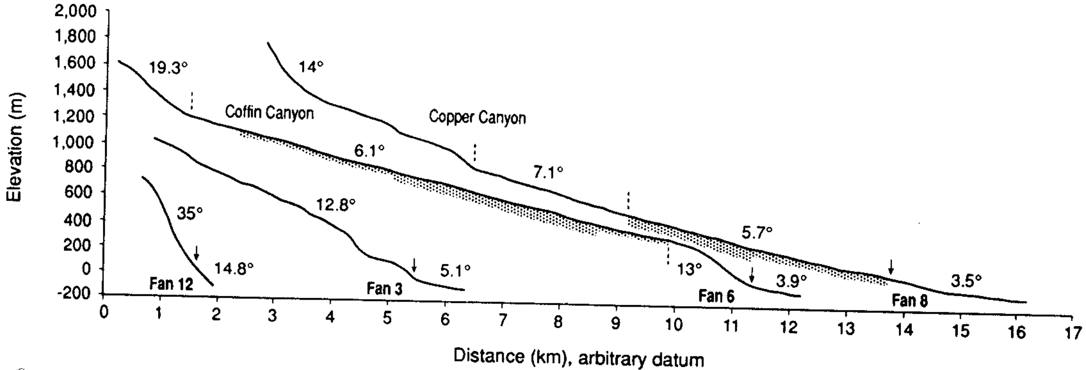


Figure 14.16 Long profiles of the feeder channels for four fans in the vicinity of Copper Canyon, Death Valley (see Fig. 14.17 for planview locations). Average slopes of the feeder channel or segments thereof are labelled. The stippled pattern denotes segments containing stored sediment. Zones of greatest sediment storage are denoted by the thickest pattern. Vertical exaggeration is 2.5. Vertical datum is mean sea level.

drainage basin enlargement because sediment can be maintained either as side-sloping colluvium or as deposits on the feeder-channel floor. The principal effects of sediment storage in the feeder channel are lower fan sedimentation rates and, in the extreme case, the trapping of sediment-gravity flows that do not have the runout capability to continue past the lower-gradient zones to the fan site. This selective trapping of sediment-gravity deposits increases the volume of fluid-gravity deposits at the fan site inasmuch as they can readily bypass the lower-gradient zones.

The volume of material stored in a feeder channel is variable, depending upon the long profile characteristics and the width of the reaches conducive to storage. Feeder channel long profiles can range from consistently steep to step-like (Fig. 14.16). The reaches of reduced slope in stepped feeder channel profiles may be sufficiently gentle to instigate deposition from catastrophic flows. The volume of material that can accumulate in these gently sloping reaches increases with increasing channel width. Two examples of feeder channels that have stepped profiles containing zones of sediment storage are the Coffin Canyon and Copper Canyon fans of Death Valley. Feeder channel erosion appears to be dominant in the reaches of these channels with slopes of greater than 7°, whereas at least some sediment aggradation has occurred in reaches with lesser slopes (Fig. 14.16).

The ability of the feeder channel to store sediment commonly increases with increasing drainage basin size, probably reflecting structural complexities in the underlying bedrock. This relationship is illustrated by the 14 neighbouring fans and cones located in the vicinity of Copper Canyon in south-eastern Death Valley. The drainage basins of these features vary in area from $<0.5\,km^2$ to $10\,km^2$ (Fig. 14.17). The two largest fans, Copper Canyon and Coffin Canyon, have relatively large drainage basins characterized by third- and fourth-order feeder channels (Fig. 14.17). Second-order channels make up the feeder channels in the four intermediate-sized drainage basins (numbers 1, 3, 4, and 9 of Fig. 14.17). The eight small fans or cones have equally small drainage basins containing just first-order channels (Fig. 14.17). Essentially all stored sediment in this region occurs in the two largest drainage basins (Copper and Coffin Canyons) and is concentrated in their highest-order channels (Fig. 14.17).

