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Influence of Late Quaternary Climatic Changes on Geomorphic and Pedogenic Processes on a Desert Piedmont, Eastern Mojave Desert, California

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Radiocarbon dating of late Quaternary deposits and shorelines of Lake Mojave and cation-ratio numerical age dating of stone pavements (Dorn, 1984) on the adjacent Soda Mountains piedmont provide age constraints for alluvial and eolian deposits. These deposits are associated with climatically controlled stands of Lake Mojave during the past 15,000 yr. Six alluvial fan units and three eolian stratigraphic units were assigned ages based on field relations with dated shorelines and piedmont surfaces, as well as on soil–geomorphic data. All but one of these stratigraphic units were deposited in response to time-transgressive climatic changes beginning approximately 10,000 yr ago. Increased eolian flux rates occurred in response to the lowering of Lake Mojave and a consequent increase in fine-sediment availability. Increased rates of deposition of eolian fines and associated salts influenced pedogenesis, stone-pavement development, and runoff–infiltration relations by (1) enhancing mechanical weathering of fan surfaces and hillslopes and (2) forming clay- and silt-rich surface horizons which decrease infiltration. Changes in alluvial-fan source areas from hillslopes to piedmonts during the Holocene reflect runoff reduction on hillslopes caused by colluvial mantle development and runoff enhancement on piedmonts caused by the development of less-permeable soils. Inferred increases in early to middle Holocene monsoonal activity resulted in high-magnitude paleo-sheetflood events on older fan pavements; this runoff triggered piedmont dissection which, in turn, caused increased sediment availability along channel walls. Thus, runoff-infiltration changes during the late Quaternary have occurred in response to eolian deposition of fines, pedogenesis, increased sheetflood activity in the Holocene, and vegetational changes which are related to many complicated linkages among climatic change, lake fluctuations, and eolian, hillslope, and alluvial-fan processes.

INTRODUCTION

The Pleistocene–Holocene climatic transition has served as the basis for models that assess the impact of climatic change on hillslope and fluvial processes, alluvial-fan sedimentation, and soil development in desert basins of the southwestern United States (Melton, 1965; Lustig, 1965; Bull, 1974; Wells, 1978; Mayer and Bull, 1981; McFadden and Tinsley, 1985). Observed distributions of alluvial-fan sediments and their associated soils on desert piedmonts reflect changes from moister to drier conditions. This climatic change affected runoff–infiltration regimes, sediment availability and yield, eolian dust input, and soil-moisture regimes. In previous studies, the inferred responses of geomorphic–pedogenic systems to the Pleistocene-to-Holocene climatic change have relied primarily on relative-age dating methods, such as soil-profile or stone-pavement (surface layer of interlocking clasts) development for determination of the ages of piedmont deposits. Independent age controls on stratigraphic, geomorphic, and pedogenic features, and the Pleistocene-to-Holocene climatic change are difficult to establish in desert basins.

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Many desert piedmonts in the Mojave Desert of California are characterized by strandlines of late Quaternary pluvial lakes (Blackwelder, 1954). Recent low-altitude aerial reconnaissance of selected piedmonts indicates that many shorelines either truncate older alluvial-fan segments or are truncated by younger fan segments. One such piedmont is that of the Soda Mountains which slopes eastward toward Silver Lake playa, site of the former climatically controlled pluvial Lake Mojave (Fig. 1; Ore and Warren, 1971). Silver Lake playa covers an area of 26 km^2 along the axis of an elongate north–south trending basin. The playa, at an elevation of 276.5 m, is the present-day terminus of the Mojave River which originates in the San Bernardino Mountains approximately 200 km to the southwest and drains an area of approximately 11,600 km^2. In historic times, the playa has contained water only after large storm events in the San Bernardino Mountains and subsequent flooding of the Mojave River (Troxell and Hofmann, 1954). However, during the late Quaternary, the playa was submerged at least 10 m below the waters of Lake Mojave, one of several pluvial lakes which formed a chain along the ancestral Mojave River (Fig. 1). Water filling Lake Mojave exited at the north end of Silver Lake playa via an outlet at an elevation of 285 m, and overflow drained northward toward Lake Manly at the southern end of Death Valley (Fig. 1; Blackwelder, 1954). During the late Pleistocene, only a very small portion of the San Bernardino Mountains was glaciated (Porter *et al.*, 1983); thus, glacial meltwaters provided only a small fraction of the water to Lake Mojave relative to precipitation in these mountains. The various stands of Lake Mojave apparently record changes in relative moisture conditions during the late Quaternary in the source area of the Mojave River.

A late Quaternary stratigraphic sequence is established for alluvial-fan and eolian deposits on piedmonts flanking Silver Lake playa and is based upon morphologic properties of fan surfaces (i.e., stone pavements) and soil properties. Radiocarbon dating of late Quaternary Lake Mojave deposits and shorelines along the northwestern margins of Silver Lake playa (Wells *et al.*, 1984) and cation-ratio age estimates of varnish on stone pavements on the adjacent Soda Mountains piedmont (Dorn, 1984) provide age constraints and a basis for correlation of alluvial deposits of the Soda Mountains piedmont associated with climatically controlled stands of Lake Mojave, herein defined as the pre-8000 yr B.P. pluvial lake formed at the terminus of the ancestral Mojave River. Radiometric- and numerical-age estimates of these deposits and geomorphic features, as well as their stratigraphic and topographic relations, are the basis for establishing the timing of geomorphic events and changes in pedogenic processes and establishing a detailed late Quaternary geomorphic history. The purposes of this paper are (1) to compare the timing of geomorphic events at Lake Mojave with paleoenvironmental reconstructions based on published macrofossil data and pluvial histories of other closed basins in the southwestern United States, and (2) to infer the impact of the Pleistocene–Holocene climatic change on geomorphic–pedogenic processes based upon the radiometric dates and paleoenvironmental reconstructions.

