Geological Society of America
Special Paper 368
2003

Regional response of alluvial fans to the Pleistocene-Holocene climatic transition, Mojave Desert, California

Eric V. McDonald
Division of Earth and Ecosystem Science, Desert Research Institute, 2215 Raggio Parkway, Reno, Nevada, 89512, USA

Leslie D. McFadden
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico, 87131, USA

Stephen G. Wells
Desert Research Institute, 2215 Raggio Parkway, Reno, Nevada, 89512, USA

ABSTRACT

Alluvial fan deposits along the Providence Mountains piedmont in the eastern Mojave Desert that (1) are derived from diverse rock types, (2) are dated with luminescence techniques and soil-stratigraphic correlations to other relatively well dated fan, eolian, and lacustrine deposits, and (3) have some of the highest peaks in the Mojave Desert, provide a unique opportunity to study the influence of Pleistocene-Holocene climatic transition on regional fan deposition across diverse geomorphic settings. Geomorphic and age relations among alluvial and eolian units along the Providence Mountains and Soda Mountains piedmonts indicate that most of the late Quaternary eolian and alluvial fan units were deposited during similar time intervals and represent region-wide changes in geomorphic factors controlling sediment supply, storage, and transport.

Deposition of alluvial fans in the desert southwestern United States during the latest Pleistocene has been largely attributed to (1) a more humid climate and greater channel discharge and (2) time-transgressive changes in climate and an increase in sediment yield. Stratigraphic and age relations among depositional units demonstrate that a regional period of major alluvial fan deposition occurred between ca. 9.4 and 14 ka, corresponding with the timing of the Pleistocene-Holocene climatic transition. This age range indicates that deposition of these fans is not simply a result of greater effective moisture and channel discharge during the last glacial maximum. Increases in sediment yield during the Pleistocene-Holocene transition have been largely attributed to a time-transgressive decrease in vegetative cover with an increase in hillslope erosion. Geomorphic relations along the Providence Mountains, however, suggest that that changes in vegetation cover during the Pleistocene-Holocene climatic transition may have had a limited impact on hillslope instability and sediment yield because of (1) the inherently high infiltration capacity of coarse-textured soils and colluvium, (2) possible strong spatial variations in soil cover across hillslopes, and (3) modern vegetation cover appears to provide enough stability for the buildup of soils and colluvium. An increase in sediment yield may instead be largely due to an increase in extreme storm events, possibly an increase in tropical cyclones. Extreme storms would provide the rainfall intensity and duration to mobilize permeable sediments from mountain catchments and into distal fan areas.

McDonald, E.V. McFadden, L.D. and Wells, S.G., 2003, Regional response of alluvial fans to the Pleistocene-Holocene climatic transition, Mojave Desert, California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and paleohydrology of the Mojave and southern Great Basin Deserts: Boulder, Colorado, Geological Society of America Special Paper 368, p. 189–205.

INTRODUCTION

The impact of Pleistocene-Holocene climate change on major periods of alluvial fan deposition on desert piedmonts in the southwestern United States has been the focus of many investigations. Two general models describing the linkage between climate change and a major cycle of alluvial fan deposition have evolved from these studies. One model suggests that the formation of alluvial fans occurred largely during the latest Pleistocene when climatic conditions were more humid than at present (Melton, 1965; Lustig, 1965; Ponti, 1985; Christenson and Purcell, 1985; Dorn et al., 1987). This model indicates that a more humid climate led to greater stream discharge and hence an increase in sediment transport resulting in fan deposition. A second model suggests that a cycle of fan aggradation occurred largely as a sequence of geomorphic responses to time-transgressive changes in climate and vegetation during the Pleistocene-Holocene transition (Bull and Schick, 1979; Wells et al., 1987, 1990; Bull, 1991; Harvey and Wells, 1994; Harvey et al., 1999). According to this model, a cycle of fan deposition was triggered by a transition from a wetter to a relatively drier climate when a reduction in effective soil moisture resulted in a loss of vegetative cover on hillslopes that, in turn, resulted in an increase in sediment supply and surface runoff from increasingly barren slopes.

Determining temporal linkages between fluctuations in climate and alluvial fan deposition has been a challenging and controversial problem for a variety of reasons. First, there are few well-dated deposits that can be temporally linked to detailed records of climate change because of the difficulty in dating alluvial fan deposits. This is complicated further by a significant variation in the precision of different methods used in determining relative and numerical ages of alluvial stratigraphic units. The most successful linking of climatic change to alluvial fan deposition have been studies of mountain piedmonts that border pluvial lake basins containing dated lacustrine deposits and shoreline features (Wells et al., 1987; Harvey and Wells, 1994; Reheis et al., 1996; Harvey et al., 1999). Results of these studies have demonstrated that a pronounced period of alluvial fan aggradation in the Mojave Desert is linked to a period of climatic change associated with the Pleistocene-Holocene transition.

A second fundamental problem is determining if the control of geomorphic factors is secondary to the control of climate change in triggering periods of alluvial fan deposition across a region. Factors such as tectonic stability, mountain height, and the size and lithology of the drainage basin may exert a strong influence on alluvial depositional processes (Bull, 1991) and, in turn, the possible timing of fan deposition. If the timing of alluvial fan deposition is strongly dominated by some aspect of climate change, then the temporal relations between fan deposition and variations in climate should occur largely in a similar fashion across a region and across diverse geomorphic settings. Regional evaluation of fan deposition has been difficult because of a lack of adequate regional stratigraphic correlations (reinforced by adequate age control) among fan deposits across diverse geomorphic settings.

The Quaternary piedmont deposits in the Mojave Desert of California (Fig. 1) provide a unique setting in which to examine the timing of late Quaternary climate fluctuations on alluvial fan stratigraphy across diverse geomorphic settings. Stratigraphic and geomorphic relations among alluvial fan, lacustrine, and eolian deposits on the Soda Mountains piedmont (hereafter SMP) along the western margin of the Silver Lake playa (hereafter Silver Lake) in the Mojave Desert provide a well-documented record of late Pleistocene and Holocene climatic change and periods of eolian and alluvial fan deposition (Wells et al., 1987, 1989, this volume; Enzel et al., 1989, 1992; Harvey and Wells, 1994; Harvey et al., 1999). Quaternary alluvial and eolian deposits along the western margin of the Providence Mountains piedmont (hereafter PMP) provide a different geomorphic setting with which to examine the influence of climate change on alluvial fan deposition. First, the diverse rock types of the Providence Mountains (Miller et al., 1985), ranging from coarse-grained plutonic to microcrystalline carbonates, have created four lithologically dissimilar fan chronosequences that are juxtaposed along the mountain front. Second, the drainage basins in the Providence Mountains are considerably largely and at a higher elevation than those of the Soda Mountains (Fig. 2). Soil-stratigraphic correlations between soils formed in alluvial fan deposits on each piedmont, supplemented with numerical age estimations for alluvial and eolian units from the Providence Mountain fans, provide a (1) regional stratigraphic framework of late Quaternary alluvial fan and eolian deposits and (2) adequate age control for examining the impact of changes in climate on fan deposition across diverse geomorphic settings.

The purpose of this paper is to examine the relative influences of Pleistocene-Holocene climate change and diverse geomorphic settings on the timing and mechanisms of alluvial fan deposition. Specifically, this paper (1) presents the late Quaternary stratigraphy and geochronology common to the Providence Mountains piedmont and Soda Mountains piedmont, (2) demonstrates consistency in the timing of key eolian and alluvial depositional events across the east Mojave Desert, and (3) evaluates the role of related changes in climate, vegetation, and geomorphic response associated with alluvial fan deposition during the Pleistocene-Holocene transition.

Geomorphic setting

The Providence Mountains. The Providence Mountains are a prominent feature along the eastern edge of the Mojave Desert (Fig. 1). Elevations range from ~600 m in distal fan areas to >2000 m at the mountain tops (Fig. 2). Fan deposits along the western margin of the Providence Mountains grade to an extensive area of sand sheets associated with the Kelso Dunes. The modern climate of the Providence Mountains is typical of the Mojave Desert with annual rainfall ranging from ~150 mm annually along the alluvial fans to ~250 mm annually at the mountain tops based on regional relations between recorded annual precipitation and elevation (Fig. 3). Most of the annual precipitation in

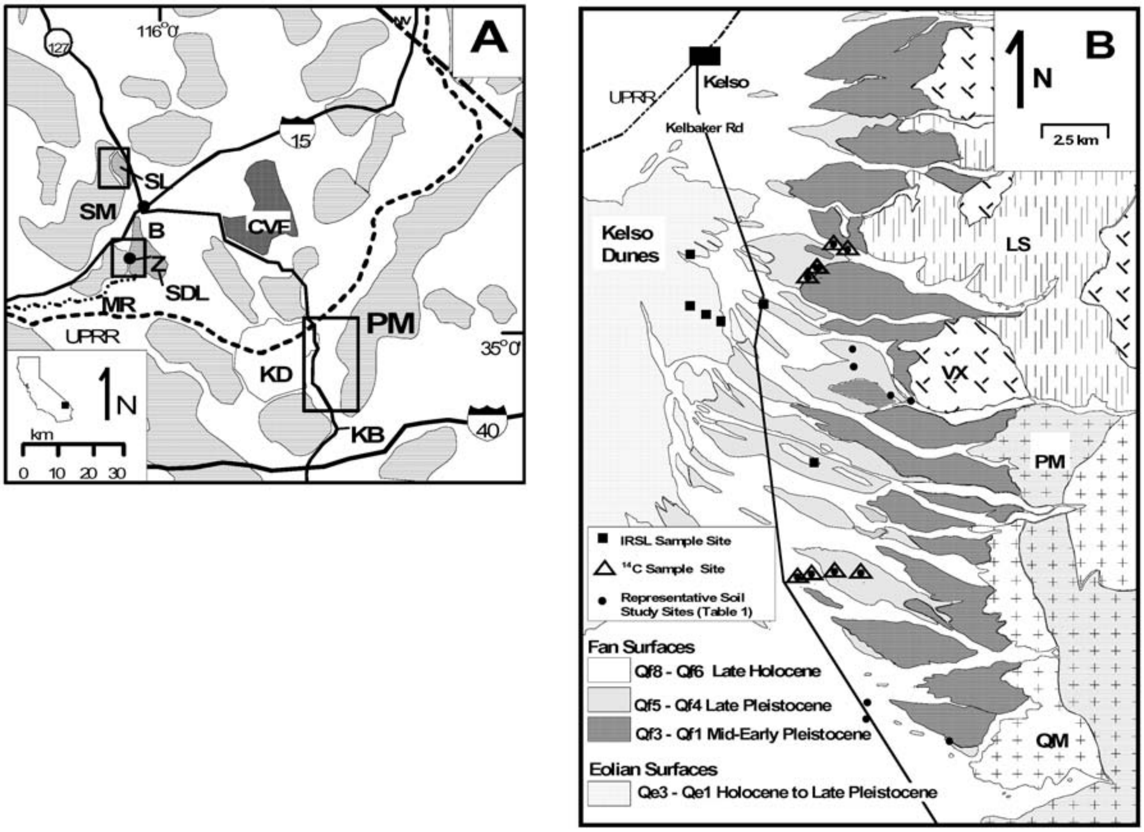

Figure 1. A: Location of study area (open box) along the Providence Mountains (PM) piedmont in relation to study areas along the Soda Mountains (SM) adjacent to the Silver Lake Playa (SL), specifically, Wells et al. (1987), and Harvey and Wells (1994) and Harvey et al. (1999). Other map abbreviations: MR—Mojave River (dash-dot-dot line), B—Baker, UPRR—Union Pacific Railroad (dashed line), CVF—Cima volcanic field, OD—Old Dad Mountain, KD—Kelso Dunes, and KB—the Kelbaker road. B: General distribution of Quaternary depositional units along the Providence Mountains piedmont, sample sites for ^{14}C and infrared stimulated luminescence (IRSL) age control, and locations of representative soil study sites (Table 1). Piedmont deposits further subdivided (dotted line) into sequences based upon the dominant rock types that make up the alluvium: PM—mixed-plutonic rocks, QM quartz monzonite; LS—limestone and marble, and VX—volcanic-mixed. NV—Nevada (long dash–short dash is Nevada-California state line), Z—Zzyzx, SDL—Soda Lake Playa.

the east Mojave Desert is associated with winter Pacific frontal storms. Modern vegetation along the fans is predominantly Mojave Desert Scrub dominated by *Larrea tridentata* (creosotebush) and *Ambrosia dumosa* (white bursage). The vegetation along the mountain hillslopes ranges from blackbrush (*Coleogyne ramosissima*) and Mojave yucca (*Yucca schidigera*) to juniper/pinyon woodland (predominantly on north-facing slopes).

