Chapter 14

Processes and Forms of Alluvial Fans

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Introduction

Alluvial fans are a conspicuous conical landform commonly developed where a channel emerges from a mountainous catchment to an adjoining valley (Figs. 14.1 and 14.2). Although present in perhaps all global climates, fans in deserts have been the most studied due to their excellent exposure and ease of access. Drew (1873), working in the upper reaches of the Indus River valley in the western Himalaya of India, provided the earliest illustrations and scientific description of desert alluvial fans (pp. 445–447):

> The accumulations to which I give this name [alluvial fans] are of great prevalence in Ladākh, 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 fans 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 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, but have increased exponentially in number since then. The spectacular fans of western North America have been the dominant focus of research, but notable work on fans has also increased in other arid and semi-arid regions, including in Peru, Argentina, Chile, southern Europe, east-central Africa, the Middle East, Iran, Pakistan, India, China, and Mongolia. The growth of fan research has been fuelled by multi-disciplinary needs, including for environmental and geological hazards mitigation (neotectonics, slope stability, flood control, urban planning, groundwater cleanup, hazardous waste disposal), civil engineering (construction of highways, dams, and other infrastructure), delineating groundwater resources, understanding climate change, archeological studies, petroleum geology and rock-record interpretation, mining of aggregate and ores, and continued basic research in geomorphology, sedimentology, hydrogeology, and engineering geology. More recently, desert-like alluvial fans imaged on Mars have created a challenge to understand the fan-forming surficial processes of other planets (e.g. Moore and Howard 2005).

This chapter provides: (a) an up-to-date synthesis of the literature on desert alluvial fans, (b) a framework for understanding fan processes, form, and evolution, and (c) a discussion of the issues that plague fan research. The latter point is especially critical because 'alluvial fan' is used unscientifically by a faction of authors for virtually any subaerial environment on an arbitrary basis. This synthesis thus emphasizes fundamental concepts on the processes and forms of fans, many of which are exemplified by our case studies in the southwestern USA. Though illustrated by fans in deserts, the concepts provided herein also are applicable to fans forming under other climates (Blair and McPherson 1994b).

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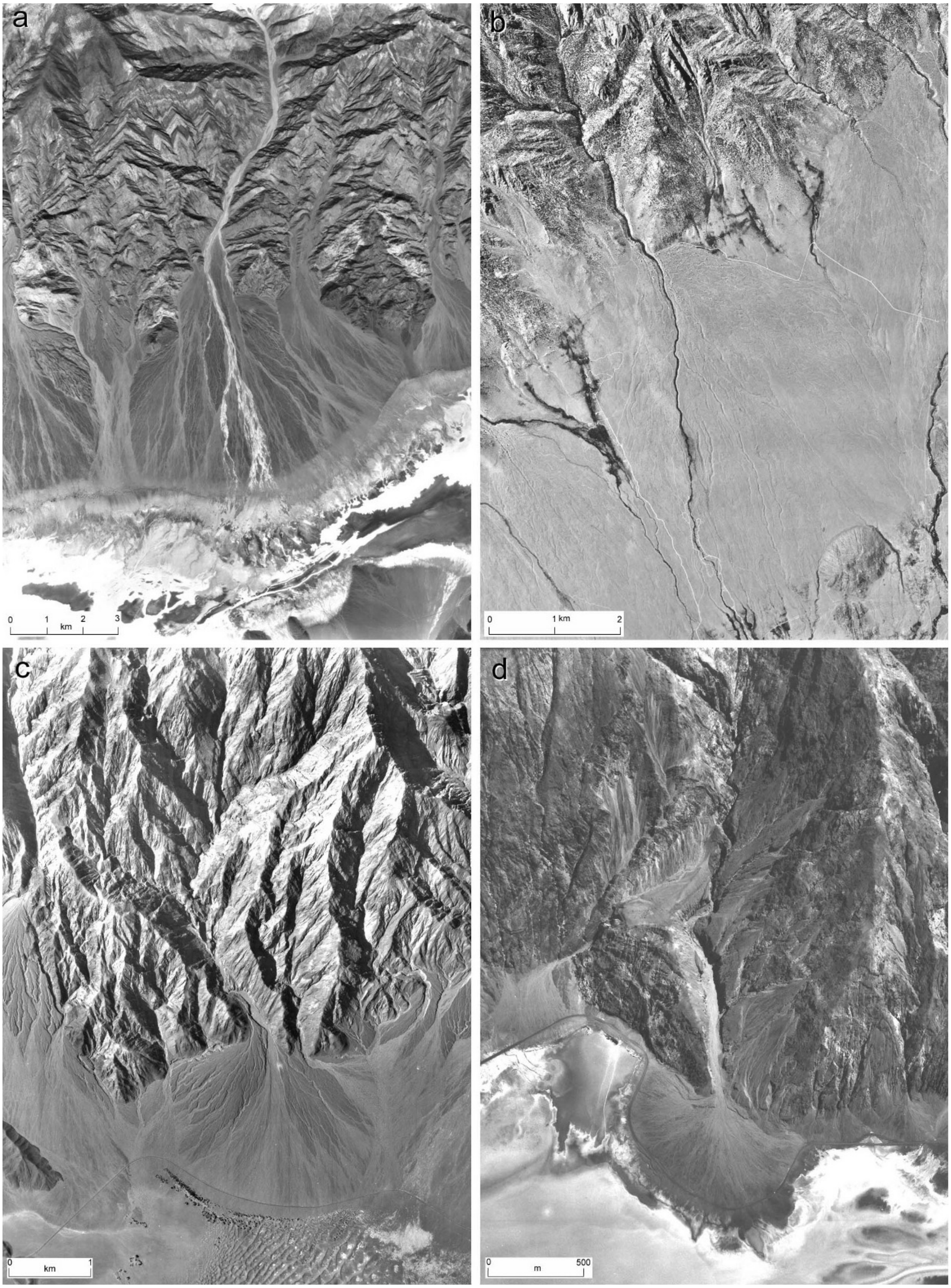

Fig. 14.1 Aerial photographs of selected alluvial fans from California, including: (**a**) Trail Canyon fan of southwestern Death Valley, (**b**) Tuttle Canyon fan of southern Owens Valley, (**c**) Grotto Canyon fan of northern Death Valley, and (**d**) South Badwater fan in southeastern Death Valley

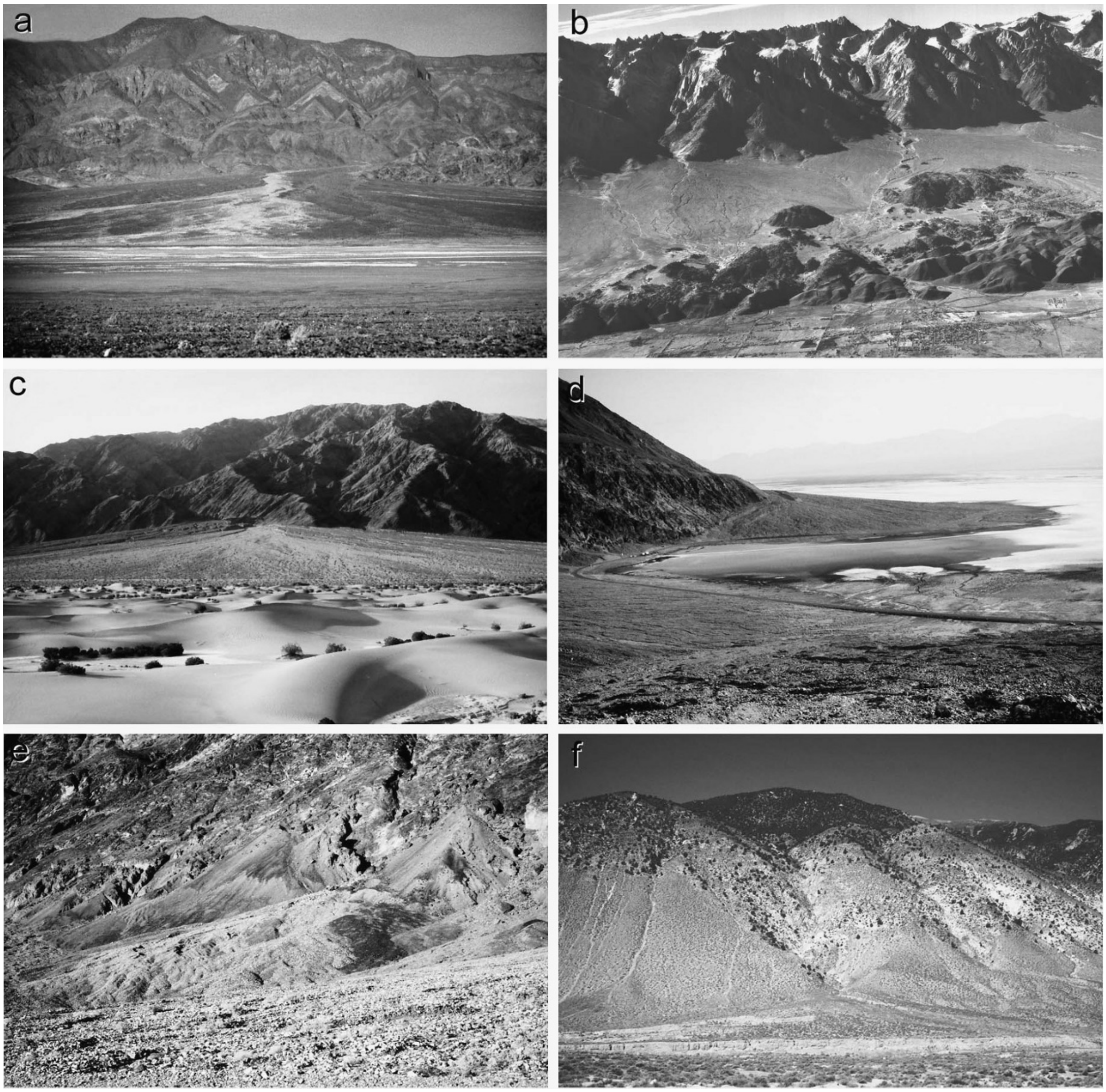

Fig. 14.2 Overview photographs of alluvial fans, including: (**a**) Trail Canyon fan of southwestern Death Valley, (**b**) Tuttle and Lone Pine Canyon fans of southern Owens Valley, (**c**) Grotto Canyon fan of northern Death Valley, (**d**) South Badwater fan of southeastern Death Valley, (**e**) small fan north of Badwater, Death Valley, and (**f**) the Rifle Range fan near Hawthorne, Nevada. The Trail Canyon, South Badwater, North Badwater, and Rifle Range fans are bordered distally by playas, the Tuttle and Lone Pine fans by an axial river, and the Grotto Canyon fan by an aeolian erg

General Features

Alluvial fans are aggradational sedimentary deposits shaped overall like a segment of a cone radiating downslope from a point where a channel emerges from a mountainous catchment (Drew 1873, Bull 1977) (Figs. 14.1, 14.2, and 14.3). Thus, fans constitute a sedimentary environment with a conspicuous morphology. Alluvial fans are arcuate in plan view, either spanning outward from the range front in a 180° semicircle, or having a more restricted pie-piece plan resulting from lateral coalescence with other fans to form a bajada. Cross-fan profiles display a plano-convex geometry, and radial profiles either exhibit a

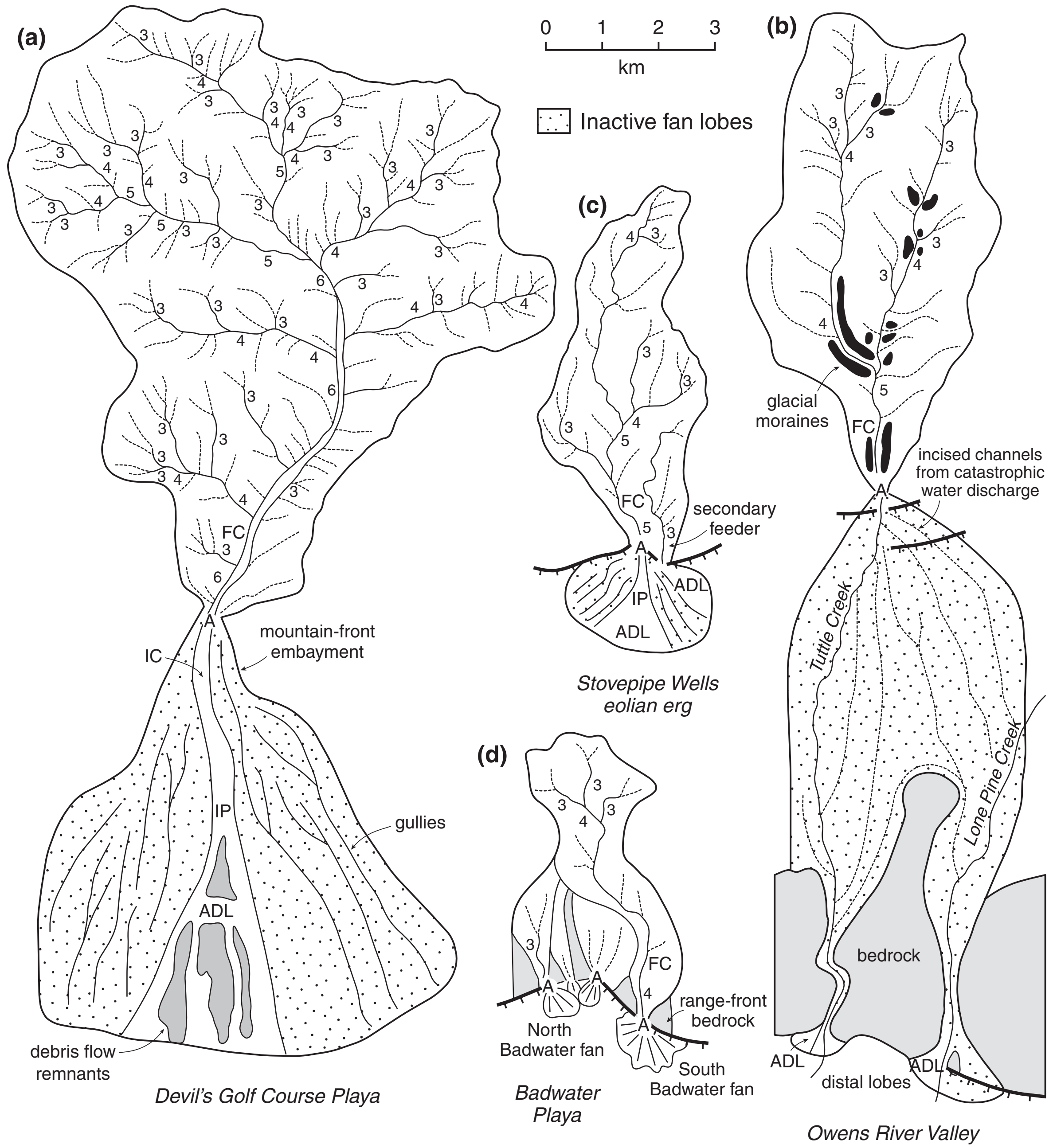

Fig. 14.3 Plan-view diagram of fans illustrated in Fig. 14.1 and their catchment drainage nets based on 1:24,000 topographic maps, aerial photographs, and fieldwork, including: (**a**) Trail Canyon fan, (**b**) Tuttle Canyon fan, (**c**) Grotto Canyon fan, and (**d**) Badwater fans. First-order channels are not depicted in the catchments due to scale. Second-order channels are dashed, and higher-order channels are solid lines labelled by order. The feeder channel (*FC*) of the catchment leads to the fan apex (*A*). Other labelled features are the fan incised channel (*IC*), intersection point (*IP*), and the active depositional lobe (*ADL*)

constant slope like a cone segment, or have half of a plano-concave-upwards geometry (Fig. 14.4). Fans typically extend 0.5–10.0 km from the mountain front (Anstey 1965, 1966), with larger fans reaching nearly 20 km (Blair, 2003). Desert vegetation on alluvial fans varies from sparse cacti and other xerophytes in hyperarid settings to more dense grass, shrubs, or trees in semi-arid regions.

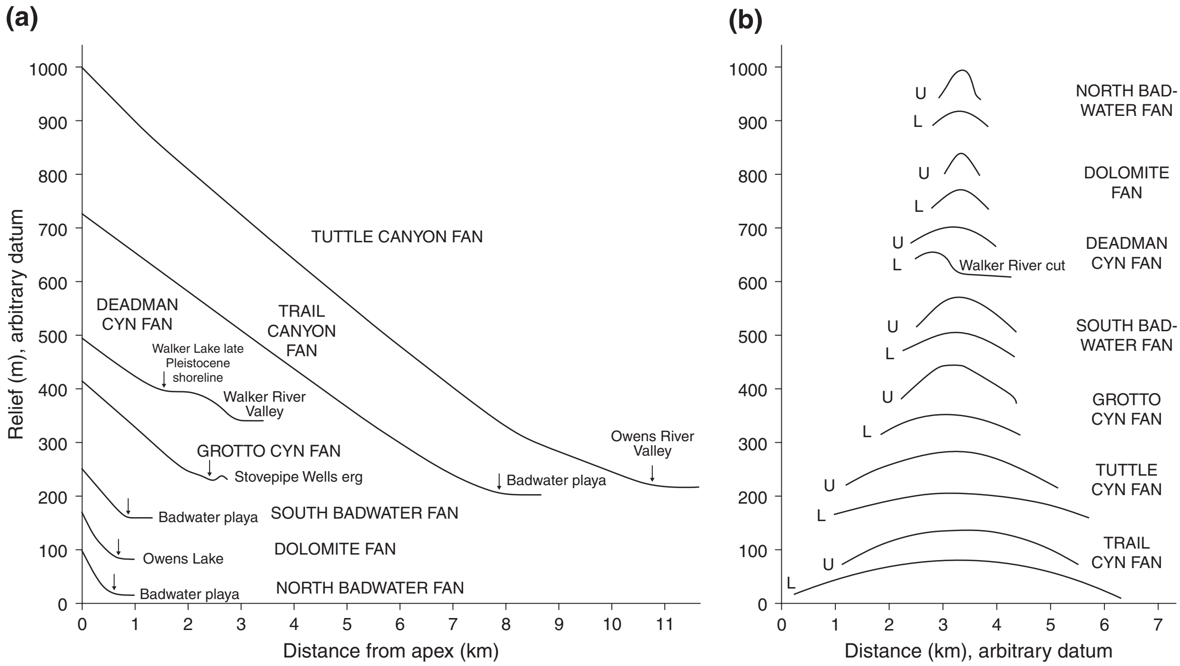

Fig. 14.4 Radial profiles (**a**) and cross profiles (**b**) of fans illustrated in Fig. 14.1 plus of the Dolomite fan of Owens Valley, California, and the Deadman Canyon fan of Walker Lake, Nevada. Vertical exaggeration is 10X. Arrows above the radial profiles denote boundaries between the fans and neighbouring environments. Cross profiles illustrate upper (*U*) and lower (*L*) transects

Alluvial fans develop by the accumulation of sediment where a channel exits an upland drainage area (Drew 1873). Fans deposits typically are coarse-grained and poorly sorted due to the: (a) relatively short sediment-transport distance, (b) involvement of mass-wasting and flash-flood processes instigated by high relief, and (c) rapid loss of flow capacity in the piedmont (foot of mountain) zone. Fan deposits mainly consist of virgin (first-cycle) sediment that is produced through weathering and erosion of uplifted bedrock. Although fans can locally be dominated by fine sediment, they overall comprise some of the coarsest deposits on Earth. Their description, as used herein, thus requires grain-size terminology that details gravel and megagravel, with classes such as pebbles, cobbles, boulders, blocks, and megablocks defined by the length of the intermediate axis (d_I) of the clast (Fig. 14.5).

Fans comprise the most common element of a spectrum of high-sloping deposits found in the piedmont. Steep mountain-flanking deposits lacking fan morphology are called alluvial slopes (Hawley and Wilson 1965), and high-sloping deposits rimming volcanoes are called volcanic aprons. Wind-blown deposits that mantle mountain fronts are termed aeolian ramps. Glacial drift and moraines may also occur in desert piedmont settings (e.g. Fig. 14.6a). Fans are bordered distally by volcanic, aeolian, fluvial, lacustrine, or marine environments (Fig. 14.3). They are easily differentiated from neighbouring river environments by their textures and characteristic fan form, including high radial slope values that contrast with the $< 0.5°$ slope of rivers (McPherson et al. 1987, Blair and McPherson 1994b).

Alluvial fans are directly linked with an upland catchment, also called a drainage basin, that constitutes the area from which water and sediment are discharged to a specific fan (Fig. 14.6b, c, and d). The area, relief, bedrock type, and other features may notably differ between even adjoining catchments. Catchments are separated from each other by drainage divides. Rather than being fixed, these divides, and thus catchment area, change with time due to dynamic factors such as headward erosion, stream piracy, and slope failures. Catchments of desert fans vary in elevation from ~sea level to over 6000 m, and, therefore, may be sparsely vegetated or thickly forested, and can contain valley glaciers and lakes. Thus, because of relief,

PARTICLE LENGTH (dI) km	m	mm	ϕ	GRADE	CLASS	FRACTION Unlithified	Lithified
1075			–30	very coarse	Megalith	Megagravel	Mega-conglomerate
538			–29	coarse			
269			–28	medium			
134			–27	fine			
67.2			–26	very fine			
33.6			–25	very coarse	Monolith		
16.8			–24	coarse			
8.4			–23	medium			
4.2			–22	fine			
2.1			–21	very fine			
1.0	1048.6		–20	very coarse	Megablock		
0.5	524.3		–19	coarse			
0.26	262.1		–18	medium			
	131.1		–17	fine			
	65.5		–16	very coarse	Block		
	32.8		–15	coarse			
	16.4		–14	medium			
	8.2		–13	fine			
	4.1	4096	–12	very coarse	Boulder	Gravel	Conglomerate
	2.0	2048	–11	coarse			
	1.0	1024	–10	medium			
	0.5	512	–9	fine			
	0.25	256	–8	coarse	Cobble		
		128	–7	fine			
		64	–6	very coarse	Pebble		
		32	–5	coarse			
		16	–4	medium			
		8	–3	fine			
		4	–2	very fine			
		2	–1	very coarse	Sand	Sand	Sandstone
		1	0	coarse			
		0.50	1	medium			
		0.25	2	fine			
		0.125	3	very fine			
		0.063	4	coarse	Silt	Mud	Mudstone or Shale
		0.031	5	medium			
		0.015	6	fine			
		0.008	7	very fine			
		0.004	8		Clay ↓ ?		
		0.002	9				
		0.001	10				
		0.0005	11				
		0.0002	12				
		0.0001	13				

Fig. 14.5 Index of grain size terminology used in chapter (after Blair and McPherson 1999)

desert fans may have catchments with other microclimates such as alpine tundra.