STRATIGRAPHIC AND GEOMORPHIC RELATIONS IN SILVER LAKE AND SODA MOUNTAINS PIEDMONT AREAS

Shoreline Geomorphic Features and Deposits

Deposits of the Silver Lake playa area include beach and offshore facies of Lake Mojave as well as interlacustrine playa-surface facies. Eleven shorelines are preserved along the northern and western margins of Silver Lake playa (Fig. 2; Table 1). From highest to lowest, the main shorelines are designated A through K, with

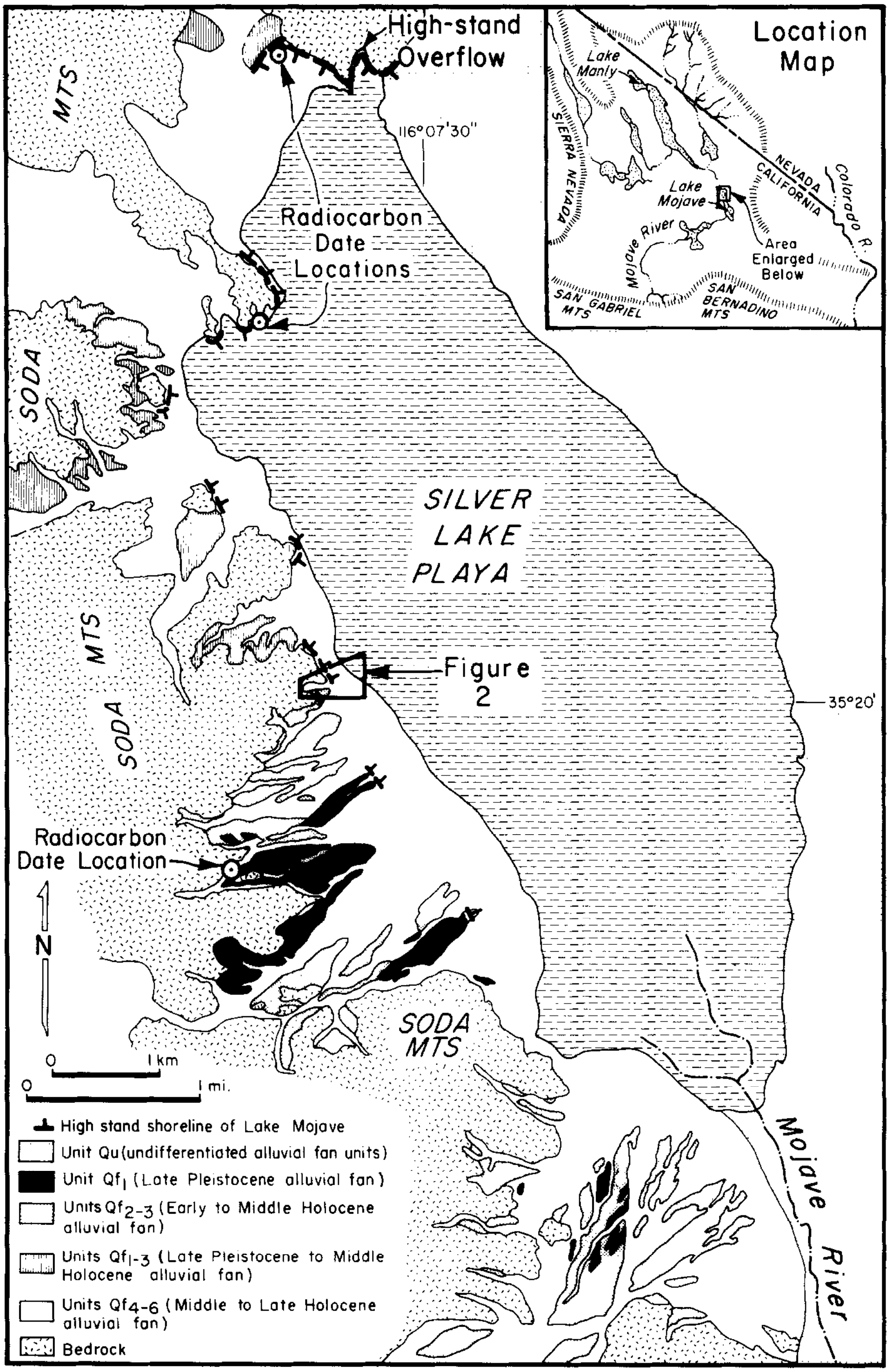

FIG. 1. Location map showing late Pleistocene lakes and drainages of eastern Mojave Desert, and a generalized map showing the surficial geology of the Soda Mountains piedmont, west of Silver Lake playa, California. Locations are shown for radiocarbon dates obtained during this study.

