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Response of alluvial fan systems to the late Pleistocene to Holocene climatic transition: contrasts between the margins of pluvial Lakes Lahontan and Mojave, Nevada and California, USA

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Abstract

Dated shorelines of late Pleistocene pluvial Lakes Lahontan (Great Basin Desert, northwest Nevada) and Mojave (Mojave Desert, eastern California) provide timelines for the assessment of alluvial fan sedimentation at the lake margins during the late Pleistocene to early Holocene. Two sets of alluvial fan systems have been mapped: the Stillwater fans, feeding Lake Lahontan; and the Zzyzx fans, feeding Lake Mojave. Their contrasting morphologies suggest different responses of the two fan systems to late Pleistocene to early Holocene climatic change. At the time the Stillwater fan systems underwent minimal sedimentation, with the catchment hillslopes apparently stable. The Zzyzx fans experienced major changes in water and sediment supply from the catchment hillslopes. There was a major phase of hillslope debris-flow activity, followed by fanhead trenching and distal fan progradation. Both areas were wetter and colder in the late Pleistocene than they are today, but during the transition to the Holocene the Zzyzx area was more likely to experience intense rains associated with the monsoonal penetration of warm moist tropical air into the Southwest. Vegetation reconstructions for the late Pleistocene to the early Holocene suggest that catchment hillslopes in the Mojave supported a desert shrub vegetation, but those in the Stillwaters supported juniper woodland and grasses at low elevations and pine at higher elevations. Contrasts in hillslope vegetation cover together with storm activity may account for the different responses of the alluvial fans to climatic change during the Pleistocene to

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Holocene climatic transition. After the falls in lake levels of Lakes Lahontan and Mojave in the early Holocene, both areas underwent aridification, resulting in reductions in hillslope vegetation cover. Increased storm runoff led to fanhead trenching and distal progradation of the alluvial fans. Variations in fan style at that time may relate primarily to base-level conditions resulting from different gradients on the exposed lake shores.

Keywords: Alluvial fans; Pluvial Lake Lahontan; Pluvial Lake Mojave; Late Pleistocene climates; Palaeovegetation

1. Introduction

Arid-zone alluvial fans are highly sensitive to environmental change (Harvey, 1997). They act as stores for sediment produced by mountain catchments, and hence may preserve a record of the history of sediment delivery to the fan. Since fan surfaces are formed by depositional processes, fan morphologies reflect these processes. If the environment changes the fan surface responds by a change in style of depositional or erosional regime and/or in the location of zones of erosion or deposition on the fan.

The erosional or depositional response of a fan to a change in process is governed by critical power relationships between the power required to transport the sediment supplied and the actual transporting power (Bull, 1979). These relationships are controlled by variations in flood runoff and sediment supply (Bull, 1979; Bull, 1991). Excess sediment supply will lead to sedimentation, whereas excess power, resulting from reduced sediment supply or increased runoff, will lead to erosion. The relationships may be modified by tectonics. Tectonic activity may alter the relief of the source area, influencing sediment production, or the gradient of the fan itself, influencing transporting power. The relationships may be also modified locally by base-level changes, influencing the erosional/depositional regime in the distal fan zone.

The morphology and sediments of an alluvial fan therefore preserve a record of past environmental changes. A major problem however, is to determine whether changes in fan processes have been caused by tectonic activity, climatic change or intrinsic geomorphic conditions of the fans themselves. This latter aspect may be further complicated by the presence of geomorphic thresholds (Schumm, 1977) causing differential responses to environmental change. The determination of the age relationships of phases of erosion or deposition on alluvial fans is critical for the interpretation of the geomorphic record; so too is the assessment of the spatial or regional extent of changes in fan regime. On this basis attempts can then be made to relate changes in fan geomorphology to tectonic, climatic or other factors.

This paper deals with two contrasted mountain-front alluvial fan systems in the American Basin and Range province: the Stillwater fans in the Great Basin Desert of northwest Nevada; and the Zzyzx fans in the Mojave Desert of southeast California (Fig. 1). An assessment is made of the extent to which differences in fan regime between the two areas over the period from the late Pleistocene to the early Holocene, may be due to climatic, vegetation, or other differences between the fan environments. During the late Pleistocene, both fan systems terminated in pluvial lakes, Lake Lahontan in Nevada, fed

Table 1
Stillwater and Zzyzx fans: elevations

Fan group	Stillwaters	Zzyzx
Mountain range	Stillwaters	Soda Mts
Pluvial lake	Lahontan	Mojave
Elevation zones (m)		
Maximum	2690	690
Max—fan zone	1500	420
Upper shoreline	1340	287
Lower shoreline	1240	275
Modern playa	1192	270

largely by drainage from the Sierra Nevada, and Lake Mojave in California, fed by the Mojave River drainage originating in the Transverse Ranges (Table 1). In both cases, dated lake shorelines provide good time-lines for the correlation, relative dating and interpretation of the fan sequences.

2. The study areas

2.1. The Stillwater fans

These are mountain-front fans, fed by catchments in the Stillwater range of northwest Nevada. Elevations range from less than 1200 m on the floor of the Carson Sink playa, up to almost 2700 m at the mountain tops (Table 1). Bedrock geology of the mountain catchments includes several zones (Willden and Speed, 1974). Supplying sediment to small fans in the south of the study area, is the Table mountain zone of Late Tertiary basalts. To the north, supplying the large fans in the central part of the study area, is a complex group of early Tertiary rhyolites, dacites and andesites. Further north, supplying the northernmost fans in the study area are Triassic sedimentary mudrocks. The mountain front is fault bounded, though unlike the Dixie mountain front in the Dixie Valley, on the other side of the Stillwaters, which experienced major fault movement in response to the 1954 earthquake (Bell and Katzer, 1987), there is little evidence of recent tectonic activity. There are minor lineations and one scarp in the fan toe zone of the central fans, which may reflect minor recent faulting. Tectonic deformation of the Stillwater mountain front over the period since the late Pleistocene is less than the deformation related to isostatic rebound following desiccation of pluvial Lake Lahontan (Adams and Fontaine, 1996, Adams and Wesnousky, 1998, Adams and Wesnousky, in press).

The fans toe out at the eastern margins of the Carson Sink, a modern playa remnant of Pleistocene pluvial Lake Lahontan. High Lake Lahontan shorelines are evident along the mountain front and across the alluvial fans.

There have been few previous studies of fans in the Lahontan area. As a preliminary to this study, Harvey and Wells (1996) used relationships with the Lahontan shorelines to identify the extent of Holocene fan segments on the Stillwater fans. Ritter et al. (1996) have similarly used shoreline evidence to differentiate between older and younger fan segments in the Buena Vista valley, a former northern arm of pluvial Lake Lahontan. In the neighbouring Dixie Valley, but not part of the Lahontan system, Bell and Katzer (1987) and John (1993) have mapped fan surfaces of various Late Pleistocene and Holocene ages.

