ALLUVIAL FAN PROCESSES AND FORMS

TERENCE C. BLAIR and JOHN G. McPHERSON

INTRODUCTION

Alluvial fans are a prominent landform type commonly present where a channel emerges from mountainous uplands to an adjoining valley. Although occurring in perhaps all global climatic regimes, fans in deserts traditionally have been the most studied due to their excellent exposure and ease of access. This chapter attempts to (a) provide an up-to-date synthesis of the literature on alluvial fans in desert settings, and (b) introduce a framework for their understanding based on concepts that have emerged during the last 120 years of scientific research. This synthesis emphasizes recent developments in fan studies as well as published and unpublished results from our own work in the south-western United States. The conceptual framework developed in this chapter, despite being exemplified by fans from deserts, is also applicable to fans forming under other climatic conditions.

Alluvial fans are sedimentary deposits with a form that resembles the segment of a cone radiating downslope from a point where a channel emerges from an upland (Bull 1977) (Figs 14.1 and 14.2). Fans commonly have a semi-circular or pie-piece plan-view shape (Figs 14.1 and 14.3), whereas cross-profiles display a plano-convex geometry (Fig. 14.4). Radial profiles either exhibit a constant slope like that of a cone (Fig. 14.5), or have half of a concave-upwards geometry. Fan radii typically extend from 0.5 to 10.0 km from the mountain front (Fig. 14.3) (Anstey 1965, 1966). Fan deposits either radiate unabated in a 180° arc (Fig. 14.1d) or are laterally restricted by and coalesce with neighbouring fans to form a bajada (Fig. 14.1a and 14.1c).

The construction of alluvial fans results from the accumulation of sediment where a stream exits an upland area and the transporting medium loses its power and thereby its carrying capacity. Alluvial fans almost invariably consist of coarse-grained, poorly sorted deposits due to (a) the relatively short transport distance of the sediment from its source, (b) the involvement of mass wasting processes instigated by high relief, and (c) the rapid loss of carrying capacity of the flow. A more progressive loss of flow power downslope, particularly on larger fans, results ideally in coarse-grained (boulder) sediment deposition in the proximal area and relatively finer-grained (cobble, pebble and sand) sediment more distally (e.g. Lawson 1913, Blissenbach 1954). Downslope, fans are bordered by aeolian, fluvial, lacustrine, or marine environments (Fig. 14.3). They are easily differentiated from the neighbouring fluvial environments by the characterisistic fan morphology, including radial slope values of 2 to 20° (e.g. Anstey 1966), which contrast with ≤0.5° slope values for gravelly fluvial systems (McPherson *et al.* 1987).

Fans comprise one element of a spectrum of relatively high-sloping deposits found in the piedmont (foot of mountain) zone. Steeply inclined, mountain-flanking alluvial deposits lacking distinctive individual fans have been termed alluvial slopes (Hawley and Wilson 1965), whereas high-sloping subaerial deposits rimming volcanic centres are called volcanic aprons. Windblown deposits that steeply mantle mountain fronts are termed aeolian sandsheet ramps. Glacial moraines may also border fans of desert settings (e.g. Derbyshire and Owen 1990). Continental deposits with low slopes, such as those of longitudinal fluvial systems or lacustrine systems (Fig. 14.1), also can lie interspersed with alluvial fans in the piedmont zone (e.g. Hunt and Mabey 1966, Hunt *et al.* 1966).

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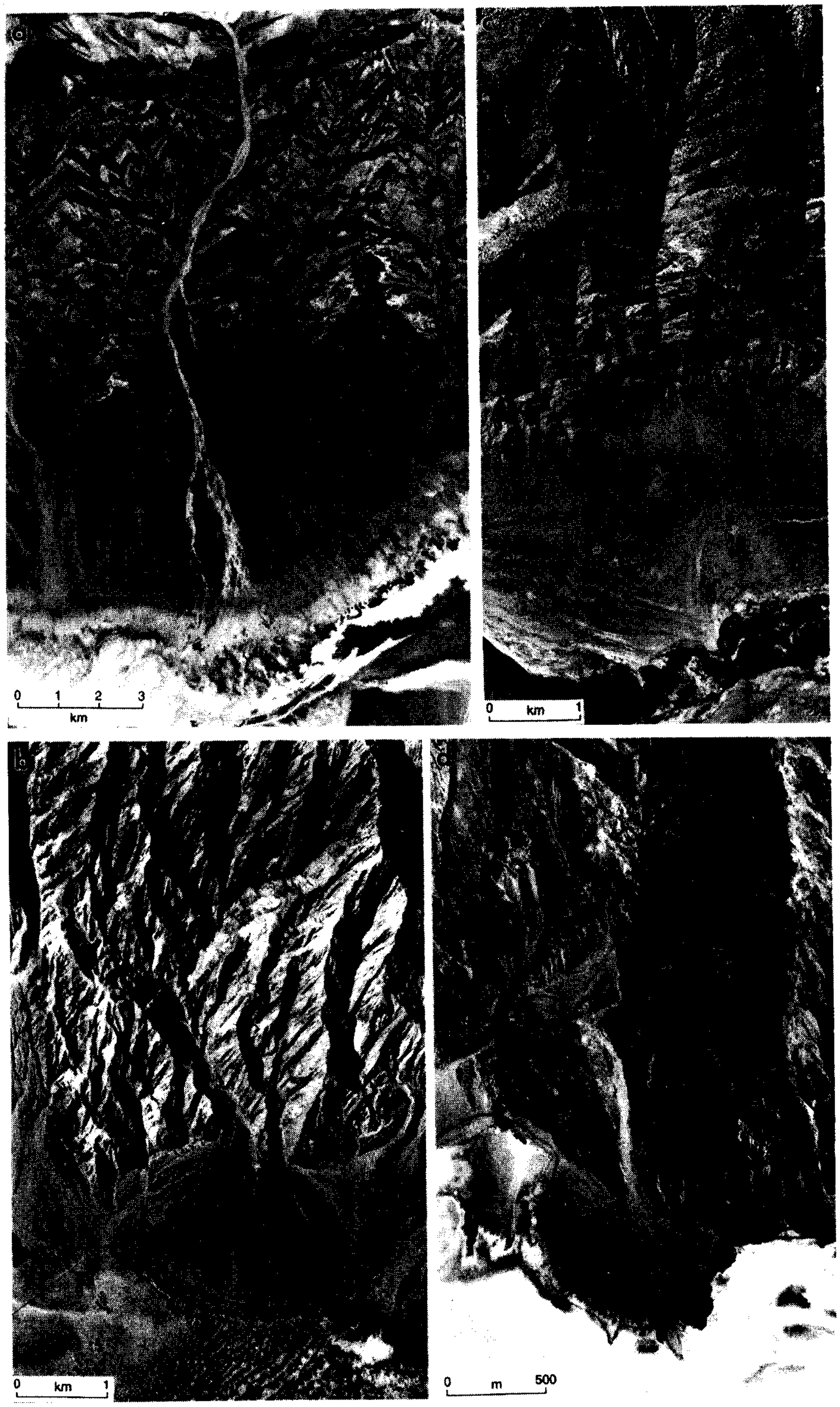

Figure 14.1 Aerial photographs of selected alluvial fans: (a) Trail Canyon fan of south-western Death Valley, California, (b) Grotto Canyon fan in northern Death Valley, (c) Deadman Canyon fan near Walker Lake, Nevada, and (d) South Badwater fan in south-eastern Death Valley.

