4 Late Pleistocene and Holocene Changes in Hillslope Sediment Supply to Alluvial Fan Systems: Zzyzx, California

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ABSTRACT

Catchment hillslopes supplying alluvial fan surfaces at Zzyzx, in the Mojave Desert, California, have been mapped. Late Pleistocene to Holocene ages have been assigned to their surface features by correlation with alluvial fan surfaces on the basis of the field characteristics of rock varnish and soil development. Pleistocene to Holocene ages have been assigned to the alluvial fan surfaces on the basis of stratigraphic relationships to dated lake shorelines of Pleistocene Lake Mojave. Late Pleistocene fan aggradation was dominated by debris flow deposition, fed from active hillslopes. The late Pleistocene to Holocene transition saw a switch away from widespread hillslope mass movement processes towards hillslope stabilisation and localised dissection. This resulted in a reduction of sediment supply to the fans and a switch to fluvial processes involving episodic fanhead dissection and distal progradation. The causes appear to be climatically induced changes in weathering and hillslope processes in the catchment areas.

INTRODUCTION

The fluvial system in desert mountain regions is often characterised by two strongly contrasting but related zones, a dominantly erosional mountain catchment zone, supplying sediment to a mountain-front sediment storage zone, dominated by alluvial fans (Bull, 1977, 1991; Harvey, 1989). The behaviour of the whole system depends on the processes and rate of sediment generation within the mountain catchment, the processes and rate of sediment transport from the hillslopes to the channal and fan system (i.e. the strength of coupling within the system) and on the processes within the fan environment itself. Evidence for Pleistocene geomorphic processes may be expressed by the morphology of the catchment hillslopes (Oberlander, 1989), but above all by the characteristics of the alluvial fans. Fans are depositional forms whose morphology, especially surface slope, may be a direct response

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to depositional style and may be near the threshold slope between erosional and depositional regimes (Bull, 1979). Should the rate of sediment supply from the mountain catchment or the style of sediment transport through the alluvial fan environment change, then the regime on the fan may switch towards greater aggradation or dissection (Gerson *et al.*, 1978). Thus the alluvial fan may be an important and sensitive indicator of sediment supply and transport relationships, not only in the context of current behavioural style but in that the sedimentary sequences within the fan may preserve the most complete signal available of past environmental change within the mountain catchment (Bull, 1991).

THE MOJAVE SEQUENCE

Much of the previous work on arid-zone mountain geomorphic sequences has been primarily concerned with alluvial fans. Many such studies demonstrate complex histories of Quaternary fan aggradation and dissection (Harvey, 1984a, 1990). The alluvial fans of the Great Basin–Mojave Desert region of the American south-west are classic examples (e.g. Blissenbach, 1954; Hooke, 1967), especially those in Death Valley (Denny, 1965; Hunt & Mabey, 1966; Hunt, 1975). There, Quaternary sequences of alternating aggradation and dissection have resulted in multi-faceted, multiple age surfaces on large alluvial fans that reflect climatically controlled variations in water and sediment supply from the mountain catchments (Dohrenwend *et al.*, 1991). In Fish Lake Valley, north-west of Death Valley, detailed chronological studies involving ^{14}C and tephra dates have been used to link alluvial fan deposition primarily to climatic transitions from relatively cold to relatively warm conditions (Slate, 1991).

However, in most cases, the detailed chronology is not well understood. Recent work by Dorn and colleagues in Death Valley, on dating and palaeoenvironmental reconstructions from desert rock varnish (Dorn & Oberlander, 1981; Dorn *et al.*, 1987, 1989; Dorn, 1983, 1984), proposes relationships between Quaternary climatic fluctuations and alluvial fan aggradation and dissection sequences (Dorn, 1988), with at least three major partially diachronous aggradation cycles corresponding to the more humid major Pleistocene 'glacials' and shorter dissection-progradation phases with the more arid 'interglacials'. However, as pointed out by Wells & McFadden (1987), these interpretations are based on experimental dates only, and do not have supporting data linking varnish microtopography to fan depositional processes.

In two areas to the south of Death Valley, Wells *et al.* (1984, 1987, 1990a) and McFadden *et al.* (1989) have established a chronology for alluvial fan deposition. For fans issuing from the Soda Mountains towards Silver Lake (Figure 4.1), a modern playa, but a remnant of pluvial Lake Mojave, stratigraphic relations between alluvial fan sediments and ^{14}C dated lacustrine sediments and lake shorelines, as well as dated packrat middens in dissected fan channels, have been used to establish a chronology of piedmont deposition. Two shorelines of pluvial Lake Mojave have been dated to *ca.* 14 000 BP and *ca.* 8500 BP, a time interval effectively spanning the Pleistocene–Holocene transition. For fans issuing from the Cima volcanic field to the east of Baker (Figure 4.1), the chronology has been established using stratigraphic relations between fan sediments and K–Ar dated volcanic flows. In both areas, field properties of the relative development of soil profiles, desert pavements and rock varnish coatings for each dated alluvial fan surface are used to characterise fans of differing age and correlate fans across desert piedmonts. These studies correlate fan aggradation