Quaternary depositional units along the PMP were subdivided using relative degrees of development of soils and desert pavements and stratigraphic relations among depositional units (Table 1; Figs. 4, 5). Eight alluvial fan units (Qf1–Qf8, oldest to youngest) and three eolian sand units (Qe1–Qe3, oldest to youngest) have been recognized and are described in detail elsewhere (McDonald, 1994; McDonald and McFadden, 1994).

Late Quaternary alluvial fan units are also separated along the mountain front into four sequences based upon the dominant rock types that make up the alluvium: (1) PM—leucocratic to mesocratic mixed-plutonic rocks (syenite, syenogranite, monzodiorite); (2) QM—quartz monzonite; (3) LS—limestone, marble, and minor amounts of volcanic; and (4) VX—rhyolitic tuff and rhyodacite with lesser amounts of plutonic and limestone. Identification of rock types is based on the mapping of Miller et al. (1985). There is no evidence of tectonic activity along the mountain front during the late Quaternary.

The Soda Mountains. The Soda Mountains lie ~110 km to the northwest of the Providence Mountains (Fig. 1). Elevations range from ~270 m in distal fan areas to nearly 700 m at the mountain tops. Fan deposits along the eastern margin of the Soda Mountains grade to the western margins of the Silver Lake playa and Soda Lake playa basins. These two playas are the remnant of Pleistocene pluvial Lake Mojave. Modern annual rainfall ranges from ~60 mm along the alluvial fans to ~100 mm (estimated) at the mountain tops (Fig. 3). Modern vegetation along the fans and mountain ridges is predominantly Mojave Desert Scrub including

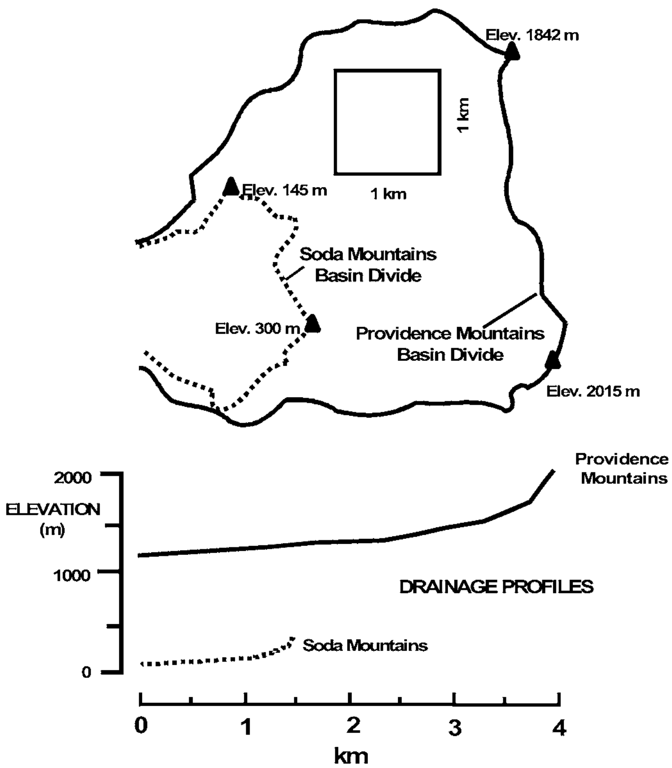

Figure 2. Schematic diagram comparing typical areas and ephemeral stream profiles of drainage basins in the Soda Mountains and Providence Mountains. Elevations along basin perimeter represent two highest elevations along divide. Outline of Soda Mountains drainage basin has been rotated 180°. Drainage basin shown for the Providence Mountains is the headwaters for Winston Wash. The drainage basin shown for the Soda Mountains is the major source area of the alluvial fans studied by Wells et al. (1987).

creosotebush and bursage. Bedrock geology is predominantly metavolcanics and granitics.

Previous studies of the geomorphology and late Quaternary history of the Soda Mountains and pluvial Lake Mojave have focused predominantly along the western and northern margins of Silver Lake playa (Wells et al., 1987, 1989; McFadden et al., 1989; Enzel et al., 1992) and along the western boundary of Soda Lake playa near Zzyzx (Wells et al., 1990; Harvey and Wells, 1994; Harvey et al., 1999; Harvey and Wells, this volume). These studies established detailed chronologies of hillslope response as well as alluvial fan and eolian deposition by comparing the degree of soil formation, desert pavement development, and stratigraphic relations to well-dated pluvial lake shorelines. There is no evidence of tectonic activity along the mountain front during the late Quaternary.

Geochronology

Age control for alluvial and eolian deposits in the Providence Mountains is derived from (1) infrared stimulated luminescence (IRSL) ages of sands associated with alluvial and eolian deposits (Clarke, 1994; Edwards, 1993), (2) soil-stratigraphic correlations to SMP alluvial units using a soil development index (Harden, 1982), and (3) radiocarbon dating of pedogenic carbonate (Wang et al., 1996). All radiometric ages cited and preferred stratigraphic correlations between the Soda and Providence Mountains are shown in Figure 4.

Radiocarbon ages of pedogenic carbonates are reported as measured AMS ^{14}C dates and modeled ^{14}C ages (Fig. 4). Modeled ages are measured ^{14}C ages adjusted using a diffusion/reaction model that attempts to account for the various processes and factors controlling the ^{14}C content of soil carbonate (Amundson et al., 1994; Wang et al., 1994, 1996). This modeling approach was developed because measured ^{14}C ages may underestimate the age of a soil because of (1) a possible time lag between deposition and the onset of soil formation and (2) the time required to form a carbonate coating of adequate thickness for radiocarbon dating.

Unless otherwise noted, all radiocarbon ages cited in this paper are expressed as calibrated ages in order to compare them with the cited IRSL ages. Radiocarbon ages were calibrated using the CALIB v. 3.0 program of Stuiver and Reimer (1993).

Profile development index (PDI) values shown in Figure 4 and values from other studies cited in the text are calculated using methods in Harden (1982) and Harden and Taylor (1983) and all values (this study as well as cited studies) are based on profile maximum values listed in Taylor (1988).

LATEST QUATERNARY STRATIGRAPHY OF THE PROVIDENCE MOUNTAINS PIEDMONT

Holocene deposits

Alluvium of units Qf8 and Qf7 are inset into all other deposits or overlap these deposits, indicating that these are the youngest fan deposits along the piedmont. Unit Qf8 consists of sediments of the active wash and weakly vegetated bars and channels that lack soil development and desert pavements (Figs. 4, 5; Table 1). The next oldest deposit, unit Qf7, is generally within ~1 m of the active wash and is largely confined to narrow terraces along active channels. The unit Qf7 alluvium consists of moderately to poorly stratified sandy-pebble (grus) stream and sheetwash deposits (PM, QM sequences) to well-stratified pebble-gravel braided stream deposits (VX, LS sequences). Soils developed on unit Qf7 are characterized by a thin (0.5–1.0 cm) incipient Av horizon, a lack of B horizons, and weak stage I carbonate morphology (carbonate stage morphology after Gile et al., 1966; Table 1). Incipient pavements have formed in a few places on the VX and LS Qf7 deposits. Nearly all clasts on Qf7 surfaces are unweathered on the upper surfaces, but the undersides may be very weakly oxidized. The oldest radiocarbon dates on pedogenic carbonate range from 4980 cal. yr B.P. (4410 ± 110 ^{14}C yr B.P.) for PM sequence soils to 5900 cal. yr B.P. (5110 ± 60 ^{14}C yr B.P.) for LS sequence soils (Fig. 4). Modeled radiocarbon ages range from ca. 4 to 6 ka for the PM Qf7 soils

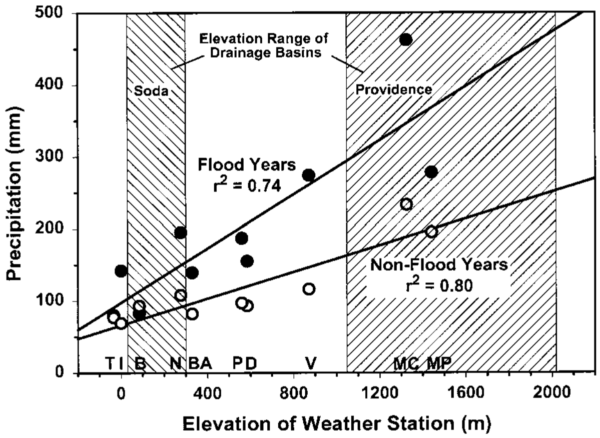

Figure 3. Regional trends in annual precipitation across southern California deserts based on precipitation records for 1948–1999. Flood years (filled circles, upper regression line) represents mean annual precipitation for years when flooding of the Silver Lake playa occurred (1969, 1978, 1980, 1983, 1992, 1998). Nonflood years represents mean annual precipitation for all nonflood years. Weather data from: T—Thermal, I—Indio, B—Blythe, N—Needles, BA—Baker, P—Twentynine Palms, D—Daggett, V—Victorville, MC—Mitchell Caverns, MP—Mountain Pass.

TABLE 1. TYPICAL SOIL CHARACTERISTICS OF THE FOUR FAN SEQUENCES

Fan Unit		Fan sequence			
		PM	QM	VX	LS
Qf8	Horizon:	No soil	No soil	No soil	No soil
Late Holocene	Texture:	Sand	Sand	Sand to loamy sand	Sand to loamy sand
(active wash)	Stage:	0	0	0	0
	Pavement:	None	None	None	None
Qf7	Horizon:	Avk-AC-Ck-C	Av-A-AC-Ck-C	Avk-ACk-Ck-C	Avk-ACk-Ck-C
Late Holocene	Texture:	Loamy sand	Loamy sand	Loamy sand	Sandy loam
	Stage:	I	I	I	I
	Pavement:	None	None	None to very weak	None to very weak
Qf6	Horizon:	Avk-Bwk-Ck-C	Av-A-Bw-Ck-C	Avk-Bwk-Bk-Ck-C	Avk-Bwk-Bk-Ck-C
Late Holocene	Texture:	Sandy loam	Loamy sand	Loamy sand	Sandy loam
	Stage:	I	I	I	I–II
	SB:	Cambic	Cambic	Cambic	Cambic
	Pavement:	Weak	Very weak to none	Weak to moderate	Weak to moderate
Qf5	Horizon:	Avk-Bwk-Btk-Ck-C	*Fan unit not found*	Avk-Bwk-Bk-Ck-C	Avk-Btvk-Bk-Ck-C
Early Holocene	Texture:	Sandy loam		Sandy loam	Loam
to latest	Stage:	I–II		I–II	II–III
Pleistocene	SB:	Cambic or argillic		Cambic/calcic	Calcic
	Pavement:	Moderate to weak		Moderate to strong	Moderate to strong
Qf4	Horizon:	Avk-Btk-Bk-Ck-C	Av-ABv-Bt-Bk-Ck-C	Avk-BAv-Bwk-Bkm-Ck-C	Avk-Btvk-Bwk-Bkm-Bk-Ck-C
Late	Texture:	Sandy clay loam	Clay loam	Sandy loam	Loam
Pleistocene	Stage:	III	I–II	III–IV	III+
	SB:	Argillic	Argillic	Petrocalcic	Petrocalcic
	Pavement:	Moderate to strong	Weak to moderate	Strong	Strong
Qf3	Horizon:	Avk-BAvk-Bt-Bkm-Ck-C	Av-BAv-Bt-BCk-Ck-C	Avk-BAv-Btk-Bk-Bkm-Bk-Ck-C	Avk-Btvk-Bwk-Bkm-Bk-Ck-C
Middle	Texture:	Clay loam	Loam	Sandy clay loam	Loam
Pleistocene	Stage:	III–IV	I	IV	IV
	SB:	Argillic/petrocalcic	Argillic	Argillic/petrocalcic	Petrocalcic
	Pavement:	Strong	Moderate to weak	Strong	Strong to very strong
Qf2	Horizon:	Avk-Btk-Bkm-Ck-C	Av-Bt-Btk-BCk-Ck-C	Avk-BAvk-Btk-Bk-Bkm-Ck-C	Avk-Bkm-Bk-Ck-C
Mid–early	Texture:	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy loam
Pleistocene	Stage:	IV	I	IV	IV–V
	SB:	Petrocalcic	Argillic	Argillic/petrocalcic	Petrocalcic
	Pavement:	Moderate to weak	Weak to moderate	Strong to moderate	Moderate to strong

Note: PM—mixed-plutonic; QM—quartz monzonite; VX—mixed-volcanic; LS—limestone. Age estimations of fan units in Table 2. Unit Qf1 not shown because unit is highly eroded. Horizon—typical soil horizon sequence; texture—finest texture of any B or AC horizon; stage—soil carbonate stage; SB—strongest diagnostic B horizon; pavement—general quality of desert pavement where either best developed or best preserved.

