the vicinity of Yermo (near the Calico-Newberry fault) apparently existed between 12,210 ± 430 and 9,050 ± 350 years B.P. (Reynolds and Reynolds 1985).

The majority of the discharge of the Mojave River is during a very small portion of the year. Troxel and Hofman (1954) calculated that during a 47 year period, 70% of the volume of the river's discharge occurred less than 10% of the time and that 90% of the flow occurred during 23% of the time. This flow-volume distribution is typical of the majority of rivers draining into the Mojave Desert from the eastern flank of mountains (Troxel and Hofman 1954). For the vast majority of these rivers, 90% of the flow volume occurs during one percent of the time (Troxel and Hofman 1954).

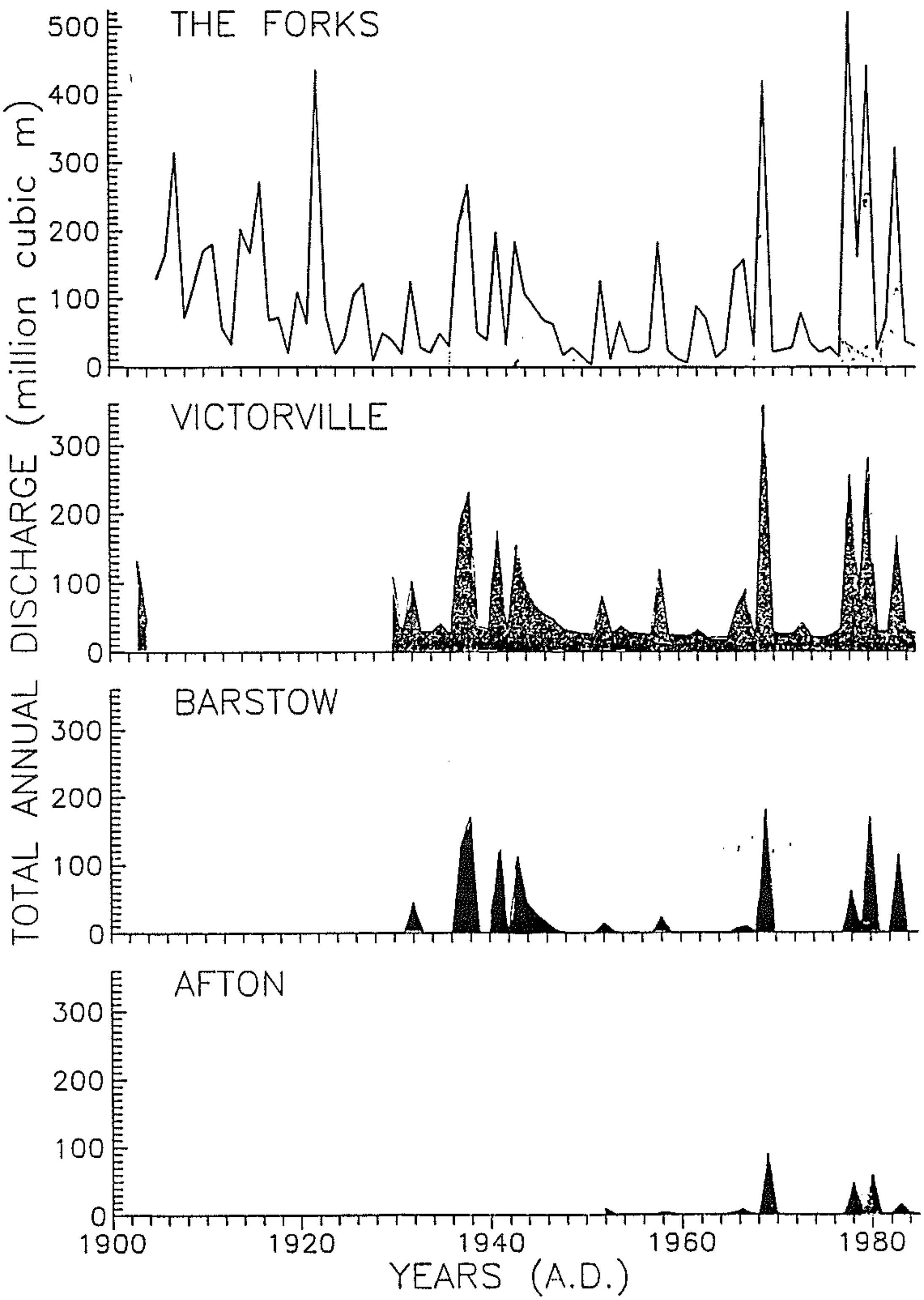


Figure 39. Annual discharge (10^6 m^3), in downstream direction (from top to bottom) for: 1) The Forks (1905-1985) - the combined discharge of Deep Creek and West Fork, which are the two tributaries that form the Mojave River, 2) Lower Narrows near Victorville (1903-1904 and 1929-1985), 3) Barstow (1930-1985), and Afton (1930-1931 and 1952-1985). Based on U.S. Geological Survey data (different years).

Given that the discharge of the Mojave River is over short time periods, the long-term average discharge does not accurately represent the Mojave River hydrological system. A few authors have presented average annual discharges for short time periods and emphasized the extreme temporal variability in the average (e.g., Antevs 1937; Hardt 1971). Hardt (1971) estimated the average discharge between 1931 and 1968 at The Forks was approximately 70 million cubic meters per year. He also showed that during relatively wet periods (1937-1946), the average discharge was 128 million cubic meters per year and during relatively dry years the average was 38 million cubic meters per year (table 13). It should be noted that 71% of the discharge in Victorville during the dry period was related to base flow (discharge from the Mojave river aquifer) and only 28% was related to base flow at this station during the wet period (table 13). Differences between Hardt's (1971) annual averages and those given by the Mojave River Agency (1985) are related to the wet period in the late 1970s and to the large flood in 1969.

During the water year of 1978, the San Bernardino Mountains received 2.0 to 2.6 times the average precipitation, resulting in 250% runoff in the Mojave River headwaters. This was the largest increase in runoff, relative to an average, for any river draining east into the California desert. In 1978, the percentage of runoff from mountainous watersheds increased in a southerly trend across California (California Department of Water Resources 1979).

Ground Water Conditions in the Mojave River Watershed. The boundary of the Mojave River ground-water basin does not conform to the present-day topographic boundaries. The ground-water basin also includes several of the closed basins such as Coyote Lake, Troy Lake, Harper Lake, and portions of El Mirage and Apple valleys (California Department of Water Resources 1967). The

TABLE 13

Average Annual Discharge (in million cubic meters) for Long-Term, Wet, and Dry Periods in The Mojave River Basin

	The Forks	Victorville	Barstow	Afton
Long-Term (1983-1968)	70	57	19	10
Wet Period (1937-1946)	128	108	62	32
Dry Period (1947-1964)	38	35	2.3	1.2

Mojave River ground-water basin is divided into three major sub-basins (Mojave River Agency 1982):

(1) the lower Mojave basin between the Calico-Newberry fault in the Newberry basin to Afton Canyon;

(2) the middle Mojave basin in the Barstow area between the Helendale and Calico-Newberry faults; and

(3) the upper Mojave basin of Victor Valley between the Helendale fault and The Forks.

The majority of recent studies involving groundwater associated with the Mojave River assume that any water east of the Afton Canyon is not available for human use. Earlier studies of this region included the Crucero, Cronese Lakes, Soda Lake, and the Silver Lake basins in the ground-water basin of the Mojave River. The first ground-water studies were conducted by McClure, Sourwine and Tait (1918) and Thompson (1929) which included detailed well data along the Mojave River and at its terminal playas. Thompson demonstrated the relative shallow depth of the water table in the Crucero valley and in Soda Lake basin and concluded that subsurface flow out of the northern end of Silver Lake basin has occurred because of the water-table gradient between the town of Baker and the ghost town of Silver Lake.

The Mojave River flow is the major recharge source for the Mojave River alluvial aquifer. Extreme flood events are the most significant recharge events to this aquifer, especially near Barstow and in the Newberry basin (Buono and Lang 1980). Recharge volumes to the aquifer are estimated by the loss of river discharge between gauging stations. Buono and Lang (1980) estimated 302 and 348 million cubic meters of recharge to the aquifer along the river between The Forks and Afton Canyon during the extreme floods of 1969 and 1978, respectively. These values are approximately five times the long-term annual average (59 million cubic meters from 1931- 1968) which was estimated by Hardt (1971) and four times the estimates of the Mojave River Agency (1982) for the period 1905-1980 (85 million cubic meters). The larger recharge volume during the winter 1977-1978 is explained by Buono and Lang as the result of two factors. The construction of The Forks Dam after the 1969 flood increased recharge and reduced the loss of water to the area downstream of Afton Canyon (figure 36). There was an even distribution of precipitation and stream flow during the winter of 1978.

Historical Records and Archives of Hydrologic Conditions

Historical records and archives were studied to document large floods and/or lake stands along the Mojave River and at its terminus, respectively. Limited information on the physical environment in this part of California prior to the twentieth century was found. However, there exist some written records on the flow conditions along the Mojave River and its terminal basins: Soda Lake, Silver Lake, and Cronese Lake playas. Drover (1979) dated human occupation of the Cronese Lake area at 560 ± 110 years B.P. and 390 ± 140 years B.P. He assumed that wet conditions and flooded playas were needed to support human occupation in this area and concluded that Cronese Lake was flooded in the twelfth, late sixteen, and early seventeenth centuries. Drover's date of 390 years ago for human occupation corresponds to the last major Holocene lake stand in Silver Lake playa (figure 19), and these periods of increased moisture are supported by tree-ring indices in southern California (Schulman 1947) (see section below).

Most of the travelers, trappers, and official explorers crossed the area through Soda Lake, Afton Canyon (Cave Canyon), and Camp Cady. Very few notes were found for Cronese Lakes and even fewer for Silver Lake. Silver Lake and

East and West Cronese Lakes are the actual terminal basins for the Mojave River floods. Thus, the paucity of information may reflect the possibility that travelers crossed the region in the southern portion, heading toward Afton Canyon on the dry Soda Lake, while Silver Lake and/or Cronese Lake contained flood water.

The basic assumption used while reading historial documents (reports, diaries, and summaries by historians) was that any person crossing the Mojave Desert would record in his writings a lake or large amount of water; this assumption is similar to the perception threshold of Hirsch and Stedinger (1987).

Early Travelers During the Spanish/Mexican Period. Fray Francisco Garces was the first European to keep a diary while traveling from the Colorado River to San Gabriel Mission through the Mojave River drainage basin. He crossed the dry Soda Lake playa on March 9, 1776 and continued through Afton Canyon where he may have stopped at a cave (Coues 1900). He continued along the Mojave River until he reach the area of present-day Victorville and crossed the San Bernardino Mountains on March 22, 1776. Garces named the river "Arroyo de los Matires," which is the name that appears on Font's map from 1777 ("R. de los Matires"). All maps through the mid-1850s show a Mojave River confluence with the Colorado River (see summary of maps in Preston 1974); some explorers searched for the confluence along the Colorado River, north of present-day Needles, California. Garces, on his return trip, once again crossed the Mojave River on May 18-20, 1776, but this time, he only traveled along the river's upper portions (Coues 1900).

Little information about the Mojave River was recorded during the remainder of the eighteenth century. Some information on Spanish and Mexican travelers exists for the beginning of the nineteenth century, but none exists concerning any hydrologic event on the river. The travelers usually went north of Silver Lake along the Spanish Trail, continuing upstream to Camp Cady, meeting the river at its middle and upper portions.

Jedediah Strong Smith found dry conditions in Soda Lake playa in the 1820s. He was probably the first non-Spanish American to reach the Pacific Ocean along a southern trail that followed a river he called the "Inconstant River" (because of the alternating dry bed and base-flow reaches) during the summers of 1826 and 1827 (Morgan 1975). Smith noted relatively drier conditions and white appearance of the playa surface in 1827 than the previous year. The change from a moist to dry playa might be explained by the storms of 1825 that affected runoff from the San Bernardino Mountains and subsequent drying during the following two years. During 1825, the Santa Ana River experienced one of its largest floods (San Bernardino County Flood Control District 1972; Troxel et al. 1942). It should be noted that both the Santa Ana River and the Mojave River head in the same portion of the San Bernardino Mountains, flowing to the west and east, respectively, with a common watershed boundary at their source area. The San Bernardino County Flood Control District report (1972) suggests that the 1825 flood was similar to the "largest in record," the 1862 flood. Estimated annual precipitation in San Bernardino (based on Los Angeles computed precipitation index and San Bernardino rainfall from 1879 to 1970) suggest similar precipitation during 1825 and 1862.

In 1829, Captain Ewing Young, with a party of trappers (including Kit Carson), traveled along the Mojave River. Young, however, did not mention any floods or wet playas (Dale 1918; Sabin 1914).

Fifteen years passed between Captain Young's expedition and the Fremont

Expedition in 1844 (Jackson and Spence 1970). The Fremont Expedition, which included scientists (and again, Kit Carson), traveled down the Mojave River from Victorville along the Old Spanish trail. They then left the trail and continued all the way to "the end of the river" where they rejoined the Old Spanish Trail (Jackson and Spence 1970). If they did indeed reach the end of the river, they did not mention that playas were at the terminus of the Mojave River. Thompson (1929) believes Fremont never reached the playas, but left the river 30 miles west of Soda Lake. Thus, there is no mention of wet conditions at the playas or the Mojave River during the expedition.

The American Period. San Bernardino was founded in 1851 by Mormons from Salt Lake City, Utah. Others settled along the Mojave River, especially at its headwater area and the upper Mojave River valley (Peirson 1970). During the Pacific Railroad expenditures of the 1850s, one party, headed by Lieutenant R.S. Williamson in 1853, searched for routes through the San Bernardino Mountains to the Colorado River. Williamson et al. (1856) discovered that Silver Lake was the physical termination of the Mojave River; however, a few months later, part of the Whipple Party (Whipple 1856) was still looking for the Mojave River confluence along the Colorado River. Williamson found shallow flow along the entire length of Afton Canyon; however, Soda Lake and Silver Lake playas were dry. He could not find any active channel in the Mojave River Sink. He located Soda Springs and camped there while exploring Silver Lake and Soda Lake.

The temporary Camp Cady was established in the 1860s on the Mojave River close to its junction with the Spanish trail. On May 4, 1960, Lieutenant Carr of Major Carleton's unit passed through East Cronese Lake (Casebier 1972). The postal returns of Camp Cady were forwarded to the Adjutant General's office each month from February 1865 to April 1871. The post returns for December 1867 through February 1868 were blank and may be related to the flood of December 1867. It seems that there was no permanent camp during the 1862 storm which may have resulted in flood damage to the camp (figure 39). In 1865 Coues (1900) followed Garces' diaries and stayed in Camp Cady. Although his comments are quite detailed, there is no mention of floods or wetter conditions in the playas. Camp Cady was abandoned in 1871. Approximately four years later, Lieutenant Eric Bergland found Soda Lake dry (Bergland 1876). At this time an important hydrologic data base was established as precipitation data were collected in San Bernardino beginning in 1870.

Although there is no direct evidence, lake stands in Silver Lake and Soda Lake basins may have been produced during the large floods of the late 1880s and the beginning of the 1890s. Estimations of these floods (in 1884, 1886, 1889, and 1891) were conducted by the USACE (1956) (figures 36 and 37). San Bernardino County Flood Control District (1972) summarizes evidence for storms in the San Bernardino Mountains during the late 1800s. Actual measurements of precipitation and runoff began in the Mojave River watershed during the 1880s (figures 36 and 37). Troxel et al. (1942), while analyzing the 1938 flood, gave a summary of the historical floods in southern California. The U.S. Weather Bureau (1962) and Pyke (1972) discussed some of the meteorological conditions during storms in southern California.

Historical Lake Stands During the Twentieth Century

Table 14 summarizes data on historical records of lake stands in Soda Lake and Silver Lake playas from the late 1800s to the mid 1980s. The results of the data analysis are discussed below.

The first historical record of a lake stand in the terminal basins of the

TABLE 14

Summary of historical evidence and previous studies of lake stands in Silver Lake, Soda Lake, and Cronese Lakes playas

Year (A.D.)	Remarks	Source	Depth (m)	Playa Flooded
1894	no flow reached	1		No
1895	Dagget, Ca			No
1896	1884-1902			No
1897				No
1898				No
1899				No
1900				No
1901				No
1902				No
1903		1, 2	?	SIL?
1904				-
1905				-
1906	dry (T&T Railroad)	3		No
1907				?
1908				-
1909				-
1910	LAKE	3	<1 ?	SIL
1911				-
1912				-
1913				-
1914	?			
1915				-
1916	LAKE	2, 1, 3	3.2	SIL, SOD, CL
1917				-
1918				-
1919				-
1920	LAKE OF LOCAL SOURCE	2		CL
1921	flow passed Afton	2		-
1922	LAKE	2,4	2	SIL, SOD, CL
1923	no flow passed	1, 5, 4		No
1924	Baker, Ca			No
1925	1923-1937			No
1926				No
1927	flow passed Afton	1, 5		No
1928				No
1929				No
1930				No
1931	no flow at Barstow	6		No
1932	flow passed Afton	6, 7		No
1933	no flow at Barstow			No
1934				No
1935	low flow at Barstow			No
1936	no flow at Barstow			No
1937	flow passed Afton			No
1938	LAKE	5, 8	7, 3.2	SIL, SOD, CL?
1939	low flow at Barstow			No
1940	no flow at Barstow			No

TABLE 14 (continued)

1941	flow passed Afton		?
1942	no flow at Barstow		No
1943	flow passed Afton	7	SOD?, CL?
1944	"	7	-
1945	"	7	-
1946	"	7	-
1947	no flow at Barstow	7, 6	No
1948	"	7, 6	No
1949	"	7, 6	No
1950	"	7, 6	No
1951	"	7, 6	No
1952	flow passed Afton	7, 6	?
1953	no flow at Barstow	6	No
1954	and at Afton	6	No
1955	"	6	No
1956	"	6	No
1957	"	6	No
1958	flow passed Afton	7, 6	?
1959	no flow at Barstow	6	No
1960	and at Afton	6	No
1961	"	6	No
1962	"	6	No
1963	"	6	No
1964	"	6	No
1965	flow passed Afton	6	?
1966	"	6	?
1967	"	6	?
1968	no flow at Barstow	6	No
1969	LAKE	10, 11	SIL, SOD, CL?
1970	no flow at Barstow	6	No
1971	"	6	No
1972	flow passed Afton	6	?
1973	low flow at Afton	6	No
1974	"	6	No
1975	"	6	No
1976	"	6	No
1977	"	6	No
1978	LAKE	9, 10, 11	SIL, SOD, CL
1979	low flow at Barstow	6	No
1980	LAKE	6, 10	SIL?, SOD?, CL
1981	low flow at Afton		No
1982	"		No
1983	LAKE	10	SIL, SOD, CL?
1984	low flow at Afton		No

1- Antevs (1937), 2- Thompson (1929), 3- Myrick (1963), 4- Daingerfield (1939), 5- Conkling et al. (1934), 6- United States Geological Survey (different years), 7- Ruchelwicz (1978), 8- Blaney (1957), 9- Drover (1979), 10- Air photographs and other direct observations, 11- Wells et al. (1984) and Wells, McFadden and Dohrenwend (1987).

Mojave River mentioned in the literature occurred in 1903 (Antevs 1937). Mojave River discharge apparently did not reach Dagget, California (14 km downstream from Barstow) during the years 1894-1902 (Antevs 1937). Thompson (1929) mentioned a large flood circa 1900. No floods were noted by other studies during this time (figure 37), no other historical source was found for this lake stand, and the percent of annual discharge and other flow data do not support it either (Blaney and Ewing 1935).

In 1906, the Tonopah and Tidewater (T & T) railroad was built from Ludlow through Broadwell Lake, Crucero, Soda Springs, Baker, and the town of Silver Lake (Myrick 1963). In November 1905 reconstruction began at Ludlow toward Silver Lake. The railroad crossed the San Pedro, Los Angeles and Salt Lake (SP, LA & SL) railroad at Crucero in the southern end of Soda Lake playa. The T & T railroad was established across Silver Lake playa in March 1906 at which time the tracks were laid on the playa floor. These tracks were flooded during the years 1910 (Myrick 1963), 1916 (about three meters of water [Thompson 1929, Myrick 1963]), and possibly during 1907 (Myrick 1963). The SP, LA & SL tracks were partially destroyed in Afton Canyon during the floods of 1907, 1910, 1916, and 1938.

Other lake stands in Silver Lake were observed after floods of the Mojave River in 1922 (two meters [Thompson 1929]; [Daingerfield 1939]; [Myrick 1963]), 1938 (2.1 m feet and 6.7 m [Blaney 1957] and [Daingerfield 1939], respectively), 1969, 1978, 1980, and 1983 (Wells et al. 1987). All of these lake stands are related to winter floods. Only one lake event occurred during the summer (1920) and was restricted to East Cronese Lake. Cronese Lake was flooded during winter storms in 1969, 1978, and 1980.

Flood Hydrology Recorded in Afton Canyon

This section will determine whether floods passing through Afton Canyon were the result of local precipitation or precipitation in the headwaters of the Transverse Ranges. Systematic hydrological records are used to calculate the total annual discharge in five gauging stations along the Mojave River. Two of them (Deep Creek and West Fork) were combined because these gauging stations are just upstream from The Forks. This procedure was applied by other researchers and agencies during their investigations of the Mojave River (e.g., USACE 1986; Mojave River Agency 1982).

Figure 39 demonstrates the downstream reduction in total annual discharge at The Forks, Victorville (Lower Narrows), Barstow, and Afton (in Afton Canyon). Only during years with large annual discharges (usually related to one to four floods during the winter season) did water reach and pass Afton Canyon. This yearly filtering process of the flow downstream from the headwaters to the terminal basins is the cumulative effect of the filtering of single floods. Figure 40 shows the hydrographs for Victorville and Afton for the well-recorded floods during the winters of 1969 and 1978 (Buono and Lang 1980) and the daily precipitation for Lake Arrowhead in the San Bernardino Mountains, the source area for these large floods. Victorville gauging station responds to almost any storm in the San Bernardino, especially those that exceed 2.54 cm of precipitation. Only a small fraction of the storm-related floods reach Afton (figure 39).

Recharge to the alluvial aquifer and the length of the Mojave River seems to be the simplest filter mechanism for all the floods (figure 38). The significance of this filter and related threshold conditions is that only large floods or series of floods result in lake-forming events (figure 36). Figure 41 summarizes the floods that reach Afton, and figure 42 shows plotting

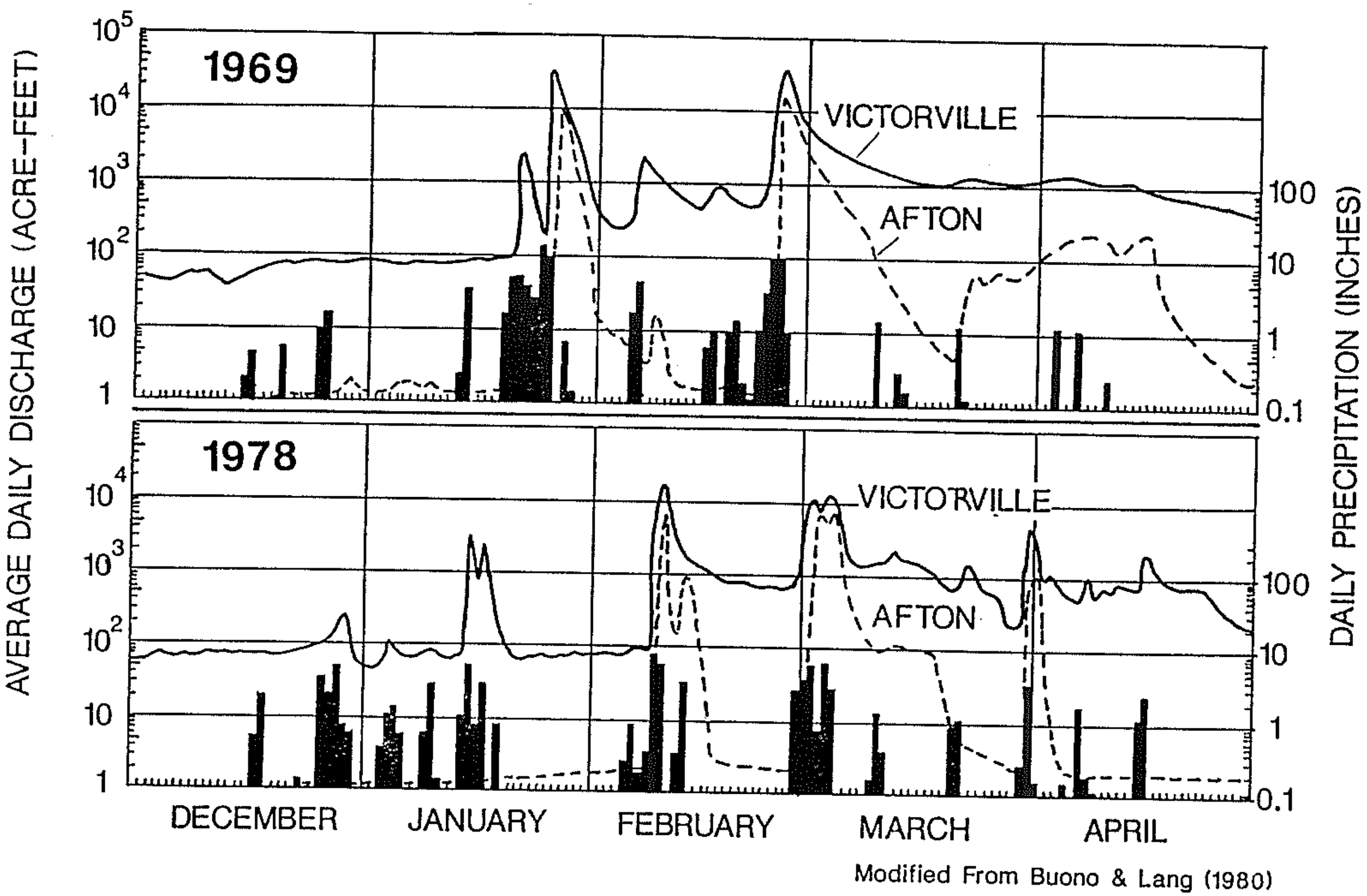


Figure 40. Average daily discharge during winters of 1968-1969 (upper) and 1977-1978 (lower) for Victorville (solid line) and Afton (dashed line) in response to precipitation in the San Bernardino Mountains (bars). Modified from Buono and Lang (1980). The shaded area shows the loss between Victorville and Afton. Note: Logarithmic scale for both precipitation and stream discharge.