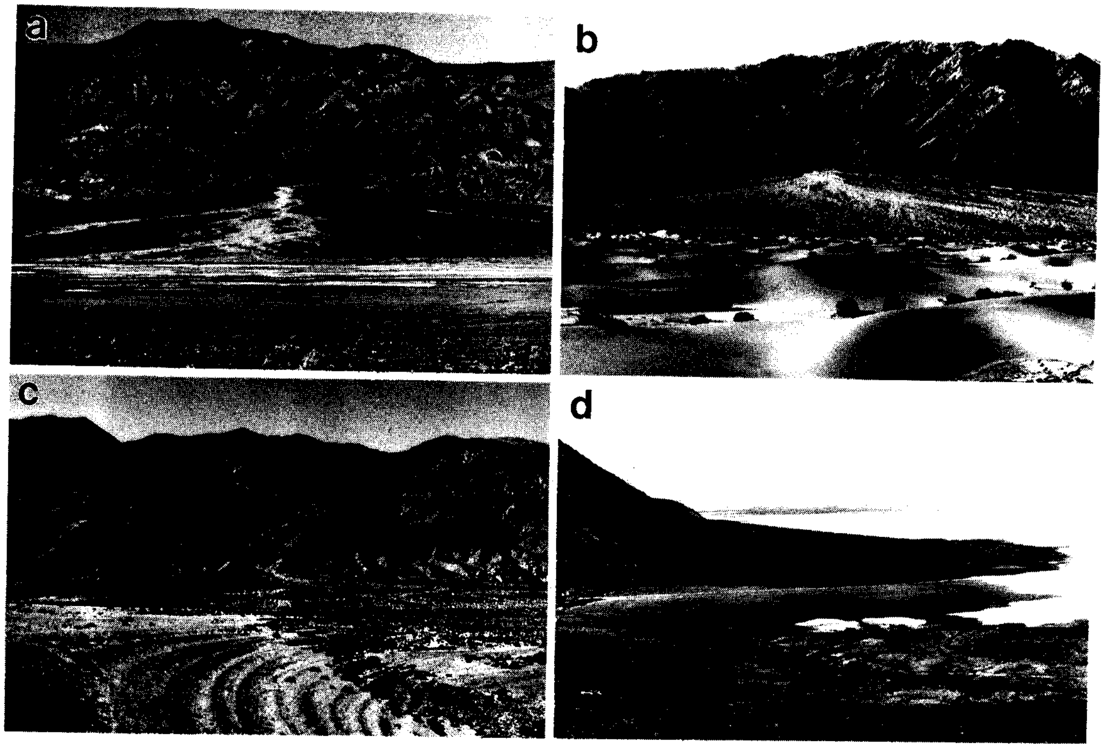

Figure 14.2 Ground-level photographs of alluvial fans illustrated in Figure 14.1: (a) Trail Canyon, (b) Grotto Canyon, (c) Deadman Canyon, and (d) South Badwater. The Trail Canyon and South Badwater fans are bordered distally by playas, whereas the Stovepipe Wells aeolian erg bounds the Grotto Canyon fan. Linear ridges along the margin of the Deadman Canyon fan are former lake shorelines.

The major morphologic features of the alluvial fan system are the drainage basin, feeder channel, apex, incised channel, distributary channels, intersection point, active depositional lobe, and headward-eroding gullies (Fig. 14.3). The drainage basin constitutes the upland area from which sediment and water discharge are derived. Alluvial fan drainage basins in desert settings typically are characterized by steep slopes and short first, second, or up to fifth-order ephemeral channels (Fig. 14.3). The highest-order stream in the drainage basin that leads to the fan is called the feeder channel. Usually only one prominent channel is present, although some fans may have multiple feeders (e.g. Fig. 14.3b). The apex of a fan is the point at the mountain front where the feeder channel emerges from the highlands (Drew 1873). This point represents the most proximal, and usually the highest, part of the fan. The apex is obvious where the mountain front is sharp (Fig. 14.3c and d), but is less distinctive where the feeder channels have carved large embayments (Fig. 14.3a).

The incised channel is a downslope extension of the feeder channel on the fan (Fig. 14.3a). It may comprise a singular trunk stream or one that divides downslope into several distributary channels. Incised channels are commonly, although not always, present (Fig. 14.3), occurring most typically on fans with longer radii. Incised channels usually terminate in the upper or medial part of the fan, but may also extend completely to the distal margin. The downfan position where an incised channel ends by merging with the fan slope is called the intersection point (Hooke 1967). Flows depart from the incised channel on to the fan surface at this point and laterally expand. The fan segment downslope from the intersection point typically is the site of sediment aggradation in an area termed the active depositional lobe (Fig. 14.3). The arc length of the active depositional lobe is a function of the radius of the lobe and the maximum angle of flow expansion, or the lobe expansion angle. Lobe expansion angles may be 180° on small fans but more typically are between 15° and 90° on larger ones (Fig. 14.3). Headward-eroding gullies are common features on the distal parts of fans (e.g. Denny 1967), particularly in older, temporarily inactive areas away from the

