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Late Quaternary variations in alluvial fan sedimentologic and geomorphic processes, Soda Lake basin, eastern Mojave Desert, California

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ABSTRACT

Alluvial fans at the front of the Soda Mountains at Zzyzx, in the Mojave Desert, California, have responded differently to late Pleistocene to Holocene climatic changes. The alluvial fans have been mapped in the field and the depositional facies interpreted as debris-flow and fluvial channel and sheetflood sediments. The relative age relationships of the fan segments have been determined primarily on the basis of soil development. The overall sequence has been established in relation to dated shorelines of late Pleistocene pluvial Lake Mojave, and the ages suggested by regional correlations. Six sets of alluvial fan deposits have been identified and labeled, oldest to youngest, Qf0–Qf5. Qf0 and Qf1 sediments predate pluvial Lake Mojave I (18.5–16.5 ka). Qf0 sediments are seen only in sections in fanhead trenches. Soil characteristics and regional correlations suggest an age for Qf0 much greater than for Qf1. Qf1 appears to date from the late Pleistocene, but prior to the Lake Mojave I highstand. Qf2 dates from the period following the Lake Mojave I and II highstands (18.4–16.6–13.7–11.4 ka) but prior to the youngest dated shoreline of pluvial Lake Mojave (10–9.3 ka). Fan depositional phases Qf3–Qf5 postdate the youngest lake shoreline, and are therefore Holocene in age.

From the late Pleistocene to the Holocene there was a switch from deposition dominantly by debris-flow to fluvial channel and sheetflood processes, which was accompanied by changes in fan style from fan aggradation to progradation and dissection. However, during the mid Holocene (ca. 4.3–3.5 ka) the Qf4 sediments suggest a short-lived reversal of this trend with a local increase in sedimentation and a short-lived reversion to debris-flow deposition on some fans. Different fans along the mountain front responded differentially to climatic change over the period since the late Pleistocene, with the largest fans switching from debris-flow to fluvial processes first, and some of the smallest fans becoming inactive during the Holocene. The results indicate that the fan processes are controlled by water and sediment supply from the hillslopes, switching as these processes changed in response to climatic changes. There is no evidence for tectonically induced change over this period, and changes in fan geomorphology induced by base-level change are restricted to the toe areas of some fans. At the local level, topographic catchment thresholds control the response of individual fans to climatically induced changes in runoff and sediment supply.

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INTRODUCTION

Geomorphologists and sedimentologists are confronted with the challenge to elucidate the relative influence of tectonic activity, climatic change, and intrinsic geomorphic conditions on alluvial fan processes (Bull, 1977; Nilson, 1982; Frostick and Reid, 1989; Blair and McPherson, 1994; Ritter et al., 1995; Harvey, 1997). Wells et al. (1997) have argued that the identification of regional patterns of age relationships of alluvial fan surfaces provide an indication of the underlying controls of alluvial fan depositional sequences, whereby:

1. geologically instantaneous and contemporaneous deposition over a series of fans within a restricted area would imply control by intrinsic thresholds related to individual storm events;
2. temporally limited but regionally correlative fan deposition would imply response to regional climatic change; and
3. long-term, regionally noncorrelative fan deposition would imply tectonic control.

Previously we have demonstrated that geologically instantaneous storm-generated deposition yielded significant spatial and temporal variations in alluvial fan facies within northwest England (Wells and Harvey, 1987). Those variations were a result of intrinsic thresholds influenced by the geomorphology of individual watersheds, which in turn controlled water-to-sediment ratios during the storm event. We hypothesized that, for those small alluvial fans, intrinsic thresholds serve as a primary control on the depositional and geomorphic processes, whereas, fluctuations in climatic and tectonic regimes are secondary controls operating over larger regions and over longer periods of time. In this paper, we test this hypothesis and elucidate the spatial and temporal variations in sedimentologic and geomorphic processes operating on alluvial fans in the Mojave Desert, California. These fans are in a very different environment, and include fans that are that are significantly larger and that formed over longer periods of time.

Age control for sequences of alluvial fan deposition in arid continental environments is uncommon. However, recent work within the eastern Mojave Desert over the past decade has established a regional chronology for geomorphic and environmental change spanning the last 100 ka. This has been based on: (1) studies of soil-profile development (Wells et al., 1987; Reheis et al., 1989; McFadden et al., 1989); (2) radiocarbon age estimation of pedogenic carbonate (McDonald, 1994; McDonald and McFadden, 1994; Wang et al., 1994, 1996; McDonald et al., 1996); (3) cosmogenic dating of surface exposure and K-Ar and Ar-Ar dating of basalt lava flows (Turrin et al., 1984; Wells et al., 1995); (4) radiocarbon-dated geomorphic and sedimentologic features associated with pluvial lakes (Wells et al., 1987, this volume; McDonald et al., this volume); and (5) luminescence-dated eolian deposits (Clarke, 1994; Amundson et al., 1994; Lancaster and Tchakerian, this volume).

In this paper, we capitalize on this setting to establish a stratigraphy for 15 alluvial fan complexes at Zzyzx, situated along the mountain front of the southern Soda Mountains (Fig. 1). We identify changes in the sedimentology and geomorphology of the stratigraphic sequences that occurred during fan development. The Zzyzx area provides an opportunity to document differential fan behavior since the late Pleistocene. The fans are fed by a range of different-sized catchments on a variety of bedrock geologies, and extend to the margins of Soda Lake, a modern playa occupying the floor of the lake basin of Pleistocene pluvial Lake Mojave (Fig. 1). The high lake shorelines have been dated (Wells et al., 1987, 1990a; Enzel et al., 1989a), and the morphostratigraphic relationships between them and fan segments allow a broad chronology of fan development to be identified.

First we establish the stratigraphy of the alluvial fan surfaces in relation to the framework provided by the paleo-shorelines. We characterize the fan surfaces by their soil profile development, and by correlation, we set the sequence within its regional context. In the second part of the paper we describe the geomorphic development of the fan complexes within the timeframe established from the soil chronosequences. We identify different patterns of morphological development, related to threshold-controlled responses to climatic change over the last 30 ka.

Late Pleistocene to Holocene environmental change in the Mojave Desert

Evidence for previous climates in the Mojave Desert comes primarily from two sources: paleo lake levels (Wells et al., 1998, this volume) and vegetation reconstructions based on pollen and macro plant remains preserved in packrat (*neotoma*) middens (Van Devender, 1977; Spaulding, 1985, 1990; Wells and Woodcock, 1985; Woodcock, 1986; Grayson, 1993). Lake levels in pluvial Lake Mojave were high during the late Pleistocene, reaching maxima at 18.5–16.5 ka and 13.7–11.4 ka, in response to strong zonal atmospheric circulation (Knox, 1984) and a southward shift in the midlatitude westerlies bringing high precipitation to the Transverse Ranges (Wells et al., 1990a). This circulation broke down during the Pleistocene-to-Holocene climatic transition (Bull, 1991), and meridional circulation allowed the penetration of subtropical "monsoonal" air into the Mojave Desert (Bryson and Lowry, 1955; Bryson, 1957), bringing summer convectional rainstorms. Lake Mojave desiccated after ca 9.3 ka, but shallow lakes have formed episodically during the Holocene in response to northern Pacific air masses bringing high precipitation to the Transverse Ranges in winter (Enzel et al., 1989a, 1989b; Wells et al., 1990a, 1998; Enzel and Wells, 1997). Today, several weather types cause flooding in the desert southwest (Ely, 1997), of which monsoonal conditions are the most likely to cause geomorphic activity in small desert mountain catchments.

The late Quaternary vegetation sequence in the Mojave region reflects the climatic sequence, with a general lowering of vegetation zones during the Pleistocene, but an increase in elevation during the Holocene. However, altitudinal vegetation reconstructions for late Pleistocene in the Mojave suggest that the limited elevation of the Soda Mountains was insufficient for the development of Juniper woodland (Harvey et al., 1999). Throughout the late Pleistocene and early Holocene the vegetation of the

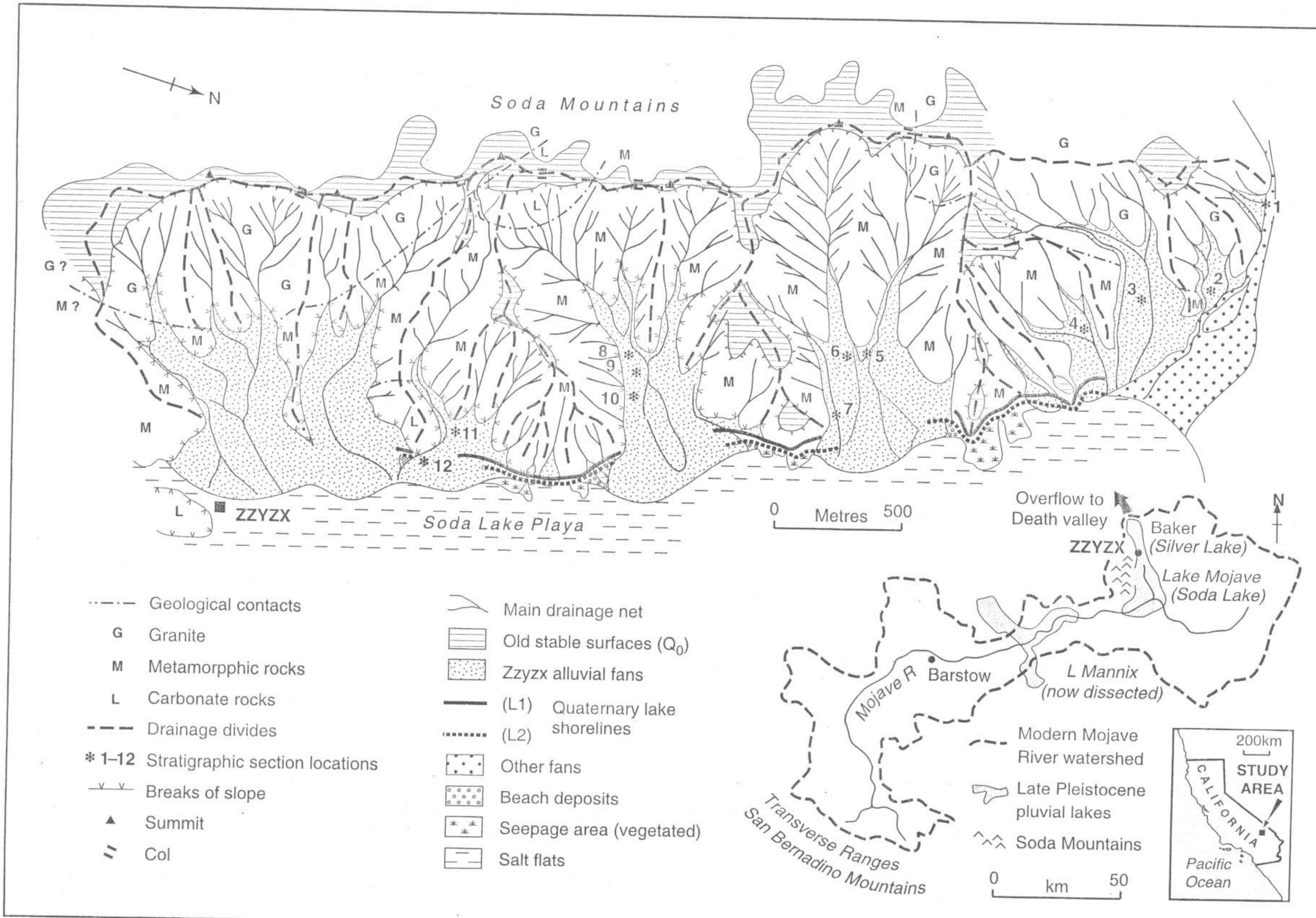

Figure 1. General and location maps of the southern Soda Mountains and Zzyzx fans, showing Geology and locations of shorelines of pluvial Lake Mojave. Also shown are locations of described sections (see Fig. 6). Insets show location within California and within the Mojave River system.

Soda Mountains and the Zzyzx fans would have been temperate desert scrub. The modern thermophilous desert vegetation developed following the mid-Holocene (Grayson, 1993).