The modern climate of the area is typical of the Great Basin Desert with precipitation totals less than 200 mm, much of which falls in winter, but with the occasional summer storm. Mean annual temperatures are ca. 10°C, with high summer (July mean ca. 20°C) and low winter (January mean ca. 0°C) temperatures (Houghton et al., 1975). The modern vegetation in the fan zone is typical of this part of the Great Basin Desert, dominated by shadscale desert scrub communities, but passes upwards into Pinyon/Juniper woodland in the mountains, with montane conifers locally at the highest elevations.

2.2. The Zzyzx fans

These are mountain-front fans fed by small catchments in the Soda Mountains within the eastern Mojave Desert of southeast California. Elevations range from 270 m on the floor of the Soda Lake basin to almost 700 m at the mountain tops (Table 1). Bedrock geology of the mountain catchments includes two main rock types: Cretaceous metavolcanics and Cretaceous granite. Locally, there are small outcrops of metamorphosed Cretaceous limestone (Harvey and Wells, 1994). The mountain front probably parallels an ancient fault line, but there is no evidence for tectonic activity during the Quaternary. The fans are backfilled into the mountain catchments, suggesting a long period of tectonic stability (Bull, 1977, 1978).

The fans toe out at the western margins of the Soda Lake basin, a modern playa remnant of Pleistocene pluvial Lake Mojave. Two Lake Mojave shoreline zones are evident along the mountain front and across the fan toes.

Previous studies of the Zzyzx fans and their catchments (Wells et al., 1990a; Harvey and Wells, 1994) involved detailed mapping of the fan surfaces in relation to the Lake Mojave shorelines. At Silver Lake, in the northern part of the Soda Mountains, detailed chronologies of fan deposition have been established (Wells et al., 1987, 1990b; McFadden et al., 1989), using evidence from soil and pavement development, in relation to the shoreline sequence of pluvial Lake Mojave. Other studies in the eastern Mojave Desert (Wells et al., 1990b; McDonald and McFadden, 1994) have used evidence from soils and pavements to establish the relationships between Quaternary fan, dune and lake sediments. Further north, sediment sequences on the Death Valley fans (Hunt and Mabey, 1966) have been used to suggest relationships between Pleistocene climates and geomorphic activity (Dorn, 1994).

The modern climate of the Zzyzx area is typical of the Mojave Desert with rainfall totals less than 100 mm, much of which falls in winter, but with a stronger summer storm component than in the Stillwater area. Summer temperatures in the Mojave are very high (often exceeding 40°C) and winter temperatures are moderate (Houghton et al., 1975). The modern vegetation is typical of the Mojave Desert, a thermophilous desert scrub in both the fan and mountain zones.

3. Methodology

The alluvial fan units were mapped in the field, in the Stillwaters onto air photo enlargements at a scale of ca. 1:8000. At Zzyzx, they were mapped onto basemaps at a scale of 1:6000, (produced by enlargement of the 1:24,000 topographic sheets) onto which details had been added from air photos.

In the Zzyzx area, the mapping was based on the recognition in the field of discrete sedimentary units, defined on the basis of morpho-stratigraphic relationships with each other and with the palaeo-lake shorelines. The units mapped were grouped into relative ages by the relationships with the shoreline features. Away from the shoreline zone correlations were made, using multiple evidence criteria based on soils, rock varnish and pavement development, similar to those used by McFadden et al. (1989), elsewhere in the Mojave Desert. The underlying assumption is that once a surface ceases to be geomorphically active, soil formation proceeds especially through the accretion of windblown dust and subsequent transformation by pedogenic processes into a soil profile with recognisable horizon development. Given the constraints of comparable parent materials, topography and climate, the degree of horizon development is related to the timespan involved (Birkeland, 1985; Bull, 1990). Simultaneously the original depositional fabric of the surface is modified by the processes of desert pavement formation (McFadden et al., 1987). On exposed clasts of appropriate lithologies, rock varnish forms. Both these processes are time-dependent.

There have been numerous chronosequence studies in the American West, dealing with soil, pavement and varnish development (see Birkeland, 1990; Harden, 1990), including studies focused on the Mojave Desert (McFadden et al., 1987; Wells et al., 1987, 1995; McFadden et al., 1989; McDonald and McFadden, 1994; McFadden et al., 1998). The latter provide a framework for studies at Zzyzx. In the field, soil profiles were described. The fan surfaces were mapped, and differentiated using the multiple evidence criteria developed by McFadden et al. (1989) applied to the numerous exposures of fan sediments and overlying soils. The details are presented elsewhere (Wells et al., 1990a; Harvey and Wells, 1994; Wells and Harvey, in prep). In this paper, we focus primarily on the changing fan morphology over the time period spanned by the lake shorelines of late Pleistocene pluvial Lake Mojave.

In the Stillwaters, there are fewer exposed sections, and the fan surfaces are more heavily vegetated and often obscured by layers of Holocene Lahontan dust (Adams and Wesnousky, in press). There have also been fewer studies of soil development in this region (Chadwick and Davis, 1990; Chadwick et al., 1984; Adams and Wesnousky, in press). Furthermore, the climatic differences between the Mojave Desert and the northwestern Great Basin may mean that direct comparisons between the soils may be misleading. In the Stillwaters therefore, more reliance was placed on the morpho-stratigraphic relationships (Harvey and Wells, 1996).

Given that the lake shorelines are approximately of similar age (late Pleistocene to early Holocene) in both areas (see below), there is a basis for geomorphic comparisons.

There are considerable differences between the two areas in alluvial fan development, especially for the late Pleistocene to early Holocene time period. This suggests either different climatic sequences or differential response to climatic change between the two areas.

To consider how these two factors interact, palaeoclimatic scenarios (derived from published sources and ongoing research) were assessed in relation to vegetation reconstructions, indicative of catchment vulnerability to erosion. Some of the vegetation data were derived from published sources, but some new data are also included.

4. Pluvial lake shorelines

The dated shorelines of pluvial Lakes Lahontan and Mojave (Table 2) provide a framework for the correlation and dating of the alluvial fan surfaces. The high shoreline of Lake Lahontan (at 1340 m) dates from ca. 13 ka BP, after which the lake level fell to an intermediate level (to ca. 1235 m by ca. 10.5 ka BP). The lake then fell further, with possibly a minor early Holocene rise (to ca. 1220 m) (Davis, 1982, 1985: Morrison, 1991; Adams and Fontaine, 1996; Adams and Wesnousky, 1998), before its final disappearance early in the Holocene. The shorelines can be traced almost continuously along the mountain front of the Stillwater Range, in some places as erosional features cut in bedrock or cutting older alluvial fan sediments (Fig. 2a). Otherwise, the shorelines are marked by coastal depositional features (Adams and Wesnousky, in press), often forming a staircase of beach ridges in a belt along the mountain front, ranging between the highest and lowest shoreline elevations. Locally the shorelines are crosscut by younger fan segments (Fig. 2b).