All but incipient catchments have a converging drainage net with typically short channel segments. The catchment drainage net can be characterized by stream order (Horton 1945, Strahler 1957), with first-order channels (those lacking tributaries) and the area they drain located at divides between catchments, or between sectors of a single catchment. Second-order channels form farther downslope where two first-order channels join, third-order channels form where two second-order channels join, etc. (Fig. 14.3). Channel

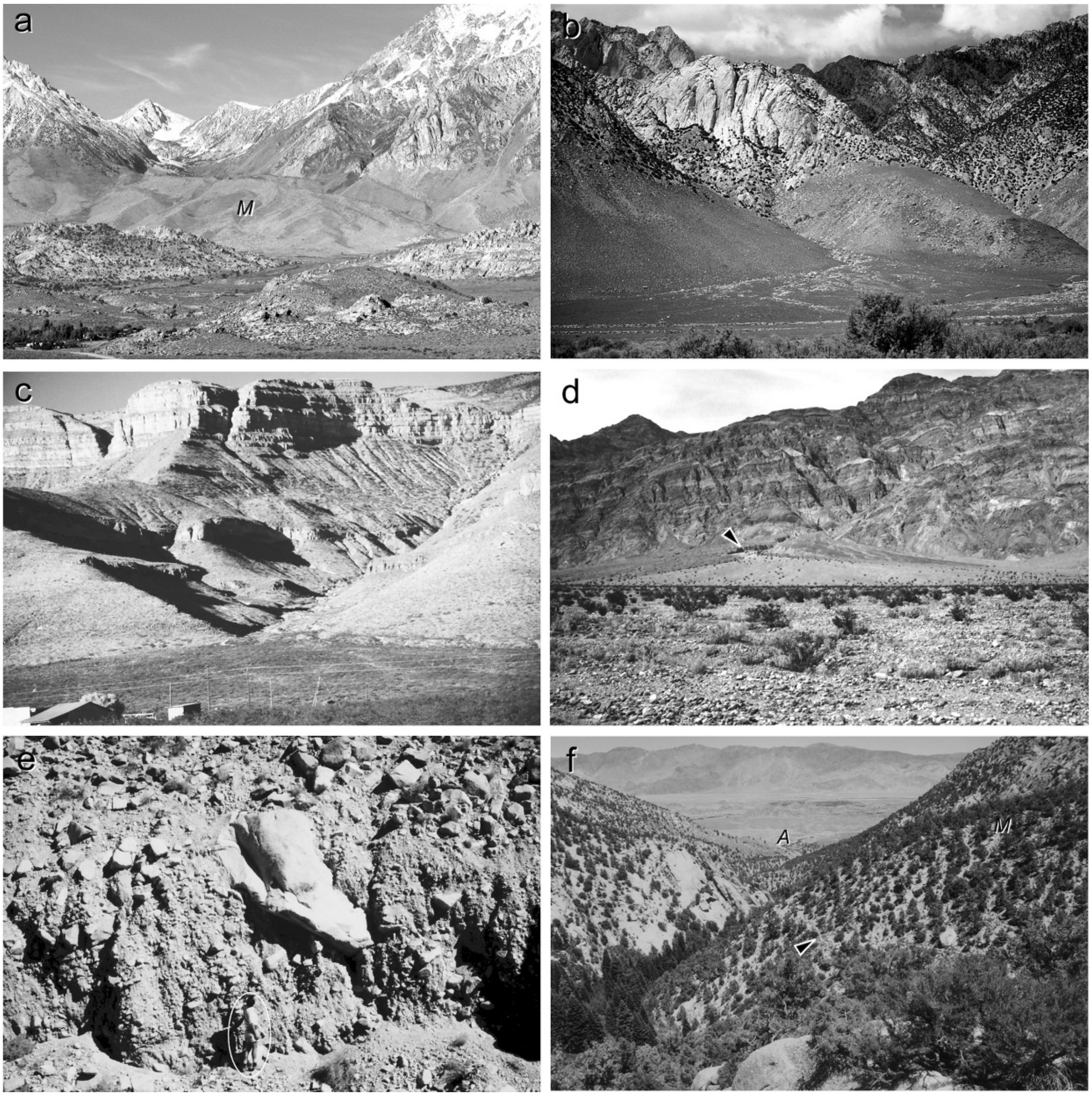

Fig. 14.6 Photographs of various catchment slope materials. (**a**) View of terminal moraine (*M*) ~500 m high deposited in the lower part of the Bishop Creek fan catchment and upper piedmont prior to deglaciation, Owens Valley, California. Glaciation widely stripped colluvium from the granodiorite bedrock comprising the catchment slopes. (**b**) View of Cartago fan of southern Owens Valley, with exfoliated granodiorite cliffs forming slopes in the upper catchment, and with colluvium mantling the lower slopes. (**c**) Interstratified limestone and shale bedrock extensively mantled by colluvium comprise the catchment slopes of the Lead Canyon fan, south-central New Mexico. (**d**) View of Titus Canyon fan, northern Death Valley, with a large catchment of both stratified carbonate bedrock and colluvial slopes. The fan possess a proximal incised channel (*arrow*) feeding a distal active depositional lobe (light coloured). (**e**) Exposure of colluvial deposits in the lower catchment of the Copper Canyon fan, Walker Lake, Nevada (geologist for scale). (**f**) Downslope view of the lower catchment of the Tuttle Canyon fan, Owens Valley. Bouldery glacial moraines (*M*) lead to the fan apex (*A*). A trail (*arrow*) is marked for scale

ordering requires topographic maps with sufficient detail to delineate the drainage net. Our studies show that maps can be no smaller than 1:24,000 scale and with 12.2 m (40 ft) contours to achieve an accurate depiction of all of the channels. The converging pattern of the catchment drainage net causes all channels to funnel to the highest-order channel, called the feeder channel, that leads to the fan. The feeder channel commonly is oriented at a high angle to the mountain front. Usually only one feeder channel is present, although some fans may have secondary feeders (e.g. Fig. 14.3c). Fan catchments in deserts typically have ephemeral first, second, or up to about eighth-order feeders. The feeder channel is perennial for some desert fans, such as the Lone Pine fan in Owens Valley, California (Blair 2002), where snowmelt or icemelt from high in the catchment sustain base flow.

The key elements of an alluvial fan are the apex, incised channel, intersection point, active depositional lobe, older surfaces, and headward-eroding gullies. The apex of a fan is the point at the mountain front where the feeder channel emerges from the catchment (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, but is less distinct where the feeder channel has carved an embayment. The incised channel, also called the fanhead trench (Eckis 1928), is a downslope extension of the catchment feeder channel onto the fan (Fig. 14.3). It usually is a single trunk stream that merges downslope with the fan surface. Incised channels are not always present or well developed, occurring most commonly on fans with longer radii, or those that have intra-fan fault scarps. They usually terminate in the proximal or medial part of the fan, but can extend to the distal margin in cases where distal-fan fault scarps are present, or where base level in adjoining environments has notably dropped. The down-fan position where an incised channel ends is called the intersection point (Hooke 1967). Flows through the incised channel laterally expand onto the fan surface at this point. The fan segment downslope from the intersection point is the site of sediment aggradation in an area termed the active depositional lobe (Fig. 14.3). The arc length of this lobe is a function of its radius and angle of expansion. Lobe expansion angles may be 180° on small fans, but more typically are between 15° and 90°. Old fan surfaces with varnished pavements typically are present lateral to the active depositional lobe or incised channel. Headward-eroding gullies are common features on the distal fan, particularly in inactive areas away from the active lobe. Headward erosion by these gullies, either as single channels or a downslope-converging network, may eventually progress sufficiently upslope to intersect the incised channel, possibly causing autocyclic switching of the active depositional lobe to another part of the fan (Denny 1967).

Conditions for Alluvial Fan Development

Three conditions necessary for optimal alluvial fan development are: (a) a topographic setting where an upland catchment drains to a valley, (b) sufficient sediment production in the catchment to construct the fan, and (c) a triggering mechanism, usually sporadic high water discharge and less commonly earthquakes, to incite the transfer of catchment sediment to the fan. The most common topographic setting for fans is marginal to uplifted structural blocks bounded by faults with significant dip-slip. An example of this setting is in the extensional Basin and Range province of the western USA, where an upland with adjoining lowland configuration is tectonically developed and maintained. Other topographic settings conducive to the development of alluvial fans are where tributary channels enter a canyon or valley (e.g. Drew 1873, Blair 1987a, Webb et al. 1987, Florsheim 2004), or where bedrock exposures possessing topographic relief form by differential erosion (Sorriso-Valvo 1988, Harvey 1990).

Sediment production in a catchment, the second condition for fan development, typically is met given time because of the presence of relief, and because of incessant weathering of rocks at the Earth's surface. Sediment yield from a catchment increases exponentially with relief due to the effect of gravity on slope erosion (Schumm 1963, 1977, Ahnert 1970). The types of rock weathering in desert catchments that produce sediment are: (a) physical disintegration, including fracturing, exfoliation, ice- or salt-crystal growth in voids, and root wedging, and (b) chemical alteration, encompassing reactions such as hydrolysis, dissolution, and oxidation (e.g. Ritter 1978). 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 rocks. Thus, the catchments of alluvial fans along faulted mountain fronts overall are ideal sediment producers due to their location on a structural block where relief is maintained, and where tectonic fracturing is common. In contrast, catchments in non-tectonic settings, such as along paraglacial valleys, may have previously deposited sediment available for building a fan, although it may become depleted (e.g. Ryder 1971). Catchments developed on bedrock spurs created by variable erosion, or from tectonism that has ceased, may also generate fans for which sediment supply is limited. Fans in these latter settings may have processes similar to those formed in tectonic settings, but their evolutionary scenarios may differ due to the lack of maintained relief and sediment supply.

The third necessity for fan development is a mechanism to move catchment sediment to the fan. The key processes achieving this transport are related to water input and mass wasting. These processes are promoted by flood conditions resulting from heavy or prolonged precipitation, rapid icemelt or snowmelt, or the rapid release of impounded water due to failure of a natural dam (e.g. McGee 1897, Beaty 1963, 1990, Leggett et al. 1966, Caine 1980, Cannon and Ellen 1985, Wieczorek 1987, Costa 1988, Blair 2001, 2002). The topography and shape of fan catchments make them prone to generating catastrophic floods. Mountains induce precipitation by causing vertical airflow that triggers condensation (Houghton et al. 1975, Hayden 1988). Precipitation that falls in these catchments is quickly funnelled through the short segments of the converging drainage net to the feeder channel, giving rise to flows with the potential to move extremely coarse sediment (e.g. French 1987, Patton 1988, Blair and McPherson 1994b, 1999). Flash-flood potential is greatest in catchments with high relief, multiple high-order channels, and a rotund shape (Strahler 1957). Flash floods also are important for inducing mass-wasting events that rapidly increase sediment discharge and create new first-order channels (Patton 1988).

Net fan aggradation requires that discharge from the catchment loses competency and capacity upon reaching the fan. This loss results from: (a) a lessening of slope at the fan site, or (b) decreases in both flow depth and velocity due to lateral expansion caused by the loss of confining channel walls either at the apex, or at the intersection point. Deposition is instigated on many fans by a pronounced slope decrease (e.g. Trowbridge 1911, Beaty 1963), although such a change does not always exist (Bull 1977). This relationship is illustrated by comparing the slope of the 1-km-long segments of the lower feeder channel and upper fan (thus 1 km on either side of the apex) for 132 fans in Death Valley, California, using 1:24000-scale topographic maps. The slope of the lower feeder channel segment is significantly greater (> 1°) than the upper fan in 40% of these cases, is within 1° in 56% of the cases, and in 4% the upper fan is steeper than the lower feeder channel (Fig. 14.7). Thus, in 60% of these cases, fan aggradation must result from flow expansion rather than decreasing slope on the upper fan.

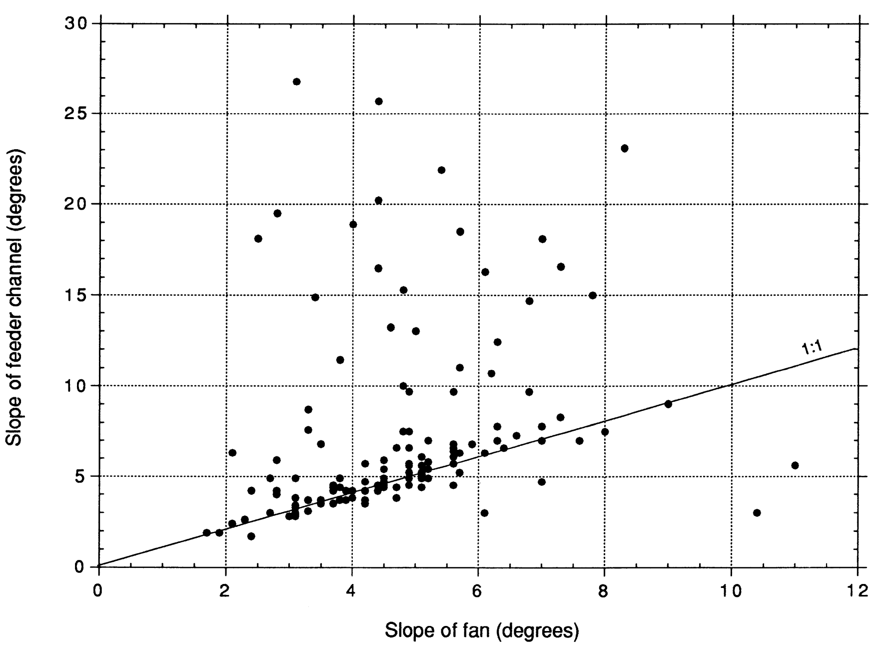

Fig. 14.7 Cross-plot of the slope of the 1-km-long segment of the feeder channel upslope from the fan apex versus the slope of the 1-km-long segment of the upper fan immediately downslope from the apex for 132 Death Valley fans based on 1:24,000 scale topographic maps

Not all channels issuing from mountain fronts construct alluvial fans. Perennial rivers with highly integrated catchments, such as the Kern, San Joaquin, and Feather Rivers of California, and the Arkansas and Platte Rivers of Colorado, maintain channel banks and flow competency. Instead of building fans at the piedmont, these rivers instead either maintain bedload-dominated fluvial tracts, or bypass the piedmont by incision. Alternatively, the piedmont linked to glaciated or recently deglaciated catchments may feature moraines or other till deposits instead of alluvial fans (Fig. 14.6a).

Given the necessary conditions for development, it follows that alluvial fans are most prevalent in active tectonic belts, where relief is maintained, and catastrophic discharge and sediment production are promoted. Of the tectonic belts, those characterized by normal and strike-slip faulting are most conducive to fan development, such as the Basin and Range Province of the western USA, the East African-Red Sea-Dead Sea rift system, piggyback basins of compressional settings such as in northern Chile, and escape zones of the western Himalaya. Relief also is tectonically developed in fold and thrust belts, though fans therein likely are more ephemeral due to the lateral instability of the range fronts.

Primary Processes on Alluvial Fans

Inasmuch as alluvial fans are aggradational deposits, their understanding requires a knowledge of the processes that transport sediment to and within this environment. Sedimentary processes active on alluvial fans are of two types called primary and secondary (Blair and McPherson 1994a, b). Primary processes are those that transport sediment from the catchment or range front to the fan. They include rockfalls, rock slides, rock avalanches, earth flows, colluvial slips, debris flows, incised-channel floods, and sheetfloods. Primary processes overall cause fan construction, and enlarge the catchment by sediment removal. They mainly are triggered by intense precipitation or earthquakes, and thus are mostly infrequent and of short duration, but have high impact with respect to fan aggradation. Secondary processes, in contrast, modify sediment previously deposited on a fan by any of the primary processes. They include overland flow, wind erosion or deposition, bioturbation, soil development, weathering, faulting, and toe erosion. Secondary processes typically result in fan degradation, and, except for faulting and some overland flows, are associated with normal or noncatastrophic conditions. Although they are of limited importance to fan construction, secondary processes dominate the fan surface except in areas recently affected by a primary depositional event due to the infrequency of the latter (Blair 1987a).

All primary fan processes are instigated by failure of catchment slopes, and the downslope transfer of the destabilized material. Catchment slopes consist of two unique material types, bedrock and colluvium. Bedrock is usually present as cliffs or flanks that form steep (50–90°) slopes in the catchment (Figs. 14.2 and 14.6b, c, d). In contrast, colluvium constitutes the commonly gravel-dominated, unsorted to poorly sorted, fine to coarse sediment loosened from the bedrock cliffs through weathering, and deposited along the lower cliffs or in the catchment channels (Fig. 14.6c and e) (e.g. Drew 1873, Sharpe 1938, Rapp and Fairbridge 1968, Rahn 1986, Turner 1996). Slopes formed of colluvium commonly are near the angle of repose (30–40°), but range from 15° to 56° (Campbell 1975). Colluvium can be repositioned in a catchment by flows through the drainage net or, less commonly but more drastically, by glaciers to form moraines (Fig. 14.6a and f). Fan catchments may have slopes underlain principally by bedrock, principally by colluvium, or, most typically, by some of each.

Different primary processes are activated in a fan catchment depending on whether the failed slope material is of bedrock or colluvium, and on the transport mechanism that is instigated. Failed slope material can be transported from the catchment to the fan by: (a) fluid-gravity processes (i.e. water flows), in which colluvial particles are moved by the force of water, (b) sediment-gravity processes, in which colluvial particles and any contained fluids are transported by the force of gravity acting directly on the sediment, or (c) rock-gravity processes, in which commonly disintegrating bedrock is transported by the force of gravity acting directly on the bedrock (e.g. Middleton and Hampton 1976, Blair and McPherson 1999). Sediment may also be moved to the fan by ice-gravity processes, in which colluvium is pushed or carried by the force of gravity acting on glacial ice, and deposited as moraines or till (Derbyshire and Owen 1990, Blair and McPherson 1999, Blair 2001, 2002). Ice-gravity processes, however, are only noteworthy to piedmont sedimentation in highly glaciated settings, and commonly produce landforms other than fans (e.g. Fig. 14.6a). Primary fan processes thus can be grouped into three key types: (a) rock gravity flows generated by failure of bedrock slopes in the catchment, (b) sediment-gravity flows generated by failure of colluvial slopes in the catchment, and (c) fluid-gravity flows generated by failure of colluvial slopes in the catchment (Blair and McPherson 1994a, b).

Rock-Gravity Processes from Bedrock Slope Failures

Four types of rock-gravity processes instigated by destabilized bedrock comprising either the range front or fan catchment slopes are rockfalls, rock slides, rock avalanches, and earth flows. All four are initiated by failure, under the force of gravity, of bedrock usually exposed in the upper catchment. Rockfalls, rock slides, and rock avalanches represent a gradational spectrum of processes related to the brittle failure of bedrock, whereas earth flows constitute a more ductile style of failure by certain rock types.

Rockfalls, Rock Slides, and Rock Avalanches

The processes of rockfall, rock slide, and rock avalanche all derive from the progressive lowering of the internal friction and shear strength of brittle bedrock exposures due to: (a) fracturing and weathering, (b) slope steepening due to downcutting or undercutting, or (c) ground motion from earthquakes (Hadley 1964, Morton 1971, Keefer 1984, 1999, Plafker and Ericksen 1984, Statham and Francis 1986, Cotecchia 1987, Hencher 1987, Beaty and DePolo 1989, Harp and Keefer 1989, Sidle and Ochiai 2006). Unlike other primary processes, water is not relevant to the transport of rockfalls, rock slides, or rock avalanches. Conditions that promote these processes are where: (a) range-front faults are splayed, and bedrock blocks are tectonically sized, (b) syntectonic or inherited fracture patterns in an uplifted mass are oriented nearly parallel to the mountain front or feeder channel, (c) the range front is composed of sedimentary strata dipping at a high angle, with failure likely along bedding planes, (d) other discontinuities, such as metamorphic foliation planes, dip at a high angle near the range front, (e) slopes are oversteepened through increasing relief, or (f) large exfoliation blocks are developed.

Rockfall, the simplest of the processes initiated by failure of bedrock slopes, encompasses the downward rolling or skipping under the force of gravity of individual particles, especially gravel (Drew 1873). The clasts usually are angular in outline due to their liberation from fractures or exfoliation planes. Rockfall deposits commonly mantle the base of cliffs in the catchment or at the range front, forming colluvial talus slopes or, if funnelled, talus cones or incipient alluvial fans (Fig. 14.8a, b, and c) (e.g. Turner 1996, Turner and Makhlouf 2002). Rockfall clasts may also roll or bounce directly from the range front to the fan (Beaty 1989, Beaty and DePolo 1989), where they constitute outsized clasts (Fig. 14.8d). Besides rolling or skipping as individual particles, transport on talus cones and fans may also occur more collectively as grain flows in tongues or chutes (Fig. 14.8b and c) (e.g. Bertran and Texier 1999).

Rock slides, in contrast, constitute larger blocks or megablocks that break away from bedrock cliffs along faults or geological discontinuities, and move either rapidly or slowly downslope as a coherent mass above a basal glide plane (Varnes 1978). As implied by their name, rock slides are differentiated by their sliding transport mechanism, as opposed to the rolling or skipping motion of rockfalls (Sharpe 1938, Mudge 1965). The commonly curved excavation of the bedrock formed by detachment of a rock slide is called the slide scar. Slide scars typically become new fan catchments because they constitute a concavity in the bedrock wherein subsequent precipitation will converge. Rockfall deposits commonly are present along the base of a slide scar due to brecciation from shear along the detachment. Rock-slide deposits accumulate either near the base of the bedrock slopes, or as megaclasts on the fan (Fig. 14.8e).

The failure of a large, fractured bedrock cliff more typically occurs as a rapid and catastrophic downward fall accompanied by partial to widespread disintegration and pulverization to produce a brecciated mass called a rock avalanche (Figs. 14.8f and 14.9a, b) (Harrison and Falcon 1937, Mudge 1965, Shreve 1968, Browning 1973, Hsü 1975, Hunt 1975, Porter and Orombelli 1980, Nicoletti and Sorriso-Valvo 1991,

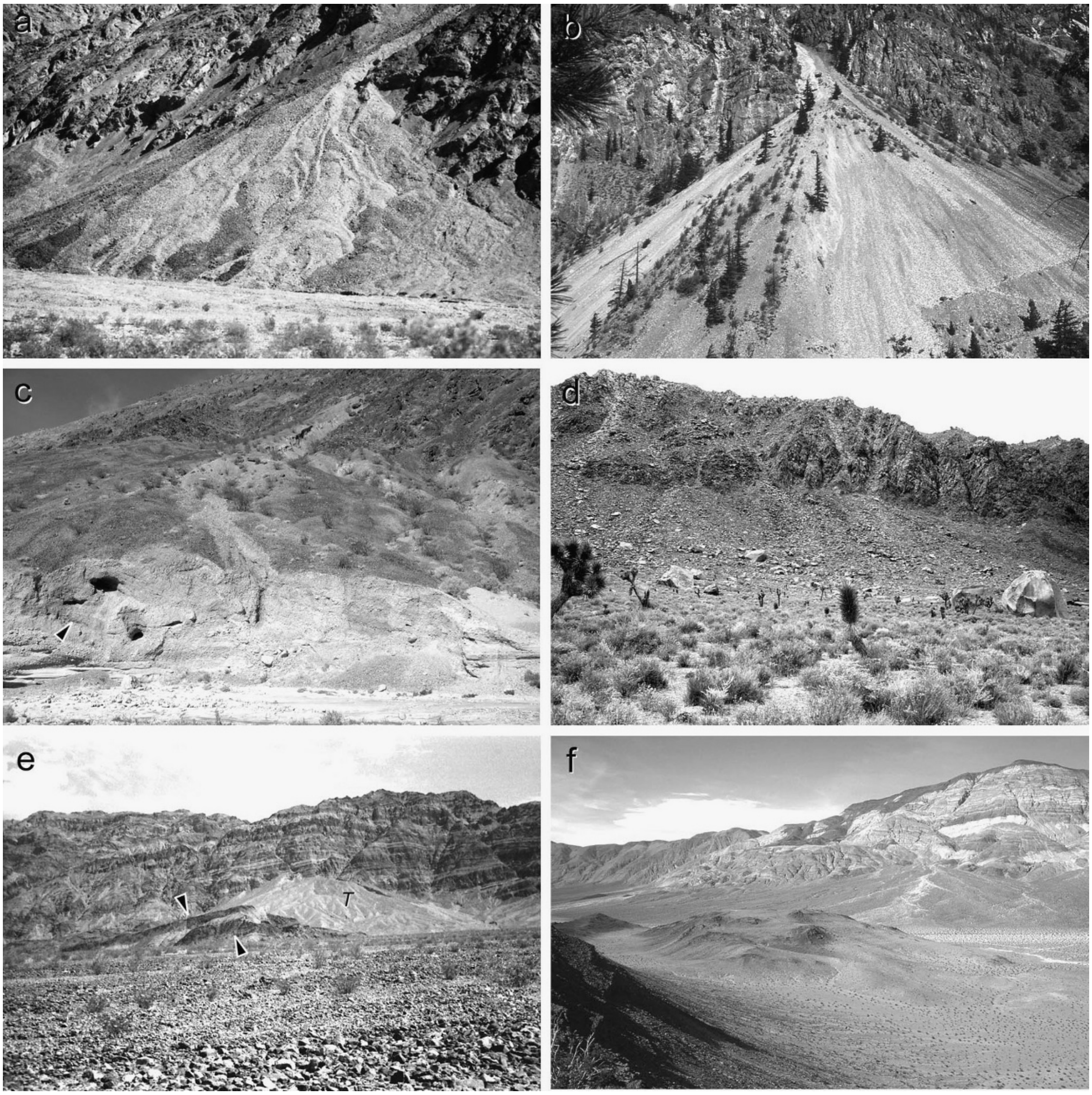

Fig. 14.8 Photographs of rock-gravity flow deposits. (**a**) Colluvial cone in Death Valley with prevalent chutes. Older chutes are darker from rock varnish. (**b**) Rockfall talus cone with active grain-flow chutes located along the Fraser River near Lillooet, British Columbia. (**c**) Incipient fan in Eureka Valley, California, with toe cuts that reveal a scallop-shaped stratigraphy resulting from the accumulation of sediment in rockfall chutes (e.g. *arrow*). (**d**) View of loose boulders transported by falling and rolling to the piedmont from a fault-bounded range front, Owens Valley, California. The particles are shaped by fractures in the granitic bedrock. (**e**) Two megablocks of carbonate rock (*arrows*) with d_I of 255 and 380 m transported to the piedmont as rock slides from the range front; South Titanothere Canyon fan, Death Valley. These megaclasts are being buried by subsequent gravelly rockfall talus (*T*). (**f**) View of 90 m high mounded rock-avalanche deposits (*centre*) on the distal Panamint Canyon fan, California

Blair 1999a, c). Rather than rolling or sliding, avalanches mainly achieve motion by transforming into a dry granular flow. This transformation occurs as the rock mass disintegrates during the fall stage, or during impact with the piedmont. Brecciation may progress further during transport, especially along the base where shear is greatest due to friction and to the weight of the overlying mass. Rock avalanches are known to move at speeds of about 25–100 m/s (Erismann and Abele 2001). They typically undergo deposition in the piedmont zone due to a lessening of slope, lateral expansion, and basal and lateral friction. Total runout distance also is related to the kinetic energy of the fall and the potential energy acquired during downslope movement, both of which increase with the height of the fall (Hsü 1975, Melosh 1987; Fauque and Strecker 1988; Hart 1991). Failure of a part of a range-front facet between two fan catchments can create a new catchment and fan (Blair 1999a).