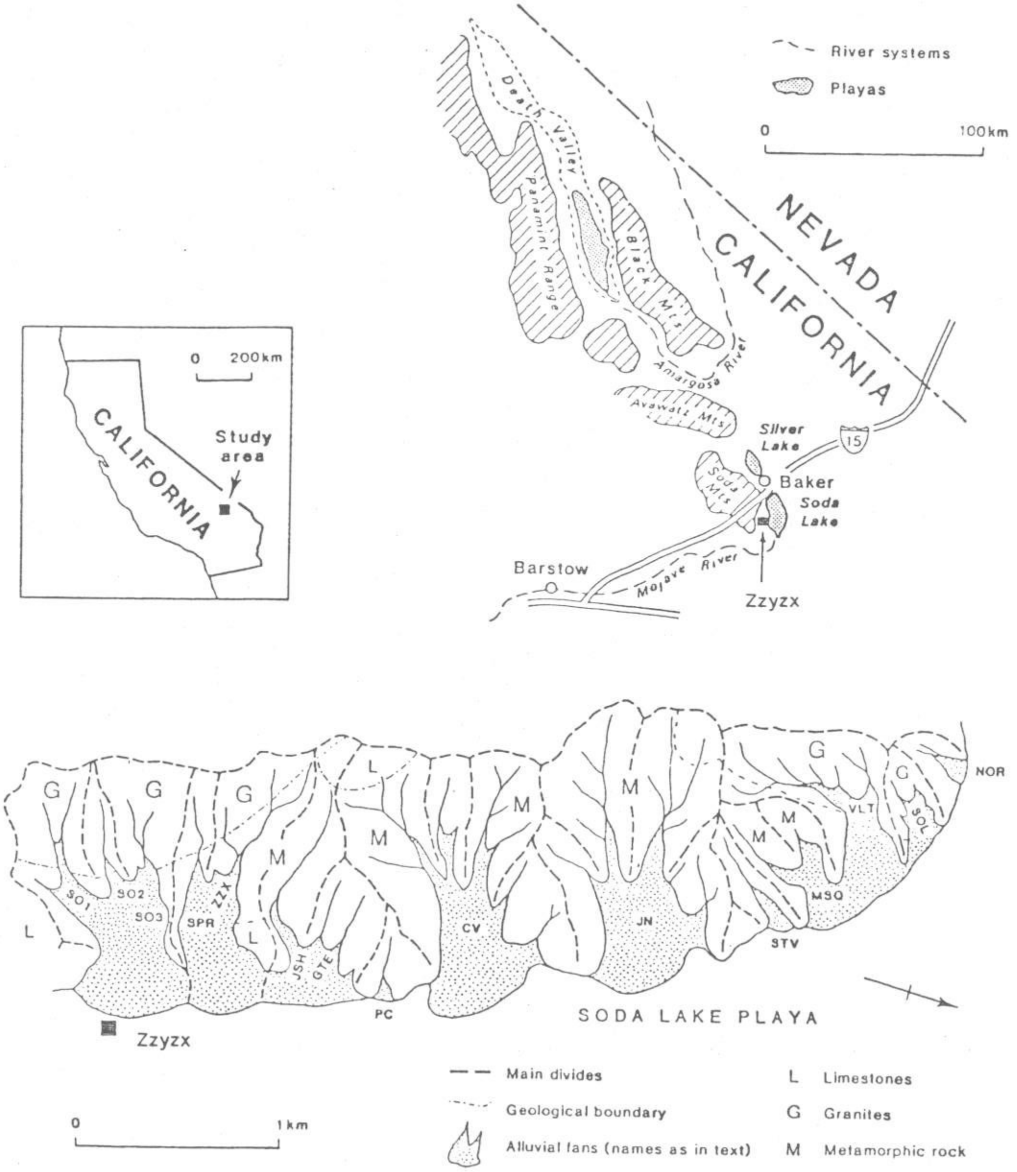


Figure 4.1 Location maps, Zzyzx fans and catchments. Letters on main map identify individual fans, groups of fans and catchment areas; SO1,2,3, Southern Group; SPR, Springer fan; ZZX, Zzyzx fan; JSH, Josh fan; GTE, Gate fan; PC, Palm cone; CV, Camino Viejo fan; JN, Johnny fan; STV, Steve fan; MSQ, Mesquite fan; VLT, Vulture fan; SOL, Solitary fan; NOR, Northern fan

resulting from destabilization of hillslopes and fan dissection resulting from large-scale flooding, with the time transgressive climatic changes during the Pleistocene–Holocene transition. The sequence of fanhead dissection and distal deposition-progradation during the Holocene is inferred to be a delayed and complex response to the widespread fan deposition occurring during the Pleistocene–Holocene transition, and to decreased permeability of the fan deposits due to pedogenesis, resulting in increased runoff and the reworking of the older alluvial fan sediments (Wells *et al.*, 1987; Ritter, 1991).

Although both in Death Valley and at Silver Lake the sequence of fan dynamics, and at Silver Lake the chronology, is fairly well understood, there has been little work linking detailed stratigraphic and morphologic evidence for past hillslope processes with the associated down-piedmont alluvial fan sequences. This paper is an attempt to rectify that. It is based on field observations made in the southern Soda Mountains, to the south of Silver Lake, in the catchment areas of the Zzyzx fans (Figure 4.1). These fans feed into the margins of Soda Lake, a modern playa but also formerly part of Pleistocene Lake Mojave.

THE ZZYZX FANS

The Field Evidence

The Zzyzx fans issue from the eastern flank of the Soda Mountains (Figure 4.2), draining catchments developed on Mesozoic granites and metamorphic rocks, including metamorphosed limestones (Figure 4.1). The fans range from small steep debris cones to larger fluvially dominated fans, with sedimentary and geomorphic sequences indicating a progressive trend from debris flow towards fluvial processes (Wells *et al.*, 1990b; Harvey, 1992).

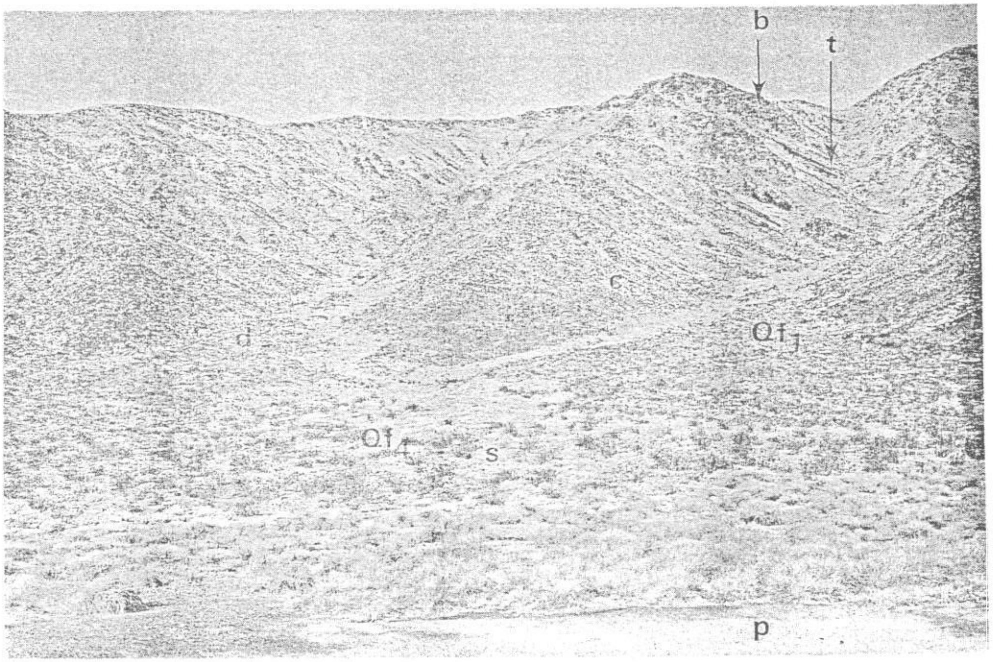


Figure 4.2 Zzyzx mountain-front fans: Johnny fan. Note: b, varnished bedrock outcrops; varnished talus slope; c, colluvial slope; Qf_1, Qf_4, fan surface age class, see text; d, fa deposits : debris flows; s, fan deposits : fluvial deposits; p, modern playa sediments

Both the fan surfaces and the hillslopes have been mapped on the basis of evidence for geomorphic processes and age. For the fan surfaces, field-based age-related criteria were established on the basis of the degree of rock varnish development, desert pavement and soil development (after McFadden *et al.*, 1987, 1989), and stage of $CaCO_3$ accumulation (after Gile *et al.*, 1966). A nomenclature based on that used by Wells *et al.* (1987) has been used to describe six age categories from Qf_0 for the oldest fan sediments (probably mid-Pleistocene) to Qf_5 for the youngest, recently and currently active, fan sediments.

Locally, ages of the fan segments have been assigned on the basis of the stratigraphic relationships between fan surfaces and the dated Lake Mojave shorelines (Wells *et al.*, 1987, 1989). Segments pre-dating the older shoreline (Qf_1) relate to the late Pleistocene, those dating from the period between the two shorelines (Qf_2), relate to the Pleistocene–Holocene transition and those post-dating the younger shoreline (Qf_{3-5}) are Holocene in age. The facies have been described using the criteria outlined by Wells and Harvey (1987) for modern alluvial fan sediments, into a range of debris flow, transitional and fluvial facies in alluvial fan sediments.

The Zzyzx Fan Sequences

The detailed sequence has been described elsewhere (Wells *et al.*, 1990b) and only a summary is given here (Figure 4.3). Sediments of Qf_0 age are only seen buried by younger sediments. The fan surfaces, especially in proximal areas, are dominantly of Qf_1 (late Pleistocene) age. Most of these deposits are debris flows and only on the larger fans do they grade distally into fluvial deposits. Clearly, the late Pleistocene here was a period of fan aggradation, dominated by debris flow deposition. By the end of the Pleistocene some limited fanhead trenching had begun; Qf_2 deposits form small inset terraces within the fanhead trenches of the larger fans as well as small progradation zones in the distal areas.

During the Holocene there was a dramatic change in the behaviour of the alluvial fans. On some of the smaller fans sedimentation ceased and the fan surfaces stabilised; on a few others there was minor incision of the fan surfaces but very little other geomorphic change (Harvey, 1992). On all of the larger fans and on most of the others, fanhead trenching of the proximal areas and extensive progradation of the distal areas by fluvial processes took place (Figure 4.3). This process has been episodic with major phases occurring in Qf_3 (mid Holocene?) times, again in Qf_4 (late Holocene?) and finally in Qf_5 (very recent) times. From Pleistocene to Holocene times there was a switch from proximal and mid-fan aggradation, dominantly by debris flow processes, to fanhead trenching and distal progradation, dominantly by fluvial processes. These are clearly responses to late Pleistocene to Holocene climatically induced changes in water and sediment supply from the catchment areas of alluvial fans.