The high shoreline zone of Lake Mojave involves two high shorelines (at 287 and 285 m), related to the Lake Mojave I and II highstands, dating from ca. 18.5 to 16.5 ka BP and from ca. 14 to 11.5 ka BP, respectively. The lake levels fell intermittently to a lower shoreline (at ca. 278 m), which dates from the early Holocene (ca. 10–8.5 ka BP)

Table 2
Shoreline sequences and dates

Lake Lahontan
Early Sehoo (35–22 ka): high lake levels (but lower than 1250 m)
Mid Sehoo (22–13 ka): rise to maximum lake level at 1340 m
Late Sehoo (13–ca. 10.5 ka): rapid fall in lake level to ca. 1235 m
Early Holocene desiccation, possibly with a late lake stage to ca. 1220 m
Chronology and dating from various sources including: Davis (1982), Morrison (1991), Adams and Fontaine (1996)
Lake Mojave
Lake Mojave I (18.5–16.5 ka): high lake level (287 m)
Intermittent lake (16.5–14 ka): fluctuating lake levels, periodically reaching high levels
Lake Mojave II (14–11.5 ka): high lake level (285 m)
Intermittent lake (11.5–8.5 ka): fluctuating, but generally falling lake levels, final rise to ca. 278 m at ca. 8.5 ka
Chronology and dating from various sources including: Wells et al. (1987), Enzel et al. (1989a), Brown et al. (1990), Wells et al. (1990b,c)

youngest shoreline forms a near-continuous feature a few m above the modern playa floor (Fig. 2c), either as an erosional bench or as a beach. This shoreline forms a secondary erosional feature across the distal zones of the alluvial fans. It is crosscut by younger fan segments (Fig. 2d).

In both areas three sets of alluvial fan surfaces can be defined in relation to the lake shorelines (Fig. 2). These are:

Group 1 (older fan surfaces), predating the high shorelines.

Group 2 (intermediate fan surfaces), dating from between the high and low shorelines.

Group 3 (younger fan surfaces), postdating the low shorelines.

Each fan group relates to broadly similar periods in both areas; Group 1 to the Pleistocene prior to ca. 18.5–13 ka, Group 2 to the late Pleistocene to Early Holocene (ca. 13–10.5 to ca. 8.5 ka), Group 3 to the Holocene.

5. Alluvial fan surfaces

The spatial extent of the three groups of alluvial fan surfaces, as defined by their relationships to the lake shorelines and mapped in the field, are summarised in Figs. 3 and 4.

5.1. Group 1 fan surfaces

In both areas, Group 1 fan surfaces are extensive, indicating substantial period(s) of fan building prior to the late Pleistocene. In the Stillwaters, Group 1 surfaces are multiple (Harvey and Wells, 1996), especially in the apex areas of the larger fans where they grade upstream into depositional terraces in the feeder valleys. On the basis of the relationships with Lake Lahontan shorelines, Group 1 fan surfaces clearly relate to deposition prior to the maximum lake levels of Lake Lahontan. These surfaces are multiple, and especially on the higher surfaces, preserve well developed desert pavements, characterised by highly fractured angular clasts. The pavements lie over well developed soil profiles which show pale Av horizons, thick argillic Bt horizons (> 30 cm) with 7.5YR hues, and Bk horizons with at least Stage II carbonate morphology (terminology after Gile et al., 1966, modified by Machete, 1985). This degree of soil and pavement development, both on the Stillwater western mountain front (Harvey and Wells, 1996) and in the Dixie Valley, to the east (AMH, unpublished field notes), suggests that at least the higher surfaces may well be pre-Sehoo (pre-late Pleistocene) in age. This observation also accords with the work of Ritter et al. (1996) in the Buena Vista valley to the north.

At Zzyzx, the Group 1 surfaces appear to be simpler, although the sections through the fan deposits often suggest multiple phases of deposition. The relative immaturity of the soils developed on the Group 1 surfaces, in comparison to those on stable interfluves above the fans (Bt horizon soil colours of 7.5YR hues as opposed to 5YR; carbonate accumulation of stage II as opposed to stage III), together with the relative immaturity of the pavements (Wells and Harvey, in prep), would suggest ages in the tens of thousands rather than hundreds of thousands of years (McFadden et al., 1989; Amit et al., 1993).

Buried by the main Group 1 sediments, but exposed in some of the fanhead trenches, are older fan sediments capped by thick, stage III pedogenic calcrete (Wells et al., 1990a; Harvey and Wells, 1994). These sediments relate to deposition earlier in the Pleistocene, and may be the equivalent of older fan segments identified in Death Valley (Dorn, 1994) and elsewhere in the Mojave, Colorado and Sonoran Deserts (Bull, 1991).

5.2. Group 2 fan surfaces

The main differences between the Stillwater and Zzyzx fans are in the extent of Group 2 (Late Pleistocene to Early Holocene) surfaces. On the Stillwater fans Group 2 surfaces are restricted to small areas just below the high shoreline (Fig. 3), and are dissected by the incision which followed the disappearance of the lake (Harvey and Wells, 1996). At a few sites, Group 2 fan deposits can be seen to interdigitate with lake sediments (Harvey and Wells, 1996). More often they form a thin veneer of fan deposits resting on lake sediments. Desert pavement, where visible, is less well developed than on Group 1 surfaces, and in the few exposed sections, soil profiles show much less maturity than those on Group 1 surfaces (thinner, less argillic Bt horizons, with weaker rubification of 10–7.5YR hues, and less mature carbonate morphology of stages I to II).

It is clear that while there was a substantial lake in the Lahontan basin there was minimal sediment input from the Stillwater mountain catchments. This is substantiated by the composition of the shoreline beach features whose sediments are almost wholly derived by longshore movement rather than by local input from the mountain catchments, clearly evident where drift directions cross geological boundaries (Adams and Fontaine, 1996). There is little evidence of hillslope instability. Most of the Stillwater hillslopes are colluvially-mantled stable slopes. The major sediment input to the lake came from the major rivers entering the lake (Davis, 1982), and locally by coastal erosion of older fan and lakeshore deposits, rather than by stream input from the bordering small catchments in the Stillwater Range. This accords with the observations of Ritter et al. (1996) (Ritter, personal comm.) in the Buena Vista valley to the north of the Stillwater Range, where they also note an absence of fan sediments contemporaneous with the Lake Lahontan highstand.