Rock-avalanche deposits on alluvial fans have variable but diagnostic features and forms. They typically comprise massive units 10 to > 100 m thick present as: (a) irregular or conical forms, (b) arcuate to U-shaped levée-snout forms with either low or high length-to-width ratios, or (c) continuous lobes (Figs. 14.8f and 14.9a, b) (Hadley 1964, Burchfiel 1966, Gates 1987, Fauque and Strecker 1988, Evans et al. 1989, 1994, Blair 1999a, c, Hermanns and Strecker 1999, Philip and Ritz 1999, Hewitt 2002). The upslope ends of these deposits either extend directly from the range front, or are detached from it by small to great distances. Where exposed, the basal avalanche and underlying fan deposits are deformed, including by thrusting and injection. Large rock avalanches may produce a fan and catchment in a single event, as exemplified by the 1925 Gros Ventre avalanche in Wyoming, the 1970 Huasaracan avalanche in Peru, and the 1987 Val Pola avalanche in Italy (Blackwelder 1912, Voight 1978, Plafker and Ericksen 1984, Costa 1991, Erismann and Abele 2001, Govi et al., 2002, Schuster et al. 2002). Other large cases, such as at Hebgen Lake, Montana in 1959 (Hadley 1964), did not produce a fan or catchment because of the breadth of the collapsed range-front bedrock, and the lack of funneling of the moved material.

Irrespective of depositional form, rock-avalanche deposits diagnostically consist of pervasively shattered, angular clasts of gravel to megagravel separated by variable amounts of cataclastic matrix (Fig. 14.9c), leading to the term 'megabreccia' (e.g. Longwell 1951, Burchfiel 1966, Shreve 1968). Clasts of all sizes are internally shattered, but remain intact or are only slightly expanded. Finer clasts derive from the disaggregation of shattered clasts. Detailed textures such as jigsaw breccia and crackle breccia have been differentiated (Yarnold and Lombard 1989). Avalanche clasts have a composition that directly matches the bedrock source. Particles are commonly of a single lithology due to the homogeneous bedrock from which avalanches are derived, giving rise to the term 'monolithologic breccia.'

Earth Flows

Earth flows constitute the glacier-like, slow or episodic downslope movement of a small to large volume of bedrock as a partially ductile mass. Earth flows are generated where fine-grained bedrock, especially bedrock bearing water-sensitive expandable clay minerals, comprise upland slopes (Varnes 1978, Keefer and Johnson 1983). Earth-flow movement most commonly occurs during sustained wet-season rainfall following a dry period. When wetted, the sensitive bedrock loses shear strength and gains plasticity. Earth flows are thus activated by failure, under the force of gravity, of fine-grained bedrock on steep slopes through water infiltration, and aided by loading (Fleming et al. 1999). Places and rock types where earth flows are documented to be common are upland slopes of: (a) Neogene mudstone and Mesozoic melange in the San Francisco Bay area, (b) Cretaceous to Eocene shale in the dry interior of British Columbia, Canada, and (c) Cenozoic volcanic tuff sequences in the American Rocky Mountains (Fig. 14.9d, e) (Krauskopf et al. 1939, Crandell and Varnes 1961, Keefer and Johnson 1983, Bovis 1985, 1986, Shaller 1991, Bovis and Jones 1992, Varnes and Savage 1996, Fleming et al. 1999).

Earth-flow movement is related to increased pore-water pressure, and is accommodated by sliding along a basal glide plane developed along an internal discontinuity, such as between weak and strong layers, or zones of saturation (e.g. Keefer and Johnson 1983). Lateral expansion and contraction of the mass during flow shows that it undergoes internal ductile deformation, whereas the presence of fissures, lateral ridges, and thrusts attest to brittle behaviour (Fig. 14.9d, e). The cavity at the upslope end of an earth flow, from which the mass has detached, is called the head scar. Once generated, earth flows may be reactivated in whole or in part by lubrication from subsequent water input that commonly is concentrated in the head scar. Lateral expansion of the distal end of high-volume earth flows reaching the piedmont

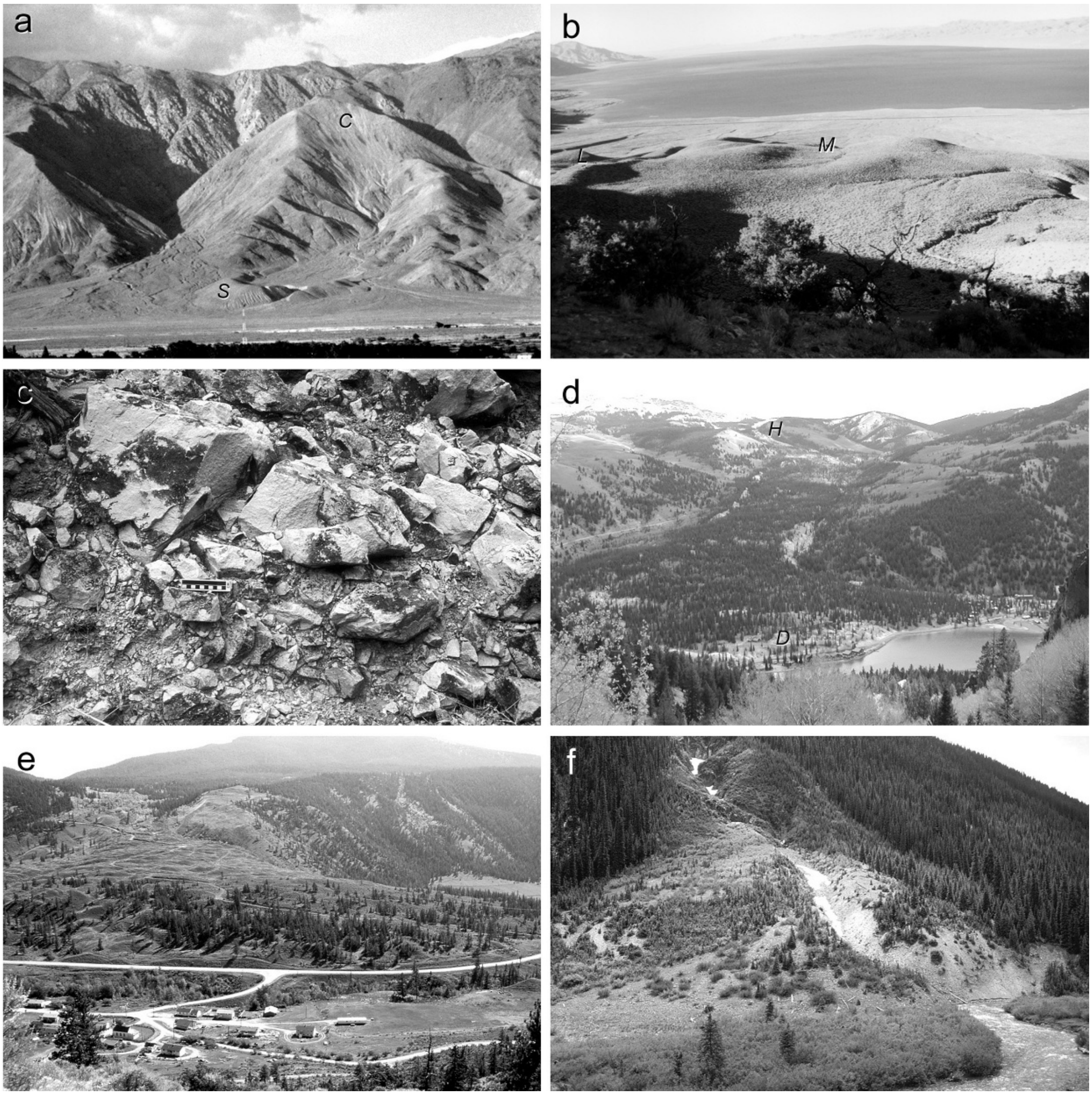

Fig. 14.9 Photographs of fans with various types of rock-gravity and sediment-gravity flows. (**a**) View on North Long John fan, Owens Valley, of a prominent rock avalanche with levées leading to a 108-m-high frontal snout (*S*). The avalanche originated by failure of bedrock previously present in the range-front scar (*C*). (**b**) Downslope view of the avalanche mounds (*M*) and levées (*L*) that are partly dissected by gullies; Rose Creek fan delta, Walker Lake, Nevada. (**c**) Exposure of the North Long John rock avalanche showing an unstratified and unsorted, very angular texture of muddy, cobbly, fine to coarse pebble gravel. Scale bar is 15 cm long. (**d**) Cross-valley view of the Slumgullion earth flow, southwestern Colorado, derived from a head scar (*H*) in volcanic bedrock. The earth flow has expanded at its distal end (*D*) to form a fan ∼2 km wide. Photograph provided courtesy of the U.S. Geological Survey. (**e**) Overview of the alluvial fan formed by the Pavilion earth flow, south-central British Columbia. (**f**) Fan formed from slips of colluvium mantling the steep catchment, Conundrum Creek valley near Aspen, Colorado. The lower catchment and fan were later incised by water flow

can produce an alluvial fan, such as for the Carlson earth flow in Idaho (Shaller 1991), the Pavilion in British Columbia (Fig. 14.9e), and the Slumgullion in Colorado (Fig. 14.9d). The presence of the thickest part of an earth flow at its distal end, including on a fan, is due to the continued movement of the upper part of the mass to the zone of accumulation, where it stabilizes.

Sediment-Gravity Processes from Colluvial Slope Failures

Colluvial Slips

Sediment-gravity processes on alluvial fans generated from colluvial slope failures include colluvial slips, debris flows, and noncohesive sediment-gravity flows. Colluvial slips (also called colluvial slides or slumps) consist of intact to partially disaggregated masses of destabilized cohesive colluvium that move either slowly or rapidly downslope above a detachment horizon (Varnes 1978, Cronin 1992). The detachment may develop at a zone of weakness within the colluvium, but more commonly it constitutes the contact between colluvium and the underlying bedrock, where infiltrated water is perched. Colluvial slips can be triggered in a dry or unsaturated state, such as in response to earthquakes (Keefer 1984), but most often are initiated by the addition of rainfall or snowmelt in volumes that saturate the sediment (Caine 1980, Ellen and Fleming 1987, Reneau et al. 1990). Colluvial slopes fail in this state because of the lowered resisting forces related to increased hydrostatic pore pressure and decreased shear strength (Campbell 1975, Hollingsworth and Kovacs 1981, Mathewson et al. 1990). The presence of clay in the colluvium promotes failure by lowering permeability and providing strength to the interstitial fluid phase.

Colluvial slips commonly accumulate in the catchment at the base of the failed slope or within the drainage net. They also can build an alluvial fan in cases where they are funnelled through a low-order catchment directly to the piedmont. Fans built mainly by colluvial slips are common in the high elevation of Colorado, where they develop at the base of bedrock shoots (Fig. 14.9f). These fans are active mostly during spring snowmelt, especially below shoots that had their tree cover damaged by snow avalanches or fire. The deposits are of thick to massive beds of muddy gravel texturally like the colluvium.

Debris Flows

Debris flow is the most important sediment-gravity process type with respect to the volume of material delivered to alluvial fans. Such flows consist of a mixture of sedimentary particles spanning from clay to gravel, along with entrained water and air, that move downslope in a viscous state under the force of gravity (Blackwelder 1928, Sharp and Nobles 1953, Johnson 1970, 1984, Johnson and Rahn 1970, Fisher 1971, Hooke 1987, Coussot and Meunier 1996, Iverson 1997). Debris flows are instigated as failed colluvium in the catchment in response to the addition of a notable amount of water that undergoes rapid infiltration and runoff to form a flash flood. Water input is from: (a) rapid precipitation, such as from a thunderstorm, (b) heavy rainfall following previous sustained rainfall that saturated the colluvium, or (c) rapid snowmelt or icemelt from warming air temperature (Costa 1984, 1988). As with colluvial slips, the generation of a debris flow is promoted where colluvium contains mud. The presence of mud induces failure and debris-flow initiation by lowering the permeability of the colluvium, allowing hydrostatic pore pressure to increase and overcome shear strength, leading to the rapid downslope movement of a mud-bearing mass. Slopes that promote debris-flow initiation typically are at $\sim$27–56°, with slopes $>$ 56° too steep to maintain a colluvial mantle, and slopes $<$ 27° having a lower propensity for failure (Campbell 1975). Because flash floods are infrequent, and the accumulation of colluvial sediment requires time, the recurrence interval of debris flows is relatively long, varying from about 300 to 10000 years (Costa 1988, Hubert and Filipov 1989). Debris flows locally are more frequent where conditions are presently ideal for their generation (e.g. Jian and Defu 1981, Jian and Jingrung 1986, Cerling et al. 1999).

More specifically, debris flows are initiated from colluvium by one of two mechanisms, both of which cause disaggregation and dilatancy as the failed mass transforms into a cohesive flow resembling wet concrete (Johnson and Rahn 1970, Campbell 1974, 1975, Costa 1988). One way that transformation is achieved is through the disaggregation of a wet colluvial slip as it moves downslope. The change from a slip to a flow occurs as shear expands from the base to throughout the mass, and clasts begin to move independently. The second triggering method is by rapid erosion where flashy runoff intersects colluvium in the drainage net (e.g. Cannon et al. 2001). Such erosion can cause the undercutting and sloughing of sediment along the channel sides, leading to quick sediment bulking of the flow. Water in this case dissipates its energy by dispersing clasts through churning, tossing, and mixing to produce a debris flow (Johnson 1970, 1984). The presence of mud in the colluvium provides cohesive strength to the ensuing flow. The generation of debris flows either by slip or erosion is promoted in fan catchments by the presence of steep and poorly sorted colluvial slopes, combined with a converging drainage net that concentrates colluvial sediment and overland flows in the same area (e.g. Reneau et al. 1990).

Debris flows move as a viscous mass in a non-Newtonian laminar manner, causing them to be nonerosive even though they can transport clasts weighing several tons (Johnson 1970, Rodine and Johnson 1976). Debris flows have been observed to move at speeds of 1–13 m/s (Sharp and Nobles 1953, Curry 1966, Morton and Campbell 1974, Li and Luo 1981, Li and Wang 1986). Individual flows typically are 1–10 m thick within catchment channels, and thin by lateral expansion upon reaching the fan. They improve flow efficiency in the catchment by shearing off their sides or base in rough zones, outer bends, or where the channel rapidly widens. A debris flow event can entail a single pulse, but more commonly consists of several surges caused by the episodic addition of sediment via multiple slips or sloughs, or from the repeated generation and breaching of jams between boulders, logs, and pathway elements (Blackwelder 1928, Fryxell and Horberg 1943, Sharp and Nobles 1953, Johnson 1984).

Particles in debris flows are supported by the high density and strength of the mass related to cohesive, dispersive, and buoyant forces (Middleton and Hampton 1976, Costa 1984, 1988). The differential response of boulders to buoyant and dispersive forces generated by small differences in density between them and the rest of the material, along with kinetic sieving, cause boulders in a moving debris flow to become concentrated at the top (Johnson 1970). Friction at the base of a debris flow makes it move more slowly than the top, resulting in the progressive conveyance of the boulder-rich upper tread to the front of the flow. Frontal boulder accumulations typically are interlocked and lack pore-fluid pressure, forcing the flow either to cease, or to push aside the frontal boulders (Johnson 1984, Iverson 1997, Major and Iverson 1999).

Once initiated, a debris flow moves until gravity forces decrease to the point where they no longer can overcome the shear strength. Debris-flow mobility is aided by the lubricating effect of the muddy pore fluid, which facilitates motions of grains past one another, and mediates grain contacts (Iverson 1997). The cessation of a debris flow primarily results from thinning to the point where the plastic yield strength equals the shear strength (Johnson 1970), a process promoted by expansion, and aided by dewatering and a lessening of slope. These conditions, and thus deposition, are most common where debris flows depart from the catchment onto a fan. Debris flows may bypass the upper fan if an incised channel is present because the channel walls prevent flow expansion. Deposition in this case commences when the flow reaches the active depositional lobe (Fig. 14.10a). As in the catchment, debris flows may also be halted on the fan prior to critical thinning due to the damming of coarse clasts at the margins, or the jamming of clasts and logs with flow-path obstacles such as boulders or trees. The extent of the deposits on a fan from a single debris-flow event, including radial run-out distance, ultimately is a function of the debris-flow volume given that the continued addition of sediment prevents critical thinning (Blair 2003).

Debris-flow deposits on alluvial fans consist of unsorted to extremely poorly sorted, muddy to gravelly sediment present mainly as levées and lobes (Blackwelder 1928, Sharp and Nobles 1953, Beaty 1963, 1974, Johnson 1970, Costa 1984, Blair and McPherson 1998, 2008). Levées constitute sharply bounded, radially oriented ridges typically 1–2 m wide and 1–4 m tall present in parallel pairs separated by a 2–10 m gap (Fig. 14.11a, b). They represent the boulder-rich fraction of a debris flow that was selectively conveyed to the flow front during motion, and then pushed aside and sheared from the lateral margins as the flow continued downslope. Paired levées may extend for tens to hundreds of metres down the fan, and be joined at their ends by a snout. Levées can be slightly sinuous and widen along their outer curves where the debris flow followed a previous drainage. They are characteristically boulder-rich, with the *a-b* plane of elongated boulders aligned about parallel to the trend of the levée. This fabric is produced as the boulders are pushed aside from the front of the flow. Boulders and other clasts usually are interlocked (clast-supported) on the outer levée margins (away from the interlevée area), and are supported by abundant matrix on their inner sides (Fig. 14.11a, b). Mangled tree logs and limbs also may be present.

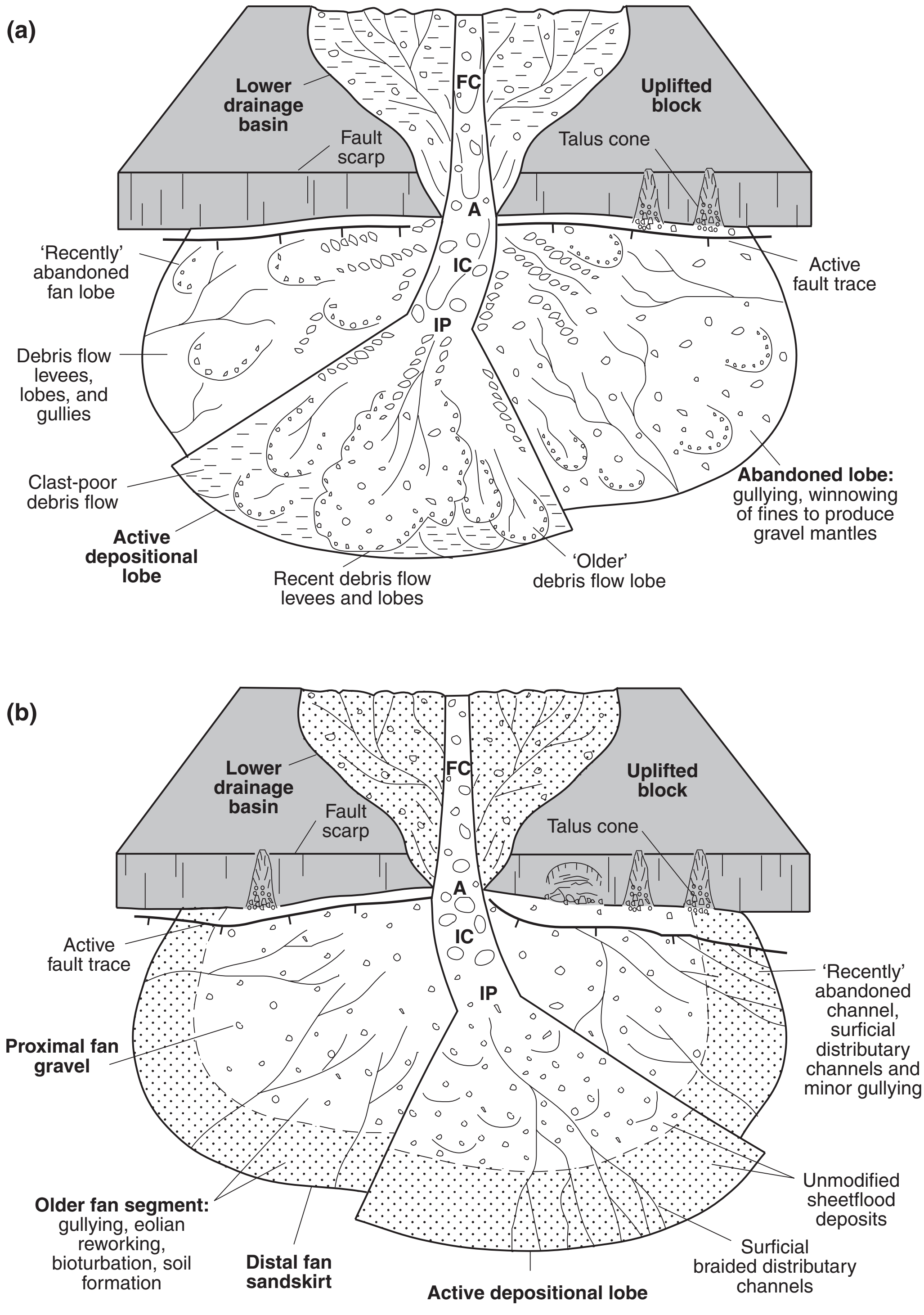

Fig. 14.10 Schematic diagrams of the common processes on alluvial fans, including for those dominated by debris flows (**a**) or sheetfloods (**b**). Labels denote the catchment feeder channel (*FC*), fan apex (*A*), incised channel (*IC*), and intersection point (*IP*)

Fig. 14.11 Photographs of debris-flow deposits. (**a**) Downfan view from apex of Dolomite fan, Owens Valley, of two sets of paired levées 150–250 cm tall deposited during a 1984 debris-flow event. Note the clast-rich outer levées on either side of an older ridge (*O*). (**b**) View of inside of 1984 debris-flow levée on the proximal Dolomite fan; shovel for scale. (**c**) View of 50 cm thick clast-rich and matrix-rich debris-flow lobe deposited in 1984 on the Dolomite fan. (**d**) View of 1984 debris-flow lobe on the medial Dolomite fan consisting of clast-rich (*R*) and clast-poor (*P*) phases that were partly winnowed (*W*) during falling flood stage. (**e**) Overview of 1984 debris-flow deposits (light) on the Dolomite fan consisting of proximal levées (*upper arrow*) and distal lobes (*lower arrow*). The latter terminate at the fan toe, where a depositional slope gap is apparent. Older levées are visible in pre-1984 deposits of the proximal fan. (**f**) View of 1990 clast-poor debris-flow lobe on the Copper Canyon fan, Walker Lake, Nevada. Note that the flow delicately divided around the desert plants despite the concentration gravel clasts at the lobe margin

Debris-flow deposits most abundantly are present on alluvial fans as radially elongated lobes 1–100 m wide and ∼0.05–2 m thick (Fig. 14.11c, d). Lobes are commonly continuous for hundreds of metres downfan beginning at the apex of the fan or active depositional lobe, or at the distal ends of paired levées (Fig. 14.11e). Lobes in the latter case represent material that passed between the levées, and continued to flow farther downslope. The margins of the lobes usually are sharp and steep (> 45°), but delicately wrap around pre-flood features such as plants (Fig. 14.11f). Texturally, debris-flow lobes are mud-rich and matrix-supported, and are either clast-rich or clast-poor. Unlike levées, boulders are uncommon in lobe deposits. Clast-rich lobes consist of muddy, pebbly cobble gravel with sharp lateral and distal margins outlined by a commonly clast-supported fringe of coarse to very coarse pebbles, cobbles, and possibly wood fragments (Fig. 14.11c, d). Clast-poor debris-flow lobe deposits, also called mudflows, are similar to clast-rich lobes except that they lack abundant coarse pebbles and cobbles, consisting instead of muddy very fine to medium pebble gravel, or pebbly mud (Figs. 14.11f and 14.12a). Like clast-rich lobes, they have sharp margins typically fringed by wood and pebbles, although clast-poor lobes tend to be thinner (< 50 cm), and become mud-cracked during desiccation.

