discharge crosses or infiltrates steep slopes mantled by abundant sediment. Slopes that promote debris flow initiation typically have a 27 to 56° dip (Campbell 1975). Slopes greater than 56° commonly are too steep to maintain a mantle of colluvium whereas slopes of less than 27° have a diminished propensity for failure by gravity-induced mechanisms. Because flashfloods are relatively infrequent, and because the sediment accumulation sufficient to produce a debris flow requires time, the recurrence interval of debris flows is relatively long, varying from 300 to 10 000 years (Costa 1988, Hubert and Filipov 1989). Locally, where conditions are abnormally ideal for their generation, they are more frequent (e.g. Jian and Defu 1981, Jian and Jingrung 1986).

Investigations of active debris flows illustrate that they move in surges, with boulders concentrated either at the front or on top of the flow (e.g. Blackwelder 1928, Fryxell and Horberg 1943, Sharp and Nobles 1953, Johnson 1970, 1984). The surges are caused by the addition of new material by intermittent slope failure, bank failure and sloughing, or the development and breaching of temporary dams caused by the interaction of clasts and channel constrictions. Sedimentary particles in moving debris flows are supported by the high density and strength of the flow caused by cohesive, dispersive, buoyant, and locally turbulent forces (Middleton and Hampton 1976, Costa 1984, 1988). Cohesive strength is provided by the contained clay, whereas buoyancy is promoted by high concentrations of coarse grains. The differential response of boulders to buoyant and dispersive forces, caused by small differences in density between them and the rest of the material, results in the concentration of boulders at the top and front (Middleton 1970, Fisher 1971). Debris flows generally move with laminar character (Johnson 1970, Rodine and Johnson 1976). The lack of turbulence compels debris flows to be generally non-erosive despite the fact that they are capable of transporting boulders weighing several hundred tons (Rodine and Johnson 1976).

Debris flow movement downslope is sustained until its shear strength increases sufficiently to overcome gravity forces. Flow cessation ultimately results from the thinning of the flow to the point where the plastic yield strength equals the shear stress. This process may be aided by dewatering, which leads to increased frictional contact between grains. Debris flows containing boulders and cobbles may also be halted before critical thinning or dewatering has occurred by the damming effect of the coarse clasts at the frontal and lateral margins (Pierson 1985), or by their jamming against obstacles in the flow path such as upright trees or protruding boulders of older deposits (Blair 1987a).

Three types of debris flows active on alluvial fans can be differentiated. Two types, called clast-rich debris flows and clast-poor debris flows, can be distinguished on the basis of the volume of gravel (Fig. 14.10). The term rubbly debris flow has been used as a synonym for the clast-rich variety, whereas mudflow equates to the clast-poor type. The amount of gravel in a debris flow is a function of the availability of gravel in the source sediment rather than a reflection of variations in flow strength. Therefore, the clast-rich and clast-poor terms are recommended inasmuch as the processes involved in them are identical (e.g. Johnson 1984). Additionally, a single event may produce both clast-rich and clast-poor debris flows.

The third type of debris flow, called non-cohesive debris flow, is a specialized clast-rich type generated where clay is absent (Jarrett and Costa 1986, Blair 1987a). The absence of clay results in the lack of cohesive strength in the flow; instead sediment is supported by dispersive, turbulent, buoyant, and structural-grain forces. In general, the resultant deposits of cohesive and non-cohesive clast-rich debris flows are similar, although those of the non-cohesive variety are more vulnerable to erosion due to the lack of cohesive bonding between grains. In addition, the runout distance of a cohesive debris flow is likely higher than a non-cohesive one because the clay serves to reduce the effective normal stresses between the clasts, hindering frictional locking (Rodine and Johnson 1976).

Clast-rich debris flows of either the cohesive or non-cohesive variety typically occur on fans as lobes and levees present within the incised channel or directly on the fan surface (Fig. 14.10). Pre-existing topographic irregularities such as gullies commonly are filled by the passing debris flow. Clast-rich debris flows of the proximal fan generally consist of levee deposits, whereas relatively thin but more widespread lobes characterize deposits distally (Fig. 14.10a). Debris flow levees are produced by the lateral displacement of the coarse sediment from the snout of the moving flow and by the high internal friction in the zone of shearing at the flow margins (Sharp 1942, Johnson 1970, 1984). The levees represent parallel ridges of sediment left behind after the flow has waned and most of the debris has moved out into the lobes at the end of the flow path (Fig. 14.10). Flow surging commonly produces stacked beds in the debris-flow lobes (Fig. 14.10a and e). Falling-stage of a debris-flow event may result in the production of a clast-poor phase (Fig. 14.10e). Waning-stage water discharge also will commonly erode and winnow the surface of the newly deposited debris flow (Fig. 14.10e) (Beaty 1963, Johnson and Rahn 1970). This winnowing process can result from high subsequent drainage basin discharge caused by the release of stored groundwater tapped by the slope failure that initiated the debris flow activity (Mathewson *et al.* 1990).

Clast-poor debris flow deposits differ from their clast-rich counterparts by not forming levees and by having lobes that are more extensively thinned before deposition. The resultant deposits are lobes that smoothen pre-existing topography and have planar surfaces due to the lack of protruding clasts (Fig. 14.10f and h). Clasts and tree branches that may be present are concentrated along the lobe margins (Fig. 14.10g). Desiccation cracks are common in clast-poor debris flows due to the high clay content (Fig. 14.10f). These debris flows, like their clast-rich counterparts, are susceptible to erosion by falling-stage or subsequent water flows (Fig. 14.10f and h).

FLUID-GRAVITY PROCESSES

Fluid-gravity flows are Newtonian fluids characterized by the lack of shear or yield strength and by the fact that sediment and water remain in separate phases during transport (Costa 1988). The sediment-support mechanism in this flow type is fluid turbulence. Transport results either from suspension or from the rolling and saltating of sediment along the base of the flow by the transfer of energy from moving water to the individual particles. Sediment concentration in water flows typically is ≤ 20% by volume, with flows containing 20 to 47% sediment being termed hyperconcentrated (Costa 1988). Hyperconcentrated flows may achieve low shear stress values but, as in water flows, and in contrast to debris flows, sediment and water remain in separate phases and turbulence is the major support mechanism (Beverage and Culbertson 1964, Costa 1988). As hyperconcentration develops, sediment fall velocities decrease and buoyant or dispersive stresses aid sediment support.

Two types of fluid-gravity flow processes are operative on alluvial fans: sheetfloods (unchannelized or unconfined flows on the fan lobes) and incised channel flows. Both flow types result from the rapid concentration in the drainage basin of runoff from snowmelt or rainfall, leading to catastrophic discharge downslope. Sediment mantling the slopes or valleys of the drainage basin may be eroded by flow turbulence and carried to the fan site. Both sheetfloods and channelized flows can have sediment concentrations ranging from low to hyperconcentrated, depending on the intensity of the flow and the availability of sediment in the flow path.

Sheetfloods

A sheetflood is a broad expanse of unconfined runoff moving downslope (McGee 1897). The flow event is of relatively low frequency and high magnitude (Hogg 1982), while the flow itself is generally shallow and short-lived and has a limited travel distance. Sheetflooding is produced by catastrophic discharge, most commonly from high-intensity rainfall, combined with the absence of channelized drainage.