At Zzyzx, the picture is completely different. After the deposition of Group 1 fan deposits, and approximately coincident with the Group 2 fan sediments there was major hillslope debris-flow activity (Harvey and Wells, 1994). Group 1 fan sediments are often buried at the fan margins by younger debris-flow deposits derived from the neighbouring hillslopes (Fig. 4). These deposits display a varnish characteristic of Group 2 deposits (Harvey and Wells, 1994). Group 1 fan surfaces were then deeply trenched by fanhead trenches within which Group 2 sediments were deposited as inset terraces (Fig. 2d and Fig. 4). Group 2 fans themselves prograded beyond the high shorelines, cut into Group 1 fans (Fig. 4), only later to be trimmed by the low shoreline at the end of Group 2 time. Group 2 surfaces here show some degree of pavement and soil development, but markedly less than Group 1 surfaces.

These phenomena indicate a much more active geomorphic system at Zzyzx than in the Stillwaters. Early in Group 2 time, there was sufficiently high soil moisture, which together with storm activity acting as a trigger, allowed hillslope debris flows to occur (Harvey and Wells, 1994). Later, high runoff from the mountain catchments and probably also from the pavement-mantled older fan surfaces (Wells et al., 1987; McDonald et al., 1997), had sufficient power to cut fanhead trenches, and there was sufficient sediment mobility to allow deposition as inset terraces and as prograding distal fans. High rates of geomorphic activity, including a major phase of fan sedimentation occurring at the same time as Group 2, have also been recognised on other fans in the eastern Mojave area (Wells et al., 1987, 1990c).

5.3. *Group 3 fan surfaces*

In both the Stillwater and Zzyzx areas, Group 3 surfaces are extensive, and show only immature soil and pavement development. They indicate considerable Holocene alluvial fan activity, several phases of which can be identified. The phases probably reflect climatic changes during the Holocene. However, there are contrasts between the two areas in the setting of the Holocene fan segments. On the Stillwater fans, deep trenching occurred after lake levels fell and the Holocene fan segments extend below these trenches (Fig. 3; Harvey and Wells, 1996). At Zzyzx, Holocene deposition essentially continued the fan progradation trend initiated in Group 2 time on the larger fans, but was relatively minor on the smaller debris cones (Harvey, 1992). Trenching did occur, but is primarily fanhead trenching rather than a response to base-level change.

The major contrasts during the Holocene between the two areas (fans of Group 3, Figs. 3 and 4) seem to relate to the different influence of base-level change, rather than to differences induced by climatic or other environmental change. On the Stillwater fans, as the deep lake receded, steep gradients were exposed on the emergent lake shoreface. These were sufficient to induce incision, topographically separating the Groups 2 and 3 fan segments. At Zzyzx, recession of the much shallower lake exposed gentler shoreface gradients. These were insufficient to trigger major incision, and except on the smallest fans and debris cones, where minor shoreline dissection may have been related as much to shoreline erosion as to base-level lowering, incision into the older deposits was primarily through continuation of shallow fanhead trench development. The fans prograded from intersection points well above the shorelines, out across the shoreline zone, by processes related to proximal water and sediment supply conditions rather than to base-level change.

Thus, in terms of water and sediment delivery to the fans rather than of base-level change, the major contrasts between the two areas are those which occurred during deposition of the Group 2 fan segments (late Pleistocene to early Holocene). Water and sediment delivery reflect climate and vegetation. To account for these contrasts, the evidence for contrasting climatic and vegetation characteristics between the Stillwaters and Zzyzx is assessed below.

6. Climatic reconstructions

Two expressions of late Pleistocene to early Holocene climates need to be considered: first the *regional* climatic conditions that led to the formation of the large pluvial lakes, and second, the *local* climatic conditions to account for the different geomorphic regimes identified within the alluvial fan systems.

Climates in the American West depend on two characteristics of the general circulation, the overall position of the polar front, governed by the polar jetstream, and the degree of zonality or meridionality of airflow, again governed by the behaviour of the polar jet. The seasonal movement of the polar jet is well known. So too is its southward displacement during Pleistocene glacial conditions, which coupled with strongly zonal flow (Knox, 1984; Bull, 1991) brought high precipitation to the Southwest. Today, zonal airflow brings about westerly dominance, whereas meridional flow, especially in summer, allows the penetration of warm moist sub-tropical air from the Gulf of Mexico or the eastern tropical Pacific to enter the Southwest under 'monsoonal' conditions (Bryson, 1957; Bryson and Lowry, 1955; Bull, 1991). This effect may be enhanced by warm sea surface temperatures in the eastern Pacific, and therefore may be heightened during El Niño conditions (Enzel and Wells, 1997; Ely, 1997).

To account for the presence of large lakes, reconstructions of late Pleistocene climates over much of the American West argue for both a depression of temperatures (by ca. 3–8°C in relation to today's temperatures), and an increase of precipitation (of between 60 and 300% greater than today) (Mifflin and Wheat, 1979; Davis, 1982; Grayson, 1993; Wells et al., 1990c). The high precipitations resulted from southward displacement of the jetstream, and strongly zonal flow (Knox, 1984), bringing high winter precipitation especially of snow to the Sierra Nevada feeding Lake Lahontan (Davis, 1982), and to the Transverse Ranges in southern California feeding Lake Mojave (Enzel et al., 1989a). Over the mountain ranges within the Great Basin and the Mojave areas precipitation totals were also high, as evidenced by the presence of lakes in smaller enclosed basins, in addition to those fed by the Sierra Nevada and the Transverse Ranges (Mifflin and Wheat, 1979; Wells et al., 1998).

Lake Lahontan had an early highstand prior to the glacial maximum (ca. 22 ka, Benson et al., 1990), but reached maximum elevations after the peak of glaciation in the Sierras (ca. 13.5 ka). Lake Mojave sustained high levels through Lake Mojave I and II phases, during and after the glacial maximum (ca. 18.5–11.5 ka). This pattern suggests the southward displacement of the jetstream prior to the glacial maximum and its later return north as deglaciation occurred. After the glacial maximum high precipitation may have been enhanced by increased energy in the global circulation, resulting in more moisture in the atmosphere and greater penetration into continental interiors, and perhaps by the breakdown of easterly flow off declining Cordilleran glaciers. Another factor may have been the depression in the lapse rate during Pleistocene glaciation. Precipitation carried onshore during the glacial maximum may have affected both eastern and western slopes of the Transverse ranges, but only the western slope of the higher Sierras. In the Mojave area during the glacial maximum, but in the Lahontan area before and after the glacial maximum, the appropriate combinations of (a) lapse rate, (b) the occurrence of moisture bearing storms and (c) relatively low evaporation rates, resulted in the dramatic growth of the pluvial lakes.

