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Soil Genesis on Beach Ridges of Pluvial Lake Mojave: Implications for Holocene Lacustrine and Eolian Events in the Mojave Desert, Southern California

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Summary

Silver Lake and Soda Lake playas, Mojave Desert, California, are bounded by locally well preserved shoreline features that reflect the presence of pluvial Lake Mojave. A well preserved sequence of five beach ridges is present in the northernmost part of Silver Lake playa. Radiocarbon dating show that the topographically highest three beach ridges range from <13,600 to approximately 9,000 years in age. Soils have formed primarily in a sandy eolian mantle that was deposited on top of the higher three beach ridges after the drying of Lake Mojave, between 6,000 and 9,000 yrs B.P. Minimal soil development had occurred in gravelly beach deposits prior to this time period. Weakly developed soils occur in gravelly sandy deposits of the two lower, undated beach ridges. Morphological, textural, and chemical analyses of the soils indicate that eolian processes have strongly influenced soil development on beach ridges. The accumulation of eolian sand on the gravelly beach ridge soils influences pedogenesis because of the lower permeability and shallower depth of water infiltration in sand compared to that of the highly permeable beach gravels. Soil formation has also intensified by the presence of playas that provided a source of silt, clay and salts. The degree of soil development in the lowest beach ridges indicates several lake stands in Silver Lake playa during the past 6,000 years. These may be as young as the latest Holocene, as supported by radiometrically dated lacustrine sediments from Silver Lake playa.

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1 Introduction

Silver Lake playa (fig. 1) has been the location of several studies that have focussed on the nature of late Quaternary climatic change and landscape evolution in a desert environment (Crozer-Campbell & Campbell 1937, Bode 1937, Ore & Warren 1971, Wells et al. 1987, 1989, McFadden 1988, McFadden et al. 1989, Reheis et al. 1989, Enzel et al. 1989, Brown et. al. 1990). Lake-stand events are recorded by remnants of beach ridges and other shoreline features located around the margin of Silver Lake playa (fig. 2). Radiocarbon dating of pelecypod shells from beach ridge deposits of pluvial Lake Mojave, of which Silver Lake playa is a remnant,

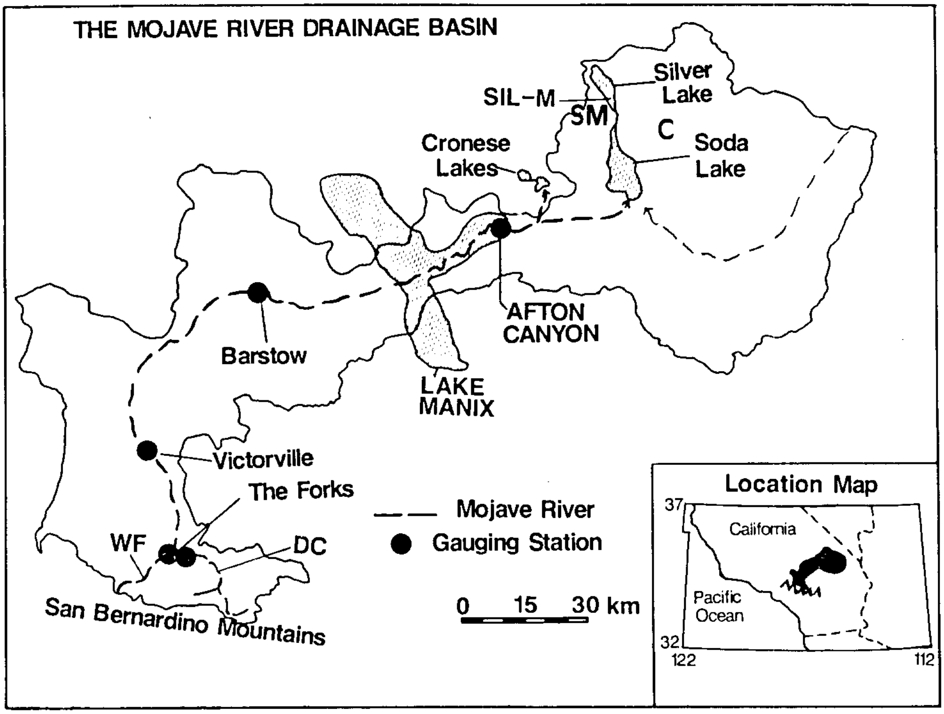

Fig. 1: *Location map of the Mojave River drainage basin in southern California, showing significant physiographic and geographic features of the eastern Mojave desert, southern California.*
WF = West Fork; DC = Deep Creek; C = Cima volcanic field; SM = Soda Mountains; SIL-M = Location of core M.

indicates that pluvial Lake Mojave persisted episodically from 22,000 yrs B.P. until about 9,000 yrs. B.P., after which the lake disappeared. This occurred in response to the glacial-to-interglacial climatic change that occurred in the early Holocene (Ore & Warren 1971, Wells et al. 1989, Brown 1989). The availability of this geochronologic data, as well as geochronologic data from experimental age dating studies, has enabled a detailed understanding of the history of pluvial Lake Mojave during the Latest Pleistocene and Holocene as well as elucidation of the impact of climatic changes on geomorphic and pedologic processes on the evolution of adjacent desert piedmonts in this region.

Beach ridges are common geomorphic landforms associated with pluvial lakes in the western United States, yet, there have been relatively few studies focussing on the processes of soil development on this landform. Most previous studies of soils associated with deposits of pluvial lakes have used the degree of soil development to correlate the deposits with past lake stands (Morrison 1965, Fleischhauer 1982).