The characteristics of sheetflooding are well illustrated by a catastrophic event that occurred on the Roaring River fan in Rocky Mountain National Park, Colorado (Blair 1987a). This sheetflood event was caused by the failure in the upper drainage basin of a human-enlarged natural dam containing a cirque lake. An aerial photograph of the active sheetflood demonstrates it to be continuous over the entire

Figure 14.10 Photographs of clast-rich and clast-poor debris flow deposits. (a) Overview of the deposits from a 1984 debris flow event on a 1.5-km-long fan near Dolomite in Owens Valley, California. The flow divided downslope into numerous lobes. (b) Side view of matrix-supported boulder deposits constituting the recent debris flow levees on the Dolomite fan. Army shovel for scale. (c) Lobes spilled laterally from a breach in the levee of the Dolomite fan debris flow. Geologist for scale (arrow). (d) Oblique perspective of the recent clast-rich, interdigitate lobe margins of the Dolomite fan debris flow. Army shovel for scale. (e) Overview of the downfan lobe on the Dolomite fan in which clast-poor debris flow deposits accumulated above the clast-rich ones. Both of the flows were winnowed in their central area by water discharge that immediately followed debris flow deposition. (f) Overlapping clast-poor debris flows on the Copper Canyon fan, Walker Lake, Nevada. The lower flow (foreground) occurred in 1982, the upper one (middle ground) in 1990. Winnowing and slight dissection of the lower flow occurred during the intervening eight years. Geologist (upper-right) for scale. (g) Close-up of the 1990 Copper Canyon fan clast-poor debris flow. Note that the flow delicately divided around the desert plants despite the concentration there of gravel clasts. Desiccation cracks are present on the surface of the flow. (h) Waning-stage water flows during the 1990 Copper Canyon event winnowed fines from the central part of the debris flow deposits (photograph centre). Note the winnowed, darkened, and sparsely vegetated surface on the 1982 clast-poor debris flow (foreground).

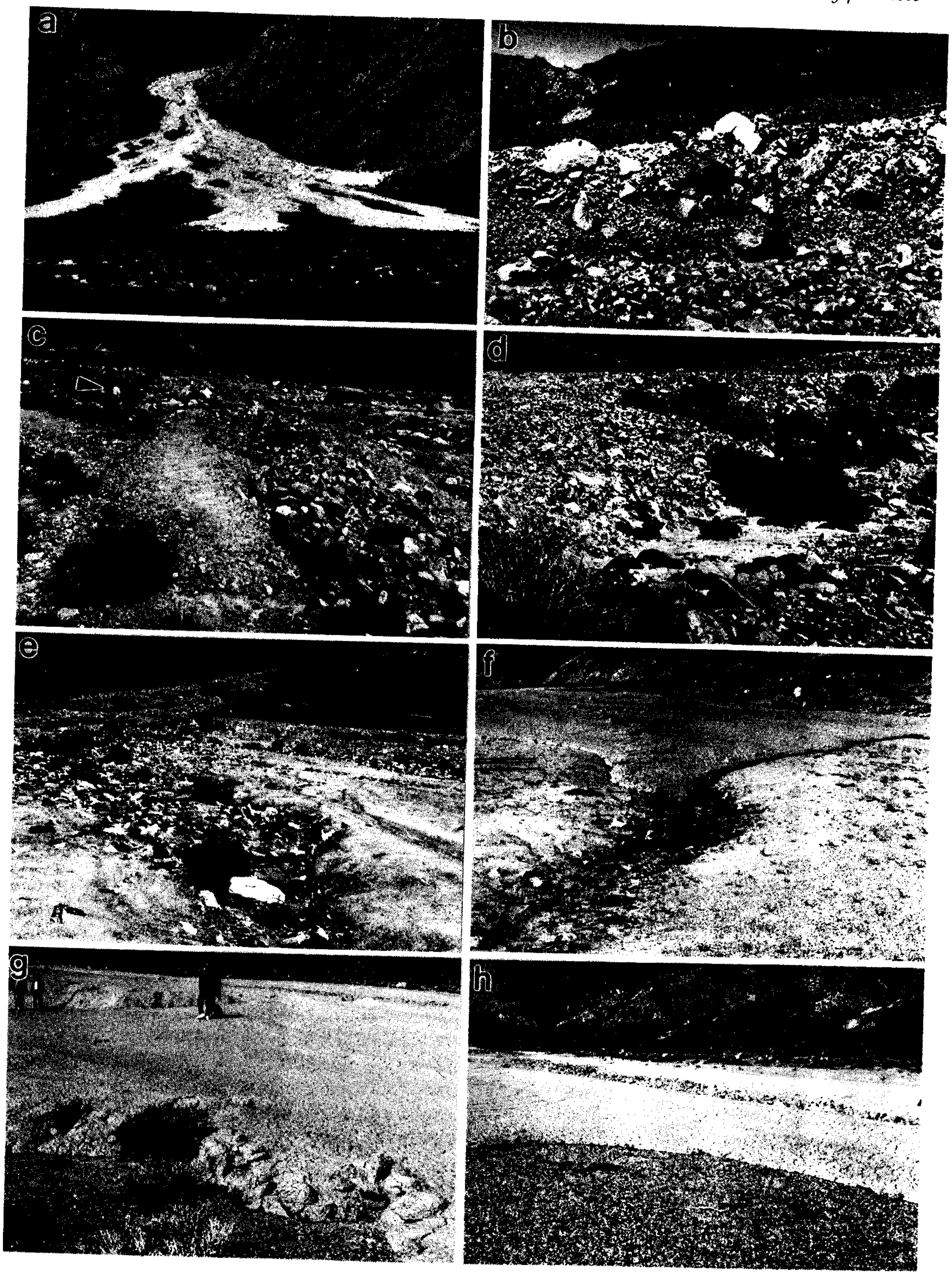


Figure 14.11 Photographs of alluvial fan sheetflood deposits. (a) Vertical trench exposure of alternating cobble–pebble gravel and laminated granular sand produced by the 15 July 1982 Roaring River sheetflood. The dark horizon near the top of the trench was deposited ten months after the flood. (b) Up-fan view of Roaring River fan sheetflood deposits immediately after flood cessation. A prominent sandskirt occurs in the foreground. The gravelly sheetflood surface is locally modified by a channel carved during falling flood stage. (c) View of the relatively smooth and sloping sheetflood surface on the Roaring River fan not modified by falling stage channel incision. (d) Oblique aerial photograph of fans in western Arizona displaying transverse ribs of sediment-deficient sheetflood origin (road for scale). (Photo provided courtesy of S.G. Wells.)

320-m-long active depositional lobe, which had an expansion angle of 120°. Hydraulic reconstructions indicate that this sheetflood had an average depth of 0.5 m, a velocity of $4.4\ m\ s^{-1}$, and a maximum water discharge value of $45.6\ m^3\ s^{-1}$. Supercritical flow generated up-fan migrating transverse waves on the water surface with antidune bedforms on the sediment surface below, similar to the sheetflood features described nearly a century earlier by McGee.