During the Holocene and at present the existence of ephemeral lakes in the Mojave Desert, and river floods elsewhere in the southwest (Ely, 1997), have been particularly associated with meridional airflow and monsoonal conditions, allowing the penetration of tropical air into the desert Southwest (Bull, 1991). Anomalous atmospheric pressure patterns over the eastern Pacific and high sea surface temperatures, especially under El

Niño conditions, enhance this effect, bringing heavy precipitation into the southwest, particularly to the source areas of the Mojave River in southern California (Enzel and Wells, 1997; Enzel et al., 1989a,b).

High precipitation and lower temperatures resulting from the southward displacement of the polar jet may account for the high lake levels during the late Pleistocene, but alone cannot account for the differences in geomorphic activity between the Stillwater and Zzyzx fans. El Niño conditions tend to produce sustained high rainfalls in the Sierra Nevada, the Transverse Ranges, and other mountain areas, but may not necessarily produce much geomorphic activity in small fan catchments in the Mojave and Great Basin deserts. Therefore, more important would be local climatic conditions leading to exceptionally intense rainfalls within the Mojave and Great Basin Deserts themselves, rather than climatic conditions in the source areas of the major drainages feeding the lake basins.

Of the three types of flood-producing storm identified by Ely (1997), winter Pacific storms may be important for moderate-sized drainages but are less likely to generate the localised intense rainfalls needed to produce significant geomorphic activity in small fan catchments. More important would be either localised intense summer thunderstorms, or late summer eastern Pacific tropical storms moving north into the desert areas. Both of these would be associated with a dominantly meridional airflow and low pressure developing over the desert areas, ie. 'monsoonal' conditions.

The contrast between the Stillwater and Zzyzx Group 2 fans, is essentially that during the Pleistocene to Holocene transition there was very little geomorphic activity in the Stillwaters, but at Zzyzx there is evidence for major slope processes, major fanhead trenching and distal progradation of the fans. There is other geomorphic evidence of major flood activity in the Mojave Desert at that time (Wells and Dohrenwend, 1985; Bull, 1991).

One possibility that may account for this contrast is that during the Pleistocene to Holocene climatic transition, as the jetstream moved north (Fig. 5) and zonal circulation weakened, 'monsoonal' summer convectional rainfall may have affected the Mojave area in the south, but not the Lahontan area further north. Later, during the Holocene, the climates in both areas became hotter and drier. Desert climates, with periodic meridional flow conditions, became established by the mid-Holocene (Knox, 1984).

Fig. 5 suggests the possible climatic scenarios during the late Pleistocene, the Pleistocene to Holocene transition and subsequently during the Holocene. The lakes were produced by high precipitation over the lake-source areas (enhanced by cool conditions and low evaporation rates over the lake basins themselves), conditions favoured by a southerly track of Pacific storms. Geomorphic activity on the fans results primarily from 'monsoonal' conditions involving the penetration of moist tropical air into the Southwest. During the Pleistocene to Holocene transition this was more

Fig. 5. Summary of postulated Late Pleistocene–Holocene changes in airmass circulation conditions in the American West, compared to modern flood-producing storms (based on ideas put forward by Enzel et al., 1989a,b; Brown et al., 1990; Wells et al., 1990a; Bull, 1991; Ely, 1997).

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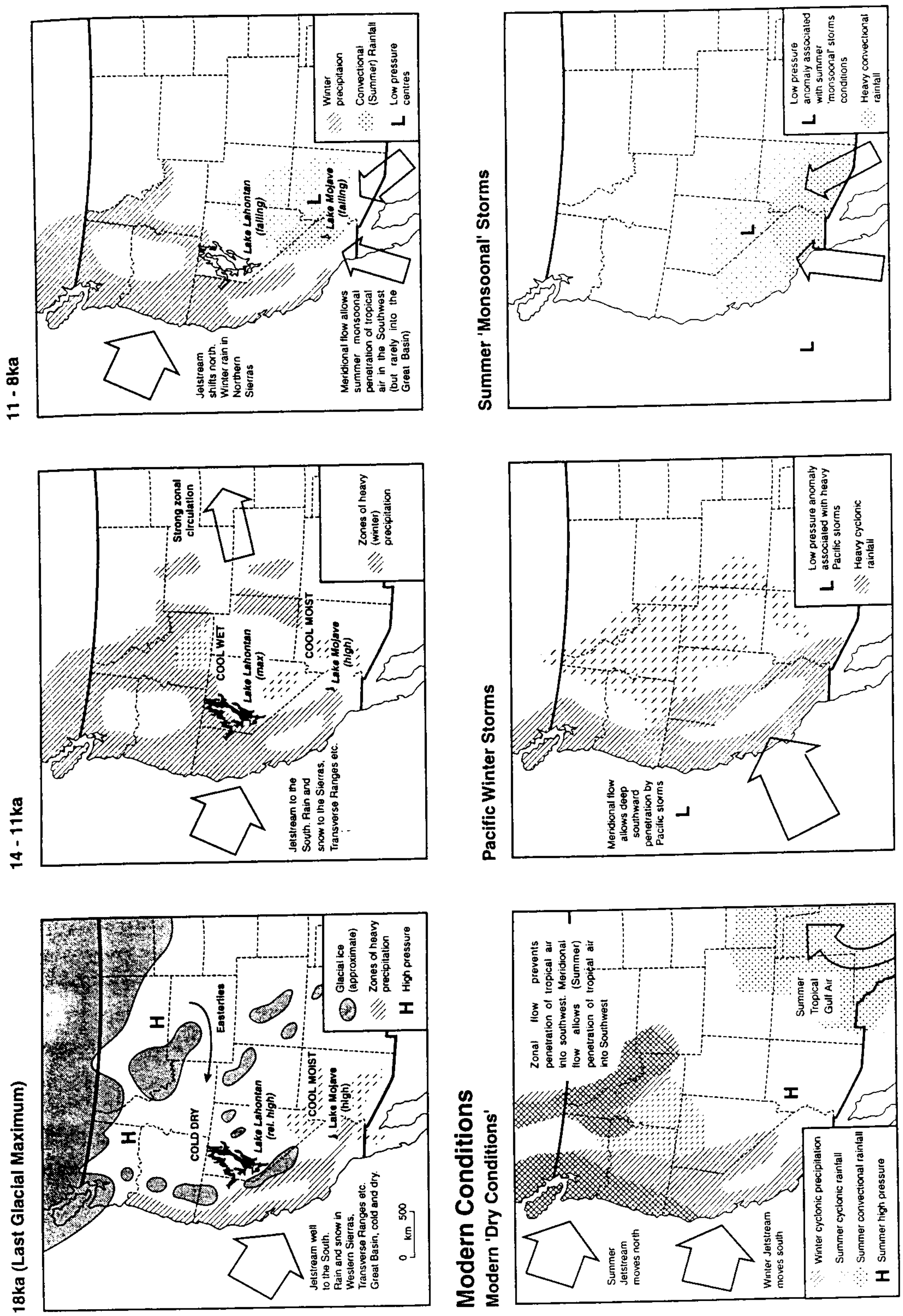

effective in the south of the area, in the Mojave, than further north in the Lahontan basin.