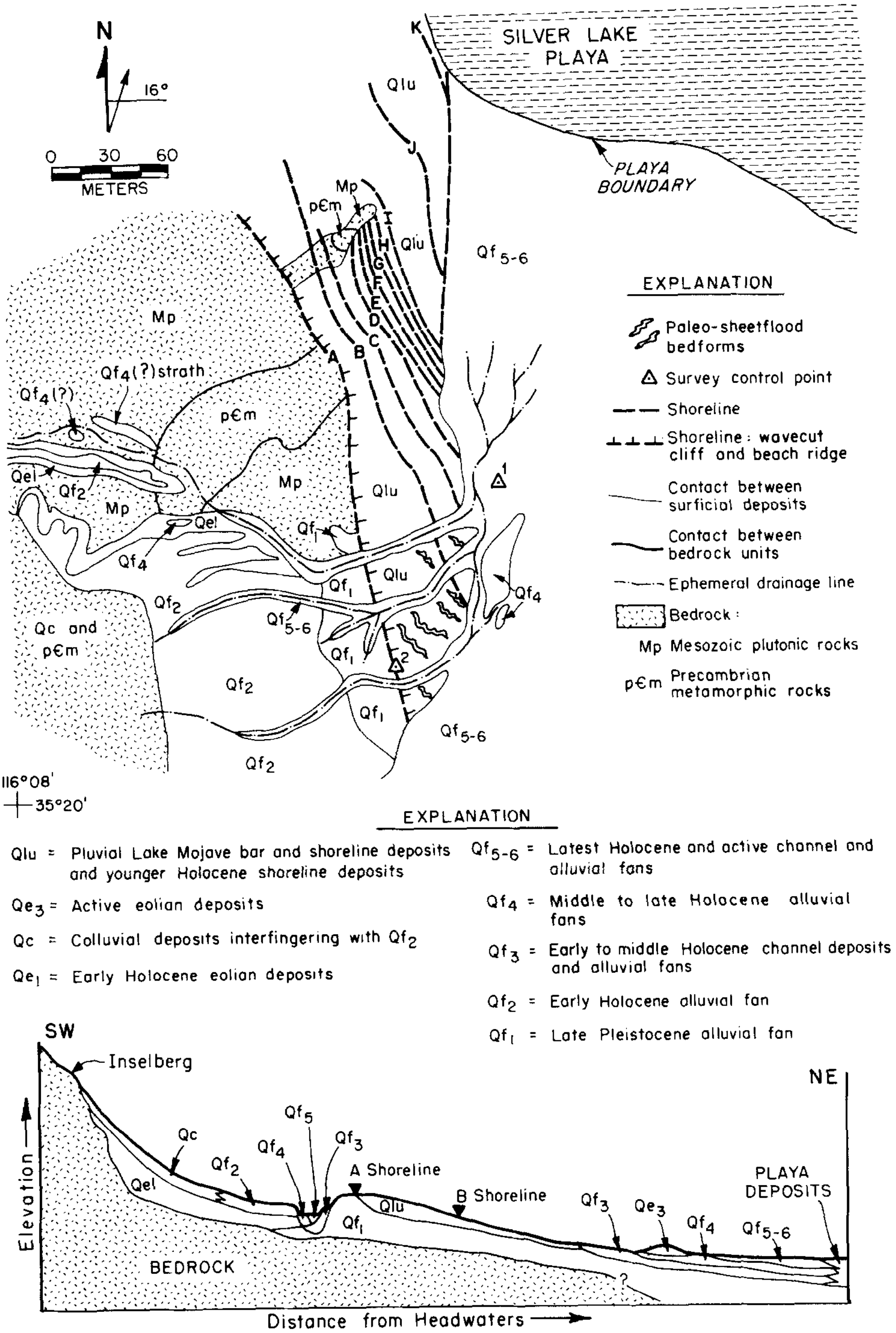

FIG. 2. (Top) Detailed surficial geology of a portion of the Soda Mountains piedmont based on a plane table and alidade survey (see Fig. 1 for location). Quaternary units are from Wells *et al.* (1984) and the bedrock geology is from Troxel (1982). (Bottom) Composite schematic cross section showing general stratigraphic and topographic relations of Quaternary stratigraphic units and Lake Mojave shorelines in the locality of the Figure 2A map area as well as the overall Soda Mountain piedmont.

slightly lower and locally preserved shorelines designated by a prime (B′). These shorelines are correlated primarily on the basis of height above the playa floor which lies at an approximately uniform elevation of 276.5 m. The highest shorelines, A and A′, stand 9 to 11 m above the playa floor and are marked by prominent wave-cut cliffs, beach ridges, and beach faces. Shorelines A–A′ are best preserved on bedrock promontories and, to a lesser extent, on older alluvial-fan deposits (Fig. 1). Beaches associated with shorelines A–A′ are typically veneered with well-developed stone pavements and are locally dissected (Fig. 3). The next highest shorelines, B–B′, stand approximately 7 m above the playa floor and display no prominent beach or wave-cut features. Nine weakly expressed shorelines occur below shorelines B–B′, from 6.8 to 0.5 m above the playa floor (Table 1). The prominence of shorelines A–A′ is influenced by the stabilization of this shoreline at the elevation of the overflow outlet (Table 1).

Ages of Lake Mojave deposits and their associated shoreline features are based on the radiocarbon dates reported by Ore and Warren (1971). Shoreline A–A′ ranges in age from approximately 15,500 to 10,000 yr B.P. and occurs between elevations of 288 and 285 m. Radiocarbon dates of pelecypod shells (*Anadonta californiesis*) (11,860 ± 95 yr B.P.; DIC-2824) and lithoid tufa and (10,850 ± 75 yr B.P.; DIC-2823) (Fig. 1) substantiate the dates of Ore and Warren. Shoreline B–B′ is correlated with the last and lowest stand of Lake Mojave at an elevation of ca. 283 m. Three of the four radiocarbon dates associated with this shoreline indicate an age of <9500 yr B.P., and the potential age range is estimated between 10,500 and 8000 yr B.P. (Wells *et al.*, 1984). Shorelines D through K can be related via hydrologic records to levels of historic flooding (Table 1). Shoreline C is the only shoreline between shoreline B–B′ and those formed during historic flooding and could represent a post-B regressive lake phase, a middle to late Holocene lake stand, or a prehistoric flood event.

Piedmont Deposits and Geomorphic Features

The piedmont of the deeply embayed eastern flank of the Soda Mountains is a complex mosaic composed predominantly of six subaerially exposed, late Quaternary fan deposits (Figs. 1 and 2). These consist of poorly to very poorly sorted fluvial bouldery sand, as well as some interstratified debris-flow sediments that are derived from plutonic and metavolcanic rocks and coarse-grained Tertiary(?) gravels of the Soda Mountains. In the distal parts of the piedmont, younger fan deposits (0.3–3.0 m thick) overlap older fan deposits and are prograding over Silver Lake playa. In the distal and medial portion of the piedmont, the oldest recognized surficial fan unit stratigraphically overlies a partly truncated, strongly developed soil and a well-cemented older fan deposit. The consistent presence of buried soils below thin, surficial deposits indicates that little widespread erosion occurred prior to fan deposition in the study area.

Discrimination between six alluvial-fan units is based on stratigraphic relations, geomorphic characteristics (e.g., depositional relief, pavement properties), and soil development. The general lithologic similarity of the deposits justifies the use of weathering and soils data for estimates of relative age and definition of piedmont mapping units (Birkeland, 1984). The major geomorphic, sedimentologic, and pedogenic characteristics of these units are summarized in Tables 2 and 3.

Units Qf6 and Qf5 are inset into, or overlap, all other deposits and, therefore, are the youngest fans. The clasts are nearly always unweathered and form bar-and-swale topography. Occasional clasts, however, possess indurated and typically abraded carbonate coatings; thus, they have been reworked from older fan deposits. Reworking of older deposits also explains the occasionally varnished and/or reddened clasts observed on Qf6 surfaces (Table 1). A soil profile has not formed on this unit.

Unit Qf4 deposits are deeply inset into units Qf3, Qf2, and Qf1 in the medial to proximal piedmont area and overlap these deposits in the distal piedmont areas. As with units Qf5 and Qf6, the presence of indurated and abraded carbonate coatings on clasts and subangular clasts of older indurated fan sediment shows that some clasts in unit Qf4 have been derived from older fan deposits. Unit Qf4 can be readily distinguished from younger units by the presence of significant varnish on clast surfaces and strong reddening of the undersides of most clasts (Table 2). The secondary carbonate of soils present in unit Qf4 occurs as soft powdery coatings on clasts (Stage I of Gile *et al.*, 1966) at depths >1.0 m (Table 3). Secondary gypsum was not observed; however, the high percentage weight loss upon sodium acetate digestion prior to particle-size analysis indicates the presence of at least some salts more soluble then carbonate. A thin, slightly reddened and discontinuous Bw horizon is observed beneath larger clasts of the pavement (Table 2). This association has been attributed to a moist microenvironment below large clasts that encourages relative increases in chemical alteration (McFadden, 1982; McFadden and Bull, in press).