Debris-flow deposits on a given alluvial fan may be dominantly of (a) levées, (b) clast-rich lobes, (c) clast-poor lobes, or (d) levées in the proximal zone that give way downfan to lobes (Fig. 14.10a). Case studies reveal that the presence or absence of the various forms is a function of the typical texture of the catchment colluvium (Blair and McPherson 1994b, 1998, 2008, Blair 1999f, 2003). For example, surface forms and facies reveal that the Dolomite alluvial fan of Owens Valley, California, consists mostly of levées in the proximal fan and clast-rich lobes in the distal fan (Blair and McPherson 1998). A similar pattern was produced on this fan during the afternoon of 15 August 1984 by a multiphase debris flow triggered from a strong thunderstorm. A total of ~50,000 m^3 of sediment was deposited during this event as multiple paired levées extending for 200–300 m on the proximal fan, and giving way to continuous 200–400 m long lobes on the distal fan (Fig. 14.11e). The lobes extend downslope from the ends of the conjugate levées, and consist mostly of a clast-rich phase that is overlain and offlapped by clast-poor phase. Boulders are abundant in the levées but are essentially absent in the lobes. Seven major levée-lobe tracts, each representing a single surge, were deposited during this debris flow event.

The transition from levées to lobes for each of the 1984 debris flow surges on the Dolomite fan took place in response to the selective depletion of boulders (Blair and McPherson 1998). This depletion was caused by the preferred movement during flow of boulders to the upper part of the debris flow due to buoyancy and dispersion, and then to the front due to higher velocity of the upper versus lower treads of the flow in response to basal drag. Boulders concentrated at the front of this debris flow were pushed aside by the main flow mass, and then were sheared off and left behind as levées (e.g. Sharp 1942). This process in the Dolomite debris flow ensued until the boulder content of a given surge was depleted. A loss of boulders, typically at a distance of ~250 m from the fan apex, caused the boulder-deficient central part of the debris flow to continue downslope beyond the ends of the levées, where it expanded and then accumulated as a clast-rich lobe. A clast-poor lobe stage, representing the more dilute debris flow tail, capped and offlapped the downslope ends of the clast-rich lobes. Deposition of proximal levées and linked distal lobes by each of the seven major debris-flow surges was caused by a generally consistent texture per surge of muddy pebble cobble gravel with some boulders. A greater content of boulders in the colluvium would have caused a greater dominance of levées on the fan, whereas a lower boulder content would have caused a dominance of lobes. The generally consistent texture of the seven tracts implies that each surge was instigated by freshly sloughed colluvium of roughly similar content.

Another attribute of debris flow fans exemplified by the Dolomite case is the relationship between process and surface slope. The levée-dominated proximal part of the Dolomite fan has a surface slope of 9–12°, whereas the zone with clast-rich lobes has a slope of 3–5°, and the clast-poor lobes 2–3° (Blair and McPherson 1998). The proximal to distal inflection of slope takes place over a short distance to create two pronounced radial segments. The coincidence of this slope inflection with the depletion of boulders in the deposits, and with a change from levées to lobes, shows that the slope is a product of the process. More specifically, the 9–12° slope of the levéed segment reflects the highest magnitude of slope for which transport is not possible given the shear strength of the typical debris-flow mix yielded from the catchment. Similarly, flows producing the clast-rich lobes ceased motion at slopes of 3–5°, and clast-poor lobes at 2–3°. These relationships show that the fan slope results from the dominant aggradational process, not vice-versa, and that the process in the case of the Dolomite fan is a function of the sedimentary texture, including boulder content, yielded during a given colluvial failure in the catchment.

Alluvial fans dominated by clast-poor debris flows (mudflows) are a special case representing situations where coarse gravel is not shed in abundance from the catchment despite relief. This scenario occurs where fan catchments are underlain by easily disaggregated shale, siltstone, sandstone, or fine-grained volcanic rocks, or where intense tectonic shear has pulverized more coherent bedrock (Blair and McPherson 1994b, Blair 2003). Examples of this fan type, such as the Cucomungo Canyon fan in Eureka Valley, California (Fig. 14.12a), have slopes of 2–4°, indicating that this is the common slope range at which the flow shear strength is no longer exceeded by gravity forces.

Noncohesive Sediment-Gravity Flows

Noncohesive sediment-gravity flows (NCSGFs) form where catastrophic water discharge in a catchment intersects sandy and gravelly colluvium containing little mud. Such material is loose because mud is the main agent providing cohesive strength to colluvium. Water erosion of noncohesive colluvium normally produces a fluid-gravity flow, but catastrophic discharge intersecting abundant loose colluvium can cause erosion and bulking so extreme that the water-sediment mixture rapidly transforms into a NCSGF. NCSGFs are similar to debris flows in many respects, but low mud content precludes cohesive strength. Clasts, including boulders and blocks, are instead supported during transport by dispersive, buoyant, and structural-grain forces. Like debris flows, transportation is laminar, and thus NCSGF are nonerosive.

NCSGFs are not well understood, but can be characterized by two examples. A documented NCSGF occurred 15 July 1982 on the Roaring River alluvial fan in Rocky Mountain National Park, Colorado (Jarrett and Costa 1986, Blair 1987a). This event was triggered by failure of a man-made dam containing a reservoir in the upper catchment. The impounded water was rapidly released when the dam failed, and within a few hours the ensuing flash flood moved about 280,000 m^3 of sediment to the fan. Much of the sediment was eroded from mud-poor glacial moraines present along the feeder channel that consist of sand, pebbles, cobbles, boulders, and blocks derived from the colluvium mantling gneissic bedrock. Extreme erosion where the turbulent flash flood intersected the moraine produced a NCSGF that deposited two fan lobes 220 and 600 m in length, and 11–13 m thick. The lobe margins are partly delineated by jams between boulders, logs, and upright trees (Fig. 14.12b). Paired but non-parallel boulder-rich levées 1.5 m tall were sheared from the margins of the first lobe, and extend for 70 m from the fan apex. Significant sedimentation during this event also occurred from sheetflooding (next section) that followed deposition of the NCSGF lobes.

Major NCSGF events have been reconstructed for near-surface deposits of the Tuttle, Lone Pine, and several other fans of the Sierra Nevada piedmont along Owens Valley, California (Figs. 10.1b and 10.2b) (Blair 2001, 2002). Glaciers, moraines, and cirques are present in the upper catchments of these fans, and moraines built of repositioned colluvium are present in the lower catchment or on the upper fan as a result of more expansive glaciation during latest Pleistocene time (Figs. 14.3b and 14.6f). The moraines consist of mud-poor sand, gravel, and blocks derived from granitic bedrock. Massive matrix-supported lobes of sandy cobbly boulder gravel 3 to $>$ 8 m thick span across most of these $\sim$10 km long fans (Fig. 14.12c and d). Fine to medium blocks (d_I of 4–15 m) also are present. The lobes formed in response to rapid erosion of moraines in the catchment due to the failure of moraine or ice dams that naturally impounded water. The rapid release of the water caused extreme erosion of the moraine and sediment down stream, transforming the material into NCSGFs that were catastrophically deposited across the fans. The surficial NCSGF deposit of the Tuttle fan has a volume of $\sim$140 million m^3. Following NCSGF deposition, continued catastrophic flood discharge eroded channels through these deposits (Fig. 14.12d), and moved this sediment to the distal fan where it built sheetflood lobes.

Fluid-Gravity Processes from Colluvial Slope Failures

Fluid-gravity flows, or water flows, are Newtonian fluids characterized by a lack of shear strength, and by the maintenance of sediment and water in separate phases during transport (Costa 1988). Turbulence causes sediment to move either as suspended or quasi-suspended

Fig. 14.12 Photographs of various fan flow types. (**a**) View of 1997 mudflow deposits 35 cm thick and > 20 m wide on the medial Cucomungo fan, Eureka Valley, California; arrows point to steep margin. These deposits extend outward from a central channel (*C*), enveloping plants and aggrading a planar bed upon the relatively smooth surface of 1984 mudflow deposits. (**b**) Upfan view of the distal margin of NCSGF on the Roaring River fan, Colorado. The margin consists of a boulder-log jam ∼ 2 m tall. (**c**) NCSGF exposure 4 m tall on the Tuttle Canyon fan, Owens Valley; fieldbook for scale. Note the matrix support, lack of sorting, and presence of calcium carbonate coatings on clast undersides (*C*). (**d**) Downslope view of sand-bedded channel (*C*) 10 m wide and 3 m deep cut by catastrophic discharge into NCSGF deposits of the Tuttle Canyon fan. (**e**) Incised channel of a fan derived from the Smith Mountain pluton, Death Valley. The channel bed consists of boulders, lateral to which sandy gravel was deposited. (**f**) Downfan view of incised-channel wall of the proximal Warm Spring Canyon fan, Death Valley. The wall contains a side relict of older incised-channel deposits (*IC*) inset within debris-flow sequences (*D*)

load, or by the rolling or saltating of particles as bedload along the flow base. Sediment concentration in fluid-gravity flows typically is ≤ 20% by volume, but may reach ∼ 47% (Costa 1988). Flows in the latter case, called hyperconcentrated, achieve low shear strength and have reduced fall velocity of particles, but retain water flow properties, including transport from turbulence, and the maintenance of sediment and water in separate phases (Nordin 1963, Beverage and Culbertson 1964, Costa 1988, Coussot and Meunier 1996). More recently, others have erroneously applied 'hyperconcentrated flow' or 'hyperconcentrated flood flow' to debris flows, or to a mechanically uncertain flow proposed to be transitional between water flow and debris flow.

Fluid-gravity flows are generated in a fan catchment as a result of the concentration of water as overland flow in the drainage net due to input from precipitation, snowmelt, or natural dam failures. Overland flow is achieved when the infiltration capacity of the colluvium is exceeded, and runoff begins. Colluvium mantling catchment slopes is eroded by runoff via undercutting and entrainment. Should the eroded colluvium contain mud, the water-sediment mixture then typically transforms into a sediment-gravity flow, such as a debris flow. The generation of a fluid-gravity flow from catchment runoff under these conditions thus requires the presence of generally mud-free colluvium. Two types of fluid-gravity flows, incised-channel floods and sheetfloods, are important primary fan processes generated this way.

Incised-Channel Floods

Incised-channel floods constitute the continued confined transfer of a flash flood from the feeder channel across the fan. If present, the walls of an incised channel prevent the flood from expanding, causing flow depth and competency achieved in the feeder channel to be maintained. Deposits from an incised-channel flood thus are mainly of the coarsest clasts (commonly cobbles and boulders) derived from the catchment, or eroded from the walls or floor of the channel. Incised channels typically have a floor of coarse clasts 0.5–3 m thick, and may contain drapes of finer sediment deposited during falling flood stage (Fig. 14.12e) (Blair 1987a, 1999d, 2000). The lateral repositioning of the incised channel coincident with incision can produced terraces or stranded margins (Fig. 14.12f) (e.g., Blair 1999f). Incised channels primarily serve as conduits for discharge across the upper fan. Their deposits thus mostly comprise an armoured channel bed set within other primary deposits such as debris flows, NCSGFs, or sheetfloods.

Sheetfloods

A sheetflood is a short-duration, catastrophic expanse of unconfined water (McGee 1897, Bull 1972, Hogg 1982). Sheetfloods are instigated by torrential precipitation such as from a thunderstorm, or from the release of impounded water due to the failure of a natural dam (Blair 1987a, Gutiérrez et al. 1998, Meyer et al. 2001). Sheetfloods readily develop on alluvial fans where flash flood discharge from the catchment is able to expand. Expansion is promoted by the conical surface of a fan, and begins either at the fan apex or on an active depositional lobe located downslope from an incised channel (Fig. 14.10b).

The characteristics of alluvial-fan sheetflooding are illustrated by the catastrophic event of 15 July 1982 on the Roaring River fan in Rocky Mountain National Park, Colorado (Blair 1987a). An aerial photograph taken while the sheetflood was underway shows water and sediment discharge over a 320-m-long active depositional lobe with an expansion angle of 120°, and fed by an incised channel 160 m long present between two previously deposited NCSGF lobes. The length of this lobe was restricted by the opposing valley margin. At the time of the photograph, transverse upslope-breaking waves typical of supercritical flow (Froude number > 1) were present on the water surface in 43 radially oriented trains 3–6 m wide, 10–250 m long, and with wavelengths of 5–25 m. The trains covered ∼20% of the lobe area, and were developed in the deepest part of the sheetflood. Hydraulic calculations from the waves show that the sheetflood had an average depth of 0.5 m, a velocity of 3–6 m/s, maximum water discharge of 45.6 m^3/s, and a Froude number of 1.4–2.8. Post-flood evaluation of this lobe showed a 2° to 5° sloping surface of cobbly pebble beds 3–6 m wide and 10–20 cm thick separated by more widespread pebbly sand 5–20 cm thick (Fig. 14.13a). Trenches revealed a sheetflood sequence up to 5 m thick consisting mostly of rhythmically alternating beds with the same textures and thickness as the surface units (Fig. 14.13b). Clasts within the couplet beds are clast-supported and imbricated, and the pebbly sand is laminated. The surface was partly incised during falling flood stage, forming channels within which coarse clasts were concentrated. Much of the sheetflood surface was remolded during subsequent noncatastrophic discharge into shallow channels

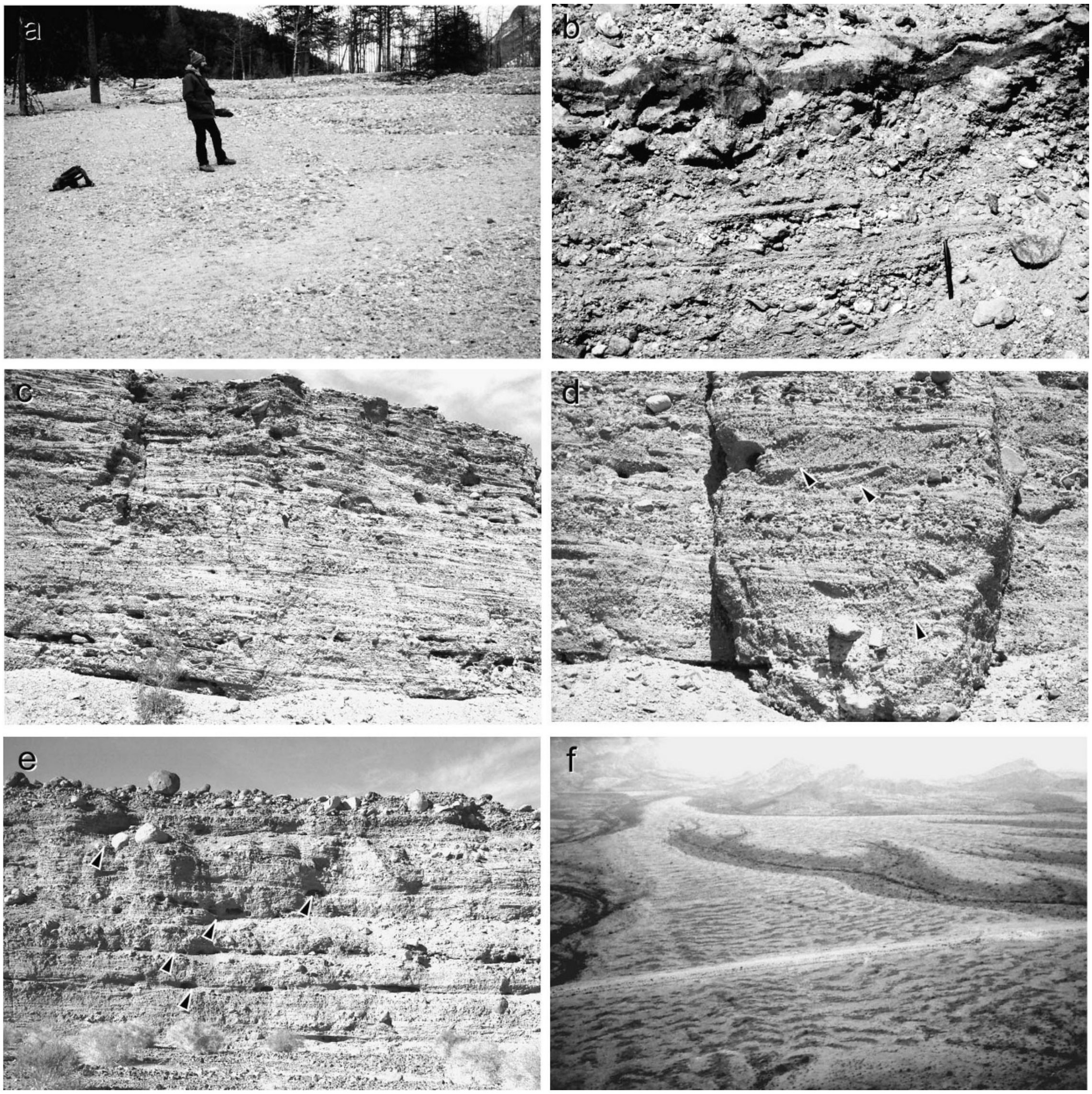

Fig. 14.13 Views of alluvial fan sheetflood deposits. (**a**) Photograph taken soon after sheetflood deposition in 1982 on the Roaring River fan in Colorado. The surface is smooth, slopes 4°, and has not been modified by falling-stage channel incision. Gravel beds ~2 m wide and more widespread sand beds are apparent. (**b**) Vertical trench in 1982 sheetflood deposits of the Roaring River fan near the site of previous photograph showing alternating couplets of cobble–pebble gravel and laminated granular sand with a slope similar to the fan surface. The dark silty horizon near the top of the trench was deposited ten months after the flood by secondary spring snowmelt discharge. (**c**) View of a 12-m high exposure of the proximal Anvil fan, Death Valley, dominated by planar-bedded couplets 5–25 cm thick of sandy very fine to medium pebble gravel and sandy cobbly coarse to very coarse pebble gravel. Beds slope 5° downfan, to the right. (**d**) Close-up view of Anvil fan sequence 2 m thick of sheetflood couplets containing three wedge-planar backset beds ~20 cm thick; arrows at base. Backsets dip 7–15° upfan, (leftward). (**e**) Exposure 7 m thick on Anvil fan of sheetflood couplets and backset beds separated by recessively weathered sand and bouldery cobbly pebble gravel; dark, e.g. arrows. The recessive beds are from secondary reworking. They divide the section into 7 sets 50–200 cm thick, each representing the deposits of a single sheetflood. (**f**) Oblique view of fan in western Arizona displaying transverse ribs of sediment-deficient sheetflood origin; road for scale. Photograph provided courtesy of S.G. Wells

wherein a sediment lag accumulated upon the couplet sequences, armouring them from further erosion.

Alternating cobbly pebble gravel and pebbly sand couplets also dominate exposures of other waterlaid fans, such as the Anvil and Hell's Gate fans in Death Valley, and the distal Tuttle and Lone Pine fans in Owens Valley (Fig. 14.13c) (Blair 1999b, d, 2000, 2001, 2002). These beds are not horizontal, but instead are oriented at a 2–5° slope. Backset (upslope-dipping) cross beds dipping 5–28° formed by supercritical flow also are found within couplet sequences in some of the fans, and couplet sequences commonly are divided by cobble lags that rest upon erosional surfaces (Fig. 14.13d and e). Sheetflood couplets have been documented in other fan sequences (Van de Kamp 1973, Harvey 1984b, Gomez-Pujol 1999, Meyer et al. 2001), and in the rock record (Blair 1987b, Blair and Raynolds 1999).

The sheetflood process is known from the alluvial fan case studies, and is supported by hydraulic studies in flumes (Gilbert 1914, Fahnestock and Haushild 1962, Kennedy 1963, Jopling and Richardson 1966, Simons and Richardson 1966, Shaw and Kellerhals 1977, Blair 1987a, Langford and Bracken 1987, Blair 1999b, d, 2000, 2001). The deposition of multiple (5–20) couplets during a single sheetflood is related to the autocyclic nature of trains of water and sediment waves, called standing waves, that form in supercritical flow. Supercritical standing waves rhythmically develop and terminate numerous times in a single flood. More specifically, they: (a) initiate, (b) lengthen in extent and heighten in magnitude, (c) migrate upslope, (d) become unstable and oversteepen, and then (e) terminate either by gently rejoining the flood, or more commonly by violently breaking and shooting downslope. Backset-bed (antidune) units accumulate during the first three of these stages as bedforms that are in phase with the surface waves. These bedforms are preserved if the standing wave terminates by gently remingling with the flow. The couplets are produced from the more common violent termination, called breaking, of the standing wave train. Such termination results in a rapid and turbulent washout that erodes the antidune bedforms, and temporarily suspends fine pebbles and sand. The coarse component of the couplet beds is deposited in a ~3–6 m wide tract as the washout bore of the breaking wave shoots downslope. The laminated fine couplet member accumulates more widely thereafter by fallout of the quasi-suspended load. Irregularities in bedding are locally caused by flow-path obstacles, such as boulders, that incite flow separation and scour. Because standing waves develop in the relatively deepest part of the sheetflood, new wave trains initiate in a position lateral to recent depositional tracts. Repetitive generation and washout of standing waves during a single sheetflood causes autocyclic lateral and vertical amalgamation across the fan or active lobe of numerous couplets ± backset beds. Coarser gravel lags bounding sheetflood sequences form by surficial incision of channels during falling flood stage, or during later non-catastrophic discharge. These lags thus delineate the deposits of individual catastrophic sheetfloods (Fig. 14.13e), and account for nearly all of the time but little of the stratigraphy of the stacked sheetflood sequences (Blair 1999d).