Previous work on alluvial fans in the Mojave Desert and adjacent areas (Bull, 1991) indicates that fans responded to climatically induced pulses of sediment, supplied from the hillslopes of the catchments or from dissection of older fan deposits. Major late Pleistocene fan accumulation from active hillslope sources has been recognized in Death Valley (Denny, 1965; Hunt and Mabey, 1966; Bull, 1991; Blair and McPherson, 1994), and within the Mojave basin at Silver Lake (Wells et al., 1987, 1990b; McFadden et al., 1989) and in the Providence Mountains (McDonald and McFadden, 1994; McDonald et al., 1996; McDonald et al., this volume). A major pulse of activity has been identified during the Pleistocene to Holocene climatic transition (Bull, 1991; Harvey et al., 1999), coincident with major piedmont flooding (Wells and Dohrenwend, 1985). In these areas pulsed phases of fan activity occurred at various times during the Holocene. Previous studies of the Zzyzx fans include a general description (Wells et al., 1990c), general morphometric summaries (Harvey, 1992a, 1992b), a consideration of contrasts in hillslope processes within the fan catchments between the late Pleistocene and the Holocene (Harvey and Wells, 1994), and a consideration of the effects of the late Pleistocene to Holocene climatic transition on fan processes (Harvey et al., 1999). In this paper we present a detailed study of the fan geomorphic and sedimentologic sequences within the context of the regional alluvial fan sequences, and consider how the morphology of the Zzyzx fans responded to climatically induced changes in fan processes since the late Pleistocene.

RESEARCH AREA AND METHODOLOGY

The Zzyzx fans are located at the mountain front along the eastern margin of the southern Soda Mountains in the eastern Mojave Desert (Fig. 1). The mountain front is tectonically stable, according to the criteria of Bull (1978), and the fans have backfilled into the mountain catchments. These catchments are developed on three major Mesozoic bedrock lithologies; granitic rocks, metavolcanics, and limestones (Fig. 1).

Two high lake shorelines of Pleistocene pluvial Lake Mojave are preserved as a zone of erosional notches on the bedrock interfluves between the fans, at ~10–12 m above the modern playa floor (elevation of the modern playa floor: ~275–280 m). These shorelines were formed during highstands, coincident with perennial lake stages Mojave I and II, between ca. 18.4–16.6 and 13.7–11.4 ka (Enzel et al., 1989a; Wells et al., 1990a, 1998, this volume; Brown et al., 1990), when the lake reached 287 m and 285 m altitudes, respectively. On the fans one composite shoreline zone can be identified at about this altitude (L1 on Figure 1). A lower shoreline is evident ~2–3 m above the margins of the modern playa, this shoreline, at ~280 m, is probably the equivalent of the lowest ancient shoreline identified at Silver Lake, the northern extension of pluvial Lake Mojave (Fig. 1), and dated to ca. 10–9.3 ka (Wells et al., 1987). That shoreline (L2 on Figure 1) can be traced around the bedrock interfluves and across the fans at Zzyzx.

Geomorphic and sedimentologic mapping

Fifteen alluvial fan complexes were distinguished on the basis of geographic location, including from south to north: Southern (SOS, SOC, SON), Springer/Zzyzx (SPR, ZZX), Josh/Gate (JSG, GTE), Palm Cones (PC), Camino Viejo (CV), Johnny (JNF), Steve (STV), Mesquite (MSQ), Vulture (VLT), Solitary (SOL), and Northern (NOR) fan complexes (see Figure 2 for locations). They range from relatively large fluvially dominant fan complexes to small steep debris cones (Fig. 3), comprising stratified fluvial and sheetflood and massive debris-flow deposits respectively (Fig. 4). Within these 15 complexes, 32 individual alluvial fan apices have been identified (Fig. 2). The geomorphology and sedimentology of the fans were mapped in the field at a scale of 1:6000 onto base maps constructed from enlargements of the U.S. Geological Survey 1:24,000 topographic maps, with some details added from vertical black and white aerial photography. Morphology, sedimentology, and age-related properties of the fan surfaces were recorded on the base maps from observations in the field. Mapping of the fan morphology involved delineation of the major geomorphic units within each fan. In the fan-toe areas special attention was paid to the field relationships between these units and the shoreline remnants. The depositional characteristics of the fans were mapped on the basis of surface form and exposure of the sedimentary features in section, using a modification of the facies scheme previously developed (Table 1; Wells and Harvey, 1987).

Alluvial fan stratigraphy

Age relationships of the alluvial fan deposits were established by (1) observing topographic positions in relation to the pluvial lake shorelines, (2) observing and measuring postdepositional fan-surface modification, (3) recording basic stratigraphic relations (e.g., inset and overlapping), and (4) observing soil-bounded unconformities in vertical sections. On the basis of field relations with the shorelines and stratigraphic position, three groups of fan segments and associated stratigraphic units could be identified:

(i) Alluvial fan surfaces and their underlying deposits that are truncated by and therefore older than the oldest and highest shoreline (L1 on Figure 1) are designated as unit Qf1.

(ii) Alluvial fan surfaces and their underlying deposits that truncate the L1 shoreline zone, but which are truncated by the younger shoreline (L2 on Figure 1) are designated as unit Qf2. These were laid down during the period between the two shorelines.

(iii) Alluvial fan surfaces that truncate and therefore postdate the younger shoreline (L2 on Figure 1) are designated as units Qf3, Qf4, and Qf5 (oldest to youngest).

Differentiation between these three groups and between the three units within the youngest group was achieved on the basis

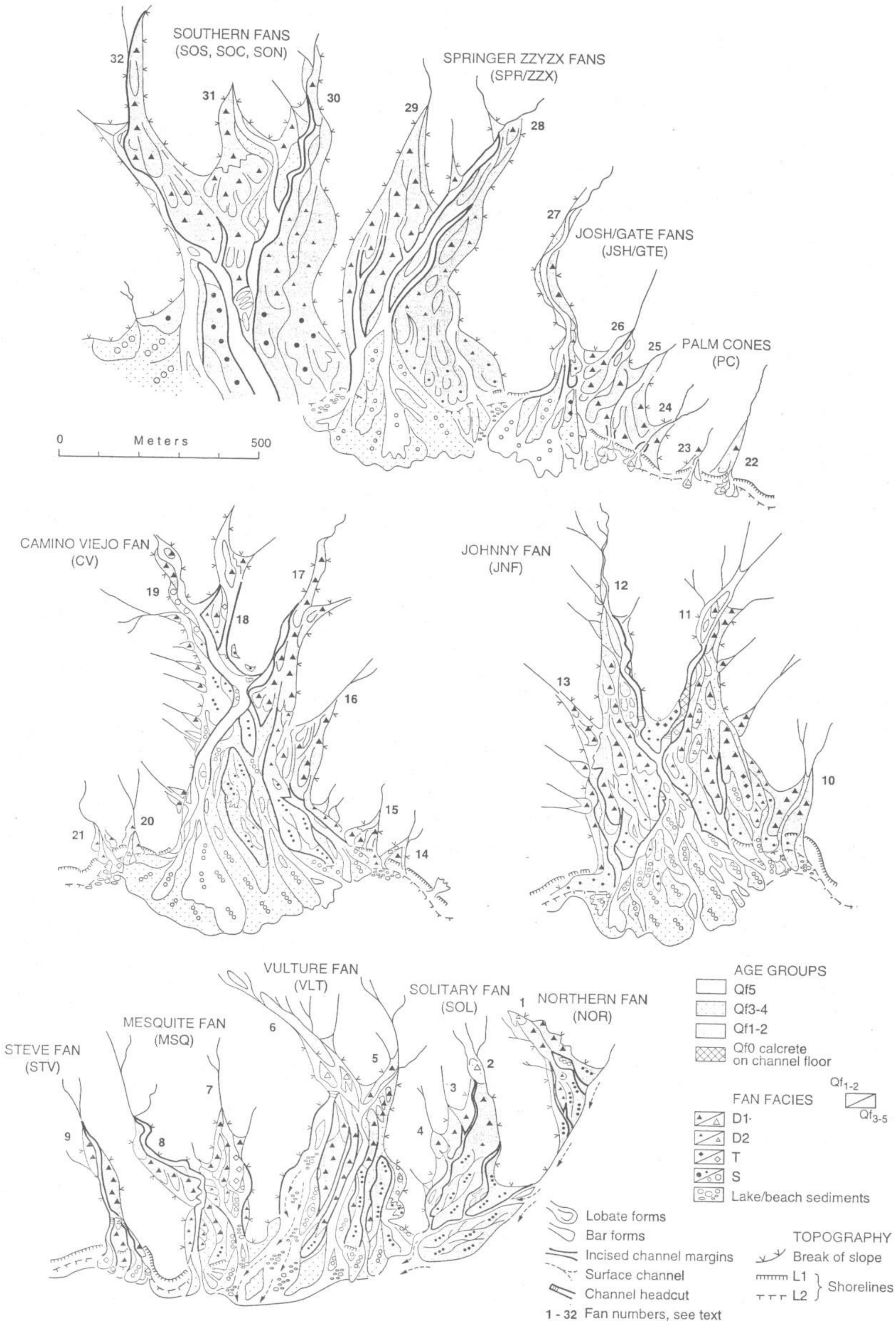

Figure 2. Summary map of the sedimentary units on the Zzyzx alluvial fans. Abbreviations in capitals refer to fan complexes, numbers refer to fan apices feeding discrete fan segments (see text). For the sedimentary units, solid symbols relate to Qf1–2 and open symbols to Qf3–5 age units.

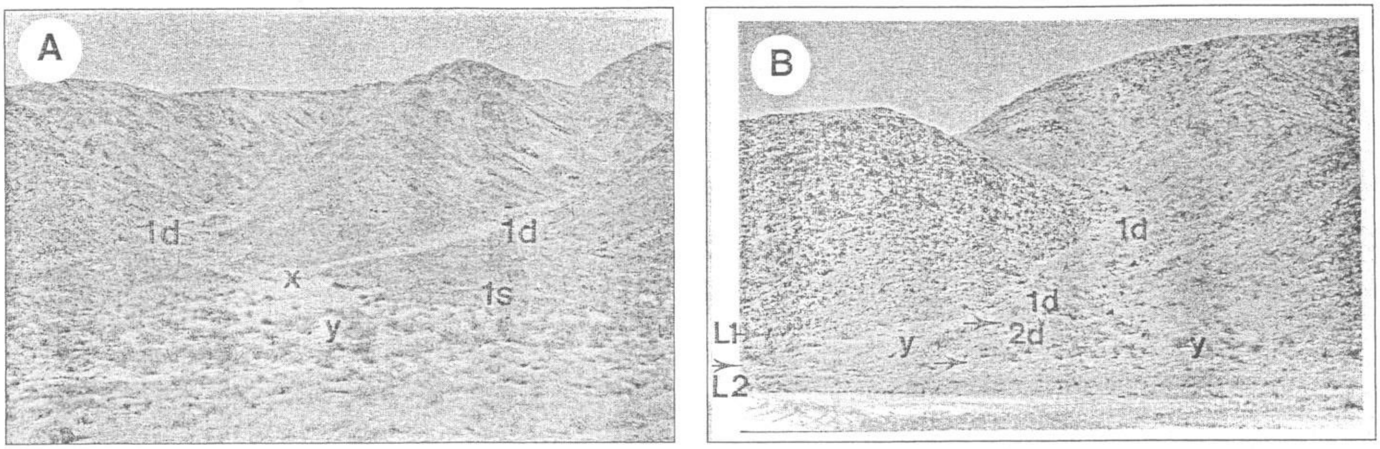

Figure 3. General views of selected Zzyzx fans. A: Johnny Fan, a large fluvially dominant fan. B: Steve Fan, a steep debris-flow dominated fan (for locations see Fig. 2). 1d—Qf1 debris-flow deposits; 1s—Qf1 fluvial deposits; 2d—Qf2 debris-flow deposits; x—location of Qf0 deposits exposed in fanhead trench; y—younger (Qf3–5) fan deposits; L1—upper shoreline; L2—lower shoreline.