As much as 5 m of stratified sand- to boulder-sized sediment was deposited on the Roaring River fan by this sheetflood (Blair 1987a). The deposits include laminated pebbly sand interbedded with pebble or cobble gravel in couplets 5 to 20 cm thick and oriented at an angle of 4°, parallel to the fan slope (Fig. 14.11a). Gravel deposition occurred during the wash-out phase of the antidune train, whereas the granular sand was deposited during fall-out of the suspended load after antidune destruction. Repetition of antidune development and destruction resulted in the stacking of up to 15 couplets of gravel and pebbly granular sand throughout the sheetflood deposit. A skirt of planar-bedded granular sand accumulated down-fan from the gravelly couplets (Fig. 14.11b). The surface of the deposits produced during the sheetflood was partly incised during the flood falling-stage, producing two channels 4 to 5 m across and 0.4 m deep (Fig. 14.11b). The smoothly dipping surface of the sheetflood was preserved elsewhere on the lobe not carved during falling-stage (Fig. 14.11c). The presence of the diagnostic gravel and sand couplets and planar-bedded sand-skirt deposits on fans throughout the south-western United States suggests that sediment-laden sheetflooding is an important, but poorly recognized, fan-building process.

Wells and Dohrenwend (1985) have reconstructed

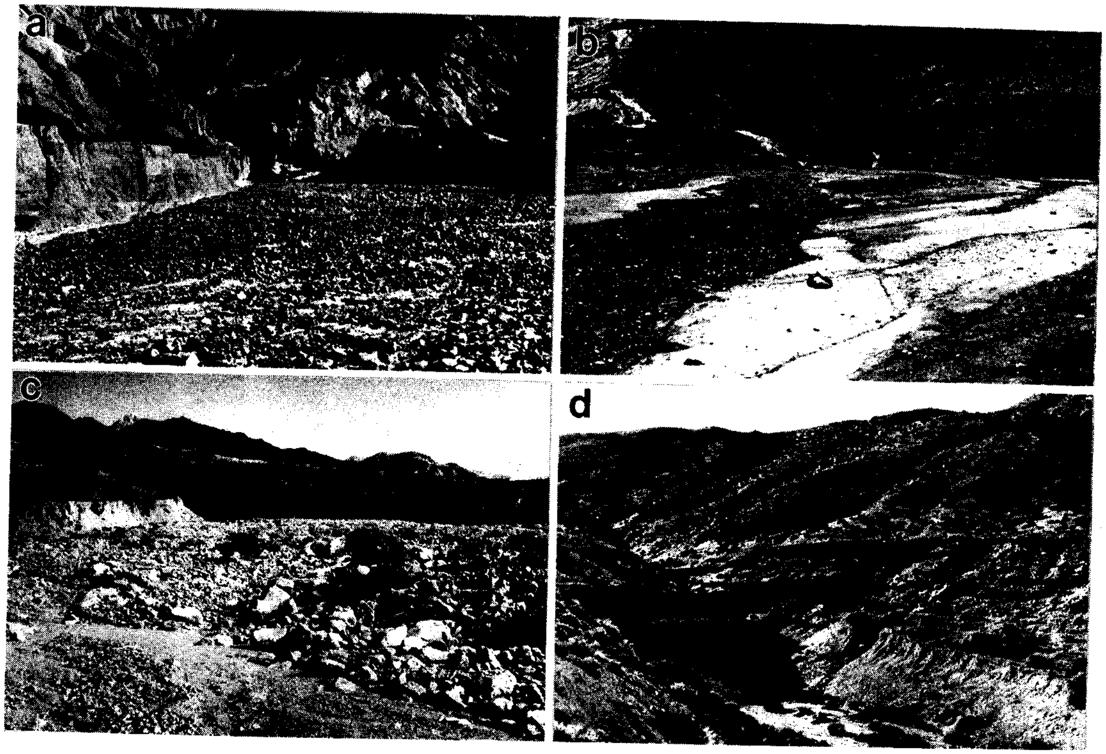


Fig. 14.12 Photographs of incised channels. (a) Up-fan perspective of an incised channel of a fan from Death Valley. Note the vertical, 3-m-high channel walls and the relatively flat floor consisting of cobbles and unwinnowed debris flows. (b) View of the proximal part of the incised channel of the Mosaic Canyon fan, Death Valley. Winnowed pebbles and smooth-surfaced, clast-poor debris flows occur on the channel bottom. (c) Incised channel of a fan derived from the Smith Mountains granitic pluton, Death Valley. The channel floor contains a coarse mantle of boulders lateral to which finer gravelly and sandy sediment was deposited. (d) Terraced fine-grained deposits (lower-right) occur in the incised channel of this fan located north of Copper Canyon, Walker Lake, Nevada.

latest Pleistocene to middle Holocene sheetflood events on alluvial fans in the Mojave Desert of California and Arizona based on the presence of transversely oriented bedforms consisting of sand, granules, and pebbles. These features, called transverse ribs, resemble starved ripples (Fig. 14.11d). They have wavelengths of 2 to 6 m and indicate that multiple, sediment-deficient sheetfloods with estimated flow velocities of 0.3 to 0.6 m s^{-1} occurred on these fans.

Incised Channel Flows

Incised channels serve as conduits for catastrophic flows on the upper fan, facilitating the transfer of sediment-gravity flows or sheetfloods downslope. Confining walls in these channels usually are 1 to ≥4 m high (Fig. 14.12). Channel floors may be nearly flat or display low-relief erosional or depositional forms (Fig. 14.12). Water flows travelling through incised channels may deposit only the coarsest sediment fraction due to higher flow competency created by the channel wall confinement (Fig. 14.12c). Finer-grained sediment, including terraces (Fig. 14.12d), may accumulate on or lateral to these deposits during the waning flood stage or during smaller discharge events. Incised channels also will accommodate the passage of sediment-gravity flows, the falling-stage fraction of which may also be deposited in the channel (Fig. 14.12b). Winnowing of fines from the deposits left by the passage of these flows may leave a flat bed of cobbles and boulders (Fig. 14.12a).

SECONDARY PROCESSES ON ALLUVIAL FANS

The long periods of time between successive primary depositional episodes on alluvial fans expose the surficial sediment to modifications by the secondary processes. These processes include reworking by water, aeolian activity, bioturbation, groundwater activity, particle weathering, and pedogenesis. The deposits may also be modified by neotectonic action such as faulting, tilting, or folding.

SURFICIAL REWORKING BY WATER

Discharge from rainfall or snowmelt in a fan drainage basin only infrequently produces a primary depositional event. On most occasions water discharge to the fan, whether of gentle or catastrophic character, is sediment-deficient. These discharge events, called overland flows (Horton 1945), may be capable of winnowing fine sediment from the surface of previous primary deposits (Fig. 14.13). Overland flows can occur in incised fan channels and on either active or inactive depositional lobes. The winnowed sediment typically is sand and clay but can range in size to pebbles and cobbles (e.g. Beaumont and Oberlander 1971). This sediment is moved farther down-fan, possibly even to neighbouring environments off the fan. The reworking of the surface of primary deposits on the fan by overland flows is the most widespread and active secondary process.

Erosive overland flows also result in the production of rills and headward-eroding gullies on the fan surface. Rills are initiated by the convergence of overland flow across the fan as a result of slight topographic or textural variations. They range from shallow features to channels with walls 10 to 50 cm high (Fig. 14.13e and f). A more advanced state of dissection produces gullies, which commonly occur on the distal fan and lengthen by eroding on their upslope end (Fig. 14.13f and g) (Denny 1967). The height of the gully walls may exceed 1 m (Denny 1965). A lag of the coarsest sediment fraction present in the primary deposit from which the fines have been removed typically covers the bottoms of the rills or gullies (Fig. 14.13b and c). Gullies or rills typically attain a distributary pattern that radiates down-fan either from the apex or the intersection point.