Unit Qf3 is inset into units Qf1 and Qf2. The surfaces of unit Qf3 converge with active channels downfan and in the distal piedmont areas are <2 m above the active channel. Unit Qf3 is the youngest unit displaying interlocking pavements which are more strongly varnished than pavements of younger surfaces. The undersides of nearly all of the large clasts in these pavements are strongly reddened. Carbonate in soils on Qf3 surfaces occurs as thin, discontinuous, powdery coatings on clasts (Stage I), often overlying thick, abraded coatings on reworked clasts. The number of reworked clasts from the Bk horizon in unit Qf3 is less than in the younger fan deposits. Secondary gypsum occurs as fine, thin needles in the Bky horizon.

Unit Qf2 is the oldest and one of the most prominent Holocene fan units of the upper piedmont. This unit is as much as 5 m above all younger units in the proximal and medial piedmont areas, and in most locations, Qf2 deposits adjoin and onlap onto bedrock hillslopes. In the distal areas, unit Qf2 is >1.5 m above younger units. Much of unit Qf2 is characterized by well-developed stone pavements with nearly 50% reduction in depositional relief of original bar-and-swale topography (Table 2). The calcareous Bwk horizon is several decimeters thick, and the secondary carbonate morphology is Stage II. As with unit Qf3, secondary gypsum occurs in the Bky horizon.

Unit Qf1 is the oldest subaerially exposed fan deposit recognized on the piedmont flanking the western and northern margins of Silver Lake playa. This unit is best exposed in the medial piedmont areas, although it occurs locally near the highest shoreline of Lake Mojave (Fig. 1). Bar-and-swale topography is almost completely obliterated (Table 2). Soils on Qf1 deposits have B horizons as thick as those on Qf2 deposits, but the upper 15 cm of the B horizons contains significantly more clay and silt (Table 3), and the carbonate morphology is Stage II and locally Stage III.

The moderate- to well-developed stone pavements of Qf1 and Qf2 fans are locally mantled by regularly spaced curvilinear bands of fine gravel oriented perpendicular to fan slope. These features are apparently bedforms which developed on stone pavements during high-magnitude sheetflood events (Wells and Dohrenwend, 1985). Fan surfaces with bar-and-swale topography preserved do not have any of these bedforms mantling the surface, suggesting that the bedforms were unable to form on bar-and-swale topography due to the large surface roughness. However, field observations indicate that these features do not

TABLE 1. SUMMARY OF GEOMORPHIC, STRATIGRAPHIC, AND AGE RELATIONS OF SHORELINES AND ALLUVIAL-FAN UNITS

Shoreline	Height of shoreline above playa (m)	Estimated age of shoreline	Height of geomorphic features and historic levels (m)	Geomorphic and stratigraphic relations near the playa–piedmont boundary
A	10.1 to 11.3	Latest Pleistocene	11.0—overflow level	Shoreline A–A′ truncates unit Qf1
A′	8.8	(15,500–10,500 yr B.P.)	11.3 to 8.5—prominent beaches, beach ridges, wave-cut cliffs	Distal unit Qf2 grades shoreline B–B′, truncates or overlaps shoreline A–A′, and rests on unit Qe1
B	7.3 to 7.0		7.3—level of alluvial unit Qf2 near playa margin	Unit Qf3 truncates shoreline B–B′ and is locally overlain by unit Qe2
B′	6.8 to 6.7	Early Holocene (9500–8000 yr B.P.)		Paleosheetflood deposits rest on units Qf1 and Qf2 and shoreface deposits of Lake Mojave
C	4.4 to 4.9	Middle to late Holocene(?)		Unit Qf4 is inset into dissected upper piedmont and dissected shoreface of Lake Mojave
C′	4.0			Unit Qf5 is inset into and overlaps unit Qf4 and cuts shoreline C–C′
D	3.1 to 3.4	Historic	3.1—January 1916 to July 1917 level	Shorelines D through K truncate all units except those in active channels
E	2.4 to 2.6	Historic		
F	2.0 to 2.2	Historic	2.1—March 1938 to September 1939 level	
G	1.8 to 1.8	Historic	1.8—June 1969 level	
H	1.5	Historic		
I	1.2 to 1.3	Historic		
J	0.8 to 0.9	Historic		
K	0.5 to 0.6	Historic		

occur on the stone pavements of unit Qf3 or any younger unit, suggesting that the bedforms are contemporaneous with or predate unit Qf3.

Eolian Deposits

Three eolian units are distinguished on the basis of stratigraphic position, soil development, and preservation of primary sedimentary structures. The oldest eolian unit, Qe1, underlies unit Qf2 in the area shown in Figure 2 and on parts of the piedmont to the north of this area. The lack of a buried soil suggests rapid deposition of unit Qf2 over Qe1. Unit Qe2 overlies the youngest date lacustrine deposits (8350 ± 300 yr B.P.; Ore and Warren, 1971) and possesses a weakly developed soil with an 8-cm-thick Bw horizon (7.5YR 6/6 dry) and Stage I to II carbonate morphology. The youngest eolian unit, Qe3, covers large areas of the modern land surface in the northern portions of the study area. This unit is currently being deposited and is characterized by dunes, by the preservation of primary sediment structures, and no soil development.

LATE QUATERNARY GEOMORPHIC HISTORY

Ages of Deposits and Geomorphic Features

Piedmont depositional units and geomorphic features have been assigned approximate ages on the basis of field relations with dated shorelines (Table 1; Figs. 2 and 3), cation-ratio age estimates of rock varnish on fan-surface pavements, a radiocarbon date of a pack rat midden, and soil–geomorphic data (Fig. 4).

The earliest late Quaternary event clearly recorded along the western margin of Silver Lake playa is the deposition of unit Qf1 alluvial fans. The next recorded event is the occurrence of a high lake stand occurring as early as 15,350 ± 240 yr B.P. (Ore and Warren, 1971). During this lake stand, shoreline processes truncated Qf1 surfaces and reworked Qf1 deposits into beach ridges and shorefaces (Fig. 2). A cation-ratio age estimate of ca. 36,000 yr B.P. was obtained from a well-varnished stone pavement on unit Qf1 that is truncated by the high shoreline (Dorn, 1984); thus, deposition of Qf1 fans occurred prior to 15,500 yr B.P. We believe that the highest, latest stand in Lake Mojave occurred between 15,500 and 10,500 yr B.P., with little fluctuations in water level because of the control exerted by the bedrock spillway. The lack of any regional diastem, the relatively continuous radiocarbon record (Wells *et al.*, 1984), the lack of buried soils in lake-margin deposits, and the prominence of shoreline features at the level of shoreline A suggest a long period of high stand in the lake during the latest Pleistocene. Lajoie and Robinson (1982) documented similar deep-water conditions in Mono Basin, California, from 14,000 to 12,000 yr B.P.