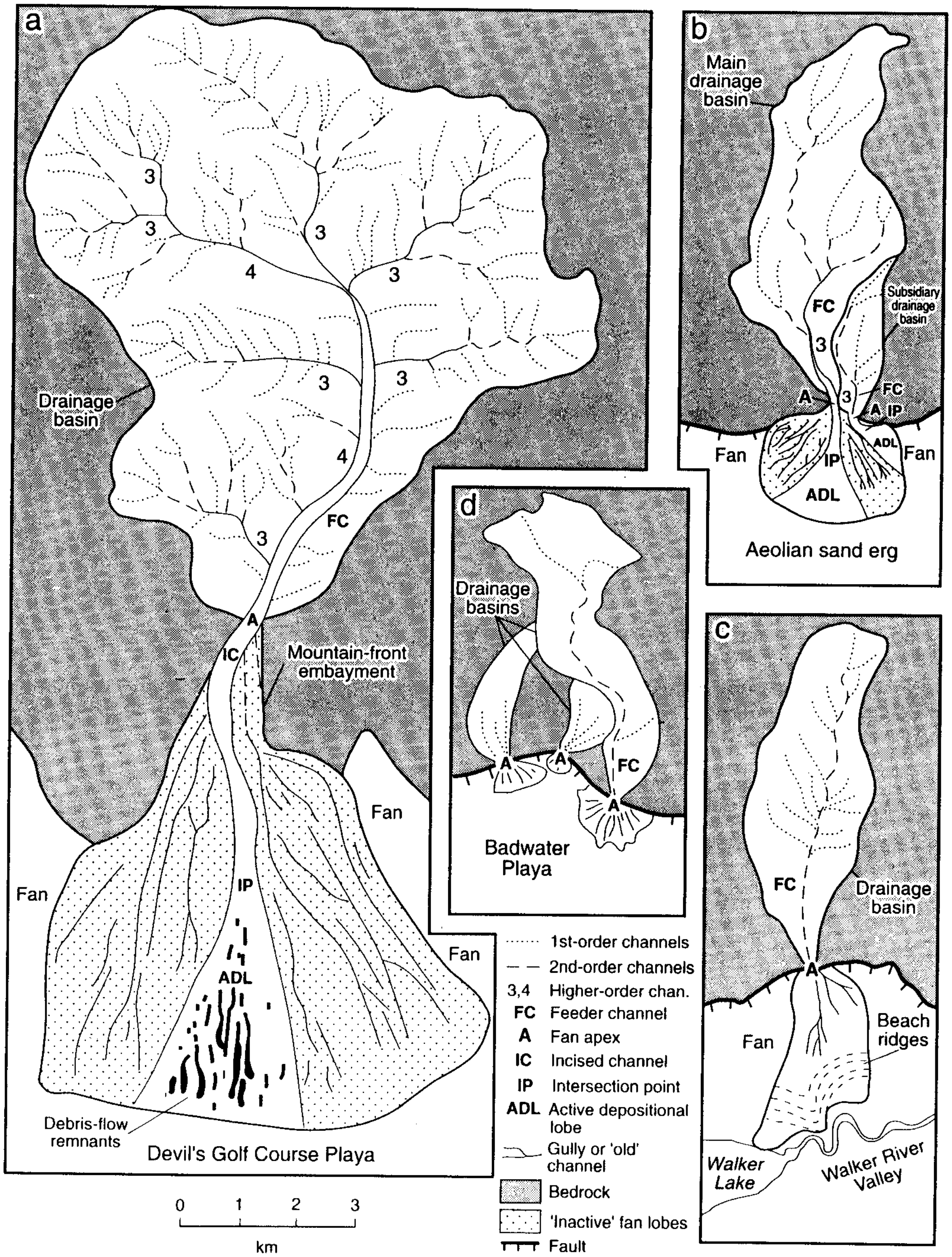

Figure 14.3 Planview line sketches based on topographic maps and aerial photographs of the fans and drainage basins illustrated in Figure 14.1: (a) Trail Canyon, (b) Grotto Canyon, (c) Deadman Canyon, and (d) Badwater fans.

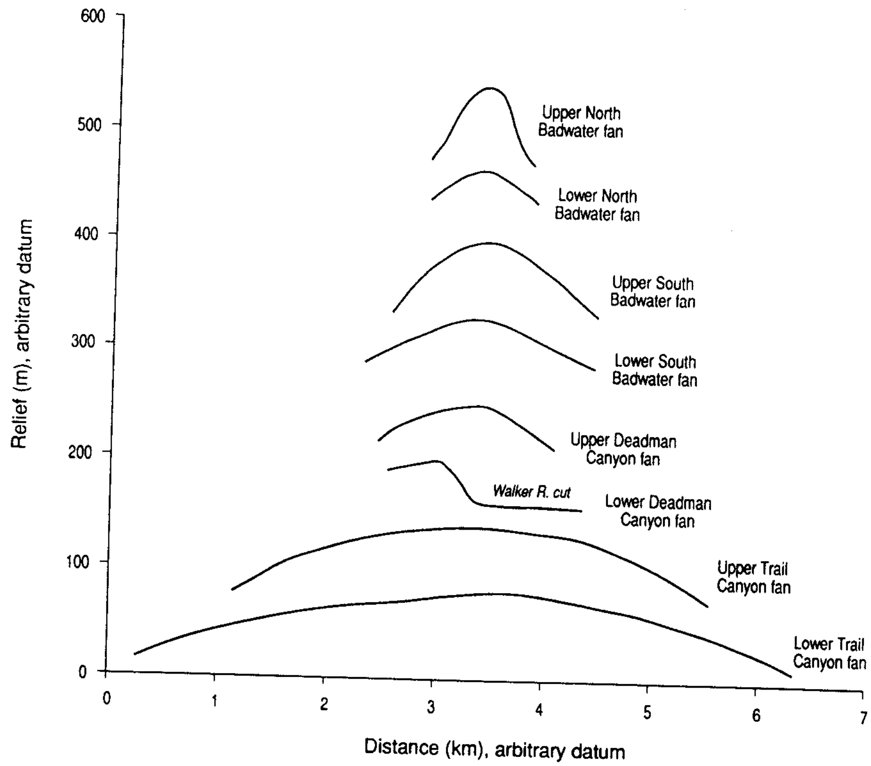

Figure 14.4 Cross profiles of fans illustrated in Figure 14.1. The cavity in the lower Deadman Canyon fan profile results from the imbalanced distribution of fan deltaic deposits and from erosion by the impinging Walker River. Vertical exaggeration is 10.

active depositional lobe (Fig. 14.3). Headward erosion by these gullies may eventually progress sufficiently upslope to intersect the incised channel, causing the position of the active depositional lobe to switch in an autocyclic manner to another part of the fan (Denny 1967).

HISTORICAL BACKGROUND

F. Drew (1873), working in the upper reaches of the Indus River in the western Himalaya of India, provided perhaps the earliest scientific description of arid-zone alluvial fans (pp. 445–7):

> 'The accumulations to which I give this name [alluvial fans] are of great prevalence in Ladakh, and are among the most conspicuous forms of superficial deposits. They are found at the mouths of side-ravines, where they debouch into the plain of a wider valley . . . . The radii of the fan are about a mile long; the slope of the ground along these radii (which are each in the direction of greatest slope) is five or six degrees. The fan is properly a flat cone, having its apex at the mouth of the ravine . . . .
>
> The mode of formation of this fan is not difficult to trace. Granting the stream of the side-ravine to be carrying down such an amount of detritus as to cause it to be accumulating, rather than a denuding stream, and there being such a relation between the carrying power of the water and the size of the material as to allow of this remaining at a marked slope, we have before us all of the conditions necessary.'