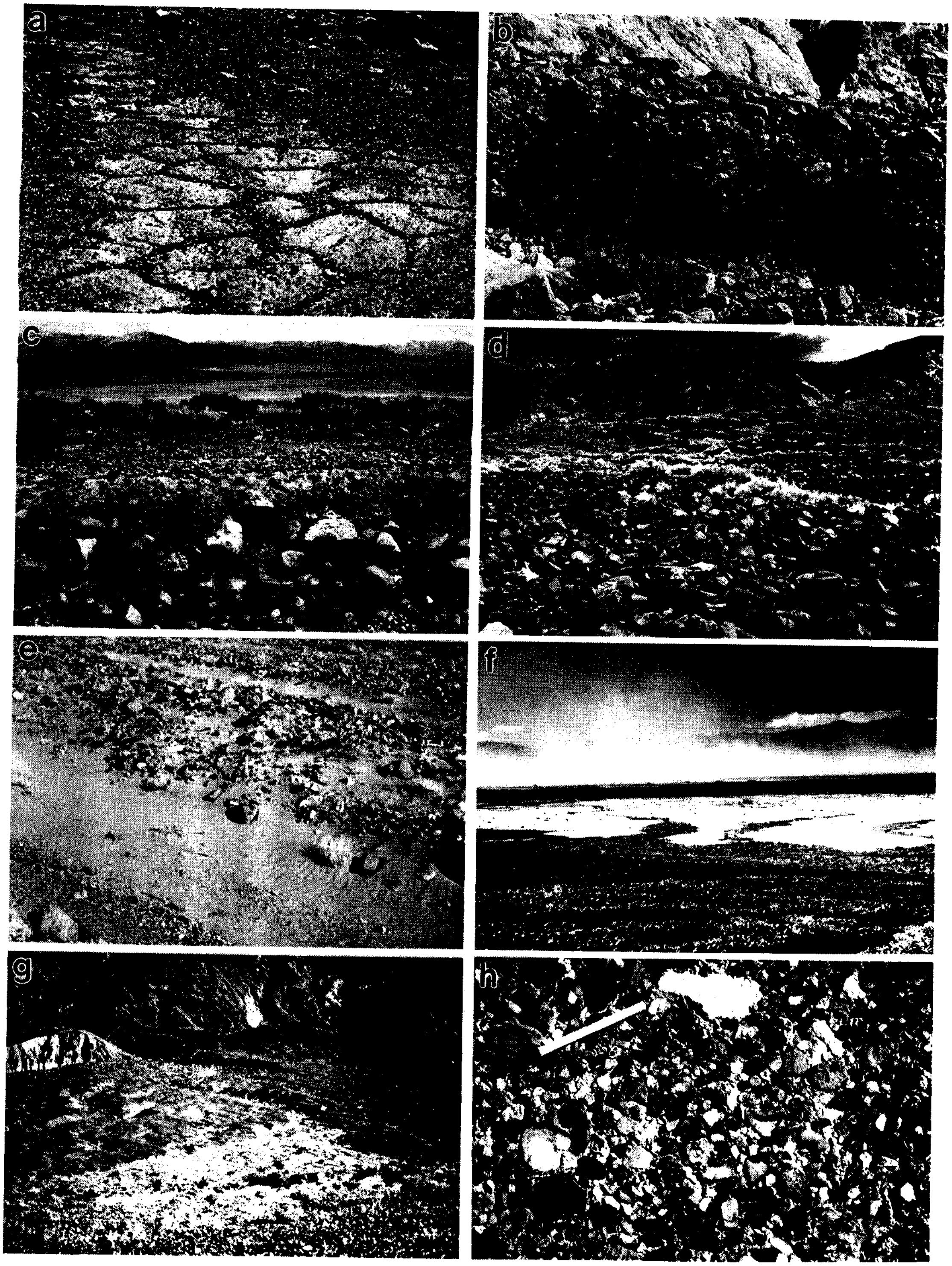
Calcite cementation of channel and gully walls or floors of a fan may result from the passage of water saturated with respect to calcium and carbonate. Precipitation from these waters can produce a hard, layered calcite cement termed case hardening. Lattman and Simonberg (1971) concluded from studies of fans near Las Vegas, Nevada, that case hardening occurs most commonly on fans derived from drainage basins underlain by carbonate or basic igneous bedrock, the weathering of which supplies abundant calcium ions, carbonate ions, and calcite-rich dust. This process can occur at a very fast rate, tightly cementing freshly exposed deposits in as little as 1 to 2 years (Lattman 1973).

AEOLIAN ACTIVITY

Exposed sand, silt, and clay on the fan surface are susceptible to erosion by wind, as demonstrated by the immense dust plumes visible in the atmosphere over deserts on windy days (Fig. 14.13f). One effect of this aeolian activity is to winnow the fine fraction until the fan surface is fortified by an immovable gravel layer called desert pavement, which protects the underlying material from further wind erosion (Fig. 14.13c and h) (Tolman 1909, Denny 1965, 1967, Hunt and Mabey 1966). The exposed gravel may be carved into ventifacts by abrasion from the passage of wind-carried sand (Fig. 14.13h).

A second effect of wind on a fan is the deposition of sand and silt as coppice dunes around plants, as isolated deposits upon the irregular fan surface (Fig. 14.13e), or as sandsheet deposits initiated by the effect of irregular topography on the windflow patterns. Aeolian deposits on alluvial fans may occur as thin accumulations of sand leeward of topographic irregularities or as relatively thick, laterally

Figure 14.13 Photographs of secondary processes on alluvial fans. (a) Surficial fine-fraction winnowing of a mud-cracked, clast-poor debris flow by subsequent overland water flows and wind erosion has left a lag of dispersed granules and fine pebbles. Furnace Creek fan, Death Valley. (b) View across an incised channel of a fan showing a 2-m-high vertical exposure of bouldery clast-rich debris-flow deposits. The deposit surface has had the fines removed by overland flow. Water flows in the channel (foreground) likewise have removed fines, leaving a bed of clast-supported gravel previously contained in the matrix-supported debris flows. North Badwater fan, Death Valley. (c) Side view of a gully on the Rose Creek fan, Hawthorne, Nevada, displaying debris flow deposits that have been winnowed at the surface by overland flow and wind. An incipient desert pavement resulted. (d) Extensive winnowing of bouldery debris flow deposits of the Shadow Rock fan, Deep Springs Valley, California, has produced a varnished, surficial boulder mantle. (e) Aeolian sand transported as wind ripples occurs in this rill on the Furnace Creek fan, Death Valley. (f) Gullies are prominent on the distal part of this fan near Titus Canyon, Death Valley. Note the dust plume in the valley centre generated by strong northerly winds achieving gusts of 80 km h^{-1}. (g) View of headward-eroding gullies (centre) on a fan in Death Valley. (h) Surface view of pebbly pavement created by wind erosion of the Bat Canyon fan, Amargosa Valley, California.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continuous sand blankets that disrupt or overwhelm fan sedimentation (e.g. Blair *et al.* 1990). In the most extreme case, aeolian sand dune complexes can migrate on to and cover the fan (Anderson and Anderson 1990).