THE ZZYZX HILLSLOPES

The Field Evidence

For the hillslopes a similar but simpler range of field-based age-related criteria was established primarily on the basis of the properties of rock varnish coatings, and only locally and where appropriate on the basis of other surface properties, such as soil or desert pave-

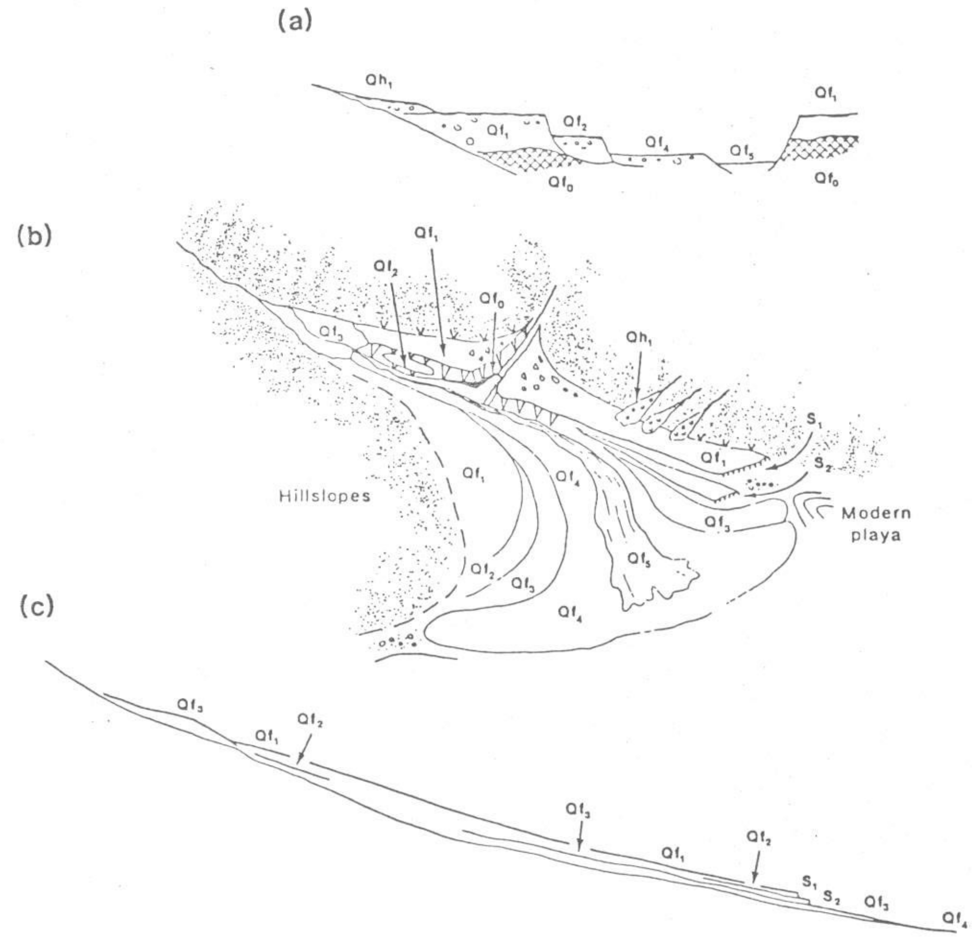


Figure 4.3 Schematic representation of Zzyzx fan surfaces. Qf_0–Qf_5, fan surface age class, see text; Qh, late Pleistocene hillslope debris flows; S_1, S_2, late Pleistocene–Holocene lake shorelines. (a) Cross-sectional relationships, near fan apex. (b) General relationships: illustrates Qf_3 deposits near apex (local); hillslope debris flows (Qh_1); relationship of fan sediments to lake shorelines (S_1, S_2). (c) Long profile relationships

ment properties. Because of the larger area involved and the wider range of surface type present, the age classification was limited to four groups, mid Pleistocene ($=Q_0$), late Pleistocene, including the Pleistocene–Holocene transition ($=Q_{1 \text{ and } 2}$), Holocene ($=Q_{3 \text{ and } 4}$), and active ($=Q_5$).

The oldest hillslope surfaces (Q_0), restricted to flatter areas near the divides and on lower spur tops, are characterised by a dominance of *in situ* weathering-related features. They exhibit well-developed desert pavements of small, closely interlocking clasts derived from the underlying bedrock, together with, on the upper but not all the lower surfaces, abundant caliche (calcrete) rubble (Lattman, 1977) derived from the weathering of a stage III to IV pedogenic calcrete horizon (Gile *et al.*, 1966). The bedrock clasts carry a complete cover of a dark rock varnish (reaching, for example, 2.5YR 2.5/2 on exposed surfaces and a paler 5YR 4/6 on their undersides). Below the pavement surfaces is a regolith within which shallow, weak to moderately developed Av and B horizons have developed (colours: 10YR 6/4 to 7.5YR 7/4). These overlie strongly developed stage III to IV petrocalcic horizons.

The majority of the hillslope surfaces appear to be late Pleistocene in age, in that they are mostly cut into the older geomorphic surfaces, and the exposed rock surfaces carry a rock varnish similar to that on rocks on alluvial fan surfaces $Qf_{1 \text{ and } 2}$, a dark varnish of 2.5 to 5YR 2.5/2 covering most of the rock surface (>75%), and partly or wholly obscuring the details of the lithology of the underlying rock.

Locally, two younger categories of hillslope feature can be recognised. Holocene forms lie within or dissect late Pleistocene forms. They carry a rock varnish ranging from very slight coloration of exposed surfaces to a partial cover reaching *ca.* 5YR 5/6, which can be correlated to that on alluvial fan surfaces Qf_{3-4}. The youngest surfaces of all are active and erosional, and dissect older surfaces. They are equivalent to fan stage Qf_5.

Hillslope Forms

Several different types of hillslope were mapped (Table 4.1, Figure 4.4), each relating to a different style of hillslope process, and age-assigned on the criteria outlined above. Old stable surfaces (Q_0) occur only in divide and spur-top locations. Exposed bedrock occurs on most of the steeper slopes and presumably at one time provided a major source of sediment to the hillslopes and alluvial fans below. Most outcrops are covered by a dark and complete rock varnish (correlating with a $Q_{1 \text{ to } 2}$ age), suggesting that there has been little sediment supplied from these sites since the end of the Pleistocene. Rock varnish does not develop on rock surfaces of the metamorphosed limestone, but most of these outcrops are above apparently stable talus or colluvial slopes and therefore also appear to have been stable for much of the Holocene. Only where bedrock is actively incised or undercut by a modern stream channel does the direct supply of sediment from bedrock into the modern sediment system appear to take place.

Planar slopes, mantled by talus, often occur downslope from bedrock outcrops (Figure 4.5(a)). These are mostly varnished by dark and complete rock varnish ($=Q_{1 \text{ or } 2}$), indicating stability since the end of the Pleistocene. Only in a very few localities are they not varnished, indicating some Holocene or recent activity. In some places the varnished scree slopes are dissected by recently active gullies and scars.

Many of the slopes, especially in the lower parts of the drainage basins, planar to concavo-convex in form, are blanketed by a stony regolith, within which the stones show a dark and complete ($Q_{1 \text{ to } 2}$-type) rock varnish, soils are present and there is some vegetation cover. These slopes may have been active as colluvial slopes during the late Pleistocene but have been largely stable throughout the Holocene.