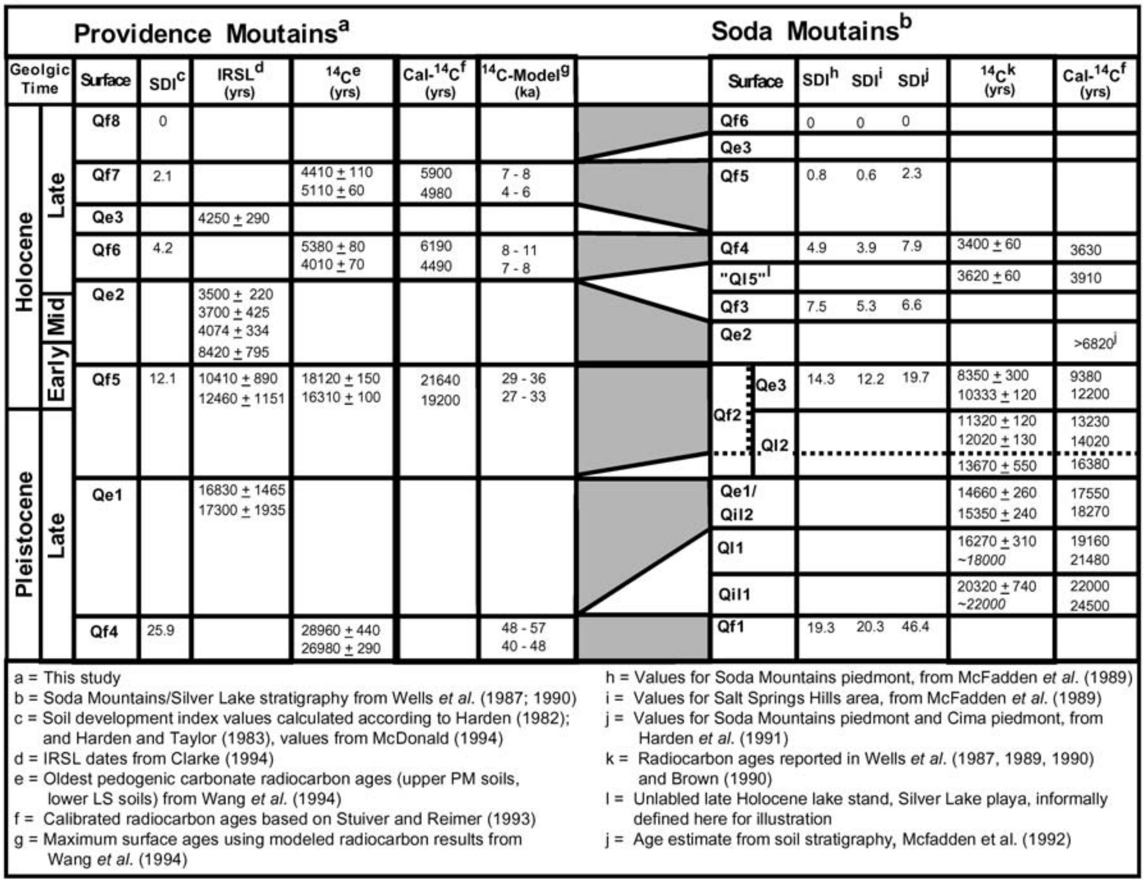

Figure 4. Regional correlations and age estimations among Quaternary fan, lacustrine, and eolian deposits in the eastern Mojave Desert. Ages in italics are based on lacustrine sedimentation rates.

and from ca. 7 to 8 ka for the LS Qf7 soils. In contrast, soil stratigraphy suggests that PM unit Qf7 is correlative with unit Qf5 along the Soda Mountains and that the latter was deposited after ca. 3.4 ka (Fig. 4; Wells et al., 1987). Moreover, Bull (1991) notes that incipient varnish on pavement clasts generally indicates a surface age of <1000 yr B.P.

Two eolian units are interstratified with Holocene alluvium (Fig. 4). Unit Qe3 consists of scattered dune and sand sheet deposits that overly unit Qf6 and distal Qf5 fan deposits and is truncated by unit Qf7 deposits. A vegetative cover on much of the unit Qe3 surface indicates that this eolian unit is temporarily stabilized. A single IRSL date of 4250 ± 290 yr B.P. (Clarke, 1994) was obtained from eolian sands just above the contact between Qe3 and the underlying Qf6 deposit. A lack of soil development on this underlying Qf6 deposit indicates that deposition of Qe3 sands must have occurred soon after deposition of the Qf6 gravel. Eolian unit Qe2 consists of multiple remnants of what once had been a widespread sand sheet that covered a large portion of the distal Qf5 surfaces (Figs. 1, 5). Distal Qf7 and Qf6 deposits are deeply inset into and truncate the eastern and southern margins of the Qe2 complex as well as distal Qf5 units. Established vegetation on much of the Qe2 surface remnants indicates that these sand deposits are currently stabilized. Four IRSL dates—3500 ± 220 yr B.P. (0.5 m deep), 3700 ± 425 yr B.P. (8.3 m deep), 8420 ± 795 yr B.P. (2.1 m deep), and 4074 ± 334 yr B.P. (8 m deep; Clarke, 1994; Edwards, 1993)—were obtained from an extensive complex of Qe2 sands that overlies distal Qf5 fans (Figs. 4, 5).

Unit Qf6 is a widespread deposit and represents a significant period of Holocene fan aggradation. The Qf6 unit is an extensive fill terrace deposit along wash channels in proximal fan areas, extends well into mountain front embayments, and extensively overlaps older deposits in distal fan areas. The PM and QM Qf6 deposits consist of poorly to moderately stratified pebble-gravel to well-stratified sandy-pebble braided stream and sheetwash deposits with a subtle bar-and-swale microtopography of low relief. The VX and LS Qf6 deposits consists of well-stratified pebble-gravel braided stream deposits and have a pronounced bar-and-swale microtopography. The PM and QM Qf6 fan deposits have a finer texture than that of the VX and LS Qf6 and Qf7 fan deposits. Soils formed on the Qf6 generally have thin (1–2 cm) Av horizons and weak Bwk horizons with stage I to II carbonate morphology (Table 1). Desert pavement development is very

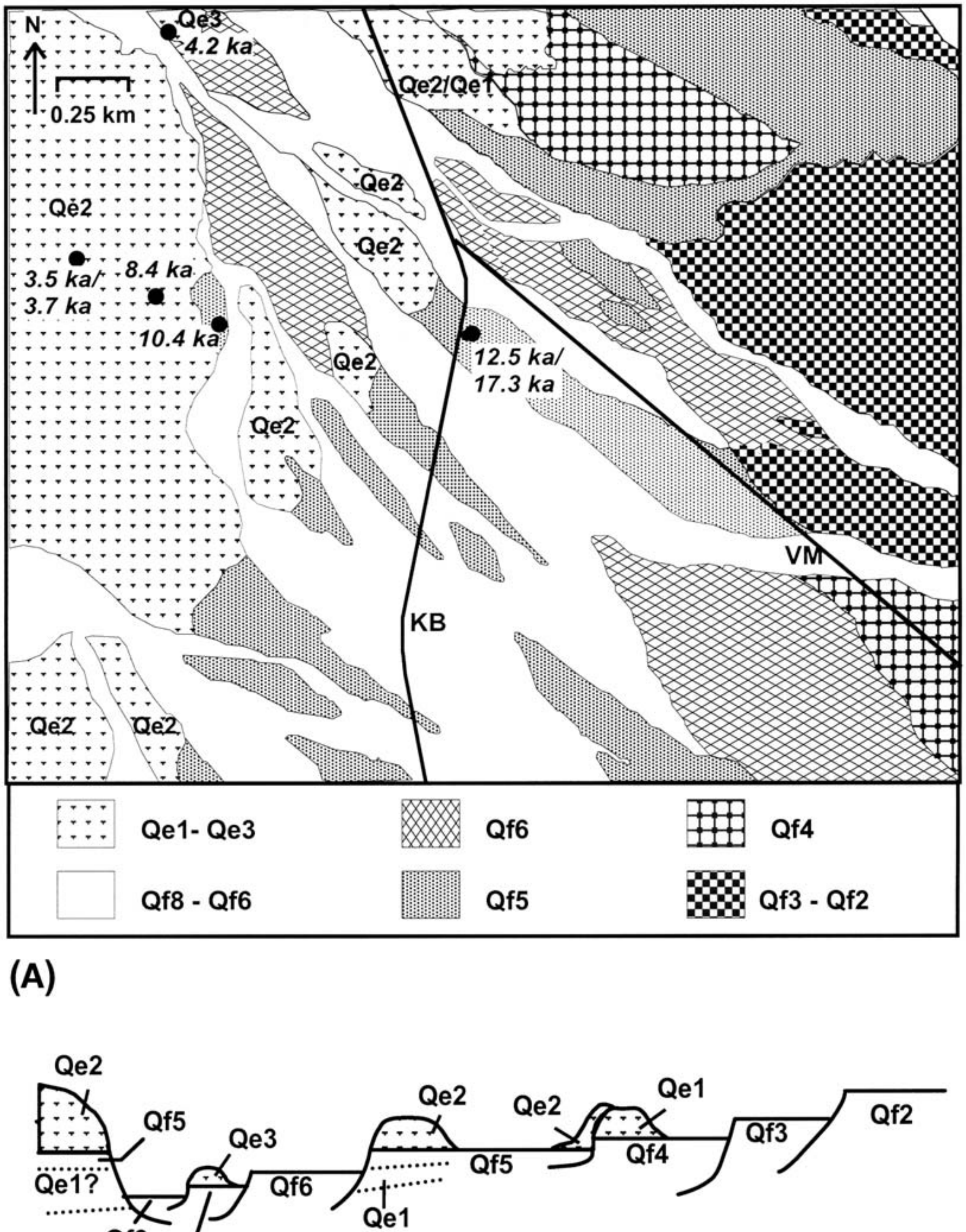

Figure 5. A: Map of Quaternary depositional units along part of the LS fan sequence. Map units defined in Table 1. Italic-labeled dots show location and age of infrared stimulated luminescence sample sites shown in Figure 4. Abbreviations: KB—Kelbaker road and VM—Vulcan Mine access road. B: Generalized schematic cross section of alluvial fan and eolian units shown in A.

weak to moderate depending on the rock type (Table 1). Unit Qf6 can be distinguished readily from unit Qf7 by the accumulation of incipient varnish on siliceous pavement clasts and the weak degree of dissolution of limestone clasts on Qf6 surfaces and the development of a weak B horizon. The oldest radiocarbon dates on pedogenic carbonate range from 6190 cal. yr B.P. (5380 ± 80 ^{14}C yr B.P.) for soils of the PM sequence to 4490 cal. yr B.P. (4010 ± 70 ^{14}C yr B.P.) for soils of the LS sequence (Fig. 4). Modeled radiocarbon ages range from ca. 8 to 11 ka for the PM Qf6 soils and from 7 to 8 ka for the LS Qf6 soils. Geomorphic relations and IRSL ages for units Qe3 and Qe2 suggest that deposition of unit Qf6 may have begun just before 4200 yr B.P. and continued as late as ~3500 yr B.P. Soil stratigraphy suggests that PMP unit Qf6 is correlative with SMP unit Qf4. Radiocarbon ages suggest that SMP unit Qf4 was deposited after ca. 3600 ka (Fig. 4; Wells et al., 1987). Soils developed in all Qf6 deposits along the Providence Mountains piedmont, as well as soils formed in the late Holocene Qf4 deposits along the Silver Lake playa, have only weakly developed Bw horizons that overlie weak Bk or Ck horizons with stage I or II carbonate morphology.