During this study, shoreline features were mapped by aerial photographic field studies and topographically sur-

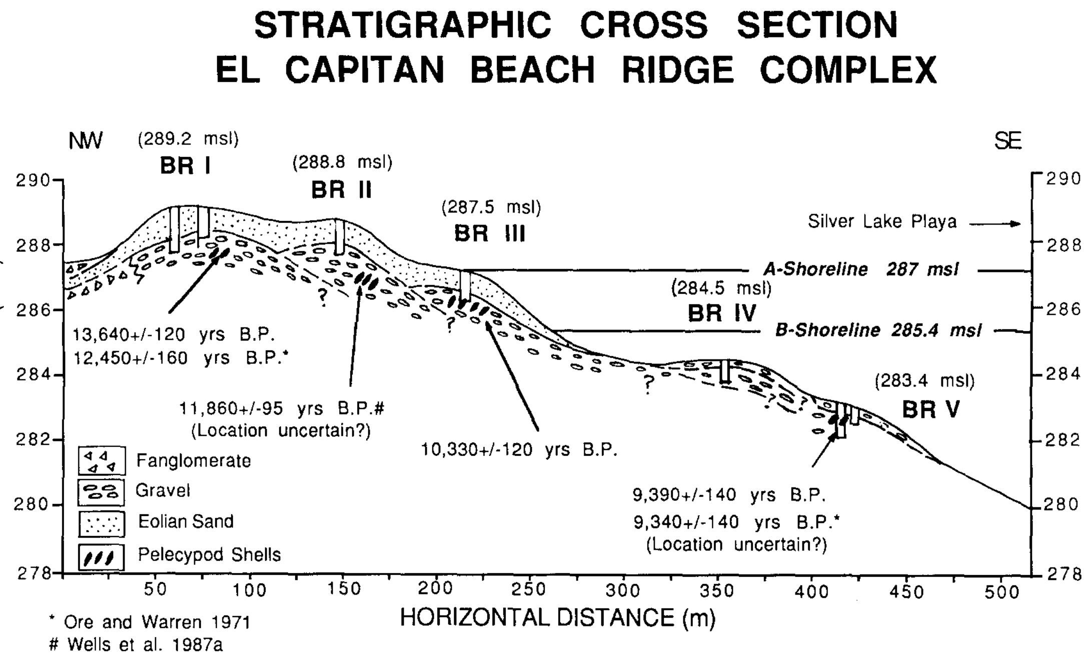

Fig. 2: *Topographic profile and geologic cross section of the El Capitan Beach Complex. Note that an eolain cover (Qe2) mantles BR1, 2, and 3. Stratigraphic contacts are inferred from description of the deposit exposed in several stream cuts. Units Qe3 and Qf3 are late Holocene eolian and middle Holocene alluvial fan units, respectively (see text for discussion).*

veyed, and the stratigraphy, sedimentology, and relationship with associated piedmont deposits of the beach ridges were studied (Wells et al. 1989). Also, we collected shell materials from deposits associated with a well preserved beach ridge complex located at the northwestern part of Silver Lake playa.

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 pluvial beach ridge deposits in California. The purposes of this study are

1. to evaluate major processes influencing the development and evolution of soils on beach ridge landforms;
2. to compare and contrast rates and processes of pedogenesis on beach ridge and piedmont landforms; and
3. to determine the timing of post-early Holocene lake stands on the basis of pedologic data for undated beach ridges present at elevations below the dated, pluvial beach ridges.

Such information provides significant data for evaluation of paleoclimatic information derived from other geological and paleontological studies.

2 Methods

Soils described and sampled were exposed in pits excavated on what were, on the basis of visual observations, the most geomorphically stable part of the beach ridge. Soils were described on beach ridges flanking Silver Lake and Soda Lake Playa with emphasis on those located along the northwestern margin of Silver Lake Playa. 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 soils for subsequent textural, morphological and chemical analysis.

Samples of the <2 mm fraction were collected for determination of pH (1:10), calcite (Machette 1985), gypsum and soluble salts (Reheis 1985), particle-size distribution determined after carbonates and soluble salts were removed after the method of Rabenhorst and Wilding (1984). Soil pH was determined with a 1:10 soil-to-water ratio. Electroconductivity values were measured using a Sybron/Barnstead PM-70CB conductivity bridge.

Wet-chemical extraction techniques were used to determine the content and nature of Fe oxides present in samples of soil ground to 80 Mesh. The dithionite-citrate-bicarbonate method of Mehra & Jackson (1960) and the oxalate extraction procedure of Schwertmann (1964) and McKeague & Day (1966) were used to estimate total ferric oxide (Fed) and poorly crystalline oxide contents (Feo), respectively. Magnetite was removed from samples prior to Fe oxide 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.

Because the degree of development of many field properties of soils is strongly time dependent (Bockheim 1980, Birkeland 1984), soil field data were 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 on piedmont deposits in the Silver Lake area as well as with other soils studied in the Mojave Desert.

3 Climate and vegetation in the study area

The present climate in the area of Silver Lake playa is hot (average summer temperatures exceeding 30°C) and arid (mean annual precipitation = 78 mm) (National Oceanic and Atmospheric Administration 1983). The climate is moderately seasonal, with more than 50% of the annual precipitation from Pacific Ocean sources arriving during the winter and early spring, and precipitation (24%) from the Gulfs of Mexico and California arriving during the summer (Pyke, 1972). Potential annual evapotranspiration exceeds annual precipitation, achieving values of 200 to 250 cm/yr (California Department of Water Resources 1967). The soil temperature regime is hyperthermic and the soil moisture regime is aridic at most sites in the study area.

Vegetation throughout most of the Mojave Desert is classified as Mojave Desert Scrub (Barbour & Major 1980). Typical vegetation includes saltbush, creosote, and various species of Opuntia, with larger perennial vegetation restricted to active washes and recently abandoned terraces; by constrast, surfaces with well developed pavements are much more sparsely vegetated.

Paleoenvironmental data from analysis of plant macrofossil remains in woodrat (*Neotoma*) middens indicate that the climate in the study area during the late Wisconsin and early Holocene was quite different from that which exists today. A juniper-pinyon-Joshua tree woodland was present throughout much of the Mojave Desert between 30,000 and 11,000 years B.P., existing in places at elevations as low as 330 meters (King 1976, Van Devender & Spaulding 1979). Van Devender et al. (1987) have also shown that elements of desert scrub community and the xeric woodland occurred as a complex mosaic throghout the latest Pleistocene and into the early Holocene.

4 El Capitan Beach Complex

4.1 Stratigraphy, geomorphology, and age constraints

Many shoreline features are found around the margins of Silver Lake and Soda Lake playas, including erosional wave-cut cliffs, depositional beach ridges, and offshore bars or spits. The most extensive shoreline features were formed during high stands of the lake which were controlled by the elevation of an outlet spillway (Wells et al 1987, 1989). Overflow and erosion of the spillway occurred between about 13,600 and 11,500 yrs B.P., causing formation of a shoreline (B-shoreline) 1.4 m below the highest shoreline (A-shoreline) (Brown 1989). Lower, less extensive shoreline features occur below the B-shoreline and above the playa, which occurs at an elevation of 275.5 m (Wells et al. 1987, Enzel 1990).