BIOTURBATION

Plants and burrowing insects, arthropods, or rodents are common in surficial alluvial fan deposits in even the most arid deserts (Fig. 14.14a and b). Plant life commonly is sustained by shallow groundwater that is present in the fan sediment. Plant roots may extend for a metre or more into the fan sediment, disrupting the original primary stratification and homogenizing the deposits (Fig. 14.14a). The desert plants also provide a habitat for animals. Colonies of rodents amid desert plants on fans may significantly alter the deposits of the primary processes by disrupting stratification and dispersing sediment (Fig. 14.14b). Burrowers may also disturb the desert pavement, exposing previously protected sediment to wind erosion.

GROUNDWATER ACTIVITY

Alluvial fans serve as important aquifers for groundwater movement from the mountains to the valley floor, affecting the deposits in several ways. Groundwater discharge or flow near the surface of the distal fan can give rise to conditions conducive for plant growth. The slow movement of groundwater rich in dissolved solids may also result in the precipitation of cements such as calcite in the sediment pores (e.g. Bogoch and Cook 1974, Jacka 1974, Alexander and Coppola 1989). Travertine can precipitate on the fan where groundwater issues to the surface at springs (Hunt and Mabey 1966). The distal parts of fans in proximity to saline water bodies such as playas or marine embayments also may be cemented or disrupted by evaporite crystal growth in pores due to the evaporative draw of these fluids through the sediment. Groundwater flow may also destabilize slopes such as channel walls or fault scarps, instigating slumping (e.g. Alexander and Coppola 1989).

NEOTECTONICS

Inasmuch as alluvial fans optimally form along tectonically active mountain fronts, the deposits commonly are disrupted by seismic events. The most conspicuous result is vertical offset of fan sediment, creating scarps 0.5 to 40.0 m high (Fig. 14.14c). These scarps usually occur near and trend parallel to the mountain fronts, but also can be oriented obliquely to them and cut the distal fan (Wallace 1984a, Beehner 1990, Reheis and McKee 1991). The scarps create unstable, high-angle slopes that will degrade by creep, slumping, and freefall to produce fault-slope colluvial wedges (e.g. Wallace 1978, Nash 1986, Berry 1990). Faulting may disrupt groundwater flow through the fan sediment, possibly creating springs that may induce slumping along the scarp (Alexander and Coppola 1989). Scarps also readily instigate the development of headward-eroding gullies (Fig 14.14c).

Other types of neotectonic modification of fan sediment have been documented. Alexander and Coppola (1989) described 1-m-deep fissures in the proximal fan formed by seismic ground shaking. Mountain front faults with a strike-slip component, such as the San Andreas fault of southern California, cause folding of fan sediment (e.g. Butler *et al.* 1988, Rockwell 1988) or significant lateral offset of the fan from its drainage basin (e.g. Harden and Matti 1989) in a process referred to as beheading. Rotational tilting of fan deposits also is a common feature caused by dip-slip along listric mountain front faults (e.g. Rockwell 1988).

WEATHERING AND SOIL DEVELOPMENT

Many types of mechanical and chemical weathering modify alluvial fan sediment, including crystal growth in voids or mineral hydration along planes of weakness (Fig. 14.14d) (Hunt and Mabey 1966, Goudie and Day 1980). Fan sediment in the vicinity of caustic evaporite playas undergoes grain size reduction by salt crystal growth (Fig. 14.14e). Another common product of weathering includes the precipitation on clasts of thin hydrous manganese oxide coatings termed rock varnish (Fig. 14.14b and d) (Chapter 6). The thickness of the varnish and its darkness have been successfully used to differentiate the relative ages of various fan lobes (e.g. Hooke 1967, Dorn and Oberlander 1981, Slate 1991). Radiocarbon dating of this varnish also provides potential for obtaining absolute ages of fan surfaces (e.g. Dorn *et al.* 1989), although problems with this new method remain (e.g. Bierman and Gillespie 1991a, b, Bierman *et al.* 1991, Reneau *et al.* 1991). Alteration of the fan deposits by weathering also occurs immediately below the fan surface. Unstable grains such as ferromagnesium minerals or feldspars alter to finer-sized products through hydrolysis and oxidation (Walker 1967, Walker and Honea 1969). Clay-sized particles also are mechani-