Scientific publications on desert alluvial fans predating 1960 are few in number and, with the exception of that by Drew (1873), are based on studies in the south-western United States. Fan research greatly increased during the 1960s, led by work in the south-western United States (Fig. 14.6). This research was in response to the growing need to identify water resources and geological hazards to accommodate the region's expanding population. The resulting studies began to reflect advances in the related fields of soil science, fluid dynamics,

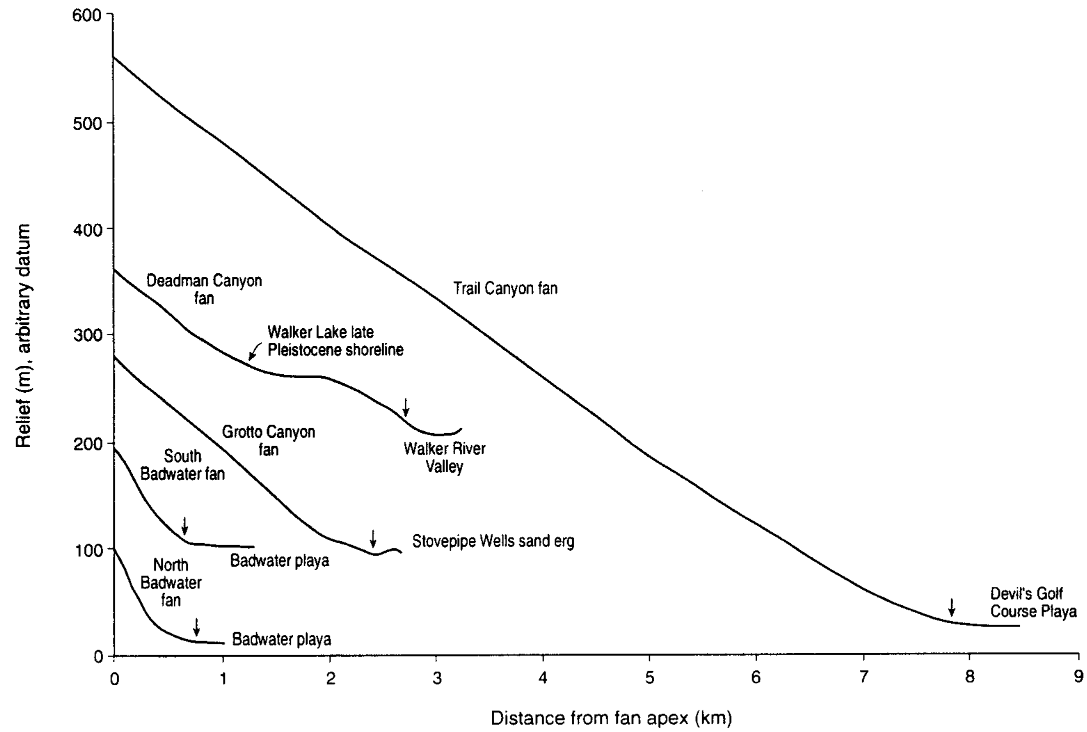

Figure 14.5 Radial profiles of fans illustrated in Figure 14.1 including, downslope, the adjoining part of their neighbouring environments. Vertical arrows denote boundaries between the fans and the neighbouring environments. Vertical exaggeration is 10.

transport mechanics, petrology, quantitative geomorphology, and aerial imagery.

The number of published papers on desert alluvial fans increased exponentially during the 1970s and 1980s, with the easily accessible and spectacular fans of the south-western United States continuing to be the dominant focus of research (Fig. 14.6). The proportion of papers dealing with fans in other desert regions also expanded during these two decades but still represents only about 20% of the total. These papers concern fans in Spain, Italy, the Middle East, Africa, Iran, Pakistan, India, Argentina, and Chile. The rapid growth of fan research from the 1970s to the present (Fig. 14.6) has been stimulated by the practical need for knowledge for geological hazards identification and mitigation (neotectonics, slope stability, flood control, urban planning, contaminated groundwater cleanup, careful selection of hazardous waste disposal sites), civil engineering (construction of highways, dams and other infrastructures), petroleum geology (predictive stratigraphy, palaeogeography, basin studies, diagenesis, and reservoir distribution and quality), mining geology (including the economic extraction of aggregate, gold, uranium, diamond, and platinum deposits), groundwater characterization (for agricultural and urban needs), archaeological studies, and continued basic research in geomorphology, process sedimentology, hydrogeology, and engineering geology.

CONDITIONS FOR ALLUVIAL FAN DEVELOPMENT

Three conditions are necessary for optimal alluvial fan development: (a) a topographic setting where a channel becomes unconfined by emerging from an upland drainage basin on to a relatively flat lowland; (b) sufficient sediment production in the drainage basin for fan construction; and (c) infrequent intense precipitation to create high water discharge needed to transport the sediment from the drainage basin to the fan site. The most typical topographic setting for alluvial fans is marginal to uplifted structural blocks bounded by faults with significant dip-slip. An example of this setting is in the Basin and Range province of the south-western United States, where

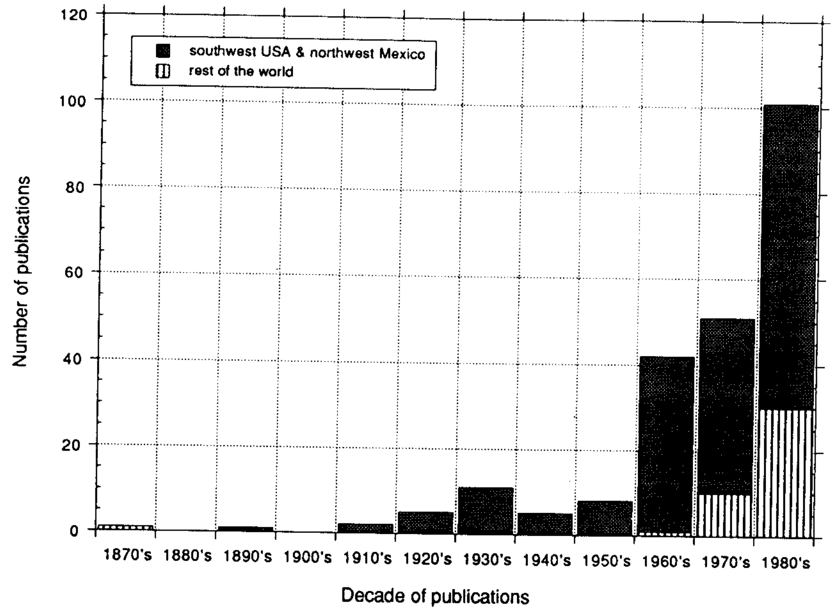

Figure 14.6 Plot of the number of publications on desert alluvial fans by decades since 1870. The numbers are based on an extensive survey of the geological literature.

an upland with adjoining lowland configuration is tectonically developed and maintained. Other topographic settings conducive to the development of alluvial fans are (a) where tributary channels enter an incised river valley, such as along the Grand Canyon of the Colorado River in Arizona (e.g. Webb *et al.* 1987), (b) where streams enter deglaciated, commonly moraine-rimmed valleys (e.g. Rust and Koster 1984, Blair 1987a), or (c) where bedrock exposures possessing topographic relief form by differential erosion (e.g. Sorriso-Valvo 1988, Harvey 1990).