Due to prevailing wind directions, lake fetch, and geologic factors, the largest and most extensively preserved shoreline features are typically found along the northern margins of both Silver Lake and Soda Lake playas (Brown 1989). The most extensive of these beach complexes was referred to as the Northern Ridge Complex (Bode 1937). Our studies show that this beach complex contains five separate beach ridges and we refer to the complex as the El Capitan Beach Ridge Complex. The beach ridges are designated as, from topographically highest to lowest, BR1, BR2, BR3, BR4, and BR5 (fig. 2).

The beach ridge deposits of El Capitan Beach Ridge Complex are exposed along stream channels. In general, the deposits of the upper three beach ridges typically consist of imbricated, lakeward dipping gravels and less commonly gravelly sand. The gravels are usually rounded to subrounded, platy, and are composed dominantly of mafic metamorphic rocks, diorite, granodiorite, and less commonly marble. The major source of these deposits is reworking of gravelly piedmont deposits derived from the Soda Mountains. Occasionally, the beach ridge gravels contain moderately to well preserved shells of the pelecypod, *Anadonta californiesis*. The uppermost 50 to 100 cm consists of increasingly sandy, massive materials (photo 1). The surface of beach ridges are characterized by a varnished pavement that consists largely of pebble and cobble-size clasts of local origin and reworked tufa.

Samples of the most well preserved shell fragments obtained from deposits associated with BR1 and BR3 were dated and yielded radiocarbon ages of 13,640±160 yrs B.P. (Brown 1989) and 10,330±130 yrs B.P., respectively (Beta - 26,456, Beta - 21,200) (Wells et al. 1989), consistent with ages from shell

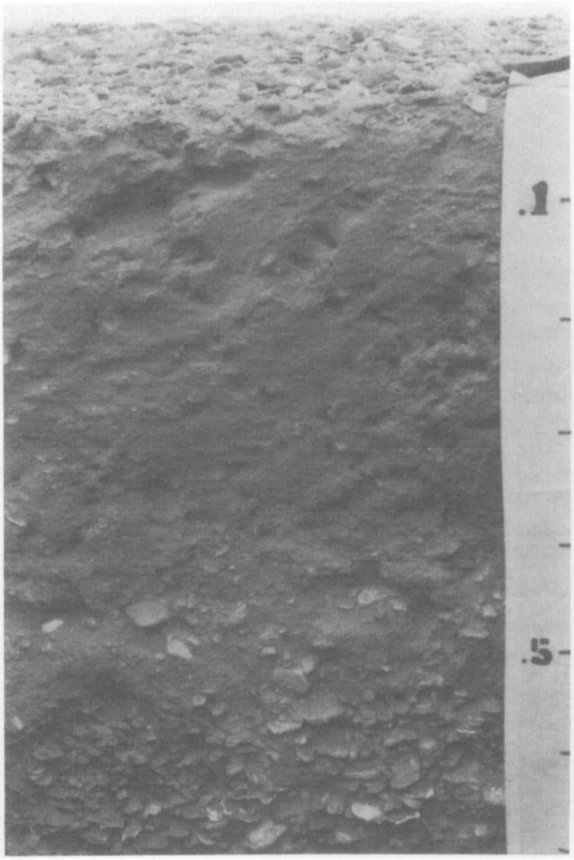

Photo 1: *Soil exposed in pit excavated on BR3, with moderately developed stone pavement, weakly developed, thin vesicular A horizon and textural B horizon. Note the rapid increase in gravel content below a depth of 45 cm. Fragments of pelecypod shells, which yielded a date of 10,330±120 yrs B.P., are visible at a depth if 65 cm. Photograph by B. Harrison.*

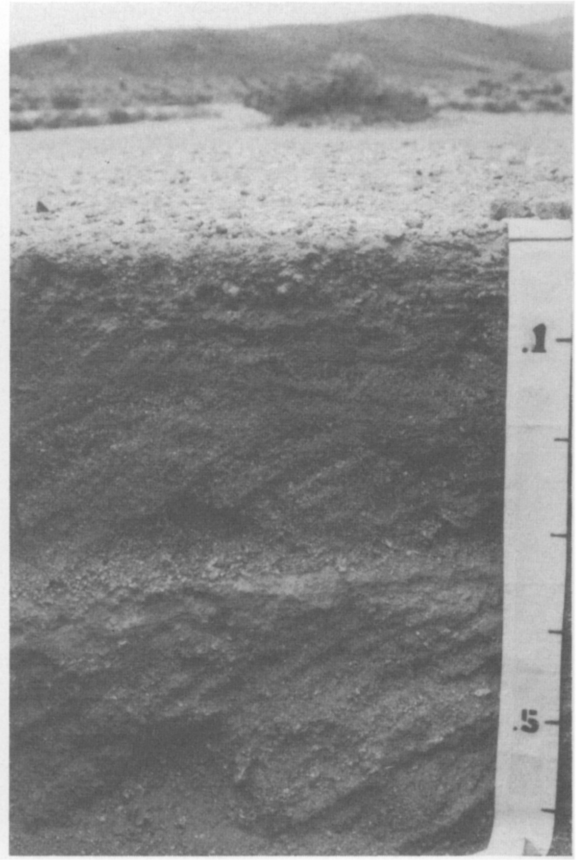

Photo 2: *Very weakly developed surface and buried soil exposed in pit excavated in gravelly sand of BR4 in the northern areas of Silver Lake playa. Note weakly developed pavement, and thin, color-B horizon. Top of buried soil occurs at a depth of 13 cm. Photograph by B. Harrison.*

and tufa materials reported in previous studies (Ore & Warren 1971, Wells et al. 1987). Radiocarbon ages from organic materials in lacustrine sediments exposed in cores of Silver Lake Playa and tufa-coated gravel also show that a lake stand associated with the B-Shoreline may have persisted until about 8,700 yrs B.P.