Several hundred years of either low lake level or dryness postdated the lake stand at shoreline A and preceded the final Lake Mojave lacustrine event recorded by shoreline B. A widespread eolian unit (Qe1) was deposited after the abandonment of shoreline A and prior to the development of shoreline B. Field relations suggest that unit Qe1 was deposited in a relatively brief period during the early Holocene before being buried by Qf2 fan deposits (Figs. 2 and 4). A decrease in effective moisture at that time, resulting in decreased vegetation density and lower lake levels or drying of the lake, would have exposed unconsolidated sands and silt in distal piedmont and axial basin areas, which would serve as source materials for Qe1 sediments. In addition, these exposed materials were potential sources of the dust that was incorporated in early Holocene soils formed on the adjacent piedmont deposits. Peterson (1980) has proposed such a process for the rapid development of clay-rich, natric horizons (Btn) in soils on the Panamint Valley piedmont.

Following this brief interlacustrine episode, Lake Mojave filled to the level of shoreline B. Radiocarbon-dated shorelines and stratigraphic relations suggest that this lacustrine period ended by 8000 yr B.P. (Fig. 4). The best exposures suggest that unit Qf2 grades to shoreline B or that deposition of unit Qf2 occurred shortly after the Lake Mojave stand at shoreline B. Qf2 fan deposits interfinger upslope with colluvium, showing that large portions of unit Qf2 were derived from hillslopes (Fig. 2). We believe that unit Qf2 records a period of hillslope destabilization and increased sediment yield from bedrock source areas during the early Holocene.

Following deposition of unit Qf2, Lake Mojave receded. Only one shoreline, C, occurs between early Holocene shoreline B and the highest historic shoreline D. Unit Qe2 was deposited after shoreline B developed and was deposited in shallow

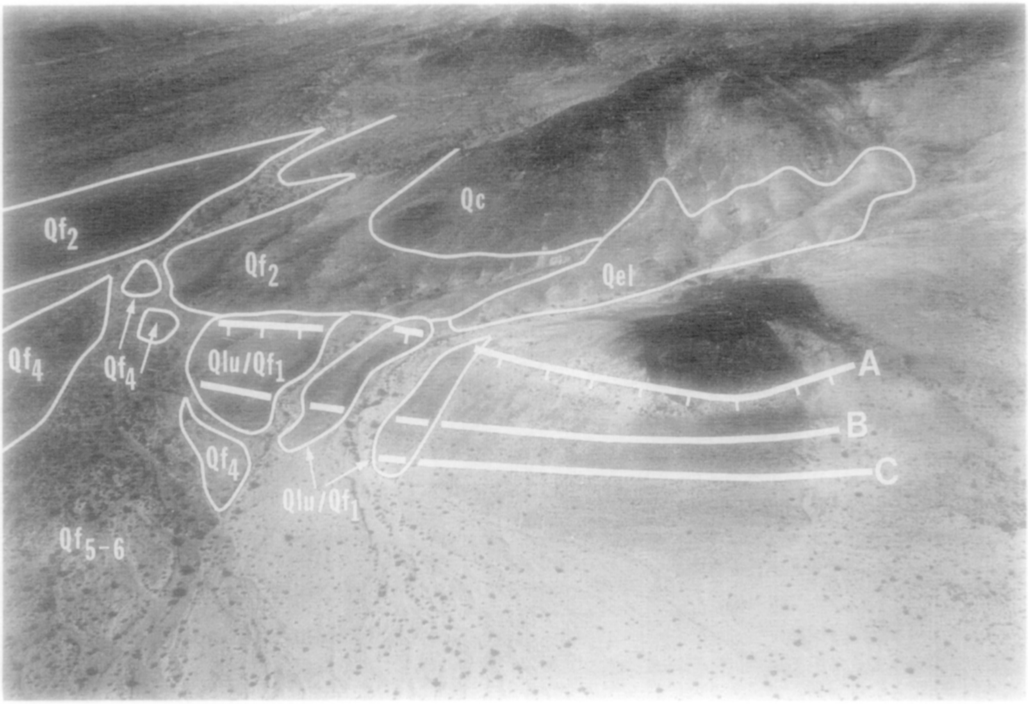

FIG. 3. Oblique aerial view of ancient Lake Mojave (A and B) and prehistoric (C) shorelines and piedmont stratigraphic units (Fig. 2); the area in the photograph is approximately the same as that shown in Figure 2.

channels cutting shoreline C. Sediments of unit Qe2 overlap unit Qf3 locally, and soils developed in both units show similar properties. We interpret the deposition of unit Qe2 as contemporaneous to or slightly later than deposition of unit Qf3 (Fig. 4).

Alluvial fan units Qf3 and Qf4 truncate the A, B, and C shorelines, respectively, along the margins of Silver Lake (Fig. 1). Reworked clasts of pedogenic carbonate coatings and deeply dissected drainage networks in proximal piedmont areas suggest that the older piedmont deposits were a major source for fans of unit Qf3 and younger. In a few cases deeply entrenched drainage lines head on the hillslopes, and these stripped areas contributed sediment into the confined channels feeding the middle to late Holocene fans. A radiocarbon date of 3400 ± 60 yr B.P. (DIC-3033) was obtained for *Neotoma* pellets in a midden which lies in an alcove 6–8 m above the channel floor, within the dissected proximal piedmont area. The midden is inset into unit Qf1 and is at approximately the same level as unit Qf3. This date and field relations suggest an age of >3400 and <8000 yr B.P. for unit Qf3, which is younger than the 8000 yr B.P. minimum age for Qf2 deposits (Fig. 4). These relations also support a cation-ratio age estimate of approximately 6000 yr B.P. for varnish from a post-early Holocene fan surface (Dorn, 1984).

Field relations suggest that many of the large discharge events which produced extensive sheetflooding of the piedmont occurred in the early to middle Holocene. The larger mean clast sizes of middle Holocene and younger fans (Table 2) suggest a major change between the tractive-force regimes of fluvial systems producing fans of unit-Qf3 age and older and those producing fans of unit-Qf4 age and younger.