Latest Pleistocene to early Holocene deposits

Alluvial fan unit Qf5 is a widespread deposit that extends far into distal fan areas (Figs. 1, 5). The PM Qf5 deposit is a noticeably coarse-textured alluvial unit that generally consists of pebble-gravel to pebble-cobble, poorly to moderately stratified sheetflood, sheetwash, and debris flow deposits. The surface of the PM Qf5 deposits generally consists of (1) large, elongated lobes or fields of cobbles and boulders (boulders up to 2–3 m in length are not uncommon in some of the larger depositional lobes), (2) remnants of debris flow levees, and (3) bouldery lobes that are 5–8 km downstream of the fan apex. These features suggest that at least the surface sediments of unit Qf5 were the result of frequent debris flow deposition. The VX and LS Qf5 deposits are moderately to well stratified and have surfaces with pronounced planar and trough crossbedding indicating that deposition was largely by ephemeral braided streams. Deposits of Qf5 age were not recognized within the QM fan sequence and may have been buried or stripped by younger deposits or may have never been deposited. Evidence of the possible widespread burial of QM Qf5 deposits is that the surface of extensive QM Qf6 deposits is only 1 or 2 m below the surface of the Pleistocene (pre-Qf5) deposits in QM fan environments. Bull (1991) notes that drainage basins of quartz monzonites appear to have produced a large pulse of sediment that overwhelmed valley floors resulting in the burial of Pleistocene and early Holocene deposits by nearly continuous deposition into the middle and late Holocene.

Soils on Qf5 deposits are moderately developed with thick (3–5 cm) Av horizons, either Bw or weak Bt horizons, and underlying Bk horizons with stage I to III carbonate morphology (Table 1). Development of desert pavement ranges from moderate to strong, with clasts that are moderately to strongly varnished; and the soil has a noticeable reduction in the depositional bar-and-swale microtopography. Unit Qf5 can be distinguished readily from younger units based upon soil and pavement development.

Distal Qf5 deposits that are marginal to the Kelso Dunes are elongated and linear and form distinct, ramp-like surfaces that are several meters above younger fan deposits (Figs. 1, 5). These ramp-like features are capped by a 0.5–1 m thick layer of moderately stratified gravel and cobbles that overlies interstratified eolian sands, sandy-pebble alluvium, and lenses of gravel-cobble alluvium. These ramps are interpreted to be the remnants of Qf5 axial washes that dissected large Qe1 distal sand sheets or dunes that prograded eastward, away from the Kelso Dunes. Subsequent erosion of the Qe1 sediments created inverted topography with axial Qf5 channel deposits forming elongated fan surfaces elevated above the modern washes.

Sand sampled from within Qf5 alluvium yielded an IRSL age of 10,410 ± 890 yr B.P., and sand sampled from within the surface layer of well-stratified cobbles and gravel yielded an IRSL age of 12,460 ± 1151 yr B.P. (Fig. 4). Soil stratigraphy suggests that unit Qf5 is correlative with unit Qf2 along the Soda Mountains and that Qf2 was deposited between ~9380 cal. yr B.P. (8350 ± 300 ^{14}C yr B.P.) and 14,020 cal. yr B.P. (12,020 ± 130 ^{14}C yr B.P.) (Fig. 4; Wells et al., 1987). The oldest radiocarbon dates on pedogenic carbonate range from 21,640 cal. yr B.P. (18,120 ± 150 ^{14}C yr B.P.) for soils of the PM sequence to 19,200 cal. yr B.P. (16,310 ± 60 ^{14}C yr B.P.) for soils of the LS sequence (Fig. 4). Modeled radiocarbon ages range from ca. 29 to 36 ka for the PM Qf7 soils and from 27 to 33 ka for the LS Qf7 soils.

Eolian deposit Qe1 occurs as a thin, discontinuous sand sheet that overlies Pleistocene fan deposits (pre-Qf5 deposits) at several locations on the piedmont (Figs. 1, 5) and underlies Qf5 deposits. As discussed above, the lateral distribution of Qe1 sands and the elevated, ramp-like features of distal Qf5 deposits indicate that unit Qe1 may have covered extensive portions of the lower piedmont at one time. An IRSL date of 16,830 ± 1465 yr B.P. was obtained from the base of a unit Qe1 remnant that overlies pre-Qf5 fan deposits. The presence of a well-developed soil, which has strongly developed Bwk horizons with 7.5 YR hues, indicates the long-term stability of the sand sheet where this IRSL date was obtained. Sand collected from a 1.5 m thick layer of eolian sand stratified with scattered lenses of gravel and cobbles and that lies below the Qf5 alluvium yielded an IRSL age of 17,300 ± 1935 yr B.P. (Fig. 5; Clarke, 1994).

Evaluation of ages for late Quaternary deposits

Although they are in correct relative order and generally in the same age range (i.e., Holocene and latest Pleistocene), radiocarbon dates of pedogenic carbonate do not agree with (1) age estimates for alluvial and eolian units based on the IRSL dates discussed above (2) current knowledge of soil-forming rates in the Mojave Desert (McFadden et al., 1989, 1992; Reheis et al., 1989, 1991; Harden et al., 1991), and (3) stratigraphic correlations with nearby and relatively well dated piedmont deposits (Wells et al., 1987). The IRSL technique used has been validated with accurate ages derived for eolian sands bracketing Mount Mazama tephra in Oregon (Clarke, 1994) and has provided stratigraphically reasonable dates elsewhere in the Mojave Desert (Rendell and Sheffer, 1996; Clarke et al., 1996).

Modeled radiocarbon ages for pedogenic carbonate may be older than the actual age of the soil if (1) noncontinuous deposition of pedogenic carbonate occurred or (2) radiometrically dead carbon from limestone were incorporated (Amundson et al., 1994; Wang et al., 1996). Both modeled and measured radiocarbon ages would overestimate the actual age of the soil and alluvium if the original alluvium contained old organic matter (Wang et al., 1996). Possible contamination with radiometrically dead carbonate from limestone was shown not to be a problem in the dates reported in this study (Wang et al., 1996). The other two potential sources of error yielding ages that are too old, however, are possible.

Noncontinuous deposition of pedogenic carbonate occurred in these soils. Pedogenic carbonates below 75 cm in the Qf5 and Qf4 soils, where the oldest radiocarbon ages occur, would have experienced the greatest degree of noncontinuous deposition because of changes in the flux of water and carbonate. Numerical modeling of soil-water balance indicates that most of the pedogenic carbonate below ~75 cm would have accumulated early in the development of soils on the Qf5 surfaces. This is because the flux of water and carbonate below 75 cm would have significantly decreased during the Holocene because of a drier climate coupled with textural development of B and Av horizons (McDonald, 1994; McDonald et al., 1996). Carbonate accumulation that predominantly occurred early in the period of soil development would result in a strong overestimation of modeled radiocarbon ages (Wang et al., 1996).

Alluvium in which the dated soils formed probably contained old, preexisting organic matter, resulting in model and measured radiocarbon dates that overestimate the true age of the Qf7 through Qf5 deposits. Alluvium would have been largely derived from deposits where accumulation of soil organic matter would have occurred, including soils formed in hillslope colluvium and floodplain sediments (Wells et al., 1987; Bull, 1991; Harvey et al., 1999). Radiocarbon dates of ca. 4410 and 5110 ^{14}C yr B.P. (4980–5900 cal. yr B.P.) on pedogenic carbonates in Qf7 fan deposits (Fig. 4) support this interpretation. Soil and pavement of the Qf7 fans have only minimal development with weak Av horizons and small discontinuous patches of incipient pavement (McDonald, 1994; McDonald and McFadden, 1994). Further, limestone surface clasts show no signs of surface dissolution or pitting; and most of the Qf7 deposits lie within a few decimeters of active wash channels. Radiocarbon age estimates for Qf6 are similar to the radiocarbon ages for Qf7; however, the stronger degree of soil and pavement development of Qf6 relative to Qf7 clearly indicates that Qf6 is at least a few thousand years older. Together, these soil and geomorphic features do not support an age of 4–5 ka (model ages of 4–8 ka) for the Qf7 soil and surfaces but are consistent with radiocarbon ages that are too old if the decomposition of older, preexisting organic carbon is incorporated into the pedogenic carbonates.

The radiocarbon content of a sediment from a pair of modern washes in the Providence Mountains yielded modern ages (Wang et al., 1996); however, these samples were derived from washes in the distal fan environment. It is unlikely that the organic carbon content of these washes accurately represents the organic carbon content that would have been associated with alluvium derived from mountain basins during deposition of older alluvial units. Radiocarbon dating of pedogenic carbonate in soils along the White Mountains in Nevada and California also resulted in an overestimation of the age of deposits independently dated by conventional radiocarbon methods due to the inclusion of older organic carbon (Pendall et al., 1994). In contrast, radiocarbon ages of pedogenic carbonate for soils formed in lacustrine beach gravel along the margin of Silver Lake playa yielded generally similar age estimates as radiocarbon dates obtained by conventional methods (McFadden et al., 1992). The closer agreement between these dating techniques probably reflects the fact that deposits of lacustrine beach gravel are not likely to contain abundant detrital organic matter that can be incorporated into pedogenic carbonates.

Because at least two of the major assumptions governing the diffusion-reaction model for radiocarbon dating of pedogenic carbonates are not validated, we do not view the modeled radiocarbon ages as reliable. These dates significantly overestimate the ages of the soil and alluvium. It is also likely that the measured radiocarbon ages on pedogenic carbonates overestimate the true age of Qf7 through Qf4 soils due to contamination by older organic carbon.

REGIONAL STRATIGRAPHIC CORRELATIONS AND GEOMORPHIC HISTORY AMONG LATE QUATERNARY DEPOSITS

Stratigraphic and age relations among late Quaternary alluvial and eolian units along the Providence Mountains piedmont indicate that most of these units are correlative with alluvial and eolian units along the Soda Mountains piedmont (Fig. 4). Luminescence dates from the Providence Mountains piedmont and conventional radiocarbon dates from the Soda Mountains piedmont and nearby playas provide adequate age control linking general periods of deposition between these piedmonts as well as with late Quaternary climatic events. Stratigraphic correlations shown in Figure 4 are strengthened by the strong similarity of PDI values and overall degree of soil and desert pavement development in fan deposits on both piedmonts. The similarity in PDI values is significant given that the PDI values from outlying areas are derived from soils described by several different scientists and that variability among PDI values can occur as a result of differences in individual methods (Reheis et al., 1989). Similar PDI values among different study areas indicates in part that progressive changes in soil morphology, such as development of structure and texture in B horizons, result in similar, but specific changes in soil development that can be readily recognized across the region by different scientists. In other words, the strongly similar degrees of soil morphology as represented by PDI values supports that these soils represent similar lengths of soil formation and provide a strong foundation for establishing correlation among alluvial units across the region.