7. Vegetation reconstructions

The level of geomorphic activity on alluvial fans depends not only on the climatic characteristics, which govern runoff power, but also on the erosional characteristics of the drainage basins, which influence the rate of sediment supply to fans. Perhaps as significant for the late Pleistocene geomorphic contrasts between the Lahontan and Mojave areas as the climatic differences, are the differences suggested by vegetation reconstructions. These not only reflect palaeoclimatic conditions, but are indicators of the erosional conditions within the fan catchments.

Radiocarbon-dated palaeo-vegetation data have been derived by a number of researchers from analyses of plant materials collected in packrat (*Neotoma* spp.) middens, both in the northwestern Great Basin (Lahontan) area (Wigand and Nowak, 1992; Tausch et al., 1993; Grayson, 1993; Nowak et al., 1994a,b), and in the Mojave Desert (Wells and Berger, 1967; Wells and Woodcock, 1985; Van Devender, 1977; Woodcock, 1986; Spaulding, 1990; Grayson, 1993; Forester et al., 1996; Wigand and Rhode, 1999). From these published data an attempt has been made to reconstruct the likely vegetation changes in the Stillwater and Zzyzx catchments over the period from the late Pleistocene to the early Holocene (Figs. 6 and 7). For this analysis, using the available data, the presence of selected key species preserved in packrat middens has been plotted against time and elevation for the two areas. The key species selected include: whitebark pine (*Pinus albicaulis*), limber pine (*P. flexilis*) and white fir (*Abies concolor*), indicative of sub-alpine and montane coniferous forests; Utah juniper (*Juniperus osteosperma*) indicative of the present Pinyon/Juniper sub-montane zone (the pinyon pine—*P. monophylla*, did not enter this region until later in the Holocene, Nowak et al., 1994a,b); and various species characteristic of temperate desert scrub, including rabbitbrush (*Chrysathammus* spp.), shadscale (*Atriplex confertifolia*), bursage (*Ambrosia* spp.), and brittlebrush (*Encelia* spp.). No species characteristic of the modern thermophilous scrub of the Mojave desert were included, as this community did not develop until later in the Holocene (Grayson, 1993). Nor were species included that today occur over a wide altitudinal range of several vegetation zones, e.g., big sagebrush (*Artemisia tridentata*). The approximate altitudinal limits for the indicator species are then considered for the late Pleistocene to early Holocene period, in relation to the present altitudinal range for the modern vegetation zones in the two areas (Figs. 6 and 7).

The analysis of the data for the Lahontan area (Fig. 6) suggests that during the late Pleistocene, open juniper woodland with a rich shrub understorey dominated by sagebrush, grew down to the shore of pluvial Lake Lahontan. In addition, a periodic elevational shift of at least one subalpine conifer, whitebark pine, to elevations as low as 1400 m highlights episodes of cooler wetter climate during the late Pleistocene. This

Fig. 6. Late Quaternary vegetation reconstruction for the Lahontan Basin, Nevada. Based on data from Wigand and Nowak (1992), Grayson (1993), Tausch et al. (1993), Nowak et al. (1994a,b).

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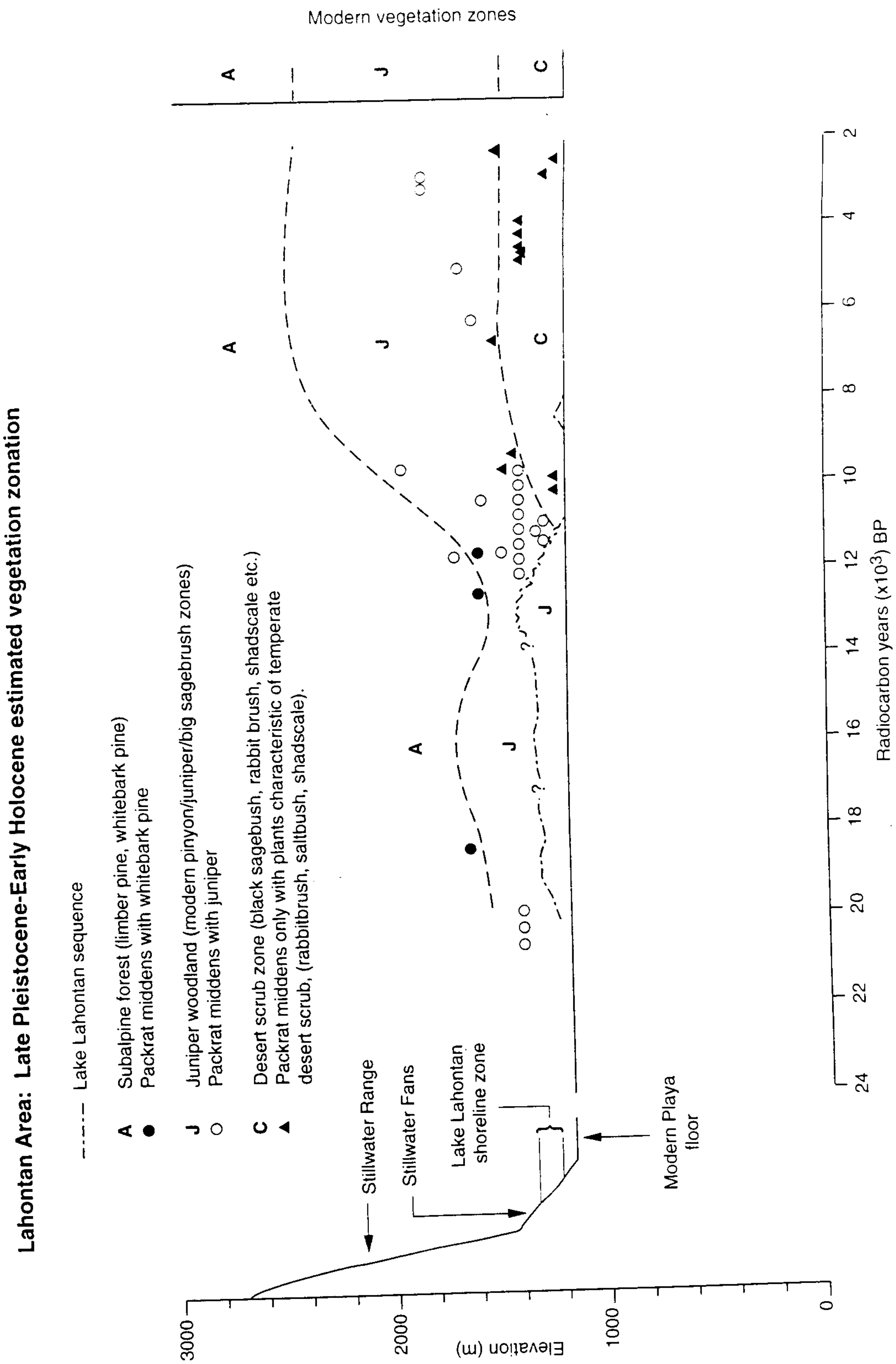