Some of the slopes, especially the colluvial slopes, have been affected by hillslope debris flow activity. Debris flow trails, levees, breached lobes and lobe fronts (Wells & Harvey, 1987) are evident (Figure 4.5(b)). Most show a varnish of $Q_{1 \text{ to } 2}$-type, again indicating stability since the end of the Pleistocene. A few of the debris flows show evidence of minor reworking later, with small younger lobes carrying a lesser degree of rock varnish, equivalent to that on Qf_3 alluvial fan surfaces, suggesting a limited phase of mid Holocene(?) hillslope debris flow activity. Many of the larger hillslope debris flows (all with $Q_{1 \text{ to } 2}$-type

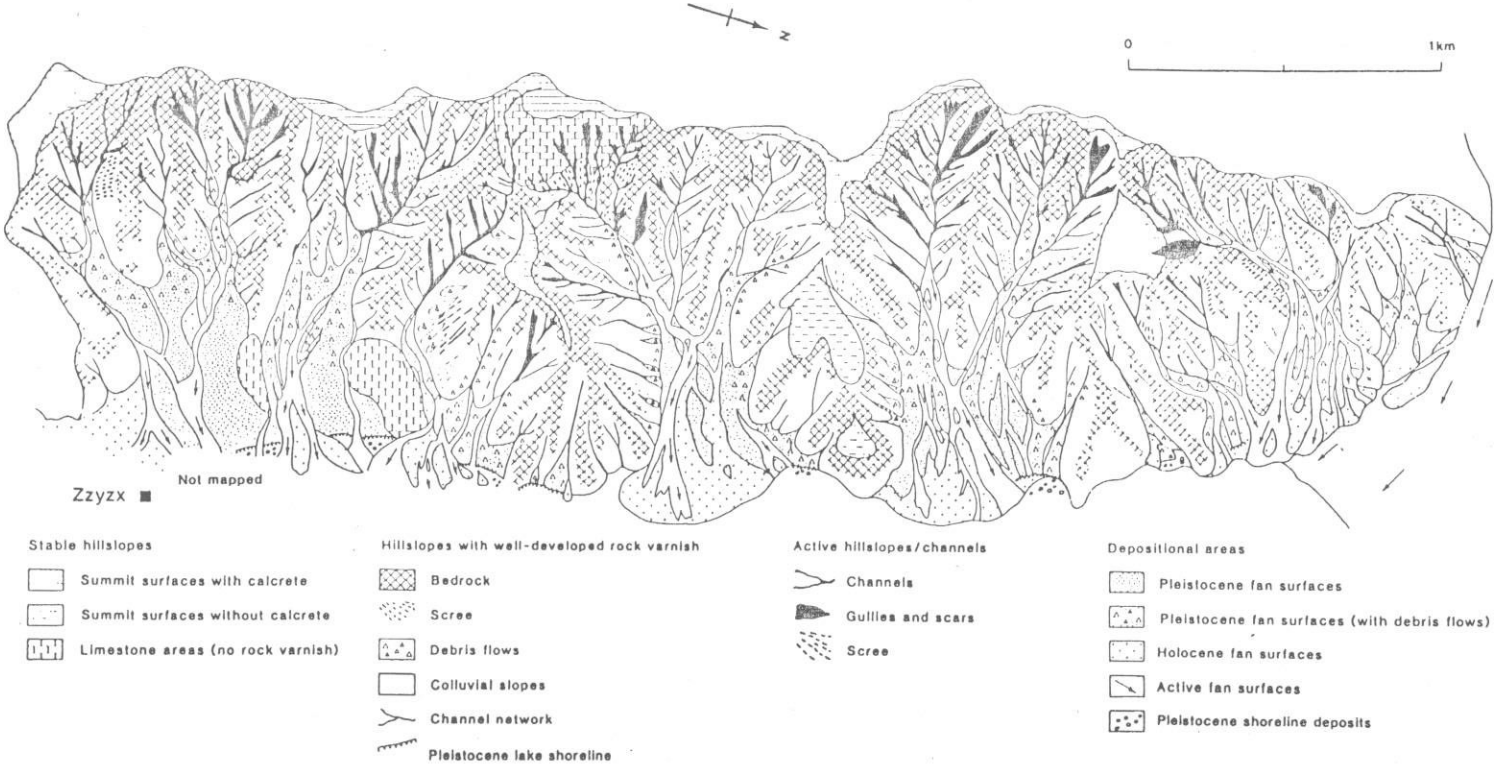


Figure 4.4 Summary map of hillslope morphology and age characteristics. Stable hillslopes either of Q_0 age or of indeterminate age (limestone areas); hillslopes with well-developed rock varnish are of late Pleistocene ($Q_{1 \text{ to } 2}$) age; hillslopes, now stable but active at some stage during the Holocene ($Q_{3 \text{ to } 4}$) are too small to be represented on this map; for the depositional areas Pleistocene fan surfaces refer to surfaces of $Qf_{1 \text{ and } 2}$ ages, Holocene fan surfaces to surfaces of $Qf_{3 \text{ and } 4}$ ages, active surfaces to Qf_5.

Table 4.1 Types of hillslope surface

Type	Age[a] (estimate)	Characteristics
Old stable surfaces	Q_0	Two surfaces, upper (older?) with calcrete rubble, both with well developed soils
Exposed bedrock	Q_{1-2}	Large areas on both granite and metamorphics, well varnished. Limestone areas: no varnish
	Q_5	Very small active areas
Talus	Q_{1-2}	Large areas of varnished scree now stabilised
	Q_5	Small active screes
Colluvial slopes	Q_{1-2}	Extensive areas, varnished boulders, some soil development, now stabilised
Hillslope debris flows	Q_{1-2}	Major wave of hillslope debris flow. Debris flow activity at end of Q_{1-2} time
	Q_{3-4}	Very localised (Q_3) debris flow activity
Dissected slopes	Q_5	Gullying and incision of drainage lines, active today

[a] By correlation of rock varnish with that on the alluvial fans. Q_0 = mid Pleistocene, Q_{1-2} = late Pleistocene, Q_{3-4} = Holocene, Q_5 = currently active.

of rock varnish) toe out on proximal or lateral alluvial fan surfaces (Figure 4.6), locally capping fan deposits of Qf_1 age and suggesting a major phase of hillslope debris flow activity right at the end of the Pleistocene, during the Pleistocene–Holocene transition.

The final type of hillslope form is the dissected hillslope, showing evidence of erosion by gullying or surface stripping. These dissected areas are directly related to the modern stream network, are currently active and appear to be wholly late Holocene in age.

Interpretation

A summary map, based on the field maps, shows the spatial distributions of these hillslope types, differentiating between Pleistocene and Holocene zones of activity (Figure 4.4). A summary of the spatial variations is given in Table 4.2. There is clear evidence of a major switch in hillslope process during the transition from the late Pleistocene into the Holocene. During the late Pleistocene most hillslopes appear to have been active, supplying abundant sediment to the fluvial system. Exposed bedrock, especially in the upper parts of the drainage basins, appears to have been weathered and to have supplied coarse clasts into the system via talus slopes. Such processes were particularly important in the basin headwaters on steep slopes, primarily but not exclusively on granite bedrock (Table 4.2). Lower down-valley, especially on the metamorphic rocks (Table 4.2), colluvial slopes fed sediment downslope.

During the Pleistocene–Holocene transition (Qf_2 times) there was a major phase of renewed hillslope debris flow activity, especially on the colluvial slopes on metamorphic rocks (Table 4.2). These debris flows supplied sediment towards the alluvial fans, but usually toed out at the base of the hillslopes rather than feeding much sediment into the alluvial fan systems themselves.