Deposits associated with BR4 and BR5 are finer grained than deposits of older beach ridges, and have a very weakly developed pavement composed of very weakly varnished clasts (photo 2). Lack of suitable materials precluded numerical-age dating of these deposits. Pelecypod shell fragments in deposits unconformably overlain by deposits of BR5 yielded an age of 9390±140 yrs B.P. (Beta - 29552), demonstrating that these deposits are associated with older, higher beach ridges. Beach ridges BR4 and BR5 are topographically higher than the faint shoreline features associated with historic flood events described by Wells et al. (1987, 1989).

4.2 Morphology, texture, and chemical properties of the soils

The soils developed on BR1, BR2, and BR3 exhibit relatively similar morphological and textural characteristics (tab. 1 and 2). This similarity is shown by values of the PDI for these soils, which range from 4.1 to 9.6. These soils have a vesicular A (Av) horizon ranging in thickness from 1 to 4 cm thick that occurs beneath the stone pavement. In most respects, the Av horizon resembles Av horizons described in other studies of soils in the Mojave Desert (McFadden 1982, 1988, McFadden et al. 1986, Wells et al 1987), although it is typically thinner than and does not have 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 (tab. 1). Where present, translocated clay occurs as thin bridges and as grain coats. 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 it cannot be considered to be an eluvial horizon (see also Peterson 1980, McFadden et al. 1986). Accordingly, the increase in clay content in the Bt horizon relative to that in the parent material is used to recognize the argillic horizon.

A significant amount of pedogenic carbonate and some soluble salts have accumulated in the profile, reflecting conditions of minimal leaching in the hot, arid climate of the lower Mojave Desert (tab. 2). Pedogenic carbonate has accumulated as thin, discontinuous coatings that occur primarily on the bottom sides of gravel (stage I morphology of Gile et al. 1966). Pedogenic carbonate is also present as disseminated carbonate. Segregated pedogenic carbonate is not observed in parts of the Bt horizon and this horizon is the zone of minimum carbonate accumulation (tab. 2). Minimal leaching also has promoted accumulation of small amounts of soluble salts and gypsum (tab. 1 and 2); the latter is observed as acicular crystals primarily located below the largest gravel clasts. Textural data suggest that salts and gypsum preferentially accumulate in clay and silt enriched parts of the soils, below the most clay enriched horizons of the profile.

pH is the lowest in the Av horizon and tends to increase slightly with depth (tab. 2). No correlation of pH with carbonate, gypsum, or soluble salt content is obvious. As was the case with carbonate, Fed content is highest in the Av horizon and decreases slightly in the Bw or Bt horizon (tab. 2). In contrast to carbonate, Fed content decreases significantly in the lower Bk horizons. Feo content does not change significantly with depth, although a very small increase in Feo content is observed in the Bw horizon of BR2 and the Av horizon of BR1.

Profile Horizon	Thickness (cm)	Color[1] Dry;Wet	Texture % G	Structure	Consistence Wet	$CaCO_3$ stage, effer., occurrence	Clay Films	Salts	Comments
NMSIL-1 (Beach Ridge 1)									
Av	0–4	10YR7/4.5; 5/4	10	p1	ss, po	es,d	lnpf	n.o.	
Bw	4–27	10YR7/4.5; 5/4.5	10	m; 2sbk	so, po	n.o.	n.o.	n.o.	
Bk	27–42	10YR7/4.5; 5/4	30	m	so, po	II;ev,d	n.o.	n.o.	
2Bk	42–84+	10YR7/3.5; 5/3	60	m	so, po	I;es,d	n.o.	n.o.	
NMSIL-2 (Beach Ridge 2)									
A	0–0.3								
Av	0.3–4	top: 10YR7/3; 5/3[2]	05	3vcpl&pr	s, p	I;e,d	4np&co	n.o.	
		bt: 7.5YR7/4; 5/3[3]	<5						
Bt	4–7	7.5YR7/4; 5/4	<5	2f&msbk	vss, po	I;e,d	br&co	n.o.	
Bwk	7–12	8.75YR74; 10YR5/4	<5	m	so, po	I;e,d	n.o.	n.o.	
Bt/Bk	12–34	10YR7/4; 5/4	<	m	so, po	e,d	n.o.	n.o.	
(Bt)		7.5YR6/4; 8.75YR5/4		m	ss, vps	e,d	br&co	n.o.	
Bky	34–60	10YR7/4; 5/4	<5	m	so, po	I;e,d	n.o.	vf Xtals	
Bk1	60–83	10YR7/4; 5/6	15	m	so, po	I-;e,d	n.o.	n.o.	
Bk2	83–90+	10YR73; 5/4	45	sg	so, po	I;e,d	n.o.	n.o.	
NMSIL-3 (Beach Ridge 3)									
Av	0–2	top: 10YR7/3; 5/3	<5	lcpl	ss, p	top: e,d	n.o.	n.o.	
		bt: 7.5YR7/4; 10YR5/4				bt: ev,d			
Bt1	2–10	7.5YR7/4; 10YR5/4	10	lm&csbk	so, po	e,d	vlnbr	n.o.	
Btk2	10–27	10YR7/4; 4/4	15	1–2f&msbk	ss, ps	es,d	vlnbr&co	n.o.	
2Bky1	27–50	10YR7/4; 5/4	35	lm&cgr	so, po	I;es,d	n.o.	Xtals on bot	
2Bky2	50–80+	10YR7/3; 5/4	50	sg	so, po	I;ev,d	n.o.	Xtals on bot	
NMSIL-4 (Beach Ridge 4)									
Av	0–3	10YR7/4; 5/4	5	2pl	ss, po	es,d	2npf	n.o.	
Bt	3–6	10YR7/4; 5/5	50	lsbk	so, po	es,d	2npf	n.o.	large root traces
By	6–13	10YR7/6; 6/6	30	m	so, po	e,d	n.o.	gyp	shells
Avb	13–16	10YR7/4; 7/6	20	2pl	ss, po	es,d	2kpf&br	n.o.	burrows
Btb	16–23	10YR7/4; 5/6	40	lsbk	ss, po	es,d	2nbr	n.o.	
Bkb1	23–40	10YR7/4; 6/6	10	m;sg	so, po	e,d	n.o.	gyp	shells
Bkb2	40–66+	10YR7/4; 5/3	20	m;sg	so, po	I;es,d	n.o.	n.o.	