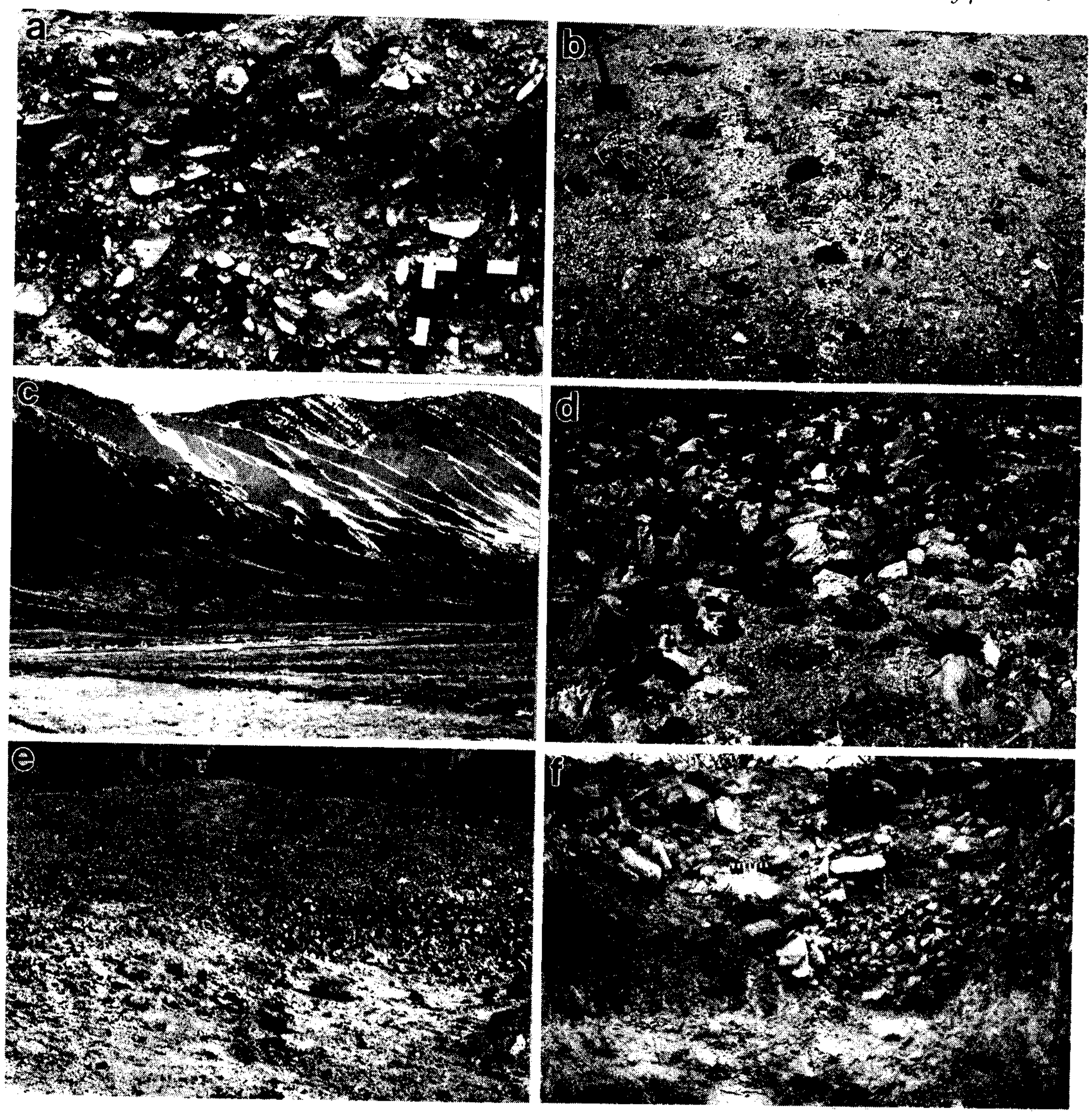

Figure 14.14 Photographs of secondary processes active on fans. (a) Gully cut of a proximal fan along the western Jarilla Mountains, south-central New Mexico. Gravelly fan and sandy aeolian deposits have been intermixed by plant root activity, resulting in the destruction of primary stratification. Reddened Bt (argillic) and white Btk (argillic and calcic) soil horizons are developed in this sediment. Pedogenic carbonate (white) extensively coats the gravel clasts. Scale bar increments are 10 cm. (b) Overview of a rodent colony comprising numerous burrows in near-surface fan sediment, Walker Lake, Nevada. Army shovel (upper left) for scale. (c) Three fault scarps ranging from 1 to 4 m high offset this fan in Deep Springs Valley, California. (d) Close-up of metamorphic cobbles located on the distal North Badwater fan in Death Valley. The clasts have been split by the growth of salt crystals along the foliation planes. (e) Overview of the distal North Badwater fan demonstrating the effect of grain size reduction due to salt weathering in proximity to the Badwater playa. (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 upper half of the photograph. Scale bar is 15 cm long.

cally added to sediment pores as the result of transportation by infiltrating water (Walker *et al.* 1978).

The long periods of time between successive depositional episodes makes the fan sediment, particularly in the inactive lobes, parent material for developing soils. Soil types found in desert fans result from the accumulation of horizons of clay, carbonate, silica, or evaporites such as gypsum (Fig. 14.14a and f). Carbonate and clay horizons are the most common soil horizon types encountered in the desert fans of south-western United States and south-eastern Spain (Gile and Hawley 1966, 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). Gypsiferous and siliceous soils are less commonly documented in fan sediments (Reheis 1986, Al-Sarawi 1988, Harden *et al.* 1991). The extent of soil profile development in fan sediment is a function of time, the aeolian flux of the materials from which the horizon is composed, and the amount of precipitation (Machette 1985, Reheis 1986, Mayer *et al.* 1988). The presence of plant roots in the sediment also serves to instigate the accumulation of soil horizons produced by downward movement of percolating waters, including clay, carbonate, and gypsum. The extent of development of soil horizons in a given area, therefore, is useful for determining the relative age and correlation of fan deposits (e.g. Wells *et al.* 1987, Slate 1991).

Well-developed or tightly cemented soil B horizons, such as petrocalcic horizons that have become exhumed by erosion, serve to armour the fan from further secondary erosion (Lattman 1973, Gile *et al.* 1981, Van Arsdale 1982, Wells *et al.* 1987, Harvey 1990). These layers also expedite the downslope movement of overland flow by reducing the permeability of the surficial deposits.

SIGNIFICANCE OF DISTINGUISHING PRIMARY AND SECONDARY PROCESSES

Although the differences between primary and secondary sedimentary processes on alluvial fans were clearly illustrated decades ago (e.g. Beaty 1963, Denny 1967), most fan articles are written without an obvious appreciation of this distinction. One consequence has been the acceptance of the assumption that secondary processes, which usually dominate the fan surface, are the principal ones constructing the fan, rather than serving merely to remould and mask the primary processes (Blair 1987a). Two major problems arising from this assumption are the reality of sieve lobes and braided distributary channels on fans. A further complication has been introduced by those trying to equate fan activity to climatic or tectonic influences on the basis of the apparent process type without considering the ramifications of the intrinsic primary versus secondary sedimentary modes.

SIEVE LOBES ON ALLUVIAL FANS

The idea of sieve-lobe deposition on alluvial fans was proposed by Hooke (1967) based on laboratory studies of small-scale (radii ≤1-m-long) features constructed of granules and sand that morphologically resembled fans. Hooke identified in these modelling experiments a surficial deposit formed by the rapid infiltration of sediment-laden water discharged from the drainage basin. A lobate deposit, termed a sieve lobe, accumulated at the point where the water was unable to effect further transport due to complete infiltration into the permeable sandy substrate. This term was applied because the permeable laboratory sediment acted as a strainer or sieve that permitted water to pass while holding back the coarse material in transport. These deposits in the laboratory simulations had the coarsest materials (granules) at the front of the lobe, and were backfilled upslope by finer (sand-sized) sediment.

Although acknowledging that his laboratory studies may have no significance to real fan processes, Hooke concluded that sieve deposits like those observed in the laboratory comprise extensive facies on seven natural fans in south-eastern California. Four of these fans were identified, including the Trollheim and Shadow Rock fans in Deep Springs Valley, the Gorak Shep fan in Eureka Valley, and the North Badwater fan in Death Valley. These fans were reported to be constructed of material derived from drainage basins underlain by bedrock that did not weather to produce permeability-reducing fine-grained sediment such as clay. Based on Hooke's work, the sieve lobe mechanism has become established as one of the major processes operative on alluvial fans (e.g. Bull 1972, 1977, Dohrenwend 1987).

Our evaluations of the exposed stratigraphy of the four natural fans identified by Hooke as possessing sieve lobes revealed that the principal primary process by which these fans have been built is, without exception, debris flows (Fig. 14.15a and b). The drainage basin bedrock has weathered to produce abundant clay in all four of these cases. As a result, the fan deposits are rich in matrix fines (Fig. 14.15b)