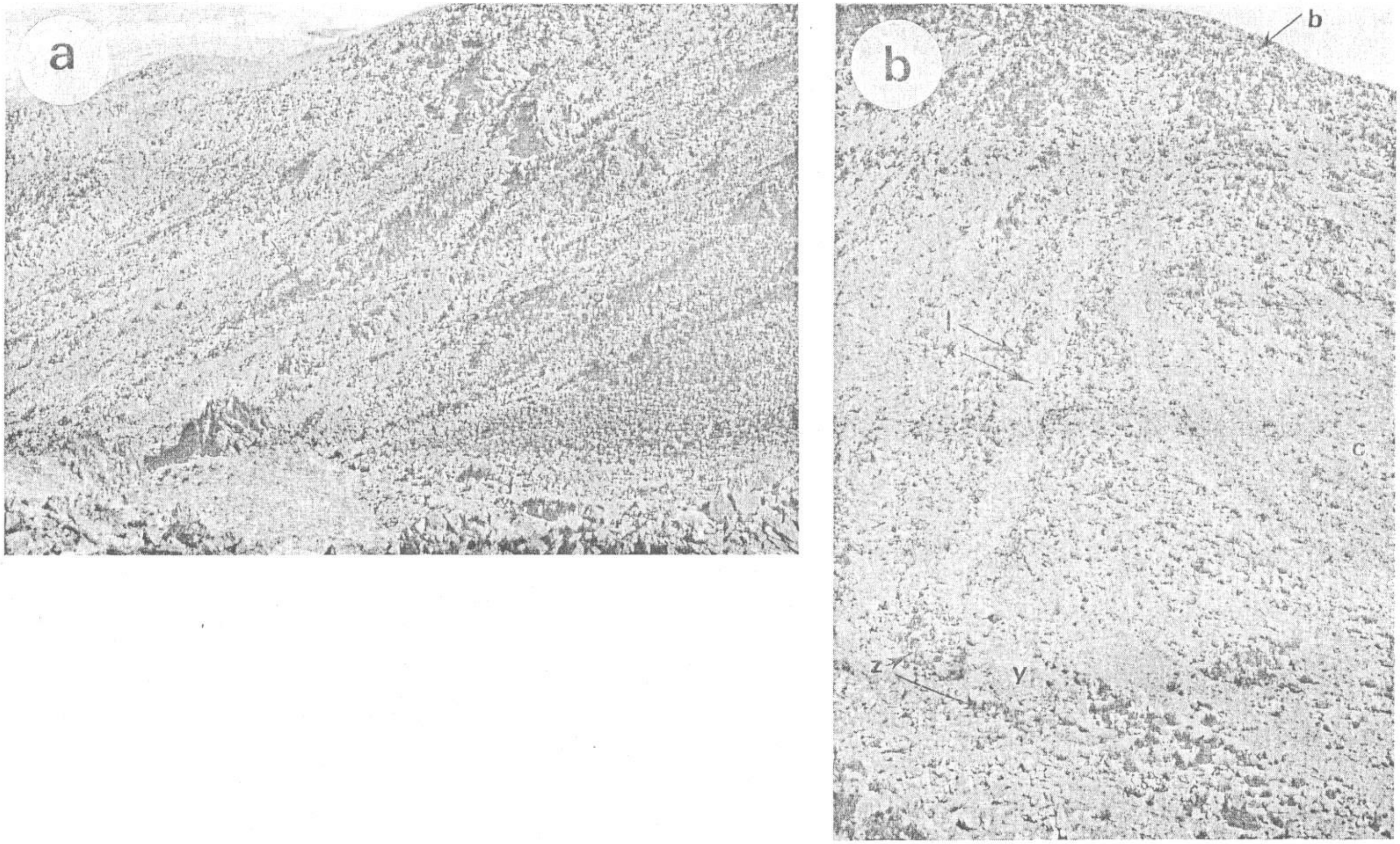


Figure 4.5 Quaternary hillslope morphology. (a) Part dissected, varnished talus slopes (t) below varnished bedrock outcrop (b). (b) Colluvial slope (c) below varnished bedrock outcrop (b), traversed by Q_{1-2} age hillslope debris flow. Note: debris flow track (X), levees (l) and minor Q_{3-4} reactivation (Y) within Q_{1-2} lobes (Z)

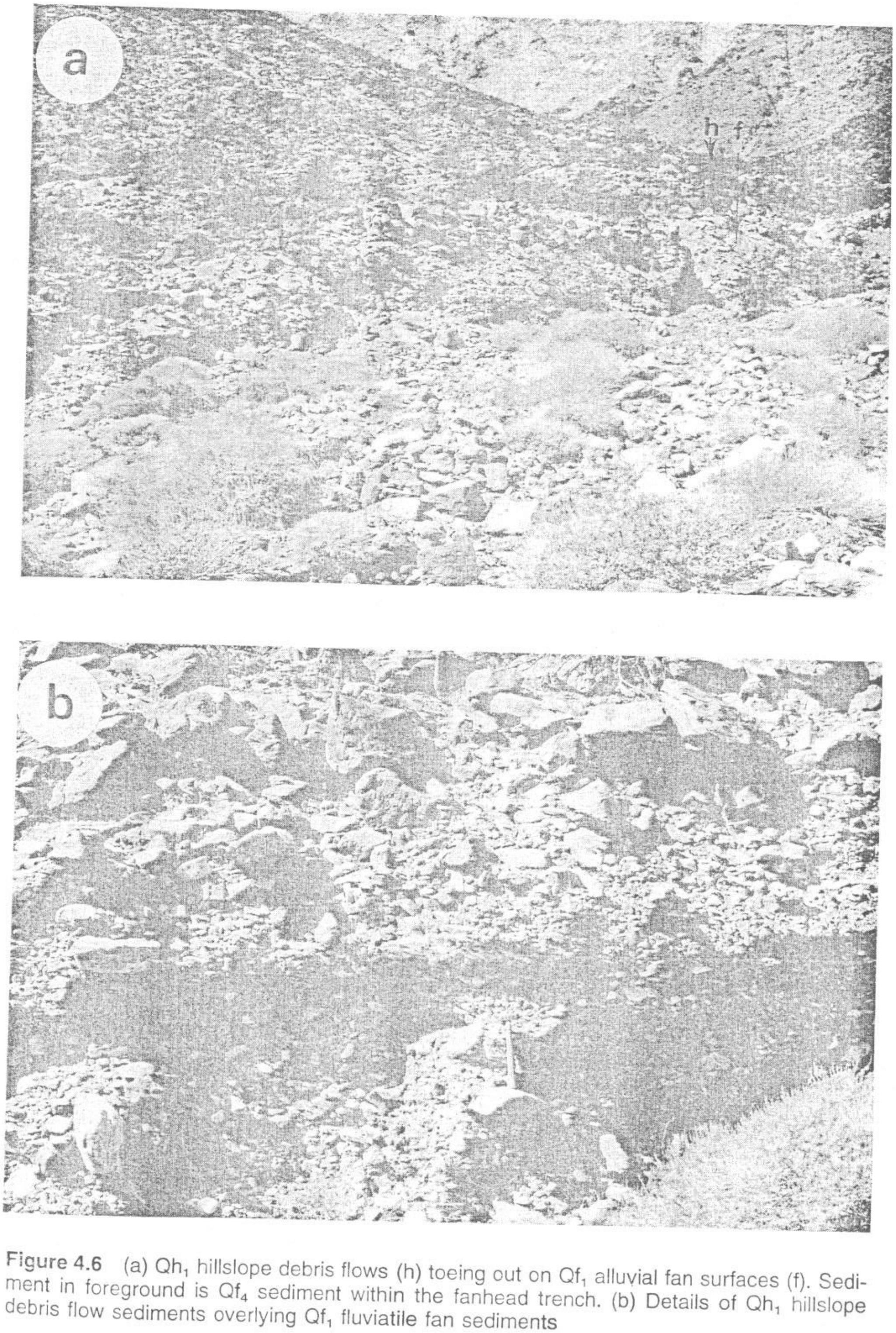


Figure 4.6 (a) Qh_1 hillslope debris flows (h) toeing out on Qf_1 alluvial fan surfaces (f). Sediment in foreground is Qf_4 sediment within the fanhead trench. (b) Details of Qh_1 hillslope debris flow sediments overlying Qf_1 fluviatile fan sediments

Table 4.2 Relative abundance of hillslope surface types

Drainage basin[a]	Rock type[b]	RC[c]	Hillslopes[d]							Fan behaviour[e]	
			Stable					Active			
			OS	RO	Sc	CS	Df	Sc	Ds	P	H
SO1	GM	2	2	3	1	3	0	1	1	DF	TF
SO2	GM	2	0	3	2	2	2	0	2	D	D
SO3	GML	2	1	3	3	2	2	0	3	DF	I
SPR	GML	2	2	2	1	3	1	1	1	D	I
ZZX	GML	2	2	3	2	2	1	0	3	DF	TF
JSH	ML	2	2	2	1	3	3	0	2	F	TF
CT/PC	M	1	1	1	0	3	1	0	1	D	P
CV-s	ML	2	2	2	1	2	3	1	2	F	TF
CV-n	M	2	2	1	0	3	3	0	1	DF	I
JN-s	M	2	2	2	1	2	3	0	3	DF	TF
JN-n	MG	2	2	3	1	2	2	0	3	DF	I
STV	M	1	0	1	0	3	0	0	0	D	(D)
MSQ	M	1	0	2	0	2	2	1	1	D	DF
VLT	G	2	1	3	2	1	2	2	3	DF	TF
SOL	G	1	1	2	0	2	1	0	1	DF	I
NOR	G	1	1	2	0	2	1	0	1	DF	I

[a] For locations, see Figure 4.1.