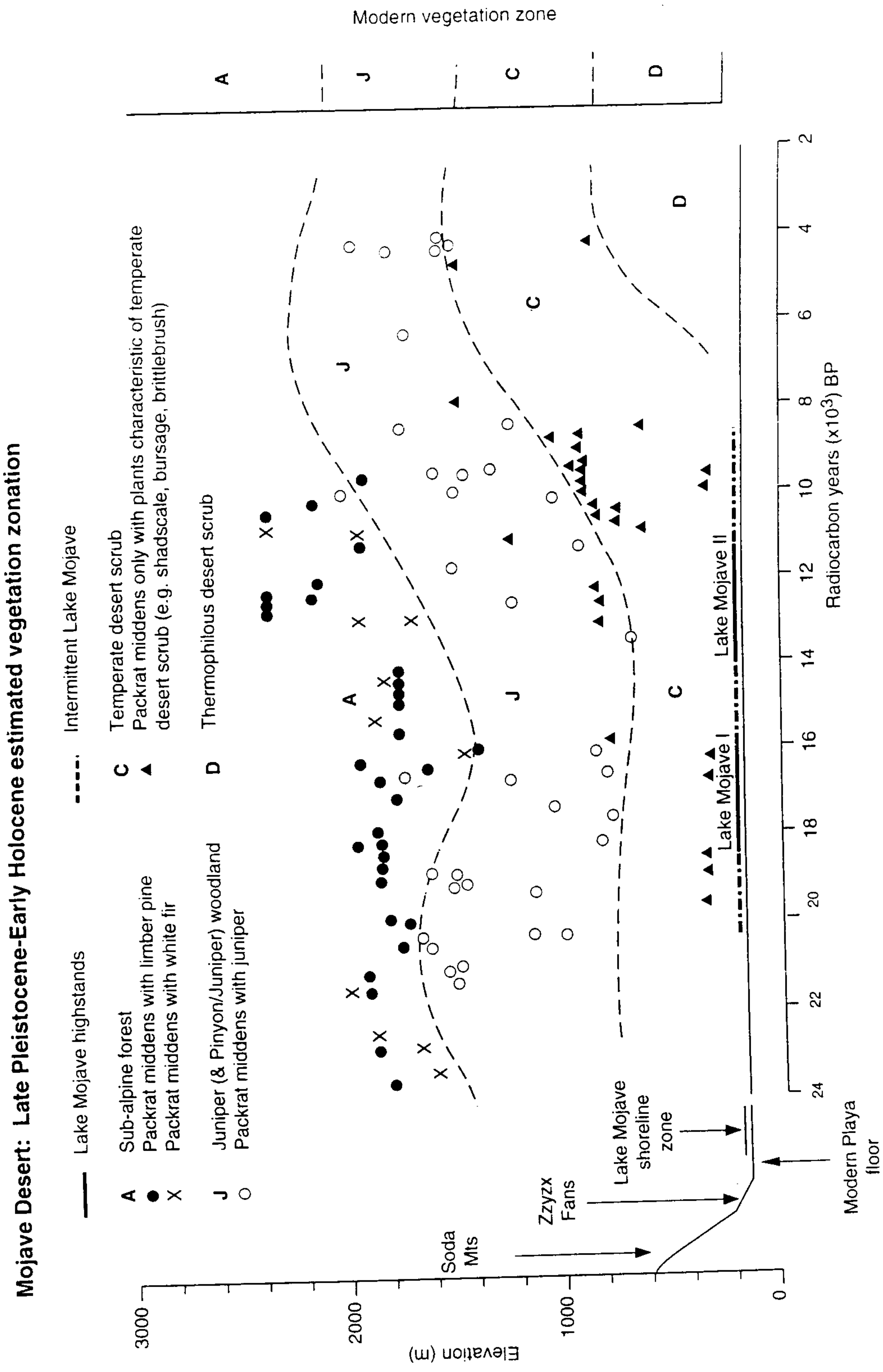

Fig. 7. Late Quaternary vegetation reconstruction for the Mojave Desert, California. Based on data from Wells and Berger (1967), Van Devender (1977), Spaulding (1985), Wells and Woodcock (1985), Woodcock (1986), Spaulding (1990), Grayson (1993), Forester et al. (1996).

would indicate that catchments feeding the Stillwater fans would have been covered by open juniper woodland, with a sagebrush understorey at low elevations, and scattered stands of whitebark pine higher up (Fig. 6). An even more important factor controlling erosion is the presence of grass. Pollen evidence from stratified packrat middens around the shores of pluvial Lake Lahontan indicates that within much of the juniper woodland there was a luxuriant grass cover (Fig. 8), similar to that today at much higher elevations in the Virginia Range, northeast of Reno (Fig. 9). This grass, mixed with the rich sagebrush-dominated shrub community, provided protection from erosion. The species comprising this vegetation assemblage today occur in areas of the Great Basin where rainfall occurs primarily in winter in relatively low intensity storms.

During the early Holocene, the vegetation along the former shores of pluvial lake Lahontan changed to temperate desert scrub, and the juniper and coniferous woodland zones moved upwards towards their present altitudes (Wigand and Mehringer, 1985; Wigand and Rhode, 1999). In the early Holocene, as the final drying of the remnant marshes lying on the floor of the Lahontan basin occurred, aeolian sediments were deposited on the surrounding fan surfaces. There is evidence for more frequent summer monsoonal events during the Holocene, but less so than in the Mojave Desert (Wigand and Rhode, 1999). The extensive Group 3 fan surfaces developed during the Holocene.