The initial shape of a fan's drainage basin and the basin's subsequent evolution are largely a product of (a) inherited local and regional structures and discontinuities such as faults, joints, and geological contacts, (b) newly imposed structural discontinuities, and (c) bedrock lithology. In general, fractured zones or other forms of geological discontinuities, whether inherited or newly created, become the locus of drainage basin development because these zones erode more quickly relative to adjoining ones. The significance of these variables, though poorly understood, can be demonstrated by the example from Death Valley. A comparison of the bedrock and structural geology in the drainage basins of the 14 fans and cones in the vicinity of Copper Canyon illustrates important interrelationships between fan and drainage basin evolution (Figs 14.17 and 14.18). One common relationship is the location of feeder channels, particularly in the area immediately upslope from the fan apex, directly along faults that trend at a high angle to the main mountain front faults (note fans 1, 2, 3, 4, 6, 7, and 9

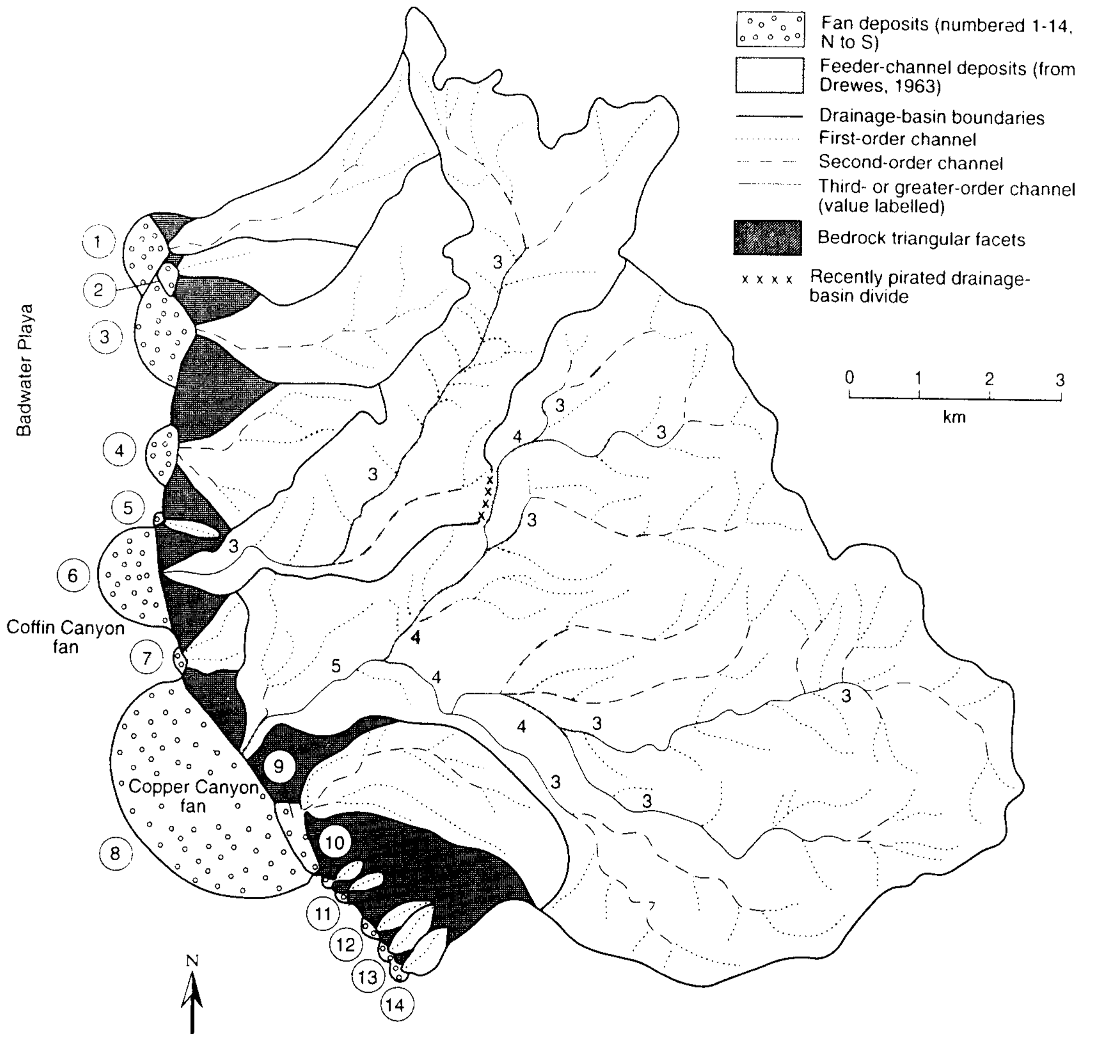


Figure 14.17 Channel distribution in the drainage basins of 14 alluvial fans and cones in the vicinity of Copper Canyon, south-eastern Death Valley. Uncircled numbers denote channel order, whereas patterned areas identify alluviated reaches of the feeder channels according to Drewes (1963). Circled numbers identify each of the 14 fans or cones.