Deciphering the late Quaternary geomorphic record in the east Mojave is rooted strongly in the record of pluvial Lake Mojave (Ore and Warren, 1971; Wells et al., 1987; Brown et al., 1990; Harvey and Wells, 1994, this volume; Harvey et al., 1999; Wells et al., this volume). A detailed history of pluvial Lake Mojave is provided by a wide range of paleoenvironmental data and age estimates on lacustrine and eolian deposits (Wells et al., 1987, 1989; Brown et al., 1990; Wells et al., this volume). Fluctuating lake levels resulted in two high lake stands bracketed by three periods of intermittent lake activity (Figs. 4, 6). Calibrated ^{14}C ages indicate that pluvial lake activity began ca. 24.5 ka (Intermittent Lake I) and ended by ca. 9.4 ka (Intermittent Lake III) with high lake stands occurring between ca. 21.5 and 19.2 ka (Intermittent Lake I) and between ca. 16.4 and 13.2 ka (Intermittent Lake II). The following discussion relates regional eolian and alluvial events to the paleoenvironmental record based on the history of pluvial Lake Mojave.

Eolian events

Deposition of unit Qe1 along both mountain piedmonts appears to have occurred during approximately the same time interval of Intermittent Lake II (Figs. 4, 6). Stratigraphic relations along the Soda Mountain piedmont indicate that deposition of unit Qe1 occurred before deposition of unit Qf2 (Wells et al., 1987). Moreover, the absence of buried soil features in the top of unit Qe1 suggest that deposition of unit Qe1 may have continued nearly until deposition of unit Qf2. A period of eolian activity coinciding with Intermittent Lake II is recorded within lacustrine deposits that just underlie sediments dated at ca. 17.6 ka (Cores SIL-I, SIL-M, Wells et al., 1989; Brown et al., 1990; Wells et al., this volume). Together, these features suggest that the onset of unit Qe1 deposition coincided with fluctuating lake levels associated with Intermittent Lake II between ca. 18.3 and 17.6 ka and that eolian deposition probably continued to some degree during the Intermittent Lake II phase (Wells et al., 1987, 1989, this volume). Fluctuating lake levels and occasional periods of drying during lake recession would enhance deflation of sand and silt from distal fluvial deposits and lake basins, increasing widespread eolian deposition along mountain piedmonts around Lake Mojave (Wells et al., 1987; Lancaster and Tchakerian, 1996, this volume).

Luminescence dating and stratigraphic relations indicate that deposition of PMP unit Qe1 began before 17.3 ka and ended before deposition of PMP unit Qf5 dated at 12.5 ka. Deposition of PMP unit Qe1 would have responded to the same increase in the supply of eolian sediment from the Lake Mojave basin that caused SMP unit Qe1. The Providence Mountains unit Qe1 is a result of an eastward expansion onto the piedmont of sand that forms the present-day Kelso Dunes and Devils Playground. Activity of both the Kelso Dunes and Devils Playground is linked to the supply of sediment from the pluvial Lake Mojave basin (Lancaster, 1994; Lancaster and Tchakerian, this volume).

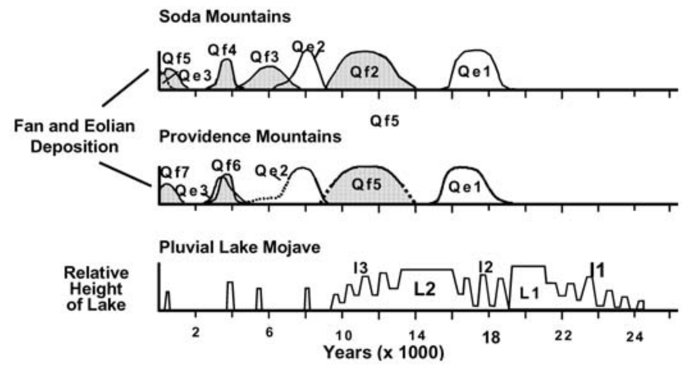

Figure 6. Summary of periods of fan and eolian deposition along the Providence Mountains piedmont and near Silver Lake–Soda Mountains and fluctuations of pluvial Lake Mojave during the last 23,000 yr. Plots of geomorphic events imply general interval of time and levels of activity but do not imply relative volumes of sediment.

Buried soils have not been identified between units Qe1 and Qf5 along the Providence Mountain piedmont, suggesting that deposition of unit Qe1 may have continued until deposition of unit Qf5. This lack of a buried soil, however, could also be due to erosional truncation of unit Qe1 during deposition of unit Qf5.

Deposition of unit Qe2 along both mountain piedmonts appears to have begun about the same time and appears to be related to an increase in the supply of eolian sediment associated with lake recession at the end of pluvial Lake Mojave (Figs. 4, 6). Stratigraphic relations among dated shoreline features indicate that deposition of unit Qe2 along the Soda Mountain piedmont began after ca. 9.4 ka and ended before 3.9 ka (Wells et al., 1987, 1989). Soil stratigraphy of shoreline and middle Holocene fan deposits suggests that deposition of unit Qe2 probably ended before ca. 6.8 ka (McFadden et al., 1992). IRSL dates and stratigraphic relations indicate that deposition of unit Qe2 along the Providence Mountains piedmont began after 10.4 ka and before 8.4 ka and was stabilized ca. 3.5 ka. An alternative explanation is that PMP unit Qe2 was deposited closer to ca. 8.4 ka and that the surface of the dated Qe2 dune complex was reactivated during the late Holocene resulting in the deposition of PMP unit Qe3 beginning at ca. 4.2 ka. The three youngest IRSL ages may instead date a layer of PMP unit Qe3 sands that overlie and truncate older Qe2 sands. Late Holocene reactivation of PMP unit Qe2 is supported by luminescence ages for sand ramps along nearby Old Dad Mountain (Fig. 1) that indicate periods of increased eolian activity between ca. 6.7 and 3.3 ka (Rendell and Sheffer, 1996; Lancaster and Tchakerian, 1996).

Alluvial fan events

Alluvial fan deposits that predate the latest Pleistocene occur along both the Soda Mountains and Providence Mountains piedmonts. A well-developed soil and desert pavement on SMP unit Qf1 is truncated by shoreline features created during highstands of pluvial Lake Mojave, indicating that SMP unit Qf1 predates pluvial lake activity during the latest Pleistocene and is older than ca. 24.5 ka. Soil stratigraphy suggests that SMP unit Qf1 is correlative with PMP unit Qf4, which was deposited before PMP unit Qe1 and before ca. 17.3 ka.

Stratigraphic and age relations among eolian and alluvial units indicate that the deposition of alluvial fan unit PMP Qf5 also appears to have coincided with deposition of SMP unit Qf2 (Figs. 4, 6). Stratigraphic relations indicate that deposition of both unit SMP Qf2 and PMP unit Qf5 occurred after deposition of unit Qe1 and before deposition of unit Qe2 (Figs. 4, 6). Geomorphic relations near Silver Lake playa suggest that deposition of unit SMP Qf2 grades to shoreline B or that deposition of SMP unit Qf2 began shortly after creation of shoreline B (Wells et al., 1987). Shoreline B formation occurred during Intermittent Lake II, and the oldest radiocarbon date for shoreline B deposits is ca. 14.0 ka. (Fig. 4; Wells et al., 1989). Stratigraphic relations and radiocarbon dating of shoreline features indicate that deposition of SMP unit Qf2 ended ca. 9.4 ka (Wells et al., 1989; Brown et al., 1990). Stratigraphic relations and IRSL dates discussed above indicate that deposition of PMP unit Qf5 occurred during a similar time interval with deposition beginning after 16.8 ka and ending before 8.4 ka (Fig. 4). Strongly similar degrees of soil development between SMP unit Qf2 and PMP unit Qf5 further support that these alluvial deposits are correlative (Fig. 4).

Stratigraphic and age relations among eolian and alluvial units suggest that the deposition of late Holocene alluvial fan units along both the Providence Mountains and Soda Mountains piedmont also may have occurred during similar time intervals (Figs. 4, 6). Deposition of PMP unit Qf6 occurred between ca. 4.2 and 3.5 ka. Deposition of SMP unit Qf3 occurred between ca. 9.4 ka and 3.6 ka, and deposition of SMP unit Qf4 occurred after ca. 3.6 ka. Geomorphic relations suggest that deposition of unit SMP Qf3 may have overlapped with deposition of unit SMP Qe2, which would place deposition of SMP unit Qf3 closer to ca. 6 ka (Brown et al., 1990; McFadden et al., 1992). Soil development reflected by PDI values suggests that SMP unit Qf4 is correlative with PMP unit Qf6 (Fig. 4). Both PMP unit Qf7 and SMP unit Qf5 have minimal soil development and lack desert pavement with interlocking clasts, suggesting that these alluvial deposits may be correlative. Lack of adequate age control, however, prevents confirming that these units may have been deposited during similar time intervals.

REGIONAL DEPOSITION OF ALLUVIAL FANS IN RESPONSE TO THE PLEISTOCENE-HOLOCENE CLIMATIC TRANSITION

Deposition of PMP unit Qf5 and SMP unit Qf2 between ca. 14 and 9.4 ka (Figs. 4, 6) indicates that this major period of fan deposition across the east Mojave was a region-wide event. A regional period of deposition is further supported by stratigraphic correlations and general age estimates (based upon the degree of soil and desert pavement development) for other fan deposits across the Mojave (McFadden et al., 1989; Bull, 1991; Wells et al., 1990; Harden et al., 1991). Region-wide fan deposition implies that this activity was a result of some aspect of climatic variation rather than active tectonics or a complex response to crossing intrinsic geomorphic conditions (Schumm, 1977; Blair and McPherson, 1994).

Relation between regional fan deposition and late Quaternary climate

Age relations of PMP unit Qf5 and SMP unit Qf2 indicate that this pronounced episode of fan deposition was not simply a result of greater effective moisture during the latest Pleistocene, as suggested by several studies (Melton, 1965; Lustig, 1965; Ponti, 1985; Christenson and Purcell, 1985; Dorn et al., 1987; Dorn, 1994; Blair and McPherson, 1994). First, fan deposition began near the end of a period of greater effective moisture, coinciding with a gradual decrease in effective moisture and pluvial lake levels during the Pleistocene-Holocene transition (Figs. 4, 6). Sedimentologic records from pluvial Lake Mojave indicate that lake levels began to significantly fluctuate at ca. 13.2 ka, with the nearly complete disappearance of a long-standing pluvial lake by ca. 9.4 ka (Wells et al., 1989, 1994, this volume; Enzel et al., 1989, 1992). Other pluvial lakes in the vicinity of the Mojave Desert also show gradual drying in conjunction with a transition to a relatively drier climate during this time interval (Quade, 1986; Smith and Street-Perrott, 1983). Paleobotanical studies for several mountains in the Mojave Desert also indicate that a gradual decrease in vegetation and effective soil moisture occurred during this time interval (Van Devender et al., 1987; Harvey et al., 1999).