TABLE 2. PROPERTIES OF DEPOSITS AND ASSOCIATED PAVEMENTS ON LATE QUATERNARY ALLUVIAL-FAN DEPOSITS ALONG THE WESTERN MARGIN OF SILVER LAKE PLAYA

Alluvial unit	Inferred age	Mean particle size[a] (cm)	Depositional bar relief[b]		Maximum[c] diameter of largest surface clast (cm)	Varnish on clasts[d] (%)	Reddening of clast undersides	
			Mean (m)	Range (m)			% Reddened	Max. red color
Qf6	Modern channel	2.4 ± 1.2	n.m.[e]	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

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

[b] Constructional relief measured between the top of the depositional (longitudinal) bar and the adjacent swale (~10 measurements/unit).

[c] Value determined on the basis of the measurement of the intermediate diameter of the largest clasts collected every 1 m over 50-m surface transects.

[d] Visual estimate if the percentage of clast covered by sufficient varnish obscures the clast lithology.

[e] Not measured.

Wells and Dohrenwend (1985) suggested that such flood events may have enhanced proximal piedmont dissection and distal fan alluviation.

Climatologic and Hydrologic Changes

Paleoenvironmental data from analysis of plant macrofossil remains in pack rat (*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 and Sonoran deserts between 30,000 and 11,000 yr B.P. (King, 1976; Van Devender and Spaulding, 1979). This woodland was present at elevations as low as 320 m where a desert scrub community of xerophytic vegetation is now stable. After 11,000 to 10,000 yr B.P., the pinyon and Joshua tree components of the woodland died out, but juniper persisted at elevations as low as 330 m until about 8000 yr B.P. (Van Devender, 1973, 1977; King, 1976). Spaulding (1982) has also shown that elements of the desert scrub were present in the Mojave Desert at elevations as high as 990 m after 15,000 yr 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° was characterized by milder, moister winters and cooler, drier summers than the present climate (Spaulding, 1982; Spaulding *et al.*, 1983; Van Devender and Spaulding, 1979). However, Galloway (1970, 1983) argues that these data do not rule out the possibility of a significantly cooler and drier climate in this region. Whatever the case, (1) vegetation change in the southwestern desert was time transgressive, implying a transitional change in the climate from latest Pleistocene to the Holocene, and (2) the effective moisture of late-glacial to early Holocene climatic regimes was significantly greater than the effective moisture of the middle to late Holocene and modern climate (Spaulding *et al.*, 1983).

Greater effective moisture in latest Pleistocene and early Holocene time is supported by pluvial-lake chronologies in the southwestern United States (Smith and Street-Perrott, 1983). Several brief latest Pleistocene high stands, lagging 4000 to 7000 yr behind the glacial maximum of 18,000 yr B.P., occurred in pluvial lakes fed from either glaciated or nonglaciated source areas (Smith and Street-Perrott, 1983). Lake Mojave underwent a similar latest Pleistocene high stand; an increase in effective moisture between 15,500 and 10,500 yr B.P. was probably necessary to maintain this lake. Several pluvial lake basins fed by nonglaciated source areas also contained early to middle Holocene lakes (Bachhuber, 1982; Fleishouer and Stone, 1982). The evidence for the presence of a short-lived early Holocene lake at Silver Lake playa is the B shoreline. This latest stand of Lake Mojave suggests significant fluctuations in effective moisture from 10,500 to 8000 yr B.P., and it also implies that average effective moisture during this period was greater than during the rest of the Holocene. These conclusions are also consistent with the inferences drawn from the paleobotanical evidence which imply a time-transgressive climatic change.

Subsequent to 8000 yr B.P., the hydrologic regime on the Soda Mountain piedmont had changed as the upper piedmont became dissected. Incipient dissection postdates deposition of unit Qf2 and predates deposition of unit Qf3, as indicated by the topographic–stratigraphic relations presented in Figures 2 and 3. For example, Qf3 and younger deposits can be traced through channels which dissect the high-stand Lake Mojave beach berm, the position of which caused deflection of Qf2 deposits (Fig. 2). However, local deep dissection of the upper piedmont occurred by ca. 3500 yr B.P., as indicated by the radiocarbon-dated midden on the face of the deep channel discussed previously. Piedmont dissection resulted in the down-fan migration of fan apices during middle Holocene and younger times. A statistically significant increase in mean grain size of Qf4 and younger deposits (Table 2; L. D. McFadden *et al.*, unpublished data) suggests (1) that the transport capabilities of the middle to late Holocene ephemeral streams increased, (2) that the availability of coarser material increased as channels cut into older, coarser grained Tertiary gravels in the proximal piedmont area, or (3) a combination of these factors.

This dissection may be due either to a decrease in hillslope-derived sediment load from early Holocene to middle Holocene time (as in a model proposed by Bull and Schick, 1979), or to the erosional forces of the large discharge events which produced the sheetflood bedforms (Wells and Dohrenwend, 1985). Field observations show that unit Qf2 has a much greater bedrock source area than any younger fan units, indicating a decrease in sediment supply from hillslopes during the Holocene. This field relation supports the Bull and Schick model (1979) which emphasizes an initial increase in sediment load in response to a climatic change that favors transport of hillslope deposits, followed by a decrease in sediment load as the hillslope supply decreases.

Sheetflood events during the middle to early Holocene are recorded as bedforms on abandoned fan surfaces of units Qf1 and Qf2. Wells and Dohrenwend (1985) determined that clasts with a mean size of 2–8 mm were mobilized on the surfaces of Qf1 and Qf2, though larger clasts were probably transported in channel areas where flows were deeper and tractive forces were higher. Paleodischarges of these floods are not known, and associated meteorological

TABLE 3. Summary of Morphological and Textural Characteristics of Soils Developed on Late Quaternary Alluvial Fan Deposits along the Western Margin of Silver Lake Playa