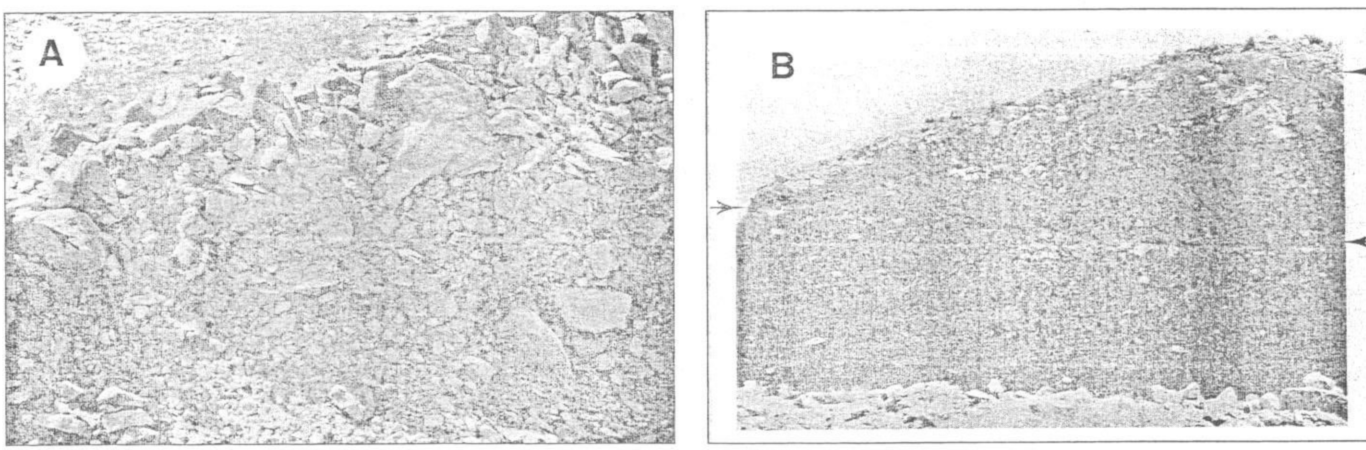

Figure 4. Examples of fan sediments. A: Coarse bouldery debris-flow deposits, Johnny Fan apex zone. B: Qf1 stratified, fluvial/sheetflood deposits; CV Fan midfan zone; arrows indicate erosional horizons.

of postdepositional modification of the fan surfaces, using criteria similar to those developed by McFadden et al. (1989), including rock weathering and varnish characteristics, and stone-pavement and soil-profile characteristics (summarized on Table 2). As observed throughout the Mojave Desert, rock weathering and varnish properties on alluvial fan surfaces show progressive changes with increasing age of deposits (Table 2). These surface properties vary with clast lithology (McDonald and McFadden, 1994). The clasts derived from carbonate source areas (Fig. 1) rarely develop varnish coatings, but do exhibit surface weathering features such as solution pits and microrills (cf. Amit and Gerson, 1986). The clasts derived from metavolcanic and mixed granitic source areas (Fig. 1) develop more extensive and thicker rock varnish coatings on progressively older fan surfaces. Granitic clasts on the older fan (Qf1) surfaces show both development of varnish coatings on some clast faces, and chemical and mechanical weathering by granular disintegration on others.

Stone pavement shows progressive development from no pavement on young (Qf5) fan surfaces to moderately developed pavements (terminology after Al-Farraj and Harvey, 2000) on the oldest (Qf1) fan surfaces (Table 2). As recognized on fan surfaces throughout this region (Wells et al., 1987; McFadden et al., 1989), particle size decreases and clast angularity increases with increasing pavement development, resulting in a progressive obliteration of any original depositional fabric. There are, however, variations in pavement properties related to original particle size and lithology of the alluvial fan deposits, whereby larger clasts take longer to fracture and form uniform pavement surfaces. The physical and chemical weathering of carbonate and metavolcanic clasts is dominated by fracture processes, typically yielding angular and interlocking pavement clasts. Diminution of clasts derived from granitic sources appears to result from fracturing and granular disintegration, ultimately producing a fine gritty-textured pavement surface. The most mature pavements, however, do not occur on the alluvial fan surfaces, but on older planated bedrock surfaces

TABLE 1. SEDIMENTARY FACIES ON THE ZZYZX FANS

D1:	Bouldery debris flows; matrix-supported large cobbles and boulders, which in section and on the surface show pronounced basal shear and frontal compressional fabrics. Surface form is of pronounced lobe and levee topography.
D2:	Fluid, muddy debris flows; matrix-supported mud-rich debris flows. Higher matrix content and smaller clasts than D1. Less obvious compressional fabric. More subdued surface relief.
T:	Stony matrix-poor debris flows and transitional deposits; loose poorly sorted cobbles and small boulders with little or no matrix, little fabric other than packing. Surface form is lobate but with less relief than on D1.
S1:	Fluvial boulder bars; large imbricated boulders—clast-supported, usually showing nose to tail sorting in bar forms.
S2:	Fluvial cobble bars; large imbricated cobbles—clast-supported, usually showing nose to tail sorting in bar forms, more common than S1. In sections show erosional bases and moderate stratification and sorting. Surface form: lobate or bar-shaped.
S3:	Fluvial gravel sheets; gravel and cobble sheets—clast-supported, locally showing imbrication, usually well sorted, and in section good stratification. Subdued sheetforms locally showing bar and swale topography.

Note: Based on Wells and Harvey, 1987.

TABLE 2. SUMMARY OF AGE-RELATED FAN SURFACE CHARACTERISTICS

Qf1:	Dark, well-developed varnish on metavolcanic or granite clasts largely obscures rock texture. Granite clasts may also show granular disintegration. On smaller sediments, well-developed pavements of fractured angular clasts occur. The larger clasts are still intact, though they may show evidence of fracture. Original depositional fabrics are obliterated. Soils show 7.5YR hue and stage II $CaCO_3$.
Qf2:	Dark varnish is present on metavolcanic and granite clasts, but rock texture is still visible through the varnish. Moderate pavement development occurs on smaller sediments, with minor fracturing of larger clasts. Original depositional fabrics are faint. Soils are thin, with A/B horizon differentiation, 10YR hue, and stage I + $CaCO_3$.
Qf3:	Spotty, pale reddish varnish occurs. There is incipient pavement development, with little or no fracturing but original depositional fabrics are only weakly preserved. Soils (10YR hue) have little or no horizon differentiation.
Qf4:	No varnish occurs, but clasts appear darkened. There is no pavement development; nor is fracturing evident, and original depositional fabrics are unaltered. There is incipient soil accumulation.
Qf5:	This unit comprises unaltered fresh sediment.

such as spur tops and summits (designated Q0, Harvey and Wells, 1994). On these low-relief surfaces the pavement is composed of relatively uniform, small, angular clasts derived from the underlying bedrock, together with fragments of fractured petrocalcic layers (caliche rubble, Lattman, 1973), derived from pedogenic K horizons capping the bedrock surfaces.

Soil morphology and stratigraphy

Many previous studies have used soil chronosequences to aid the correlation and relative dating of dry-region alluvial depositional surfaces (e.g., McFadden and Weldon, 1987; McFadden et al., 1989; Harden, 1990; Bull, 1990, 1991; Harvey et al., 1995) based primarily on field descriptions of soil horizon development (Harden, 1982, 1990; Birkeland, 1985, 1990; Harden et al., 1991) and on soil $CaCO_3$ status (Gile et al., 1966, 1981; Machette, 1985). We described soil profiles at 7 sites covering the relative age range of the Zzyzx fan surfaces. All sites were on fans GTE and JNF (Fig. 2), fed by the dominant metavolcanic lithology. Stable sites were selected (i.e., surfaces displaying minimum evidence of vertical erosion or deposition) in order to assess the maximum degree of soil development associated with a particular fan surface. Soil profiles were described in the field using the terminology of the Soil Survey Staff (1975). Twelve main soil properties were recorded at each site (Table 3). In addition, special features, such as the degree of clast weathering, were noted for each horizon where appropriate. The vertical arrangement of the soil horizons and their properties were described from the land surface down to the parent material and/or bottom of the cut. In addition, the properties of the land surface features (i.e., topography, vegetation, slope aspect) near each profile site were recorded.

SOIL CHRONOSEQUENCES AND SOIL STRATIGRAPHY

The soil profiles on the Zzyzx fans (Table 3) show comparable patterns of profile development to those described by Wells et al. (1987) and McFadden et al. (1989) on alluvial fans along the northern Soda Mountains in the Silver Lake basin (Fig. 1). A common horizon in both areas is the vesicular A (Av or Avk) horizon, ranging in thickness from 0.5 to 4 cm (McFadden, 1988; McFadden et al., 1986, 1998). These vesicular horizons

TABLE 3. FIVE PEDONS (A–E) SUMMARIZING MORPHOLOGICAL AND PHYSICAL CHARACTERISTICS OF SOILS DEVELOPED ON ALLUVIAL FAN DEPOSITS ALONG THE SODA MOUNTAINS NEAR ZZYZX, CALIFORNIA

Horizon	Thickness (cm)	Color Dry	Texture %G <2mm	Structure	Consistency Dry–wet	$CaCO_3$	Clay films	Pores	Roots	Salts	Comments
Pedon A. Geomorphic position: alluvial fan (Qf1) surface. Topographic position: cut in wall of fanhead trench. Slope: ~8°. Parent material: debris flow deposits, metavolcanic clasts. Vegetation: creosote, cactus, woody species <1%. Pavement: moderate, partially interlocked, some fracturing, metavolcanic clasts. Varnish: well developed; top 5YR 2.5/2, base 5YR 6/4, max 5YR 5/4.											
Avk	0–4	10YR 6/4; 4/4	35–40LfS granules pebbles	2 fpl 1 fsbk	so–so, po sh	Very e→n.o.	n.o.	vt–vf fdv	3f–vf	n.o.	
Btk	4–15	10YR 5/6, 8.75YR 5/4	60% SiL granules to boulders	3 cgr 1 msbk	shs, p	ev, d & s Coats: Stage I very discontinuous Top: carbonate as a result of silt (red) imput	Co 1 nbr	3 ft	3 vf: f	n.o.	Buried varnished stone
Btk$_2$	15–30	8.75YR 7/4; 10YR 5/6(u)	75% fSL cgr-boulder	Sg 1 fgr	loss, sp	Carbonate coats; clay film with thin discontinuos carbonate (sides almost continuous); highly variable, 3% to 100%	Clay films on clast tops Clay is n.o. effervescent m = es,d	inter	3 f & fv	n.o.	Salty taste throughout
Bwk	30–54	8.75YR 7/4; 10YR 5/6	>75%fSL 80–90	Sg lfgr	loss, ps	Nearly continuous; weakly laminar	n.o.	inter	3 vf		Carbonate: top—red silt; e, d; bottom—Stage I+; (≈1mm)
Bwk2	54–85	8.75YR 7/3; 10YR 5/6	>90%LfS	Sg	loso, po	es, d; thick coats on bottom; some continuous; red silt coats tops of clast; carbonate bottom, <1 mm	n.o.	Inter	1 vf & f		Carbonate rind different from above, more grainy, less thick
Btkb	85+	clay: 7.5YR 6/4 7.5YR 5/6 carb: 10YR 8/3		locally matrix gr→fsbh	H	Stage III: much carbonate that impregnates this horizon may be flushed through from above. Evidence: carbonate impregnated Bt matrix	co, & 1 nbr	n.o.		n.o.	
Pedon B. Geomorphic position: alluvial fan (Qf2) surface. Topographic position: channel cut into terrace in Qf2 gravels, 10 m up fan from burrow pit. Slope: ~5°. Parent material: alluvial fan gravels, metavolcanic clasts. Vegetation: creosote, saltbrush. Pavement: large clasts, weak. Varnish: moderate.											
Avk	0–3	10YR 6/4,5/4	>80%LS	2msbk	Sono, po	Noneffer	n.o.	2f & m v	3f & vf	n.o.	
Bwk	3–20	8.75 7/4(mixed) ped surface: 7.5YR 7/4	>70% SL	f & m/lo gr	soss, so lo	Matrix: noneff Very rare, very thin coating on sides, bottom of gravel	Co	Inter	2vf & f	n.o.	
Bk	20–35	8.75YR 7/4; 5/4 mixed	>90%SL (mostly pebbles)	Sg	lono, po	Matrix: es Gravel: 10%–80%; bottom coated with thin (<0.5m) $CaCO_3$; highly variable	n.o.	Inter	3f	n.o.	
Bky	35–60	10YR 6/4, 5/4	90% SL	Sg	loss, sp	Matrix: e Gravel: 10%–30% of bottom covered by very thin coating	n.o.	Inter	2vf & f	Gypsum crystal on one clast base	
Bk	60–70+	10YR 7/3,5/4	79%SL	Sg	loss, sp	Matrix: es Gravel: discontinuous, thin (<0.5mm on 20%–50% of clast bottom)	n.o.	Inter	n.o.	n.o.	