The recurrence of a sheetflood at a given fan position is unknown but is probably long, as such floods are rare. Notable sheetflood events occurred on the same ~25° sector of the Furnace Creek fan of Death Valley in 1984 and 2004, probably exemplifying a more active case given the large catchment of this fan and the presence of a flood-control berm. Variable tectonic tilting of sheetflood sequences of the nearby Hell's Gate fan developed along the Northern Death Valley fault shows that sheetflood events there were 2–8 times more frequent than the seismic events that caused their tilting (Blair 2000).

A variant of alluvial-fan sheetflood deposition called transverse ribs also has been described. These deposits constitute beds with crests that are sinuous and laterally discontinuous, and with troughs lacking sediment, wherein older fan deposits are exposed (Fig. 14.13f) (Koster 1978, McDonald and Day 1978, Rust and Gostlin 1981, Wells and Dohrenwend 1985). These features likely represent deposition from supercritical flows that carried a lower volume of sediment, akin to a starved ripple. The transverse ribs described by Wells and Dohrenwend have wavelengths of 2–6 m, and indicate multiple, sediment-deficient sheetflood events with estimated flow velocities of 0.3–0.6 m/s.

So why are sheetfloods on alluvial fans supercritical? By solving the Froude and Manning equations for slope, the critical slope (S_c) at which water flows change from subcritical to supercritical (Froude number of ~1.0) for a given bed texture is approximated by the equation $S_c = n^2 g/D^{1/3}$, where $n =$ the Manning roughness coefficient, $g =$ the gravitational acceleration constant of 9.8 m/s^2, and D = average flow depth in metres (Blair and McPherson 1994b). A plot of S_c for the Manning coefficients corresponding to sandy pebble to slightly bouldery cobble textures typical of alluvial fan sediment (0.024–0.040) shows that supercritical flow conditions prevail given the common range of slopes (2–5°) found on sheetflood-dominated alluvial fans (Fig. 14.14). The S_c curves further show that in the range of slopes typical of sandy and gravelly braided rivers in sedimentary basins (0.1–0.4°), flows only are supercritical with relatively great depth ($\geq$ 2.2 m for n of 0.032 and higher), consistent with observations of floods in rivers. The S_c curves thus identify two fundamentally unique water flow environments, with a nearly vertical limb corresponding to alluvial fan slopes, and a nearly horizontal limb corresponding to the river slopes in basins (Fig. 14.14) (Blair and McPherson 1994b). These curves inflect in the range of slopes (0.5–1.5°) uncommon to either alluvial fans or rivers in sedimentary basins.

Are sheetfloods on alluvial fans supercritical because they respond to the slope conditions of the fan, or, as the prominent process, do they create the fan slope? The 2–5° slope values of the surface of alluvial fans built by sheetfloods, and the 2–5° orientation of the sheetflood couplet units within the deposits, indicate that they are directly related. Antidune and plane-bed deposition are known from flume studies to be promoted by high water and sediment discharge, the latter caused by the proportional increase of flow capacity with increasing water discharge (Gilbert 1914, Simons and Richardson 1966). Supercritical flow conditions are promoted during high water and sediment discharge events because it is the flow state in which the overall resistance to flow is minimal, and in which the transport of large volumes of sediment is most efficiently accomplished (Simons and Richardson 1966). Fan catchments are ideal for generating high water and sediment discharge events due to the rapid concentration of high-volume precipitation across steep colluvium-mantled slopes. Thus, to achieve efficiency, sediment-bearing sheetfloods are supercritical and deposit sediment at slopes of 2–5°, and this depositional slope is reflected as

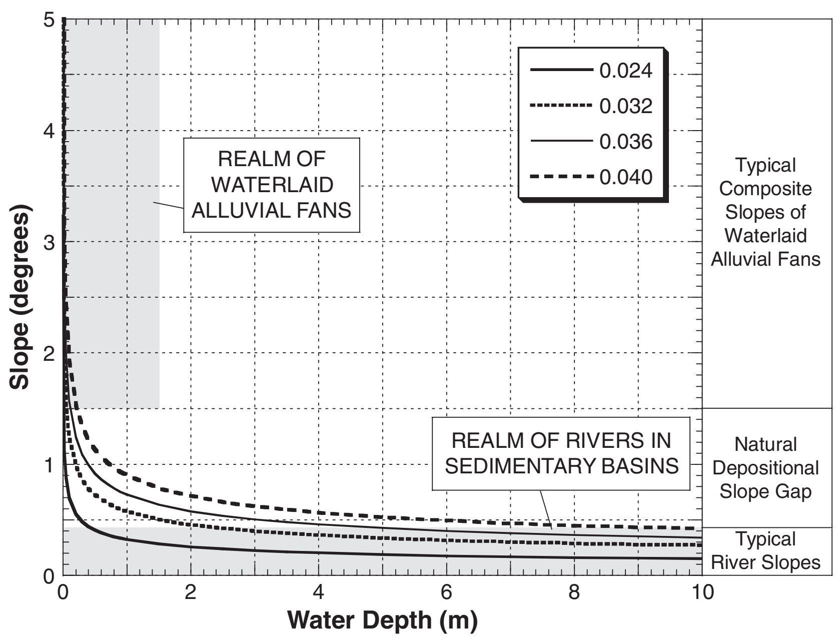

Fig. 14.14 Critical slope (S_c) curves versus water depth for Manning roughness values ranging from 0.024 to 0.040 (after Blair and McPherson 1994b). Curves are derived from the critical slope equation (see text). Turbulent supercritical hydraulic conditions exist for depth-slope scenarios above and right of the S_c curves, and subcritical conditions characterize the field below and left of curves. The typical depth-slope scenario for alluvial fans and gravelly rivers relate to opposite limbs of the S_c curves, with inflections occurring in the natural depositional slope gap. Also note that hydraulic conditions are supercritical for alluvial fans, and are commonly subcritical for rivers

the fan surface slope (Blair 1987a, 1999d). Like fans built of debris flows, sheetflood fans thus have a slope reflecting the mechanics of the main primary process. In contrast, deposition of transverse ribs may be controlled by the slope traversed by less common sediment-deficient sheetfloods.

Secondary Processes on Alluvial Fans

The long period between recurring primary depositional episodes on alluvial fans makes surficial sediment susceptible to modification by secondary processes, including surface or ground water, wind, bioturbation, neotectonics, particle weathering, and pedogenesis.

Surficial Reworking by Water

Discharge from rainfall or snowmelt in a fan catchment only infrequently produces a primary depositional event. On most occasions, water discharge to the fan is non-catastrophic and may carry limited sediment. Such discharge can slowly infiltrate through the permeable fan sediment, or it may pass through the incised channel and across the fan. These water discharge events, called sheetflows (Jutson 1919) or overland flows (Horton 1945), are commonly capable of winnowing fine sediment from the surface of previous primary deposits (Fig. 14.15a, b). Overland flows also can be triggered by precipitation directly on the fan, where winnowing further results from the impact of raindrops. The winnowed sediment typically is of sand, silt, or clay size, but can range to pebbles and cobbles (e.g. Beaumont and Oberlander 1971). This sediment is moved either farther downslope, or off the fan. A large part of mud sequences in playas, such as Badwater in Death Valley, is derived from winnowing of the adjoining fans.

Surficial reworking of primary deposits by overland flows is the most common secondary process on alluvial fans, producing rills, gullies, or coarse-grained mantles. Rills and gullies form by overland flow related to the falling stage of a wet primary process, less catastrophic catchment discharge, or rainfall directly on the fan. Rills are initiated by the convergence of overland flow as a result of slight topographic or textural irregularities. Such features, typically < 0.5 m deep and ~ 1 m wide, span downslope as distributaries from the fan apex or head of an active depositional lobe (Fig. 14.15c). Overland flow also erodes gullies that, in contrast to rills, initiate on the distal fan or at a fault scarp, and lengthen upslope through headward erosion. These features also contrast with rills by having either a single thread or contributary pattern, and by greater depth (Fig. 14.15d, e) (Denny 1965, 1967). Rills and gullies are floored by thin lags of coarse clasts left behind from winnowing, or by finer sediment that is in transit. These beds comprise minor lenses within troughs eroded into deposits from the primary processes. Another product of surficial winnowing by water is the concentration of gravel a few clasts thick called a gravel or boulder mantle (Figs. 14.15f and 14.16a). These surfaces can develop on a fan lacking recent primary events, where winnowing is extensive. They may cap an inactive lobe, or dominate the fan.

Calcite encrustation of the base or sides of channels or gullies on an alluvial fan may also result from the passage of water saturated with calcium and carbonate. Chemical precipitation from this discharge can produce a calcite crust termed case hardening. Lattman and Simonberg (1971) concluded from studies near Las Vegas, Nevada, that case hardening best develops on fans with catchments underlain by carbonate or basic igneous bedrock, the weathering of which supplies the necessary ions. This process can tightly cement freshly exposed deposits in as little as 1–2 years (Lattman 1973).

Wind Reworking and Deposition

Clay, silt, sand, and very fine pebbles on the fan surface are susceptible to wind erosion, as shown by dust plumes in the atmosphere over deserts on windy days (Fig. 14.15d). One effect of wind is to winnow the fine fraction (Tolman 1909, Denny 1965, 1967, Hunt and Mabey 1966, Al-Farraj and Harvey 2000). Protruding clasts may be carved into ventifacts by abrasion from the passage of wind-carried sand. Unlike other secondary processes, wind transport can also add sand or silt to the fan that is derived from non-catchment sources, such as from adjoining dunes, lakes, rivers, or deltas. This sediment can accumulate as: (a) aeolian

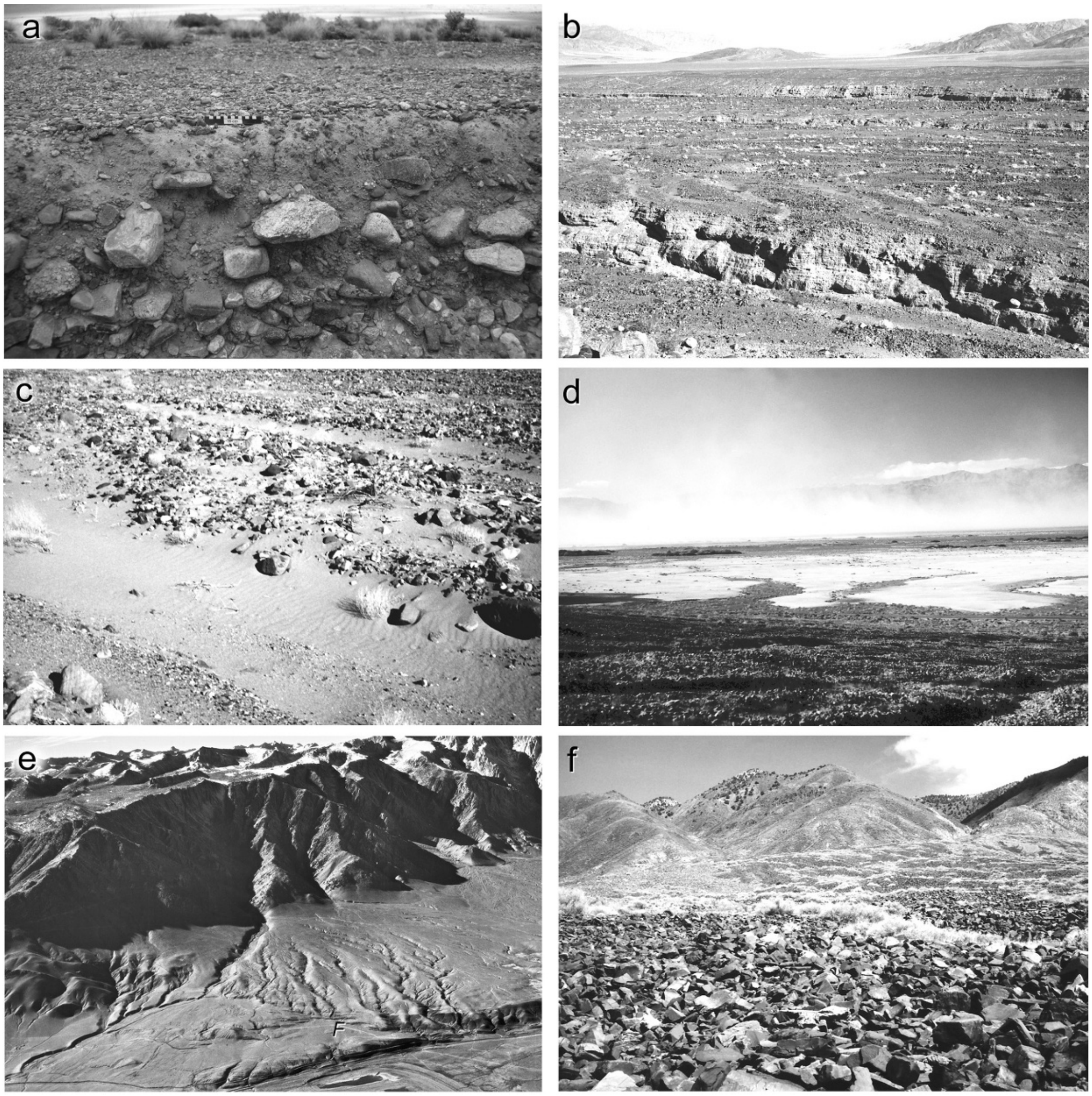

Fig. 14.15 Photographs of the products of secondary fan processes. (**a**) Side view of a gully on the Rose Creek fan delta, Hawthorne, Nevada, showing debris-flow deposits that have been winnowed at the surface by overland flow and wind to form a desert pavement. Scale bar is 15 cm long. (**b**) Surficial fine-fraction winnowing of sheetflood deposits (exposures), leaving a widespread lag of varnished cobbles; Anvil fan, Death Valley. (**c**) Aeolian sand (light-coloured) transported by wind has accumulated in rills and upon undissected gravel of the Furnace Creek fan surface, Death Valley. (**d**) Gullies are prominent on the distal part of the Hell's Gate fan, Death Valley. Note the dust plume in the valley centre generated by strong northerly winds achieving gusts of 80 km/h. (**e**) View of Carroll Creek fan, Owens Valley, containing a distal fault scarp *(F)*. Gullies are prominently eroding headward from the scarp into the older part of the fan. (**f**) Extensive winnowing of bouldery debris-flow deposits of the Shadow Rock fan, Deep Springs Valley, California, has produced a varnished, surficial boulder mantle

drift on the irregular fan surface (Fig. 14.15c), (b) nebka around plants, (c) sandsheet deposits initiated by irregular topography, or (d) sand dune complexes that either initiate or migrate onto a fan (e.g. Anderson and Anderson 1990, Blair et al. 1990, Blair and McPherson 1992). Sandsheets can form relatively thick and laterally continuous blankets that disrupt or even overwhelm fan sedimentation.

Bioturbation and Groundwater Activity

Plants and burrowing insects, arthropods, or rodents are present in surficial fan deposits of even the most arid deserts. Plant life can be sustained by rare precipitation, dew, or shallow groundwater. Plant roots may extend for a metre or more into the fan sediment, disrupting the original primary stratification and potentially homogenizing the deposits (Fig. 14.16b). Desert plants also provide a habitat for animals. Colonies of rodents amid desert plants on fans may alter primary deposits by disrupting stratification and dispersing sediment (Fig. 14.16c). Burrowers may also disturb desert pavement, exposing previously protected sediment to wind erosion.

Alluvial fans serve as important conduits of groundwater from the mountains to the valley floor, where aquifers can be recharged (e.g. Listengarten 1984, Houston 2002). Shallow groundwater flow may create conditions conducive to plant growth. The slow movement of groundwater rich in dissolved solids can also cause the precipitation of cements such as calcite in the fan sediment (e.g. Bogoch and Cook 1974, Jacka 1974, Alexander and Coppola 1989), whereas travertine precipitation may occur where groundwater issues to the surface at springs (Hunt and Mabey 1966). Distal fan sediment near playas or marine embayments may be cemented or disrupted by evaporite crystal growth in pores due to evaporative draw. Groundwater flow may also destabilize slopes, instigating slumping. Subsidence along faults, cracks, or fissures may also occur on a fan due to depression of the water table.

Neotectonics

Tectonic offset of alluvial fans is common where they are developed along seismically active mountain fronts. Faults can cause nearly vertical offset of fan sediment as scarps 0.5–10.0 m high. Fault scarps usually are present near and trend parallel to the mountain front, but they also can be oriented obliquely, and cut across the medial or distal fan (Figs. 14.15e and 14.16d) (Longwell 1930, Wallace 1978, 1984a, 1984b, Beehner 1990, Reheis and McKee 1991). Scarps create unstable, high-angle slopes that will degrade by freefall or slumping of sediment to produce fault-slope colluvial wedges (e.g. Wallace 1978, Nash 1986, Berry 1990, Nelson 1992). Faulting may disrupt groundwater flow through the fan sediment, possibly initiating springs (Alexander and Coppola 1989). Scarps also instigate the development of headward-eroding gullies (Fig. 14.15e). Fan deposits can also develop fissures during earthquake motion. Mountain-front or intra-fan faults with a strike-slip component, such as along the San Andreas or North Death Valley faults of California, alternately can cause tilting or folding of fan sediment (e.g. Butler et al. 1988, Rockwell 1988, Blair 2000), or significant lateral offset of the fan from its catchment in a process called beheading (e.g. Harden and Matti 1989). Rotational tilting of fan deposits also is a common feature caused by dip-slip along listric mountain front faults (e.g. Hooke 1972, Rockwell 1988).

Weathering and Soil Development

Many types of physical and chemical weathering modify fan sediment, including salt crystal growth in voids, exfoliation, oxidation, hydrolysis, and dissolution (Hunt and Mabey 1966, Ritter 1978, Goudie and Day 1980). These reactions take place both on the surface of clasts, and within them along fractures, foliation planes, or bedding planes. The net effect of surface weathering is the reduction of clast size, as exemplified by clasts near the evaporitic playa in Death Valley (Fig. 14.16e). Given time, even boulders can be reduced to fine sediment by weathering (Fig. 14.16a). Alteration of fan deposits by oxidation and hydrolysis also takes place immediately below the surface, where unstable grains such as feldspar or ferromagnesian minerals alter to clay minerals or haematite (Walker 1967, Walker and Honea 1969).

Another common clast modification involves the precipitation on exposed surfaces of thin hydrous ferric manganese oxide coatings called desert varnish (Figs. 14.15f and 14.16a) (Hunt et al. 1966). Variable darkness of the varnish and its microstratigraphy allow for the differentiation of relative ages of fan lobes, with the oldest lobes the darkest (e.g. Hooke 1967, Dorn and Oberlander 1981, Dorn 1988, Liu and Broecker 2007). Radiocarbon dating of varnish provides potential for obtaining absolute exposure ages of surfaces, although problems with this method remain, such as isolating enough carbon (Dorn et al. 1989, Bierman and Gille-

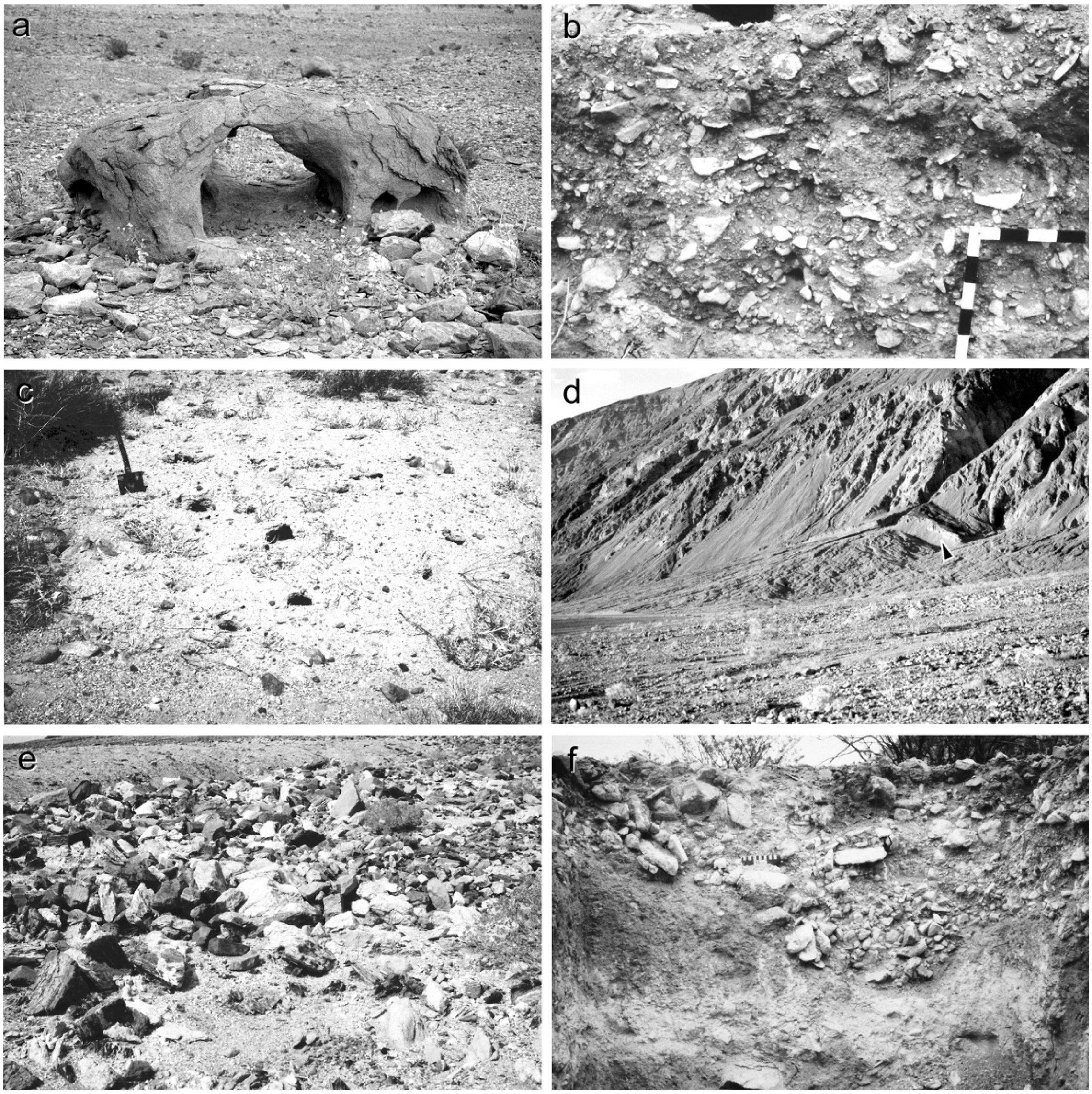

Fig. 14.16 Photographs of the products of secondary fan processes. (**a**) View of exhumed debris-flow units on the Hanaupah fan, Death Valley, where upon a varnished desert pavement has developed, and clasts have become extensively weathered, including the hollowing and disintegration of boulders 1 m long. (**b**) Gully cut of a proximal fan along the western Jarilla Mountains, south-central New Mexico. Gravelly fan and sandy aeolian deposits are intermixed by plant rooting, resulting in a loss of primary stratification. Darkened Bt (argillic) and white Btk (argillic and calcic) soil horizons are developed, and pedogenic carbonate (white) extensively coats gravel clasts. (**c**) Overview of a rodent colony comprising numerous burrows in near-surface fan sediment, Walker Lake, Nevada; shovel for scale. (**d**) Fan in Death Valley that has been offset near the apex by a fault scarp (*arrow*). Colluvium is accumulating at the base of the scarp. (**e**) View of metamorphic cobbles of the distal North Badwater fan, Death Valley, that are disintegrating due to salt crystal growth along foliation planes. (**f**) Vertical trench revealing well-developed carbonate soil horizons in a fan along the western Jarilla Mountains, New Mexico. Cobbles and pebbles of a filled gully are visible in the centre of the photograph

spie 1991, Bierman et al. 1991, Reneau et al. 1991). Optical luminescence and cosmogenic-isotope dating are other methods employed to determine the age of fan surfaces, though with questionable success due to inheritance issues related to sediment exposure prior to fan deposition (e.g. Nishiizumi et al. 1993, White et al. 1996, Matmon et al. 2005, Robinson et al. 2005, Le et al. 2007).