Sediment production in the drainage basin, the second condition necessary for fan development, usually is met given adequate time. The common achievement of this condition is due to the presence of relief and the incessant weathering of rocks under Earth's surface conditions. Sediment yield in a drainage basin is highly dependent upon the presence of relief, increasing exponentially as relief increases due to the effects of gravity on slope erosion (Schumm 1963, 1977, Ahnert 1970). The types of rock-weathering in desert drainage basins that produce sediment are (a) physical disintegration, including sheeting, fracturing, exfoliation, ice or salt crystal growth in voids, and root penetration; and (b) chemical decomposition, encompassing reactions such as hydrolysis, dissolution, and oxidation (e.g. Ritter 1978, pp. 79–167). Weathering is greatly promoted along structurally controlled mountain fronts because of tectonic fracturing, which exposes significantly more rock surface area to alteration than in unfractured situations. Thus, the drainage basins of alluvial fans along mountain front fault zones are efficient sediment producers due both to their location on a structural block where relief is maintained and to their position coincident with the zone of maximum tectonic fracturing and, hence, zone of maximum weathering.

In contrast, drainage basins in non-tectonic settings, such as along paraglacial valleys or incised river valleys, commonly have previously deposited glacial or fluvial sediment available for recycling to the fan, although this sediment has a finite volume that will become depleted (e.g. Ryder 1971). Drainage basins developed on bedrock spurs created by variable resistance to erosion, or from compressional tectonism that has ceased, may also generate fans for which a relatively limited sediment supply is available (e.g. Sorriso-Valvo 1988, Harvey 1990). Although fans from these non-tectonic settings traditionally are assumed to be identical to ones formed in tectonic settings in terms of processes, their evolutionary scenarios may be quite different due to the lack of maintenance of relief and sediment supply.

The third condition necessary for fan development is a mechanism for moving the generated sediment

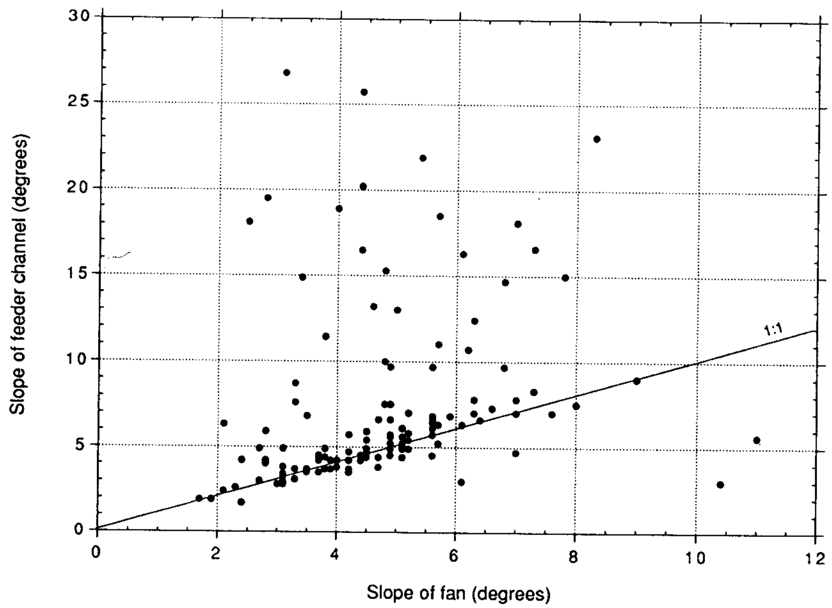

Figure 14.7 Plot of the slope of the 1-km-long segment of the feeder channel upslope from the fan apex versus the corresponding slope of the 1-km-long upper fan segment for 132 Death Valley fans. These slope values are similar (±1°) in just 56% of the cases.

from the drainage basin to the fan site. The most prominent processes known to achieve this transport are catastrophic stream discharge and mass wasting events, including flashfloods, rockfalls, rock avalanches, gravity slides, and debris flows. All of these processes require, or are greatly promoted by flood conditions manifested either as (a) short-term flashy discharge from a high precipitation event such as a thunderstorm (e.g. McGee 1897, Beaty 1963), (b) significant precipitation following sustained antecedent rainfall or snowmelt (e.g. Caine 1980, Cannon and Ellen 1985, Wieczorek 1987), (c) rapid icemelt or snowmelt events (Leggett *et al.* 1966, Beaty 1990), or (d) combinations of the above. Although drainage basins in desert settings are prone to flashy discharge, flooding of this type is by no means restricted to these climatic zones. In fact, all non-polar Earth climates contain atmospheric mechanisms that produce extensive flooding (Hayden 1988).

The topography and shape of alluvial fan drainage basins make them particularly prone to generating catastrophic floods. Mountainous topography induces precipitation in both barotropic or baroclinic atmospheric regimes by enhancing the vertical airflow that triggers condensation (Hayden 1988). Additionally, precipitation that falls in these drainage basins is quickly funnelled into the feeder channel (e.g. Fig. 14.3a), giving rise to flows with the potential to move extremely coarse sediment (French 1987). Flashflood potential is highest in drainage basins with high relief, multiple feeders, and a rotund shape (Strahler 1957).

Net fan aggradation from drainage basin discharge events requires that the floods lose some of their ability to transport sediment upon exiting the drainage basin. This loss of competency and capacity is a function of decreases in both flow depth and velocity resulting primarily from (a) the lateral expansion of flows either at the fan apex or intersection point as a result of the loss of the confining channel walls, and (b) a lessening of slope as the flow reaches the fan site. Although Bull (1977) has demonstrated that there is not always a break in slope between the feeder channel and the upper fan, deposition is instigated on many fans by pronounced slope changes (e.g. Trowbridge 1911, Beaty 1963). This relationship is illustrated by a data set of 132 fans in Death Valley, California (Fig. 14.7). The slope of the 1-km-long segment of the feeder channel adjoining the fan apex is significantly greater (>1°) than the slope of the 1-km-long segment of the incised channel or upper fan immediately below the apex in 40% of these fans. There is no appreciable difference in slope (within ±1°) in 56% of the cases, and in 4% the slope of the fan is actually significantly steeper than the slope of the feeder channel.

Not all channels issuing from mountain fronts construct alluvial fans. Perennial rivers with highly integrated drainage basins, such as the Kern River and San Joaquin River of southern California, the Feather River of northern California, and the Arkansas River and Platte River of Colorado, are capable of maintaining channel banks and flow competency. Thus, these rivers do not form alluvial fans upon emergence from their respective uplands. Instead, they maintain bedload-dominated fluvial tracts.

In conclusion, mountainous deserts commonly provide the optimal conditions necessary for alluvial fan development. They have the necessary topography to induce rainfall and catastrophic runoff, enhance sediment production, and trigger mass wasting events. Additionally, the fact that the most favourable topographic configuration for fan development is in zones of structurally controlled block faulting, where mountain fronts are tectonically maintained, makes extensional terranes such as the American Basin and Range province or the East African–Red Sea rift zones the most optimal structural setting for the deposition of widespread, well-developed fans.