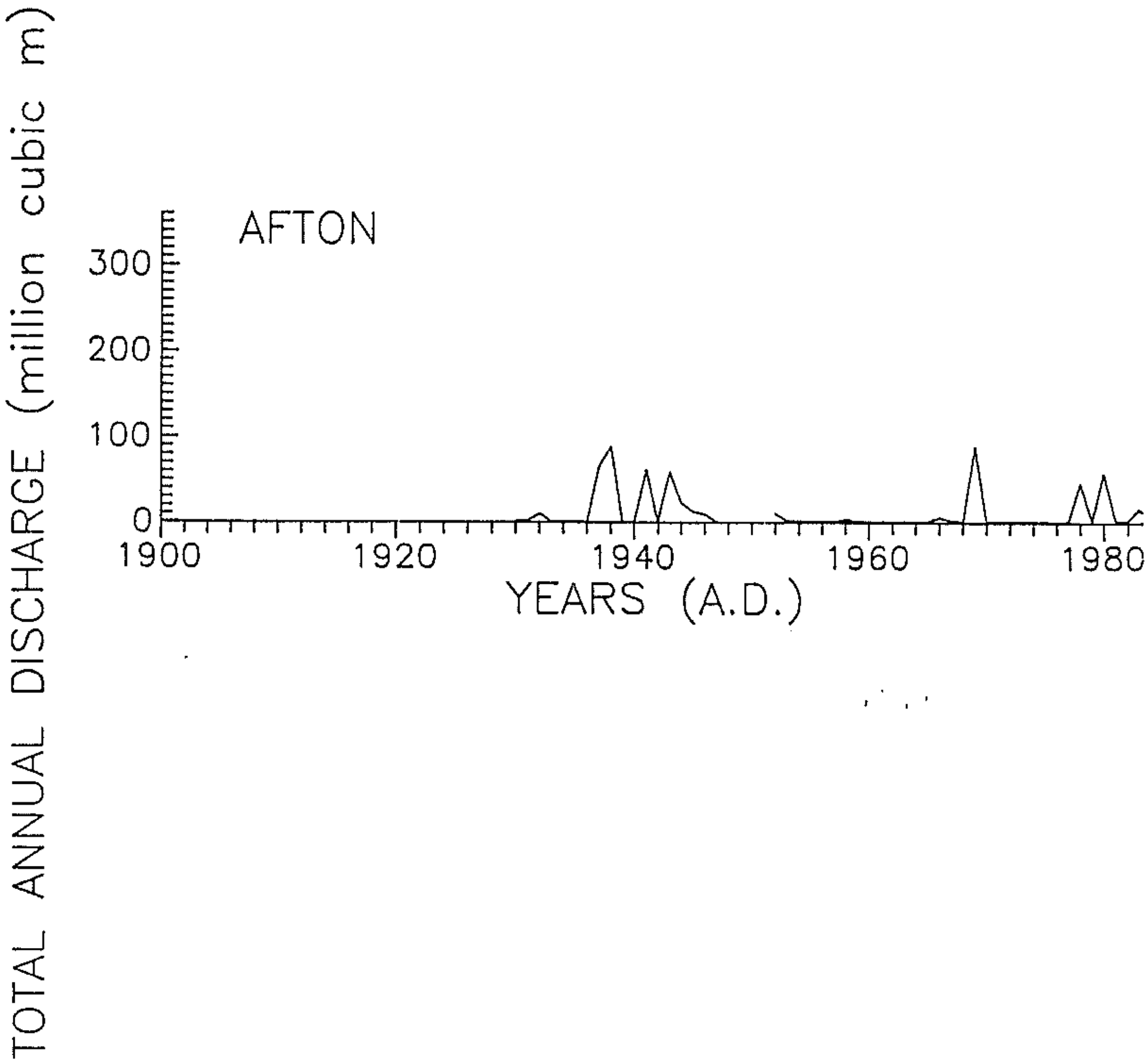


Figure 41. Annual discharge at Afton. The values for the 1930s to the 1950s are estimations by Hardt (1971) and Ruchlewitz et al. (1978).

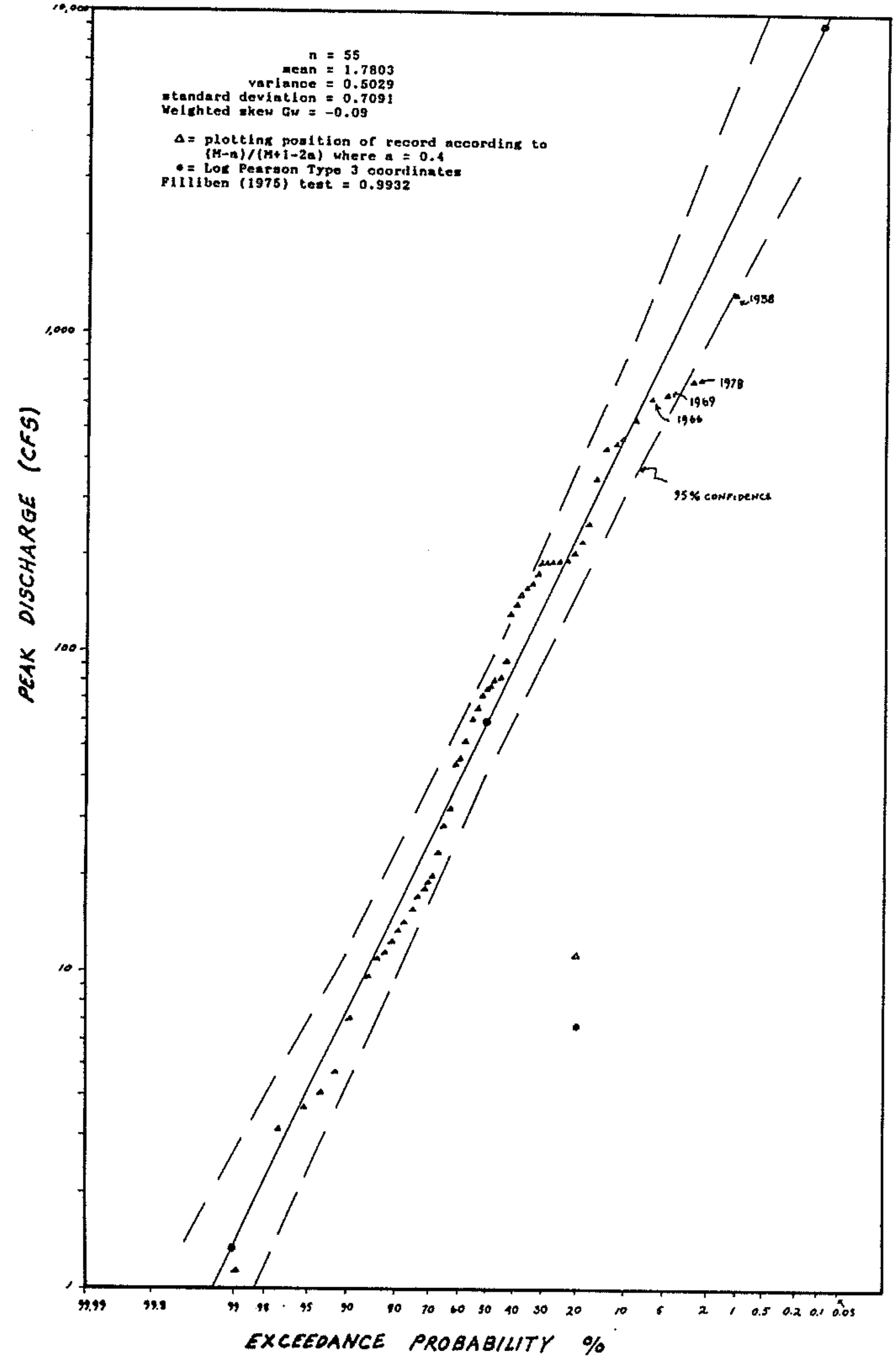


Figure 42. Exceedance probability (LPT 3) and plotting positions for the annual peak discharge series in Victorville. Including data for the period after 1970 when a regulation by the Forks Dam occurred.

positions and the fitted Log-Pearson 3 (exceedance probability) for peak discharges at Afton (Enzel, Ph.D. dissertation in preparation). The peak discharge of January 1969 (510 m^3/s) has the recurrence interval of once in 57 years (n = 34, using Weibul formula with a = 0.4). The same flood has a recurrence interval of 33 years in Victorville (n = 54) and 15 years in Deep Creek (n = 66) (Enzel, Ph.D. dissertation in preparation). This example demonstrates both the effect of the record length and the occurrence in larger floods with longer periods of record. Thus, from a conceptual standpoint, the Deep Creek record, and not the Afton record, should be used to calculate the recurrence interval for lake-building flood events. However, in this case, it would be stratigraphically inappropriate. In addition, some peak discharges are changing their position with respect to flood magnitude on the annual series, for example, the years 1969 and 1978 at Afton and Deep Creek stations (figures 42 and 43). This change in flood order can be attributed (1) to the hydrologic characteristics of the drainage basin (e.g., storage in the alluvial aquifer, figure 38) during specific floods and (2) to regulation of flood waters in the watershed after 1971 due to dam construction (figure 36).

Other methods of plotting positions of peak discharges (Cunnane 1978; Hirsch and Stedinger 1987) were applied to the headwater station (Deep Creek, resulting in recurrence intervals of 10 to 26 years (1978) and 8 to 15 years (1969) for some of the large floods that reached Afton Canyon (table 15). These values seem reasonable in that more frequent floods of these sizes would result in perennial lakes and less frequent floods would not reach Afton due to the alluvial-aquifer threshold (figure 38).

The largest flood of record, the 1862 flood reported by the USACE (1956) (figure 37), has a recurrence interval of 223 years (by the method of Gringorten 1963) to 150 and 83 years (E and B formulas, respectively, of

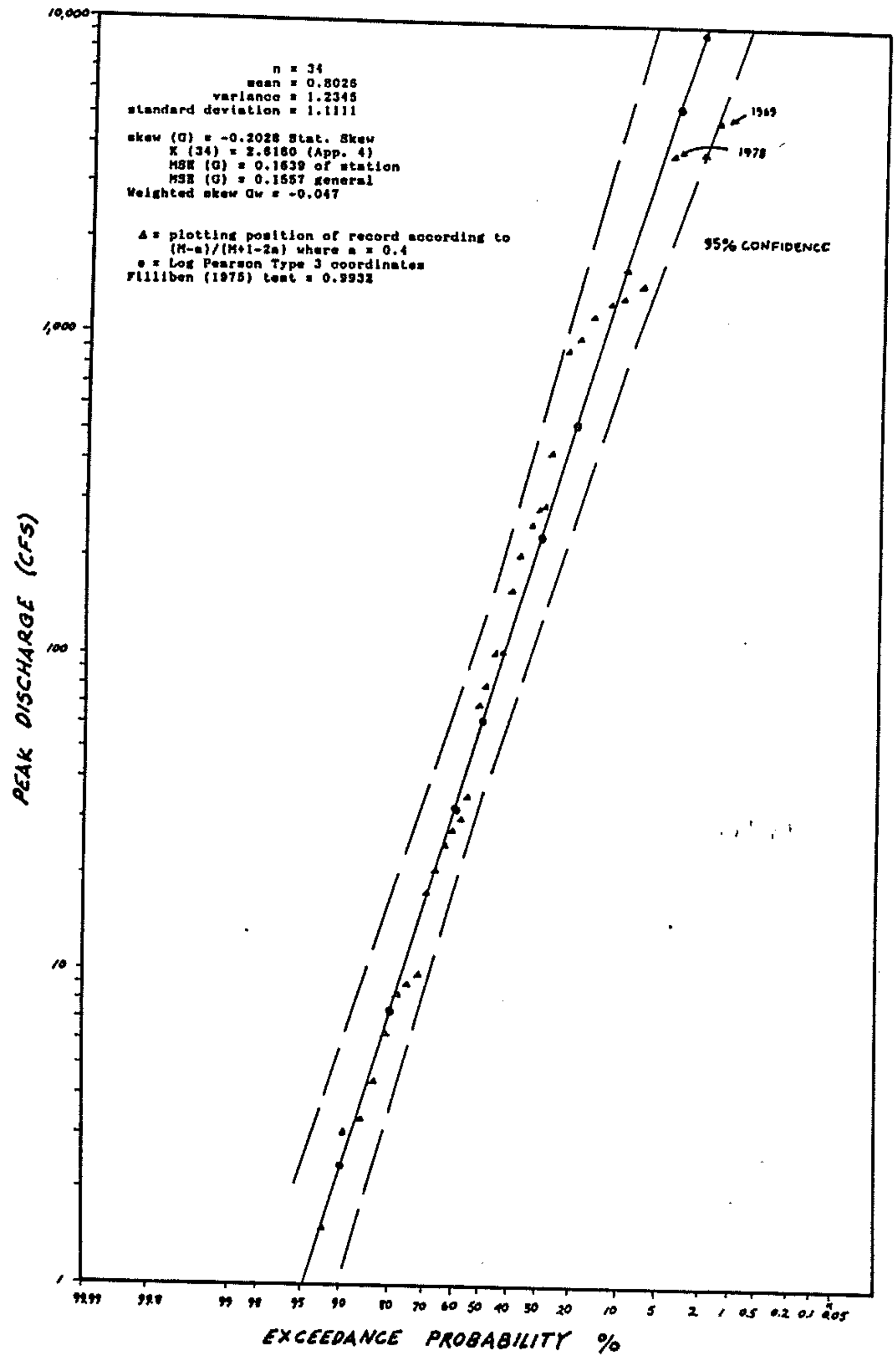


Figure 43. Exceedance probability (LPT 3) and plotting positions for the annual peak discharge series in Afton. Including data for the period after 1970 when a regulation by the Forks Dam occurred.

TABLE 15

Deep Creek Near Hesperia, CA. Plotted positions-using different formulas for systematic and historical records (see Cunnane, 1978 and Hirsch and Stedinger, 1987 for review and explanation).

water year	Qp (cfs)	#	Qp (cfs) (sorted)	(cms)	WEIBULL (1939)	HAZEN (1914)	GRINGORTEN (1963)	BENSOM (1950)	BENSOM (1950)	CONG (1979)	CONG (1979)	(IACWD)	(IACWD)	(IACWD)	HIRSCH & STEDINGER (1987) E FORMULA	HIRSCH & STEDINGER (1987) E FORMULA	HIRSCH & STEDINGER (1987) B FORMULA	HIRSCH & STEDINGER (1987) B FORMULA
		I			T	T	Pi	T	Pi	T	Pi	T	Pi	T	Pi	T	Pi	T
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1862	94000	1	94000	2662.1			0.0045	223.43							0.0067	150.00	0.0120	82.91
1867	50500	2	50500	1430.2			0.0125	80.21							0.0133	75.00	0.0241	41.45
1891	49000	3	49000	1387.7			0.0205	48.88							0.0200	50.00	0.0361	27.64
1906	10080	4	46000	1302.7	67.00	132.00	0.0285	35.15							0.0267	37.50	0.0482	20.73
1907	6920	5	37900	1073.3	33.50	44.00	0.0364	27.44							0.0333	30.00	0.0603	16.58
1909	6290	6	24800	702.3	22.33	26.40	0.0387	25.83	0.0552	18.11	0.0545	18.36	0.0511	19.57	0.0548	18.26	0.0554	18.02
1910	23000	7	23000	651.4	16.75	18.86	0.0538	18.57	0.0701	14.27	0.0692	14.44	0.0660	15.16	0.0695	14.38	0.0702	14.23
1911	6250	8	23000	651.4	13.40	14.67	0.0690	14.50	0.0850	11.77	0.0840	11.90	0.0809	12.37	0.0843	11.86	0.0850	11.76
1914	9350	9	21700	614.5	11.17	12.00	0.0841	11.89	0.0998	10.02	0.0988	10.12	0.957	10.45	0.0991	10.09	0.0997	10.02
1915	7160	10	19000	538.1	9.57	10.15	0.0992	10.08	0.1147	8.72	0.1136	8.81	0.1106	9.04	0.1138	8.78	0.1145	8.73
1916	23000	11	16600	470.1	8.38	8.80	0.1143	8.75	0.1296	7.72	0.1283	7.79	0.1255	7.97	0.1286	7.78	0.1292	7.73
1918	11000	12	16400	464.4	7.44	7.76	0.1295	7.72	0.1445	6.92	0.1431	6.99	0.1404	7.12	0.1434	6.97	0.1440	6.94
1920	4760	13	15400	436.1	6.70	6.95	0.1446	6.92	0.1594	6.27	0.1579	6.33	0.1553	6.44	0.1582	6.32	0.1588	6.30
1921	2200	14	12400	351.2	6.09	6.29	0.1597	6.26	0.1743	5.74	0.1726	5.79	0.1701	5.88	0.1729	5.78	0.1735	5.76
1930	340	15	11000	311.5	5.58	5.74	0.1748	5.72	0.1891	5.29	0.1874	5.34	0.1850	5.40	0.1877	5.33	0.1883	5.31
1931	1600	16	10080	285.5	5.15	5.28	0.1900	5.26	0.2040	4.90	0.2022	4.95	0.1999	5.00	0.2025	4.94	0.2030	4.92
1932	7900	17	9350	264.8	4.79	4.89	0.2051	4.88	0.2189	4.57	0.2170	4.61	0.2148	4.66	0.2172	4.60	0.2178	4.59
1933	168	18	8910	252.3	4.47	4.55	0.2202	4.54	0.2338	4.28	0.2317	4.32	0.2297	4.35	0.2320	4.31	0.2325	4.30
1934	2340	19	7900	223.7	4.19	4.26	0.2353	4.25	0.2487	4.02	0.2465	4.06	0.2445	4.09	0.2468	4.05	0.2473	4.04
1935	2760	20	7340	207.9	3.94	4.00	0.2505	3.99	0.2635	3.79	0.2613	3.83	0.2594	3.85	0.2615	3.82	0.2621	3.82
1936	2170	21	7160	202.8	3.72	3.77	0.2656	3.77	0.2784	3.59	0.2761	3.62	0.2743	3.65	0.2763	3.62	0.2768	3.61
1937	6800	22	7040	199.4	3.53	3.57	0.2807	3.56	0.2933	3.41	0.2908	3.44	0.2892	3.46	0.2911	3.44	0.2916	3.43
1938	46600	23	6920	196.0	3.35	3.38	0.2958	3.38	0.3082	3.24	0.3056	3.27	0.3041	3.29	0.3058	3.27	0.3063	3.26
1939	1850	24	6920	196.0	3.19	3.22	0.3109	3.22	0.3231	3.10	0.3204	3.12	0.3189	3.14	0.3206	3.12	0.3211	3.11
1940	2610	25	6810	192.9	3.05	3.07	0.3261	3.07	0.3379	2.96	0.3352	2.98	0.3338	2.00	0.3354	2.98	0.3358	2.98
1941	5500	26	6800	192.6	2.91	2.93	0.3412	2.93	0.3528	2.83	0.3499	2.86	0.3487	2.87	0.3502	2.86	0.3506	2.85
1942	395	27	6740	190.9	2.79	2.81	0.3563	2.81	0.3677	2.72	0.3647	2.74	0.3636	2.75	0.3649	2.74	0.3654	2.74
1943	19000	28	6350	179.8	2.68	2.69	0.3714	2.69	0.3826	2.61	0.3795	2.64	0.3785	2.64	0.3797	2.63	0.3801	2.63
1944	490	29	6290	178.1	2.58	2.59	0.3866	2.59	0.3975	2.52	0.3943	2.54	0.3934	2.54	0.3945	2.54	0.3949	2.53
1945	6350	30	6250	177.0	2.48	2.49	0.4017	2.49	0.4123	12.43	0.4090	2.44	0.4082	2.45	0.4092	2.44	0.4095	2.44
1946	5800	31	5800	164.3	2.39	2.40	0.4168	2.40	0.4272	2.34	0.4238	2.36	0.4231	2.36	0.4240	2.36	0.4244	2.36

TABLE 15 (continued)