Fan sediment also serves as a parent material for developing soils, especially on the inactive lobes where the surface is stable. Soils develop by the translocation of clay or solutes from the surface to shallow depth by infiltrating water, usually from precipitation directly on the fan, that then dries in the vadose zone to produce horizons enriched in clay, carbonate, silica, or gypsum (Fig. 14.16b, f). Although organic-enriched (*Ao*) or aeolian-related vesicular (*Av*) horizons may form on fans, B soil horizon are the most prevalent. These horizons form where infiltrating surface water desiccates, at which depth translocated clay attaches to grains, and solutes precipitate. B horizons enriched in clay (argillic, *Bt*), calcium carbonate (calcic, *Bk*), or mixed clay and carbonate (*Btk*) are the most common types present in fans of southwestern USA and Spain (Gile and Hawley 1966, Walker et al. 1978, Gile et al. 1981, Christenson and Purcell 1985, Machette 1985, Harvey 1987, Wells et al. 1987, Mayer et al. 1988, Reheis et al. 1989, Berry 1990, Blair et al. 1990, Harden et al. 1991, Slate 1991, Ritter et al. 2000). Gypsiferous and siliceous horizons are less commonly documented in fan sediment (Reheis 1986, Al-Sarawi 1988, Harden et al. 1991). Soil-profile development in fan sediment is a function of the time that a fan surface has been stable, the local or aeolian flux of the materials from which the horizon is composed, and the typical amount and wetting depth of precipitation (Machette 1985, Reheis 1986, Mayer et al. 1988). The presence of plant roots in sediment promotes soil development by providing pathways for infiltrating water. The extent of soil-horizon development in a given area is useful for determining the relative age and correlation of fan deposits (e.g. Wells et al. 1987, Slate 1991).

Extensively developed soil horizons can produce lithified zones, including calcrete (also called caliche or petrocalcic horizon), silcrete, and gypcrete. Subsequent exhumation of tightly cemented soil horizons armours the fan from further secondary erosion, and expedites the downslope movement of overland flow (Lattman 1973, Gile et al. 1981, Van Arsdale 1982, Wells et al. 1987, Harvey 1990).

Significance of Distinguishing Primary and Secondary Processes

Primary versus secondary processes on alluvial fans have long been understood (e.g. Beaty 1963, Denny 1967), but much confusion remains because of the failure of many to appreciate their differences. The greatest problem has resulted from assuming that secondary processes, which usually dominate the fan surface because of their frequency, are the principal processes constructing the fan, rather than realizing that they mostly surficially remould and mask primary deposits. Outgrowths of this erroneous view include the ideas of sieve lobes and braided streams on fans, and equating fan activity to climatic influences.

Sieve Lobes on Alluvial Fans

The concept of sieve-lobe deposition on alluvial fans originated from laboratory studies of small-scale (radii $\leq$ 1-m-long) features constructed of granules and sand that morphologically resembled fans (Hooke 1967). In these experiments, a lobate deposit was identified as forming by the rapid infiltration of sediment-laden water into the permeable sand substrate. This feature, termed a sieve lobe, formed in the sand box where water was unable to achieve further transport due to infiltration. Although acknowledging that these studies may lack significance to real fans, it was concluded that sieve lobes like those of the laboratory comprise extensive deposits on seven natural fans in California (Hooke 1967). These fans were reported to be constructed of material derived from catchments underlain by bedrock that did not weather to produce permeability-reducing fine sediment. Based on this work, the sieve lobe mechanism has become established as one of the major processes operative on alluvial fans (e.g. Bull 1972, 1977, Spearing 1974, Dohrenwend 1987). An evaluation of the exposed stratigraphy of the type fans identified as possessing sieve lobes, however, revealed that

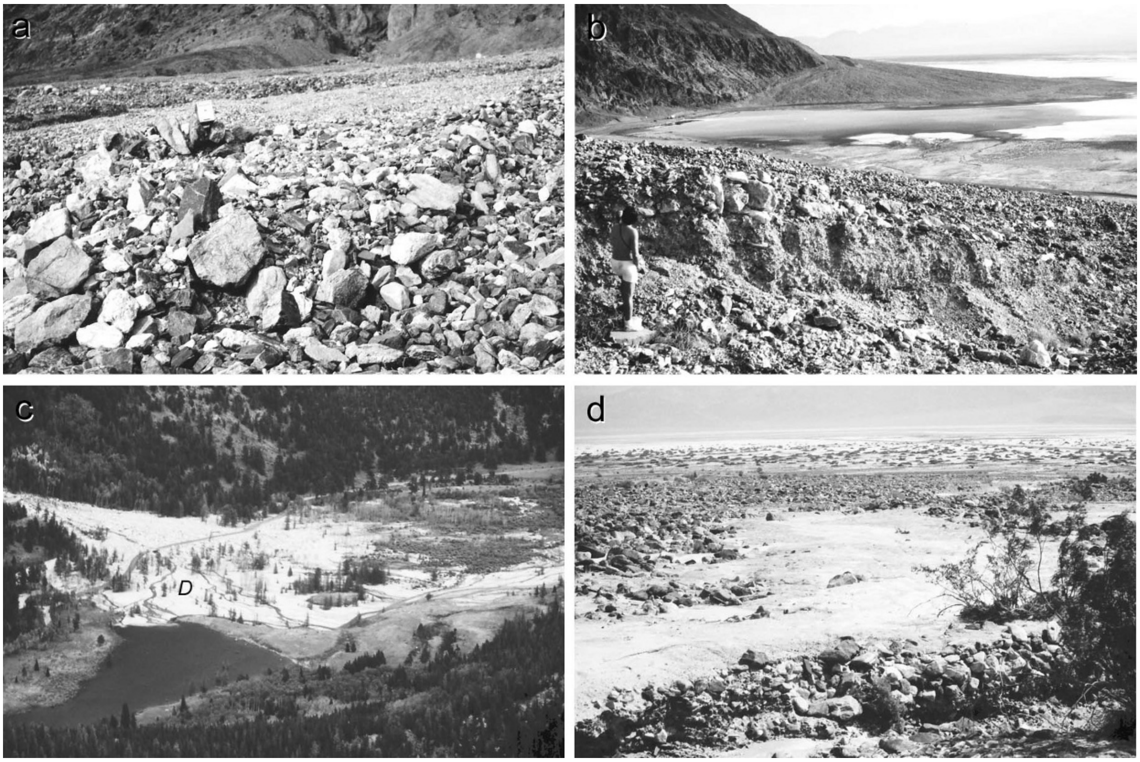

Fig. 14.17 Photographs of misidentified fan processes. (**a**) Oblique view of one of the type 'sieve lobes' (photograph centre), North Badwater fan, Death Valley. (**b**) View of 1.5-m-high channel wall cut in the vicinity of the previous photograph revealing matrix-rich debris-flow deposits below a zone containing the proposed sieve lobe. The fine sediment has been removed from the surficial part of the debris-flow deposits by overland flow, leaving an arcuate mass of winnowed gravel incorrectly called a sieve lobe. (**c**) Overview of the Roaring River fan, Colorado. Secondary post-flood braided distributary channels (*D*) were carved into the fan surface underlain solely by sheetflood deposits. (**d**) View of light-coloured, clast-poor debris flows on the Trail Canyon fan, Death Valley. These flows give a misleading braided distributary appearance to the fan when viewed from a distance

they are constructed by debris flows (Fig. 14.17a, b). The catchment bedrock in these cases has weathered to produce abundant mud, at odds with the sieve lobe concept. Instead of developing through sieving, these features represent the surficial part of clast-rich debris-flows lobes from which the matrix has been removed by secondary overland flows (Blair and McPherson 1992). Matrix is abundant at depth in the deposits in all of these cases.

Braided Distributary Channels on Alluvial Fans

Perhaps the greatest misconception concerning alluvial fans is the widely held belief that they are constructed from braided distributary channels by the same processes that are operative in braided streams. This view results from the apparent presence of channels with a braid-like pattern on many fan surfaces. The idea was popularized by Bull (1972) who wrote (p. 66):

> Most of the water-laid sediments [of alluvial fans] consist of sheets of sand, silt, and gravel deposited by a network of braided distributary channels. . . . The shallow distributary channels rapidly fill with sediment and then shift a short distance to another location. The resulting deposit commonly is a sheetlike deposit of sand, or gravel, that is traversed by shallow channels that repeatedly divide and rejoin. . . . In general, they [the deposits] may be cross-bedded, laminated, or massive. The characteristics of sediments deposited by braided streams are described in detail by Doeglas (1962).

Our examination of the stratigraphic sequence of numerous fans displaying shallow braid-like channels reveals that, in every case, these features are surficial and formed either by slight rilling during waning flood stage, or through later secondary surficial winnowing and remoulding of primary deposits, including of debris flows and sheetfloods (e.g. Fig. 14.17c). Additionally, the stratotypes of Doeglas (1962) for braided streams that were concluded by Bull (1972) to form on fans, such as lower-flow-regime planar and trough crossbedding, are not found in exposures of waterlaid fans. The calculation of critical slopes shows that such structures cannot form on fans (Fig. 14.14). Other issues are illustrated by two fans reported to be built by braided distributary channels, including the Trail and Hanaupah Canyon fans of Death Valley (Fig. 14.1a and 14.2a) (e.g. Nummedal and Boothroyd 1976, Richards 1982). Such channels on the Hanaupah fan actually have a contributary, rather than distributary pattern (see Richards 1982, p. 249) that formed by headward erosion of gullies into debris-flow deposits of the inactive part of the fan. The light-coloured 'channels' on the Trail Canyon fan also are shallow secondary features cut into debris flows, and the most vivid of these features comprise clast-poor debris-flow lobes (Fig. 14.17d).

The failure to understand the origin of the apparent 'braided distributary channels' has caused the inability of many to recognize the major constructive processes, such as sheetfloods and debris flows. The surficial reworking of primary deposits, combined with their long recurrence intervals, is probably why it was not until Blackwelder (1928) that the importance of debris flows in fan construction was recognized. Similarly, the masking of sheetfloods by surficial remoulding was concluded by Blair (1987a) to be the reason that it was previously not appreciated as principal fan-building process.

Implications for Climate Change-Process Model for Alluvial Fans

The downcutting of incised channels on alluvial fans (i.e. fanhead trenching) and the dissection of the fan surface by rilling and gullying have been attributed by many authors to be a consequence of climatic change. Fan sequences undergoing dissection are believed to have accumulated during more moist periods in the past, and thus represent fossil fans (e.g. Blissenbach 1954, Lustig 1965, Melton 1965, Williams 1973, Nilsen 1985, Harvey 1984a, b, 1987, 1988, Dohrenwend 1987, Dorn et al. 1987, Dorn 1988). Although the validity of this climate-response hypothesis has been questioned (e.g. Rachocki 1981), and the difficulty of establishing time stratigraphy and climate-sensitivity parameters remains, this hypothesis has been widely reiterated. It is based on the idea that moister past conditions caused greater sediment production in the catchment, and that aggradation concurrently took place as a result of the expedient transfer of this sediment to the fan. As a corollary, this model claims that sediment production in the catchment is retarded during periods of greater aridity, causing water flows to depart the catchment without sediment, thereby eroding the fan. At odds with this view is the fact that the fans used to support it, such as those of the Panamint piedmont in Death Valley, have been the sites of historical aggradation (e.g. Fig. 14.17d), and that the catchment of these and many other desert fans remain well-stocked with colluvium. Primary aggradational events are documented on fans around the globe, casting further doubt on the climate-caused fossil-fan theory. Additionally, the moister late Pleistocene conditions of fans in settings such as Death Valley were still more arid than the present setting of many other areas with alluvial fans. Finally, as shown by case studies, rills and gullies are intrinsic secondary processes active, irrespective of climate, during periods between infrequent primary events.

Controls on Fan Processes

At least five factors influence fan processes, including catchment bedrock lithology, catchment shape, neighbouring environments, climate, and tectonism. Although complicated due to interactions, the impact of each of these variables can be examined.

Catchment Bedrock Lithology

The type of bedrock underlying the catchment is the main control on the primary processes of alluvial fans (Blair and McPherson 1994a, b, 1998, Blair 1999b, d, f). Rocks of differing lithology yield contrasting sediment suites and volumes due to their variable response to weathering. Bedrock in desert settings optimal for fan development, especially tectonically maintained mountain fronts, yields sediment in varying size and volume depending on: (a) the style of fracturing in proximity to faults, (b) the presence or absence of internal discontinuities such as bedding planes or foliation planes, and (c) the reaction to chemical weathering and non-tectonic types of physical weathering. These effects can be exemplified by a survey of sediment found in fan catchments underlain by various bedrock in the southwestern USA.

Granitic to dioritic plutons and gneissic bedrock split into particles ranging from sand to very coarse boulders due to jointing, fracturing, exfoliation, and granular disintegration. The coarse sediment size of fans derived from plutons results from a commonly uniform joint pattern developed due to a homogeneous, coarsely crystalline fabric. Gneissic rocks typically yield more bladed, platy, or oblate boulders due to anisotropy from the metamorphic foliation. Boulders from both of these lithotypes are either angular, reflecting the joint pattern, or are more rounded depending upon the degree of weathering along the clast edges. Very fine pebbles and sand (grus) also are commonly produced from granitic or gneissic rocks related to physical disaggregation of crystals typically of this size. Clay-sized sediment is only a minor product in arid settings because it forms either through tight tectonic shearing (Blair 1999c, 2003), or more importantly by hydrolysis of feldspar and accessory minerals. Such reactions are slow especially in hyper-arid deserts, and thus mud yield requires long residence time in the colluvium.

Bedrock consisting of tightly cemented dense sedimentary rocks, such as quartzite, undergoes significant brittle fracture in proximity to mountain-front faults, producing angular pebbles, cobbles, and boulders. Little sand, silt, or clay is generated in this situation due to effective cementation of the matrix grains. Dense carbonate rocks also respond to tectonism in a brittle fashion, producing bladed, platy, or oblate clasts. If present, interstratified soft sedimentary rocks such as shale add a clay fraction to the colluvium, and cause the intervening brittle rocks to fracture and weather to produce tabular clasts.

Finer-grained catchment bedrock, such as pelitic metamorphic rocks, shale, mudstone, or volcanic tuff, commonly weather to yield sediment varying in size from boulders to clay, with an abundance of the finer sizes but a deficiency of sand. This size suite results from the formation of gravel due to fracturing, and of silt and clay, but not sand, from disaggregation. Thus, thickly mantled colluvial slopes comprising cobbles, pebbles, and clay are commonly developed on bedrock of this type.

The various weathering styles of bedrock, and the colluvial textures they produce, promote different modes of erosion and sediment transport. Fractured brittle bedrock slopes yield rockfalls, rock slides, and rock avalanches, whereas water-sensitive fine-grained bedrock such as shale may yield earth flows. Bedrock that weathers to produce abundant gravel and sand but little mud sheds colluvium with low cohesion. Failure of these slopes in response to water input incites incised-channel and sheetfloods, and more rarely, NCSGFs, on the coupled alluvial fan. Finer-grained rocks, such as shale, pelitic metamorphic rocks, and volcanic rocks, more commonly yield mud as well as gravel, forming cohesive colluvium. The failure of such colluvium with the addition of water typically produces debris flows.

The contrasting processes resulting from the cohesive versus noncohesive catchment colluvium are illustrated by two examples. The adjoining Anvil and Warm Springs Canyon fans and their catchments in Death Valley are forming under identical tectonic, climatic, and topographic conditions, but the Anvil fan is built mainly by sheetfloods, and the Warm Spring fan by debris flows (Blair 1999b, d, f). This difference is the result of contrasting bedrock types underlying their catchments, which leads to cohesive colluvium in the Warm Spring fan catchment and noncohesive colluvium in the Anvil catchment. Differing bedrock lithotypes can also affect the rate of colluvium erosion, as exemplified by the Nahal Yael catchment in Israel. Bull and Schick (1979) concluded that the grusy colluvium from granitic rocks has been mostly stripped, whereas areas underlain by amphibolite have been only partly stripped due to greater cohesion.

Catchment Shape and Pre-Existing Geology

The overall shape and evolution of a catchment can impact the operative sedimentary processes on an alluvial fan. Catchment shape affects side slopes, feeder-channel profile, relief, propensity for flash flood promotion, and sediment-storage capacity. Slope angles, along with bedrock type, may determine whether rockfalls, rock avalanches, colluvial slips, debris flows, or flash floods are promoted. The presence or absence of storage capacity in the catchment also affect sediment delivery to the fan site. Relief and area may determine the volume of sediment that can be generated and transported in a single flow, whereas the elevation of the catchment affects the chances of receiving significant precipitation from either rainfall or snowfall. The orientation of the catchment with respect to sunlight, or the track of major storms, can also influence weathering, erosion, and transport activity, and thereby fan aggradation.

The ability of catchments to rapidly transmit or store sediment varies with their area, which can range from < 1 to $> 100\,\mathrm{km}^2$. The smallest catchments may consist only of a single valley carved along a fracture in bedrock, with dislodged clasts rapidly transferred to the fan. Feeder-channel incision and widening can proceed with time, allowing storage of colluvium or of primary deposits such as debris flows. Progressively greater storage occurs with catchment enlargement because sediment can be maintained either as side-sloping colluvium or as deposits on the floor of the drainage net. The volume of sediment stored in a feeder channel depends on the long profile and width. The long profiles of feeder channels can range from consistently steep to step-like (Fig. 14.18). The reaches with reduced slope in stepped feeder-channel profiles may induce deposition from passing flows, the volume of which increases as a function of channel width. Two examples of feeder channels that have stepped profiles containing zones of sediment storage are the Coffin and Copper Canyon fans of Death Valley. Feeder channel erosion is dominant in the reaches of these feeder channels with slopes of $> 7°$, whereas sediment deposition has occurred in reaches sloping $\leq 7°$ (Fig. 14.18). Storage of sediment may lessen aggradational rates on the fan, but alternatively may allow for the generation of high-volume primary flows capable of constructing large alluvial fans (e.g. Blair 2003).

The ability of the feeder channel to store sediment appears to increase with catchment size, probably reflecting structural complexities in the underlying bedrock. This relationship is illustrated by the 20 adjoining fans in the vicinity of Copper Canyon in Death Valley. The catchments of these fans vary in area from < 0.5 to $60\,\mathrm{km}^2$ (Fig. 14.19). The largest fans, numbers 2, 5, 8, 12, and 14, have relatively large catchments with fourth- to sixth-order feeder channels, whereas the smaller catchments have second- or third-order feeders. Most stored sediment in this sector of the Black Mountains occurs in the two largest catchments (Coffin and Copper), and is concentrated along their highest-order channels.

The initial shape of a fan catchment and its subsequent evolution are largely a product of: (a) inherited (pre-existing) local and regional structures and discontinuities such as faults, joints, and geological contacts, (b) newly imposed (neotectonic) structural discontinuities, and (c) bedrock lithology. In general, fractures or other discontinuities, whether inherited or neotectonic, become the locus of catchment development because these zones erode more quickly relative to adjoining

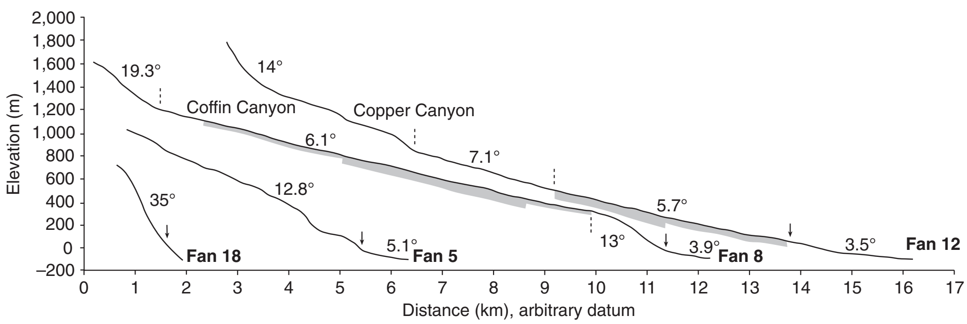

Fig. 14.18 Long profiles of the feeder channels for four fans in the vicinity of Copper Canyon, Death Valley (see Fig. 14.19 for plan-view locations). Average slopes of the feeder channel segments are labelled. The shaded pattern denotes segments with stored sediment, with pattern thickness depicting greatest sediment storage. Vertical exaggeration is 2.5X; vertical datum is mean sea level

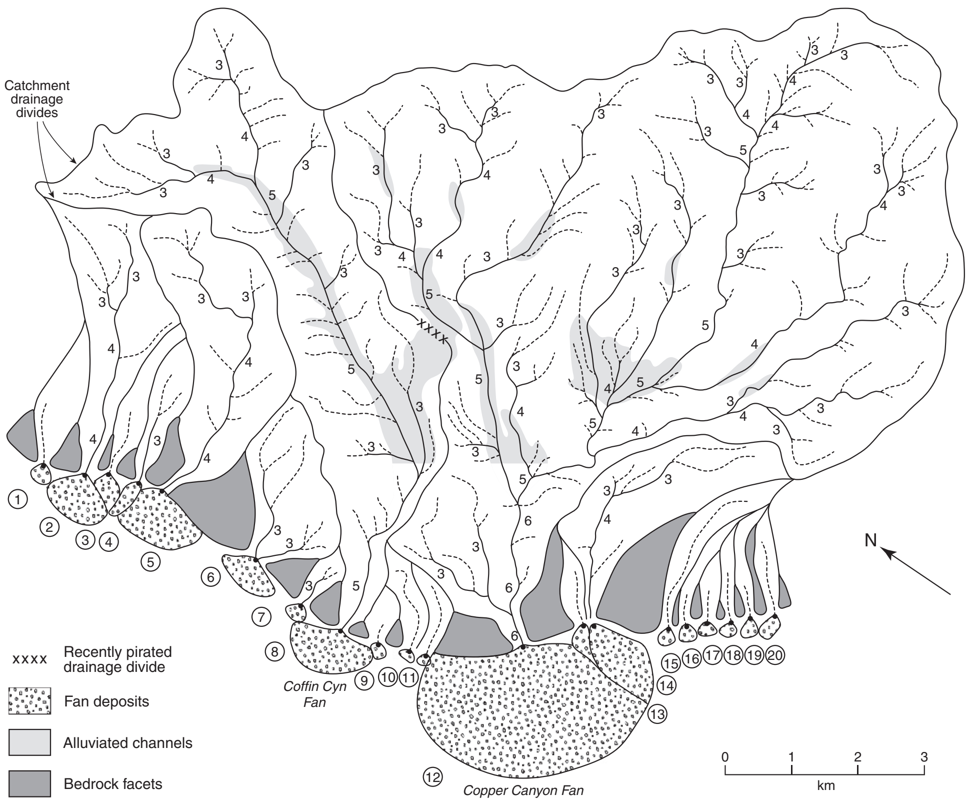

Fig. 14.19 Twenty fans (circled numbers) and their catchment drainage nets in the vicinity of Copper Canyon, Death Valley, based on 1:24,000 scale topographic maps with 12.2 m (40 ft) contours. First-order channels in the catchments are not shown due to map scale; second-order channels are dashed; and higher-order channels are solid lines labelled by order. Alluviated channels are after Drewes (1963)

ones, and thus focus overland flow. This factor is exemplified by comparing the catchment drainage net of the 20 fans in the Copper Canyon vicinity of Death Valley (Fig. 14.19) with their underlying geology (Fig. 14.20). These maps show that the position and orientation of feeder channels of the largest fans coincide with faults trending at a high angle to the mountain front. This relationship is due to enhanced weathering and erosion along the pre-existing structures. Another example of how inherited geology affects catchment and fan development is provided by the Copper Canyon fan. This catchment is centred on a down-dropped block, the surface of which is composed of relatively soft Miocene-Pliocene sedimentary rocks (fan 12, Figs. 14.19 and 14.20). The resultant high sediment yield has produced the largest fan in this sector of the Black Mountains piedmont. By contrast, nearby small fans have catchments developed upon relatively unfractured anticlinal flanks of Precambrian metasedimentary rock.