TABLE 3. FIVE PEDONS (A–E) SUMMARIZING MORPHOLOGICAL AND PHYSICAL CHARACTERISTICS OF SOILS DEVELOPED ON ALLUVIAL FAN DEPOSITS ALONG THE SODA MOUNTAINS NEAR ZZYZX, CALIFORNIA (continued)

Horizon	Thickness (cm)	Color Dry	Texture %G <2mm	Structure	Consistency Dry–wet	$CaCO_3$	Clay films	Pores	Roots	Salts	Comments
Pedon C. Geomorphic position: alluvial fan (Qf2) surface and on depositional bar. Topographic position: excavation into stream-cut in bar. Slope: 5–8°. Parent material: alluvial fan gravels. Vegetation: saltbrush, creosote, cactus, 5% cover. Pavement: moderate. Varnish: moderate to dark. Profile exhibits evidence of bioturbation (infilled burrow); strongly developed Bt associated with burrow.											
Av	0–3	10YR 6/4, 4/4	>80SL	2fpl	Soft vss, po	Top = n.o. n.o.	n.o.	3f & vf vesic.	2f	n.o.	
B	3–16	7.5YR 6/4, 4/6	>90SL	Sg	loss, po	Red silty caps clast; minimal amount on bottom; n.o.	n.o. coats on stone	inter	2vf f	n.o.	Bt is not observed.
Bt	16–35	Ped 7.5YR 5.5/6 5YR 5/4 H: 7.5YR 5/6; (w) 5/4	75ScL	Fsbk gr	hs, p	n.o.	2nbr films on stones 2n films on grain	inter	1vf	n.o.	
C (burrow)	35–45	10YR 7/3; 5/4	65 granule pebbles S	Sg	loso, po	n.o.	n.o.	inter	2f	n.o.	
Btkb	45–63	6.75YR 6/4; 10YR 5/6	>90SL	M	hs, p	Stage I: discontinuous coats, sides and bottom Weakly–slightly e, d	1nbr 1n film grain	inter	3f	n.o.	
Bk1b	63–104	10YR 7/4; 4/4	>80LfS	sg	lono, po	Coating thickness = 0.1–0.5 mm Matrix: strongly effective carbonate on side (thin) and discontinuous on bottoms	n.o.	inter	2f 1m	n.o.	Clear, smooth?
Bk2	104–128+	10YR 6/4, 4/4	>80LS	sg	loso, po	Eff, d; red fine sand and silt in clast top; thin discontinuous coats on bottom; maximum 20% cover, most less	n.o.	inter	1f	n.o.	
Pedon D. Geomorphic position: alluvial fan (Qf3) surface. Topographic position: inset terrace, within fan. Slope: ~5° Parent material: alluvial fans gravels, metavolcanic clasts. Vegetation: creosote, grasses. Pavement: weak. Varnish: slight to moderate.											
Av	0–2.5	10YR 6/4; 5/4	30LfS	cpl	so–so,po sh	e, d	n.o.	vf–f dv & t	3vf–f	n.o.	Locally few vesicles
Bwk	2.5–30	10YR 6/6; 4/5	>90LS	m; lmgr	so–vss,po lo	es, d; fine red silt in top; bottom–very thin on side; very rare thin coat but on few clast	n.o	inter	2f–vf	n.o.	
Bk	30–70	10YR 6/4; 5/6	>80S	sg	loso,po	Thin discontinuous on bottoms; 40% to 50% cover; es, d; % decrease with depth	n.o.	inter	n.o.	n.o.	
Bk2	70–80+	10YR 6/4; 4/6	>90LS	sg	loso,po	Very thin discontinuous coat that thins with depth; es, d	n.o.	inter	n.o.	n.o.	

TABLE 3. FIVE PEDONS (A–E) SUMMARIZING MORPHOLOGICAL AND PHYSICAL CHARACTERISTICS OF SOILS DEVELOPED ON ALLUVIAL FAN DEPOSITS ALONG THE SODA MOUNTAINS NEAR ZZYZX, CALIFORNIA (continued)

Horizon	Thickness (cm)	Color Dry	Texture %G <2mm	Structure	Consistency Dry–wet	$CaCO_3$	Clay films	Pores	Roots	Salts	Comments
Pedon E. Geomorphic position: alluvial fan (Qf4) surface, depositional bar. Topographic position: stream cut into bar on fan surface. Slope: ~5°. Parent material: Alluvial fan gravels, metavolcanic clasts. Vegetation: creosote <5%, saltbrush, cactus. Pavement: none. Varnish: none to very slight. Varnish on some clasts, interpreted as reworked from older fan deposits surface clasts bases 7.5 YR 6/6 exhibit salt weathering cryptographic surface crust.											
Av	0–2	10YR 7/3; 4/3	>80LS	2msbk	soso,po	e, d	n.o.	3vf & fdv	3f	n.o.	
Bk	2–18	10YR 7/4; 4/4	>80LS	sg	loso,po	e, d Very rare on side and clast bottom (<1%)	n.o	inter		n.o.	
Bk2	18–43	10YR 6/4; 5/4	>90LS	sg	loso,po	es, d Discontinuous on sides; <1–22 at bottom silt cap	n.o.	inter	2f–vf	n.o.	
Bk3	43–69+	10YR 7/4; 4/4	>90S	>sg	loso,po	Very thin (<0.1 mm); side/bottom; <1% of clast surface; w/r, e, d	n.o.	inter	n.o.	n.o.	Silt (red) on clast surface. Reworked carbonate coated pebbles.

Note: Terminology (abbreviations) follows Soil Survey Staff (1975).

commonly occur beneath very weakly to strongly developed pavements. Stone pavements and Av horizons are genetically linked, forming by aeolian accretion, dilation, and vertical lifting processes (Wells et al., 1985; McFadden et al., 1986, 1998; McDonald, 1994; McDonald et al., 1996). Within the southern Soda Mountains the Av horizons are typically thicker on the relatively older fan surfaces, a trend observed by McDonald (1994) on the Providence Mountains fans. Such observations support the use of stone pavement and soil properties for estimating relative ages of the underlying alluvial fan deposits. In both regions of the Soda Mountains, the vesicular horizons developed on younger (e.g., units Qf3 and Qf4) and on the oldest (Qf1) alluvial fans contain disseminated pedogenic calcium carbonate (Avk horizons). Pedogenic calcium carbonate was not observed in the Av horizons developed on alluvial fan unit Qf2 within the Zzyzx area.

Fan surfaces and soils postdating the youngest Lake Mojave shorelines

The youngest alluvial fan surface (unit Qf5) shows no soil or pavement development, reflecting recent depositional processes on these fans. Alluvial fan unit Qf4 has relatively thick but weakly developed calcic (Bk) horizons (< stage I) with very thin, discontinuous carbonate coatings on the sides and bottoms of clasts. The broad distribution of pedogenic carbonate through the profile may result from the coarse texture (>80% gravel) and relatively high permeability of these deposits. Clasts within the soil horizons of unit Qf4 show signs of being reworked from older alluvial fan deposits. The top horizons contain buried clasts with degraded varnish coatings. The lower horizons include carbonate-coated pebbles in which the carbonate coatings are thick and degraded. On such clasts the thickest carbonate coatings do not occur systematically along the bottom or along the sides of the clasts. These data indicate that coarse sediment within alluvial fan unit Qf4 is derived, in part, from older fans that have better-developed soils with thicker accumulations of pedogenic calcium carbonate. Reworking of older soils into unit Qf4 occurs in part because these deposits are inset within and topographically below the older fan deposits. The maximum horizon dry color is 10YR 6/4, indicating almost no reddening.

The soil formed in the next oldest fan, unit Qf3, is similar to unit Qf4 in that it is coarse grained with thick but weakly developed calcic horizons. The profile of unit Qf3 is different, however, in that it contains a weakly developed 27-cm thick Bwk horizon and stage I carbonate horizon (Table 3). Fine pink to very pale brown (maximum color 8.75YR 7/4) silt can be observed capping coarser clasts.

Fan surfaces and soils predating the youngest Lake Mojave shorelines

Alluvial fan unit Qf2 truncates the highest shoreline of pluvial Lake Mojave (L1), but is truncated by the youngest Lake Mojave shoreline (L2). Soil profiles developed on alluvial fan unit

Qf2 show significant spatial variations on some alluvial fans (Table 3). Pedon B is characterized by Av-Bwk-Bk-Bky-Bk horizons, whereas Pedon C is characterized by Av-Bw-Bt-C horizons. Maximum dry colors for Pedon B are typically 8.75YR 7/4 both on ped faces and on disaggregated samples with loose to granular structure in the Bwk horizon. Pedon C displays maximum dry colors of 5YR 5/4 and is subangular blocky in the Bt horizon. Spatial variations in profile development have been observed by McDonald and McFadden (1994) on fan surfaces in the Providence Mountains, and they have correlated these fans to unit Qf2 in our study area. However, in the southern Soda Mountains, the spatial variability in profile development appears to reflect spatial variation in bioturbation associated with burrowing. Higher permeability along these macropores may favor enhanced translocation of clays. Thus, the soil profile properties of Pedon B more accurately reflect the nature of soils developed on unit Qf2. This profile has pedogenic calcium carbonate accumulation stage I+.

The oldest stratigraphic unit that occurs on the alluvial fan surfaces (Qf1) is truncated by the highest shoreline (L1). The surfaces are characterized by the moderate to well-developed pavement with numerous overturned stones displaying 5YR 5/4 undersides. Many of the surface clasts have deeply weathered fractures, which penetrate at least 15% of the clast diameter. The soil profile developed in this unit is characterized by a 8.5YR 7/4 (maximum dry color), 26 cm Bt horizon. The degree of calcium carbonate accumulation varies between stage II+ with local zones of weak laminar layers (stage III). Where observed, the base of this unit lies stratigraphically over a truncated, very well developed soil in older alluvial fan sediments.

The oldest alluvial fan unit (Qf0) observed in the study region has no geomorphic expression at the land surface and occurs only where exposed in sections, buried by younger alluvial fan deposits. Unit Qf0 is distinguished from overlying alluvial fan deposits by a soil-bounded unconformity. The soil profile associated with the unconformity is always eroded such that the entire soil profile was never observed. Field morphologic descriptions show that the soil profile, prior to its truncation, was well developed. In places, the profile is characterized by a 7.5YR 5/6, subangular blocky Btkb horizon with stage III pedogenic calcium carbonate accumulation.

LOCAL AND REGIONAL CORRELATIONS AND AGE ESTIMATES FOR ALLUVIAL FAN DEPOSITS

Systematic description of soil and stone pavement properties remains one of most fundamental and consistent methods for establishing stratigraphic relations and for providing local and regional correlations of Quaternary deposits in arid environments. The soils within both the Soda and Silver Lake basins exhibit progressive changes in the morphological properties on successively higher and stratigraphically older alluvial fan deposits. In both areas, these changes can be used to establish a chronosequence because of similar parent material, elevation and regional topography, flora, and climatic history. However within the Soda Lake basin study area, the soils lack the direct isotopic age control determined for alluvial fans within the Silver Lake basin (Wells et al., 1998). Within the Soda Lake basin, age estimates of the soils and their underlying deposits are based on (1) the geomorphic relation of the fan deposits to the shorelines and (2) on correlations with a nearby soil chronosequence that has isotopic age constraints. Based upon comparisons between the soil profiles described above and the profiles of alluvial fans in the Silver Lake basin (Wells et al., 1987; Reheis et al., 1989) as well as those methods discussed above, we infer the following local correlations:

Those alluvial fans postdating the youngest shoreline (L2), units Qf5, Qf4, and Qf3 of the Zzyzx fans, correlate with the late Holocene Qf5–6, middle Holocene Qf4, and early Holocene Qf3, respectively, in the Silver Lake area.

Those alluvial fans forming between shorelines L1 and L2, unit Qf2, correlate with the latest Pleistocene to early Holocene Qf2 observed in the Silver Lake basin.

Those alluvial fans predating the highest shoreline L1, units Qf1 and Qf0, correlate with late Pleistocene Qf1 and middle (?) Pleistocene Qf0 alluvial fans of the northern Soda Mountains area.

A concern over the use of soil-geomorphic data for providing age estimations and for establishing regional soil-geomorphic correlations is that much remains unknown about how rates of pavement evolution and soil development vary with lithology. Many chronosequence studies have been limited to deposits composed of similar lithologies, e.g., igneous and metamorphic siliceous lithologies (Birkeland, 1990), or calcareous lithologies (Lattman, 1973; Gerson et al., 1985; Amit and Gerson, 1986; Harden et al., 1991; Amit et al., 1993; Al-Farraj and Harvey, 2000). Direct comparison among chronosequences composed of contrasting lithologies has been difficult because of a lack of adequate age control. Recent advances in Quaternary numerical dating techniques (luminescence and cosmogenic surface exposure dating), however, have enhanced the use of Quaternary alluvial units and geomorphic surfaces for interpreting local and regional geologic and climatic events within the Mojave Desert (Wells et al., 1990b, 1995, 1998; McDonald, 1994; McDonald and McFadden, 1994; McDonald et al., 1996). Using the Harden (1982) soil development indices (SDI), McDonald (1994), McDonald and McFadden (1994) and McDonald et al. (1996) have demonstrated that correlations yield reasonably consistent age ranges for alluvial deposits across the Mojave. Using the regional correlations of McDonald and McFadden (1994) and McDonald et al. (1996) and new dating results (Wells et al., 1995; Anderson and Wells, this volume, Chapter 6), we have refined the age estimates for the deposition of the Zzyzx fan sequences in the southern Soda Lake basin (Fig. 5).