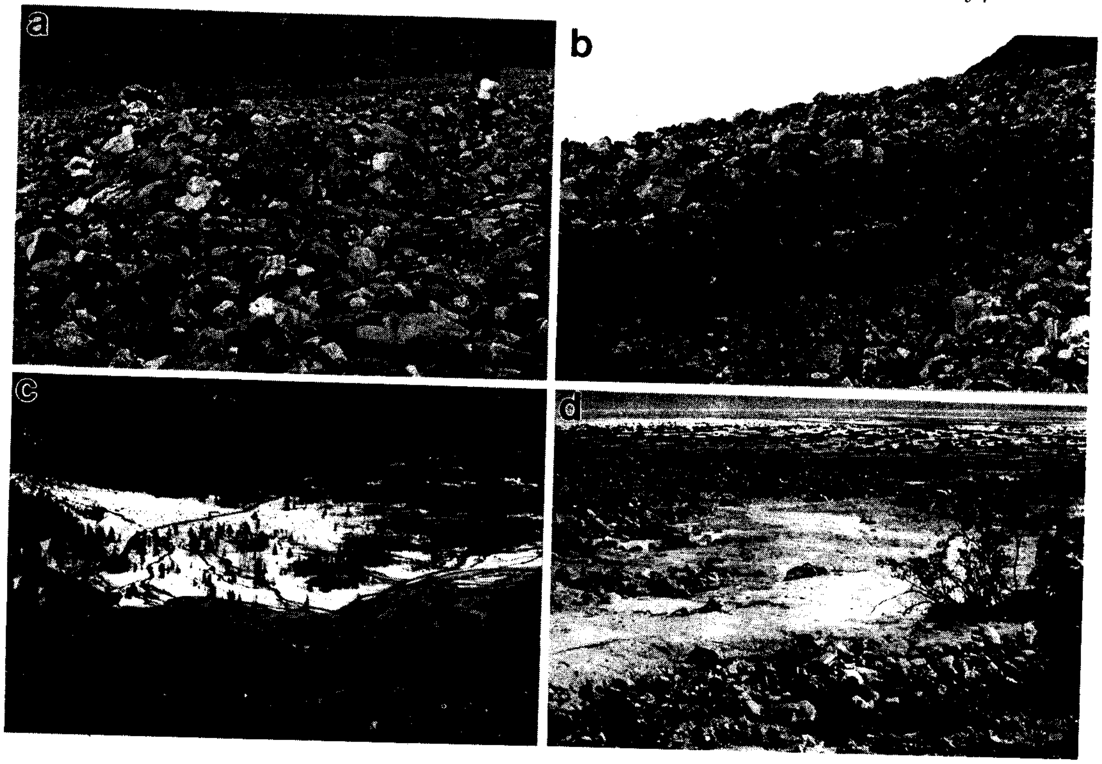

Figure 14.15 Photographs of purported sieve lobes, braided distributary channels, and masked sheetfloods. (a) Oblique view of one of the type sieve lobes (photograph centre), North Badwater fan, Death Valley. (b) View of vertical cut 1.5-m-high in a channel wall in the vicinity of Figure 14.15a. This view reveals matrix-rich debris flow deposits below a zone containing the identified sieve lobe. The fines have been removed from the surficial part of the debris flow lobes on this fan by overland flow, leaving an arcuate mass of winnowed gravel erroneously identified as a sieve lobe. (c) Overview of the Roaring River fan, Colorado. Braided distributary channels 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. The presence of these flows within shallow channels gives a misleading braided distributary appearance to the fan (Figs 14.1a and 14.2a) when viewed from the distance (e.g. Nummedal and Boothroyd 1976).

and have low permeabilities, conditions that conflict with those listed by Hooke as necessary for sieve lobe development. Based on our examination of the identified sieve lobes on these natural fans, we alternatively conclude that these clast-supported, matrix-free lobate masses are the surficial part of clast-rich debris flow lobes from which the matrix has been removed by secondary overland flows. The lobate forms described by Hooke and observed on these fans are identical to the clast-rich debris flow lobe margins. Our interpretation is further substantiated by the presence at depth of matrix-supported debris flow deposits which have not been subjected to surficial winnowing and that still contain abundant interclast matrix (Fig. 14.15b). The existence of the sieve-lobe process on alluvial fans, therefore, remains only a hypothetical consideration.

BRAIDED DISTRIBUTARY CHANNELS ON ALLUVIAL FANS

Perhaps the greatest misconception concerning alluvial fans is the belief that they are constructed from braided distributary channel systems. This view results from the common presence of shallow channels with a distributary pattern on many fan surfaces. The idea especially 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 crossbedded, laminated, or massive. The characteristics of sediments deposited by braided streams are described in detail by Doeglas (1962).'

Our analysis of the stratigraphic sequence of numerous fans displaying braided distributary channels reveals that these features invariably are surficial and formed either by incision during waning flood stage or through secondary winnowing and remoulding of primary deposits, including debris flows (Figs 14.13b, c, f, and 14.15b) and sheetfloods (Figs 14.11b, c, and 14.15c) (Blair 1987a). Furthermore, stratotypes described by Doeglas (1962) for braided streams, such as planar and trough crossbedding, are not found in vertical cuts of sediments associated with these braided distributary channels.

Other evidence commonly cited as support for the assumption that braided fluvial systems are responsible for fan construction includes the vivid depiction of braided distributary channels on aerial or oblique photographs of fans. An example of a fan reported to be built by braided distributary channel activity on the basis of this type of evidence is the Trail Canyon fan of Death Valley (Fig. 14.1a and 14.2a) (e.g. Nummedal and Boothroyd 1976). A field examination of this fan, however, reveals that the apparent light-coloured distributary channels present on photographs are shallow surficial features cut into the tops of debris flows by secondary processes, and that these channels are filled by clast-poor debris flows (Fig. 14.15d). An extreme consequence of the common misidentification of secondary channels as primary fan-building processes has been the reduction of alluvial fans to just a type of braided stream system (Miall 1978, p. 33).

Conversely, a failure to isolate the braided distributary channel features on alluvial fans as a secondary process has resulted in the inability of many researchers to clearly recognize the major constructive processes, such as sheetfloods and debris flows. This problem ensues despite the fact that the surficial carving of debris flow and sheetflood deposits is now well established (e.g. Beaty 1963, Lustig 1965, Johnson 1970, Blair 1987a). The surficial reworking of these primary deposits, combined with their long recurrence intervals, is probably why it was not until Blackwelder's (1928) paper that the importance of debris flows in fan construction was recognized (Costa 1984). Similarly, the masking of sheetfloods by surficial remoulding was concluded by Blair (1987a) to be the reason that sheetflooding, to this day, is not a more widely recognized fan-building process.

IMPLICATIONS FOR CLIMATIC AND TECTONIC EFFECTS ON FAN DEVELOPMENT

The enlargement of the incised channels on alluvial fans by downcutting (i.e. fanhead trenching) and the dissection of the fan surface by gullying have been attributed by many researchers to be a consequence of climatic change (e.g. Dohrenwend 1987). The fan sequences upon which dissection is occurring are believed to have accumulated during periods of different, usually more moist, past climates (e.g. Blissenbach 1954, Lustig 1965, Melton 1965, Williams 1973, Nilsen 1982, 1985, Harvey 1984a, b, 1987, 1988, Dorn *et al.* 1987, Dorn 1988). Although the scientific validity of this oversimplified 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 accepted. It is based on the idea that different, generally more moist, past climates resulted in greater sediment production in the drainage basin, and that aggradation concurrently took place as a result of the expedient transfer of this sediment to the fan. As a corollary, sediment production in the drainage basin is considered in this model to be retarded during periods of usually more arid climates, causing water flows to depart the drainage basin without sediment. The lack of sediment in these departing flows makes them highly erosive as they cross the fan, resulting in incised channel downcutting and gully formation.

Harvey (1984a, b, 1987, 1988), for example, noted that gullying of the fan surface and downcutting in the incised channels in his Spanish study area occurred upon older surficial deposits constructed by debris flows or sheetfloods. The change from active fan aggradation, indicated by debris flow or sheetflood accumulation, to the present state of dissection, as indicated by gullying and incised channel enlargement, was attributed to a reduction in sediment availability in the drainage basin triggered by climatic change from the middle Pleistocene to the present. This relationship, however, might more simply be interpreted as an intrinsic sedimentological process resulting from the surficial reworking by secondary processes of deposits from primary processes with low recurrence intervals. The largely non-tectonic setting of these Spanish fans and the relatively low relief of their drainage basins would suggest that the recurrence interval of catastrophic primary events is low, and that secondary processes predictably would dominate the fan surfaces.