Tab. 1: *Summary of selected morphological data for soils on beach ridges or shoreline features in the study area.*

Profile Horizon	Thickness (cm)	Color[1] Dry;Wet	Texture % G	Structure	Consistence Wet	$CaCO_3$ stage, effer., occurrence	Clay Films	Salts	Comments
NMSIL-5 (Beach Ridge 5)									
Av	0–0.5	top: 10YR7/4; 5/4 bt: 7.5YR7/4; 5.4	20	lnpl	ss, po	ev,d	vinco	n.o.	
Bw/Bt	0.5–9	7.5YR7/4; 5/6	50	lfsbk	so, po	es,d	lnbr	n.o.	banded Bt layer
By	9–15	7.5YR7/4; 5.4	30	sg	so, po	es,d	n.o.	gyp	
Cu	15–60+	10YR7/4; 5/4	30	sg	so, po	es,d	n.o.	n.o.	
NMSIL-6 (Shoreline A, South Silver Lake Playa)									
Av	0–2.5	10YR6/3; 43	1	2c&vcpl	p, s	ev,d	lnbr&co	n.o.	
Btk1	2.5–9	10YR7/3; 4/3	20	2f&msbk	so, po	ev,d	lnbr	n.o.	
Btk2	9–19	7.5YR7/4; 5/4	15	1-2f&csbk	so, po	I-;ev,d	lnpo	n.o.	
Bky1	19–36	10YR5/3; 4/3	15	lm&cgr	so, po	I;ev,d	n.o.	gyp	
2Bky2	36–55	10YR5/3; 4/3	25	lmgr	so, po	II;ev,d	n.o.	gyp	
Cox	35+	10YR6/3; 5/3	—	sg	so, po	I;ev,d	n.o.	n.o.	
NMSIL-7 (Shoreline B, South Silver Lake Playa)									
Av	0–6	10YR7/3; 5/3	10	3vcpl	ss, ps	se,d	n.o.	n.o.	
Btk	6–17	10YR6/4; 5/4	20	2f-fgr	ss, ps s, p	se,d	vlnbr	n.o.	
2Bky1	17–24	10YR6/4; 5/3	60	1f&msbk	ss, po	se,d	n.o.	gyp	soft nods; grain coats
2Bky2	24–35	10YR6/4; 5/3	60	1fgr;1bsbk	ss, po	se,d	n.o.	gyp	nod
2Bky3	35–40	10YR7/3; 5/3	70	1f&msbk 1f&mgr	ss, po	I;se,d	n.o.		nods; clast bot
2Bky4	40–58	10YR7/4; 5/3	80	sg	ss, po	I;se,d	n.o.	gyp	on clast bots
2Bky5	58–90+	10YR6/4; 5/3		sg	ss, po	II;ev,d	n.o.		grain coats

Tab. 1: *Summary of selected morphological data for soils on beach ridges or shoreline features in the study area. (Continuation)*

Profile Horizon	Thickness (cm)	Color[1] Dry;Wet	Texture % G	Structure	Consistence Wet	$CaCO_3$ stage, effer., occurrence	Clay Films	Salts	Comments
NMSIL-8 (Beach Ridge 1)									
Av	0–1	top: 10YR7/3; 5/4 bt: 10YR6/6; 4/4	2	3mpl	s, p	es,d	4npo	n.o.	
Btk	1–10	7.5YR6/5; 4/4	5	2msbk	ss, po	e-es,d	1nco&films	n.o.	
Bk	10–30	7.5YR6/5; 4/6	5	m	vss, po	I,es,d	1nco	n.o.	lenses of carbonate
Bk2	30–47	8.75YR7/4; 5/5	10	m	so, po	ev,d	n.o.	n.o.	
Bk3	45–75	10YR6/4; 5/4	20	m	so, po	I;es,d	n.o.	n.o.	
Bk4	75–110	10YR6/4; 4/4	25	m	so, po	I+;ev,d	n.o.	n.o.	
Bk5	110–120+	10YR7/3; 7/5	50	sg	sokpo	I;e,d	n.o.	n.o.	
NMSIL-1 (Shoreline A, Soda Lake Playa)									
Av	0–2	10YR7/3; 4/3 ped: 7.5YR6/4; 4/6	<5	3mpl&pr	s, p	I;se,d	4npo	n.o.	
Btk	2–25	7.5YR4/4; 5/4 5YR6.25/4 ped: 7.5YR4/4; 5/4	30	2msbk	ss, ps	I;e,d	1nbr&co	no.	cracks with fine sand tonges mottled
Bkyx1	25–45	10YR7/4; 4/3	65	1f&mgr	so, po	I;se,d	n.o.	bitter taste and salt splitting	
Bkxy2	45–73	10YR6/3.5; 4/4	50	sg	so, po	I;e,d	n.o.	salt splitting	
Bky	73–85+	10YR5.5/3; 4.3	60	sg	so, po	I;e,d	n.o.	gyp	coats clast
NMSOL-2 (Shoreline B, Soda Lake Playa)									
Avk	0–2	10YR7/3; 4/3	60	lcgr	ss, ps	I;e,d	n.o.	n.o.	
A/Bky	2–4.5 4.5–34+	7.5YR7/4; 4/4	60	m	so, ps	e,d	n.o.	gyp coat gyp Xtals	
NMSOL-3 (Shoreline A, Soda Lake Playa)									
Av	0–2.5	7.5YR7/4; 4/6	10	2cpl	s, p	ev,d	vlnpo&co	n.o.	
Btk1	2.5–8	7.5YR7/4;5/6	30	1f&csbk	ss, ps	es,d	vinpo	n.o.	
Btk2	8–24	10YR7/4; 5/4	25	1-2f&msbk	ss, ps	I;se-ev,d	vinpo	n.o.	
Bk1	23–38	10YR6.5/3.5; 5/4	40	1f&csbk	ss, po	I;se,d	n.o.	n.o.	
Bk2	38–50	10YR7/3; 5/3.5	25	1f-vcgr;sg	so, po	I;ev,d	n.o.	n.o.	
Cox	50–75+	10YR5/3; 6/2	50	sg	so, po	se,d	n.o.	n.o.	