[b] G, granite; M, metamorphics; L, limestone (in order of abundance).

[c] RC, relief class (within drainage basin), 1, <250 m; 2, >250 m.

[d] OS, old surfaces; RO, rocky outcrop; Sc, scree; CS, colluvial slopes; Df, debris flows; Ds, dissection; 0, not present; 1, present; 2, common; 3, abundant.

[e] P, pleistocene; H, Holocene; D, debris flow; F, fluvial sedimentation; DF, proximal debris flows, distal fluvial sedimentation; TF, fanhead trenching, distal fluvial sedimentation; I, dissection throughout; P, passive (brackets indicate limited importance).

The fan response to high rates of sediment supply during the late Pleistocene (Qf_1) was aggradation, primarily by debris flow processes, burying previous fan surfaces. Only on the larger fans did debris flows dilute downfan to allow fluvial deposition. Only at the very end of the Pleistocene–Holocene transition (Qf_2 times) does fanhead trenching begin.

During the early Holocene the hillslopes stabilised, allowing rock varnish to develop on exposed surfaces of hitherto active free faces, talus slopes, bouldery colluvial slopes and hillslope debris flows. The fan environments became starved of sediment and responded by fanhead trenching and distal progradation, in a switch from a sediment-rich debris flow regime to a sediment-poor fluvial regime. Fan dissection was accentuated by the switch from debris flow deposition on relatively steep fan surfaces to fluvial transport over the same gradients, involving excess stream power and resulting in dissection of the proximal fan surfaces (Harvey, 1984b, 1989).

During the Holocene, on the steepest slopes in the headwaters of the larger watersheds, especially but not exclusively on granite rocks (Table 4.2), hillslope dissection by gullying occurred. This caused some sediment supply to the fan environment, but on a much more restricted basis than hitherto. Episodically, on several occasions (during $Qf_{3\text{ and }4}$ times), there was a minor renewal of sediment supply from the hillslopes, causing localised reactivation of hillslope debris flows and supplying debris flow deposits to fan apex areas, Qf_3 or Qf_4

deposits locally burying Qf_1 sediments (Figure 4.3). However, whether these edisodes could be related to Holocene climatic fluctuations or simply represent a delayed and complex response to the Pleistocene to Holocene changes is not certain. As a whole the Holocene is overwhelmingly a period of low coarse sediment supply from the hillslopes, dissection of the fan proximal regions and sedimentation, by fluvial processes, causing fan progradation in distal areas.

DISCUSSION

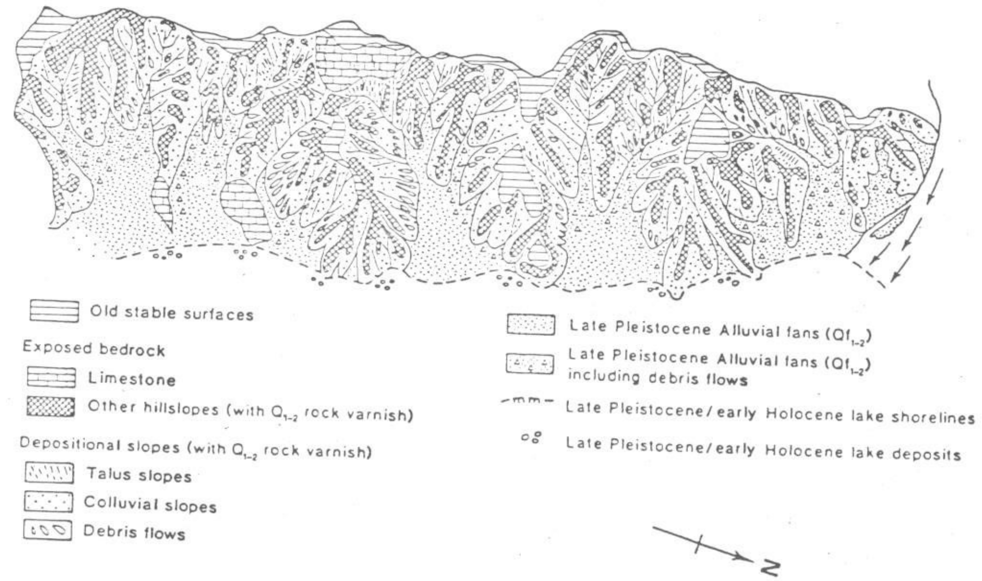
Climatic Implications

There are clear contrasts between late Pleistocene and Holocene geomorphic systems (Figure 4.7), which suggest contrasts between Pleistocene and Holocene climates. The conventional interpretation would be of a transition from a mild(?), moist 'pluvial' late Pleistocene to a hot, arid Holocene, with minor fluctuations since, to account for variations in sediment production during the Holocene. There has been some discussion (Brackenridge, 1978; Galloway, 1983) on the amount by which late Pleistocene climates would need to have been cooler or wetter than those of today, in order to account for either vegetation distributions (Van Devender & Spaulding, 1983; Spaulding, 1990) or high lake levels (Smith & Street-Perrott, 1983). The transition period itself is interpreted to have had an increased monsoonal airflow and associated rains (Enzel *et al.*, 1990), apparently sufficient to result in the widespread growth of succulents and grasses in the northern Mojave Desert, increased discharges in the Colorado and Mojave rivers, and high lake levels in pluvial Lake Mojave (Bull, 1991; Wells *et al.*, 1989). By 8000–9000 yr BP, the disappearence of California juniper and replacement of resident species by desert scrub documents the establishment of the typical hot, dry Holocene climatic regime (Spaulding & Graumlich, 1986).

The geomorphological evidence from Zzyzx very strongly suggests major differences in sediment production and transport mechanisms between the late Pleistocene and the Holocene brought about by changes during the Pleistocene–Holocene transition. The contrasts imply differences in *both* temperature *and* precipitation between the late Pleistocene (Qf_1) and the Holocene (Qf_3 onwards). High rates of sediment generation characterised many of today's arid areas during the late Pleistocene, both in the American south-west (Meyer *et al.*, 1984) and in other arid regions, notably Israel (Gerson, 1982). These were followed during the Holocene, under conditions of increased aridity, by periods of hillslope stripping and enhanced fluvial activity (Bull & Schick, 1979; Bull, 1991).

During the Pleistocene (Qf_1) the Zzyzx hillslopes saw greatly enhanced weathering rates over those that exist today, indicating a much greater moisture availability and probably lower temperatures. It is easy to envisage frost action as an important weathering process in the Panamint Mountains, supplying the Death Valley fans, as they reach altitudes of over 3000 m a.s.l, but the Soda Mountains at Zzyzx barely reach an altitude of 600 m. It could be argued that considerably wetter and colder climates in the late Pleistocene would have been necessary for such weathering processes to have occurred there. Similarly, for the widespread mass movement processes to transport the sediment downslope, especially by debris flow processes, as observed preserved on the Zzyzx hillslopes, high soil moisture contents and high rainfall intensities or durations would be required (Caine, 1980) during the late Pleistocene and the Pleistocene–Holocene transition.