Alluvial unit	Horizon[a]	Depth (cm)	Color, dry matrix	Texture[a]	Structure[a]	Consistencies[a]		Clay films[a]	Particle size (<2mm)[b]		
						Dry	Moist		Sand	Silt	Clay
Qf5	Avk	0–1	10YR 7/3	gfsl	1mpl/sbk	s	s,p	o	62.0	22.6	15.4
	Ck	1–12	10YR 6/4	gs	sg	lo	no,po	o	86.2	9.7	4.1
	C	12+	10YR 6/4	gs	sg	lo	no,po	o	91.6	5.2	3.2
Qf4	Avk	0–4	10YR 7/3	fsl	3mpl/3sbk	sh	s,p	4npo	55.9	28.6	15.5
	Ck1	4–17	10YR 7/4	gs	sg	lo	no,po	o	87.7	8.3	2.3
	Ck2 upper	17+	10YR 7/3	gs	sg	lo	no,po	o	94.9	4.5	0.6
	Ck2 lower	~100	10YR 7/3	gs	sg	lo	no,po	o	95.3	3.4	1.3
	Bw[c]	0–0.5	7.5YR 5/4	gsl	sg	lo	no,po	co	72.3	17.5	10.2
Qf3	A	0–0.3	10YR 7/3	sl	sg	lo	ss,sp	o	57.6	28.7	13.8
	Avk	0.3–5	10YR 7/6	gscl	3mpl/3sbk	h	s,sp	4npo	59.7	14.5	25.8
	Bwk	5–15	7.5YR 7/6	gsl	sg	lo	ss,po	co	76.7	7.6	15.7
	Bky upper	15+	10YR 6/3	gs	sg	lo	so,po	o	95.0	4.6	0.4
	middle	35	10YR 6/3	gs	sg	lo	so,po	o	94.1	4.3	1.6
	lower	60	10YR 6/4	gs	sg	lo	so,po	o	92.0	4.4	3.6
Qf2	A	0–0.2	10YR 7/3	ls	sg	lo	ss,sp	o	72.1	25.6	2.3
	Avk	0.2–2	10YR 7/4	sl	3mpl/3sbk	h	s,sp	4npo	57.0	27.3	15.7
	BAvk	2–13	7.5YR 6/6	sl	3vcsbk	sh	ss,sp	1npf;co	71.8	16.1	12.1
	2Bwk	13–25	7.5YR 6/6	gsl	m/1mgr	so	ss,sp	co	75.1	14.3	10.6
	2Bk	25–41	10YR 6/6	gsl	m	so	ss,po	o	78.5	9.2	12.3
	2Bky	41–62	10YR 7/6	gls	sg	lo	ss,po	o	84.4	7.8	7.9
	2Bk	62+	10YR 7/4	gls	sg	lo	no,po	o	35.1	7.8	7.1
Qf1	A	0–0.5	10YR 7/3	ls	sg	lo	ss,sp	o	—	—	—
	Avk	0.5–6	10YR 7/3	cl	3cpl/3msbk	sh	s,p	4npo	38.2	34.2	27.6
	AvBk	6–15	8.75YR 7/3	scl	3msbk	sh	s,p	3npf,co	54.3	25.1	20.6
	2Btks	15–48	7.5YR 6/4–6	gls	m/1fgr	h	ss,po	br,co	79.2	16.0	4.8
	2Bk	48–70	10YR 6/6	gs	m	h	no,po	o	90.1	7.6	2.3
	2Bk	70+	8.75YR 6/4	gs	sg	lo	no,po	o	87.3	9.4	3.3

[a] Notations from Soil Survey Manual and revised Chap. 4, Soil Survey Manual (Directive 430-U, Issue 1, SCS, Washington, D.C.).

[b] Particle size distribution measured using the pipette method after removal of calcium carbonate and soluble salts by the sodium acetate digestion method.

[c] Discontinuous Bw horizon described below gravel clasts in pavement.

controls are not clearly understood; however, Van Devender and Spaulding (1979) suggested that after 8000 yr B.P. summer monsoonal conditions expanded because warmer global temperatures favor the development of the Bermuda High. Intensified seasonal monsoon circulation and rains have been documented in the African–Asian regions of the Northern Hemisphere and attributed to solar radiation changes associated with variations in orbital parameters (Kutzbach, 1981; Kutzbach and Otto-Bliesner, 1982). Enlarged lakes in these regions between 10,000 and 5000 yr B.P. correspond to a peak in solar radiation about 10,000 to 9000 yr B.P., with a return to near-modern values by 5000 yr B.P. (Berger, 1978; Kutzbach and Otto-Bliesner, 1982). Similarly, intensified monsoonal conditions in the early to middle Holocene in the Silver Lake area could have led to the extreme flood events. Comparable relations between paleosheetflood bedforms and fan surfaces are found throughout the Mojave Desert, suggesting a regional climatic control for the sheetfloods. The large monsoonal events hypothesized for the Mojave Desert area in the early Holocene also may have resulted in the post-early Holocene and prehistoric shoreline C. Historic shorelines along Silver Lake playa have been produced by flood events on the Mojave River; thus, a lake-filling event caused by the sheetflood events would require enough water to raise a late to middle Holocene lake level about 1 m above the historic shorelines to shoreline C (Table 1).

GEOMORPHIC–PEDOGENIC RESPONSES TO LATE QUATERNARY CLIMATIC CHANGES

Comparison of the late Quaternary geomorphic history of the Silver Lake area with paleoclimatic reconstructions permits evaluation of the impact of climatic change during the latest Pleistocene and Holocene on fan deposition, hillslope stability, eolian activity, and soil development. Disappearance of pinyon and Joshua tree components from the plant record in this part of the Mojave Desert, between 11,000 and 10,000 yr B.P., is coincident with the post-10,500 yr B.P. lowering of Lake Mojave. Following the Lake Mojave high stand, rapid deposition of unit Qe1 occurred at a favorable piedmont location near sediment source areas. During the early Holocene lake readvance (sometime between ca. 9500 and 8000 yr B.P.), unit Qe2 was deposited; however, shortly after drying of Lake Mojave about 8000 yr B.P., units Qf3 and Qe2 were deposited. These temporal relations suggest systematic linkages between climatic change and geomorphic events (Fig. 4). We believe that these linkages and geomorphic responses are related primarily to adjustments in runoff and infiltration relations.

Pedogenic and Weathering Responses

Reduction in effective moisture after and possibly during the late Pleistocene–Holocene climatic transition probably also influenced depths of wetting, and carbonate and clay translocation in soils (McFadden and Tinsley, 1985). High temperatures coupled with low annual precipitation favor shallow depths of accumulation of carbonates and soluble salts in the soil. The relatively large amounts of secondary carbonate, gypsum, silt, and clay in the soils indicate that eolian dust and potentially solutes in rainfall are the primary source of these pedogenic accumulations (Table 3). However, the accumulation of silt and clay during the Holocene reduces soil permeability and lowers infiltration capacity (Musick, 1975); it also favors shallow depths of accumulation of secondary materials (McFadden and Tinsley, 1985).