in Figs 14.17 and 14.18). This relationship is caused by and illustrates the promotion of weathering and erosion along fracture zones. These zones likely represent structural discontinuities established prior to the onset of the present tectonic setting in which fan deposition is occurring. Another example of how inherited structures affect drainage basin and fan development is the Copper Canyon system. This basin is centred on a major down-dropped block, the surficial part of which is composed of relatively soft Miocene and Pliocene sedimentary rocks (fan 8, Figs 14.17 and 14.18). The resultant high sediment yield in this drainage basin has produced the largest fan in this sector of Death Valley. By contrast, fans or cones 5, 10, 11, 12, 13, and 14 (Figs 14.17 and 14.18) are relatively small, in large part because their drainage basins are developed along relatively unfractured anticlinal structures in Precambrian metasedimentary rocks. The lack of fracturing, relative youth of the structures, and low erodibility have resulted in, at most, only incipient fan and drainage development.

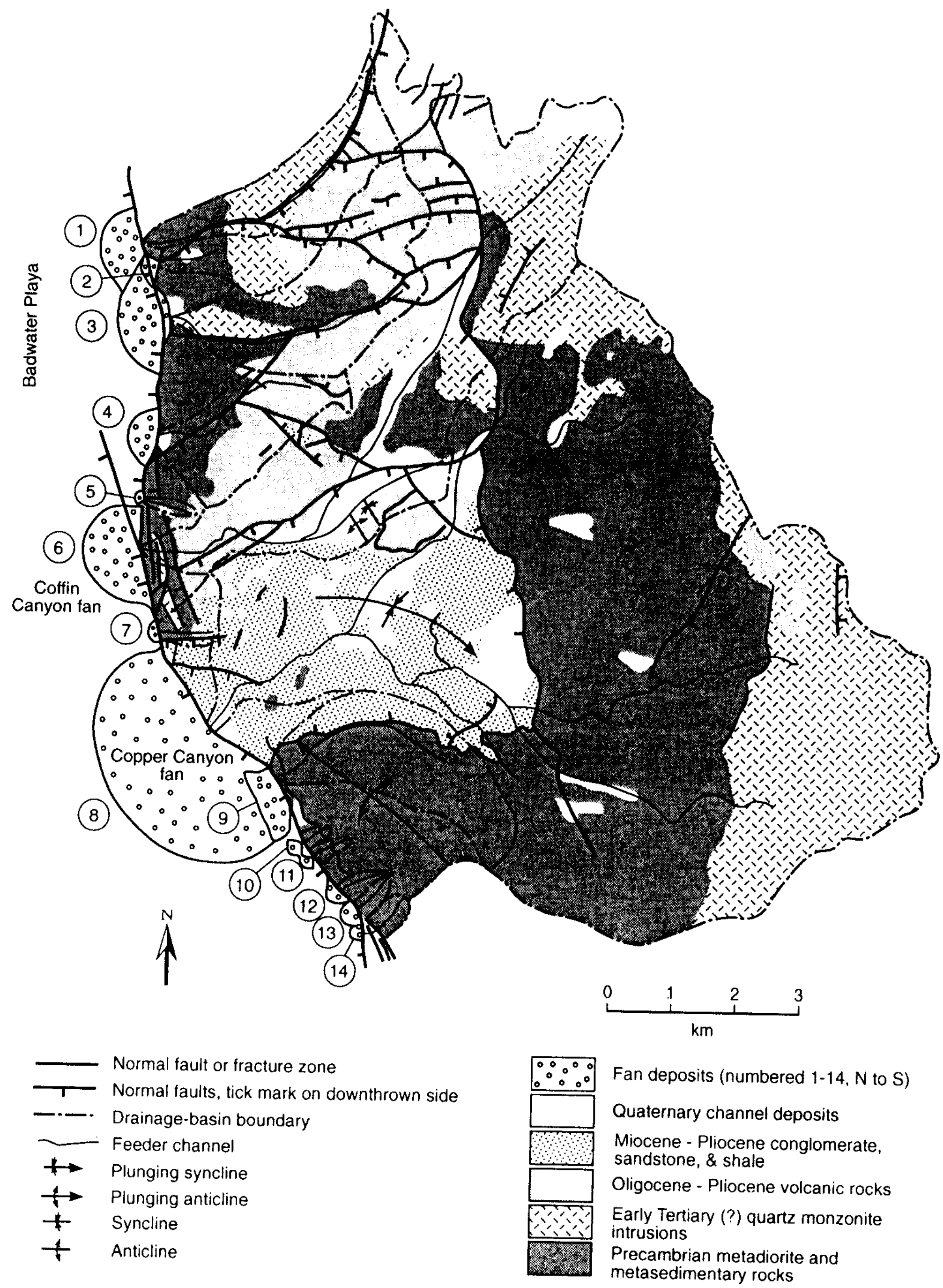


Figure 14.18 Bedrock and structural geology of the drainage basins of 14 alluvial fans and cones in the vicinity of Copper Canyon, Death Valley (after Drewes 1963). Fan feeder channels also are denoted.

EFFECTS OF NEIGHBOURING ENVIRONMENTS

Aeolian, fluvial, volcanic, lacustrine, or marine environments that border alluvial fans can impact the operative fan processes by modifying the conditions of deposition at the fan site. Aeolian activity can be detrimental where windblown deposits interfere with the fan processes. Aeolian sandsheet or dune complexes along the toes of fans commonly limit the runout distance of water flows or debris flows, inducing deposition in ponds (Fig. 14.19a). Aeolian deposits may migrate on to the medial or proximal fan, more seriously disrupting the primary depositional processes. The migration of a sand erg to the proximal part of the fans in northern Panamint Valley, California, for example, has caused debris flows to become impounded in the proximal zone, increasing the aggradation rate there at the expense of the distal region (Anderson and Anderson 1990).