1947	2740	32	5690	161.1	2.31	2.32	0.4319	2.32	0.4421	2.26	0.4386	2.28	0.4380	2.28	0.4388	2.28	0.4392	2.28
1948	840	33	5500	155.8	2.23	2.24	0.4471	2.24	0.4570	2.19	0.4534	2.21	0.4529	2.21	0.4535	2.20	0.4539	2.20
1949	248	34	5050	143.0	2.16	2.16	0.4622	2.16	0.4719	2.12	0.4681	2.14	0.4678	2.14	0.4683	2.14	0.4687	2.13
1950	708	35	4760	134.8	2.09	2.10	0.4773	2.10	0.4868	2.05	0.4829	2.07	0.4826	2.07	0.4831	2.07	0.4834	2.07
1951	40	36	4690	132.8	2.03	2.03	0.4924	2.03	0.5016	1.99	0.4977	2.01	0.4975	2.01	0.4978	2.01	0.4982	2.01
1952	2830	37	3320	94.0	1.97	1.97	0.5076	1.97	0.5165	1.94	0.5125	1.95	0.5124	1.95	0.5126	1.95	0.5129	1.95
1953	144	38	2900	82.1	1.91	1.91	0.5227	1.91	0.5314	1.88	0.5272	1.90	0.5273	1.90	0.5274	1.90	0.5277	1.89
1954	7340	39	2830	80.1	1.86	1.86	0.5378	1.86	0.5463	1.83	0.5420	1.85	0.5422	1.84	0.5422	1.84	0.5425	1.84
1955	313	40	1760	78.2	1.81	1.81	0.5529	1.81	0.5612	1.78	0.5568	1.80	0.5570	1.80	0.5569	1.80	0.5572	1.79
1956	6740	41	2740	77.6	1.76	1.76	0.5681	1.76	0.5760	1.74	0.5716	1.75	0.5719	1.75	0.5717	1.75	0.5720	1.75
1957	1150	42	2610	73.9	1.72	1.71	0.5832	1.71	0.5909	1.69	0.5863	1.71	0.5868	1.70	0.5865	1.71	0.5867	1.70
1958	12400	43	2340	66.3	1.68	1.67	0.5983	1.67	0.6058	1.65	0.6011	1.66	0.6017	1.66	0.6012	1.66	0.6015	1.66
1959	6920	44	2200	62.3	1.63	1.63	0.6134	1.63	0.6207	1.61	0.6159	1.62	0.6166	1.62	0.6160	1.62	0.6162	1.62
1960	112	45	2170	61.5	1.60	1.59	0.6286	1.59	0.6536	1.57	0.6306	1.59	0.6314	1.58	0.6308	1.59	0.6310	1.58
1961	1580	46	1850	52.4	1.56	1.55	0.6437	1.55	0.6504	1.54	0.6454	1.55	0.6463	1.55	0.6455	1.55	0.6458	1.55
1962	7040	47	1600	45.3	1.52	1.52	0.6588	1.52	0.6653	1.50	0.6602	1.51	0.6612	1.51	0.6603	1.51	0.6605	1.51
1963	627	48	1580	44.7	1.49	1.48	0.6739	1.48	0.6802	1.47	0.6750	1.48	0.6761	1.48	0.6751	1.48	0.6753	1.48
1964	409	49	1150	32.6	1.46	1.45	0.6891	1.45	0.6951	1.44	0.7897	1.45	0.6910	1.45	0.6898	1.45	0.6900	1.45
1965	443	50	1020	28.9	1.43	1.42	0.7042	1.42	0.7100	1.41	0.7045	1.42	0.7059	1.42	0.7046	1.42	0.7048	1.42
1966	21700	51	840	23.8	1.40	1.39	0.7193	1.39	0.7248	1.38	0.7193	1.39	0.7207	1.39	0.7194	1.39	0.7196	1.39
1967	15400	52	708	20.1	1.37	1.36	0.7344	1.36	0.7397	1.35	0.7341	1.36	0.7356	1.36	0.7342	1.36	0.7343	1.36
1968	654	53	696	19.7	1.34	1.33	0.7495	1.33	0.7546	1.33	0.7488	1.34	0.7505	1.33	0.7489	1.34	0.7491	1.33
1969	23000	54	654	18.5	1.31	1.31	0.7647	1.31	0.7695	1.30	0.7636	1.31	0.7654	1.31	0.7637	1.31	0.7638	1.31
1970	559	55	627	17.8	1.29	1.28	0.7798	1.28	0.7844	1.27	0.7784	1.28	0.7803	1.28	0.7785	1.28	0.7786	1.28
1971	3320	56	559	15.8	1.26	1.26	0.7949	1.26	0.7993	1.25	0.7932	1.26	0.7951	1.26	0.7932	1.26	0.7933	1.26
1972	8910	57	503	14.2	1.24	1.23	0.8100	1.23	0.8141	1.23	0.8079	1.24	0.8100	1.23	0.8080	1.23	0.8081	1.24
1973	6810	58	490	13.9	1.22	1.21	0.8252	1.21	0.8290	1.21	0.8227	1.22	0.8249	1.21	0.8228	1.22	0.8229	1.22
1974	1020	59	443	12.5	1.20	1.19	0.8402	1.19	0.8439	1.18	0.8375	1.19	0.8398	1.19	0.8375	1.19	0.8376	1.19
1975	503	60	409	11.6	1.18	1.17	0.8554	1.17	0.8588	1.16	0.8523	1.17	0.8547	1.17	0.8523	1.17	0.8524	1.17
1976	5050	61	395	11.2	1.16	1.15	0.8705	1.15	0.8737	1.14	0.8670	1.15	0.8695	1.15	0.8671	1.15	0.8671	1.15
1977	696	62	340	9.6	1.14	1.13	0.8857	1.13	0.8885	1.13	0.8818	1.13	0.8844	1.13	0.8818	1.13	0.8819	1.13
1978	24800	63	313	8.9	1.12	1.11	0.9008	1.11	0.9034	1.11	0.8966	1.12	0.8993	1.11	0.8966	1.12	0.8966	1.12
1979	5690	64	248	7.0	1.10	1.09	0.9159	1.09	0.9183	1.09	0.9114	1.10	0.9142	1.09	0.9114	1.10	0.9114	1.10
1980	16400	65	168	4.8	1.08	1.07	0.9310	1.07	0.9332	1.07	0.9261	1.08	0.9291	1.08	0.9262	1.08	0.9262	1.08
1981	130	66	144	4.1	1.06	1.06	0.9462	1.06	0.9481	1.05	0.9409	1.06	0.9439	1.06	0.9409	1.06	0.9409	1.06
1982	2900	67	130	3.7	1.05	1.04	0.9613	1.04	0.9629	1.04	0.9557	1.05	0.9588	1.04	0.9557	1.05	0.9557	1.05
1983	16600	68	112	3.2	1.03	1.02	0.9764	1.02	0.9778	1.02	0.9705	1.03	0.9737	1.03	0.9705	1.03	0.9704	1.03
1984	4690	69	40	1.1	1.02	1.01	0.9915	1.01	0.9927	1.01	0.9852	1.01	0.9886	1.01	0.9852	1.01	0.9852	1.01

TABLE 15 (continued)

The basic formula (i-a)/N+1-2a) is used, i=order of flood event (including systematic and historical records). When formulas for only the systematic record are used: i=(i-3), such as in the Weibull and the Hazen Formulas (column F and C), the values of a is 0.0 in the Weibull Formula and 0.5 in the Hazen Formula. In the following equations k is the i'th order (5 in the specific case) that we can assume with high confidence that our record includes all the historical floods which are equal to it or larger. That means that there are k extreme floods above some threshold, s is the length in years of the systematic (s=66) according to the definition of Bulletin 17B, n is the historical record length (n=125), e - the extreme flood events within the systematic record (e=2). The Gringorten Formula for i=1...k is (i-44)/(n+.12) and i-k+e-.44)(s+.12) for i=k+1...i. For i=k+...i, Hirsch and Stedinger (1987) summarize the following formulas: (n-1))+((n-k)/(n+1))*((i-k)/(s-e)) (Benson), (k/(n+1))+((n-k+1)/(n+1))*((i-k)/(s-e+1)) (Cong Formula), and ((k+.5)/(n+1))+((n-k)/(n+1))*((i-k.5)/(s-e)) (IACWD Formula). The E (Exceedence) Formula is ((i/(k+1))*(n/k) for i=1...k, and (K/n)+((n-k)/n)*((1-k)/(S-e+1)) for i=k+1...i.

The B (Bayesian) Formula is (i/(k+1))*((.5+k)/(.5+9.5+n)) and ((.5+k)/(.5+9.5+n))+(1-((.5+k)/(.5+9.5+n)))*((i-k)/(s-e+1)), for the same ranges, respectively.

T is the return period and Pi is the exceedence probability.

The threshold used in this analyses is 1000 cubic meter per second.

The assumption is that any flood of this magnitude would be recorded if it had occurred since 1859.

Hirsch and Stedinger 1987). Prediction of the 1862-flood recurrence interval from a Log-Pearson 3 probability curve, based on peak discharges calculated for The Forks Dam by the USACE without the 1862 peak discharge, results in a recurrence interval of 150 years.

If the Hirsch and Stedinger (1987) formulas are used, floods with recurrence intervals of 5 to 10 years can result in ephemeral lakes in the terminal basins downstream of Afton Canyon. However, if only those lake stands lasting more than a year are used (i.e., from the paleoclimate perspective for adequate water accumulation), the recurrence interval for floods is greater than 10 years. But it should be noted that the low-frequency peak discharges are usually grouped together during the last century, indicating there are shorter periods when their probability is larger.

Geologic Evidence of Afton Canyon Floods. The incision and formation of Afton Canyon is related to overflow water from late Pleistocene Lake Manix. Detailed investigation of Lake Manix and Afton Canyon during the late Pleistocene is currently being investigated (Meek, Ph.D. dissertation in progress). In this study, the geomorphology of the canyon was investigated to reconstruct the discharges of any historical or Holocene floods that produced lakes in the terminal basins.

Within the canyon, the terraces and other alluvial and fluvial features can be divided into three major categories.

(1) The high terraces are those inset into the canyon below the elevation of Lake Manix deposits (figure 44). These high terraces are subdivided into two sets, according to their elevation above the Mojave River channel. One, at 29 to 31 meters and a lower terrace, 23 to 25 meters above the river (figure 45).

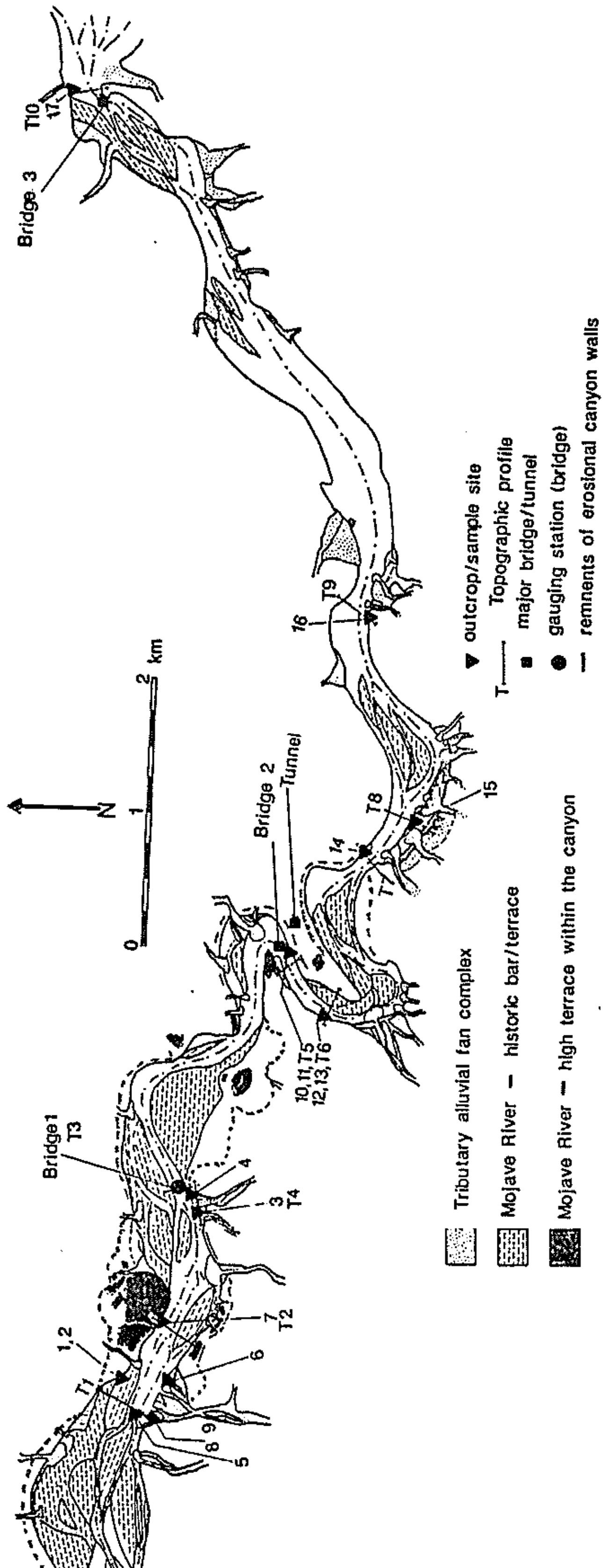


Figure 44. Afton Canyon - Late Quaternary geological units within the canyon, locations of outcrops and sample sites, topographic profiles, and major constructions. The railway route is not shown.

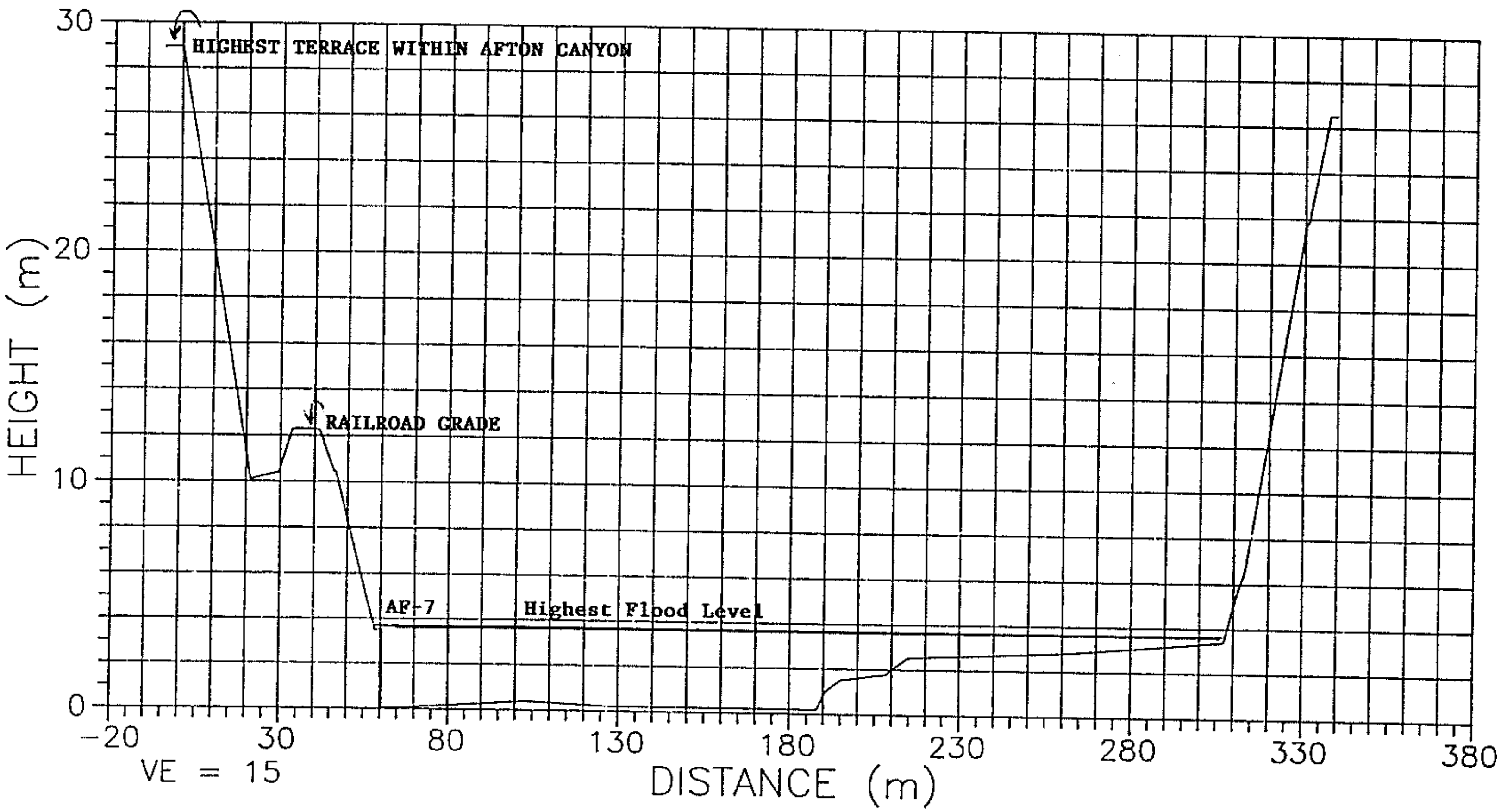


Figure 45. Selected topographic profiles in Afton Canyon, see Figure 44 for location.

The isotopic age of these terraces have not been determined and, therefore, are mapped as a single unit. Their geologic age range is inferred to be latest Pleistocene to middle Holocene. The significance of the terraces is related primarily to the evolution of the canyon rather than to the reconstruction of past flows of the Mojave River, and therefore not investigated in detail.

(2) The alluvial fans forming at the tributaries to the Mojave River within the canyon and are useful for paleohydrologic studies (figure 44). The majority of the alluvial fan surfaces are characterized by soils with Av horizons, which demonstrates the youthful geologic age, e.g., middle to late Holocene. A soil described on the highest of 10 alluvial fan surfaces in Afton Canyon (figure 46) is similar in horizon development as the soil developed on the middle to late Holocene surface in the Silver Lake piedmonts (unit Qf4 of Wells, McFadden and Dohrenwend 1987). The surface of this fan is 19 meters above the Mojave River channel and has a gradient toward the river of 0.046. If the Mojave River did not change its lateral position significantly since the deposition of this alluvial fan, at least 5 to 7 meters of incision of the main stream occurred over a few thousand years. The existence of 10 surfaces since the middle (?) Holocene supports a high rate of incision of the Mojave river channel during the last few thousand years. This rate of incision may be related to two major mechanisms: (1) extreme flood events that are relatively confined in the steep-walled canyon and (2) episodic tectonic activity during the late Holocene.

(3) The canyon contains several fluvial landforms and associated deposits that are related to the most recent elevation of the Mojave River (figure 44). These features are typically less than a few meters in height above the main channel, and in some cases have interfingering stratigraphic relations with

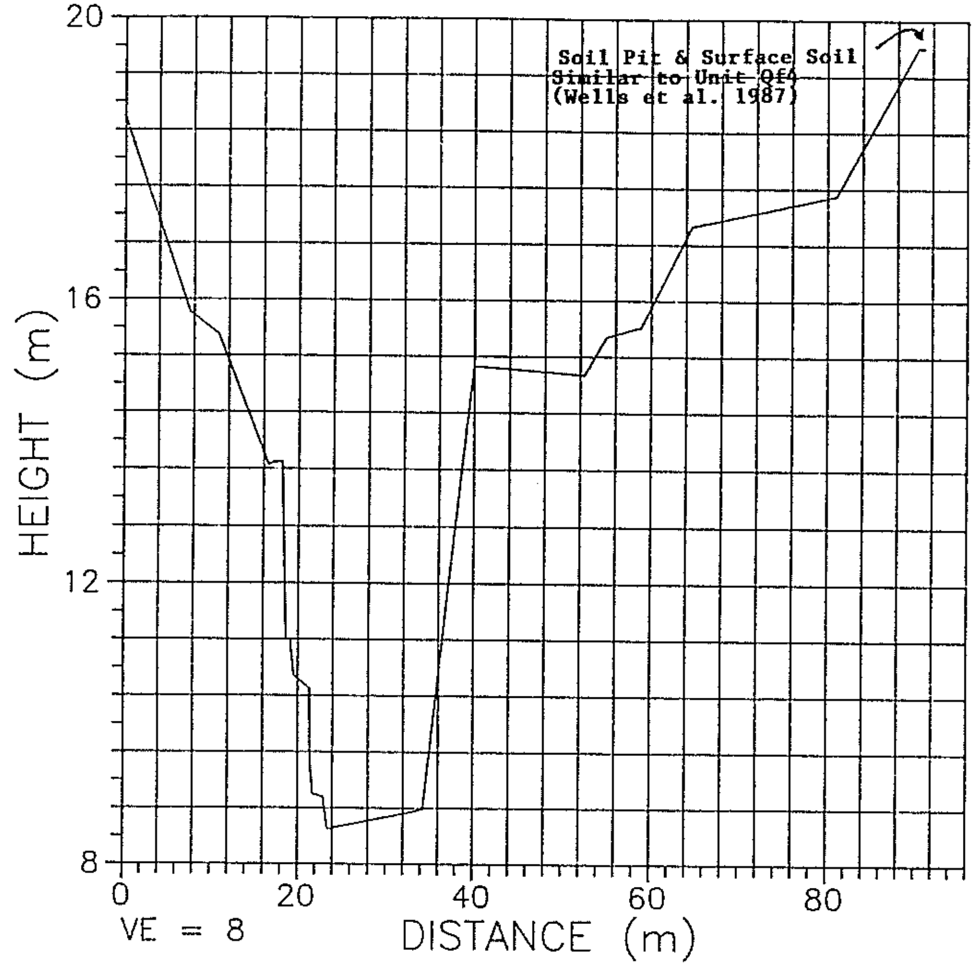


Figure 46. Selected topographic profiles in Afton Canyon. See Figure 44 for location.

the tributary alluvial-fan complexes. No soil horizons are found associated with any of these features. This observation and the presence of recent cultural artifacts (mainly related to railroad construction and/or trains) suggest historical ages for these deposits which are certainly no older than a few hundred years.

Figure 44 also shows the locations of selected topographic profiles and sample sites that display some evidence relating them to large floods. The map does not illustrate the position of the Union Pacific railroad (formerly San Pedro, Los Angeles and Salt Lake) along the canyon but shows the location of the three major bridges and the old tunnel associated with the railroad. The bridges were rebuilt after being damaged (with a portion of the tracks) in the 1938 flood.

Interpretation of the Peak Discharges. The peak discharge of the 1969 flood is 510 m^3/s with a stage of 3.17 m. This stage height is similar to the flow height interpreted from flood lines observed on the railroad bridge column (figure 47, T3 on figure 44). The highest flood line on this bridge should be that of the 1969 flood since bridge was constructed after the 1938 flood. A measured cross-sectional area of approximately 250 m^2 yielded an average velocity of 2.0 m/sec during the 1969 peak discharge.

The USACE (1986) routed peak discharges similar to those during the 1938 flood from The Forks to Victorville, Barstow, and Afton. The result, 991 m^3/s (35,000 cfs), is almost twice the maximum discharge recorded in 1969. There is evidence that the railroad tunnel near cross-section T5 (figure 44) was filled with water during the 1938 flood and that the bridge was destroyed (Myrick 1963). Using data obtained at cross-section T5 (figure 48) [the elevations of the tunnel and the bridge above the Mojave River (using an area

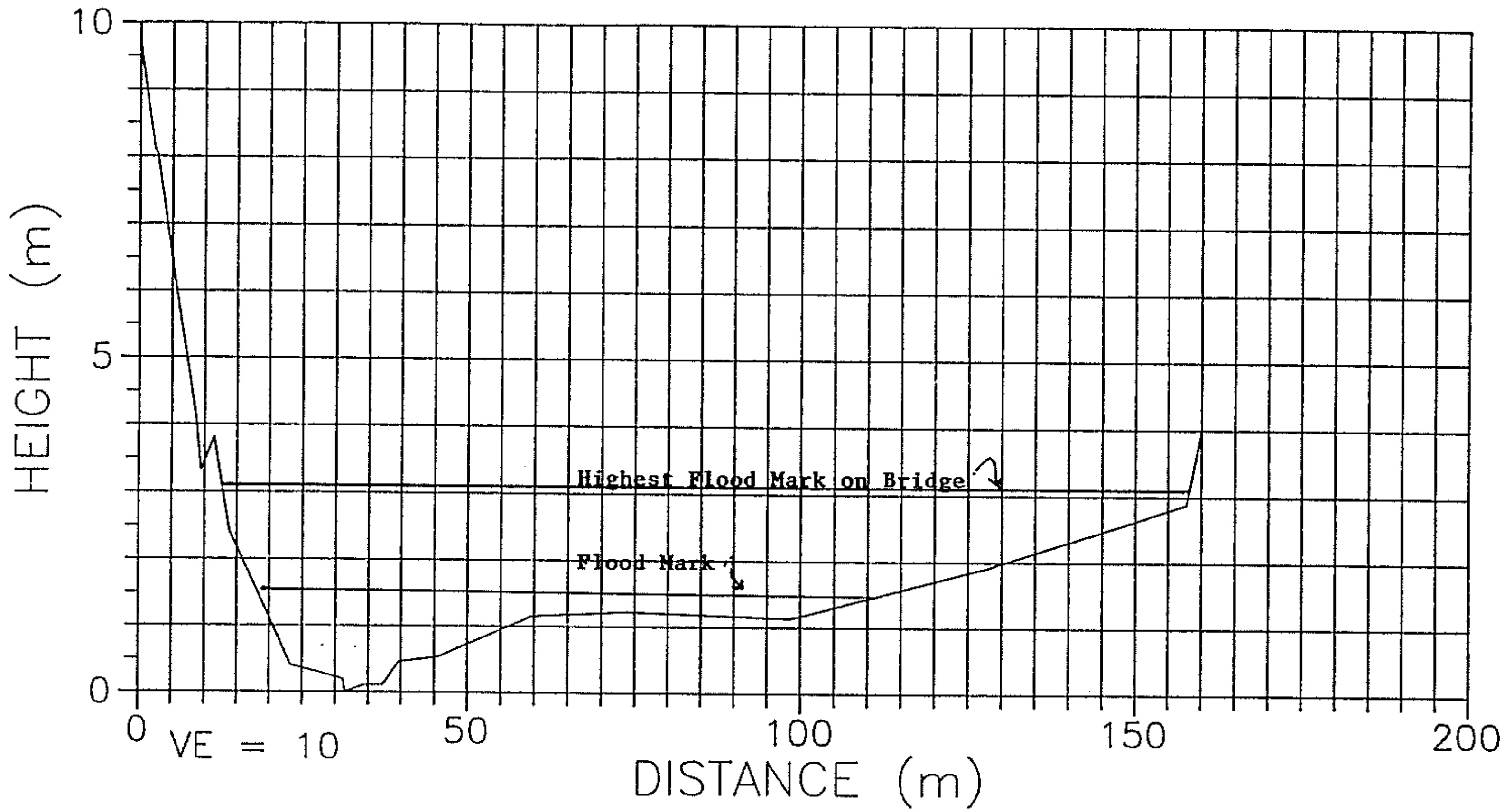


Figure 47. Selected topographic profiles in Afton Canyon. See Figure 44 for location.