PRIMARY PROCESSES ON ALLUVIAL FANS

Sedimentary processes active on alluvial fans are of two types, primary and secondary. Primary processes are herein defined as those responsible for transporting sediment from the drainage basin to the fan. These processes include rockfalls, rock avalanches, gravity slides, debris flows, sheetfloods, and incised-channel floods (Fig. 14.8). Primary processes generally result in fan construction or aggradation and act concomitantly with the enlargement of the drainage basin due to sediment removal. Primary sedimentary events generally are triggered by rare and catastrophic flashfloods or earthquakes. They therefore are of short duration but high impact with regard to fan construction. In contrast, secondary processes are those events that cause the remobilization or modification of sediment that previously had been deposited on the fan by any of the primary processes. Included in this category are overland flow, wind erosion, bioturbation, soil development, sediment weathering, faulting, and case hardening (Fig. 14.8). Secondary processes most commonly result in fan erosion or degradation and, except for faulting and some overland flows, are associated with normal or non-catastrophic conditions. Although they may have minimal influence on fan construction, secondary processes usually dominate the surface features of a fan except in areas recently affected by a primary depositional event (Blair 1987a).

The primary processes common on alluvial fans or in their drainage basins are divided into two classes: fluid-gravity flows and sediment-gravity flows. Sediment transportation and deposition in fluid-gravity flows, or the synonymous term water flows, are caused by the downslope movement of water in response to the force of gravity. Transportation in these flows is accomplished by the force of moving water acting on the sedimentary particles. In contrast, downslope transportation in sediment-gravity flows is caused by the force of gravity acting directly on the sedimentary particles, which causes the movement of any contained fluids (Middleton and Hampton 1976). Sediment-gravity events encompass a collection of processes termed mass wasting or mass movements due to the fact that they entail the slow to rapid downslope transfer of large volumes of rock or its overlying sedimentary cover (Varnes 1978).

Prior to Blackwelder's (1928) article on the occurrence of debris flow activity on the bajadas of southern California, fans were believed to be built entirely by fluid-gravity flows. This misconception arose due to the configuration of the drainage net, feeder channel,and incised channel, leading to the term alluvial in alluvial fan. A recent study by Derbyshire and Owen (1990) of fans along the Karakoram Mountains of north-western India, where Drew (1873) coined the term alluvial fan, has demonstrated that sediment-gravity processes also are important on these fans in addition to the water-flow processes recognized by Drew. The term alluvial is maintained today when discussing continental fans despite this history, although it is now well established and widely recognized that fluid-gravity flows are only one of several sedimentary processes responsible for alluvial fan construction.

SEDIMENT-GRAVITY PROCESSES

Sediment-gravity processes are fundamental to the formation of all alluvial fans. Almost all sediment reaching a fan is at least partially transported by some kind of sediment-gravity mechanism active in the drainage basin. In many fans, particularly those with small drainage basins, these processes are capable of depositing sediment directly at the fan site.

The initiation of all sediment-gravity processes in

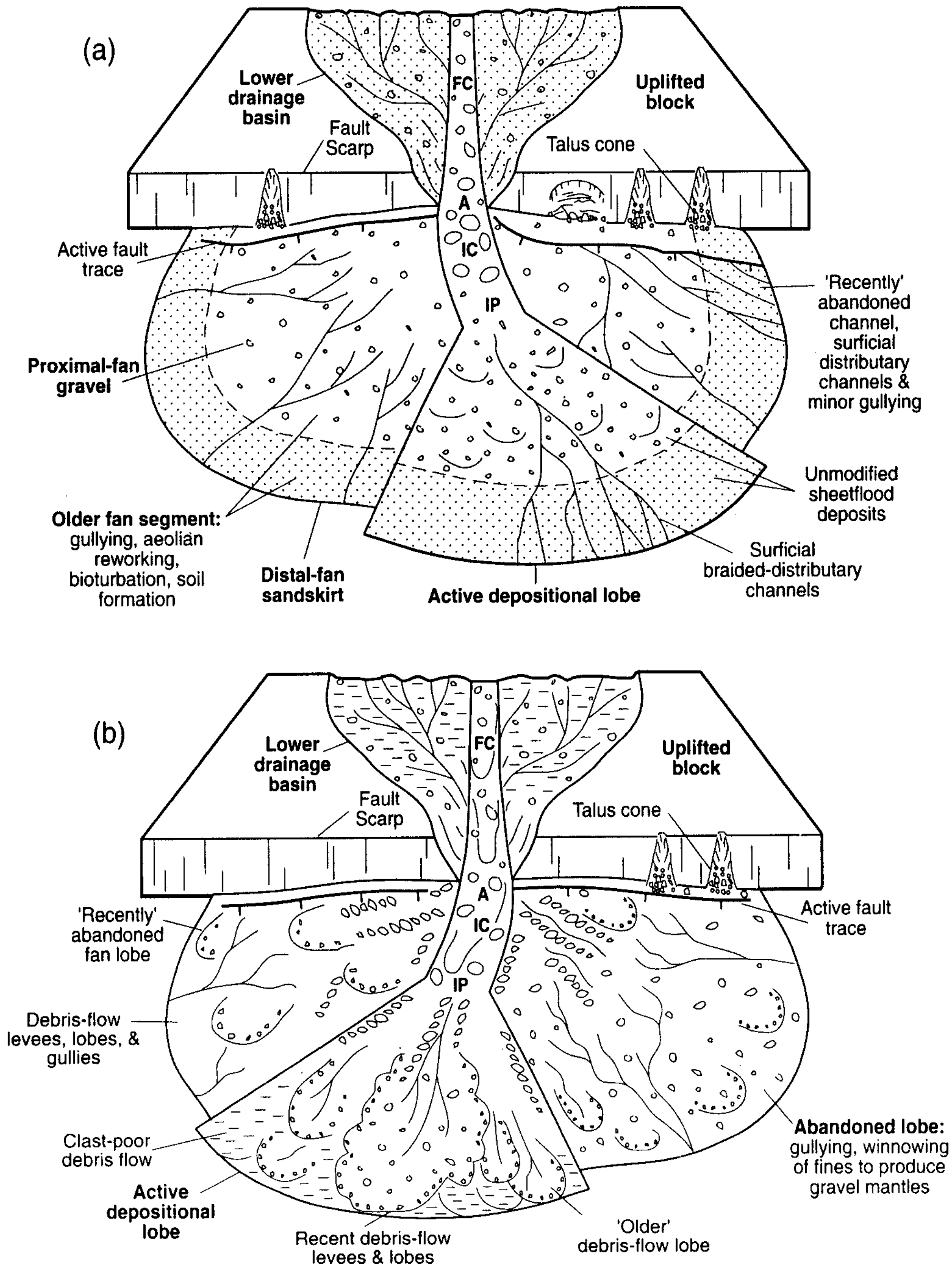

Figure 14.8 Schematic diagrams of the common primary and secondary processes on alluvial fans, including (a) those on fans dominated by water flows, and (b) those on fans dominated by debris flows. These diagrams are based on numerous fans studied by the authors. Abbreviations are A = fan apex, FC = drainage basin feeder channel, IC = incised channel on fan, IP = fan intersection point.