The minimum age for our oldest fan unit (Qf0) is suggested by comparisons with soils in the Cima volcanic field (Wells et al., 1995) where stratigraphic relations between alluvial fans and basaltic lava flows are well defined and the lava flow surfaces have multiple cosmogenic surface-exposure dates. Given the minimal degree of Bt horizon preservation but the stage III pedogenic

		S Soda Mts (Zzyzx) This study	Estimated age (ka) a	Pluvial Lake Mojave b	Silver Lake and vicinity c	Providence Mountains d	Cima Piedmont e
HOLOCENE	Late	Modern sediments			Qf_5	Qf_9	Qf_9
HOLOCENE	Late	Qf_5	< 1.8		Qf_5 [Qe3]	Qf_8	Qf_8
HOLOCENE	Middle	Qf_4	4.3–3.5		Qf_4 (3.4)	Qf_7 (4.4–2.2)	Qf_7
HOLOCENE	Early	Qf_3	9.3–5.2		Qf_3 [Qe2]	Qf_6 (5.4–2.8)	Qf_6
HOLOCENE	Early	L_2	10–9.3	Youngest shoreline	Ql_2 (8.4)		
		Qf_2	11.5–9.3	Intermittent lake	Qf_2 (10.3–9.2) Qe_1	Qf_5 (18.1–10.4)	Qf_5
PLEISTOCENE	Late	L_1	14–11.5 18.4–16.6	Lake Mojave II (14–11.5) Lake Mojave I (18.4–16.6)	Ql_1 (20.3–14.7)		
PLEISTOCENE	Late	Qf_1	c 34–18.4		Qf_1	Qf_4 (28.7–26.9)	Qf_4
PLEISTOCENE	Late						Qv_5 (72–65)
PLEISTOCENE	Midde	Qf_0	> 68			Qf_3	
PLEISTOCENE	Midde						Qv_4 (130)
PLEISTOCENE	Midde						Qv_3 (170–150)
						Qf_2 (=Bishop Ash 780)	

Figure 5. Regional correlation between the late Quaternary sedimentary units recognized on the Zzyzx fans and those recognized on other fan groups within the eastern Mojave Desert. a—date ka, adopted in this study; b—from Brown et al. (1990), Wells et al. (1990a, 1997, this volume); c—from Reheis et al. (1989), Wells et al. (1997, 1998), Anderson and Wells (this volume, Chapter 6); d—from McDonald (1994), McDonald and McFadden (1994), McDonald et al. (1996), Wang et al. (1996); e—from McDonald and McFadden (1994), Wells et al. (1995).

$CaCO_3$ accumulation associated with Qf0, these fan deposits may be correlated with Cima alluvial fan unit Qf3 in the Cima volcanic field (McDonald and McFadden, 1994). The fan deposits in the Cima area are overlain by a basaltic lava flow (unit Qv4 of Wells et al., 1995), which has surface exposure ages of 65 ± 9 ka and 72 ± 7 ka. The lack of a well-developed Bkm (pedogenic petrocalcic and capping laminar layer) on Qf0 soils would suggest an age less than that of the Providence Mountains alluvial fans interbedded with the 0.74 Ma Bishop ash (unit Qf2 of McDonald and McFadden, 1994, and McDonald et al., 1996).

Alluvial fan unit Qf1 predates the high shoreline of Lake Mojave (L1, 18.4–16.6 ka) and postdates the buried sediments of unit Qf0. The suggested correlation of our Qf1 with alluvial fan unit Qf4 in the Cima volcanic field (McDonald and McFadden, 1994) suggests that Qf1 was deposited after ca. 34 ka, the average age of two cosmogenic surface exposure ages derived from a basaltic flow underlying that deposit. These bracketing ages are supported by recent work of Anderson and Wells (this volume, Chapter 6), in which Qf1 is correlated with alluvial fan deposits in the Dumont basin, north of Silver Lake, which have been radiocarbon-dated to between 30 and 18 ka. We favor an age closer to 30 ka because the relative degree of stone pavement and soil development appear to require at least >10,000 yr to form (Machette, 1985; McFadden et al., 1989; Amit and Gerson, 1986; Amit et al., 1993).

Alluvial fan unit Qf2 postdates the high shoreline zone (L1, 18.4–11.5) but predates the low shoreline (L2, 10–9.3 ka), thus falling within the late Pleistocene to early Holocene transition period (Wells et al., 1987, 1994, this volume; Harvey et al., 1999). Alluvial fan units Qf3, Qf4, and Qf5 postdate the low shoreline (L2, ca. 9.3 ka), and are therefore are all of Holocene age. Correlations between the Soda Lake basin fans and the IRSL- (infrared stimulated luminescence) dated alluvial fans of the Providence area and the radiocarbon-dated sequences of Silver Lake basin (Wells et al., 1987) and the Dumont basin (Anderson and Wells, this volume, Chapter 6) yield specific age estimates for the deposition of Qf3 between 9.3 and 5.2 ka, Qf4 between 4.3 and 3.5 ka, and Qf5 to post-1.8 ka.

LATE QUATERNARY GEOMORPHIC DEVELOPMENT OF THE ALLUVIAL FANS

The alluvial fans along the southern Soda Mountain front differ from one another in their age relations, morphology, and sedimentology, reflecting variations in their source-area geomorphology (Harvey and Wells, 1994; Fig. 1). The distal reaches of the all fans, excluding SOL and NOR (Fig. 2) toe out upon and interfinger with the fine-grained fill of the Soda Lake playa. Thus, the distal reaches of the alluvial fans have responded to a progressive basin-filling (Wells et al., 1989, this volume). Since the local lowering of base level through the fall in lake level to ca. 9.3 ka, the playa floor has been accumulating sediment. Over the past 10 ka, sedimentation rates on playa floors within this region range up to ~1.2 m/1000 yr (Wells et al., this volume). Thus, the distal geometry of the fan complexes may in part reflect a rise in base level of up to ~10 m during the Holocene.

The spatial distribution of sedimentary facies (Table 1) and stratigraphic units within the 15 alluvial fan complexes is illustrated in Figure 2. Not every alluvial fan complex exhibits the complete sequence of stratigraphic units; rather, some fan complexes are dominated by older stratigraphic units (i.e., SOL, NOR, SON on Figure 2) and others have extensive areas dominated by younger units (i.e., CV, VLT on Figure 2). On a limited number of fans sediments of the younger stratigraphic units are present near the fan apex (e.g., MSQ, VLT on Figure 2), whereas, on the majority of fans the younger stratigraphic units dominate the distal fan zones.

Sedimentology, morphology, and chronology of the alluvial fan complexes

At the northern end of the mountain front, two small fans (NOR, SOL, Figure 2) issue from relatively small drainage basins with moderate relief developed on granitic bedrock (Fig. 1). The distal fans are topographically above the former lake levels but have been trimmed by a channel of a large alluvial fan that wraps around the mountain margin. Both fan complexes are dominated by late Pleistocene sediments (unit Qf1, Figure 2). Proximal debris flows (D1 facies grading downfan to D2; Table 1) give way downfan to alternating debris flows and fluvial sheet gravels (D2 and S2 facies on Table 1; Fig. 6, sections 1, 2). The Qf1 fan surfaces are incised by ephemeral channels throughout their lengths, and Holocene fan deposits (primarily Qf4) occur within the wider reaches of these fan trenches. In the apices of these complexes, two generations of hillslope debris flows were deposited directly on the older fan surfaces. The older set of hillslope deposits (D1 facies, Table 1) are either late unit Qf1 or Qf2 age, and the younger hillslope deposits are Qf4 transitional deposits (T facies, Table 1).

The next set of alluvial fan complexes to the south are VLT, MSQ, and STV fans (Fig. 2), whose source areas are primarily in metavolcanic rocks, but with granitic terrain in the upper part of the catchment feeding VLT fan (Fig. 1). The distal portions of these complexes either are trimmed by the shorelines or prograde across the playa floor. On the VLT complex only the upper shoreline (L1, Figure 1) is clearly observed, but both upper and lower shorelines (L1, L2, Figure 1) are present on MSQ and STV fan complexes. These fan complexes are dominated by late Pleistocene (unit Qf1) sediments, debris flows (D1, D2 facies, Table 1) on STV fan and proximal debris flows, grading distally to fluvial sediments on VLT and MSQ fans (Fig. 2). Field relations provided evidence for a late phase of Qf1 sedimentation of significantly coarser bouldery D1 facies than in the earlier depositional events, which were dominated by more fluid debris flows (D2 facies; Figure 6, sections 3, 4). The late Pleistocene fan sediments are trimmed by shoreline L1 (Fig. 1), indicating that primary fan sedimentation had ceased in these reaches before 18.6 ka. Fan trenching followed Qf1 deposition, eroding through the L1 shoreline. Small volumes of unit Qf2 were deposited as insets within the trench and in the distal zones of VLT and MSQ fans topographically below the upper shoreline. During the Holocene, VLT and MSQ fan complexes have undergone proximal trenching and distal progradation of younger (mostly Qf4) fluvial sediments (S2, S3, Table 1). During the middle Holocene, young debris flows (Qf4) were deposited proximally, especially on MSQ fan complex (Fig. 2). On STV fan complex the L1 shoreline truncates Qf1 debris flows. Latest Pleistocene–early Holocene (Qf2) debris flows were deposited across the L1 shoreline, and prograded to beyond that shoreline, where these deposits were then trimmed by the L2 shoreline. Holocene Qf3, Qf4, and Qf5 transitional and fluvial deposits are inset below the L2 shoreline, prograding onto the Soda Lake playa.

The two largest fan complexes (JNF, CV, Figure 2) issue from catchments dominated by metavolcanic rocks, but with small exposures of granitic rocks in the northern subcatchment of JNF fan and limestone in the southern subcatchment of CV fan (Fig. 1). Both fan complexes are dominated by late Pleistocene (Qf1) sediments composed of proximal debris flows grading to stratified fluvial sediments in midfan (Fig. 6, sections 5–10). On the JNF complex, middle Pleistocene Qf0 sediments and an associated petrocalcic horizon are exposed by fan trenching in midfan and underlie the Qf1 sediments (Fig. 6, sections 5, 6). On both fan complexes major hillslope debris flows of late Qf1 or Qf2 age toe out on the Qf1 fan surfaces (Fig. 6, section 10). On both fan complexes, the distal portions of Qf1 segments are trimmed by shoreline L1 (Fig. 2). The Qf1 deposits were trenched proximally prior to the deposition of unit Qf2, which forms inset terraces within the fanhead trenches (Fig. 6, section 8), and then prograde from former intersection points to extensive distal fan surfaces of fluvial sediments. They are cut by shoreline L2 (Fig. 2). Further incision then occurred in the fanhead trenches of both fan complexes and Holocene (Qf3, Qf4, and Qf5) fluvial sediments were deposited as inset terraces within the fanhead trenches and prograded distally (Fig. 2).

South of CV fan complex there are several small debris cones (referred to as PC on Figure 2), and larger debris cones (GTE) of the composite JSH/GTE fan complexes (Fig. 2) that have source areas in metavolcanics. Both shorelines are well preserved along the mountain front in this area. The small PC cones and GTE fan complex are characterized by late Pleistocene (Qf1) debris flows (D1, Table 1) which have been eroded by the L1 shoreline to form a steep wavecut scarp. Debris flows of unit Qf2 age are deposited in trenches that cut shoreline L1, but these deposits are trimmed by shoreline L2, forming a smaller wavecut scarp. Holocene (units Qf3, Qf4, and Qf5) transitional deposits (T facies, Table 1) are set in trenches cut through both shorelines and prograde short distances away from the wavecut scarps. The JSH fan is more complex with proximal Qf1 debris flows (D1 facies, Table 1) changing distally to Qf1 or younger Qf2 fluid debris flows (D2 facies, Table 1) and fluvial sediments (S2 facies, Table 1). As elsewhere, exposures in latest Pleistocene sediments show the youngest parts of unit Qf1 to be coarse bouldery debris flows (D1 facies, Table 1) over older finer debris flows (D2 facies, Table 1; Figure 7, section 11). The shorelines are not observed on JSH complex because of