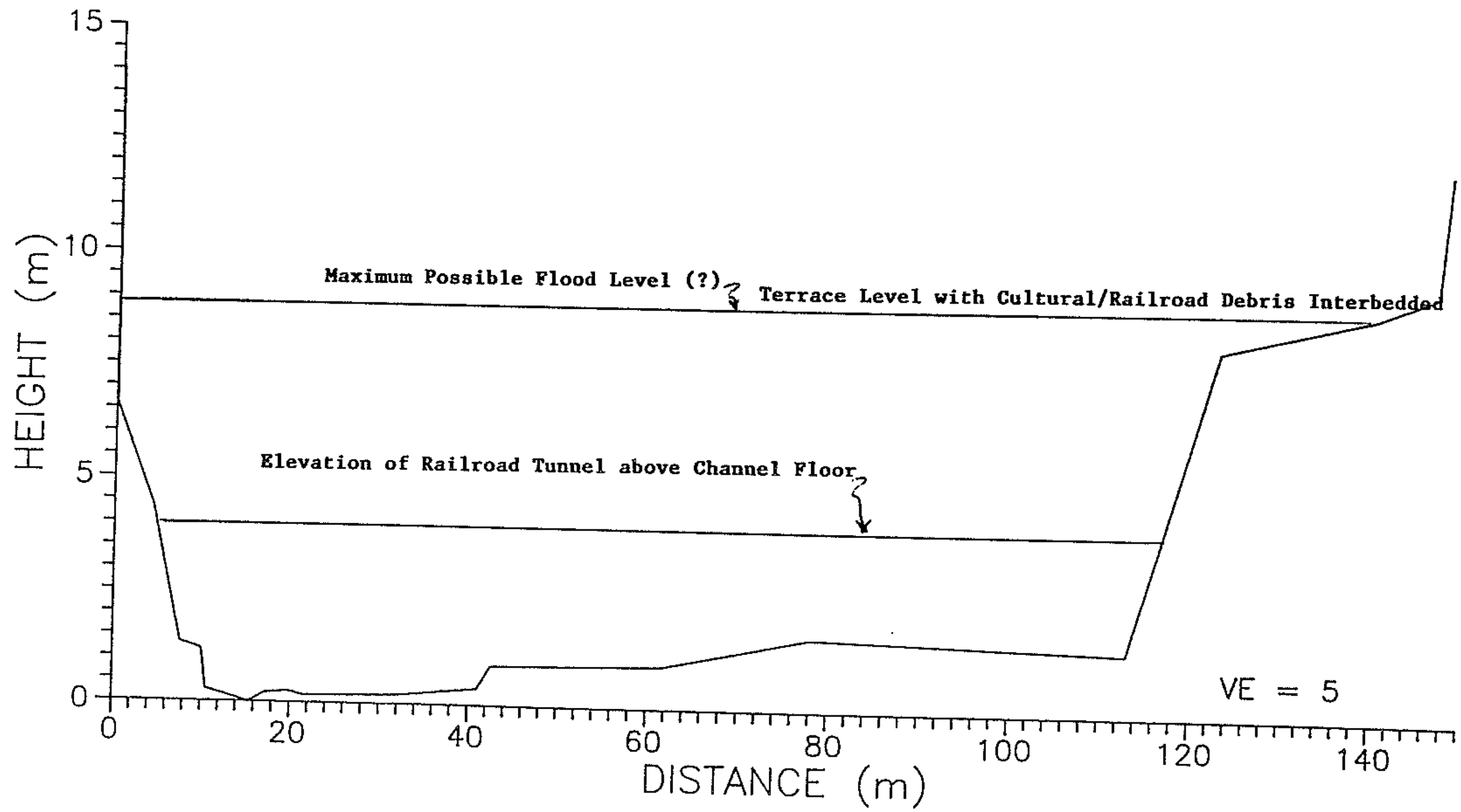


Figure 48. Selected topographic profiles in Afton Canyon. See Figure 44 for location.

of about 370 m^2 and hydraulic radius of 120 m), the Mojave River bed slope (0.004), and the estimated n = 0.05 for the reach between T5 and T6], a discharge of 900 m^3/sec was calculated via the slope-area method. This corresponds well to the routed value. However, using the terrace elevation at T5 (eight to nine meters above the stream, figure 48), this method yielded a discharge value exceeding 6,000 m^3/sec, approximately three times more than any known or estimated discharge in the headwaters of the Mojave River (since 1862). This suggests that the flood of 1938 did not reach the terrace level and may not be responsible for the cultural debris and railroad material found in the deposits.

The major conclusion from the studies in Afton Canyon is the lack of a long-term fluvial geomorphic record of flood events that allows quantitative discharge estimates. The paucity of information on paleofloods which overlap in time with the Holocene record of lakes in Soda Lake and Silver Lake basins limited the investigation.

Anomalous Northern Pacific Climatic Patterns During Lake-Building Flood Events in the Twentieth Century and the Middle to Late Holocene

Introduction. Understanding the present-day relations among atmospheric circulation, precipitation characteristics, and flood patterns is essential to the prediction of water supply, geomorphological processes, and flood hazards in a drainage basin (e.g., Cayan and Peterson 1987; Baker 1988) It also is necessary to the interpretation of paleoclimatic proxy-data as recorded in closed hydrological systems.

The purposes of this section are: (1) to demonstrate a correlation between northern Pacific anomalous atmospheric circulation patterns and lake-building flood events at terminus the Mojave River and (2) to interpret past climatic conditions in southern California and in the southern Great Basin during the middle to late Holocene. These interpretations will be based on deposits in the Mojave River terminal basins and published tree-ring chronologies from southern California, the San Bernardino Mountains (Schulman 1947, 1956; Stokes et al. 1973), and Baldwin Lake (Stokes et al. 1973) in the San Bernardino Mountains. This approach was based upon similar approaches taken during recent flood studies in the western U.S. Maddox et al. (1980) and Hirschboeck (1987) concluded that catastrophic flood events in the western U.S. can be grouped into four major categories and linked to specific types of anomalous atmospheric circulation patterns. Namias (e.g., 1978, 1980), Pyke (1972), and the U.S. Weather Bureau (1962) demonstrated close relations exist between North Pacific sea surface temperature and atmospheric circulation and storm patterns on the west coast of North America. Because the headwaters of the Mojave River watershed experience large storms in the San Bernardino Mountains that cause lake-building floods, storm patterns and their relation to Pacific atmospheric systems were studied for those years with these events (figure 49). During the twentieth century, eight extreme floods in the Mojave River produced documented lake stands in Silver Lake and/or Cronese Lakes playas. These floods were during the winters of the water years 1910, 1916, 1922, 1938, 1969, 1978, 1980, and 1983 (figure 36; table 14). Other years with large volumes and relatively high peak discharges also occurred in the basin, but no direct evidence for a lake stand was found (see sections above).

Analysis. Figures 37 and 39 show those years with large discharge in the headwater stations of the Mojave River and the filtering process of flood flows downstream, respectively. Afton Canyon and the terminal basins only receive a portion (10 - 30%) of these floods (figure 50). During "normal"

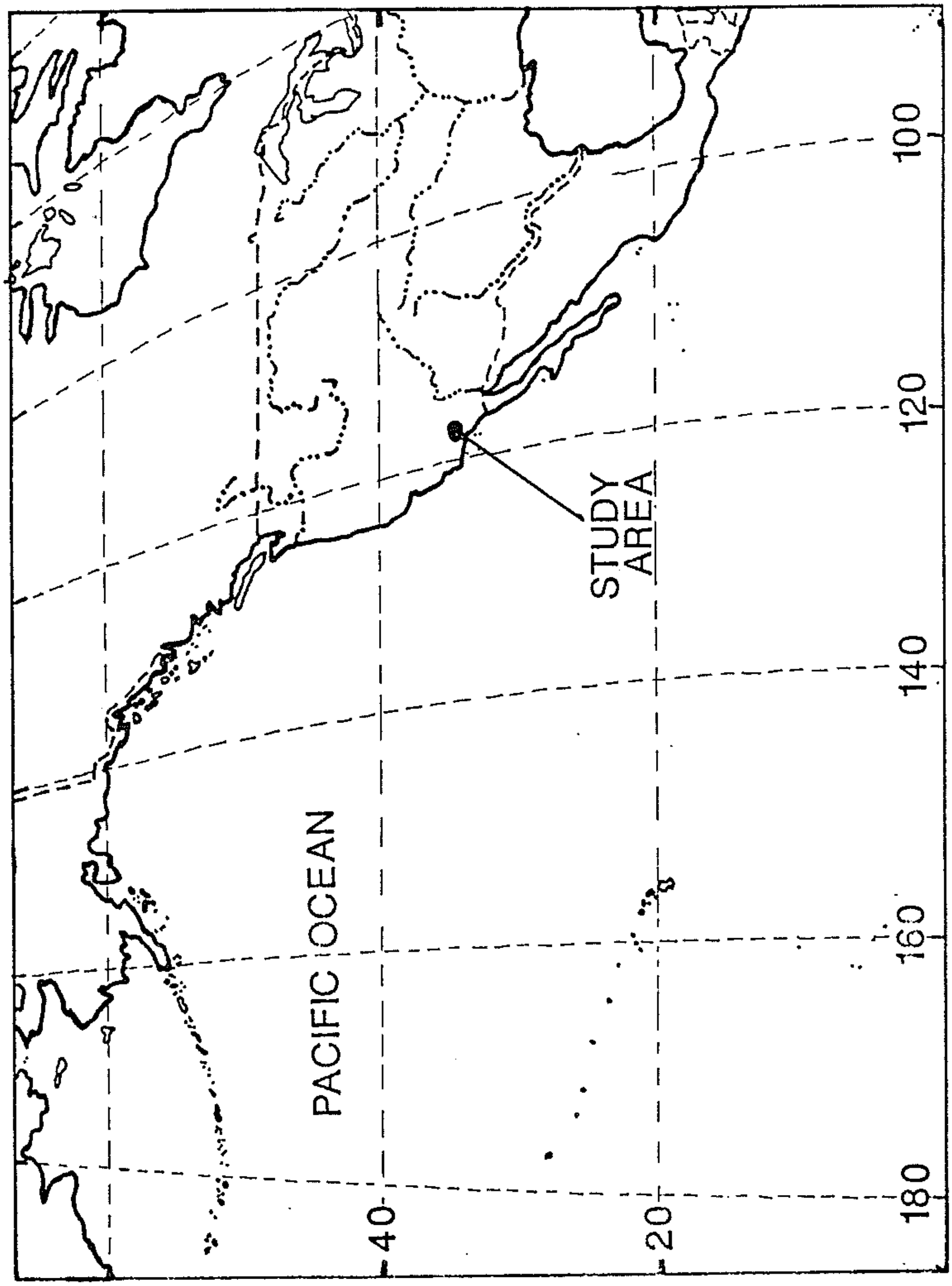


Figure 49. The position of the Mojave River drainage basin relative to the north Pacific Ocean.

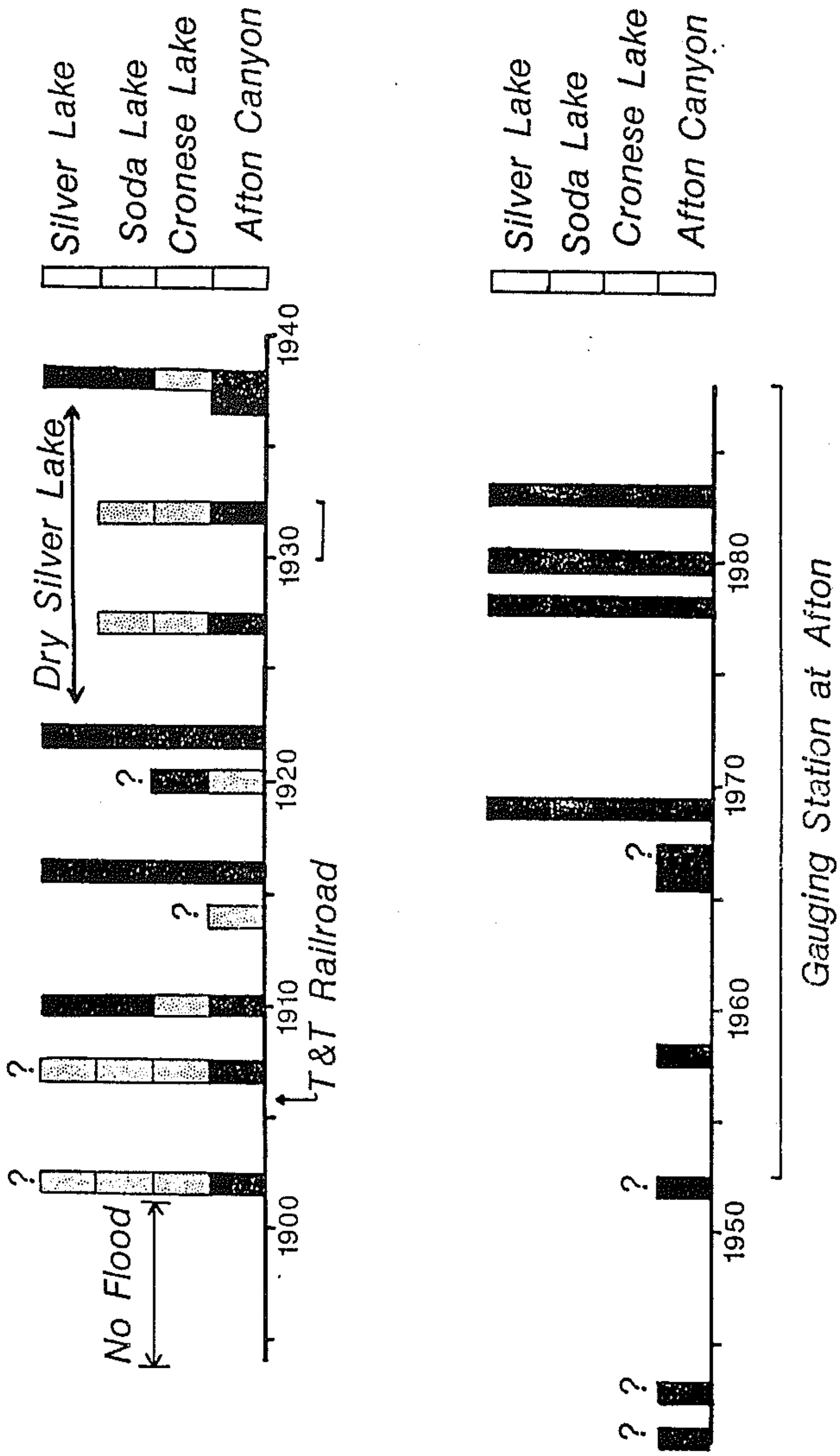


Figure 50. Documented floods since 1894 that passed Afton Canyon, and passed or filled the terminal basins of the Mojave River (Cronese Lakes, Soda Lake, and Silver Lake playas). Shaded bars where we suspect that the event occurred but not direct evidence was found. Question marks where the evidence is not fully conclusive. See Table 14 for the detailed information.

years, no flood waters derived from the headwater region reaches Afton Canyon. This hydrologic system is modelled in figure 38. Those years either with floods that formed lakes or with large floods that could have formed, but were not documented as lake-building floods, are divided into two sets of months which experienced the floods. One includes twenty-nine one-month periods with large flow in the headwaters (including the lake events), and another set includes only the eight months with lake-building flood events (a subset of the first set of twenty-nine months). The analysis of these data sets was applied to the data of the North Pacific sea level pressure (SLP) because this is the measured atmospheric characteristic with the longest record. Thus, the early lake events can be included in the analysis (systematic upper air data collection began in the late 1930s).

Figures 51 and 52 illustrate the normal North Pacific SLP for the months of January and February; December and March are quite similar and are, therefore, not shown. Figures 53 and 54 show the composite SLP conditions during the twenty-nine months and the eight month cases, respectively. Although both sets show a large departure from mean SLP, the eight cases show larger anomalies. Figures 55 and 56 show the anomalies (defined as the composite from mean in millibars (mb)) of these two sets and the negative anomaly offshore from California for both cases. The anomaly for the eight-case set has greater values and is closer to the shore of the U.S. than the twenty-nine month set; it should be noted that the six mb anomaly is more than two standard deviations from normal.

During the months of lake-building flood events, the North Pacific subtropical high has been reduced in size (compare figures 51 and 52 with 53 and 54). The high is typically connected to the sea-level high pressure ridge, extending from Idaho to northern and central California. The high

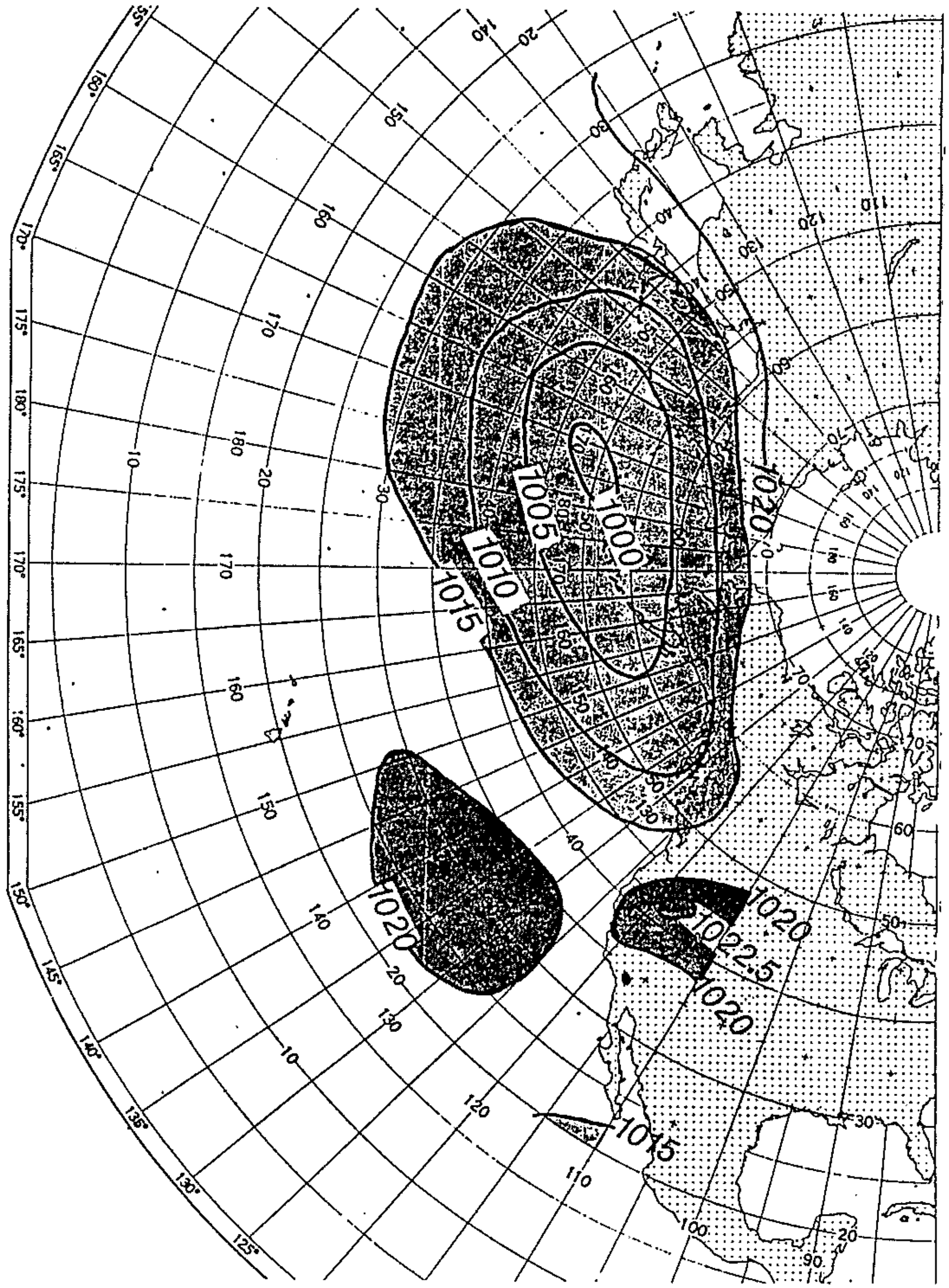


Figure 51. Normal North Pacific sea level (SLP) pressure (in millibars) for January.

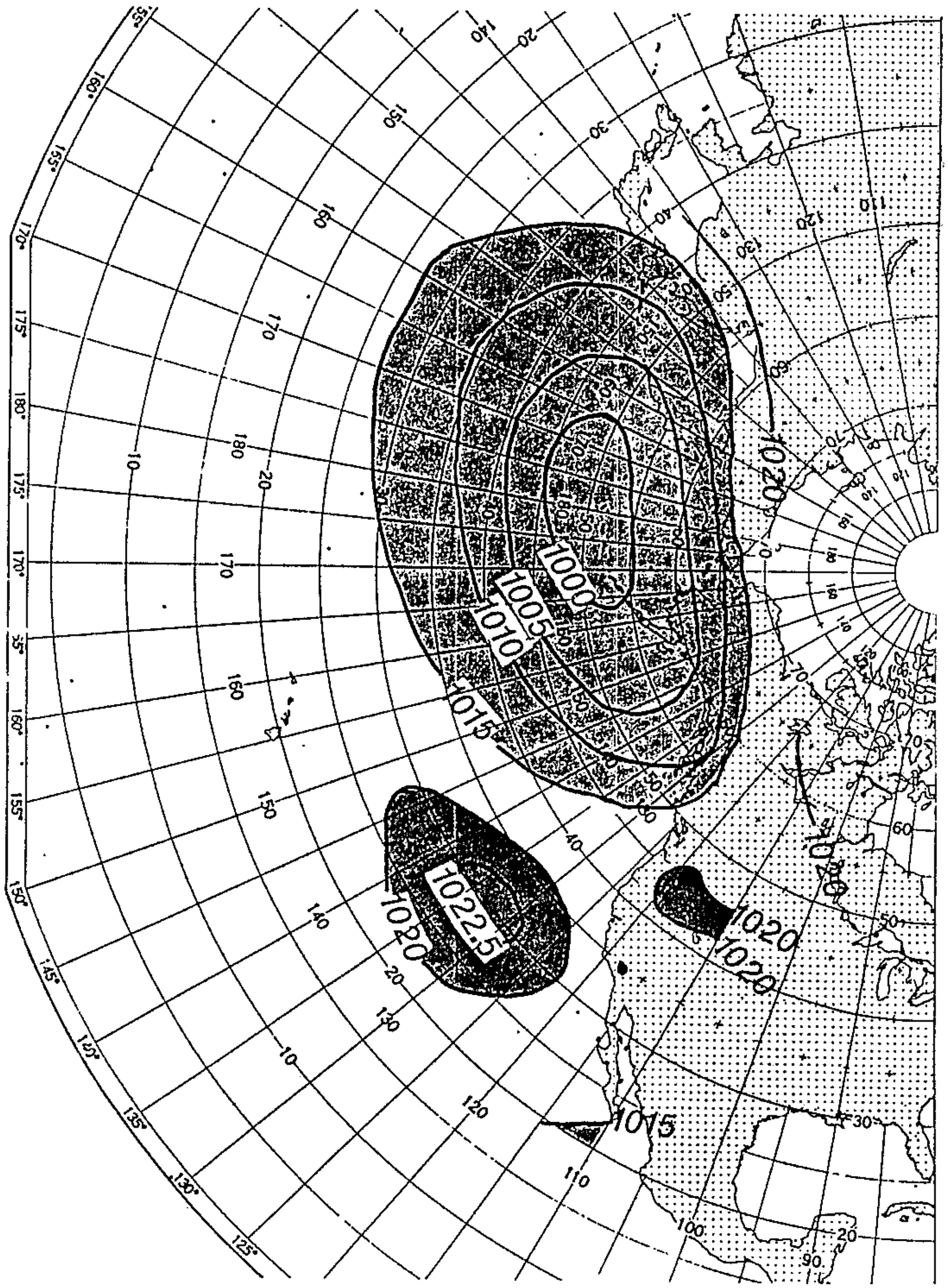


Figure 52. Normal North Pacific sea level (SLP) pressure (in millibars) for February.