Second, fan deposition appears to have been minimal between ca. 24 and 14 ka when paleoenvironmental data also indicate that there was a considerable increase in effective moisture. Paleobotanical and soil hydrology data suggest that precipitation in the Sonoran and Mojave Deserts may have increased by at least 40–150% above current mean annual rainfall during the latest Pleistocene (Spaulding, 1985; Van Devender et al., 1987; Phillips, 1994; McDonald et al., 1996). Evidence that both the Providence and Soda Mountains were subjected to greater effective moisture during the latest Pleistocene is provided by linkages among anomalous, historic atmospheric circulation patterns over the north Pacific Ocean, flooding of the Mojave River, and development of ephemeral lakes that occupied the nearby Silver Lake playa (Enzel et al., 1989, 1992). Historical flooding and ephemeral lakes correlate with years of regional changes in the oceanic-atmospheric circulation patterns. These changes generally consisted of a southern shift in the Aleutian low and subtropical jet stream. The southern shift of the jet stream resulted in a considerable increase in the frequency of frontal storms sweeping in from the Pacific across southern California. Similar but more persistent atmospheric circulation patterns appear to have resulted in the formation of pluvial Lake Mojave during the latest Pleistocene (Wells et al., 1989; Enzel et al., 1989, 1992; Enzel and Wells, 1997). Although formation of these perennial lakes was due primarily to increased rainfall and flooding in the Transverse Ranges (~250 km to the west of the Providence Mountains), a considerable increase in annual precipitation probably also occurred across the Mojave Desert. Evidence for this is the considerable increase in regional rainfall associated with years of historic flooding of the Silver Lake playa, indicating that sufficient moisture was delivered across the coastal mountains and into the Mojave Desert (Fig. 3). Similar increases in annual rainfall due to increases in frontal storm activity likely occurred during the latest Pleistocene as well.

An increase in ephemeral channel flow most likely would have coincided with regional increases in effective moisture. For example, there was a slight increase in ephemeral stream activity along the Providence Mountains during the winters of 1992–1993 and 1997–1998 when there was a considerable increase in regional rainfall associated with anomalous storm events discussed in the preceding paragraph. There appears to have been minimal sediment transport associated with these years with above average rainfall, however. Increased channel flow throughout most of the latest Pleistocene without a corresponding increase in alluvial sedimentation implies a high water-to-sediment ratio. The predominance of fan aggradation coinciding with the Pleistocene-Holocene transition indicates a regional geomorphic response leading to a significant increase in the flux of sediment into ephemeral drainages across the region discussed in more detail below (Wells et al., 1987; Harvey and Wells, 1994; Harvey et al., 1999).

The relative influences of drainage basin morphometry and bedrock lithology on fan deposition

Perhaps as significant as alluvial fan deposition coinciding with the timing of the Pleistocene-Holocene climatic transition is the fact that regional fan aggradation occurred despite considerable geomorphic differences among drainage basins in the Providence and Soda Mountains. Generally, drainage basins in the Providence Mountains are considerably larger and at higher elevations than drainage basins in the Soda Mountains. For example, one of the largest drainage basins along the western flank of the Providence Mountains has a basin area of ~8.8 km^2 and ranges in elevation from ~1200 to 2000 m (Fig. 2). In contrast, one of the largest basins along the Soda Mountains has an area of ~1.9 km^2 and ranges in elevation from ~100 to 300 m. The catchments within the Soda Mountains are also generally steeper, and the main trunk streams have much smaller valley width-to-height ratios compared to catchments and trunk streams in the Providence Mountains. Another key geomorphic contrast is the wide variation in rock types that make up the drainage basins along the Providence Mountains. Stratigraphic sequences of fan deposits along the Providence Mountains piedmont that are physically correlative have been derived from drainage-basin source areas consisting of diverse rock types such as coarse-grained plutonic, microcrystalline siliceous, and massive carbonate rocks. The one exception is the absence or lack of exposure of QM unit Qf5 (Table 1), which is derived from quartz monzonite.

The geomorphic diversity among drainage basins results in an equally wide range of key variables controlling sediment supply. These include sediment production, sediment size, channel discharge, water-to-sediment ratio, and sediment storage within each basin. For example, sediment production and hillslope hydrology can strongly vary among drainage basins composed of either coarse-grained plutonic and carbonate rock types (Bull, 1991). If sediment supply to alluvial fans were primarily due to an increase in effective moisture and stream activity during the latest Pleistocene, it is reasonable to expect that the timing of fan aggradation would have varied considerably among the different basin rock types across the Providence Mountains and between the diverse basin morphometry of the Providence and Soda Mountains. This is because varied responses in sediment production, supply, and transport could be expected from such a diversity in drainage basin geomorphology. Our conclusion that the timing of fan aggradation along these two mountain piedmonts was similar and occurred between 14 and 9 ka indicates that alluvial fan deposition, at least in the east Mojave, Desert was not due primarily to an increase in effective moisture and concomitant increase in channel discharge associated with a period of increase pluvial activity between ca. 24 and 9 ka.

REMAINING QUESTIONS: THE INTERRELATED ROLES OF CLIMATE CHANGE, VEGETATION RESPONSE, AND SEDIMENT SUPPLY IN REGIONAL FAN AGGRADATION

Pronounced aggradation of alluvial fans across the desert southwestern U.S. between ca. 14 and 9.4 ka, therefore, has been attributed to an increase in sediment yield corresponding with time-transgressive changes in climate and vegetation during the Pleistocene-Holocene transition (Wells et al., 1987, 1990; Bull, 1991; Harvey and Wells, 1994; McDonald, 1994; McDonald and McFadden, 1994; Reheis et al., 1996; Harvey et al., 1999). Specifically, a cycle of fan deposition was triggered as a result of the transition from a wetter to a relatively drier climate when a reduction in effective soil moisture resulted in a reduction in the vegetative cover on hillslopes that, in turn, resulted in an increase in soil erosion and a concomitant increase in sediment supply. Numerous paleobotanical studies indicate that throughout the Mojave Desert there was a gradual upward shift in the elevation of vegetation coinciding with a decrease in effective soil moisture through the end of the latest Pleistocene and into the early Holocene, between ca. 14 and 8 ka (e.g., Spaulding, 1985; Van Devender et al., 1987; Harvey et al., 1999; Wigand and Rhode, 2002). Fan entrenchment and stabilization of the alluvial fan surface followed when a decrease in sediment supply from increasingly barren hillslopes resulted in an increase in steam power leading to incision of the alluvium.

There are two critical factors among all the studies of alluvial fans cited above. First is that an increase in sediment yield resulted from time-transgressive changes in vegetation and a concomitant decrease in the stability of soils along drainage basin hillslopes. Second is that there was a considerable increase in sediment stored on drainage basin hillslopes as soil and colluvium as a result of greater effective moisture that enhanced weathering of basin bedrock during the latest Pleistocene. An assessment of vegetation, geomorphic, and climatic attributes in the Providence Mountains provides an opportunity to conduct a generalized evaluation of hillslope dynamics during the Pleistocene-Holocene climatic transition. Results of this evaluation, discussed in more detail below, suggest that increased sediment yields in the Providence Mountains cannot be attributed primarily to time-transgressive changes in vegetation and increasing erosion of soils along basin hillslopes.

Vegetation change and hillslope erosion

The role of time-transgressive changes in vegetation along basin hillslopes in triggering an increase in sediment yield and fan aggradation during the Pleistocene and Holocene transition along the Providence Mountain piedmont may have been limited compared to hillslope response to vegetation change cited in other studies. Field observations of current soil and colluvial cover across hillslopes along several PM drainage basins (lying between ~1100 and 1700 m) indicate that most of the bedrock along these slopes is covered by between 10 and 50 cm of soil and colluvium. Vegetation ranges from that dominated by creosotebush and white bursage to blackbrush and Mojave yucca (*Yucca schidigera*) at higher hillslope elevations (juniper/pinyon woodland is largely along north-facing slopes). Further, plant density is high, with much of the soil surface protected by shrub canopies (Fig. 7). The fact that an appreciable cover of soil and colluvium are present indicates that soil is probably stable under a temperate desert scrub. In other words, hillslope areas that probably underwent a change in vegetation from predominantly juniper/pinyon woodland to temperate desert scrub can still develop and maintain an appreciable cover of soil and colluvium. Thus, modern soil and vegetation relations suggest that it is unlikely that changes in vegetation cover alone would have been a primarily responsible for an increase in soil erosion and sediment yield.

Another key relationship is that a reduction in plant cover across desert hillslopes may not result necessarily in an increase in soil erosion. First, soils along basin hillslopes during the late Pleistocene probably contained abundant clasts, including the soil surface, from local weathering of the bedrock. Although the effect of surface stones on surface runoff is complex and depends on such factors as stone size, percent cover, and the degree to which a stone is imbedded into the soil surface, surface stone cover has been shown to increase infiltration and decrease surface runoff by providing surface roughness limiting overland flow and increasing surface microtopography, which enhances infiltration (Yair, 1987; Poesen, 1992; Abrahams et al., 1994). Stone cover can also protect exposed soil by limiting erosion from raindrop impact. Second, hillslope runoff derived from colluvium

Figure 7. Photograph of hillslope at ~1500 m elevation showing typical vegetation cover for PM basin hillslopes. The majority of vegetation in view consists of blackbrush, Mojave yucca, and galleta grass (*Hilaria jamesii*). Hillslope covered with ~1 m of colluvium and soil.

has been shown to be highly limited except under exceptionally high rainfall intensities because of the overall high rate of surface infiltration relative to exposed bedrock areas. Moreover, surface runoff generated by exposed bedrock along hillslope ridgelines can be absorbed entirely by colluvium downslope (Yair, 1987, 1992; Yair and Enzel, 1987). The potentially high infiltration capacity of hillslope soil and colluvium suggests that changes in either vegetation type and/or density may have had a limited impact on the stability and erosion of soils along basin hillslopes and promoting an increase in sediment yields.

Soil cover and sediment storage along basin hillslopes

Geomorphic factors governing soil formation and the storage of sediment along basin hillslopes would have varied considerably among the different rock types that make up the Providence Mountains suggesting that removal of sediment stored in the form of an extensive soil and colluvial cover due to climatic transition may have had a limited role. Based on current knowledge of weathering processes in desert environments, it is reasonable to conclude that an stable, appreciable cover of soil and colluvium may have developed along many of the basin hillslopes underlain by coarse- to medium-grained plutonic rocks found in the southern part of the Providence Mountains (PM and QM sequences). These rock types are conducive to enhanced weathering, especially grussification, during prolonged periods of greater effective soil moisture (Birkeland, 1984; Bull, 1991). In contrast, the formation of an extensive cover of soils and colluvium stabilized along basin hillslopes underlain by limestone, marble, and volcanic rocks along the northern portion of the Providence Mountains

(VX and LS sequences) was probably limited. Soil formation along these hillslopes would be limited relative to that of the plutonic rock types because of the resistance of microcrystalline to massive carbonate and siliceous rocks to disintegrate into fine-textured colluvium that would enhance soil formation. Although the addition of dust would enhance the accumulation of a fine-textured matrix in soils derived from carbonate and volcanic materials, especially in conjunction with increased eolian activity associated with deposition of unit Qe1, it is unknown if the rate of accumulation along basin slopes would have been sufficient to dramatically impact the character of these soils.

Development of an extensive cover of stable soil and colluvium would be restricted further on LS and VX basin hillslopes compared to soils formed on the PM basin hillslopes due to considerable differences in basin topographic relief. The mean hillslope angle for LS and VX basins exceeds 40° and is ~10°–20° steeper than PM hillslopes (Fig. 8). We are not implying that soil cover would be absent on LS and VX hillslopes of the Providence Mountains but that the soil thickness and lateral extent would probably be substantially less than that found on hillslopes underlain by plutonic rocks. Field observations of the modern soil cover suggest that the overall degree of soil cover among the LS drainage basins is considerably less than that of the PM drainage basins. We hypothesize that sediment derived from weathering of LS and VX basin hillslopes was largely stored as talus or colluvial wedges along valley bottom channels rather than as an extensive cover of soil along hillslopes.