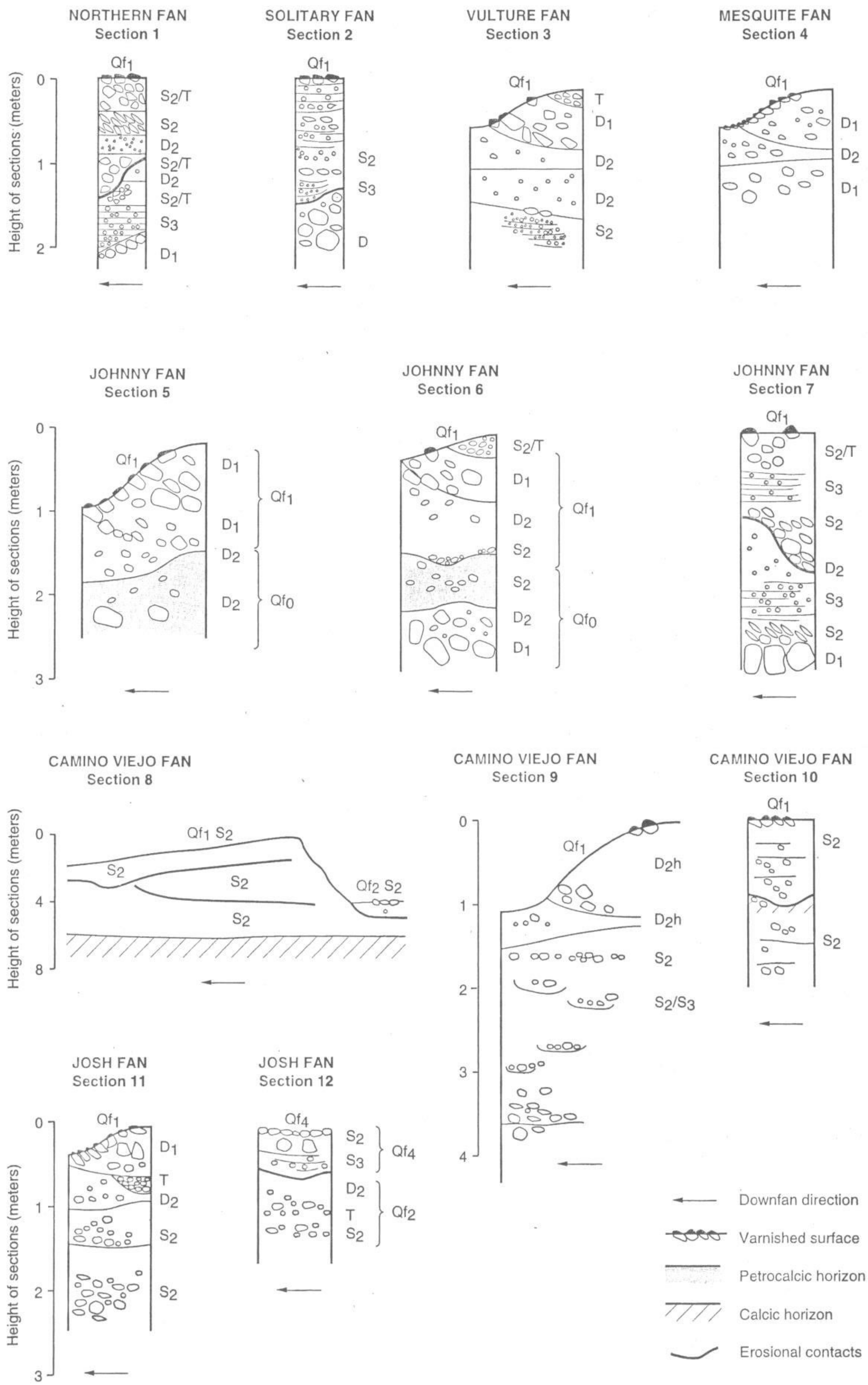

Figure 6. Schematic stratigraphic sections (see Fig. 1 for locations).

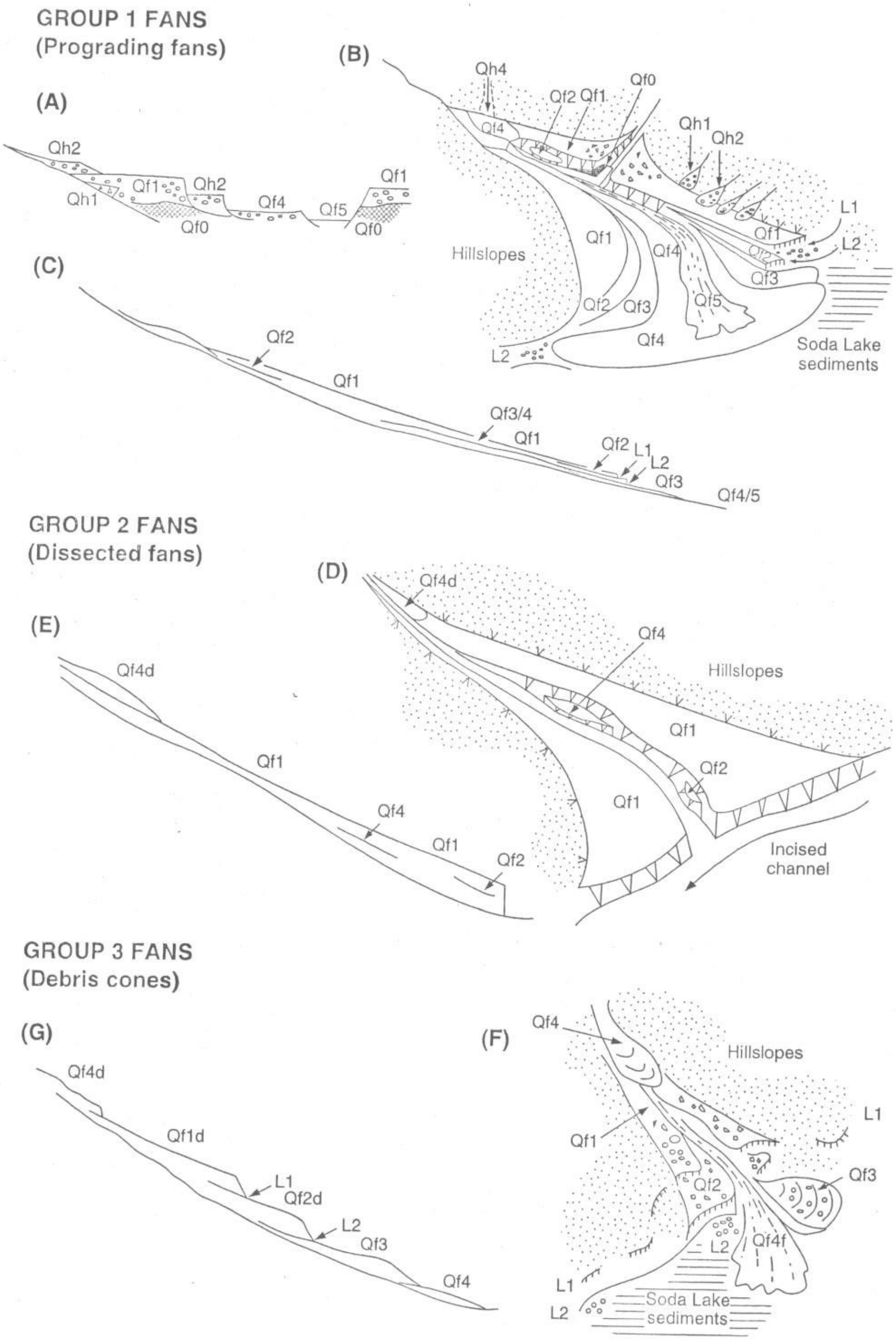

Fig. 7. Schematic models of fan development for the fan groups identified on Table 5, showing (A) schematic cross-fan profile for Group 1 fans, (B) schematic model and (C) summary downfan profile for Group 1 fans, (D) schematic model and (E) summary downfan profile for Group 2 fans, and (F) schematic model and (G) summary downfan profile for Group 3 fans.

extensive middle Holocene (Qf4) deposition of fluvial sheet gravels (Fig. 6, section 12) in the distal zone.

The southernmost fan complexes (SPR, ZZX, and SON, SOC, and SOS fans, Figure 2) are fed by steep drainage basins developed dominantly on granitic rocks (Fig. 1) with smaller areas on metavolcanics and limestone. Both shorelines are visible on ZZX and SON fans but have been obscured in the distal areas of SOS (Fig. 2) by human alteration of the fan surface. The apices of the larger fan complexes (ZZX, SON, SOS, Figure 2) show late Pleistocene massive bouldery debris-flow deposits (D1 facies, Table 1), grading distally into finer, more fluid debris flows or fluvial deposits (D2 or S2 facies, Table 1). On each fan complex the surfaces of the late Pleistocene fans are trenched, and on the larger fans younger, dominantly fluvial deposits, prograde across the shorelines (Qf2 on ZZX and SON fans, and Qf3–5 throughout). The distal end of SPR fan complex has been truncated by ZZX fan, and the distal deposits on SOC fan complex are middle Holocene (Qf4) debris flows.

LATE QUATERNARY VARIATIONS IN ALLUVIAL FAN PROCESSES AND DEVELOPMENTAL STYLES

Classification of fan evolutionary style

During fan development, changes in the supply of water and sediment to a fan may cause changes in the relative importance and spatial distribution of erosion and deposition. This will result in changes in the morphological style of the fan. We have recognized five process-based morphological styles in the Zzyzx fan complexes (Table 4; see also Harvey, 2003), and have grouped the fans on the basis of similar evolutionary sequences of fan style over the period of fan development. From the field evidence mapped and summarized on Figure 5, and with the fan surfaces being assigned to age groups according to their surface and soil properties (Table 2; Fig. 2), it is possible to classify the fans at two scales.

Classification at the scale of the fan complex

At the scale of the fan complex, we identify three main styles of fan evolution that have produced the present-day plan-view assemblages of stratigraphic and sedimentologic units and characteristic longitudinal profiles (Fig. 7). The larger, fluvially dominated fan complexes (VLT, MSQ, JNF, CV, JSH, ZZX, SON, SOS on Figure 2) show plan-forms of typical telescopic fans (Harvey, 1997), and long-profiles with successive intersection points (Fig. 7A–C). Several fan complexes show styles dominated by dissection (Fig. 7D–E). The two northern fans (NOR, SOL, Figure 2) show some dissection and relatively little Holocene depositional activity. The SPR fan complex shows plan and long-profile characteristics dominated by local base level–induced dissection and is tributary to ZZX fan, whose incising channel provides a local base level for SPR fan. The final major group of fan complexes comprises all the smaller fans and debris cones (STV, CV and PC cones, GTE fans, and SOC fan, Figure 2). These steep fans and cones all show very minor trenching with spatially limited progradation that is restricted to distal lobes (Fig. 7F–G).

Classification at the scale of the individual fan apex/segment

At the scale of the 32 discrete fan apices recognized in the field (Fig. 2), it is possible to identify the fan segments fed by each apex, and to classify each by the dominant process style at each of the stages of fan evolution recognized (Table 5). For each time period represented by an alluvial fan stratigraphic unit, the dominant geomorphic style for each apex-fed fan segment has been assessed and the fan segment classified into one of 3 major groups (Table 5—note that two groups include subgroups). This classification allows trends in the geomorphic evolution of the fan complexes to be identified (Fig. 8).

Group 1 fan segments (Table 5; Fig. 8) are all large alluvial fans. Group 1a (VLT 5, 6, JNF 12, CV 19, JSH 27, ZZX 28, SON 30, SOS 32; for locations see Figure 2), show a characteristic aggradation to progradation trend with a progressive shift from debris flow to fluvial processes from the late Pleistocene into the Holocene. On Group 1b fans (MSQ 7, 8), the mid-Holocene (Qf4) sequences are complicated by significant debris-flow activity.

Group 2 fan segments are dissected fans and comprise two subgroups: Group 2a (NOR 1 and SOL 2) dissected in relation to the channel of the neighboring large fan complex, and Group 2b (JNF 11, CV 17, 18, SPR 29), tributary fans, where dissection is related to local base-level lowering, following the incision of the main fan channels.

TABLE 4. PROCESS-BASED FAN MORPHOLOGICAL STYLES, RECOGNIZED IN THE ALLUVIAL FANS OF THE SOUTHERN SODA MOUNTAINS

1. Aggradation	On nontrenched fan complexes, defined as deposition that takes place near fan apices and that may extend distally over much of the fan surfaces. On fan surfaces that had been previously trenched within the fanhead area, younger fan deposits that may occur within the trench are also a form of aggradation.
2. Progradation	This is the case of proximal trenching by the trunk channel and deposition on the distal fan surfaces. Distal deposition may extend the distal limit of the fan complex.
3. Dissection	With little addition of sediment to the fan complex, processes of dissection may occur. These include trenching of the fan surface by the trunk channel or incision by channels heading on the fan surface. The main zone of dissection may be at the fan apex, midfan, or in distal fan areas.
4. Complex behavior	Alluvial fans may show combinations of erosion and deposition unrelated to each other, such as proximal aggradation concurrent with distal dissection.
5. Stabilization and/or passive or limited activity	This is the case where under current conditions there is little or no sediment provided to, or erosion from, the fan complex. There are no fresh erosional forms, with the whole fan surface showing evidence of stability, through stone pavement and soil development. The implication is that there has been minimal erosion or deposition for a period longer than that required for the initiation of identifiable soil and pavement formation to take place.

Note: See also Harvey (2003).