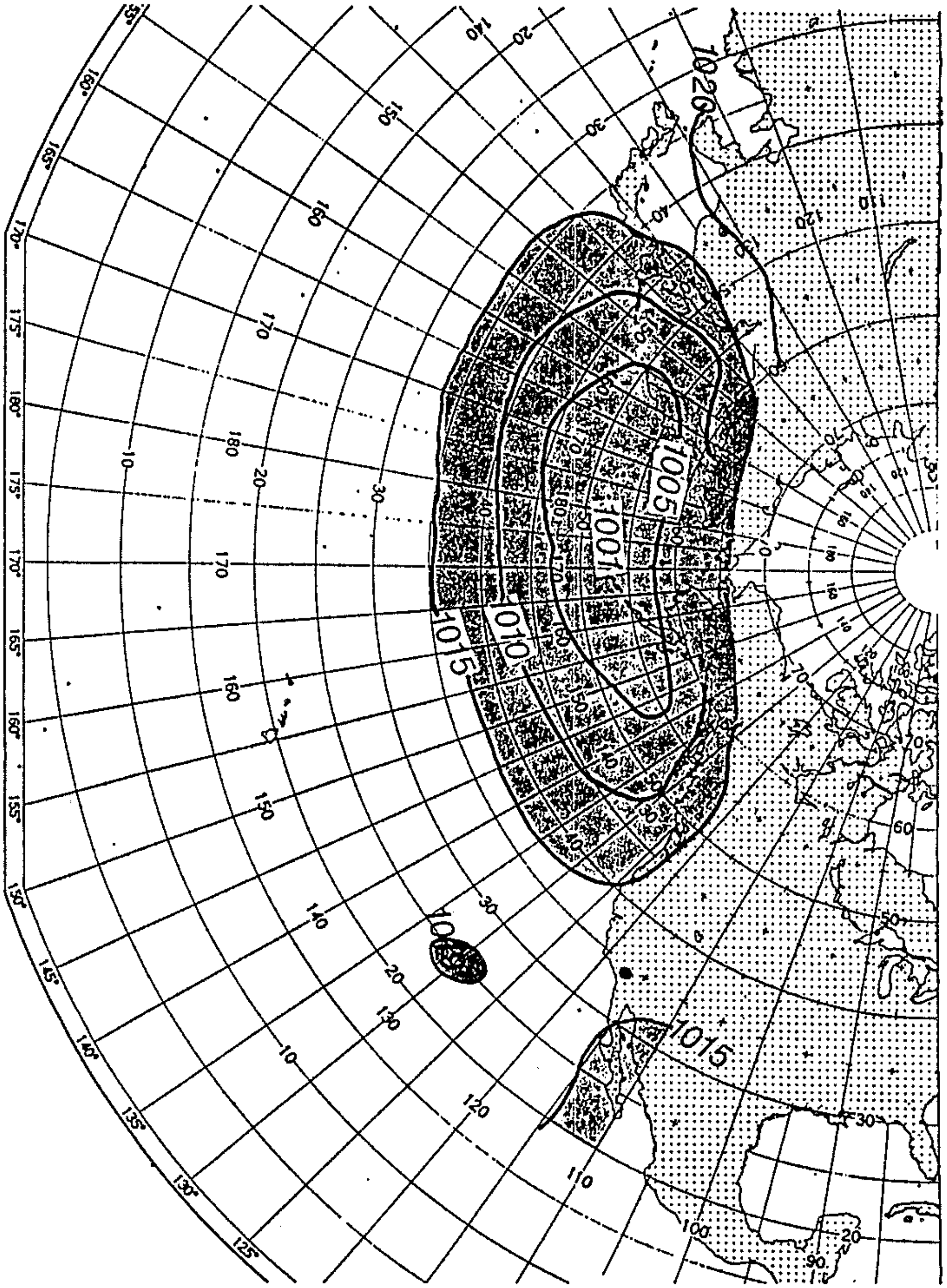


Figure 53. Composite sea level pressure (in millibars) for 29 winter months with medium to large floods in the Mojave River drainge basin.

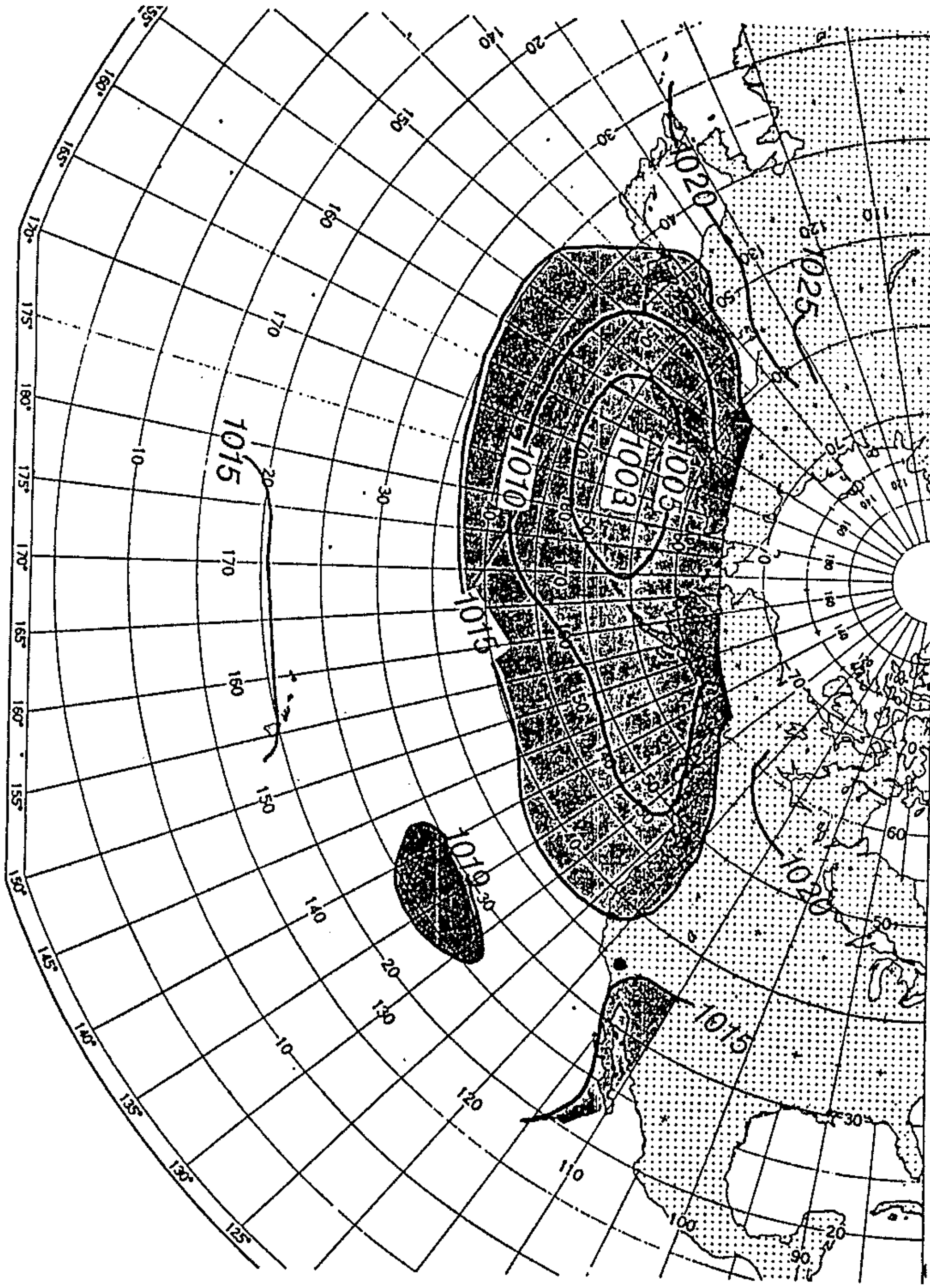


Figure 54. Composite sea level pressure (in millibars) for the eight months during which a lake-building flood event occurred in the study basin.

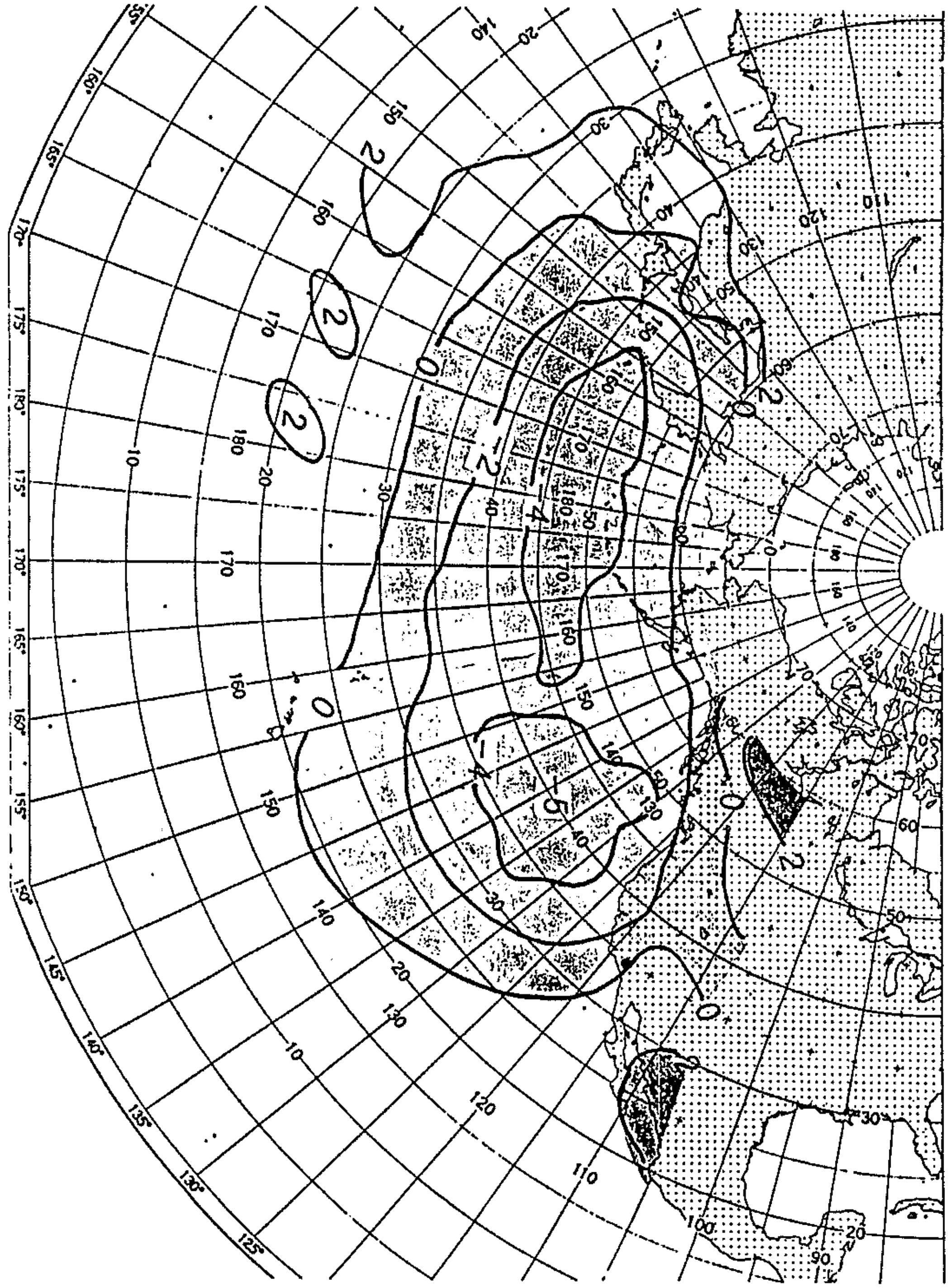


Figure 55. Composite SLP anomalies of the 29 months with medium to large floods in the study basin.

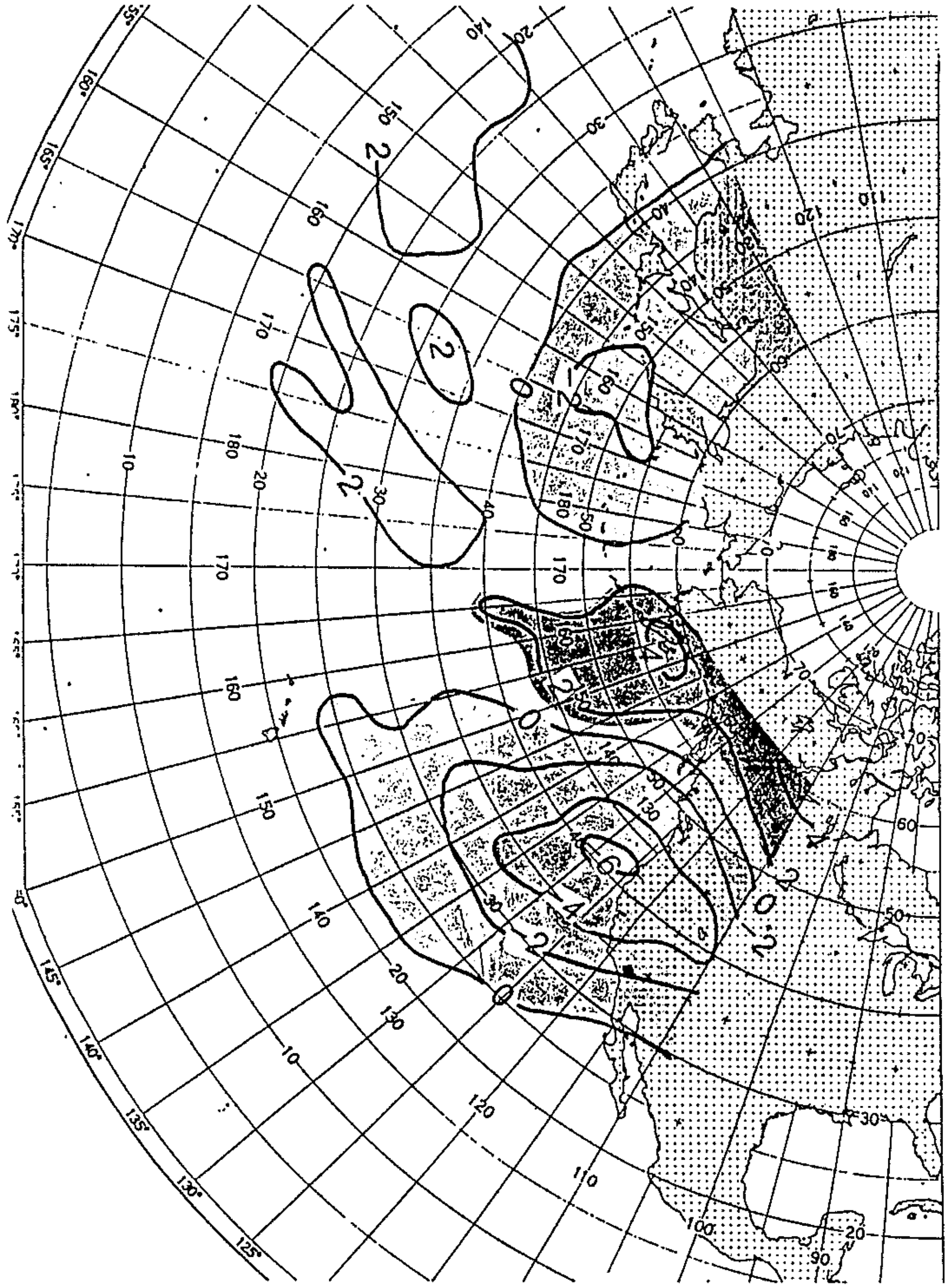


Figure 56. Composite SLP anomalies for the eight months during which a lake-building flood event occurred in the study basin.

pressure over the northwestern U.S. disappeared during the anomalies (figure 53 and 54). A low pressure area formed over Baja California as the 1,015 isobar migrated from 23°N to 35°N, which is similar to its early spring position. The most prominent sea-level atmospheric feature is the shifting of the eastern portion of the Aleutian Low toward the south and on shore over the northwestern U.S. The Aleutian Low is normally over the Gulf of Alaska during this time. This phemonenon is illustrated in the composite SLP anomalies (figure 56) and shows a blocking high in the area of the Gulf of Alaska. The pronounced anomaly of negative six millibars is also the result of this shift.

Although the results of the twenty-nine case analysis show similar patterns, there are major differences between the two sets. Only remnants of the blocking high are seen over the Gulf of Alaska. The pronounced low is located over the eastern North Pacific Ocean and only marginally on shore. The low over Baja California is not as far north in the eight-case set; the 1,015 isobar is only at 32°N and not 35°N.

The height of the 700 mb contour during two months of the eight cases is shown in figures 57 and 58. These maps were previously discussed by Wagner (1969), Stark (1969), Green (1969), Namias (1978 and 1980) and Dickson (1980). The main phenomena the maps illustrate for the North Pacific region are a blocking high over Alaska and a trough or cutoff low offshore form the west coast of North America.

Figure 59 summarizes the subtropical jet-steam position for the 1969, 1978, 1980, and 1983 events, based on Bonner, Pyke and Hickey (1971) and satellite images (see section 2). These data, in conjunction with conversations by Pyke (1972) and the U.S. Weather Bureau (1962), suggest that all the extreme storms producing lake stands in the Mojave River terminal basins are related to the position of the subtropical jet and warm air laden

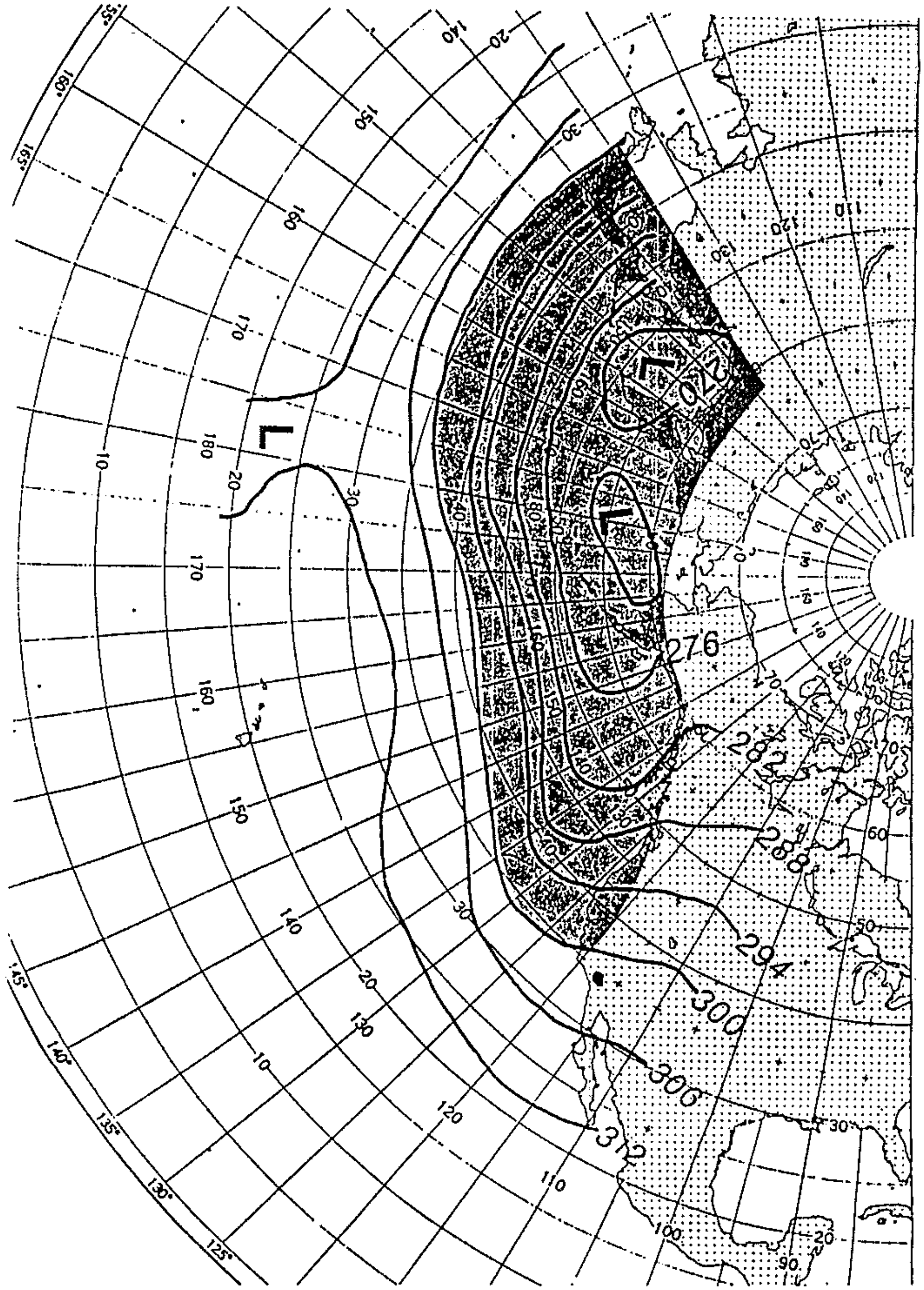


Figure 57. Mean North Pacific 700-millibar height (decameters) for February 1969 (modified from Stark, 1969).

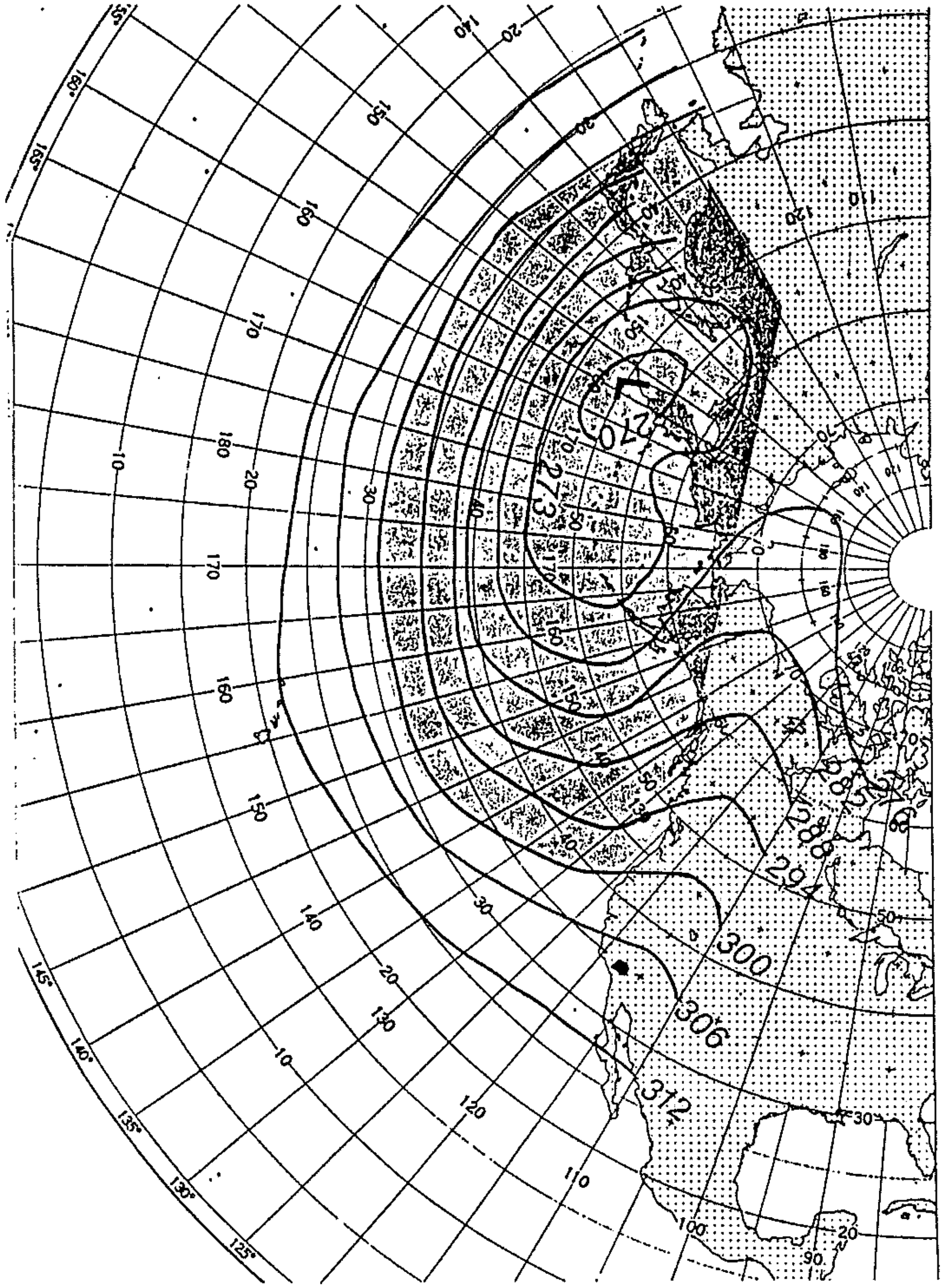


Figure 58. Mean North Pacific 700-millibar height (decameters) for February 1980 (modified from Dickson, 1980).