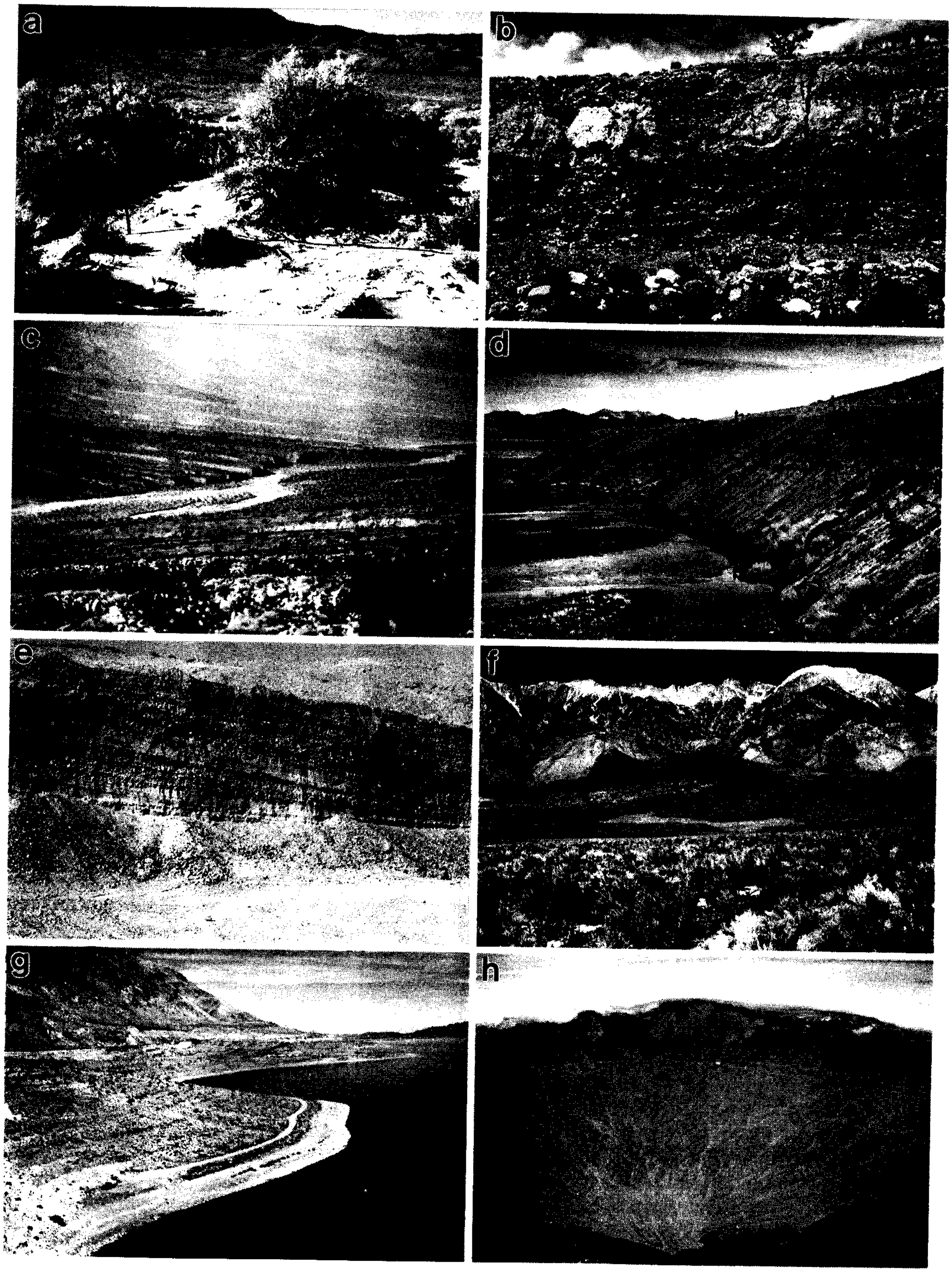
Aeolian fine sand and silt also have greatly modified the primary processes active on alluvial fans in the Alamogordo area of south-central New Mexico. An influx of aeolian sediment during the middle Holocene has caused the sedimentary processes on the Alamogordo fan, located along the front of the Sacramento Mountains, to change from principally sheetflood to channelized flow (Fig. 14.19b). This change resulted from the cohesive strength of the invading silty aeolian sediment which led to bank stability, thereby favouring channelized flows rather than sheetfloods. In another case on the nearby western Jarilla Mountain piedmont, aeolian sandsheet deposition has been so high relative to fan activity that fan sedimentation has been reduced to just minor alluvial activity in isolated arroyos cut into the aeolian deposits (Blair *et al.* 1990).

Fluvial environments, usually in the form of longitudinally oriented ephemeral or perennial rivers, may alter fan processes by eroding their distal margins and steepening the overall slope. An example is where Death Valley wash has incised the toes of converging fans in northern Death Valley (Fig. 14.19c). Another example is from near Schurz, Nevada, where the Walker River has eroded part of the distal Deadman Canyon fan, distributing the sediment into the river's floodplain (Figs 14.1 and 14.19d).

The occurrence of either lacustrine or oceanic water bodies marginal to fans can have a profound effect on the fan processes. Subaerial fan flows quickly transform into other features, such as Gilbert-delta foresets, upon reaching a shoreline (Fig. 14.19e) (Sneh 1979, McPherson *et al.* 1987). This situation limits the runout distance of fan processes, causing aggradation higher on the fan than normally would occur. The slopes of the distal fan inundated by either lake or marine waters may be significantly steepened as the result of concentrated proximal fan aggradation or from erosion by waves or longshore currents (Fig. 14.19g). Subsequent drops in water level can expose oversteepened lower slopes, across which subaerial primary flows accelerate instead of the more common deceleration that occurs in the distal fan (Fig. 14.19h). Beach, longshore drift, or shoreface accumulations on these eroded margins (e.g. Link *et al.* 1985, Beckvar and Kidwell 1988, Newton and Grossman 1988), alternatively, may create benches or ridges that can locally impound the primary flows. Flat-lying evaporitic peritidal or playa environments may develop in the distal fan area (e.g. Hayward 1985, Purser 1987), inducing particle weathering and inciting primary fan flows to undergo deposition due to a pronounced slope reduction (Fig. 14.19h).