TABLE 5. CHANGES IN FAN STYLE THROUGH THE LATE PLEISTOCENE AND HOLOCENE FOR THE FAN SEGMENTS FED BY THE 32 FAN APICES IDENTIFIED IN FIGURE 2

			Pleistocene			Holocene	
Fan	D	B	Qf1	Qf2	Qf3	Qf4	Qf5
Group 1a							
VULT-5	.056	.34	Ac	Pf	Pf	Ac	Pf
VULT-6	.237	.38	Ac	Pf	Pf	Ac	Pf
JN-12	.349	.30	Ac	Pf	Pf	E(Pf)	Pf
CV-19	.455	.25	Af	Pf	Pf	Pf	Pf
JSH-27	.205	.28	Ac	Ad	Pf	Af	Pf
ZZX-28	.256	.30	Ac	Pf	Af	Pf	Pf
SON-30	.187	.34	Ac	Pf	Af	Af	Pf
SOS-32	.262	.35	Ac	Pf	Pf	Pf	Pf
Group 1b							
MSQ-7	.062	.43	Ac	Pf	X	Ad	E(Pf)
MSQ-8	.097	.36	Ad	Pf	X	Ad	Pf
Group 2a							
NOR-1	.037	.33	Ac	E(Ad)	Z	E(Ad)	X
SOL-2	.065	.34	Ac	Z	E(X)	Ac	X
Group 2b							
JN-11	.293	.41	Ac	Pf	Af	Af	X
CV-17	.224	.33	Ac	Pf	X	Pf	X
CV-18	.108	.39	Ac	Pf	X	Pf	X
SPR-29	.104	.35	Ad	X	X	X	X
Group 3							
SOL-3	.012	.44	Ad	Z	X	Z	Z
SOL-4	.006	.33	Ad	Z	X	Z	Z
STV-9	.072	.40	Ad	Pd	Z	E(Pd)	X
JN-10	.039	.41	Ad	Pd	Z	X	Z
JN-13	.059	.46	Ad	Z	Z	Z	Z
CV-14	.019	.38	Ad	Pd	Z	Z	Z
CV-15	.062	.32	Ad	Pd	Z	Pd	Z
CV-16	.037	.36	Ad	Ad	Z	Pd	Z
CV-20	.010	.44	Ad	Pd	Pd	Pd	Pd
CV-21	.012	.40	Ad	Pd	Pd	Pd	X
PC-22	.033	.41	Ad	Pd	Z	Pd	Z
PC-23	.010	.42	Ad	Pd	Z	Pd	Z
GT-24	.020	.45	Ad	Pd	X	Pd	Z
GT-25	.062	.45	Ad	Pd	Z	E(Pd)	Z
GT-26	.037	.44	Ad	Ad	Z	Ad	Z
SOC-31	.076	.44	Ad	Ad	X	Pd	Pd

Note: D—Drainage area to fan (km^2); B—Basin slope (bedrock relief/bedrock basin length). Fan styles: A—aggradation, P—progradation, f—fluvial, c—composite, d—debris flow, X—dissection, Z—passive and/or limited activity, E—complex behavior (dominant behavior shown in parentheses).

Group 3 fan segments are all relatively small fans or cones (Table 5). This group shows a sequence of latest Pleistocene debris-flow aggradation followed by latest Pleistocene to early Holocene progradation by debris-flow processes. There is a trend during the Holocene toward limited activity and stabilization. Only the larger fans in this grouping (STV 9; CV cones 20, 21; SOC 31) show continued progradational activity during the Holocene.

Trends in late Quaternary evolution of the fan groups

The morphological trends over the late Quaternary are summarized by the schematic models shown on Figure 7, and by the summary Table 6 and Figure 8. Several overall trends can be identified. (1) There is a trend in sedimentary processes over the past 30 ka from debris-flow activity toward fluvial processes, especially for the larger fans (Table 6; Fig. 8). During the late Pleistocene, 56% of the fan segments were aggrading by debris-flow processes, and by mid Holocene only 13% were experiencing debris-flow aggradation. (2) There is a trend in depositional style from aggradation toward progradation in both large and small fans (Table 6; Figure 8). During the late Pleistocene, all of the fan segments were aggrading, but by late Holocene no fans had an aggradational style. (3) In addition, there is a trend in the geomorphic style toward dissection, which is most apparent on

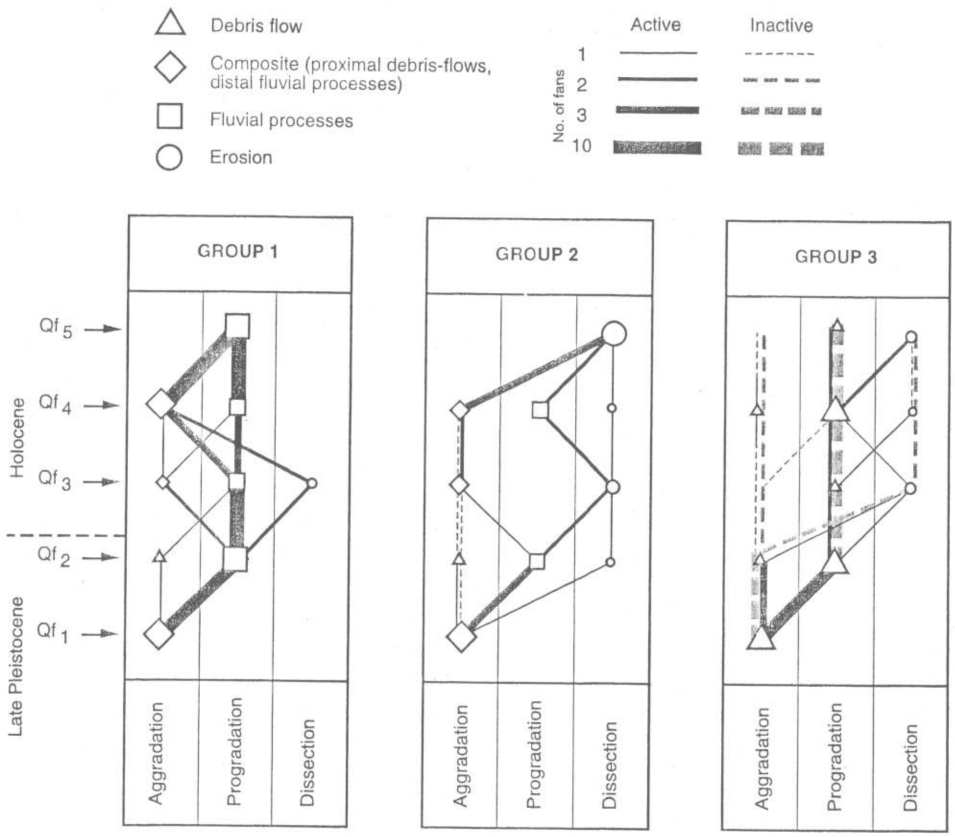

Figure 8. Schematic diagrams to illustrate the changes in fan style (for definitions see Table 4) through late Quaternary time on the three groups of fans (see Table 5). Symbol sizes and line thicknesses are proportional to the number of fans showing specific processes at each time stage, or specific changes in processes between successive time stages, respectively. Dashed lines indicate inactivity, i.e., where there is no evidence of erosional or depositional change between successive time stages, and the morphology is inherited.

tributary fans influenced by falling local base levels caused by incising main channels. During the latest Pleistocene to early Holocene only 3% of the fan segments experienced dissection, but by early Holocene 32% were being dissected (Table 6; Figure 8). (4) Finally, there is a trend in the geomorphic processes toward stabilization of the fan surfaces, especially on the smaller cones (Table 6, Figure 8). During the latest Pleistocene to early Holocene, only 9% of the sampled fans were inactive, however, by late Holocene 38% had become inactive.

Summary of the late Quaternary fan sequences

During the late Pleistocene (between 30 and 18.6 ka, unit Qf1) all fans were aggrading. The hillslopes within the source areas were actively supplying sediment to the fans by a variety of processes (Harvey and Wells, 1994), including rockfall processes forming talus slopes below rock outcrops, slopewash processes forming colluvial mantles on the footslopes, and hillslope debris-flow processes forming debris-flow lobes. Alluvial fan aggradation ranged from debris flows on the smaller fans and near fan apices to fluvial and sheetflood processes on the larger fans. The field evidence suggests that the last phases of hillslope debris-flow activity continued after the cessation of late Pleistocene fan sedimentation and may have continued during the transitional period from latest Pleistocene to the Holocene (Qf2).

During the latest Pleistocene–early Holocene transitional period (ca. 11.5–9.3 ka, unit Qf2), 18% of the sampled fans were aggrading by debris-flow process, 32% were prograding by debris-flow processes, 38% were prograding by fluvial processes, 3% were being dissected, and 9% were relatively inactive (Table 6). The larger fans (Group 1) developed fanhead trenches and prograded distally by fluvial processes. On the largest fans of this group some fluvial deposition occurred within the fanhead trenches (Qf2), later to be dissected to form terraces (Fig. 5). On the smaller fans and cones (Group 3) some dissection within the distal areas occurred following the fall in pluvial Lake Mojave from the higher shoreline. During this transitional period, debris-flow activity was such that depositional lobes prograded beyond shoreline L1. On many hillslopes there was renewed hillslope destabilization very late during Qf1 time or into Qf2 time, resulting in debris-flow lobes extending onto Qf1 fan surfaces (Figs. 5, 7; Harvey and Wells, 1994; Harvey et al., 1999).

Between 8.5 ka and 5.2 ka (Qf3) only 9% of the fan segments were aggrading by composite and fluvial processes; 6% and 18% were prograding by debris-flow and fluvial processes, respectively; 32% were undergoing dissection, and 35% were stabilized. During the early Holocene, hillslope debris-flow activity ceased, and the hillslopes either stabilized or underwent a switch to fluvial erosion focused along the linear headwater channels (Harvey and Wells, 1994). There is little evidence of deposition

TABLE 6. CHANGES IN FAN STYLE: SUMMARY

Category	Pleistocene Qf1 (%)	Qf2 (%)	Qf3 (%)	Holocene Qf4 (%)	Qf5 (%)
Aggradation					
Debris flow	18 (56)	6 (19)	– –	4 (13)	– –
Composite (+Fluv)	14 (44)	– –	3 (9)	6 (19)	– –
Progradation					
Debris flow	– –	10 (31)	2 (6)	10 (31)	1 (3)
Fluvial	– –	12 (38)	6 (19)	6 (19)	11 (34)
Dissection	– –	1 (3)	10 (31)	2 (31)	8 (25)
Passive and/or limited activity	– –	3 (9)	11 (34)	4 (13)	12 (38)

Note: Number of fan apices (and percentages) in each category total 32. On this table, complex behavior has been reclassified according to dominant behavior.

within the fan apices during the early Holocene. However, on the larger fans (Group 1) continued fanhead entrenchment occurred with distal progradation by fluvial or sheetflood deposition. On many of the smaller fans and cones (Group 3) there is little evidence of erosion or deposition during the early Holocene, and these fans appear to have stabilized (Table 6). On a limited number of small fans and cones, distal fan dissection and continued lobe progradation by debris-flow or transitional deposition occurred along the former shoreline zone.

During the middle Holocene (Qf4), 31% of the fans were aggrading again by debris-flow and fluvial processes, 50% were prograding by debris flow and fluvial processes, and 6% were being dissected. Minor renewal of hillslope debris-flow activity between 4.3 ka and 3.5 ka renewed the supply of sediment to the apices of some fans. Otherwise, the middle Holocene was dominated by progressive channel incision in midfan areas and extensive distal progradation by fluvial processes on the larger fans. Distal lobe progradation occurred on many of the smaller fans and cones. There was a general trend for deposition on most fans at this time, ~13% of the fan segments were inactive or stabilized.

In the past 1.8 ka, none of the fan segments have undergone an aggradational style, 37% have prograded by debris-flow and fluvial processes, 25% have been dissected, and 38% are stable. There is little field evidence for hillslope instability by mass movement. Rather, active channel incision occurs in the steeper headwater areas (Harvey and Wells, 1994). The larger fans appear to have been and are currently prograding. The late Holocene fan deposits (Qf5) are less extensive than the middle Holocene deposits. Most of the smaller cones appear to be inactive.