Effects of Adjoining Environments

Aeolian, fluvial, volcanic, lacustrine, or marine environments that border alluvial fans can impact fan processes by modifying the conditions of deposition. Aeolian sandsheet or dunes on fans (Fig. 14.21a) limit the runout distance of water or debris flows, causing aggradation in more proximal settings. The presence of dunes also can cause unconfined water flows to channelize by creating topographic barriers. For example, along the western Jarilla Mountain piedmont of south-central New Mexico, aeolian sandsheet deposition has been so high relative to fan activity that fan sedimentation has been reduced to flows in isolated arroyos cut into the aeolian deposits (Fig. 14.16f) (Blair et al. 1990).

Fluvial environments, usually in the form of longitudinally oriented rivers, may affect fans by eroding

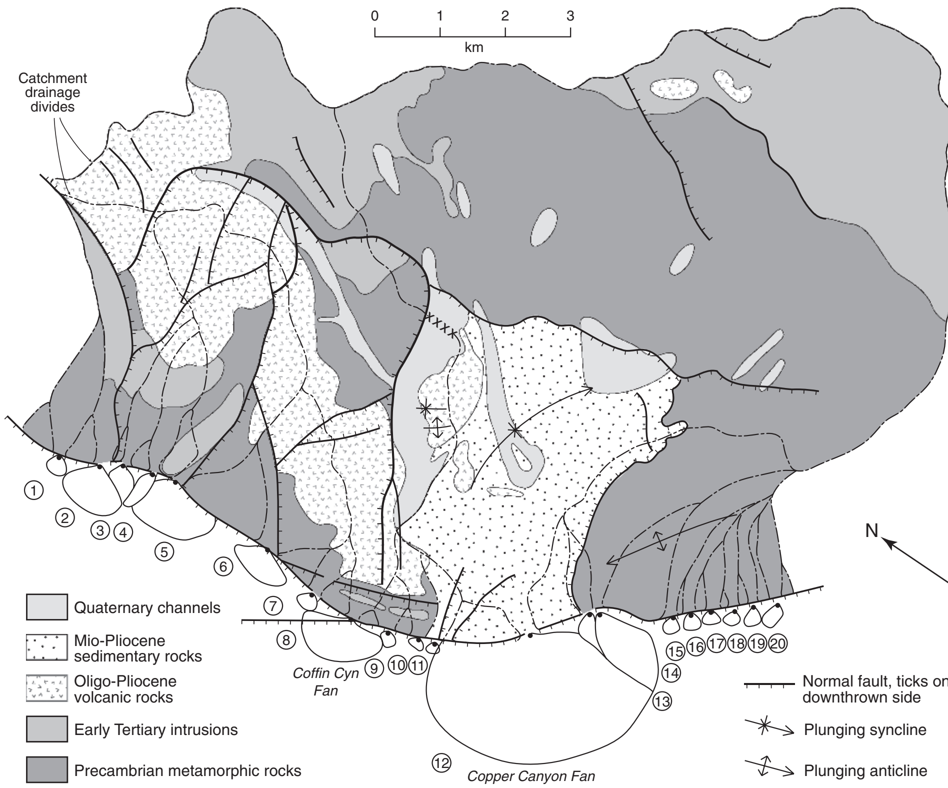

Fig. 14.20 Bedrock and structural geology underlying the catchments of 20 alluvial fans in the vicinity of Copper Canyon, Death Valley, that are depicted in Fig. 14.19 (geology after Drewes 1963)

their distal margins. An example is where Death Valley Wash has eroded the toes of converging fans in northern Death Valley (Fig. 14.21b). Headward-eroding gullies extend up-fan from these toe cuts. Another example is from near Schurz, Nevada, where the Walker River is eroding the distal Deadman Canyon fan, and distributing this sediment into its floodplain or delta (Fig. 14.21c) (Blair and McPherson 1994c). Progressive downcutting of an axial channel can also cause the fan to build at progressively lower steps to produce a telescoped pattern (Drew 1873, Bowman 1978, Colombo 2005).

The presence of lacustrine or marine water bodies marginal to fans can affect fan development in several ways. Subaerial processes may transform into other flow types, such as subaqueous debris flows or underflows, upon reaching a shoreline (Sneh 1979, McPherson et al. 1987). A fan may be significantly eroded by wave or longshore currents where it adjoins a water body, and become the site of beach, longshore drift, or shoreface accumulations (e.g. Link et al. 1985, Beckvar and Kidwell 1988, Newton and Grossman 1988, Blair and McPherson 1994b, 2008, Blair 1999e, Ibbeken and Warnke 2000). Pronounced changes in the depth of lakes, such as for Walker Lake, Nevada, can cause significant fan erosion over a large elevation range, and, upon lake-level fall, leave oversteepened slopes (Fig. 14.21d). Falling lake level also can induce the development of headward-eroding gullies, or a telescoped progradational pattern (e.g. Harvey et al. 1999, Harvey 2005). Flat-lying evaporitic peritidal or playa settings may develop in the distal fan area (Hayward 1985, Purser 1987), promoting particle weathering, and inciting primary fan flows to undergo deposition due to a pronounced slope reduction (Fig. 14.21e).

Volcanism can strongly affect fan processes by emplacing ash either in the catchments or directly on the fan, causing an interference of flows at the fan site, and potentially instigating debris flows on steep catchment slopes. Volcanic flows emanating from mountain-front faults may also cause barriers to sediment transport on

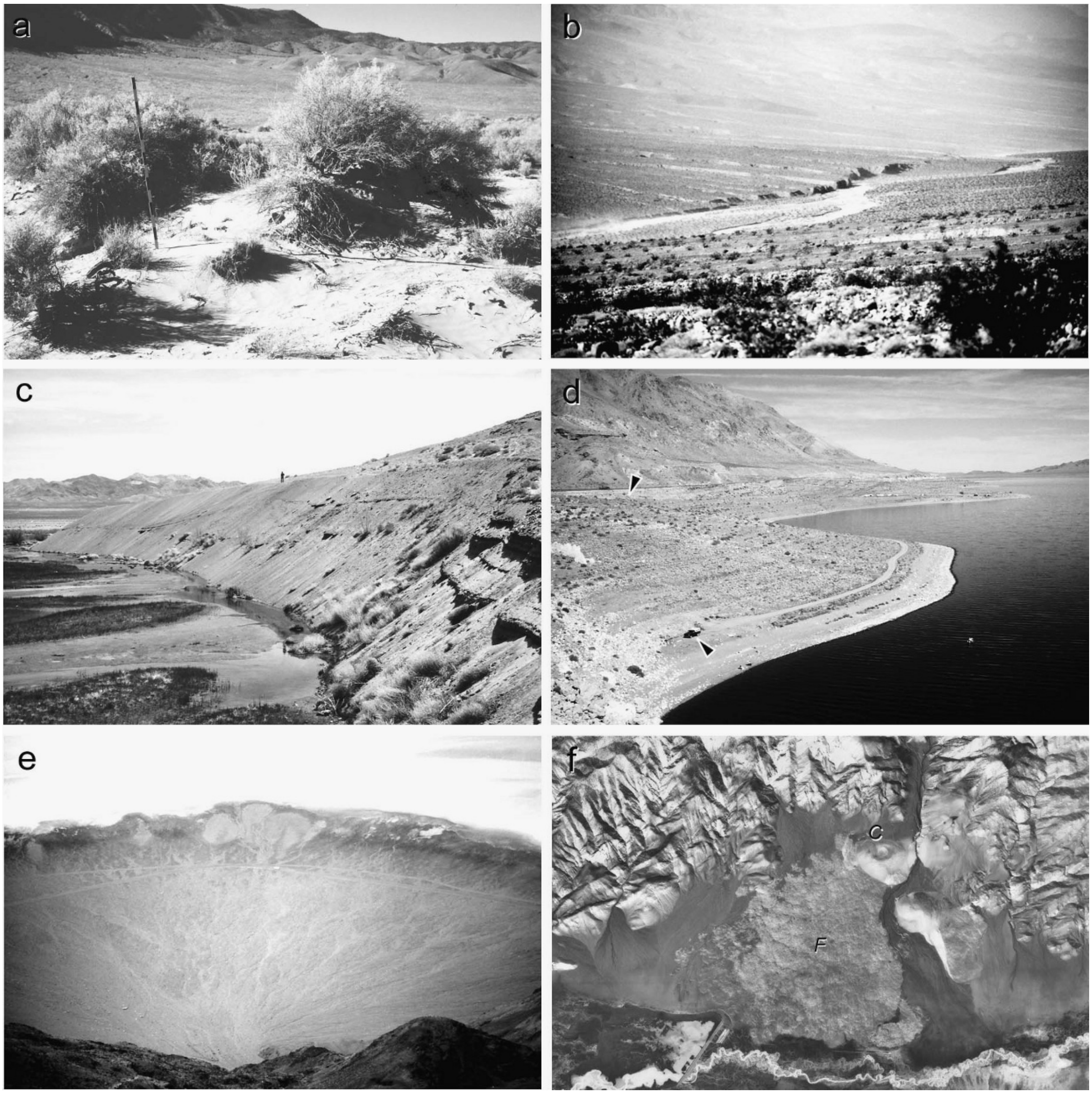

Fig. 14.21 Effects of neighbouring environments on alluvial fans. (**a**) Aeolian sandsheet deposits flanking the distal Shadow Rock and Trollheim fans, Deep Springs Valley, California. (**b**) View of eroded toes (*dark vertical walls*, photograph centre) of converging fans in northern Death Valley. Erosion has been caused by the concentration of discharge in the longitudinal Death Valley Wash. (**c**) Erosion into distal Deadman Canyon fan (*vertical wall*) by Walker River near Schurz, Nevada. (**d**) Extensive erosion by waves and longshore currents of fans adjoining Walker Lake, Nevada; vehicle (*lower arrow*) for scale. The now-exposed lower fan segment (downslope of *upper arrow*) has a greater slope than the upper segment due to erosion. (**e**) Aerial view of the Coffin Canyon fan prograding into Badwater playa in Death Valley; road for scale. Debris flow tongues reaching this playa undergo deposition due to the rapid lowering of slope. (**f**) Aerial view of fan of the Sierra Nevada piedmont in central Owens Valley widely capped by rugged basalt flows (*F*), and possessing a cinder cone (*C*) near the apex. The fan toe is bordered by Owens River

the fan surface, in extreme cases armouring the entire fan with almost unerodible basalt, such as on fans in the vicinity of the Poverty Hills in Owens Valley, California (Fig. 14.21f).

Climatic Effects

Climate is widely believed to have a major control on alluvial fans because water availability impacts factors such as weathering, sediment generation, and vegetation. However, although many conclusions have been speculated, the effect of climate on fans remains unestablished. Two directions have emerged, one evaluating climatic variables and the second associating specific fan processes to climate.

Effects of Climate Variables on Fans

Three interrelated climatic variables discussed with regard to alluvial fans are precipitation, temperature, and vegetation. These variables may be relevant to fans inasmuch as they affect bedrock weathering rates, sediment yield, and the recurrence interval of primary events. The most basic aspect of precipitation is the mean annual amount because, without rainfall, weathering and vegetation would be limited, and sediment transport would be restricted to dry mechanisms such as rockfall, rock slides, and rock avalanches. However, weathering and fan aggradation can occur even with minimal precipitation.

Two other perhaps more significant aspects of precipitation are the intensity of individual events and their frequency (e.g. Leopold 1951, Caine 1980, David-Novak et al. 2004). Both of these variables affect infiltration capacity in the catchments, which must be exceeded before overland flow and potential sediment transport can occur. Infiltration capacity is exceeded, and discharge events are generated, either by intense rainfall, or by less intense rainfall following antecedent precipitation (Ritter 1978, Cannon and Ellen 1985, Wieczorek 1987). Discharge arises in the latter case if the infiltration capacity is unable to return to its original value through percolation or evaporation. Rainfall intensity and frequency strongly affect fans by inciting primary processes. High-intensity thunderstorms probably are the most important mechanism for instigating such events in deserts, followed by extended periods of rainfall.

Another aspect of rainfall intensity and frequency that may impact alluvial fans is short-term global variations in ocean circulation patterns, such as the El Niño Southern Oscillation that causes greater precipitation along the Pacific coast of the Americas. Slope failures are documented to have been more frequent in California during the 1982–1984 and 1997–1998 El Niño episodes (Ellen and Wieczorek 1988, Coe et al. 1998, Jayko et al. 1999, Gabet and Dunne 2002). Fan aggradation was also more frequent during historical El Niño periods in Peru, and such activity there during the last 38000 years has been proposed to be mostly related to such periods (Keefer et al. 2003). A similar speculation has been made for late Quaternary deposits in the southwestern USA (Harvey et al. 1999).

The effect temperature has on fans is more poorly understood. It likely is significant, however, given that chemical weathering rates increase exponentially with temperature. Temperature gradients caused by the orographic conditions in a catchment may result in an initial decrease in weathering rates upslope due to decreasing temperature, followed by an increase in weathering at higher altitudes where freeze-thaw or heating-cooling fatigue processes become important. This trend may be complicated by the tendency for weathering rates to increase as precipitation increases with altitude.

Vegetation has long been rated an important factor concerning sediment yield from a catchment. Inasmuch as vegetation reflects climate, it is a climate variable. One factor commonly attributed to catchment plant cover is an increase in clay production due to the enhanced chemical weathering caused by organic acids near roots, and due to the greater preservation of soil moisture (e.g. Lustig 1965). Plant roots also affect sediment slope stability by strengthening its resistance to gravity as a result of increased shear strength (Greenway 1987). Differing plant types will have a variable effect on slopes due to the multitude of styles and depth of root penetration, and to the density of the ground cover (Terwilliger and Waldron 1991). Contrarily, plants may serve to produce long-term instability by causing the slopes to become steeper than they would be if the plant cover did not exist. This effect is illustrated by the common failure of slopes after vegetation is disturbed, such as after forest or brush fires (e.g. Wells 1987, Meyer and Wells 1996, Cannon and Reneau 2000, Cannon 2001).

The Question of 'Wet' and 'Dry' Alluvial Fans

A second approach with respect to climate and fans has been the attempt to relate the prevalence of certain fan processes to broad desert (dry) or non-desert (wet) categories. The main claim of this hypothesis is that debris flows prevail on fans in arid and semi-arid climates, and water flows prevail in wetter climates (e.g. Schumm 1977, McGowen 1979, Miall 1981). This hypothesis continues to be widely held even though, for nearly a century, data from fans have disproved it. For example, a catalogue of the global occurrence of historical debris flows on fans shows that they have been long known to develop under all climatic conditions (Costa 1984, Blair and McPherson 1994b). Additionally, fans dominated by sheetflooding have been shown to be present under some of the driest (Death Valley) and wettest (South Island, New Zealand) climates on earth (Blair and McPherson 1994b, Blair 1999d).

This climate hypothesis has been taken further to purport that river plains or deltas, such as the Copper River delta of Alaska, the Kosi River of India, the swampy Okavango River delta of Botswana, and even the Mississippi River delta, represent the 'humid-climate type' of alluvial fans (Boothroyd 1972, Boothroyd and Nummedal 1978, McGowen 1979, Nilsen 1982, Fraser and Suttner 1986, McCarthy et al. 2002). This hypothesis: (a) fails to acknowledge that fans as described in this chapter exist in humid as well as desert climates, (b) arbitrarily designates some river systems as fans and others as rivers, and (c) fails to recognize the scientific uniqueness of fans versus rivers in terms of hydraulic conditions, processes, forms, and facies (see Blair and McPherson 1994b for discussion).

Tectonic Effects

The most common and favourable conditions for the development and long-term preservation (including into the rock record) of alluvial fans exist in tectonically active zones that juxtapose mountains and lowland valleys. Sediment yield exponentially increases with relief (e.g. Ahnert 1970), and tectonism can both create and maintain relief. Without continued tectonism, fans may be minor or short-lived features characterized by secondary reworking. A possible example of fans of this style are those in southeast Spain developed adjacent to compressional structures formed prior to middle Miocene time (Harvey 1984a, 1988). This setting contrasts with that of an extensional basin, where relief and mountain-to-valley topographic configuration can be maintained for tens of millions of years, and where individual fans may be sites of net aggradation for 1–7 million years or more (e.g. Blair and Bilodeau 1988). Extensional and translational tectonic settings are best for fan development and preservation, whereas the lateral movement and recycling of the mountain front makes compressional regimes less ideal.

More detailed characteristics of tectonism, including rates and occurrence of uplift, down-throw, and lateral displacement, can influence the overall form and development of a fan (e.g. Fig. 14.15a). Examples of fans reflecting small-scale variations in tectonism are those along the range-front fault in southeastern Death Valley (Figs. 14.19 and 14.20). Secondary and inherited structures have impacted sediment yield and catchment development there, as demonstrated by the variations in size of the fans and their catchments. Another common relationship is that fans along the tectonically active side of half grabens overall are smaller than those of the opposing inactive side due to greater tectonic subsidence (e.g. Hunt and Mabey 1966). A larger-scale example of tectonic variation in the Basin and Range province affecting fan development is provided by maps of fault activity (Thenhaus and Wentworth 1982, Wallace 1984b). Such maps delineate sub-provinces defined by whether the age of the most recent faulting was historical, pre-historical Holocene, late Quaternary, or pre-late Quaternary. The best developed fans, such as those of Death Valley, are present in sub-provinces with the most recent faulting.

Tectonism also affects fans by influencing climate and catchment vegetation. Adjustments to elevation directly impact these variables, possibly affecting weathering or erodibility of the catchment bedrock. As a result, factors such as sediment supply rate, calibre, and flash-flood frequency may be altered, and these alterations may affect the primary sediment transport mechanisms.

Alluvial Fan Forms

Two classes of alluvial fan forms, constituent and composite, have been differentiated on the basis of origin and scale (Blair and McPherson 1994a). Constituent forms are produced directly from the primary and secondary processes building and modifying the fan, or from external influences such as faulting or interactions with neighbouring environments. Individually, they comprise a small part of the fan. Constituent forms contrast with the overall fan morphology, or the composite form, representing the consequential or resultant shape of all of the constituent forms.

Constituent Morphology

If present, the incised channel usually is the most prominent constituent form of an alluvial fan. It ranges from 5 to 150 m in width, has nearly vertical walls 1–20 m high, and extends 10's to 1000's of metres down-fan from the apex (Figs. 14.2, 14.3, and 14.6d). Outburst floods may incise additional channels of similar size on the fan (Fig. 14.12d). Smaller forms may be present within incised channels, including terraces, boulders bars, debris-flow plugs, and gullies (Fig. 14.12e and f). Alternately, a smooth channel floor may result from abundant sand or clast-poor debris flows. Other large constituent forms that may exist on fans are rock-slide and rock-avalanche deposits. These features can rise ∼10–100 m above the surface of the fan, and span 10's to 1000's of metres in plan view (Figs. 14.8e, f and 14.9a, b).

Many constituent forms have 0.5–5 m of relief and a lateral extent of 10's of metres. Rockfall clasts, rock-avalanche tongues, boulder-log jams, and debris-flow levées cause irregularities, particularly in the proximal fan, with relief of 1–4 m (Figs. 14.11 and 14.22). Individual debris-flow lobes may be 2–10 m across, and extend radially for 10's to 100's of metres with 1 m of relief. Erosive secondary forms, including gullies and winnowed mantles (Fig. 14.15e, f), may also produce features of this scale. Fault scarps and toe cutting can create walls ∼1–5 m high (Fig. 14.16d). Volcanic flows may protrude 0.5 m or more above the fan surface, and extend for 100's of metres. Lower-relief forms (≤ 0.5 m high) that extend radially for 10's to 100's of metres also are common on fans, especially rills produced by secondary erosion (Fig. 14.15c). Windblown sand and rodent colonies may form mounds of this scale (e.g. Fig. 14.16c). Sediment-deficient sheetfloods can produce widely distributed transverse ribs 20 cm high, and sediment-laden sheetflood and clast-poor debris flows may produce expansive nearly smooth areas. Smooth fan surfaces also can be formed by overland flow and aeolian winnowing (Fig. 14.16a).

Constituent forms generally are not shown in cross-fan or radial-fan profiles because their relief is less than the typical resolution of topographic maps. Constituent forms such as incised channels, levees, and lobe boundaries, may be discernible from maps with ∼ 1 m contour intervals (Fig. 14.22), or from databases generated from LiDAR.

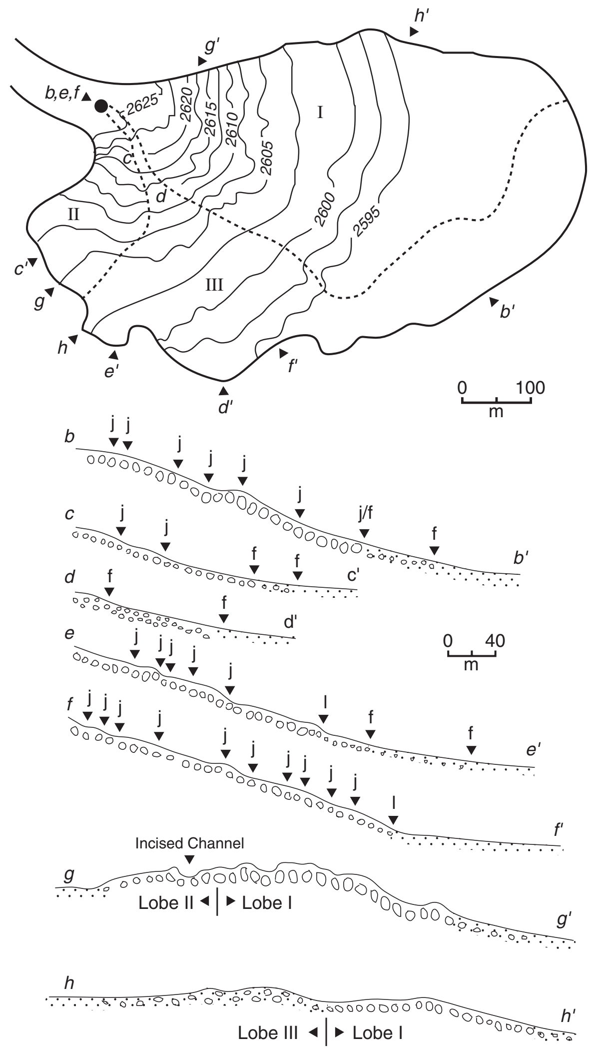

Fig. 14.22 Topographic map (*top*) and radial and cross-profiles of the Roaring River fan, Colorado, with some constituent forms labelled (after Blair 1987a). Arrows point to segment boundaries from boulder-log jams (*j*), facies changes (*f*), or lobe boundaries (*l*). Vertical exaggeration of profiles is 2.5X

Composite Morphology

The overall fan form, or composite morphology, is characterized by plan-view shape, presence or absence of incised channel, and radial and cross-fan profiles. Composite forms are more studied than the constituent forms because they can more easily be evaluated using maps and aerial imagery.

Plan-View Shape and Incised Channels

Alluvial fans have a semi-circular plan view shape where they aggrade without lateral constriction, and a pie-pieced shape where they laterally coalesce (Fig. 14.1). Lateral constriction from coalescence causes the fan radii to become elongated perpendicular to the range front. Alternately, the presence of lakes, oceans, aeolian sandsheets, rivers, or fans from the opposing range front can limit the radial length of a specific fan in a trend perpendicular to the range front (e.g. Fig. 14.21d).

Although a constituent form, the presence or absence of a prominent incised channel on a fan is an important aspect of the composite form. Incised channels promote fan progradation by transferring flows from the catchment to active depositional lobes positioned progressively farther from the range front. Incised channels, therefore, are more likely to exist and have greater length on fans with longer radii. Such fans also are more likely to possess large abandoned surfaces in the bypassed proximal zone.