Volcanism may strongly affect fan processes by depositing ash either in the drainage basins or

Figure 14.19 Effects of neighbouring environments on alluvial fans. (a) Aeolian sandsheet deposits flanking the distal margins of the Shadow Rock and Trollheim fans, Deep Springs Valley. (b) Quarry cut 5-m-high in upper Holocene deposits of the medial Alamogordo Canyon fan, south-central New Mexico. An influx of aeolian sediment (light grey) changed the transportational processes of the fan gravels (dark grey) from sheetflooding in the lower part to channels in the upper part. This change was caused by the higher resistance of the loess to erosion, resulting in the maintenance of channel walls. (c) 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 longitudinally oriented Death Valley wash. (d) Erosion into the distal Deadman Canyon fan (vertical wall) resulted from the lateral migration of Walker River, near Schurz, Nevada. Geologist (upper centre) for scale. (e) Gilbert foresets approximately 3 m thick on the distal part of the Rose Creek fan near Hawthorne, Nevada. These foresets resulted from the transformation of debris flows upon their passage into the lake below a past shoreline. (f) View of fan along the Inyo Mountains in central Owens Valley that is completely covered by rugged Holocene basalt flows (black). (g) Extensive erosion by waves and longshore currents has occurred on the fans adjoining Walker Lake, Nevada. Vehicle (lower left) for scale. The now-exposed lower segments of these fans have a much greater slope than the upper segment due to this erosion. (h) Aerial view of the Coffin Canyon fan prograding into the flat Badwater playa in Death Valley. Individual debris flows (tongues extending from the distal margin) reaching this playa undergo deposition due to the rapid lowering of slope. Van (upper centre) for scale.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directly on the fan, causing an interference of flows at the fan site, and potentially instigating debris flows on steep drainage basin slopes (McPherson *et al.* 1985). Volcanic flows emanating from mountain front faults may also cause barriers to sediment transport on the fan surface, in extreme cases armouring the entire fan with almost unerodible basalt (Fig. 14.19f).

CLIMATIC EFFECTS

Climate is widely considered to be a major control on the types of sedimentary processes found on alluvial fans on the basis of net water availability, which affects bedrock weathering and sediment generation, potential sediment transport mechanisms, and vegetation cover. Research on the interaction between climatic variables and their effect on alluvial fan development remains in its infancy due to the complexities of this interaction and the overall lack of study. Two directions of research have emerged. One deals with the specific effects of climatic variables on sediment yield such as precipitation patterns, temperature, and vegetation. The second involves the relationships between fan processes and more broad climatic regimes of deserts versus non-deserts.

Effects of Climatic Variables on Fan Development

Three interrelated, climatically controlled variables that have received some assessment with regard to fans are precipitation amounts and patterns, temperature, and vegetation. All of these variables are relevant to fans inasmuch as they affect bedrock weathering rates, sediment yield, and the recurrence interval of catastrophic sediment transport from the drainage basin. The most basic aspect of precipitation is the mean annual amount, which affects weathering rates, vegetation, and transportational rates. Without rainfall, weathering and transportational events would be inoperative, and vegetation extremely sparse. However, even with minimal precipitation weathering and fan aggradation will take place, as exemplified by Death Valley with its very low 43 mm of annual precipitation.

Two other, and perhaps more significant, aspects of precipitation are the intensity of individual events and their frequency (e.g. Leopold 1951, Caine 1980). Both of these variables affect the infiltration capacity in the drainage basins, which must be exceeded before overland flow and potential sediment transport can commence. Infiltration capacity is exceeded and discharge events generated either by intense rainfall or by relatively normal rainfall following adequate antecedent precipitation (Ritter 1978, Cannon and Ellen 1985, Wieczorek 1987). Discharge is generated in the latter case if the infiltration capacity is unable to return to its original high value by slow percolation or evaporation. The effects that these aspects of precipitation may have on fan construction are profound. For example, areas of low precipitation, such as Death Valley, potentially can have more active fan accumulation than significantly more moist deserts because precipitation characteristically occurs in the more effective, high-intensity thunderstorm style. Alternatively, the sediment production rate in the drainage basin will likely be higher in more moist deserts (e.g. Langbein and Schumm 1958), making more sediment available for potential transport.