There are no equivalent data for the immediate Zzyzx area, but from work in nearby parts of the northern and eastern Mojave Desert (in particular, Spaulding, 1985, 1990; Forester et al., 1996) a similar analysis was carried out (Fig. 7). This suggests that during the late Pleistocene, virtually the whole of the Zzyzx catchments would have

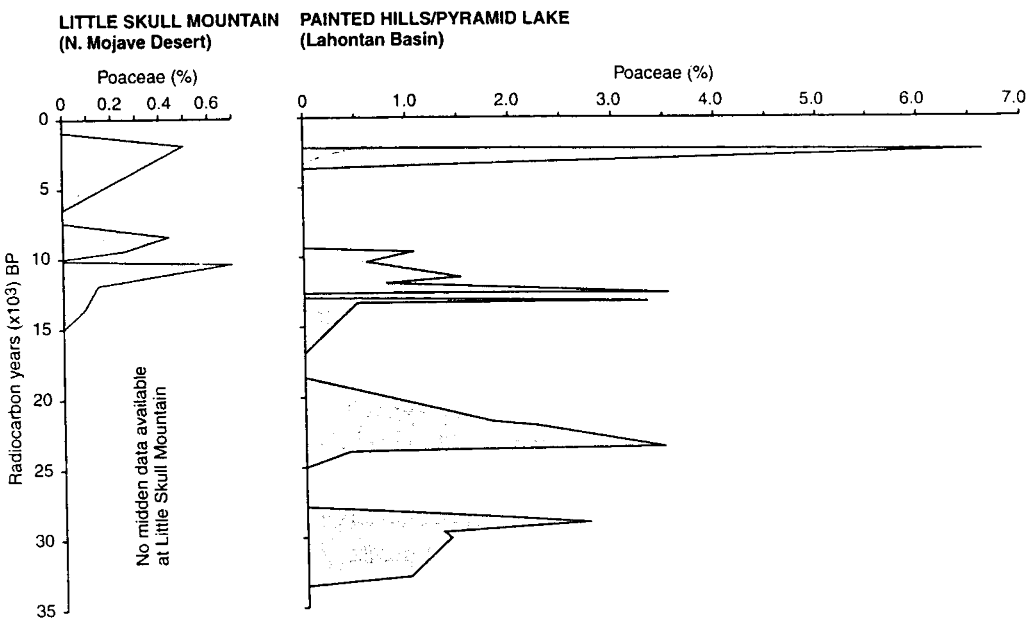

Fig. 8. Comparison of late Quaternary grass (*Poaceae*) abundance in the northern Great Basin with that in the northern Mojave Desert. Relative pollen percentages were obtained from ancient packrat middens on the west shore of Pyramid Lake (a remnant of pluvial Lake Lahontan) and from Little Skull Mountain on the Nevada Test Site about 150 km north of Zzyzx (for locations, see Fig. 1). *Note*: Scale differences. Little Skull Mountain is about 900 m higher in elevation than Zzyzx and would be expected to have more grass.

Fig. 7. Late Quaternary vegetation reconstruction for the Mojave Desert, California. Based on data from Wells and Berger (1967), Van Devender (1977), Spaulding (1985), Wells and Woodcock (1985), Woodcock (1986), Spaulding (1990), Grayson (1993), Forester et al. (1996).

Desert (Wigand and Rhode, 1999), coinciding with the main geomorphic activity of the Group 2 fans at Zzyzx.

The mitigating role of grasses, noted in the northern Great Basin may have been much less effective in the Mojave Desert. Grass abundance in the northern Great Basin was as much as 3–6 times greater than in the Mojave Desert during the same time periods (note relative percentage scales in Fig. 8). The grass event, which appears in the Little Skull Mountain record but not in the Pyramid Lake record (Fig. 8), provides additional evidence of the shift to greater summer rainfall in the Mojave between 9.5 and 8.6 ka.

8. Conclusions

There are strong contrasts between the Stillwater fans in northern Nevada and the Zzyzx fans in the Mojave Desert in relation to geomorphic activity during the late Pleistocene to early Holocene. In both cases, dated lake shorelines provide a good time framework for the dating of alluvial fan surfaces. The Stillwater fans were virtually inactive at that time but the Zzyzx fans were active, first in the form of debris flows feeding onto the fan surfaces, then in the form of dominantly fluvial processes causing fanhead trenching and distal progradation.

These differences relate to geomorphic thresholds. They cannot be explained by tectonic activity. Nor can they be explained by morphological differences which might make the Zzyzx area more prone to threshold conditions than the Stillwater area. The Zzyzx catchments tend to be smaller and steeper than those in the Stillwaters. However, within the Zzyzx area the smaller catchments are less prone to geomorphic change than the larger catchments (Harvey, 1992). Within the Stillwaters, the smaller catchments draining the basalt terrain of Table Mountain (Fig. 3), although showing local (late Pleistocene?) hillslope debris flows, do not have proportionately larger Group 2 fan surfaces than do the other Stillwater fans. The critical geomorphic differences between the two areas during the late Pleistocene to early Holocene climatic transition relate to climatic and vegetation differences. The more continuous vegetation cover given by juniper and pine woodland and their rich grassy shrub understorey, appear to have prevented both rapid runoff and high sediment production from the Stillwater fan catchments. The more open discontinuous vegetation cover of the Soda Mountains, associated with high rainfalls, allowed hillslope debris-flow activity, and especially when associated with high intensity summer rains, allowed high runoff and high rates of sediment movement within the Zzyzx alluvial fan systems.

Both areas experienced broadly similar climates in the late Pleistocene, much wetter and cooler than today with winter precipitation dominant. Heavy snowfalls in the Sierras and the Transverse ranges sustained pluvial Lakes Lahontan and Mojave respectively, but the timing differed between the two areas, with peak lake levels in pluvial Lake Lahontan following the last glacial maximum.

The most important climatic contrast in relation to geomorphic activity on the fans was the greater effectiveness of summer storms in the Mojave during the Pleistocene to Holocene climatic transition, related to the weakening of zonal circulation and the monsoonal incursion of warm moist tropical air from the Gulf of Mexico or the eastern Pacific.

The major environmental contrast between the two areas at that time was in terms of vegetation cover. In the Stillwaters, a subalpine parkland at intermediate elevations interfingered with an open juniper woodland which extended down to the lake margins. A rich mixed shrub understorey dominated by sagebrush and grasses characterized both woodlands. At the highest elevations, the mountains probably supported near-perpetual snowfields. At Zzyzx, juniper may have been present at the highest elevations, but most of the area was under relatively grass-free desert scrub. The vegetation contrasts made the Zzyzx area much more susceptible to geomorphic thresholds, which together with the climatic differences caused slope instability and greater runoff generation, resulting in a much higher level of geomorphic activity on the Zzyzx fans.

By the Holocene, as both areas came to be dominated by sparse desert scrub vegetation, the contrasts in fan geomorphology are less pronounced, and those that there are relate as much to the different influences of base level as to climatic contrasts.

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