[1] Colors are determined using the Munsell Soil color Chart.
[2] top: refers to the top of a soil ped
[3] bt: refers to the underside of the ped

Tab. 1: *Summary of selected morphological data for soils on beach ridges or shoreline features in the study area. (Continuation)*

Soils on the highest group of beach ridges and other beach ridges that occur at a similar elevation elsewhere along Silver Lake and Soda Lake playas (fig. 2) have soils with characteristics that resemble those of soils on BR1, BR2, and BR3. However, these soils contain considerably larger amounts of soluble salts, and the Av horizons have higher contents of clay and silt.

The soils on BR4 and BR5 are more weakly developed than those on the upper three beach ridges and have developed almost entirely in gravelly sand or sandy gravel (tab. 1 and 2, see photos 1 and 2). Also, BR4 has a soil formed in a thin deposit that overlies a buried soil. The soil in the upper deposit (PDI = 1.8) and the buried soil (PDI = 2.0) and the soil of BR5 (PDI = 2.0) are all similarly developed. These 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 horizons. Pedogenic carbonate occurs as thin, discontinuous coatings on the bottoms of clasts (weak stage 1) in the lowest horizon of the buried soil of BR4, but laboratory analysis indicates that a small amount of disseminated carbonate has accumulated only in the Av and Bw horizons. Laboratory analysis indicates that soluble salts and gypsum are present only in trace amounts in these soils, although a few gpysum crystals were observed in a few horizons. 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.

5 Discussion

5.1 Genesis of soils on latest Pleistocene and earliest Holocene beach ridges

Textural data for the uppermost 50 to 75 cm of the soil profiles associated with BR1, 2 and 3 indicate a depositional environment quite different from that of the high energy well sorted, cross-bedded gravelly shoreline deposits that are observed below a depth of 1 to 1.5 m. Topographic position of the beach ridges precludes a fluvial source for the uppermost sandy deposits and favors an eolian origin. The probable sources of the sand are sandy littoral and deltaic deposits exposed subsequent to dessication of pluvial Lake Mojave (Wells et al. 1987), and sandy deposits of distal fans and washes.

The lack of buried soils within the sandy deposits and the overall similarity of the soils on the upper beach ridges indicate that the accumulation of the sand occurred during a single episode. This interpretation is consistent with soil stratigraphic relations observed elsewhere in the Silver Lake area and in the Cima volcanic field, which also show evidence for a period of eolian activity during the middle or early Holocene (Wells et al 1985, 1987, 1989, Brown 1989, McFadden et al. 1986).

On the basis of the minimum ages for BR1 discussed above, it must have been abandoned and, therefore, may have been subjected to soil development for at about 3000 to 4000 years prior to deposition of the eolian mantle. The absence of an obviously buried soil implies

1. erosion and removal of a previously existing soil,

2. that the rate of soil development

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	3.9	6.4	ND[1]	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[2]	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

Tab. 2: *Summary of textural, chemical, and mineralogical data for selected soils in the study area.*

prior to burial by eolian sand was quite slow, or

3. that the eolian mantle was emplaced at least partly after BR1 and 2 were abandoned but before BR3 was established, thus decreasing the duration of the hiatus.

The lack of geomorphic evidence for significant erosion of the well preserved beach ridge landforms and soil-stratigraphic data indicate deposition of the sandy mantle as a single event, demonstrating that hypothesis 2 is most reasonable.

The low rate of soil development can be explained by two factors:

1. The open framework character of the gravels and the low water-

Horizon	Depth (cm)	Particle Size % Sand	% Silt	% Clay	Wt. % $CaCO_3$	% Sol. Salts	% Gypsum	pH ($CaCl_2$)
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
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	23.9	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

[1] ND = not detected
[2] TR = trace quantities detected

Tab. 2: *Summary of textural, chemical, and mineralogical data for selected soils in the study area. (Continuation)*

holding capacity promotes rapid infiltration of water and is conducive for translocation of silt, clay, carbonate, gypsum, and salts to depths of a meter or more. This process drastically decreases the rate of development of textural B and Av horizons, and results in coatings of carbonate on gravel clasts at depths of a meter or more.

2. A low dust influx rate, which would limit the rate of development of soils in the currently arid, hot environment, minimizes the magnitude of chemical alteration (McFadden et al. 1988, Reheis et al. 1989). A low rate of eolian dust influx in the latest Pleistocene and earliest Holocene occurred prior to dessication of pluvial Lake Mojave.

Birkeland (1984) points out that the strong influence of eolian dust influx on soil development in deserts has been documented in a large number of studies. Here, the nearby playa of Silver Lake provides an obvious source of much of the silt, clay and salts, as demonstrated by analysis of cores of Silver Lake Playa (Brown 1989) and suggested in previous studies (Peterson 1980). Depth functions for Fed also suggest an eolian origin for much of the accumulated Fe oxides, although the slight reddening in Bw or Bt horizons shows that at least some of these observed increases reflect formation of authigenic Fe oxides (McFadden 1982, McFadden & Weldon 1987). Studies of soils formed on piedmont deposits of the Soda Mountains also demonstrate the role of eolian dust on soil profile morphology (Reheis et al. 1989, McFadden et al. 1990), mineralogy and chemistry (McFadden, unpublished data).

Studies by Wells et al. (1987), McFadden et al. (1986, 1988), and Chadwick & Davis (1990) show that the rate and magnitude of eolian activity have varied considerably during the Pleistocene and Holocene in the Mojave Desert and the Great Basin. These studies indicate that the most recent major eolian event occurred during the must recent glacial-to-interglacial transition, probably triggered by increase in aridity, decreases in vegetation, and increases in source areas with sediment readily available for wind entrainment (e.g., playas) and transport. A major implication of this hypothesis is that glacial periods may have been characterized by comparatively slow development of noncumulate soils on relatively stable geomorphic surfaces (McFadden et al. 1986, 1989, McFadden 1988).