DISCUSSION

Factors controlling alluvial fan processes

The changes that have occurred since the late Pleistocene in the geomorphology of the Zzyzx fans are responses to climatic change. The Soda Mountain front is tectonically stable, and tectonics cannot have had any influence on late Quaternary fan dynamics. Base level initially fell with the fall in lake level, then would have risen with sedimentation on the playa floor during the Holocene. However, base-level change has had little effect on fan dynamics, and that effect has been restricted to the shoreline zone, primarily on the smaller fans. Fanhead trenching has occurred well above the shoreline zone, especially on the larger fan complexes, and is clearly related to changes in hydrology and sediment supply. Moreover, similar late Quaternary sequences of erosion and deposition can be seen throughout the Zzyzx fans, and can be broadly correlated with similar sequences throughout the region (Fig. 6). This indicates regional climatically led changes in hydrology and sediment supply as the primary causes of the observed changes in fan dynamics. The major change in fan style occurred between the Pleistocene and the Holocene, as an overall trend toward greater fluvial activity. This was not the result of exhaustion of the sediment reservoir in the catchment (cf. Bull, 1991); there is ample hillslope sediment availability, but was the result of climatically induced changes in hillslope processes (Harvey and Wells, 1994).

Although we can identify the overall trends, they were not uniform from group to group over the last 30 ka. Within this overall climatically led context, variations between the fan complexes must relate to the operation of geomorphic thresholds (Schumm, 1979). Three important thresholds may be operating:

1. between debris-flow and fluvial or sheetflood processes, controlled by water:sediment ratios supplied to the fan (Wells and Harvey, 1987);
2. between erosional and depositional processes, controlled by the threshold of critical stream power (Bull, 1979), defined as the relationship between actual stream power and critical power, i.e., the power required to transport the sediment supplied;
3. between activity and inactivity, which may simply be a reflection of runoff power, under conditions of very limited sediment supply.

All three thresholds are controlled by water and sediment supply from the catchments, and hence by drainage area and relief characteristics. For catchments of similar climate and geology they can be defined by measures of drainage basin area and relief (Wells and Harvey, 1987). Larger catchments have greater runoff and their fans would tend to be fluvially dominant, and steeper catchments would have higher rates of sediment supply and therefore be dominated by debris flows (Harvey, 1997). Fans from small, perhaps less steep catchments would be more likely to stabilize.

Generalized catchment thresholds between debris-flow and fluvially dominant deposition have previously been defined for the Zzyzx fans (Harvey, 1992a). Now we are able to refine that definition by considering the thresholds for the catchments of the 32 fan segments, and how the thresholds change over the Qf1–5 time scale. On Figure 9 fan processes on the 32 fan segments have been plotted in relation to drainage basin area and basin slope (Table 5), for the five time-periods (Qf1–5). On each plot, the fan styles tend to cluster, suggesting threshold conditions separating the processes.

At any one time, not all of the three threshold types defined above may operate. During the late Pleistocene (Qf1) a threshold distinguishes between fluvial and debris-flow aggradation. Then during Qf2, after fanhead trenching on most fans, a similar threshold distinguishes progradation by fluvial and sheetflood processes from progradation by debris-flow lobes. During the Holocene there is a reduction in debris-flow activity and more fans undergo dissection.

During the mid Holocene (Qf4), when hillslope debris flows were again active, a threshold similar to those during Qf1 and Qf2 times distinguishes debris-flow and fluvial-dominant fans. During the intervening Qf3 and then during Qf5, when hillslope debris flows were not active a rather different threshold is apparent, based more on drainage area than on basin slope, distinguishing continued fluvial progradation on the larger fans from inactivity on most of the smaller fans.

Throughout, fluvial processes are associated with the larger catchments and debris flows, during periods of hillslope instability, with the smaller steeper catchments. There are changes through the time sequence; during the Holocene the fluvial realm extends into smaller and steeper catchments than during the late Pleistocene. More important perhaps, is the general consistency of the threshold separating fluvial processes on the larger fans from either debris flows (during Qf1, 2, 4 periods of hillslope activity) or fan stability (during Qf3, 5 periods of hillslope inactivity). Despite the differences in bedrock geology, little distinction can be made between fan catchments on granitic and metavolcanic bedrock. The larger fans (from groups 1a, 1b on Table 5) switch from late Pleistocene composite (proximal debris flows, distal fluvial and sheetflood deposits) aggradational fans to Holocene prograding fluvially dominant fans. The smaller fans (largely composing Group 3 on Table 5), switch from late Pleistocene debris-flow activity to Holocene stability, with occasional reactivation by debris flows particularly in mid Holocene (Qf4 time). Only a few fans lie close to the thresholds between these two groups (fans 1, 2, 5, 8, 9, 16, 18, 29). They are of intermediate size, and some do show switches between modes. Many are in groups 2a and 2b (Table 5), and have been subject to local base level–induced dissection. Also, 4 of the 8 are granite-fed fans, though whether this is significant is not certain.

In summary, the changes in fan style are broadly synchronous along the mountain front of the southern Soda Mountains, and indicate response to climatically induced changes in water and sediment supply to the fans. The ways in which individual fans responded to these changes are conditioned by catchment-related thresholds.

Regional climatic implications

The variations in fan behavior at Zzyzx reflect temporal variations in runoff power and sediment supply from the catchment hillslopes during the late Quaternary, and may be partly related to vegetation cover on the hillslopes and partly to climatic and hillslope hydrological conditions. Previous climatic reconstructions, based on paleovegetation reconstructions from data derived from packrat middens, or hydrological reconstructions based on pluvial lake levels (see above), allow distinction between regional and local paleoclimates. Paleovegetation data (see above) suggest that even during the late Pleistocene the hillslopes of the southern Soda Mountains supported temperate desert scrub vegetation, rather than Juniper woodland as would have been the case in higher mountain areas (Harvey et al., 1999). Lake-level data express the regional climatic and hydrological characteristics, but not necessarily those directly related to local geomorphic controls. Fluctuations in the levels of pluvial Lake Mojave reflect conditions in the headwaters of the Mojave River system in the Transverse Ranges of southern California, rather than climatic conditions in the Mojave Desert itself (Wells et al., 1990a, 1998), but the geomorphic processes on the hillslopes of the southern Soda Mountains must reflect local climatic and hydrological conditions.

The late Pleistocene (Qf1 time) was a period of excess sediment supply from the hillslopes and aggradation on the fans. The high sediment availability and the evidence for widespread mass movement on the hillslopes (Harvey and Wells, 1994) suggests a climate perhaps with higher bedrock weathering rates and certainly much higher soil moistures than at present. This implies a climate probably colder than at present and certainly much wetter. The Pleistocene to Holocene transition (Qf2 time) was the last time of major hillslope debris-flow activity, again implying hillslope instability through slope failure and mass movement, with higher soil moistures and a wetter climate than today. However, fanhead trenching on the larger fans suggests a change in critical power relationships by an increase in runoff power in relation to Qf1 times. This supports the regional evidence for the incursions of tropical air under "monsoonal" conditions, bringing high storm rainfall intensities (Wells and Dohrenwend, 1985; Harvey et al., 1999).

During the Holocene (Qf3–5 time) a change in geomorphic regime on the hillslopes is evident, whereby widespread mass movement dominantly by debris flows in the late Pleistocene to early Holocene (Qf1–2), gave way to largely stable hillslopes affected primarily by linear fluvial incision in the headwater channels during the Holocene (Harvey and Wells, 1994). This implies a decrease in soil moistures but an increase in the effec-

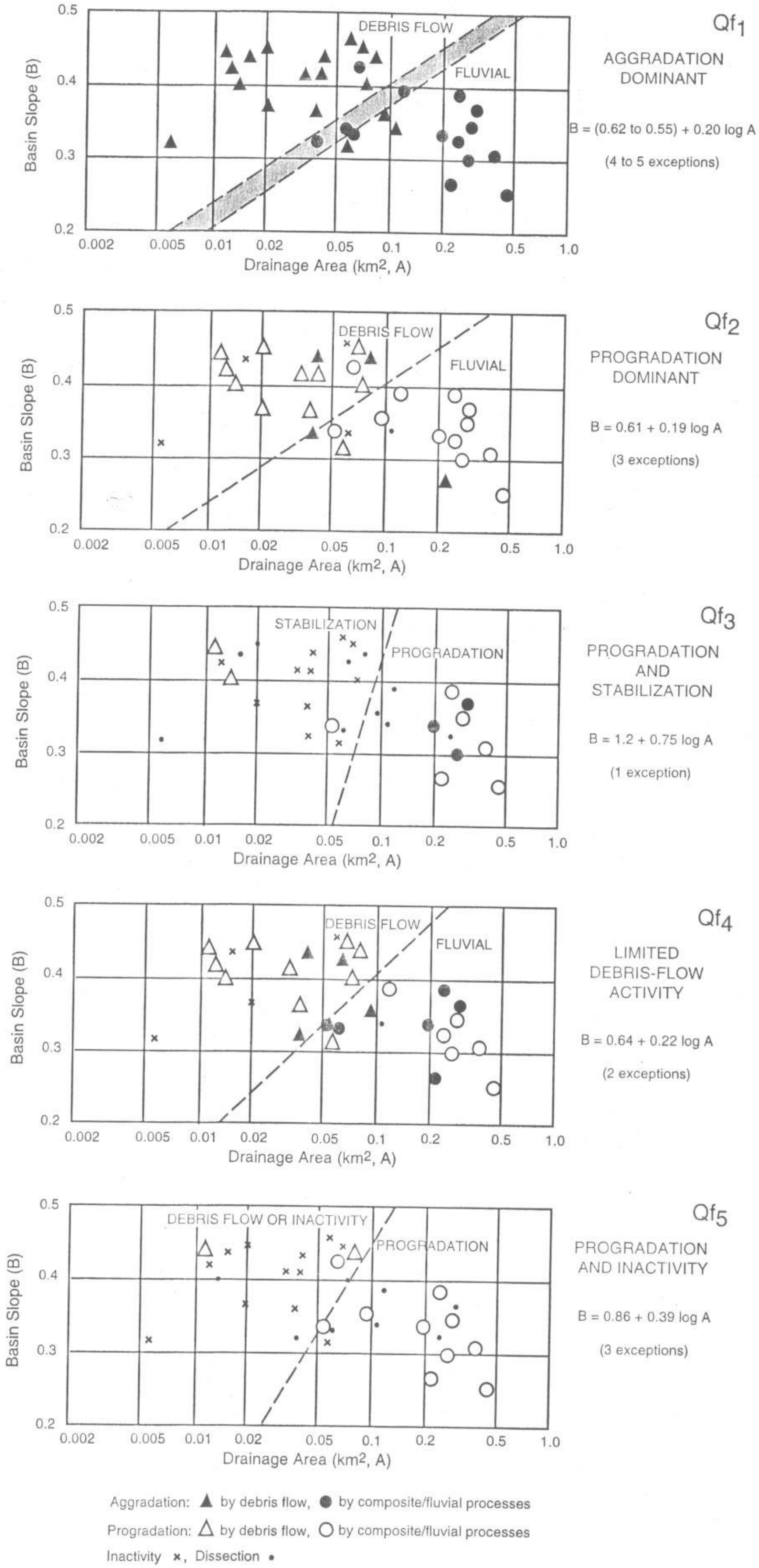

Figure 9. Dominant fan processes at times Qf1–Qf5, for the 32 fan segments, plotted against bedrock drainage area and bedrock basin slope (for definitions see Table 4). Dashed lines, and equations quoted, are for suggested threshold conditions (see text for explanation); exceptions relate to the number of anomalous cases, dissecting (local base level-controlled) fans excluded.

tiveness of storm runoff power (Bull and Schick, 1979), in keeping with a Holocene trend toward greater aridity (Baker, 1977).

The Qf4 period (ca. 4.4–3.5 ka) differs from Qf3 and Qf5 periods, in that there is evidence for localized hillslope debris-flow activity, and limited debris-flow supply to fan proximal locations. There is also evidence for continued fanhead trenching and widespread distal progradation. These trends suggest perhaps a mid-Holocene wetter period. The hillslope debris-flow activity, and especially the fanhead incision and distal progradation suggest a period of greater storm magnitude and greater runoff power.

CONCLUSIONS

1. The sedimentary and morphological sequences identified on the Zzyzx alluvial fans at the mountain front of the southern Soda Mountains accord with the emerging regional picture of late Quaternary alluvial fan sequences in the eastern Mojave Desert. The sequences identified at Zzyzx accord with those identified throughout the eastern Mojave Desert. The evidence suggests response to late Quaternary regional climatic changes.

2. In the absence of tectonic activity, or of base-level changes effective in causing major changes in fan morphology, the overriding control of alluvial fan dynamics is climatic change.

Climatic change governs the generation of water and sediment from the hillslopes of the alluvial fan catchments. Of critical importance appear to be soil moisture and weathering characteristics, influencing sediment generation by mass movement processes on the hillslopes especially during the late Pleistocene, together with the incidence of intense storm rainfalls, affecting runoff power since the late Pleistocene.

3. Alluvial fan response to regional patterns of climatic change is conditioned by local intrinsic thresholds, relating to the generation of water and sediment from the fan catchment hillslopes. The threshold conditions are subject to change as the climate itself changes.

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