Cross-Fan Profiles

Cross-fan profiles are a poorly studied element of the composite fan form. Cross-fan profiles overall have a plano-convex geometry, although variations exist. Such profiles from the upper fan, for example, have greater amplitude than those from the lower fan (Fig. 14.4b). The height and relative smoothness of the cross profiles may vary between fans due to differences in relief caused by variations in the primary processes or the degree of lateral coalescence. On the Roaring River fan, for example, cross profiles are asymmetric due to the distribution of lobes (Fig. 14.22). Cross-profile width may also vary between fans due to catchment evolution, overlap by adjoining fans, erosion from adjoining environments, or differing constituent forms.

Radial Profiles

The radial profile is a significant element of the composite fan form because it is determined by and influences primary processes. Radial profiles are characterized by slope pattern and magnitude. The radial pattern may exhibit: (a) a constant slope like that of a cone segment, (b) a distally decreasing slope depicting a half of a plano-concave-upward form, or (c) a segmented slope, where the surface inflects distally to one or more less-steep segments (Fig. 14.4a). Each of these profiles may either be smooth, or have notable irregularities resulting from the presence of rock avalanches, rock slides, or steps from boulder-log jams, fault scarps, or telescopic boundaries. The radial profile may alternately increase distally from erosion (Fig. 14.21d). Segmented profiles have been attributed to either a change in slope caused by tectonism, base-level change, or climate change (Bull 1964a). In the case of fans in Fresno County, California, Bull (1962) favoured a slope change due to catchment uplift. The Roaring River and Dolomite fans show that segmentation can result from intrinsic factors such as a change from debris-flow levées to lobes, or crossing boundaries between lobes or constituent forms (Figs. 14.11d and 14.22).

The average slope of alluvial fans ranges from 2° to 35°, with most between 2° and 20°. Except for faulting and aggradational or erosional effects of neighbouring environments, the fan radial profile is a product of the dominant sedimentary processes, and is thus called the depositional profile or the depositional slope (Blair and McPherson 1994b). Fans built entirely of rockfall talus have depositional slopes of 25– 35°, whereas the addition of debris-flow or colluvial slips can reduce the average to 15–30°. Fans dominated by colluvial slips, debris-flow levées, or NCSGFs with boulder-log jams commonly have a depositional slope of 9–18°; fans dominated by unconfined NCSGFs or clast-rich debris-flow lobes typically have slopes of 4–9°; and those dominated by clast-poor lobes commonly average 2–4°. A change from proximal levées to distal lobes, such as in the Dolomite fan case, produces a fan with a 9–15° proximal segment that inflects to a distal 4–7° segment. Sheetflood fans commonly have a radial slope that decreases progressively from about 5° proximally to 2–3° distally as a result of textural fining (Lawson 1913, Blissenbach 1952, Blair 1987a). Gravel-poor sheetflood fans and the distal part of mud-flow fans have average slopes of 1.5–3°. Thus, besides processes, facies, settings, and scale, the depositional slope of a fan is another parameter that separates them from rivers in sedimentary basins, which typically slope ≤ 0.4° (Blair and McPherson 1994b).

A faction of authors claims that fans with slopes lower than those discussed above are common (Harvey et al. 2005). Fans for which this claim is made are undocumented or misclassified, with recent articles exemplifying the latter. The first example is the swampy terminus of the Okavango River in the Kalahari Desert of Botswana. This feature has long been identified as the Okavango delta, but some now claim that it is an alluvial fan (McCarthy et al. 2002). The nearly flat (0.0015°) slope, lack of conical form, total dominance by a swamp with channels, and numerous other features provide sound evidence that it is not an alluvial fan. The second example is a 'low-angle fan' designated to exist in the Hungarian plain. A location map of the nearly flat valley with the outlined 'fan' shows that it is crossed in the 'upper fan' segment by the high-sinuosity Tisza River (Gábris and Nagy 2005), indicating that this feature is not an alluvial fan. The third example is a 'fan' in Iran that is claimed to have a slope of 0.5° (Arzani 2005). Photographs provided in the article show that the 'fan' mostly comprises lake beds. Adding a wide interval of flat lake beds to an alluvial segment greatly reduces the average slope of the transect, but does not demonstrate a low-sloping fan. A fourth example is from the western Sierra Nevada of California, where rivers are claimed to have built low-sloping fans (e.g. Weissmann et al. 2005). However, features indicative of fans in this area are not evident in facies along channel walls, on topographic maps, or when examining these flat forms on the surface or in the subsurface via ground-penetrating radar (e.g. see Figs. 3, 5, and 6 in Bennett et al. 2006). The problem in all of these examples is error in basic landform recognition and map reading that is then compounded by argument for expanding the definition of 'alluvial fans' to include the misidentified features despite their contrasting characterisitics. If the definition of alluvial fan were expanded to include these and other misidentified features, than basically all sub-aerial environments and deposits would be unscientifically classified as alluvial fans.

Morphometric Relationships Between Fans and Their Catchments

Much attention has been given to relating morphometric attributes of alluvial fans and their catchments. To date, such analysis has been based on topographic maps with scales providing insufficient accuracy. In the western USA, for example, the most detailed maps available before the 1980s, when most of the cited fan-catchment datasets were generated, had a scale of 1:62,500 and a contour interval of 40 or 80 ft. Such maps do not allow for an accurate delineation of the fan toe, which is why fans were erroneously concluded to have slopes that are gradational with neighbouring environments despite having clear slope-break boundaries on aerial photographs (e.g. Figs. 14.1 and 14.2). The reported results in these datasets thus are problematic because they may assign far too much or too little area to the fan, and because extending the fan to include flatter neighbouring environments gives inaccurately long radial lengths that lead to low slope determinations. Interpolation between contours to determine the fan apex elevation also adds error to fan height potentially equal to ± the value of the contour interval. Datasets from elsewhere have been generated from similar or poorer scale maps, or by using maps of unknown scale. Two relationships have nonetheless emerged from these studies, including area-area and area-slope.

Fan Area Versus Catchment Area

The most widely compared features of a fan and its catchment are their respective plan-view areas, which have a broad positive correlation (Fig. 14.23) (e.g. Bull 1962, 1964a, 1977, Denny 1965, Hawley and Wilson 1965, Hooke 1968, Beaumont 1972, Hooke and Rohrer 1977, French 1987, Lecce 1988, 1991, Mather et al. 2000). This relationship usually is given quantitatively as $A_f = cA_d^n$, where A_f is the fan area, A_d is the catchment (drainage) area, and c and n are empirically determined 'constants' that are not constant. The exponent n in widely referenced datasets varies from 0.7 to 1.1, and c ranges from 0.1 to 2.1 (Harvey 1989). The results produced by variations in the 'constants' alone differ so enormously as to not be relevant. For example, a catchment with an area of 50 km^2 is predicted by the area-area equation to equate to a fan with an area ranging from 1.6 km^2 to 155.3 km^2. This variation is why cross plots display a wide band of data (Fig. 14.23). Attempts have been made to isolate the effect of the variables on this relationship, but with unsatisfactory results. For example, Bull (1964a, b) concluded in his study of Fresno County, California fans that catchments underlain by erodible bedrock, such as shale, produce larger fans per unit of catchment area than catchments underlain by more resistant sandstone. In contrast, Lecce (1988, 1991) found that fans along the nearby western White Mountain front have greatest area per unit of catchment area where derived from very resistant bedrock such as quartzite.

The association of small fans with small catchments and large fans with large catchments is intuitively obvious because the movement of sediment from the catchment to the fan serves to increase the size of each. But wide data scatter and the need for changing 'constants' prove the invalidity of the commonly used fan area-catchment area relationship. As noted long ago (Lustig 1965), the problem with this equation is that it only compares the plan-view areas of three-dimensional objects, which is only valid mathematically if the vertical dimension of fans and catchments are constant, a condition that is never met. Catchment relief clearly is not constant, and in most cases fan thickness is unknown, but is highly unlikely to be constant. Further, due to dilatancy as rock transforms to sediment, even catchment volume versus fan volume are not directly comparable. Besides elementary mathematical and map-scale problems, the fan area-catchment area relationship is further complicated by a wide array of fan and catchment features that are dynamic or have a transient nature, including relief, altitude, stream piracy, tectonic beheading, sedimentary processes, variable inherited geological discontinuities, bedrock lithology, aerial constriction or overlap of fans, and the interplay with environments that border the fans.

Fan Slope Versus Catchment Area

Drew (1873) observed that fans with relatively large catchments have lower average slopes than those with smaller catchments, and this relationship has been studied by others (e.g. Bull 1962, 1964a, Denny 1965, Hawley and Wilson 1965, Melton 1965, Hooke 1968, Beaumont 1972, French 1987, Harvey 1987, Lecce 1988, 1991). Although a weak correlation is obtained (e.g. Fig. 14.23 in Blair and McPherson 1994a), wide scatter shows that issues exist. For example, compiled data show that fans with

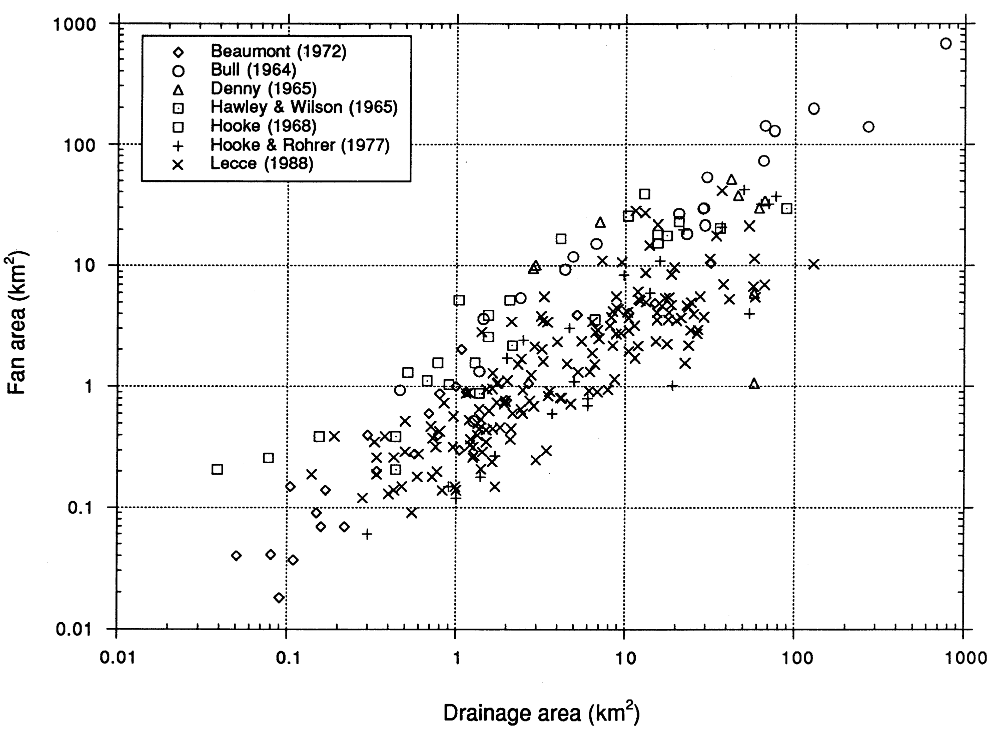

Fig. 14.23 Log–log plot of catchment area versus fan area based on data from published sources

a 2° slope relate to catchments with an area of between 0.5 and 110 km^2, and fans with a 10° slope relate to catchments with an area of 0.1 and 80 km^2, providing little discrimination. Major problems, including all those discussed for the area-area relationship, also apply to the catchment area-fan slope relationship, and additional pitfalls result from the inability to obtain accurate slope determinations from small-scale topographic maps.

Types of Alluvial Fans

Based on our research, literature synthesis, and reconnaissance of many fans around the world, we identify 13 fan types defined by their dominant primary processes and textures. The dominant processes also are reflected in their constituent and composite morphology. The 13 fan types are grouped into three classes based on whether the catchment slope material, from which the dominant primary processes are triggered, consists of bedrock (BR), cohesive colluvium (CC), or noncohesive colluvium (NC).

Table 14.1 Types of Alluvial Fans

Type BR Alluvial Fans (from Bedrock)
BR-1: Fans dominated by rockfalls
BR-2: Fans dominated by rock slides
BR-3: Fans dominated by rock avalanches
BR-4: Fans dominated by earth flows
Type CC Alluvial Fans (from Cohesive Colluvium)
CC-1: Fans dominated by debris-flow levées
CC-2: Fans dominated proximally by debris-flow levées and distally by lobes
CC-3: Fans dominated by clast-rich debris-flow lobes
CC-4: Fans dominated by clast-poor debris-flow lobes
CC-5: Fans dominated by colluvial slips or slides
Type NC Alluvial Fans (from Noncohesive Colluvium)
NC-1: Fans dominated by sandy clast-poor sheetflood deposits
NC-2: Fans dominated by sand-poor but clast-poor sheetflood deposits
NC-3: Fans dominated by gravel-poor but sandy sheetflood deposits
NC-4: Fans dominated by noncohesive sediment-gravity flows

Type BR Alluvial Fans

BR alluvial fans are dominated by deposits resulting from the failure of bedrock slopes present in the catchment or at the range front. Four types are differentiated, including those dominated by rockfall (BR-1), rock slides (BR-2), rock avalanches (BR-3), or earth flows (BR-4) (Table 14.1). Rockfall fans require the funnelling of talus through a notch in the bedrock, and then progradation by movement in chutes. These fans typically are steep (20–35°) with a straight radial pattern or one that lessens near the toe, and have a restricted (< 0.5 km) radial length (Fig. 14.8a, b, and c). Fans dominated by rock slides probably are rare given that slides usually do not accumulate in a way that produces a fan form. They thus dominate fans only where rock slides volumetrically constitute an important part of small fan, such as one otherwise built by rockfall (Fig. 14.8e). Their profiles are irregular because of the presence of rock mounds. Fans dominated by rock avalanches (BR-3) are more common, with highly disintegrated masses producing an overall smooth composite form but with rubbly constituent forms, as exemplified by the Gros Ventre avalanche fan in Wyoming. Avalanches that remain more intact can create a fan with profile irregularities, such as the North Long John and Rose Creek fans (Fig. 14.9a, b). These fans have constituent forms such as large-scale levées, lobes, and mounds. Earth-flow fans (BR-4), derived from fine-grained bedrock, build fans with greater radial length and lower slope (3–10°) than other BR types, such as the Slumgullion fan in Colorado and the Pavilion fan in British Columbia (Fig. 14.9d, e). Constituent forms include radial and concentric crevasse-like troughs and ridges.

Type CC Alluvial Fans

Type CC alluvial fans are those constructed principally by debris flows. They may or may not have an incised channel in their upper segment (Fig. 14.10a). CC fans all derive from the failure, in response to the addition of water, of colluvial slopes in the catchment containing sufficient mud volume to be cohesive. Five CC fans types are differentiated, including those with primary processes and deposits dominated by debris-flow levées (CC-1), proximal debris-flow levées and distal debris-flow lobes (CC-2), clast-rich debris-flow lobes

(CC-3), clast-poor debris-flow lobes (CC-4), and colluvial slips (CC-5) (Table 14.1; Figs. 14.9f and 14.11). Colluvial-slip fans are the steepest of these types, with an average radial slope of 15–20°. CC-1 fans also are steep at 9–18°, and CC-2 fans have a steep (9–18°) proximal segment and a lower-sloping (3–6°) distal segment. CC-3 fan slopes typically average 3–8°, and CC-4 fans 2–4°. The slope pattern of CC-2 fans is segmented, whereas the others have a straight pattern or one that slightly decreases distally. Colluvial slip (CC-5) fans are relatively smooth except for rills or gullies, and the other CC fans have constituent levées or lobes in addition to rills and gullies. Secondary processes dominate the inactive parts of the CC fans, forming desert pavement or boulder mantles. Rockfalls, rock slides, and rock avalanches may comprise a small part of these fans.

Type NC Alluvial Fans

Type NC alluvial fans are constructed principally by sheetflooding (Figs. 14.10b and 14.13). They may or may not have an incised channel in their upper segment. NC fans derive from the failure, through water erosion, of colluvial slopes in the catchment that lack sufficient mud content to be cohesive. Four types of NC fans are identified. Three are dominated by sheetflood deposits and are differentiated by texture, including those composed of gravel and sand (NC-1), sand-poor gravel (NC-2), or gravel-poor sand (NC-3) (Table 14.1). These textural divisions are designated because they provide information on the nature of the catchment bedrock, including composition and the prevalence of tectonic fracturing versus granular disaggregation. NC-1 and NC-2 are the most common of the three sheetflood types. NC-1 fans typically are derived from coarsely crystalline plutonic or gneissic bedrock, and NC-2 fans from tightly cemented brittle rock such as quartzite or carbonate. NC-3 fans arise from bedrock composed mostly of poorly cemented sandstone, where disaggregation dominates over tectonic fracturing. NC-1 and NC-2 fans typically have slopes that decrease distally from about 5° to 2.5° due to decreasing clast size. NC-3 fans have average slopes of 2–3°. Such fans may display distributary rills and headward-eroding gullies, and have a desert pavement, coarse mantle, or minor rockfall, rock-slide, or rock-avalanche deposits.

Type NC-4 fans are a special case generated from noncohesive colluvium. They are dominated by NC-SGFs, which presently are only known to form by the rapid erosion of clay-poor colluvium during catastrophic discharge triggered from dam failures, such as for the Roaring River and Tuttle fan cases (Fig. 14.12b, c, and d). These fans have depositional slopes of 4° to 8°. Typical constituent forms are one or more incised channels, levées, boulder shadow zones, boulder-log jams, rills, and gullies.

Alluvial Fan Evolutionary Scenarios

Given the concepts provided in this chapter and a freshly formed topographic setting, an idealized three-stage scenario for fan development with time can be envisaged. This scenario reflects the progressive enlargement of the fan and its catchment. Incipient or Stage 1 fans are a product of initial catchment development within uplifted bedrock. They typically are related to either inherited or neotectonic weaknesses in the bedrock. Rockfall cones and fans (BR-1) commonly form at this stage by the funnelling of loose clasts through a notch developed on a geological discontinuity. The enlargement of a talus cone to an incipient fan requires conditions in the bedrock favourable for funnelling. Incipient BR-1 fans achieve slopes lower than the ~35° slope of talus cones by progradation via chutes, and possibly by contributions from rock slides, small rock avalanches, colluvial slips, or debris flows (Fig. 14.2e). Alternatively, a catchment may be initiated by the catastrophic brittle failure of a weathered bedrock mass that moves to the fan site as a rock slide or rock avalanche to form a BR-2 or BR-3 fan. Such events produce a range-front cavity mantled by sediment, wherein water is subsequently concentrated. A third variant is for fine-grained bedrock that deforms more ductilely to create an earth-flow fan (BR-4) with a head scarp catchment. Another option is that cohesive colluvium accumulating along local depressions in the bedrock may fail when saturated by water to generate a colluvial-slip (CC-5) fan (Fig. 14.9f). All of these incipient fan scenarios involve catchment initiation through bedrock weathering, and the formation of a drainage net of first- to second-order. The incipient fan can take the form of a steep conical feature with a short radius, or it may comprise a more irregular platform for subsequent fan development.

Stage 2 encompasses the generation of the more common composite fan morphology. Fans of this stage are dominated either by debris flow or sheetflood processes, and more rarely by rock avalanches or NCSGFs. Rockfall, rock-slide, and colluvial slips may contribute small amounts of sediment. Stage 2 fans commonly have radial lengths of < 4 km, although some NCSGF fans reach $\sim$10 km in length. Stage 2 fan slopes vary from $\sim 10°$ to $18°$ where dominated by debris-flow levées, but more commonly have a 4–10° average slope. The change from Stage 1 to Stage 2 is related to: (a) the enlargement of the catchment as the drainage net develops from water erosion to include second- to perhaps fifth-order channels, and (b) the ability of the catchment to accumulate and store colluvium along slopes and within the drainage net that can then be episodically moved to the fan. The catchment during this stage still has significant bedrock exposures, but also builds noteworthy colluvial slopes.

Stage 3 is characterized by the development of an incised channel $\sim$1 km or more long through which flows are transferred across the upper fan to an active depositional lobe. Stage 3 fans typically are dominated either by debris flow lobes or sheetfloods, depending upon the cohesiveness of the catchment colluvium. The slope of such fans is 2–8° due to the dominant primary processes and to the effect of the incised channel on fan progradation. Progradation ensues by progressive lengthening of the incised channel. The development of a Stage 3 fan results from the transfer of a significant volume of sediment from the catchment to the fan. Thus, Stage 3 fans usually have relatively large catchments with a well-developed drainage net characterized by fifth- to perhaps eighth-order feeder channels. The catchment slopes typically are of bedrock in the upper reaches, and of widespread colluvium lower down.

The rate of progression through the three idealized stages varies from one fan to another, and may contrast even between adjoining fans due to differences in the catchment, such as the location of old faults or more erodible bedrock. An example from the vicinity of Titus Canyon in northern Death Valley has adjacent fans displaying all three stages of evolution. The largest and most advanced (Stage 3) is the Titus Canyon fan (Fig. 14.6d). This fan has a catchment built around a prominent structure oriented at a high angle to the range front (Reynolds 1974). Many other geological discontinuities in this catchment also induce weathering and the generation of flows that transport material to the fan, causing it to enlarge rapidly. In contrast, neighbouring fans display developmental Stages 1 or 2 depending on the position of their catchments with respect to minor discontinuities in the uplifted block.

Conclusions

Alluvial fans are a prominent conical landform developed through sediment aggradation where a channel draining an upland catchment emerges to an adjoining valley. Analysis of fans thus requires an understanding of sedimentary processes and products in this environment, and how they create the diagnostic fan form. Fans optimally develop in tectonic settings where fault offset creates relief, enhances weathering to yield sediment, and promotes flash floods that move sediment to the fan. Two types of processes, primary and secondary, are active on alluvial fans. Primary processes are those that transport sediment from the catchment to the fan, whereas secondary processes mostly modify sediment previously deposited on the fan by any of the primary processes.

Primary processes that construct fans include those triggered by the failure of bedrock (BR) slopes in the catchment or range front, and those related to the failure of either cohesive (CC) or noncohesive (NC) colluvial slopes in the catchment. Fans typically are dominated by the deposits of a single primary process, including rockfalls (BR-1), rock slides (BR-2), rock avalanches (BR-3), earth flows (BR-4), debris-flow levées (CC-1), debris-flow levées and lobes (CC-2), clast-rich debris-flow lobes (CC-3), clast-poor debris-flow lobes (CC-4), colluvial slips (CC-5), sandy gravelly sheetfloods (NC-1), sand-deficient gravelly sheetfloods (NC-2), gravel-deficient sandy sheetfloods (NC-3), or noncohesive sediment-gravity flows (NC-4). CC and NC fans may also have an incised channel. Primary processes are infrequent and of short duration, but have high impact with respect to fan aggradation. They also impart the prevailing composite fan form, including radial and cross-fan profiles. Primary processes related to bedrock failure and colluvial slip are important during the early stage of fan and catchment evolution, whereas debris flow and sheetflood fans, and more rarely NCSGF-dominated fans, develop after the incipient stage when the catchment has evolved to shed and store colluvium. Colluvium is noncohesive unless mud (especially clay) is present. Therefore, cohesive colluvium, and thus CC fans, are related to catchment bedrock that weathers to yield clay, and noncohesive colluvium and the linked NC fans are derived from catchments underlain by bedrock that yields comparatively little clay under the specific weathering conditions. The impact of cohesion is determined with the passage of a flash flood, wherein cohesive colluvium can transform into a debris flow, and noncohesive colluvium develops into a sediment-laden water flood.

Except for local aeolian deposition or volcanism, secondary processes are not important to fan aggradation, but commonly dominate the fan surface due to their prevalence during the long intervals between successive primary events. They include: (a) rilling and gullying from overland water flow, (b) desert pavement and sand-drift or nebkha deposits from wind transport, (c) desert varnish and particle weathering from hydrolysis, oxidation, salt crystal growth, and exfoliation, (d) bioturbation from plants and animals, (d) groundwater modifications, (e) soil development, (f) tectonic deformation, and (g) modification by adjoining environments, such as toe erosion or volcanism. Secondary processes, especially overland flow, can mask the features of, and thus be mistaken for, the primary processes.

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