Soil development rates in beach ridge gravels may be low, however, even with relatively high eolian activity. For example early to middle Holocene soils in sandy deposits of the oldest beach ridges and soils associated fluvial sandy gravels on the piedmont of the Soda Mountains show significant cambic B or even argillic B horizon development (Wells et al. 1987, McFadden et al. 1989, McFadden 1988, Reheis 1989). In contrast, beach-ridge landforms present in other areas of the Mojave Desert do not exhibit such soils. Field observations of high energy, gravelly shoreline and beach ridge deposits of latest Pleistocene or early Holocene pluvial lakes associated with Owens dry lake, Searles dry lake, Panamint Valley, 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 (see Smith & Street-Perrot 1983, Smith 1975, Hooke 1972, Margraf et al. 1983, and Fleischhauer 1982) show that associated soils lack reddened, clay enriched Bt horizons. The relatively low rate of accumulation of silt, clay, and other soil materials during the Holocene is attributable to the ease of translocation of such materials through these gravelly deposits.

Notably, Chadwick & Davis (1990) report that well developed soils have formed on latest Pleistocene gravelly sandy shoreline deposits of Lake Lahonton. They attribute the development of these soils to very high rates of dust influx after the dessication of areally extensive pluvial Lake Lahontan. These soils, however, have formed in much finer parent materials than those soils which formed in the sand overlying BR1, 2, and 3.

Data for the soils on BR1, 2, and 3 demonstrate that the degree of profile development varies slightly, despite the presumably equal durations of soil development. The observed variability is attributed primarily to two major factors:

1. the position of the beach ridge relative to the major transport direction of suspended eolian material, and
2. the topographic form of the beach ridge.

Thus, beach ridges that are closer to the playa and that are topographically prominant receive more dust and act as more efficient dust traps, which accelerates soil development.

5.2 Genesis and estimated age of soils on Post-Early Holocene beach ridges

In contrast to the soils on BR1, 2, and 3, the soils developed on BR4 and BR5 have developed directly in the sandy gravelly beach ridge deposits, after deposition 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 show that most eolian dust has accumulated primarily in the upper part of the soil and was not translocated deeply below the surface. This latter process probably reflects the lower permeability of the parent materials, which have sedimentological characteristics associated with deposition in a lower energy environment favored by a shallower lake (Wells et al. 1989, Brown 1989). Also, the closer proximity of these beach ridges to the playa may favor accumulation of carbonate and salt-bearing dust from the nearby playa sources.

The degree of development of soils on the lower beach ridges most closely resembles that of soils formed in middle and late Holocene deposits of the Soda Mountains piedmont. For example, the soils of fan unit Qf3, which was deposited sometimes between 3400 and 8000 yrs B.P. (Wells et al. 1987), have a PDI that ranges from 5 to 15 (Reheis et al. 1989). Fan unit Qf4, deposited sometimes between 3400 yrs B.P. and 1000 (?) yrs B.P., have soils with a PDI that ranges from 4 to 14. Temporal correlation based on degree of soil development suggests that the soils on BR4 amd BR5 are no older than soils developed on fan unit Qf4. The topographically prominent gravel bars and swales of piedmont deposits, however, may favor greater rates of extrapment of eolian materials relative to the topographically smoother beach ridges. Consequently, rates of soil development may be faster on the piedmont compared to beach ridges.

Analysis of sediments from Pit M-1 excavated in Silver Lake Playa show that lakes have formed at least four times since dessication of pluvial Lake Mojave approximately 8,700 years ago (fig. 3) (Wells et al 1989, Brown 1989). The existence of the lakes is based on the presence of thinly laminated sediments, typically present as couplets of light gray-brown silty clay and brown silty clay, that have micropaleontologic evidence indicative of fresh water conditions (Wells et al. 1989, Brown 1990). These sediments are distinguished from sediments that reflect playa or wet-playa conditions that are not laminated and have abundant desiccation cracks. Organic materials extracted from two of the lacustrine materials yield radiocarbon ages of 3,620$\pm$90 and 390$\pm$90 yrs B.P. (Beta - 25341 and - 25634). If the observed lamination of the sediments reflects annual sedimentation, the lake stands responsible for these deposits may have persisted for up to several decades (Brown 1989).

Estimates of the ages of BR4 and BR5 from pedologic data are consistent with

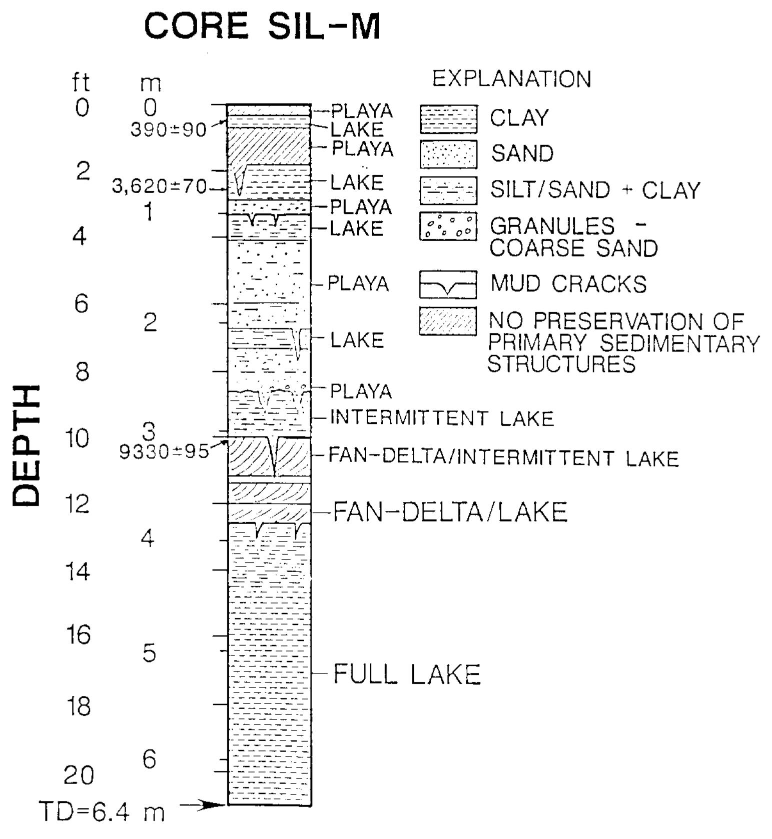

Fig. 3: *Generalized lithology and interpretation of depositional environments of sediment recoverd in a core from Silver Lake Playa.*

the lake core ages. Either BR4 or BR5 probably formed during the lake stand that occurred 3,600 years ago. Formation of BR5 during the most recent lake stand of 390 yrs B.P. cannot be ruled out, however, because even though BR5 exhibits greater soil development than is thought to be characteristic of deposits of such a young age, little independent age control exists for deposits of this age.