Another site where the activity of secondary processes has been proposed to be climatically induced is the Hanaupah and Johnson Canyon fans in Death Valley (Dorn *et al.* 1987, Dorn 1988). These fans currently exist under hyperarid conditions (Hunt *et al.* 1966). Dorn *et al.* (1987) proposed on the basis of carbon isotope data from rock varnish that aggradation probably occurred under semi-arid or even humid intervals of the Quaternary. Channel incision and gullying, it is suggested, took place during shifts towards aridity, including during the present arid cycle. This interpretation is based on at least three questionable assumptions. The first is that channel incision and gully development are not products of intrinsic sedimentological events on the fan, including falling-stage erosion or secondary surficial reworking by overland flows. A second assumption is that the fan drainage basins are completely devoid of sediment during relatively drier conditions. The presence of sediment within the drainage basins of the Hanaupah and Johnson Canyon fans and the common historical occurrence of debris flow events on fans in Death Valley, including one on the Trail Canyon fan (Fig. 14.3a), a neighbour of the Hanaupah fan, directly counter this assumption. In fact, active sedimentation on fans by primary processes throughout the south-western United States is strong evidence that they are dynamic features, not fossil forms inherited from wetter pasts (Beaty 1974). A third assumption by Dorn *et al.* (1987) is that climate shifts were drastic during the Quaternary, swinging in Death Valley between hyperarid and semi-arid, or even to humid. This conclusion is not supported by other investigators. For example, a runoff-response model by Mifflin and Wheat (1979) suggests that the widespread late Pleistocene pluvial lakes of the western Basin and Range province could have been generated and maintained by an increase in annual precipitation of 68% above the present and a 10% decrease in annual evaporation. This model predicts that hyperarid conditions would have persisted in Death Valley even during the more wet and cool late Pleistocene period. In conclusion, and as forewarned by Tolman (1909), our understanding of climatic change probably is too poorly understood at present to unequivocally attribute certain processes or stratigraphic sequences on alluvial fans to it, particularly when these features can more simply be explained by the intrinsic sedimentological processes of fan building.

Tectonic tilting of the proximal fans of Death Valley also has been proposed as an origin of incised channels (Hooke 1972), extending a hypothesis previously suggested by Eckis (1928) and Bull (1964a). Paradoxically, the fans used as examples by Hooke for tectonic arguments include the same two fans used by Dorn *et al.* (1987) for climate arguments. Although uplift of the proximal part of a fan would likely induce downcutting as proposed in Hooke's model, the cited fans in Death Valley do not show evidence that such deformation has occurred.

CONTROLS ON FAN PROCESSES

At least five key factors control or strongly influence the major sedimentary processes and deposits of alluvial fans: (a) the lithology and splitting properties of the bedrock underlying the drainage basin, (b) the shape and evolution of the drainage basin, (c) neighbouring environments, (d) climate, and (e) tectonism. These variables form a system of interacting feedback relationships that are exceedingly difficult to analyse or quantify due to their complexity and to their general lack of detailed study. The impact of each of these variables, however, can be demonstrated.

DRAINAGE BASIN BEDROCK LITHOLOGY

The type of bedrock in drainage basins from which sediment is derived has a significant impact on the primary alluvial fan process types. Rocks of differing lithology give rise to different sediment suites and volumes due to their variable response to weathering. Bedrock in desert settings optimal for fan development, especially tectonically maintained mountain fronts, produces sediment in varying sizes and amount depending upon (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 variations are not fully understood and usually are seriously underestimated with respect to fan development. Their importance can be illustrated by a survey of sediment types found in fan drainage basins of the south-western United States underlain by differing bedrock lithologies.

Granitic plutons and gneissic rocks break into particles varying from sand to very coarse boulders in response to tectonically induced jointing and fracturing, exfoliation, and granular disintegration. The equidimensional and coarse grain-size of sediment on fans derived from granite results from the uniform joint pattern commonly developed in this rock type due to its homogeneous, coarse-grained fabric. By contrast, gneissic rocks typically yield more tabular boulders due to the anisotropy imposed by the metamorphic foliation. Boulders from both of these lithologies are either angular, reflecting the joint pattern, or are more rounded depending upon the degree of chemical weathering along the edges of the joint blocks. Granules and sand-sized sediment (grus) also are a common product of the physical weathering of the granitic or gneissic rocks. In contrast, clay and silt-sized sediment usually are only minor products due to the low intensity of chemical weathering in deserts.

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 produced in this situation due to the effective cementation of the matrix grains. Dense carbonate rocks also succumb to tectonism in a brittle fashion, producing gravel-sized angular blocks. If present, interstratified soft sedimentary rocks such as shale cause the intervening brittle rocks to fracture and weather to produce tabular gravel-sized clasts as well as a prominent clay fraction.

Finer-grained drainage basin bedrock lithologies such as pelitic metamorphic rocks, shale, mudstone, or volcanic rocks commonly weather to yield sediment varying in size from boulders to clay, with an abundance of the finer grain sizes and a deficiency of sand. Thickly mantled colluvial slopes comprising cobbles, pebbles, and clay are commonly developed on bedrock of this type.

The different reactions of the various lithologies in the drainage basin to physical and chemical weathering lead to different styles of erosion and transport of the liberated sediment. Colluvial landslides and cohesive debris flows are favoured by steep slopes and sediment containing significant clay. Debris flows, therefore, are very common on fans with drainage basins established in shale, mudstone, volcanic rocks, or pelitic metamorphic rocks. By contrast, debris flows are much less common in desert fans with drainage basins developed in non-clay-producing lithologies, such as granites or quartzites. Slopes in these latter lithologies are more apt to produce rock avalanches, rockfalls, non-cohesive debris flows, and sheetfloods. The desert fans of Spain studied by Harvey (1984b, 1988, 1990) illustrate the point. Fans derived from drainage basins underlain by high-grade metamorphic bedrock rarely contain debris flow deposits, whereas neighbouring fans derived from basins set in sedimentary or low-grade metamorphic rocks consist primarily of debris flow deposits.

The above examples represent the idealized condition where the drainage basin is underlain by one rock type. More complicated scenarios develop in the case of multiple drainage basin bedrock types. These complexities could result in interspersed and mixed process types based on which part of the drainage basin is eroding at any given time. Differing bedrock lithologies can also affect the rate of denudation of the colluvial cover of respective lithologies, as exemplified by the Nahal Yael drainage basin in Israel. Bull and Schick (1979) found that the grusy colluvial cover of the granitic rocks in this drainage basin has been completely stripped, whereas areas underlain by amphibolite have been only partly stripped due to the greater cohesion of the clayey colluvial mantle.

DRAINAGE BASIN SHAPE

The overall shape and evolution of the shape of an alluvial fan drainage basin can have a major impact on the operative sedimentary processes of the fan system. Basin shape affects slope values, feeder channel profile characteristics, relief, propensity for flashflood promotion, and storage capacity. Knowledge of the impact of these factors on fan construction is in its infancy (Fraser and Suttner 1986). Slope angles in concert with lithology type may determine whether rockfalls, rock avalanches, gravity slides, debris flows, or flashfloods are promoted in a drainage basin. The presence or absence of storage capacity in the drainage basin dictates how and when the sediment is delivered to the fan site. Relief may determine the size of sediment-gravity events that can be generated, whereas the elevation of the upper drainage basin may determine the chances of receiving significant precipitation via either rainfall or snowfall. The orientation of the drainage basin with respect to sunlight or the track of the major storms may also influence weathering, erosion, and transport activity, and thereby fan aggradation.

The ability of drainage basins to rapidly transmit or store sediment varies significantly with their areal size, which can range from a fraction of a square kilometre to hundreds of square kilometres. The smallest drainage basins may consist of only a single valley carved along a fracture in bedrock, with any collected discharge or dislodged clasts rapidly transferred to the fan. Feeder-channel incision and widening can proceed with time, allowing limited storage of primary deposits such as debris flows or colluvium. Progressively greater storage occurs with