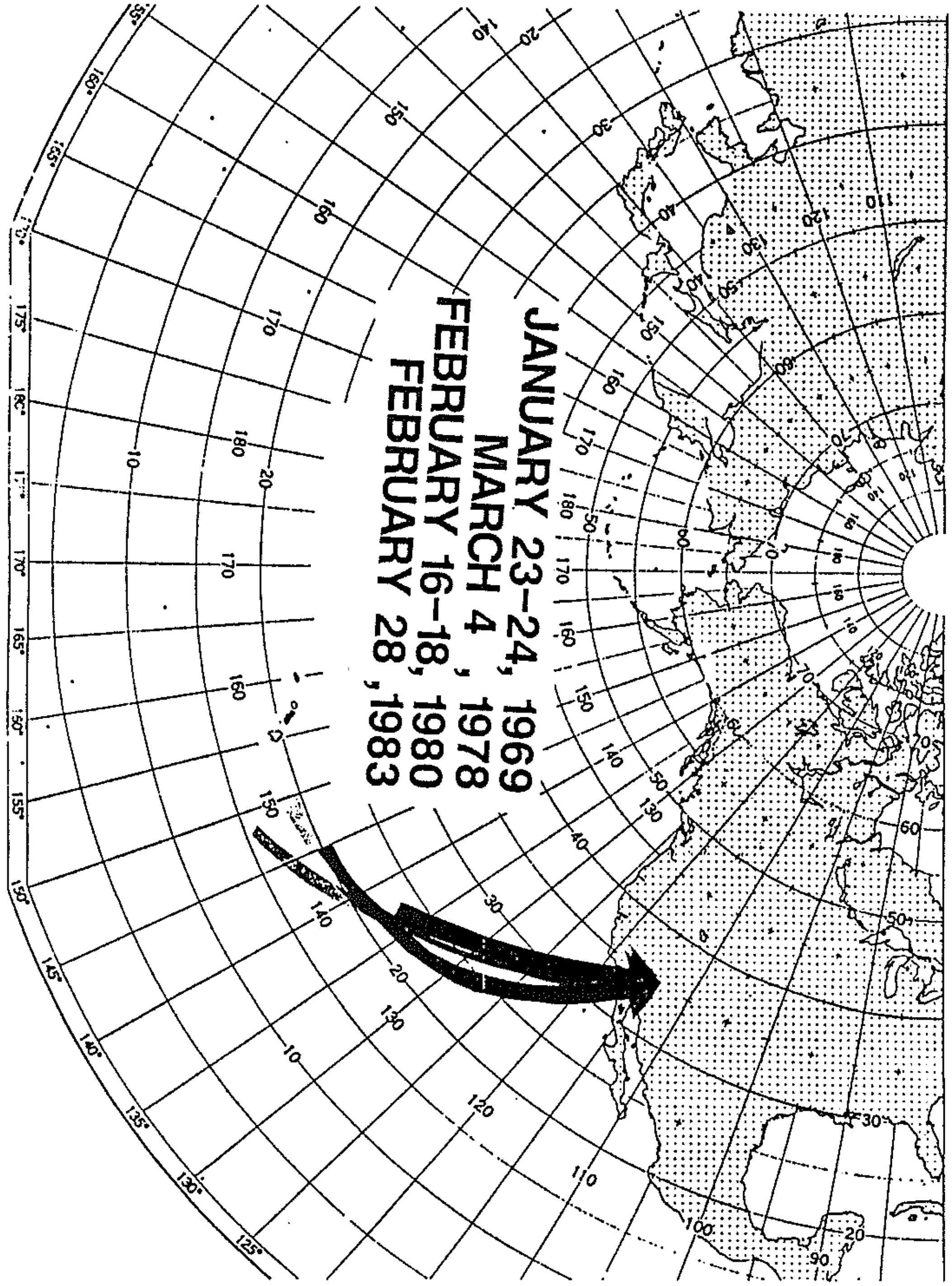


Figure 59. High clouds as approximating the location of the high velocity wind aloft during four flood producing events.

with moisture that originated northeastward of the Hawaiian Islands. This air mass had a high dew point and poured moisture into the San Bernardino Mountains area due to the orographic effect (U.S. Weather Bureau 1962). The lowered maximum temperature (- 2.2°C) during the months of the storms reported by Balling, Jr. (pers. com. 1987) for Redlands and Barstow areas can be explained by the extensive cloud cover rather than by northern cold air masses in the region. A preliminary analysis of the minimum average daily temperatures for the months of these storms show higher temperatures and support this explanation (Enzel, Ph.D. dissertation in preparation).

The analyses for persistence in the sea surface temperature and 700-mb. height patterns over the North Pacific, carried out by Namias, Yuan and Cayan (1988), included three winters with lake stands (1969, 1978, and 1980); winters are represented by January, the month with the highest persistence. These three winters were found by the authors to have the highest persistence patterns over the North Pacific. They also found during the high persistence winters, there was a southerly displacement in the maximum westerlies at 700 mb (figure 60). This displacement is related to the jet positions.

Historical lake-building flood events in the terminal basins of the Mojave River drainage system appear to occur under specific climatic events related to atmospheric circulation patterns over the North Pacific. These atmospheric patterns are represented by the illustrations in figures 54, 56, and 59. These data not only serve as an excellent base for predictive modeling of future flood activity on the Mojave River but can be used for paleoclimatic and paleohydrologic assessments of Holocene conditions.

Geologic and Paleoclimatic Implications. Within the Silver Lake basin, four lake deposits younger than the early Holocene have been documented (see

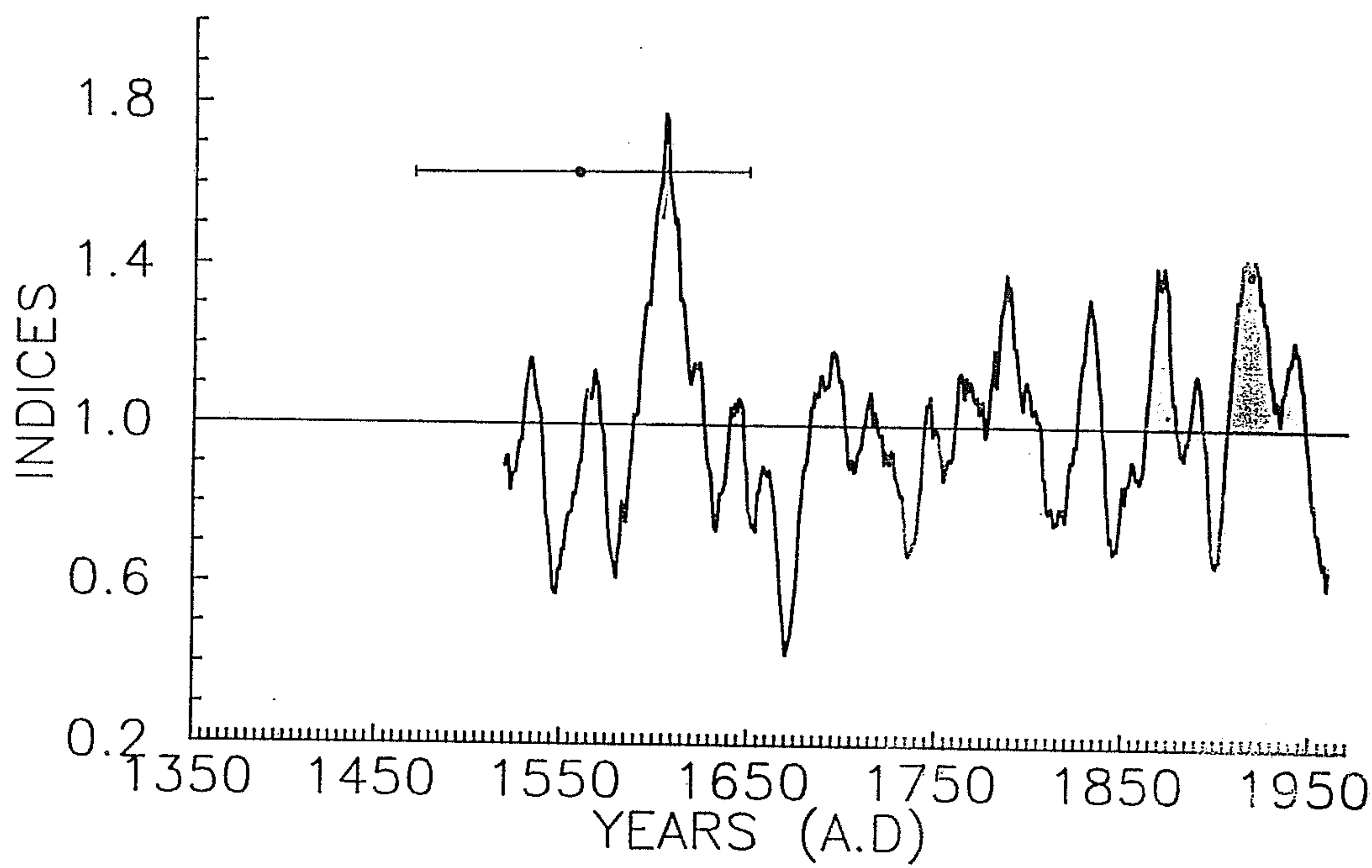


Figure 60. Thirteen years running means of Baldwin Lake tree-ring chronology (in the San Bernardino Mountains), and the 390 ± 90 radiocarbon date from the lake deposits.

section 3). Two of the lake events yielded dates of 390 ± 90 and 3620 ± 70 years B.P. (figure 21). The youngest lake deposits are composed of couplets of alternating finely laminated (millimeter scale) sediments which may represent seasonal events. This lake occurs during the most recent neoglacial episode, the Little Ice Age, which is well-dated between the 15th and early 18th centuries in Europe. The 390 year old, or Little Ice Age lake corresponds to the wet period that Schulman (1947) suggested for the southern California mountains, based on tree-ring indices and their correlation with stream flow (figures 61, 62, and 63). Schulman's (1956) San Bernardino tree-ring chronology also supports this finding (figures 64, 65, and 66). Stokes et al. (1973) published the Baldwin Lake chronology (also at the San Bernardino Mountains) developed by Furgeson (1966) which lends support to this regional climatic event (figure 67, 68, and 69).

The Little Ice Age lake deposits can be divided into two sections of upward-fining laminations. These sections may correlate to the two wet periods, separated by a very dry period, that Schulman (1947) had suggested for the late sixteenth and early seventeenth centuries (figures 61, 62, and 63). The tree-ring data also suggest the early 20th century was a relatively wet period (figure 62). During this time (1905-1938), several lake stands were documented in Silver Lake and three other years had large discharges. The two largest historical lakes occurred during 1916 and 1938 correspond with the peaks in relative moisture indicated by the tree-ring indices (figure 62). Perhaps given a few more years with flood discharges similar to those during the early 20th century, a relatively perennial lake may have developed in the Silver Lake basin. From these observations, it is concluded that climatic conditions similar to those that produced the historical lake stands could be responsible for the formation for the Little Ice Age lake in the Silver Lake

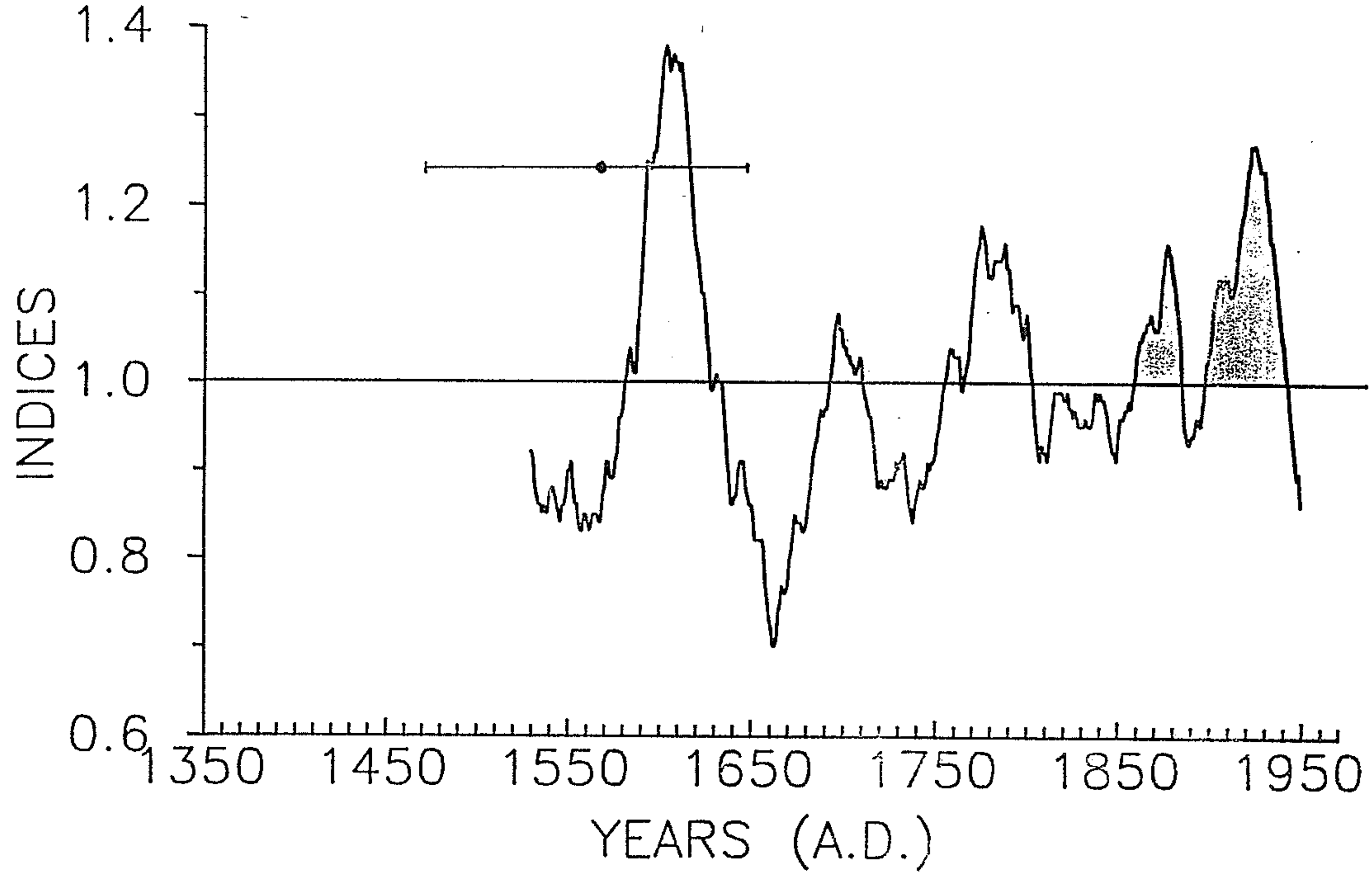


Figure 61. Thirty-five years running means of Baldwin Lake tree-ring chronology (in the San Bernardino Mountains), and the 390 ± 90 radiocarbon date from the lake deposits.

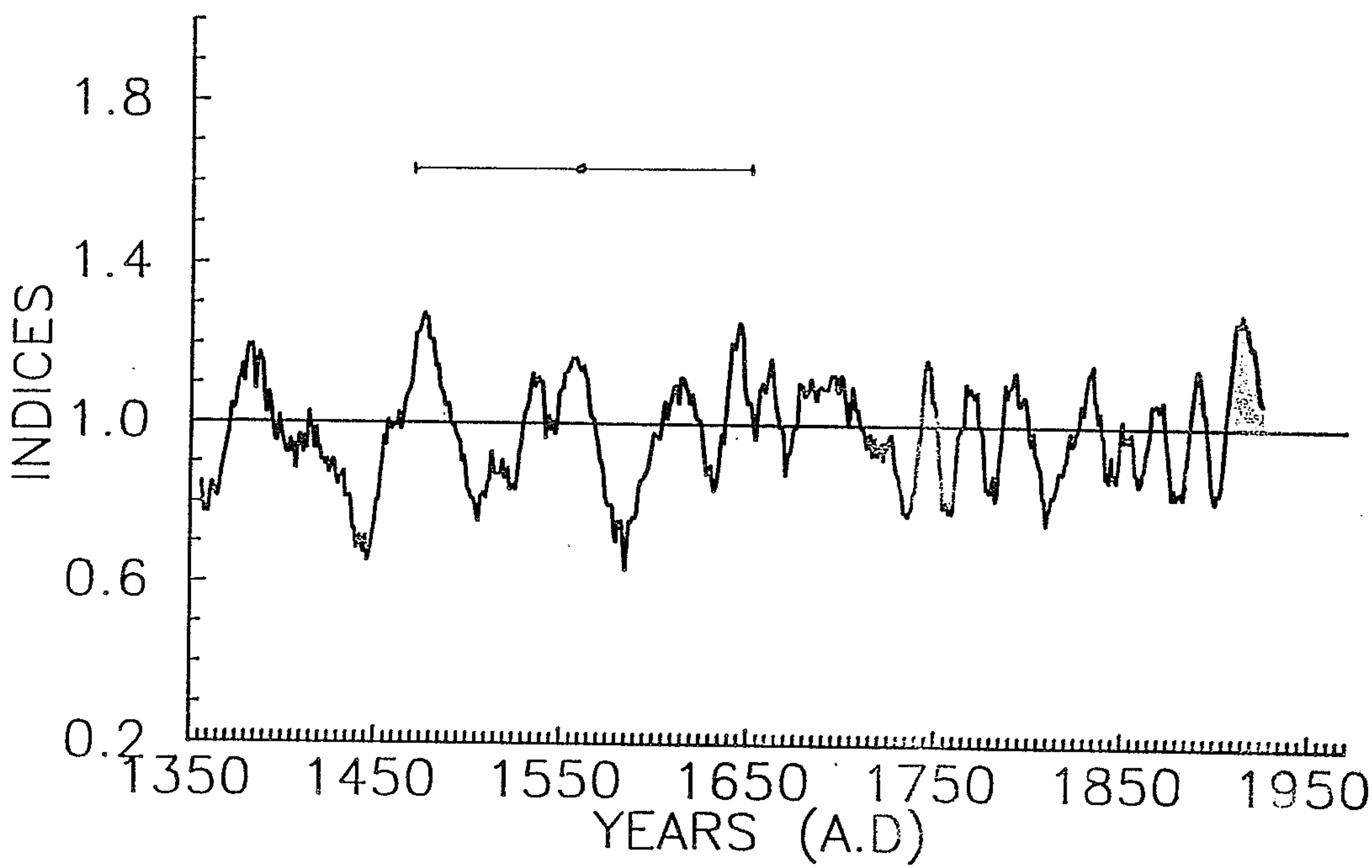


Figure 62. Thirteen years running means of San Bernardino tree-ring chronology (in the San Bernardino Mountains), and the 390 ± 90 radiocarbon date from the lake deposits.

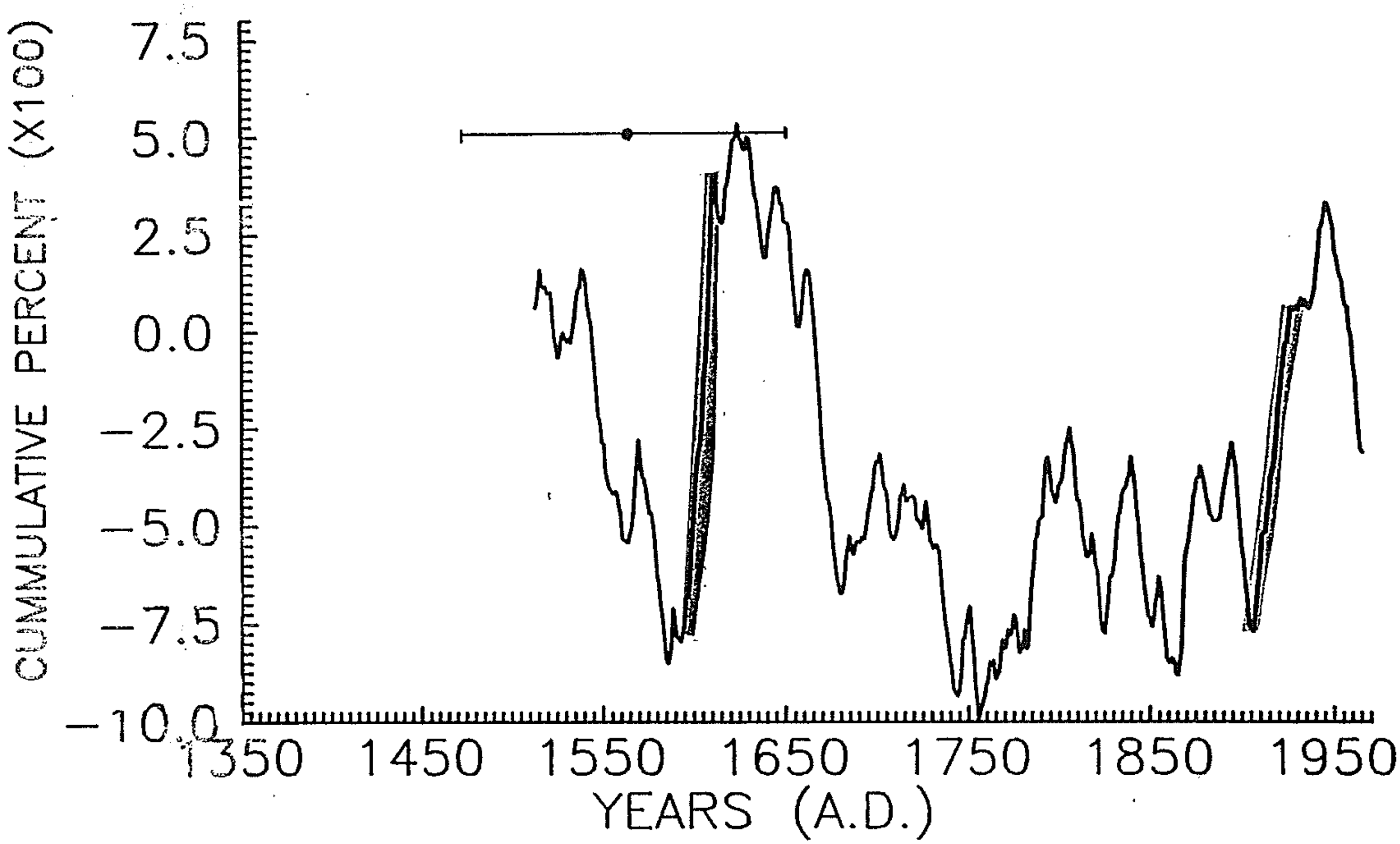


Figure 63. Cumulative departure from mean indices for the Baldwin Lake tree-ring chronology.

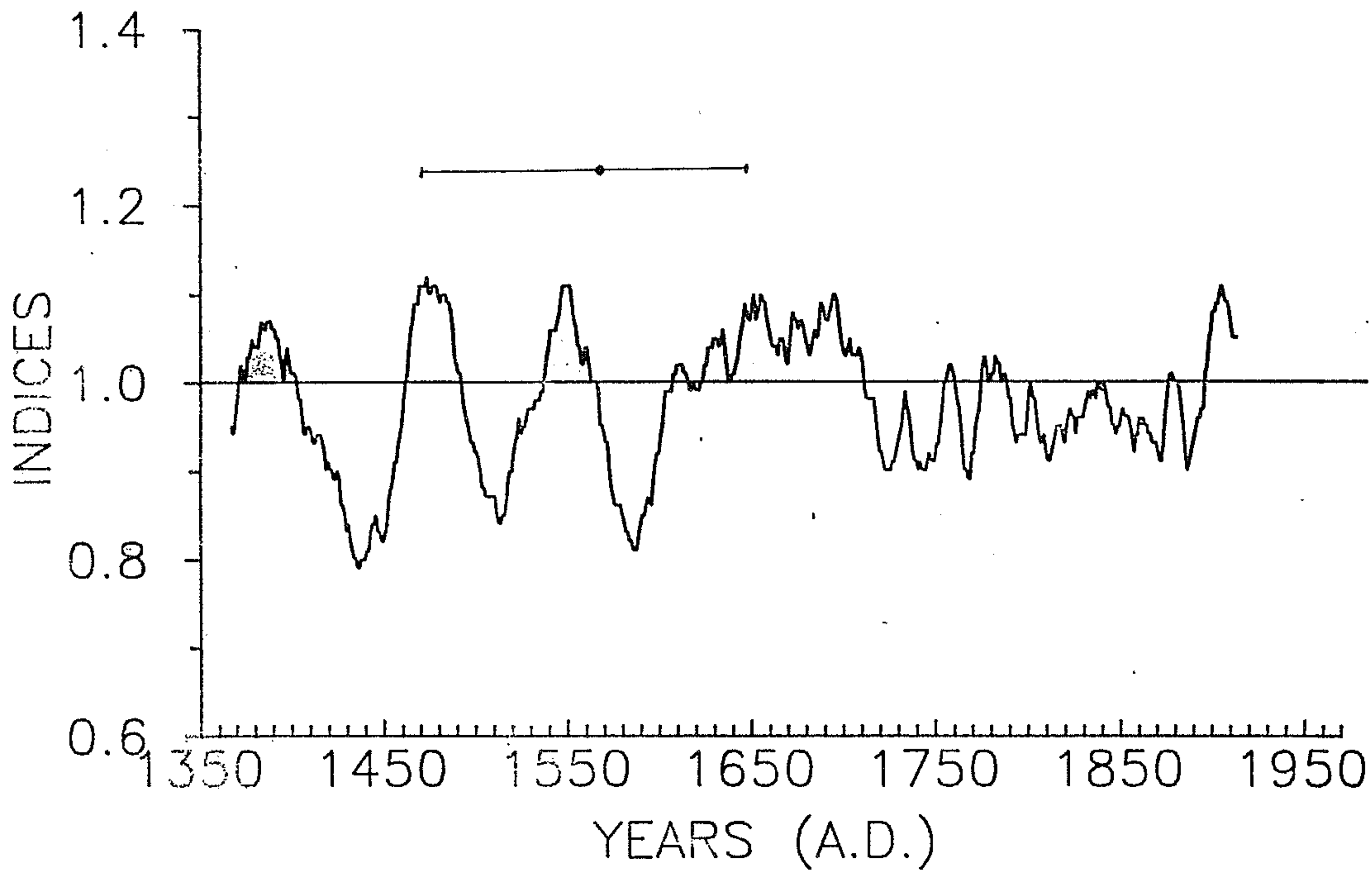


Figure 64. Thirty-five years running means for the San Bernardino tree-ring chronology and the 390 ± 90 radiocarbon date from the lake deposits.