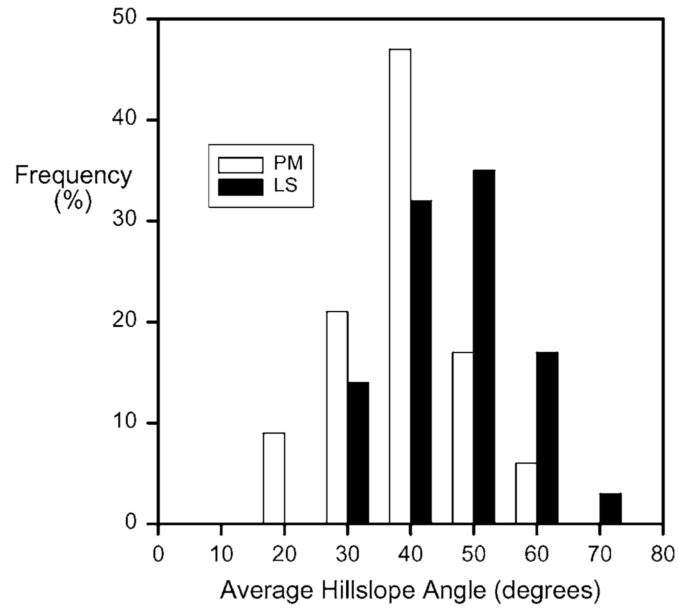

Figure 8. Frequency of hillslope angles for PM and LS drainage basins. Frequency based on measurements of 50 hillslopes for each drainage.

Extreme storm events in sediment mobilization

An apparent increase in summer monsoon activity during the early Holocene has been associated primarily with promoting channel incision and fanhead trenching and secondarily with enhanced mobilization of hillslope sediments (Wells et al., 1987, 1990; Bull, 1991; Harvey and Wells, 1994; McDonald, 1994; McDonald and McFadden, 1994; Reheis et al., 1996; Harvey et al., 1999). Increased summer storm activity has been interpreted in nearly all geomorphic and paleobotanical studies in the southwestern U.S. as an increase in summer convective storms. This interpretation is based on an early Holocene increase in the abundance of succulents and C-4 grasses preserved within packrat middens across the Mojave and Sonoran deserts (Spaulding, 1985; Spaulding and Graumilch, 1986; Bull, 1991).

Alternate interpretations are that this increase in succulents and grasses resulted from an increase in (1) late season Pacific frontal storms during April through early June when soil temperatures are warm or (2) an increase in tropical cyclones that occur during late August through early October (Van Devender et al., 1987). The potentially important role tropical cyclones may play has been largely overlooked in paleobotanical reconstructions of the desert southwest (McAuliffe and Van Devender, 1998). Tropical cyclones form in the Pacific off the coast of southern Mexico and occasionally migrate northward away for their normal paths over the Pacific and cross Baja California and Sonora Mexico (Ely, 1997). Historic tropical cyclones share strongly similar atmospheric circulation anomalies with those that produce extreme winter storms in southern California and have been responsible for flooding the Mojave River and the Silver Lake playa (Ely et al., 1994). These storms can yield several days of heavy rainfall across wide regions as they dissipate over land. Tropical cyclones have been associated with some of the largest flood events in southern Utah and Arizona (Ely, 1997). Tropical cyclones could have provided a significant source of late summer precipitation to vegetation in the Mojave during the early Holocene for similar reasons as suggested for the Arizona uplands of the Sonoran Desert by McAuliffe and Van Devender (1998). An increase in tropical cyclones, therefore, may have enhanced early Holocene increases in vegetation associated with warm-season rainfall.

Given the characteristics of tropical cyclones discussed in the preceding paragraph, an interesting question is raised: Was deposition of alluvial fans along the Providence Mountains during the Pleistocene-Holocene transition enhanced by an increase in tropical cyclone activity? Postulated changes in atmospheric circulation in the Mojave Desert may have enhanced penetration of tropical air into the desert southwest, which would have driven both convective storms and tropical cyclones (Harvey et al., 1999). A key aspect of tropical cyclones and fan aggradation is that tropical cyclones provide precipitation high in intensity, long in duration, and covering a large area. Long duration storms would provide more sustained channel flow for transporting and depositing alluvium in distal fan areas. As discussed above, distal deposits of the PMP Qf5 that are up to about eight kilometers from the mountain front are largely well bedded alluvium, complete with planar and trough crossbedding, suggesting deposition by sustained braided stream processes rather than short-lived, flashy runoff commonly associated with summer convective storms. Further, precipitation that is of high intensity and long duration would be considerably more effective in mobilizing colluvium that has a high infiltration rate.

We do not imply that summer convective storms were not an important factor in mobilizing sediment but rather raise two critical points. First, mobilization of sediment and transport into distal fan areas probably required an increase in the size and frequency of extreme storm events compared to today's climate. The regional occurrence of large-scale, sheetflood bedforms on pre-Holocene alluvial fans in the Mojave indicate that extreme storms and channel discharge events occurred during the early Holocene (Wells and Dohrenwend, 1985; Wells et al., 1987). Second, tropical cyclones may have provided a generally underrecognized source of precipitation that could have had a profound impact on regional fan aggradation. Determining the magnitude of enhanced tropical cyclones in the Mojave and their potential impact on regional fan deposition, if any, will require further investigations, especially involving paleoecology, surface-water hydrology of soils on basin hillslopes, paleoclimatology and climate modeling.

SUMMARY AND CONCLUSIONS

Geomorphic and age relations among alluvial and eolian units along the Providence Mountains and Soda Mountains piedmonts indicate that most of the late Quaternary eolian and alluvial fan units are stratigraphically correlative, were probably deposited during similar time intervals, and represent region-wide changes in geomorphic factors controlling sediment supply, storage, and transport. Similar timing of depositional events among the Providence Mountains and Soda Mountains piedmonts is significant because there is considerable variation in the geomorphology and ecology of the mountain catchments. Drainage basins along the Providence Mountains are considerably higher and larger than basins in the Soda Mountains. Further, there exists strong variation in basin morphology and rock type among the basins in the Providence Mountains. Regional fan deposition occurred regardless of lithology, size, and elevation or topographic relief of drainage basins. Wide variations in sediment production, storage, and transport are likely to be associated with diverse geomorphic settings; however, the best available geomorphic and age relations indicate that major intervals of aggradation transcended all geomorphic variation. Similar deposition intervals across the region imply that the mechanisms driving deposition are extrinsic factors related to climatic variation and not intrinsic factors such as complex response related to crossing inherent geomorphic thresholds or the instability of basin sediments due to tectonic activity.

Stratigraphic and age relations among alluvial and eolian units in the eastern Mojave Desert demonstrate that a regional period of major alluvial fan deposition occurred between ca. 9.4 and 14 ka and that correspond with the timing of the Pleistocene-Holocene climatic transition. This age range indicates that deposition of these fans is not simply a result of greater effective moisture and channel discharge during the last glacial maximum. The regional extent of fan deposition across diverse geomorphic settings strongly supports the models of Bull (1991), Wells et al. (1987), and Harvey et al. (1999) that proposed that a significant period of fan aggradation in the Mojave Desert occurred during the Pleistocene-Holocene transition. The results of this study differ from those cited above; however, in linking climate change to increases in sediment yield and fan aggradation with a concomitant increase in hillslope instability. Geomorphic relations along the Providence Mountains suggest that that changes in vegetation cover during the Pleistocene-Holocene climatic transition along the Providence Mountains may have had a limited impact on hillslope instability and sediment yield because of the (1) inherently high infiltration capacity of coarse-textured soils and colluvium, (2) possible strong spatial variations in the nature of soil cover across hillslopes, and (3) modern vegetation cover appears to provide enough stability for the buildup of soils and colluvium. An increase in sediment yield may instead be largely due to an increase in extreme storm events, perhaps an increase in tropical cyclones. Extreme storms would provide the rainfall intensity and duration to mobilize permeable sediments from mountain catchments and into distal fan areas.

Remaining problems

Although analysis of the timing of alluvial fan deposition along the Providence Mountains raises interesting questions regarding how climatic variation may drive increases in sediment yield and alluvial aggradation, several key problems remain and will require further investigation. Few studies of climatic and geomorphic factors controlling alluvial fan processes have incorporated a geomorphic analysis of hillslope environments similar to that of Harvey and Wells (1994). Further investigations are needed that integrate the spatial and temporal distribution of soils, colluvium, and vegetation across basin slopes and the hydrologic response of these slopes to variations in climate. Such investigations also need to consider if and how interrelated changes in climatic variation, sediment yield, and fan aggradation may have varied fans of Holocene and prelatest Pleistocene age relative to fans deposited during the Pleistocene-Holocene transition. The role of extreme storm events in generating discrete periods of alluvial fan deposition, especially the role of tropical cyclones, also requires further analysis.

Although IRSL ages, reinforced with stratigraphic correlation to alluvial units along the Soda Mountain piedmont the based on soil stratigraphy, provide strong local age control, the radiocarbon ages on pedogenic carbonates remain problematic. A project to date unit Qf5 and older alluvial fan deposits using in situ cosmogenic nuclides in currently under way. We hope that results will clarify age relation of unit Qf5 as well as serve as a tool for testing regional correlation of alluvial fan units.

ACKNOWLEDGMENTS

We thank Nick Lancaster, Michele Clarke, and Ann Wintle for collaboration on the IRSL dates, and Ron Amundson and Yang Wang for collaboration on pedogenic ^{14}C dates. Many thanks to the staff at UCR Sweeney Granite Mountains Reserve and the CSU Fullerton Desert Studies Center for their friendship and logistical support. We also thank NASA (NAG 5 1828), NSF (EAR 9118335), and scholarships to McDonald from the University of New Mexico, Sigma Xi, and the Geological Society of America for funding for this work. Thanks to Steven Reneau for thoughtful comments on an earlier version of this paper. The senior author is especially grateful to Steven Reneau and Arron Yair for many discussions regarding the relationship between climate change, extreme storm events, and alluvial fan response.

REFERENCES CITED

Abrahams, A.D., Howard, A.D., and Parsons, A.J., 1994, Rock-mantled-slopes, *in* Abrahams, A.D., and Parsons, A.J., eds., Geomorphology of desert environments: London, Chapman and Hall, p. 173–212.

Amundson, R., Wang, Y., Chadwick, O., Trumbore, S., McFadden, L., McDonald, E., Wells, S., and Deniro, M., 1994, Factors and processes governing the carbon-14 content of carbonate in desert soils: Earth and Planetary Science Letters, v. 51, p. 761–767.

Birkeland, P.W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Blair, T.C., and McPherson, J.G., 1994, Alluvial fan processes and forms, *in* Abrahams, A.D., and Parsons, A.J., eds., Geomorphology of desert environments: London, Chapman and Hall, p. 354–402

Brown, W.J., Wells, S.G., Enzel, Y., Anderson, R.Y., and McFadden, L.D., 1990, The late Quaternary history of pluvial lake Mojave: Silver Lake and Soda Lake basins, California, *in* Reynolds, R.E., et al., eds., At the end of the Mojave: Quaternary studies in the eastern Mojave Desert: Redlands, California, Special Publication of the San Bernardino County Museum Association, 1990 Mojave Desert Quaternary Research Center Symposium, May 18–21, 1990, p. 55–72.

Bull, W.B., 1991, Geomorphic responses to climatic change: New York, Oxford University Press, 326 p.

Bull, W.B., and Schick, A.P., 1979, Impact of climatic change on an arid watershed, Nahal Yael, southern Israel: Quaternary Research, v. 11, p. 153–171.

Christenson, G.E., and Purcell, C., 1985, Correlation and age of Quaternary-fan sequences, Basin and Range province, southwestern United States, *in* Weide, D.L., ed., Soils and Quaternary geology of the southwestern United States: Boulder, Colorado, Geological Society of America Special Paper 203, p. 115–122.

Clarke, M.L., 1994, Infrared stimulated luminescence ages from aeolian sand and alluvial fan deposits from the eastern Mojave Desert, California: Quaternary Geochronology, v. 13, p. 533–538.

Clarke, M.L., Wintle, A.G., and Lancaster, N., 1996, Infrared stimulated luminescence dating of sands from the Cronese basins, Mojave Desert: Geomorphology, v. 17, p. 199–206.

Dorn, R.I., 1994, The role of climatic change in alluvial fan development, *in* Abrahams, A.D., and Parsons, A.J., eds., Geomorphology of desert environments: London, Chapman and Hall, p. 354–402.