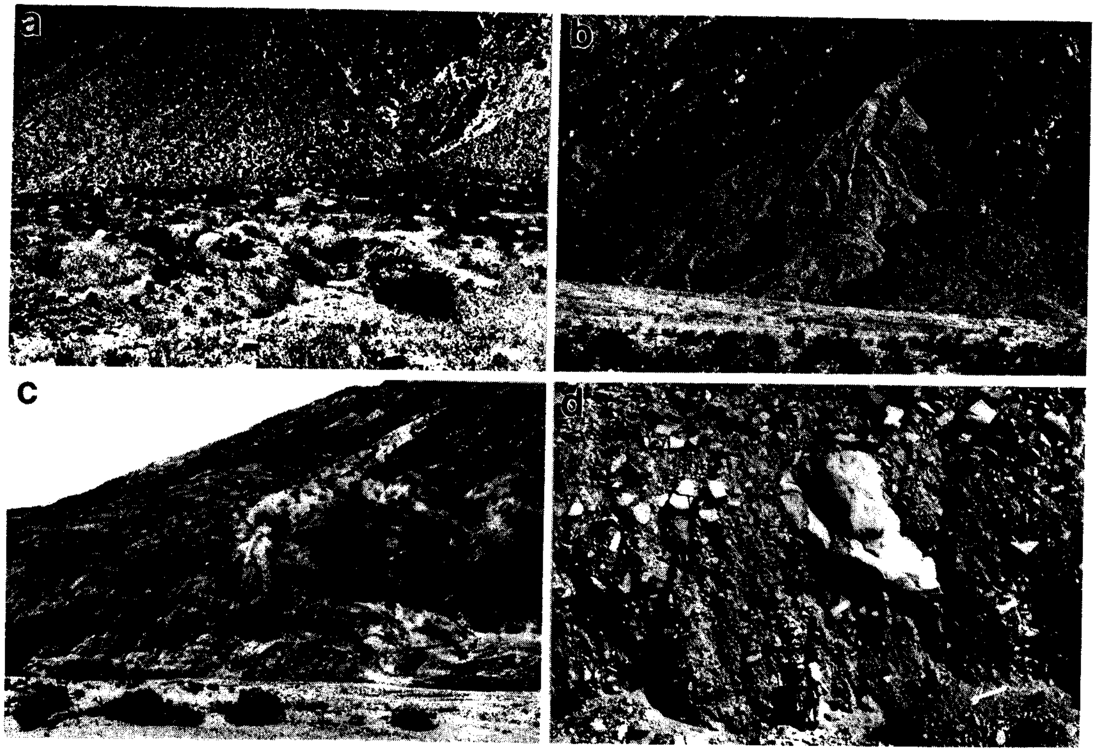

Figure 14.9 Photographs of rockfall accumulations. (a) High-sloping colluvial deposits continuously mantle the mountain front near the proximal Rifle Range fan, Hawthorne, Nevada. Geologist (left-centre) for scale. (b) View of a colluvial cone with prevalent avalanche chutes located near Morman Point in Death Valley. Rock varnish more extensively darkens the progressively older clasts on this cone. (c) View of a colluvial cone near the apex of the Cucamonga fan in Eureka Valley, California. The vertical cut reveals a scallop-shaped stratigraphy resulting from the accumulation of sediment in distinctive avalanche chutes. (d) Vertical cut through very poorly sorted colluvial sediment that accumulated by freefall at the head of the Copper Canyon fan, Walker Lake, Nevada. Geologist (lower-centre) for scale.

a drainage basin results from a reduction of the resisting forces relative to the gravity forces imposed upon the slope materials. The resisting forces may be reduced and drainage-basin slopes destabilized by several factors, including (a) bedrock fracturing and weathering, which lowers the rock's internal friction and shear strength, (b) oversteepening of the slope by toe erosion caused through either human or natural activity, (c) earthquake-caused ground motion, which can provide the initial kinetic energy for downslope movement, (d) the addition of water or gas, which increases the sediment pore pressure and shear load, causing a reduction of the effective normal stress, or (e) combinations of the above (e.g. Ritter 1978, Keefer 1984, Cotecchia 1987, Hencher 1987). Four end-member classes encompassing the continuum of sediment-gravity processes that are active in alluvial fan drainage basins and result in sediment transport to the fan are rockfalls, rock avalanches, gravity slides, and debris flows.

Rockfalls

Rockfall is the downward movement of bedrock blocks that drop from cliffs under the force of their own weight (Chapter 8). These blocks either roll or bounce towards the valley, or accumulate at the base of the cliff in near-angle-of-repose (30° to 40°) mantles called talus, colluvium, or scree deposits (Figs 14.9) (Drew 1873, Sharpe 1938, Rapp and Fairbridge 1968, Rahn 1986). Rockfall blocks initially are shaped by tectonic jointing, fracturing, or shearing; or by the release along other geological discontinuities such as lithologic boundaries, bedding planes, sheeting or cooling joints, slaty cleavage, and schistosity horizons (Hencher 1987). Blocks eventually become loosened and detached along these discontinuities with the aid of weathering and groundwater. The downward movement of unstable blocks typically is triggered by heavy rainfall, freeze–thaw action, or by the shaking motion of earthquakes (Keefer 1984, Statham and Francis 1986, Cotecchia 1987, Beaty and DePolo 1989).

Rockfall accumulations are common in alluvial fan drainage basins, and may extend outwards from the mountain front on to the proximal fan (Fig. 14.9a and b) (Beaty 1989). These deposits either continuously mantle cliff faces (Fig. 14.9a) or more commonly develop a conical shape due to the concentration of the free-falling material through a notch in the bedrock (Fig. 14.9b and c). The conical deposits, called talus cones or colluvial cones, form close to the base of a cliff mainly through numerous small rockfalls or avalanches (Drew 1873, Rapp and Fairbridge 1968). Talus cones typically are composed of angular, poorly sorted gravel (pebbles to boulders), with or without interclast sand or mud matrix (Fig. 14.9d). The matrix may be added by infiltration subsequent to clast deposition.

Rock Avalanches

The rapid fall of a large, extensively fractured or jointed bedrock mass may cause it to quickly disintegrate into boulder- to clay-sized fragments as it moves downslope and transforms into a granular flow termed a rockfall avalanche (Mudge 1965), sturzstrom (Hsu 1975), dry avalanche (Fauque and Strecker 1988), or, as used herein, a rock avalanche (Chapter 8). The sources of energy in rock avalanches, which may move at speeds exceeding $100\,km\,h^{-1}$, are the kinetic energy of the initial fall and the potential energy acquired during downslope movement from gravity (Mudge 1965, Hsu 1975, Melosh 1987, Yarnold and Lombard 1989). An important support mechanism for the clasts in such a dry flow is vibrational or acoustic energy caused by high-frequency pressure fluctuations produced by random motion of groups of fragments of debris organized into elastic waves (Melosh 1987). This process overcomes the internal friction in the flow, allowing rock avalanches to travel significant distances from the mountain front relative to other sediment-gravity flow types and even to move for short distances in an upslope direction. Most rock avalanches have runout distances of $\leq$10 km (Hart 1991, Topping 1991), with the unobstructed expansion of the debris mass commonly encountered at alluvial fan sites especially detrimental to flow continuation (Nicoletti and Sorriso-Valvo 1991).