These pedogenic accumulations are related to late Quaternary landscape changes in the Silver Lake area. The drying of a pluvial lake and exposure of unconsolidated fine sediment in the early Holocene

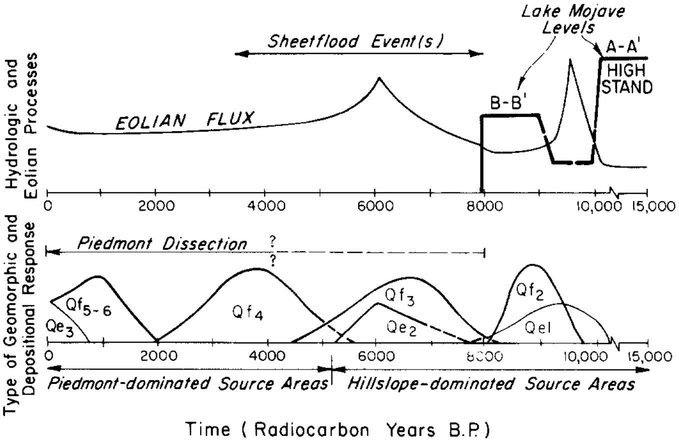

FIG. 4. Process–response model showing the timing between hydrologic and eolian processes and geomorphic and depositional responses in the Soda Mountains piedmont–Silver Lake playa area during the Pleistocene–Holocene climatic transition. Plots represent duration of event but do not imply relative volumes of deposits or specific rates of processes. Piedmont dissection refers to the medial and proximal piedmont areas and is greater in the middle to late Holocene (solid line) than in the early to middle Holocene (dashed line).

increased the extent of areas of deflatable deposits both locally and regionally. This presumably caused a sharp increase in the rate of eolian dust influx on favorably located geomorphic surfaces (McFadden *et al.*, 1984). Where a high percentage of salt-rich dust is available, secondary silt, clay, carbonate, and gypsum can accumulate in the soils. As soil permeability decreases in response to increasing silt and clay, the depth of accumulation becomes shallow. Such changes in accumulation depth may be difficult to differentiate from changes due to climatic change.

The presence of salts in soils accelerates mechanical weathering of surface clasts and this promotes the evolution of stone pavements. These processes most strongly affected medium- to coarse-grained plutonic lithologies which locally make up as much as two-thirds of the deposits. Long-term intense salt-splitting and granular disintegration, in conjunction with raindrop impact, sheetwash, and eolian processes, resulted in the reduction of depositional relief and the formation of flat, interlocking pavements that become increasingly composed of resistant, fine-grained lithologies. These processes are responsible for the differences in mean-maximum size of clasts between late Pleistocene and Holocene pavements, given the generally similar grain-size characteristics of these deposits (Table 2). However, other processes may contribute to the variation in mean-maximum grain size among Holocene pavements: (1) differences in magnitudes of individual storm events responsible for bar accumulation, or (2) lithologic controls on clast size and variation in deposit composition (L. D. McFadden *et al.*, unpublished data).

Geomorphic and Hydrologic Responses

Stratigraphic relations (Figs. 2 and 4) show that deposition of unit Qf2 postdates a significant moisture reduction, lake lowering, and deposition of eolian unit (Qel). Unit Qf2 records a period of hillslope destabilization; colluvial wedges and runoff reduction at the base of the wedges would explain increased sediment yield from bedrock source areas during the early Holocene, as Bull and Schick (1979) have suggested for desert basins in southern Israel. Our explanation for this response is that time-transgressive changes in plant communities and decreases in vegetation densities on hillslopes increased both sediment yield and runoff in spite of the reduction in effective moisture.

The timing of eolian and fan deposition may be a product of a sequence of responses that followed climatic change. In addition to a possible vegetation change, an increased flux of salts associated with eolian fines may accelerate mechanical weathering of bedrock and create hillslope instability. Wells *et al.* (1985) have suggested that the deposition of salts in eolian dust is important in the disintegration of basaltic lava flows in the eastern Mojave Desert. Eolian fines mantle hillslopes in the Soda Mountains piedmont region as well as many other hillslopes in the Mojave Desert (Smith, 1984), and enhanced mechanical weathering due to eolian deposition results in an increase in sediment availability and posteolian-activity alluvial-fan aggradation. In addition, eolian deposition may increase hillslope instability by promoting debris flow activity in that it provides the matrix needed for slurry flows (Wells *et al.*, 1982).

Cessation of Qf2 deposition may be related to limited sediment supply (Bull and Schick, 1979), and/or to adjustments of the hillslope to newly imposed runoff–infiltration balances. The bases, or footslopes, of a majority of hillslopes developed on metamorphic rocks are mantled with Qf2-age colluvium and admixed sediment of unit Qe2. The development of this debris-mantle hillslope during unit-Qf2 time enhances absorption of runoff from the bedrock and probably inhibits runoff from the base of the hillslopes, such as has been demonstrated for desert hillslopes in Israel (Yair and Lavee, 1985). Absorption of runoff at the upslope margins of colluvial wedges and runoff reduction at the base of the wedge would explain why hillslopes underlain by metamorphic bedrock could not produce runoff and sediment for Qf3 and younger units in the middle and late Holocene.

Increased monsoonal activity may have resulted in the high-magnitude sheetflood events during the early to middle Holocene. However, sheetflooding apparently may have been related to postulated changes in runoff–infiltration conditions caused by eolian deposition, stone-pavement development, and soil development. The development of stone pavements and soils decreased permeability on surfaces of units Qf1 and Qf2 and promoted increases in runoff. Similar linkages between eolian and pedogenic processes and long-term runoff–infiltration properties have been observed on basaltic lava flow surfaces in the eastern Mojave Desert (Wells *et al.*, 1985).

Upper piedmont dissection appears to be temporally related to the high-magnitude sheetflood events. This dissection, however, also may be related to the decreasing infiltration on piedmont surfaces induced by eolian deposition and soil development. Increased runoff on the piedmont surfaces apparently is necessary for dissection because many hillslopes were unable to contribute runoff and sediment as a result of absorption along thick debris-mantled wedges. Piedmont dissection thus resulted in renewed source areas and increased sediment contributions promoting deposition of units Qf4, Qf5, and Qf6 (Fig. 4). The migration of sources from hillslopes to older fan deposits on piedmonts during the Holocene has been observed in the Sonoran Desert of Arizona as well (Wells, 1978). A regional change from hillslope sediment source areas to desert piedmont source areas in southwestern United States should be expected where thick colluvial wedges on hillslopes inhibit runoff, and decreased piedmont permeability promotes runoff.

Deep piedmont dissection in upper and middle piedmont areas is recorded by large vertical separations between unit Qf3 and younger fan surfaces. This dissection is probably related to increased tractive forces in channels during middle to early Holocene sheetflood events and increased runoff resulting from increasing impermeable piedmont surfaces. Lowering of lake levels from the latest Pleistocene high stand resulted in a minor incision of beach deposits, but relatively little incision of distal piedmont deposits occurred in response to the drying of Lake Mojave.

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