The effect that temperature has on fans is more poorly understood. It is likely significant, however, due to the fact that the rates of bedrock weathering reactions increase exponentially with temperature. Temperature gradients caused by the orographic conditions in a drainage basin may result in an initial decrease in weathering rates upslope due to decreasing temperature followed by an increase in weathering rates at higher altitudes as freeze–thaw 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 considered an important control on sediment yield from a drainage basin. Inasmuch as vegetation reflects the climate, it is usually described as a climatic variable. One effect attributed to plant cover is an increase in the production of clay in the drainage basin due to the enhanced chemical weathering caused by organic acids in the vicinity of roots, and due to the greater preservation of soil moisture (e.g. Lustig 1965). Vegetation also affects sediment slope stability by strengthening its resistance to gravity as a result of the increased shear strength caused by rooting (Greenway 1987, Terwilliger and Waldron 1991). 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). Alternatively, plants may serve to produce long-term slope 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 natural fires or from human-caused activities like agriculture (e.g. Wells 1987).

Relationships Between Fans and Broad Climatic Zones: the Question of 'Wet' and 'Dry' Fans

A second research direction with regard to the climatic control of fan development is characterized by attempts to associate the prevalence of certain process types operative on fans within the broad desert (dry) versus non-desert (wet) climate classification. The central point of discussion in this realm of research is the idea that debris flow processes are most prevalent on fans of arid and semi-arid climates, and water-flow processes in climates with greater rainfall. This hypothesis can be traced back at least to Blackwelder (1928), who attributed the lack of vegetation on drainage basin slopes, a feature best met in desert settings, as one of the criteria needed to optimize debris flow generation. A plethora of scientific articles has since negated this concept by clearly demonstrating the common occurrence of debris flows in non-desert settings around the globe (see Costa 1984 for a review). In fact, debris flows may be more common in the temperate and wet climates than in desert climates due to the greater production of clay from bedrock resulting from higher chemical weathering rates. Additionally, and as previously discussed, the presence or absence of debris flows on fans primarily is a function of the bedrock lithology and morphology of the drainage basin rather than of climate.

Unfortunately, there has been a rekindling of the notion of a climatic classification of alluvial fans during the last 15 years on the basis of assuming that certain processes are only effective under certain climatic conditions. For example, the adjectival terms 'dry' and 'mudflow' were introduced for fans 'formed by ephemeral stream flow', and 'wet' for fans 'formed by perennial stream flow' (Schumm 1977, p. 246). This relationship incorrectly assumes that fans traversed by perennial rivers cannot be dominated by debris flows, and that those traversed by ephemeral channels cannot be dominated by water flows. Further, the wet fan example provided by Schumm is the Kosi River of north-eastern India, a perennial river on an alluvial plain that lacks fan morphology and has an imperceptible slope of 0.02°. The geomorphologic and sedimentologic characteristics of the Kosi River are of a low-gradient river system that bears no resemblance to an alluvial fan (Rust and Koster 1984).