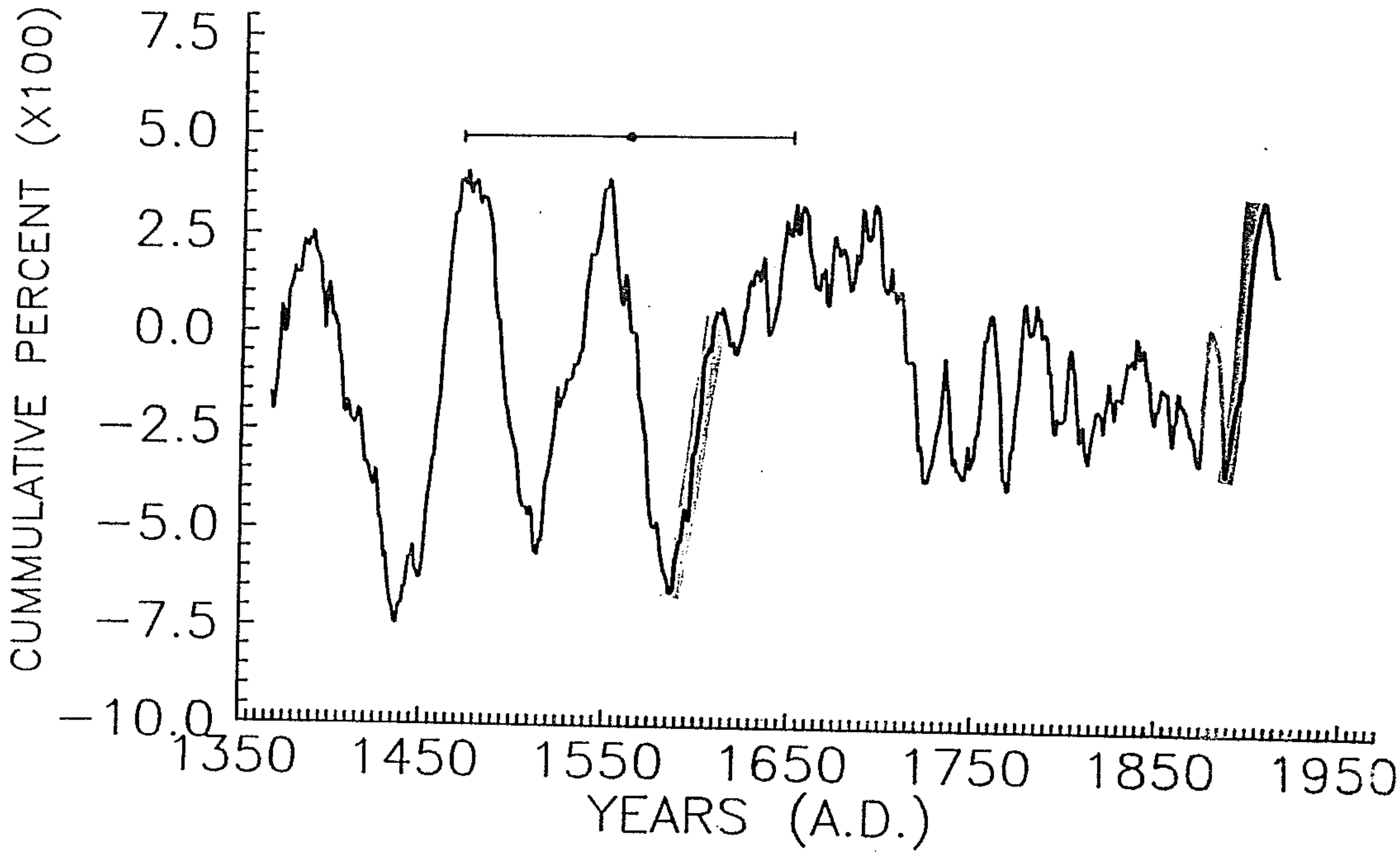


Figure 65. Cumulative departure from mean indices for the San Bernardino tree-ring chronology.

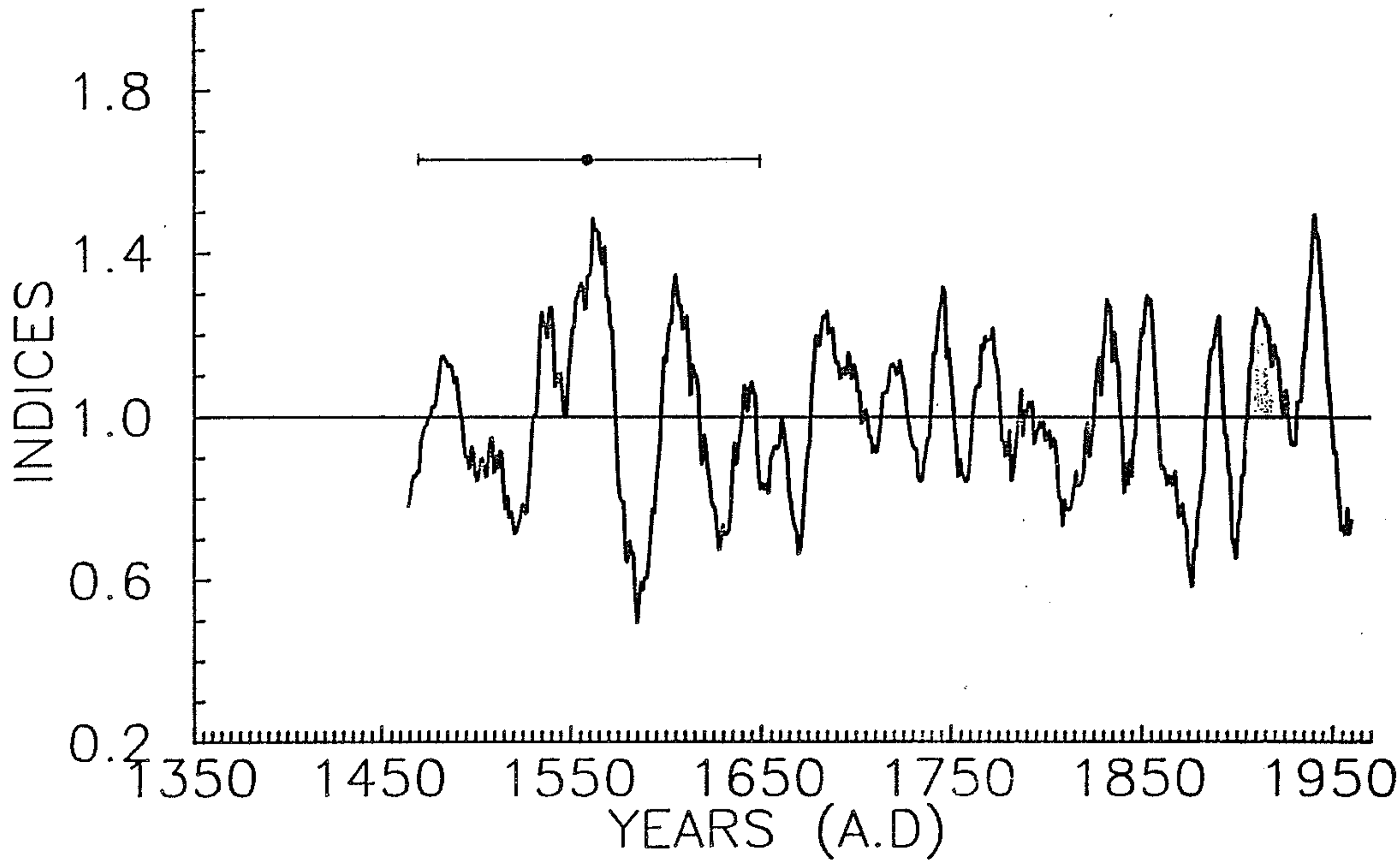


Figure 66. Thirteen years running means of Southern California tree-ring chronology and the 390 ± 90 radiocarbon date from the lake deposits.

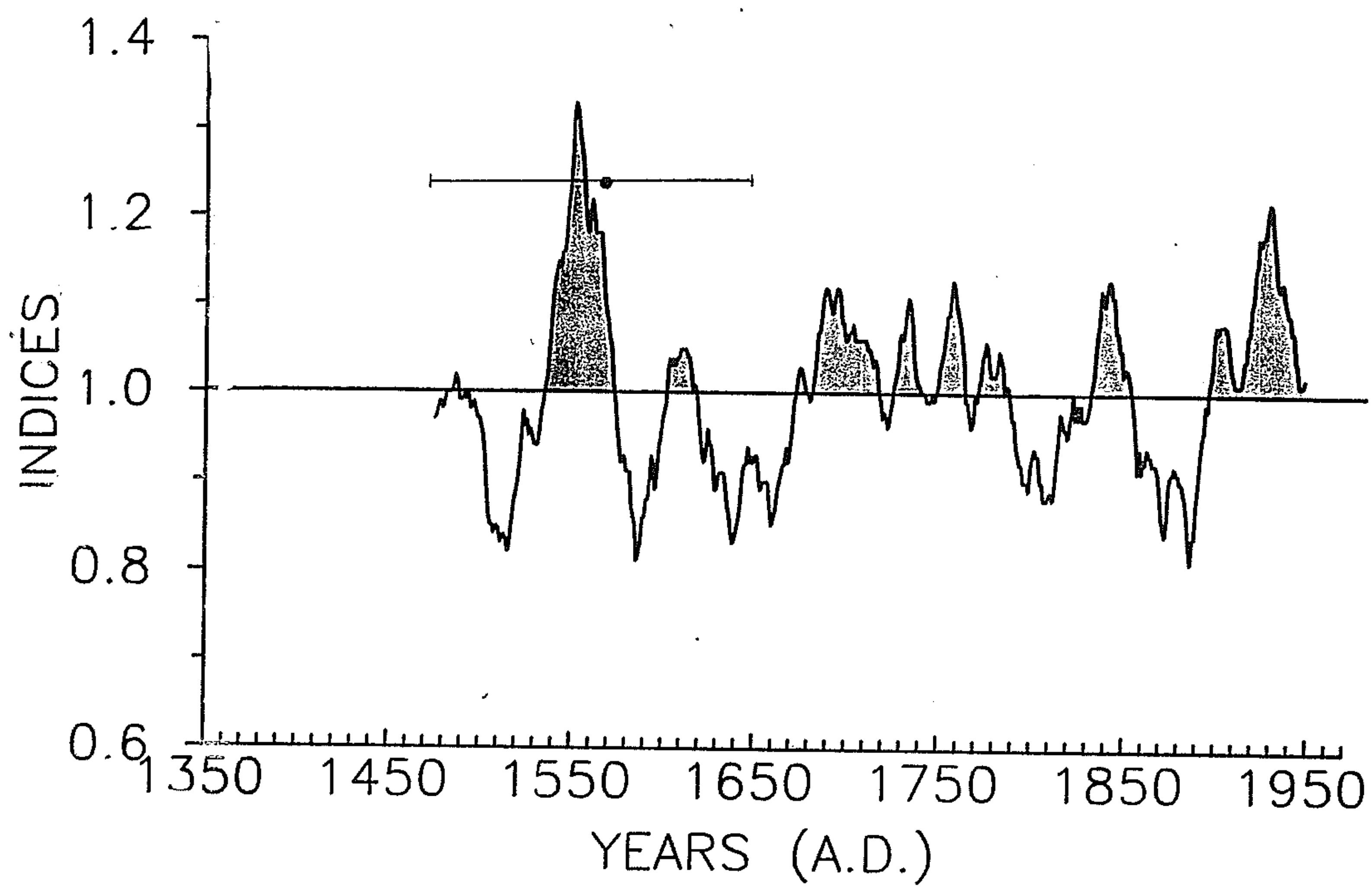


Figure 67. Thirty-five years running means for the Southern California tree-ring chronology and the 390 ± 90 radiocarbon date from the lake deposits.

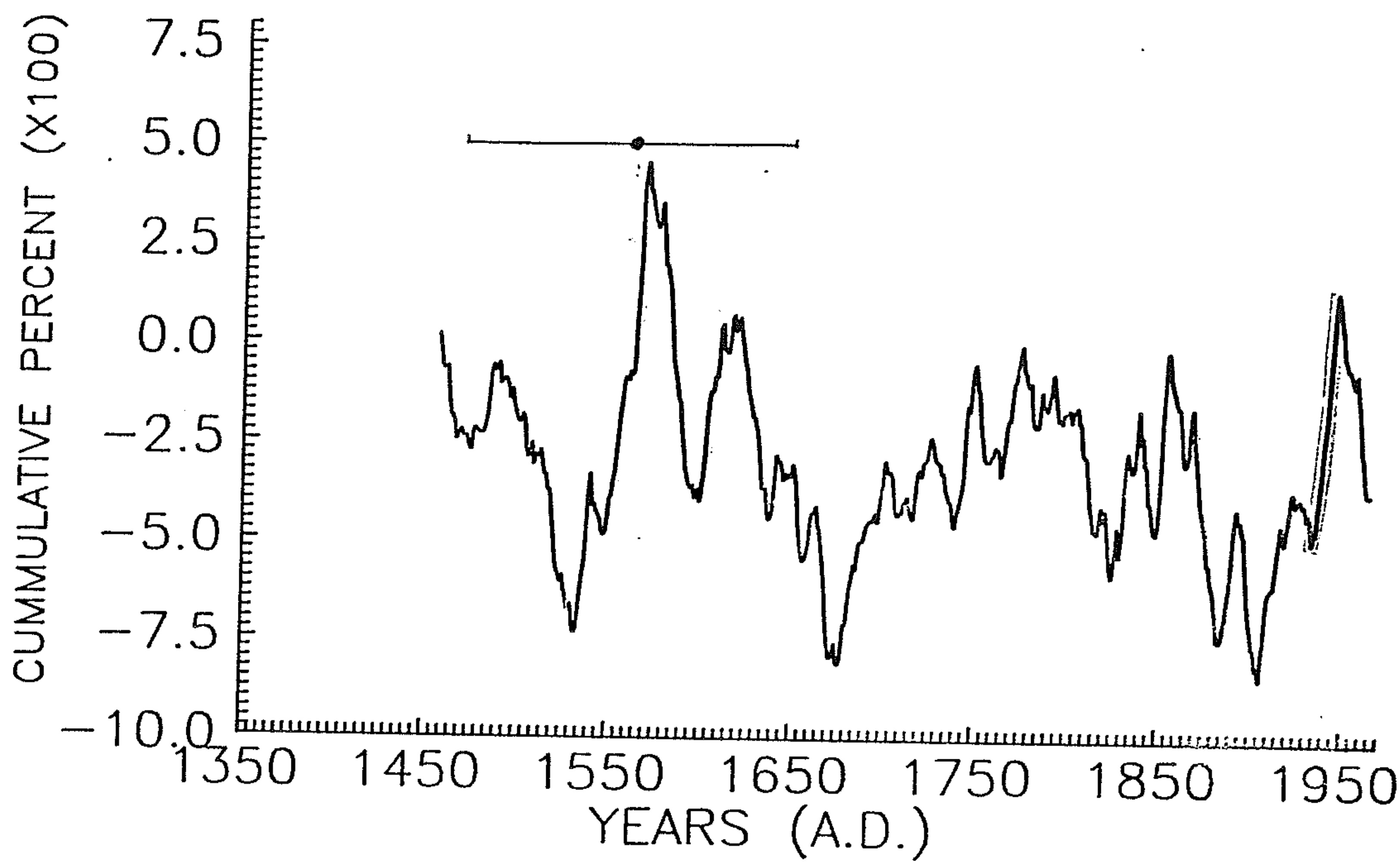


Figure 68. Cumulative departure from mean indices for the Southern California tree-ring chronology.

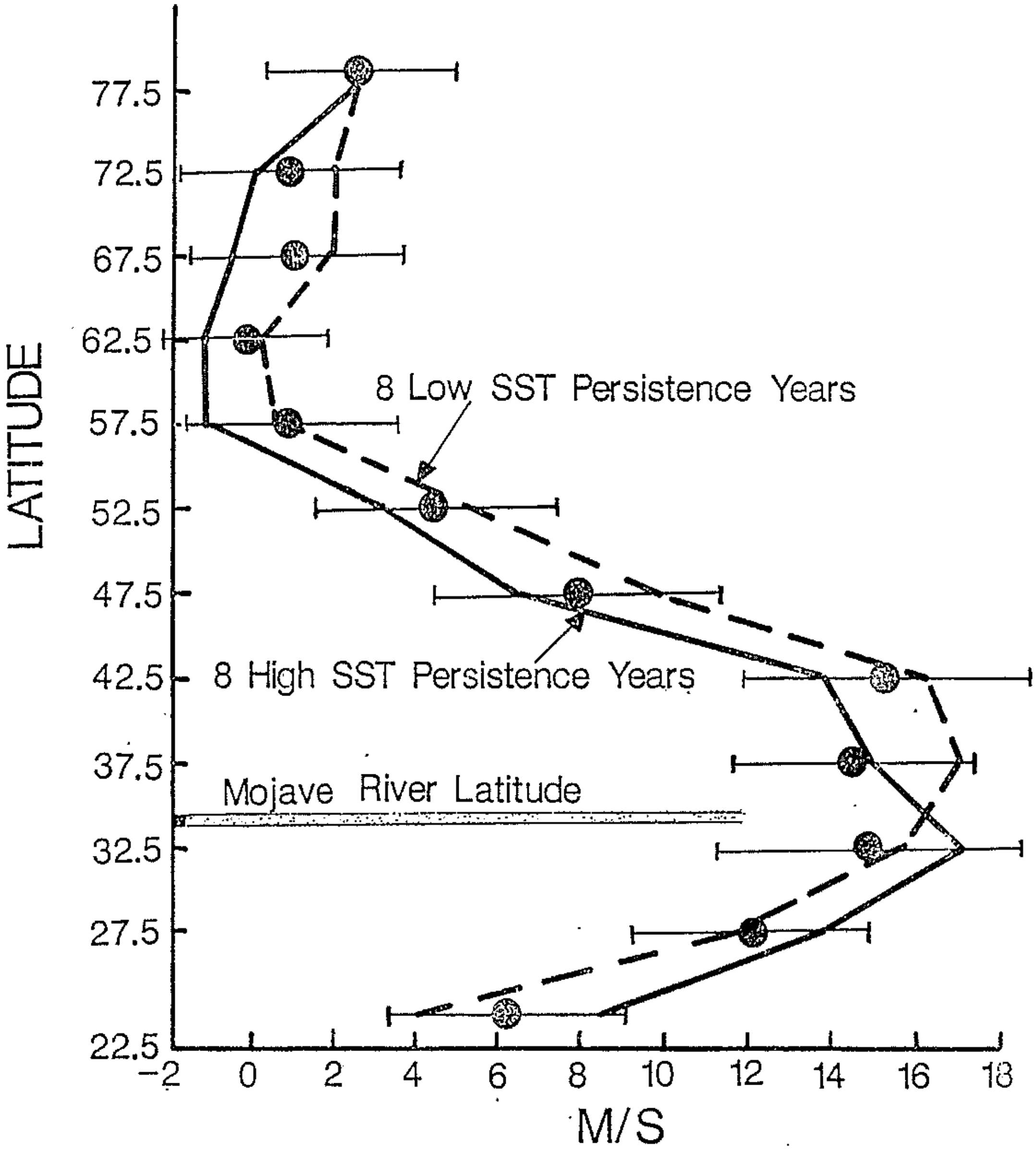


Figure 69. Composite (and range) North Pacific 700-millibar zonal wind velocities profiles (m/s) for 33 months of January (heavy dotes). Dashed line - the same during Januaries of years with low persistence of the sea surface temperature (SST) anomalies, solid line - the same during Januaries of years with high persistence of SST anomalies (modified from Namias et al. 1988).

basin. Flood discharges on the Mojave River would have to attain greater frequencies to produce a more permanent lake. Such conditions might mean that the seasonal high persistence detected by Namias, Yuan and Cayan (1988) can be extended to a decade scale (figure 60).

The model presented in section 6 indicates that a large reduction in evaporation is not solely sufficient to produce the historical lakes without large increases in Mojave River flow. The model results imply a significant increase in precipitation in the Transverse Ranges is necessary to produce such large volumes of stream flow. Three regional sources of precipitation could contribute to lake building in this region during the latest Quaternary. It seems reasonable that latitudinal shifts of cold (northern Pacific) storms to the south would be able to produce the lakes. Storms influenced by the position of the subtropical jet (figure 59) and with higher dew points like the historical events provide an excellent source of moisture-laden air. Apparently, the Mojave River watershed was at the extreme northwestern influence of summer storms of monsoonal origin, the third source of moisture, during the late Pleistocene, and too far north for the monsoonal air masses to contain sufficient moisture to produce the significant precipitation needed (Van Devender et al. 1987). Although the position of the subtropical jet is not supported by any model of the late Pleistocene paleoclimate (Kutzbach 1987), the data from this study suggest that increasing winter precipitation in the same patterns as the historical lake events may be a reasonable source. This inference appears valid especially when repeated storms increase the percent age of runoff in the Mojave watershed. Friedman and Smith (1972 and 1979) suggest that the climatic conditions during the 1968-1969 winter might resemble jet-stream position typical of late Pleistocene climates of this region. Results from this study support their speculation about modern climatic analogs for the late Pleistocene climate and suggest the need for further analyses of these relations.

MODEL ESTIMATES OF CLIMATE AND RIVER DISCHARGE:
MOJAVE BASIN, CALIFORNIA

Introduction

The aim of modern hydrologic modeling is to provide a prognosis of the future performance of a hydrologic system (Anderson and Burt 1985); however, another equally important aim is to provide an estimate of past performance of a hydrologic system, or paleohydrologic assessments. All models simplify the complexity of a hydrologic system by "selectively exaggerating the fundamental aspects of a system at the expense of incidental detail" (Anderson and Burt 1985). The model presented in this report is a simple, or first-order, representation of the complicated Mojave River system illustrated in figure 38. Because of difficulties with obtaining long-term flood records in Afton Canyon, a mass-budget model was developed and did not incorporate any flood routing analyses.

Climate-Spatial Framework. A simplified model of precipitation - discharge/ evaporation is used to examine the climatic variables that regulated the rise and fall of pluvial Lake Mojave. The model incorporates the reconstructed area and volume of Pleistocene-Holocene Lake Mojave at different stages of development (see section 3) and is based on the relationship:

$$Ve = Dt + P(Rt) - Et, \text{ where}$$

Ve = equilibrium volume at a given lake elevation

Dt = annual river discharge,

P = precipitation in the basin

Rt = annual water yield from runoff,

Et = annual evaporation from lake surface.

All values are based upon assumed temperatures. Ground-water inflow is included in Dt, and leakage form the basin is assumed to be negligible, making calculated Ve a minimum estimate. Values of Ve are converted to lake elevations. Surface area and volume of the present geometry of Silver and Soda lake basins were estimated by planimetry from topographic maps. Surface area and volume for the prehistoric lake were estimated by planimetry of a bathymetry reconstructed from well logs and cores (figure 28). Modern climate parameters, as well as assumed values for climate-related variables are given in table 16.

The Mojave fluvial-lacustrine system is similar to other pluvial systems in the great basin in that the catchment area and the lakes are situated in different climate regimes. Almost all discharge feeding the terminal playas and lakes originates in a relatively small portion of the watershed above The Forks in the San Bernardino Mountains where average annual temperature is approximately 50°F (10°C). Precipitation is 27.1 in (69 cm), and runoff, as measured by discharge at The Forks gauging station, is about 34%. In contrast, local runoff into the playas is virtually zero and annual evaporation is several times the capacity required to remove all historic discharge into the lakes. In the Pleistocene, however, a lake with an evaporative surface area of nearly 300 km^2 occupied the terminal basins and overflowed. Discharge into the lakes was not derived from melting glaciers, but directly from precipitation in the catchment area. The elevation of the ancient lake, although sustained directly by precipitation in the mountains, also was regulated by evaporation in the desert basins to the east. In this section, the relative contribution of modern and latest Pleistocene climate regimes are analyzed by the model.

TABLE 16

Modern and assumed climate parameters for the Mojave River watershed in the San Bernardino Mountains and terminal lake area near Baker, California.

	MODERN CLIMATE		ASSUMED CLIMATE		
	Annual (Average)	Storm Event	P+25%	P+50%	P+100%
Catchment Area					
Precipitation (cm)	69		86	103	138
Runoff (%)	34	38	43	51	63
Discharge at Afton $m^3 \times 10^6$	9.4	75	84	150	205
	69°F		60°F	50°F	40°F
Lake Area					
Precipitation (cm)	10		15	20	30
Runoff (%)	00		00	012	08
Evaporation (cm)	203		147	107	96

CONSTRAINTS ON LAKE DEVELOPMENT

Lacustrine History

Two high-lake stages are recognized in cores collected from Silver Lake basin (figure 29). An early intermittent lake rose in the deepest basin, reached Silver Lake basin about 22,000 years B.P., and expanded into Lake Mojave I at about 18,400 years B.P. Following a low stand between about 16,500 and 14,000 years ago, Lake Mojave II expanded to another maximum between 13,700 and 11,400 years B.P. (see section 3). Intermittent Lake conditions existed in the Mojave Basins between 11,400 and 8,700 years ago. During the Holocene shallow lakes appeared briefly four times in the Silver Lake basin (see section 3, figure 29). The constraints put in place by the geometry of the Mojave River drainage and its terminal lakes, and by general associations between temperature, evaporation, runoff, and river discharge, offer some insight into the range of climate conditions and changes that could have produced this lacustrine history observed in the terminal basins. These conditions are most easily examined in terms of stages of lake development. To do this, however, certain assumptions must be made concerning the climate in both the catchment area and in the area of the terminal lake.