Dorn, R.I., DeNiro, M.J., and Aije, H.O., 1987, Isotopic evidence for climatic influence on alluvial-fan development in Death Valley: Geology, v. 15, p. 108–110.

Edwards, S.R., 1993, Luminescence dating of sand from the Kelso Dunes, California, *in* Pye, K., ed., The dynamics and environmental context of aeolian sedimentary systems: Geological Society of London Special Publication No. 72, p. 59–68.

Ely, L.L., 1997, Response of extreme floods in the southwestern United States to climatic variations in the late Holocene: Geomorphology, v. 19, p. 175–202.

Ely, L.L., Enzel, Y., and Cayan, D.R., 1994, Anomalous North Pacific atmospheric circulation and large winter floods in the southwestern United States: Journal of Climate, v. 7, p. 977–987.

Enzel, Y., and Wells, S.G., 1997, Extracting Holocene paleohydrology and paleoclimatology information from modern extreme flood events: An example from southern California: Geomorphology, v. 19, p. 203–226.

Enzel, Y., Cayan, D.R., Anderson, R.Y., and Wells, S.G., 1989, Atmospheric circulation during Holocene lake stands in the Mojave Desert: Evidence of regional climate change: Nature, v. 341, p. 44–48.

Enzel, Y., Brown, W.J., Anderson, R.Y., McFadden, L.D., and Wells, S.G., 1992, Short-duration Holocene lakes in the Mojave River drainage basin, southern California: Quaternary Research, v. 38, p. 60–73.

Gile, L., Peterson, F.F., Grossman, R.B., 1966, Morphologic and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347–360.

Harden, J.W., 1982, A quantitative index of soil development from field descriptions: Examples from a soil chronosequence in central California: Geoderma, v. 28, p. 1–28.

Harden, J.W., and Taylor, E.M., 1983, A quantitative comparison of soil development in four climatic regimes: Quaternary Research, v. 20, p. 342–359.

Harden, J.W., Taylor, E.M., Hill, C., Mark, R.L., McFadden, L.D., Reheis, M.C., Sowers, J.M., and Wells, S.G., 1991, Rates of soil development from four soil chronosequences in the southern Great Basin: Quaternary Research, v. 35, p. 383–399.

Harvey, A.M., and Wells, S.G., 1994, Late Pleistocene and Holocene changes in hillslope sediment supply to alluvial fan systems: Zzyzx, California, *in* Millington, A.C., and Pye, K., eds., Environmental change in drylands: Biogeographical and geomorphological perspectives: Chichester, Wiley, p. 67–84.

Harvey, A.M., Wigand, P.E., and Wells, S.G., 1999, Response of alluvial fan systems to late Pleistocene to Holocene climatic transition: Contrasts between the margins of pluvial Lakes Lahontan and Mojave, Nevada and California, USA: Catena, v. 36, p. 255–281.

Lancaster, N., 1994, Controls on aeolian activity: New perspectives from the Kelso Dunes, Mojave Desert, California: Journal of Arid Environments, v. 27, p. 113–124.

Lancaster, N., and Tchakerian, V.P., 1996, Geomorphology and sediments of sand ramps in the Mojave Desert: Geomorphology, v. 17, p. 151–166.

Lustig, L.K., 1965, Clastic sedimentation in Deep Springs Valley, California: U.S. Geological Survey Professional Paper 352F, p. 131–92.

McAuliffe, J.R., and Van Devender, T.R., 1998, A 22,000-year record of vegetation change in the north-central Sonoran Desert: Paleogeography, paleoclimatology, and paleoecology, v. 141, p. 253–275.

McDonald, E.V., 1994, The relative influences of climatic change, desert dust, and lithologic control on soil-geomorphic processes and hydrology of calcic soils formed on Quaternary alluvial-fan deposits in the Mojave Desert, California [Ph.D. thesis]: Albuquerque, University of New Mexico, 383 p.

McDonald, E.V., and McFadden, L.D., 1994, Quaternary stratigraphy of the Providence Mountains piedmont and preliminary age estimates and regional stratigraphic correlations of Quaternary deposits in the eastern Mojave Desert, California, *in* Wells, S.G., et al., eds., Quaternary stratigraphy and dating methods: Understanding geologic processes and landscape evolution in southern California, *in* McGill, S.F., and Ross, T.M., eds., Geological investigations of an active margin: Geological Society of America, Cordilleran Section Guidebook, p. 205–210.

McDonald, E.V., Pierson, F.B., Flerchinger, G.N., and McFadden, L.D., 1996, Application of a process-based soil-water balance model to evaluate the influence of late Quaternary climate change on soil-water movement in calcic soils: Geoderma, v. 74, p. 167–192.

McFadden, L.D., Ritter, J.B., and Wells, S.G., 1989, Use of multiparameter relative-age methods for age estimations and correlation of alluvial fan surfaces on a desert piedmont, eastern Mojave Desert, California: Quaternary Research, v. 32, p. 276–290.

McFadden, L.D., Wells, S.G., Brown, W.J., and Enzel, Y., 1992, Soil genesis on beach ridges of pluvial lake Mojave: Implications for Holocene lacustrine and eolian events in the Mojave Desert, southern California: Catena, v. 19, p. 77–97.

Melton, M.A., 1965, The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona: Journal of Geology, v. 73, p. 1–38.

Miller, D.M., Glick, L.L., Goldfarb, R., Simpson, R.W., Hoover, D.B., Detra, D.E., Dohrenwend, J.C., and Munts, S.R., 1985, Mineral resources and resource potential map of the south Providence Mountains Wilderness Study Area, San Bernardino County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1780-A, scale 1:62,500.

Ore, H.T., and Warren, C.N., 1971, Late Pleistocene–early Holocene geomorphic history of Lake Mojave, California: Geological Society of America Bulletin, v. 82, p. 2553–2562.

Pendall, E.G., Harden, J.W., Trumbore, S.E., and Chadwick, O.A., 1994, Isotopic approach to soil carbonate dynamics and implications for paleoclimatologic interpretations: Quaternary Research, v. 42, p. 60–71.

Phillips, F.M., 1994, Environmental tracers for water movement in desert soils in the American southwest: Soil Science Society of America Journal, v. 58, p. 15–24.

Poesen, J.W.A., 1992, Mechanisms of overland flow generation and sediment production on loamy and sandy soils with and without rock fragments, *in* Parsons, A.J., and Abrahams, A.D., eds., Overland flow: Hydraulics and erosion mechanics: New York, Chapman and Hall, p. 275–306.

Ponti, D.J., 1985, The Quaternary alluvial sequence of the Antelope Valley, California, *in* Weide, D.L., ed., Soils and quaternary geology of the southwestern United States: Boulder, Colorado, Geological Society of America Special Paper 203, p. 79–96.

Quade, J., 1986, Late Quaternary environmental changes in the upper Las Vegas Valley, Nevada: Quaternary Research, v. 26, p. 340–357.

Reheis, M.C., Harden, J.W., McFadden, L.D., and Shroba, R.R., 1989, Development rates of late Quaternary soils, Silver Lake playa, California: Soil Science Society of America Journal, v. 53, p. 1127–1140.

Reheis, M.C., Sowers, J.M., Taylor, E.M., McFadden, L.D., and Harden, J.W., 1991, Morphology and genesis of carbonate soils on the Kyle Canyon fan, Nevada, USA: Geoderma, v. 52, p. 303–342.

Reheis, M.C., Slate, J.L., Throckmorton, C.K., McGeehin, J.P., Sarna-Wojcicki, A.M., and Dengler, L., 1996, Late Quaternary sedimentation on the Leidy Creek fan, Nevada-California: Geomorphic responses to climate change: Basin Research, v. 12, p. 279–299.

Rendell, H.M., and Sheffer, N.L., 1996, Luminescence dating of sand ramps in the eastern Mojave: Geomorphology, v. 17, p. 187–198.

Schumm, S.A., 1977, The fluvial system: Wiley, New York, 338 p.

Smith, G.I., and Street-Perrott, A.F., 1983, Pluvial lakes of the western United States, *in* Porter, S.C., ed., The late Pleistocene: Minneapolis, Minnesota, University of Minnesota Press, p. 190–212.

Spaulding, W.G., 1985, Vegetation and climates of the last 45,000 yr in the vicinity of the Nevada Test Site, south-central Nevada: U.S. Geological Survey Professional Paper 1329, 83 p.

Spaulding, W.G., and Graumlich, L.J., 1986, The last pluvial episodes in the deserts of southwestern North America: Nature, v. 320, p. 441–444.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C database and revised CALIB 3.0 14C program: Radiocarbon, v. 35, p. 215–230.

Taylor, E.M., 1988, Instructions for the soil development index template—Lotus 1-2-3: U.S. Geological Survey Open-File Report 233A.

Van Devender, T.R., Thompson, R.S., and Betancourt, J.L., 1987, Vegetation history of the deserts of southwestern North America; The nature and timing of the late Wisconsin-Holocene transition, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 323–352.

Wang, Y., Amundson, R., and Trumbore, S., 1994, A model for soil $^{14}CO_2$ and its implications for using ^{14}C to date pedogenic carbonate: Geochimica et Cosmochimica Acta, v. 58, p. 393–399.

Wang, Y., McDonald, E.V., Amundson, R., McFadden, L.D., and Chadwick, O., 1996, Paleoenvironmental implications of carbon and oxygen isotopes in alluvial soils, Providence Mountains, California: Geological Society of America Bulletin, v. 108, p. 379–391.

Wells, S.G., and Dohrenwend, J.C., 1985, Relict sheetflood bedforms on late Quaternary alluvial-fan surfaces in the southwestern United States: Geology, v. 13, p. 512–516.

Wells, S.G., McFadden, L.D., and Dohrenwend, J.C., 1987, Influence of late Quaternary climatic changes on geomorphic and pedogenic processes on a desert piedmont, eastern Mojave Desert, California: Quaternary Research, v. 27, p. 130–146.

Wells, S.G., McFadden, L.D., Anderson, R.Y., Brown, W.J., Enzel, Y., and Miossec, J-L., 1989, Late Quaternary paleohydrology of the eastern Mojave River drainage, southern California: Quantitative assessment of the late Quaternary hydrologic cycle in large arid watersheds: New Mexico Water Resources Research Institute Report No. 242.

Wells, S.G., McFadden, L.D., and Harden, J., 1990, Preliminary results of age estimations and regional correlations of Quaternary alluvial fans within the Mojave Desert of southern California, *in* Reynolds, R.E., et al., eds., At the end of the Mojave: Quaternary studies in the eastern Mojave Desert: Redlands, California, Special Publication of the San Bernardino County Museum Association, 1990 Mojave Desert Quaternary Research Center Symposium, May 18–21, 1990, p. 45–54.

Wells, S.G., Brown, W.J., Enzel, Y., Anderson, A., and McFadden, L.D., 1994, A brief summary of the late Quaternary history of pluvial Lake Mojave, eastern California, *in* Wells, S.G., et al., eds., Quaternary stratigraphy and dating methods: Understanding geologic processes and landscape evolution in southern California, *in* McGill, S.F., and Ross, T.M., eds., Geological investigations of an active margin: Geological Society of America, Cordilleran Section Guidebook, p. 182–188.

Wigand, P.E., and Rhode, D., 2002, Great Basin vegetation history and aquatic systems: The last 150,000 yr: Smithsonian Contributions to Earth Sciences, no. 33, p. 309–368.

Yair, A., 1987, Environmental effects of loess penetration into the northern Negev Desert: Journal of Arid Environments, v. 13, p. 9–24.

Yair, A., 1992, Headwater control on channel runoff, *in* Parsons, A.J., and Abrahams, A.D., eds., Overland flow: Hydraulics and erosion mechanics: New York, Chapman and Hall, p. 53–68.

Yair, A., and Enzel, Y., 1987, The relationship between annual rainfall and sediment yield in arid and semiarid areas: The case of the northern Negev: Catena Supplement 10, p. 121–135.

Manuscript Accepted by the Society August 1, 2002