5.3 Formation of gravel pavements on the older beach ridges

Varnished pavements on the upper three beach ridges resemble pavements observed on late Pleistocene geomorphic surfaces on the Soda Mountains piedmont and on the surfaces of late Pleistocene volcanic flows of the nearby Cima volcanic field (see Wells et al. 1985, McFadden et al. 1986, 1987, 1989). Development of these pavements has been attributed partly to development of cumulic soils formed in silt and clay rich eolian materials that accumulate below an increasingly well sorted layer of gravel resistent to mechanical weathering which is derived from the pavement materials (McFadden et al. 1986, McFadden et al. 1987). Soil-stratigraphic relations observed in the beach ridge deposits, however, indicate that the process of initiation of pavement development may be different from that proposed for piedmont and volcanic flow surfaces, given the initially low gravel content of the sandy eolian deposits.

Initiation of the gravel pavement on the topographically isolated beach ridges may be caused by concentration of gravel due to removal of sand. Perhaps deflation, which may have occurred when diminished sand supply, coupled with occasionally very strong winds associated with a favorable located wind gap, causes sand entrainment and transport. Given the estimated 10 to 20 percent gravel content of these deposits, deflation of approximately 50 to 100 cm of sand would be required to form a lag pavement. Development of the pavement would presumably preclude additional significant deflation.

Alternatively, the pavement may have formed by mechanical infiltration of eolian sand into the gravelly beach ridge deposit. The accumulation of these materials would significantly reduce porosity, perhaps favouring subsequent accretion of sand below the gravel. In either case, as sand supply diminished, slow entrapment of finer eolian materials would cause development of the vesicular A horizon. The thin, weakly developed Av horizon in beach ridge soils probably reflects the topographically smooth form of the sand mantled beach ridges. This contrasts with the rougher topography of volcanic flow surfaces and the bar-and-swale form of bouldery piedmont deposits, which favors formation of well developed, thick Av horizons.

6 Conclusions

Studies of beach ridges of pluvial Lake Mojave show that soils have formed in an eolian blanket deposited on the oldest beach ridges after dessication of the lake approximately 8,700 years ago. The pedologic characteristics of these soils directly reflects geomorphic processes that have resulted in rapid pavement development and entrapment of dust that is probably derived primarily from Silver Lake playa. The lack of buried soils in the underlying gravels is attributed to their highly permeable nature, which is inferred to promote deep translocation of eolian fines and solutes and/or greatly limited eolian dust influx during the time these gravels were subaerially exposed. The presence of relatively weakly developed soils in gravelly beach ridge deposits associated with other pluvial lakes in desert regions, therefore, may not be necessarily indicative of the occurrence of relatively recent, Holocene lakestands, but might reflect instead geomorphic circumstances that have limited eolian activity and minimized formation of textural B and Av horizons.

Weakly developed soils on the younger beach ridges have formed directly in less permeable beach ridge deposits, which has favored shallow accumulation of playa-derived constituents in dust. The ages of the younger beach ridges and the associated lakestands are estimated to range from less than 1000 yrs B.P. to 6000 yrs B.P. Deposition of eolian sand on the older beach ridges, therefore, would have occurred sometimes between 8700 and 6000 years ago. Deposition of eolian unit Qe2, a unit in the Silver Lake area that overlies late Pleistocene to early Holocene piedmont deposits (Wells et al. 1987), and deposition of much of the youngest desert loess on volcanic flow surfaces in the Cima volcanic field also probably occurred at this time (Wells et al. 1985, McFadden et al. 1986).

The proximity of pluvial lakes and behavior of these lakes in response to changes in climate strongly influences eolian activity, which has, in turn, affected rates and processes of development of soils on lacustrine landforms. Chadwick & Davis (1990) have also observed this linkage of climate and pedogenesis in studies of soils of shoreline landforms associated with Pluvial Lake Lahontan. They conclude, as did McFadden et al. (1986), that rapid cumulic soil development during the Quaternary is pulsatory, reflecting periods of aridity, playa development, and increased eolian activity. Chadwick & Davis further suggested that soil-forming intervals recognized by Morrison (1967, 1978), which were attributed to enhanced soil development in warm, wet interglacial periods, instead reflect episodic times of enhanced eolian activity. In many respects, these studies confirm the hypothesis of pulsatory eolian activity and carbonate accumulation proposed by Machette (1985).

The presence of middle-to-late Holocene lake stands indicated by this and other studies in this region is consistent with other, independent evidence for lake stands and climatic changes during this time in the Mojave Desert and adjacent regions. Studies of the piedmont deposits of the Soda Mountains and the Salt Srpings Hills, 20 km north of the study area, also suggest deposition of climatically controlled fan deposits during this time (Ritter 1988). Wells & Dorenwend (1985) and Wells et al. (1987) also suggested that a large flood event(s), perhaps caused by climatic change sometime during the early-to-middle Holocene, resulted in formation of relict sheetflood bedforms observed on the latest Pleistocene fan surfaces of the Soda Mountains piedmont and elsewhere in the southwestern United States. These climatic changes are temporally equivalent with Neoglacial advances of glaciers recognized in the Sierra Nevada in southern California and other lofty ranges of the Rocky Mountains. Recent studies of Enzel (Enzel et al. 1989, Enzel 1990) indicate that historical ephemeral lake stands in Silver Lake and the associated climatic conditions that produced these lakes may serve as analogs for the climatic conditions that produced the older Holocene lakes and, perhaps, the late Pleistocene lakes in the study area as well as other arid basins of the Great Basin.

This study illustrates the usefulness of soil-stratigraphic analysis in research concerning the evolution of pluvial Lake Mojave and late Quaternary climate change. Primarily on the basis of the age estimates obtained through these soil studies, a detailed search for evidence of Holocene lake stands in the stratigraphic record was subsequently initiated. This later study corroborated the soil-geomorphic and soil-stratigraphic evidence for the Holocene lakes, thereby providing an excellent example of how a multi-disciplinary research effort can benefit research in Quaternary paleoenvironmental studies.

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