Assumed Climate Parameters

Average river discharge measured at Afton Canyon is insufficient, by almost an order of magnitude, to maintain even a small lake in Silver Lake playa under the present climatic regime (see section 5). To explain a large Pleistocene lake, different climatic conditions are assumed, including a lower temperature in the Mojave Desert. This assumption is based upon other evidence for reduced temperatures at mid-latitudes in the western U.S. in the latest Pleistocene (Brackenridge 1978; this study). The greatest reduction in temperature is believed to be in summer when evaporation is greatest (Leopold 1951), and this assumption is supported by macrofossil studies for areas south of latitude 36°N (Spaulding, Leopold and Van Devender 1983). To observe a range of conditions with the proposed model, a reduction in average annual temperature is assumed for the terminal Silver Lake region of 10°, 20°, and 30°F (4.4°, 10°, and 15.5°C, respectively). Langbein's (1961) nomogram has been used to convert temperature at low precipitation values to lake evaporation (table 16).

It is less certain if a significant reduction in annual or wet-season temperature occurred in the San Bernardino Mountains, owing to the incursion of marine air masses and cloud cover. The lack of extensive latest Pleistocene and Holocene glacial features in the Transverse Ranges support little significant reduction in the annual temperature. Therefore, no reduction of annual temperature was assumed for the catchment area in the Transverse Ranges. The effect of this assumption, if Pleistocene temperatures were somewhat lower in the catchment area, is to provide relatively low estimates of runoff and discharge through Afton Canyon and lower projected lake elevations.

For purposes of calculation and illustration, lower temperatures in the Mojave Desert were assumed to have been accompanied by a 25%, 50% and 100% increase in annual precipitation in the San Bernardino Mountains, with an appropriate increase in runoff at The Forks an discharge down the Mojave River. Several researchers have argued that substantial increases in precipitation were required to maintain lake levels during the Pleistocene (e.g., Leopold 1951). This assumption appears valid for the study in that years of lake events during the 20th century experienced in excess of 50% increases in precipitation. Values in table 16 are based on generalized relations among temperature, precipitation, and runoff (Langbein et al. 1949; Schumm 1965; Mifflin and Wheat 1979). Discharge into the terminal lake area from a 50% increase in precipitation is negligible. A 100% increase in precipitation yields only about 2.5 cm of runoff. In the San Bernardino Mountains, on the other hand, even with no reduction of temperature, discharge through Afton Canyon under Pleistocene conditions is assumed to be two to three times the present storm discharge (table 16).

Average annual discharge through Afton Canyon is approximately 9.4 million m^3 over the historic record (see section 5). Discharge from the largest observed storm (in 1938), however, is about an order of magnitude greater than low-flow, non-storm discharge. Average discharge at Afton for three high-flow years (1938, 1969, 1978) is about 75 million m^3 (table 16). Historical flood discharge in Afton Canyon is 21.6% of discharge at The Forks, and it is assumed that the same proportion of runoff reached Afton Canyon in the Pleistocene and was added to terminal Lake Mojave.

The assumed changes in climate would greatly increase discharge out of Afton Canyon and at the same time would greatly reduce evaporation from the surface of Lake Mojave. Assumed values for climate-related variables are too generalized to be more than illustrative and each assumption could be challenged and the value refined. The values used, however, when combined with the geometry of the modern playas and bathymetry of the ancient lake, are adequate for estimating the relative importance of climatic variables in producing the observed responses in the terminal lakes.

PLEISTOCENE-HOLOCENE HYDROLOGY OF THE MOJAVE RIVER SYSTEM

Lake Holocene and Modern Playa Hydrology

The morphometry and volume of the present Silver Lake and Soda Lake basins are estimated by planimetry, and lake elevation is calculated for discharge from storms of 1938 and January and February 1969 (figure 70). Discharge from these storms was observed to produce an ephemeral lake in Silver Lake playa (see section 5). An aerial photograph taken after the 1969 events showed that lake elevation reached about 279.3 m which is 3.4 m above the playa floor. Discharge derived from the model for the February 1969 storm has a calculated elevation of 278 m, and combined discharge for the January and February 1969 storms produced a lake elevation of 278.8 m. Hence, the model only underestimates lake elevation by less than a meter.

Evaporative capacity of the flat-floored Silver Lake playa basin far exceeds the capacity for historic discharge to maintain even a smaller lake (figure 70). Historical storm discharge into the playa has a recurrence interval of about 12 years (see section 5). Discharge events of this magnitude could maintain a lake only if their frequency were nearly annual. For example, at present evaporation, an annual discharge of about 90 million m^3 would be needed to raise a maintain a lake elevation of about 279.5 m. The constriction between the two basins and its associated morphology reduces the capacity for evaporation to lake volume so that a lake would tend to be maintained at about 280 m (figures 10 and 71). The flat floor of Soda Lake playa, however, greatly increases the capacity for evaporation relative to volume (figure 71) and the near-annual volume of discharge needed to maintain a lake above 280 m.

A shallow lake, similar to the one defined above, briefly filled Silver Lake playa to an elevation of at least 280 m in the late Holocene and again during the Little Ice Age approximately 400 years ago (see section 3, figure 29). The model suggests that such a lake could be sustained only by a significant increase in the frequency of the discharge events that reached

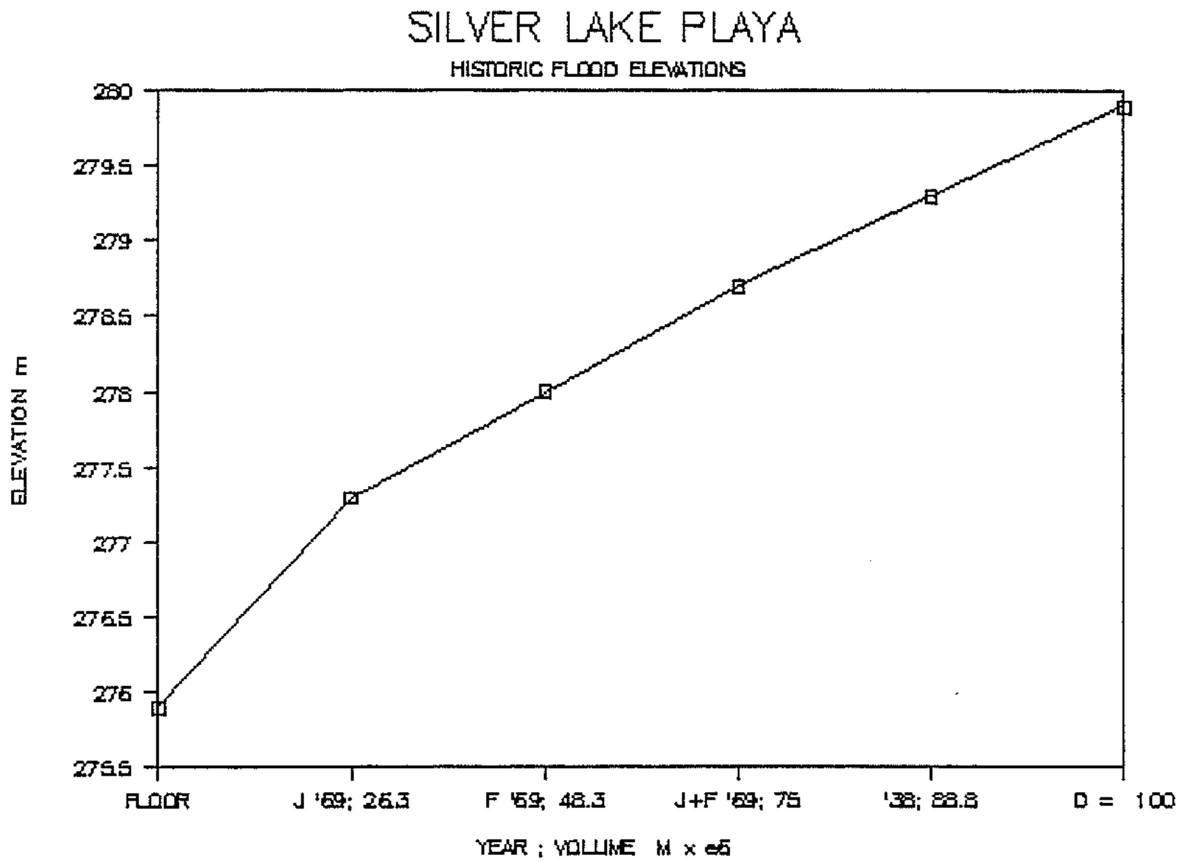


Figure 70. Effect of historic river discharge on temporary lake elevation in the Silver Lake basin. Climate variables are modern (Table 16). Estimated lake elevations are in general agreement with historic observation of flooding of the playa.

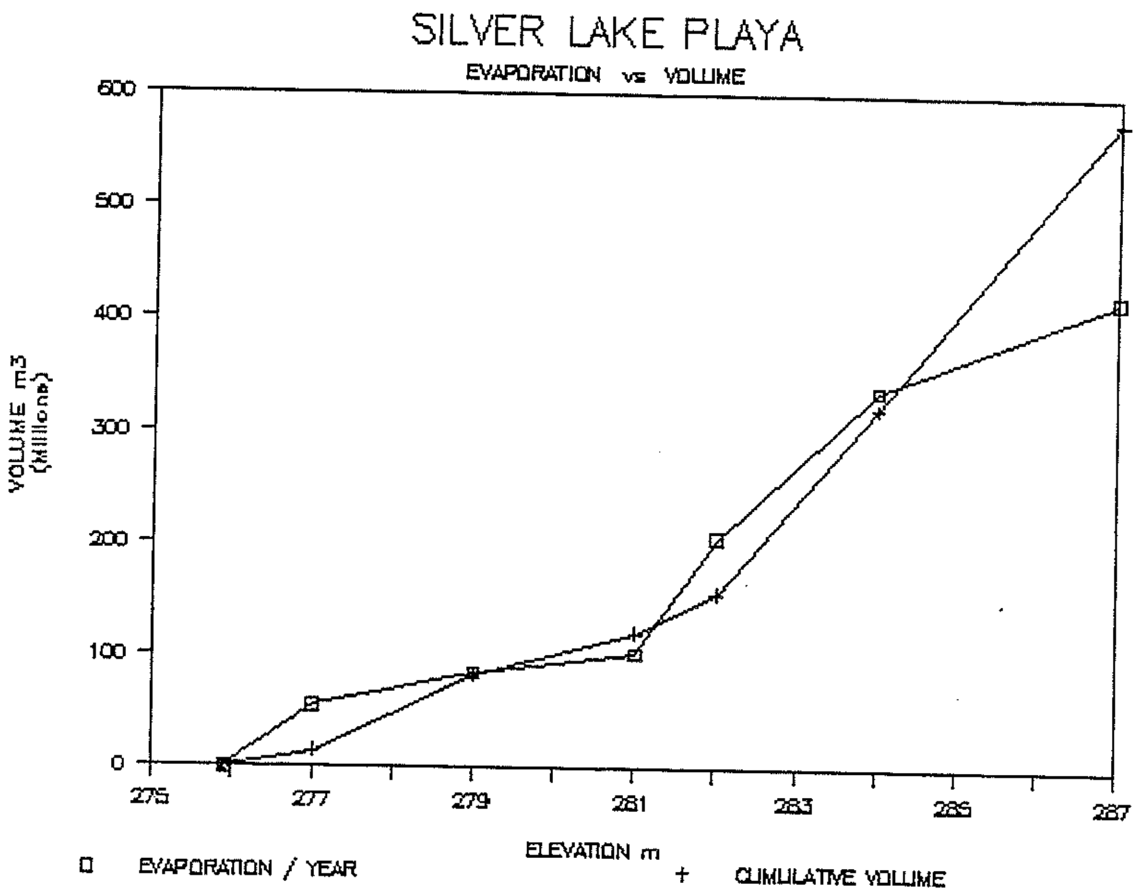


Figure 71. Potential for evaporation from modern lake surface as a function of lake elevation and volume. Note that annual evaporation exceeds volume where playa floors are flat whereas volume is greater than evaporation near the sill between Silver Lake and Soda Lake.

Afton Canyon. Although reduced temperature and evaporation in the desert would reduce the number of storms needed to maintain a lake, the model suggests an order of magnitude increase in the frequency of lake-building floods at times in the late Holocene.

Pleistocene Lake Mojave

During the Pleistocene, Lake Mojave was filled to overflowing (see section 3). Cores collected within the basin reveal high lake stands between 18,400 and 16,600 years B.P. and again between 13,700 and 11,400 years B.P. The model indicates the Mojave flow regime was dominated by frequent high-magnitude floods during these high lake stands. Historical discharge through Afton Canyon is 9.4 million m^3 per year. However, average discharge cannot be used as a basis for characterizing discharge at times of high flow in the late Pleistocene. For example, an assumed increase in precipitation in the mountains of 50%, with a proportional increase in flow based upon historical discharge values, yields a flow that is barely capable of sustaining a small lake in the deeper Pleistocene Soda Lake basin. A 100% increase in precipitation will stabilize a small lake 30 m below the elevation of overflow.

A more realistic estimate of late Pleistocene discharge, in keeping with the evidence for overflow and regional climatic change, is obtained if large historical storm events, rather than historic average discharge, are the basis for estimating Pleistocene flow. The discharge volume leaving Afton Canyon during the Pleistocene is assumed to be equivalent to the average historical storm volume (75 million m^3 per year). This volume is nearly the same as the volume of historic runoff at The Forks (34% of precipitation [Langbein et al. 1949], or 66 million m^3 per year [table 16]). Observations of historical floods show that storm discharge in Afton Canyon is 21.6% of discharge at The Forks. The basic assumption for the model is that a different flow regime was in place during times of high discharge and that storm discharge more accurately characterizes that regime. Thus, the estimates of increased Pleistocene discharge are based upon historical storm volume. If average storm discharge is projected to increase by 25% to 100%, it is possible to obtain a volume of discharge that brings the lake to the elevation of overflow.

The assumptions above and estimates in table 16 form a basis for examining the interaction of climate variables needed to explain features observed in the Lake Mojave basin. A 25% increase in precipitation from storm-regime produces a small lake with an elevation of slightly more than 250 m (figure 27) and confined to the deeper part of Soda Lake basin (figure 72). A 50% increase in precipitation overflows Soda Lake basin and brings the ancient lake into Silver Lake basin, an event that began at about 22,000 years B.P. A doubling of annually recurring historical discharge is needed to bring the lake to the elevation of the outflow sill.

It is important to emphasize these estimates are illustrative only and are not intended to characterize the actual increase in precipitation and lowering of temperature in southern California in the late Pleistocene. The values do suggest, however, that neither increased precipitation nor reduced temperature alone is sufficient, within a reasonable range of runoff and climate variability, to account for Pleistocene Lake Mojave. The option of reducing temperature much below 10°C in the Mojave Desert is probably foreclosed by recent investigations in nearby Las Vegas valley (R. Forrester, pers. com. 1988) which have yielded a range of estimates from a few degrees centigrade to as high as ten degrees centigrade. If these temperature values

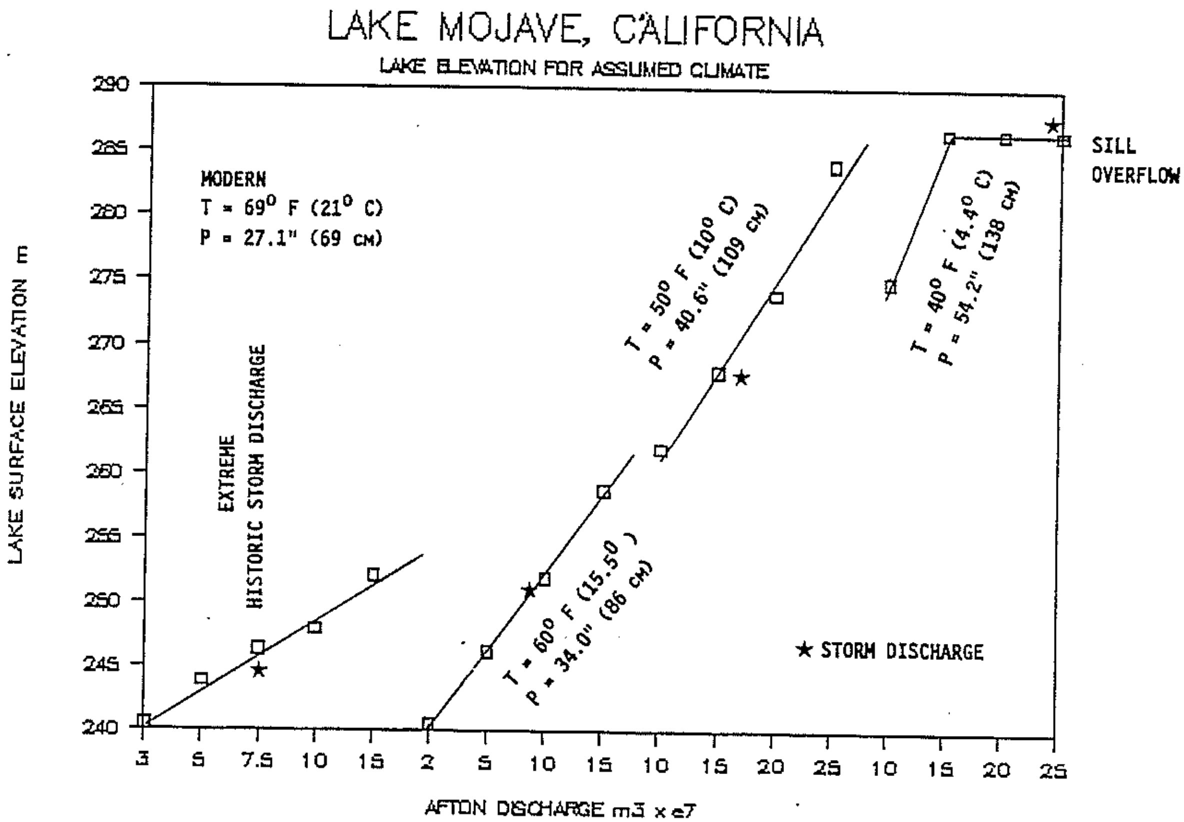


Figure 72. Calculated elevation of late Pleistocene Lake Mojave for different assumed climatic variables and discharge volumes at Afton Canyon. Star indicates the elevation of a stable lake for a storm discharge volume at runoff values in Table 16. Note that the lake does not overflow until precipitation in the mountains is nearly doubled and temperature in the lake is greatly reduced.

are correct, then precipitation greater than a 50% increase and/or a higher value of runoff are suggested by the model. The effect would be to move the lake elevation up to the projected 50% line in figure 72 toward a full lake or to shift the line toward higher precipitation.

Whatever the final estimates, the simple model proposed in this chapter seems to show that regional changes in precipitation and temperature are only part of the story. Profound changes in the frequency of storms must have accompanied regional change in climate variables to account for the high stands of Lake Mojave. The implication is that shifting air masses and jet stream patterns have played a major role in regulating storm frequency and the rise and fall of the lake (see section 5).

SUMMARY, CONCLUSIONS, AND IMPLICATIONS

High and low lake phases in the terminal basins of the Mojave River occur in a cyclic pattern between 22,000 and 8700 years ago which reveal major climatic oscillations that endured for millennia in response to major oceanic-atmospheric circulation patterns. These climatic patterns resulted in periods of significantly increased frequency of storm-related precipitation and volumes of related flood discharges which exceeded a threshold in the Transverse Ranges and along the Mojave River. Exceeding these hydrologic thresholds was required to maintain long-term lakes and result in overflow from the terminal basins into the Death Valley and Amargosa drainage basin. During this strong climatic pattern, approximately 5% of the watershed, the mountainous uplands of the Transverse Ranges (i.e., San Bernardino Mountains), apparently controlled the hydrologic and depositional history of the Mojave River terminus in Silver Lake and Soda Lake basins. The episodes of more frequent flooding which produced the Mojave I and Mojave II lake phases, 18,400 - 16,600 years ago and 13,700 - 11,400 years ago respectively, were replaced by intervals of less frequent storms and associated flooding during the last 8700 years. Within the Silver Lake basin, four short-term (tens to hundreds of years long?) lake stands occurred during the past 8700 years and apparently reflect similar climatic forcing conditions as those for the latest Pleistocene lakes. Two of the lake events yielded dates of 390 ± 90 and 3620 ± 70 years B.P. and both dates substantiate the temporal relations of these lakes to world-wide neoglaciation. The 390-year old lake also corresponds to a wet period record suggested for southern California based upon tree-ring indices and their correlation with stream flow. Correlation of tree-ring indices with the historical lake events indicate that climatic conditions similar to those that produced the historical lake-building events may be responsible for the Little Ice Age lake stand in Silver Lake basin.

Quantitative analyses of historical and Pleistocene flood hydrology and lake history are based upon conceptual and mass-budget models and provide some constraints on climatic conditions during pluvial Lake Mojave. Reduced temperature and evaporation (primarily via increased cloud cover) would reduce the number of storms needed to maintain a lake; however, the results of the model imply an order of magnitude increase in the frequency of lake-building floods is required to maintain a lake of the size observed in the geologic record. Thus, no significant changes in the temperature regime during the latest Quaternary are required to dramatically influence lake-building conditions. Average storm discharges must have increased by 25% to 100% to obtain a volume of discharge that produced overflow of pluvial Lake Mojave into the Silurian and Death Valley basins to the north. These estimates are only illustrative of the order of magnitude of conditions required to build lakes and are not intended to characterize the actual increase in precipitation.

The historical conditions of lake-building floods correlate with specific regional oceanic-atmospheric circulation patterns during the winter months of 1910, 1916, 1922, 1938, 1969, 1978, 1980, and 1983. During these months, the North Pacific subtropical high is reduced in size and a low pressure area forms over Baja California. The Aleutian low, normally over the Gulf of Alaska during the winter months, shifts southward and onshore over the northwestern U.S. These conditions result in a subtropical jet-stream position that brings warm, moisture-laden air masses over the Transverse Ranges and increased storm and flood activity in the Mojave River drainage basin. Significantly increased storm-generated runoff is required to exceed hydrologic thresholds in the Mojave River system and send flood-waters through

Afton Canyon and into the terminal basins.

Numerous studies of sedimentation rates and geomorphic processes within the region of southern California may reflect the transitional nature of climatic changes and hydrologic responses observed in the southern California area (figure 25). Gorsline and Prensky (1975) documented significant increases in offshore terrigenous sedimentation in the Pacific Ocean directly west of the study area during the latest Pleistocene. They infer increased sediment yields from oceanward drainage basins in response to increased frequency of intense precipitation during the latest Pleistocene. These processes coincide with the timing of increased flood events derived from the eastern flank of the Transverse Ranges and may provide a paleohydrologic link between paleoclimatic records based upon offshore sedimentation and subaerial environments during the late Quaternary. A record of increased storm intensity, landslide failures, erosion, and sediment yields in the southern Sierra Nevada has been suggested by Reneau et al. (1986) for period 15,000 to 9,000 years ago. Massive fill terraces also formed in the Cajon Pass area of the Transverse ranges during the latest Pleistocene (Weldon 1986). Increased sedimentation rates in the valleys of the Transverse Ranges from 14,400 to 11,500 produced fill sequences 30 to 40 m thick (McFadden and Weldon 1987). Regionally correlative alluvial-fan deposits along the margins of Lake Mojave date between 10,000 and 12,000 years B.P. (Wells, McFadden and Dohrenwend 1987). All of these geomorphic events are correlative with the last phases of pluvial Lake Mojave, the Mojave II and Intermittent Lake III phases. The increase in regional geomorphic activity of southern California reflects increased storm-related floods observed in this study. The increase in storm and flood activity is coincidental with the time transgressive change in vegetation in the Mojave Desert between 11,000 and 8,000 years ago (Van

Devender 1973, 1977). Decreased vegetational cover (tree components during this time may have enhanced the geomorphic effectiveness of storms.

The climatic conditions of increased storm-related flooding in the Mojave River has operated annually during the historic period, over centuries during the Holocene, and over millennia during the latest Pleistocene. Any prognosis of future behavior of the Mojave River hydrologic system must include the potential impacts of climatic changes on these scales. The geomorphic effectiveness of lake-building storm events in the Mojave River basin has had an adverse impact on human-made structures (e.g., railroad lines and community facilities). The apparent regional nature of these storms has had adverse impacts on areas outside of the Mojave River watershed, such as the catastrophic 1938 flood in the Los Angeles basin. Enhanced understanding of the climatic conditions producing extreme flooding events will improve the future performance of the Mojave River hydrologic system and human utilization of a large arid drainage basin.

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