LATE PLEISTOCENE



HOLOCENE

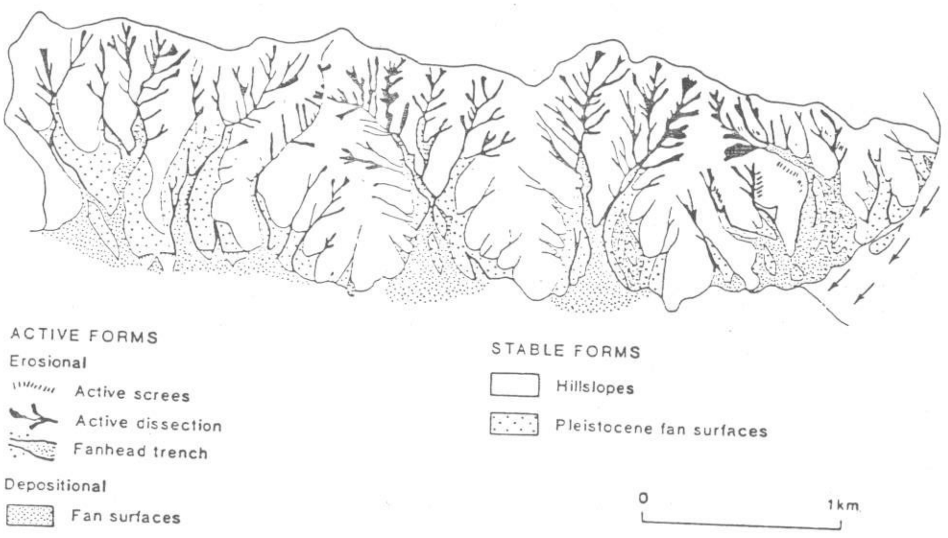


Figure 4.7 Summary maps showing contrasting zones of late Pleistocene and Holocene geomorphic activity. Definitions as for Figure 4.4. With the exception of the old stable surfaces (Q_0), the upper map shows features erosionally or depositionally active during the late Pleistocene (Q_1) and/or Pleistocene–Holocene transition (Q_2); the lower map shows features active since

Within the eastern Mojave Desert, climatic inferences from plant macrofossils in packrat middens suggest as much as a 50% decrease in precipitation and a mean warming of *ca.* 3°C during the transition from late Pleistocene to Holocene climatic regimes (Van Devender, 1973). Estimates of temperature differences between the late Pleistocene and the Holocene, derived from analyses of stable hydrogen isotopes in cellulose from fossil packrat middens from the Great Basin (Long *et al.*, 1990), suggest that growing season temperatures 3–4°C cooler than present may have persisted between *ca.* 30 000 and 18 000 BP.

Wells *et al.* (1989) have used a simple hydrological model to reconstruct the end Pleistocene Mojave River discharge necessary to result in overflow of pluvial Lake Mojave. Their study suggests that neither increased precipitation nor reduced temperature alone is sufficient to account for the late Pleistocene lake. Temperatures 10°C lower than those of today, and precipitation 50% higher, in the Transverse Ranges of southern California, which feed the Mojave River, would result in the lake levels similar to those of late Pleistocene Lake Mojave.

In addition to climatic changes, the presence of hygroscopic salts such as aerosols, related to episodic drying of pluvial Lake Mojave during the late Pleistocene (Wells *et al.*, 1989; Brown *et al.*, 1990), may have been significant for the mechanical weathering of bedrock on hillslopes neighbouring the lake. Such processes may have been more important than frost action, because of the low elevation of the Soda Mountains. However, perhaps during the late Pleistocene, an increased frequency of deep southward penetrations of cold polar air masses into the Zzyzx region, as happened in January 1990, could have enhanced freeze–thaw activity at these elevations. Evidence for this type of activity is given by Friedman & Smith (1972), who suggest that the cold air masses and jet-stream positions of the 1968–9 winter may have been similar to those of late Pleistocene climates.

Under the present climatic conditions, as in most parts of the south-west, hillslope processes are dominated by overland flow, and sediment transport by fluvial processes during flood conditions (Baker, 1977). There is no evidence for recent hillslope debris flows in this part of the Soda Mountains, suggesting that under the present climatic regime they would occur rarely, if at all. On 20 August 1988 a major storm occurred over Zzyzx, when over 60 mm of rain fell in *ca.* 45 minutes. This was a rare event, and although we do not have a precise estimate, its return period must be well in excess of 20 years. There was considerable flood damage to the Interstate Highway where it crosses the Soda Mountains west of Zzyzx, and the Zzyzx access road was totally destroyed. Despite major geomorphic change on the Zzyzx fans by fluvial processes resulting from this event, no evidence of any geomorphic change on the hillslopes by mass movement processes could be detected after the storm.

SUMMARY

It is clear that during the late Pleistocene the climate of the eastern Mojave Desert would have been both colder and wetter than that of today. This would account for the high rates of weathering and sediment production on the hillslopes and sediment transport down the hillslopes by mass movement processes. These conditions led to a state of excess sediment supply to the alluvial fans, and hence of fan aggradation, dominantly by debris flow processes. Conditions began to change during the Pleistocene–Holocene transition. There was a last main wave of hillslope debris flow activity, but much of the sediment moved did not reach the alluvial fans. Limited fanhead trenching and distal progradation began during this period. Following desiccation (and warming) to an arid climate in the Holocene, the hillslopes stabilised, but during storm and flash flood conditions the high rates of runoff generated excess stream power, causing fanhead trenching and distal fan progradation. The minor variations in fan behaviour during the Holocene may reflect smaller scale climatic fluctuations or simply represent a delayed complex response to the major Pleistocene to Holocene changes.

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REFERENCES

Baker, V. R. (1977). Stream channel response to floods, with examples from central Texas. *Geological Society of America, Bulletin*, **88**, 1057–71.

Brown, W. C., Wells, S. G., Enzel, Y., Anderson, R. Y. and McFadden, L. D. (1990). The late Quaternary history of pluvial Lake Mojave-Silver Lake and Soda Lake basins, California. In Reynolds, J. (ed.), *At the End of the Mojave: Quaternary Studies in the Eastern Mojave Desert*, San Bernadino County Museum Association and 1990 Mojave Desert Quaternary Research Center Symposium, pp. 55–72.

Blissenbach, E. (1954). Geology of alluvial fans in semi arid regions. *Geological Society of America, Bulletin*, **55**, 175–90.

Brackenridge, G. R. (1978). Evidence for a cold, dry full-glacial climate in the American southwest. *Quaternary Research*, **9**, 22–40.

Bull, W. B. (1977). The alluvial fan environment. *Progress in Physical Geography*, **1**, 222–70.

Bull, W. B. (1979). Threshold of critical power in streams. *Geological Society of America, Bulletin*, **90**, 453–64.

Bull, W. B. (1991). *Geomorphic Responses to Climatic Change*, Oxford University Press, Oxford.

Bull, W. B. and Schick, A. P. (1979). Impact of climatic change on an arid watershed: Natal Yael, Southern Israel. *Quaternary Research*, **11**, 153–71.

Caine, N. (1980). The rainfall intensity-duration control of shallow landslides and debris flows. *Geografiska Annaler*, **62A**, 23–7.

Denny, C. S. (1965). Alluvial fans in Death Valley region, California and Nevada. United States Geological Survey, Professional Paper 466.

Dohrenwend, J. C., Bull, W. B., McFadden, L. D., Smith, G. I., Smith, R. S. U. and Wells, S. G. (1991). Quaternary geology of the Basin and Range Province in California. In Morrison, R. B. (ed.), *Quaternary Nonglacial Geology: Conterminous U. S., The Geology of North America*, Volume K-2, pp. 321–52.

Dorn, R. I. (1983). Cation-ratio dating: a new rock varnish age-determination technique. *Quaternary Research*, **20**, 49–73.

Dorn, R. I. (1984). Cause and implications of rock varnish microchemical laminations. *Nature*, **310**, 767–70.

Dorn, R. I. (1988). A rock varnish interpretation of alluvial-fan development in Death Valley, California. *National Geographic Research*, **4**, 56–73.

Dorn, R. I. and Oberlander, T. M. (1981). Rock varnish origin, characteristics and usage. *Zeitschrift für Geomorphologie*, **NF25**, 420–36.

Dorn, R. I., Jull, A. J. T, Donahue, D. J., Linick, T. W. and Toolin, L. T. (1989). Accelerator mass spectrometry radiocarbon dating of rock varnish. *Geological Society of America, Bulletin,* **101**, 1363-72.

Dorn, R. I., De Niro, M. J. and Ajie, H. O. (1987). Isotopic evidence for climatic influence on alluvial fan development in Death Valley, California. *Geology,* **15**, 108–10.

Enzel, Y., Anderson, R. Y., Brown, W. J., Cayan, D. R. and Wells, S. G. (1990). Tropical and subtropical moisture and southerly displaced North Pacific storm track: factors in the growth of late Quaternary lakes in the Mojave Desert. In Betancourt, J. L. and Mackay, A. M. (eds.), *Proceedings of the 6th Annual Pacific Climate (PACLIM) Workshop*, 5–8 March 1989, California Department of Water Resources, Interagency Ecological Studies Program, Technical Report 23, pp. 135–9.