Rock avalanche events that resulted in the accumulation of sediment on fans along the Sierras Pampeanas in north-western Argentina were described by Fauque and Strecker (1988). The rock avalanche deposits on these fans have a lobate form 3 to 4 km long, 0.5 to 1.5 km wide, and are characterized by an 8 to 10-m-high frontal rim with lateral levees. Surface area per avalanche deposit varies from 1.0 to 7.5 km^2, and volume from 5 to $65 \times 10^6\,m^3$. Older fan deposits are exposed in the internal part of the lobes. This form suggests that the rock avalanche moved as a non-Newtonian viscous flow across the piedmont after falling from a high source region as much as 7 km upslope in the drainage basin. Down-fan movement of the rock avalanche was most extensive along the axial part of the flow. The resulting deposits are inversely graded, with boulders as large as 2 to 20 m across present at the top of the levees, and small boulders to silt-sized material occurring in the lower parts.

Rock avalanching also is a common process along the piedmont zones of southern California and Arizona (Burchfiel 1966, Yarnold and Lombard 1989, Hart 1991). The deposits of these rock avalanches, called megabreccias, commonly are 20 to 120 m thick and have runout distances of several kilometres. These deposits are typified by a matrix-rich lower layer that may be overlain by an upper layer consisting of highly fractured but relatively intact rock debris possessing crackle-breccia or jigsaw breccia fabrics. These zones developed due to variations in the internal motion of the avalanche materials. The formation of the matrix-rich lower layer is attributed to the pulverization of the rock mass as it moved due to shearing coupled with the weight of the overlying material, whereas the upper zone fabrics developed by the rigid deformation of the bedrock mass as it moved downslope. The deposits of the rock avalanches studied in Arizona and southern California contrast with those described by Fauque and Strecker (1988) in Argentina in that the former possess a tabular or mounded geometry and the latter have a levee and snout morphology.

Gravity Slides

Gravity slides (cf. landslides, rockslides, sediment slides, landslips, debris slides, or slumps) constitute a family of mass movements characterized by distinctive bodies of bedrock or colluvium initially positioned high on an unstable slope and moved either slowly or rapidly downward along well-defined basal surfaces called glide planes (Sharpe 1938, Varnes 1978). Gravity slides are differentiated from other types of sediment-gravity flows, such as rock avalanches, by the movement of the material as a coherent mass rather than as a granular flow of individual particles. Movement in a gravity slide occurs over the planar or gently curved glide horizon, and the sliding mass is essentially undeformed except possibly for partial disintegration of brittle rock (Ritter 1978). The glide plane may be shallow and parallel to the ground surface or it may constitute the boundary between the sedimentary cover and the underlying bedrock. The gap left behind in the slope from which the slide material detaches is called the slide scar. Slide scars typically are spoon-shaped as a result of the rotational movement of the detached material (Varnes 1978). Gravity slide processes are important in fan drainage basins by moving sediment from the slopes to the feeder channel or even directly out to the fan. In addition, first-order channels in the drainage basin commonly develop during gravity slide events (Patton 1988, Sorriso-Valvo 1988).

Both bedrock and colluvial gravity slides can be initiated by coseismic ground motions. Keefer (1984), who studied the relationship between historical gravity slides and earthquakes, found that slopes consisting of either weakly cemented bedrock, bedrock with abundant discontinuities, or colluvial material are most susceptible to seismically induced sliding. He noted that slides with shallow glide planes are triggered in proximity to epicentres by only weak ground motions (Richter-scale magnitudes of 4.0 to 5.0), whereas progressively thicker slides required progressively greater motions to initiate the movement. Keefer also concluded that both the size of a slide and its distance of transport have a positive correlation with the magnitude of the earthquake and proximity to the epicentre.

Colluvial slides most often are triggered by the addition of water to the slope materials, which increases pore pressure and decreases shear strength, making them susceptible to failure (Costa 1988, Mathewson *et al.* 1990). Water within the colluvium also serves as a lubricant that reduces glide plane friction. The accumulation of water in the sediment pores above the glide plane further enhances slope instability by increasing the shear load of the mass due to the added water weight (Hencher 1987). A common location for colluvial landslides to develop is in sediment-filled bedrock hollows of the upper slopes of the drainage basin where colluvium accumulates most rapidly, and where overland flows are concentrated by the funnelling action created by the converging topography (Reneau *et al.* 1984, 1986, 1990). The mobilization of water-saturated colluvium typically results in the transformation of the colluvial slide into a debris flow due to the granular content of the colluvium and to the entrainment of the pore water into the flow as it moves (e.g. Reneau *et al.* 1984, 1990, Costa 1988).

Debris Flows

Debris flows are a type of sediment-gravity flow characterized by a mixture of granular solids (gravel, sand, clay, tree limbs, etc.) and small amounts of entrained water and air that move downslope under the force of gravity (Varnes 1978, Johnson 1984) (Chapter 8). Debris flow is the most significant sediment-gravity process in terms of the volume of material deposited directly on alluvial fans. This sediment-gravity flow type differs from the others inasmuch as water and air are irreversibly entrained with the sedimentary particles, moving together at the same velocity as a viscoplastic body (Johnson 1970). Unlike water flows, the solid and fluid phases of a debris flow do not separate upon deposition except for slight dewatering (Costa 1988).

Debris flows are initiated by two mechanisms. The most widespread mechanism involves the transformation of a wet colluvial slide into a debris flow by the entrainment of air and water through the jostling, deformation, and loss of individuality of the particles as it moves downslope (Johnson and Rahn 1970, Johnson 1984, Reneau *et al.* 1984, 1990, Costa 1988). This transformation requires the presence of water in the colluvium and, therefore, is most apt to occur during or immediately after excessive rainfall or snowmelt when the pores are saturated (e.g. Sharp 1942, Fryxell and Horberg 1943, Sharp and Nobles 1953, Beaty 1963, 1990, Johnson 1970, Campbell 1975, Hooke 1987, Mathewson *et al.* 1990). Clay, even in amounts of just a few percent by volume, is extremely important in initiating debris flows from colluvial slides by providing strength to the interstitial fluid phase and by lowering permeability. Permeability reduction hinders the dissipation of pore fluids, causing an increase in pore pressure and a lowering of the internal friction, giving mobility to the flow. The transformation from a colluvial slide to a debris flow is due most likely to liquefaction or dilatancy (Ellen and Fleming 1987). This transformation is promoted by poor sorting, which limits the interlocking of particles and subsequent internal friction (Rodine and Johnson 1976).

The second scenario by which debris flows can be initiated is where fast-moving water intersects an area mantled by abundant sediment. The ensuing reaction, in which the water dissipates its energy by dispersing clasts through churning, tossing, and mixing, can result in the rapid entrainment of the sediment, air, and water to produce a debris flow (Johnson 1970, 1984). Johnson termed this type of initiation process the firehose effect.

The generation of debris flows by either triggering mechanism occurs most optimally where flashflood