Friedman, I. and Smith, G. I. (1972). Deuterium content in snow as an index to winter climate in the Sierra Nevada area. *Science,* **176**, 790–3.

Galloway, R. W. (1983). Full-glacial southwestern United States: mild and wet or cold and dry? *Quaternary Research* **19**, 236–48.

Gerson, R. (1982). Talus relics in deserts: a key to major climatic fluctuation. *Israel Journal of Earth Sciences,* **31**, 123–32.

Gerson, R., Bull, W. B., Fleischhauer, H. L., *et al.* (1978). Origin and distribution of gravel in stream systems of arid regions. US Air Force Office of Scientific Research, Contract Report F49–620–77-C-0115.

Gile, L. H., Peterson, F. F. and Grossman, R. B. (1966). Morphological and genetic sequence of carbonate accumulation in desert soils. *Soil Science,* **101**, 347–60.

Harvey, A. M. (1984a) Aggradation and dissection sequences in Spanish alluvial fans: influence on morphological development. *Catena,* **11**, 289–304.

Harvey, A. M. (1984b) Debris flows and fluvial deposits in Spanish Quaternary alluvial fans: implications for fan morphology. In Koster, E. H., and Steel, R. (eds.), *Sedimentology of Gravels and Conglomerates*, Canadian Society of Petroleum Geologists, Memoir 10, pp. 123–32.

Harvey, A. M. (1989). The occurrence and role of arid zone alluvial fans. In Thomas, D. S. G. (ed.), *Arid Zone Geomorphology*, Belhaven Press, London, pp. 136–58.

Harvey, A. M. (1990). Factors influencing Quaternary alluvial fan development in southeast Spain. In Rackocki, A. H. and Church, M. J. (eds.), *Alluvial Fans: A Field Approach*, Wiley, Chichester, pp. 247–69.

Harvey, A. M. (1992). Controls on sedimentary style on alluvial fans. In Billi, P., Hey, R. D., Thorne, C. R. and Tacconi, P. (eds.), *Dynamics of Gravel-Bed Rivers*, Wiley, Chichester, pp. 519–535.

Hooke, R. le B. (1967). Processes on arid region alluvial fans. *Journal of Geology,* **75**, 438–60.

Hunt, C. B. (1975). *Death Valley: Geology, Archaeology, Ecology*, University of California Press, Berkeley.

Hunt, C. B. and Mabey, D. R. (1966). Stratigraphy and structure, Death Valley, California. United States Geological Survey, Professional Paper 494A.

Lattman, L. H. (1977). Weathering of caliche in southern Nevada. In Doehring, D. E. (ed.), *Geomorphology in Arid Regions*, Allen & Unwin, London, pp. 221–31.

Long, A., Warnecke, L., Betancourt, J. L. and Thompson, R. S. (1990). Deuterium variations in plant cellulose from fossil packrat middens. In Betancourt, J. L., Van Devender, T. R. and Martin, P. S. (eds.), *Packrat Middens, The Last 40,000 Years of Biotic Change*, University of Arizona Press, Tucson.

McFadden, L. D., Wells, S. G. and Jercinovich, M. J. (1987). Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. *Geology,* **15**, 504–8.

McFadden, L. D., Ritter, J. B. and Wells, S. G. (1989). Use of multiparameter relative-age methods for age estimation and correlation of alluvial fan surfaces on a desert piedmont, eastern Mojave Desert, California. *Quaternary Research,* **32**, 276–90.

Meyer, L., Gerson, R. and Bull, W. B. (1984). Alluvial gravel production and deposition: a useful indicator of Quaternary climatic changes in deserts (a case study in southwestern Arizona). In Shick, A. P. (ed.), *Channel Processes: Water, Sediment, Catchment Controls*, Catena Supplement, **5**, pp. 137–51.

Oberlander, T. M. (1989). Slope and pediment systems. In Thomas, D. S. G. (ed.), *Arid Zone Geomorphology*, Belhaven Press, London, pp. 56–84.

Ritter, J. B. (1991). The response of alluvial fan systems to late Quaternary climatic change and local base-level change, eastern Mojave Desert, California. In Reynolds, J. (ed.) *At the End of the Mojave: Quaternary Studies in the Eastern Mojave Desert*, San Bernardino County Museum Association and 1990 Mojave Desert Quaternary Research Centre Symposium, pp. 117–18.

Slate, J. L. (1991). Quaternary stratigraphy, geomorphology, and ages of alluvial fans in Fish Lake Valley. In *Guidebook for Field Trip to Fish Lake Valley, California-Nevada*, Pacific Cell, Friends of the Pleistocene, pp. 94–113.

Smith, G. I. and Street-Perrott, F. A. (1983). Pluvial lakes of the western United States. In Porter, S. C. (ed.), *Late Quaternary Environments in the United States.* Volume I, *The Late Pleistocene*, University of Minnesota Press, Minneapolis, pp. 190–214.

Spaulding, W. G. (1990). Vegetation dynamics during the last deglaciation, southeastern Great Basin, USA. *Quaternary Research,* **33**, 188–203.

Spaulding, W. G. and Graumlich, L. J. (1986). The last pluvial climatic episodes in the deserts of southwestern North America. *Nature,* **320**, 441–4.

Van Devender, T. R. (1973). Late Pleistocene plants and animals of the Sonoran Desert: a survey of ancient packrat middens in southwestern Arizona. Unpublished PhD thesis, University of Arizona, Tucson.

Van Devender, T. R. and Spaulding, W. G. (1983). Development of vegetation and climate in the south western United States. In Wells, S. G. and Haragan, D. R. (eds.), *Origin and Evolution of Forests*, University of New Mexico Press, Albuquerque, pp. 131–56.

Wells, S. G. and Harvey, A. M. (1987). Sedimentologic and geomorphic variations in storm generated alluvial fans, Howgill Fells, northwest England. *Geological Society of America, Bulletin,* **98,** 182–98.

Wells, S. G. and McFadden, L. D. (1987). Comment and reply on 'Isotopic evidence for climatic influence on alluvial fan development in Death Valley, California'. *Geology,* **15**, 1178–9.

Wells, S. G., McFadden, L. D., Dohrenwend, J. C., *et al.* (1984). Geomorphic history of Silver Lake, eastern Mojave Desert, California: an example of the influence of climatic change on desert piedmonts. In Dohrenwend, J. C. (ed.), *Surficial Geology of the Eastern Mojave Desert*, Field trip 14 Guidebook, Geological Society of America, pp. 69–87.

Wells, S. G., McFadden, L. D. and Dohrenwend, J. C. (1987). Influence of late Quaternary climatic change on geomorphic and pedogenic processes on a desert piedmont, eastern Mojave Desert, California. *Quaternary Research,* **27**, 130–46.

Wells, S. G., Anderson, R. Y., McFadden, L. D., Brown, W. J., Enzel, Y. and Moissec, J.-L. (1989). Late Quaternary paleohydrology of the Eastern Mojave River drainage basin, southern California: quantitative assessment of the Late Quaternary hydrologic cycle in large arid watersheds. New Mexico Water Resources Research Institute, Technical Completion Report, Project 14-08-0001-G1312, 253 pp.

Wells, S. G., McFadden, L. D. and Harden, J. (1990a). Preliminary results of age estimations and regional correlations of Quaternary alluvial fans within the Mojave Desert of southern California. In Reynolds, J. (ed.), *At the End of the Mojave: Quaternary Studies in the Eastern Mojave Desert*, San Bernardino County Museum Association and 1990 Mojave Desert Quaternary Research Center Symposium, pp. 45–53.

Wells, S. G., Moissec, J-L. and Harvey, A. M. (1990b). Sedimentary processes during Holocene and Pleistocene alluvial fan deposition along the southern Soda Mountains, California: a summary. In Reynolds, J. (ed.), *At the End of the Mojave: Quaternary Studies in the Eastern Mojave Desert*, San Bernardino County Museum Association and 1990 Mojave Desert Quaternary Research Center Symposium, pp. 39–44.