Subsequently, dry (debris flow) fans were classified as those formed in arid or semi-arid regions, and wet (or fluvial) fans as those formed in humid regions (McGowen 1979, p. 43). This association fails to acknowledge the presence of debris flows and water flows on fans in desert and non-desert settings alike. Like Schumm, McGowen envisaged wet fans as those dominated by fluvial deposits. However, the examples given, namely the Kosi River of north-eastern India and the braided proglacial streams of south-eastern Alaska (Boothroyd 1972), are simple fluvial systems unrelated to alluvial fans as either originally defined or in basic sedimentologic and morphologic character. The classification of the expanding reaches of the Alaskan proglacial braided river channels having average slopes of <0.5° as fluvially dominated humid climate alluvial fans was made solely on the basis of a comparable planview braided distributary channel pattern. A marriage between Bull's (1972) 'braided distributary fan' concept and that of a fluvial-dominated, wet fan type (Boothroyd and Nummedal 1978, McGowen 1979) resulted. This fluvial or wet fan model is flawed in three respects: (a) the braided distributary channel pattern displayed on fans is a secondary rather than primary process, (b) the almost imperceptible slopes of proglacial braided rivers are readily distinguishable from their high-sloping alluvial fan counterparts, and (c) the principally lower-flow-regime conditions and resultant sedimentary structures of braided rivers, including trough and planar crossbedding, are easily differentiated from those occurring on fans, where deposition is mostly by catastrophic sediment-gravity processes or by fluid-gravity processes characterized by upper-flow-regime conditions. These fundamental differences in process and product between fans and fluvial systems are a direct reflection of the higher slope values of fans (2–20°) relative to fluvial systems (<0.5°).

TECTONIC EFFECTS

The most common and favourable conditions for the development and long-term preservation (especially with regard to the rock record) of alluvial fans exist in tectonically active zones that juxtapose mountainous uplands and lowland valleys. The creation and maintenance of relief by tectonism has an exponential effect on sediment yield by creating relief (Schumm 1963, 1977, Ahnert 1970). Without continued tectonism to maintain relief, fans may be minor and short-lived features, ultimately characterized by substantial secondary reworking. A possible example of well-studied fans of this style includes those in Spain developed adjacent to topographically expressed compressional structures formed prior to the middle Miocene (e.g. Harvey 1984a, 1988). This scenario contrasts with an active tectonic setting such as an extensional basin, where relief and the mountain-to-valley topographic configuration can be maintained for ≥50 million years, and where individual fans may be active sites of net aggradation for 1 to 7 million years (e.g. Blair 1987b, Blair and Bilodeau 1988). Extensional and translational tectonic settings are most conducive to sustaining the optimal conditions for fan development, including the maintenance of relief and the stabilization of both the mountain front boundary and the fan site. The laterally moving structures of compressional tectonic regimes are much less conducive to fan development due to the unstable position of the mountain fronts, which, through time, result in the destruction of fan sites.

The more detailed characteristics of tectonism, including rates and occurrence of uplift, downthrow, and lateral displacement, will greatly influence the overall form and development of the fan and to a lesser degree the nature of the fan processes and deposits. Even within a singular tectonic regime, such as the extensional Basin and Range province, variations in tectonism at all scales can be reflected in the alluvial fans. Examples of fans reflecting small-scale variations in tectonism are those that have developed along the active range front fault in south-eastern Death Valley in the vicinity of Coffin Canyon (Figs 14.17 and 14.18). Subsidiary structures and inherited structures there have had an important effect on sediment yield and drainage basin development as demonstrated by the major variations in fan and drainage basin size. A larger-scale example of tectonic variation in the Basin and Range province that may affect fan development is provided by a map plotting the coeval ages of most recent faulting (Thenhaus and Wentworth 1982, Wallace 1984b). This map demonstrates numerous subprovinces differentiated on the basis of the age of the most recent fault activity, including those characterized by historical, pre-historical Holocene, late Quaternary, or pre-late Quaternary faulting. The map also illustrates the dynamic character of tectonism in a setting like the Basin and Range province.

Tectonism is also a major control on fan processes and deposits through the indirect and often complex influence it has on climate and vegetation in the drainage basin. For example, changing uplift rates may adjust elevation and, in turn, the climate and vegetation of the drainage basin, possibly causing changes in weathering or erodibility of the bedrock. As a result, the important fan variables of sediment supply rate, sediment calibre, and the water-to-sediment ratio 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, can be differentiated on the basis of origin and scale. Constituent forms are herein defined as morphological features that have resulted directly from the primary and secondary processes building and modifying the fan or from external effects such as faulting or interactions with neighbouring environments. The scale of the constituent forms is small, usually only a fraction of the size of the whole fan. These features contrast with the overall fan morphology, or the composite form, which represents the consequential or resultant shape of all of the constituent forms.

CONSTITUENT MORPHOLOGY

The most prominent constituent form on an alluvial fan usually is the incised channel, which may range from 2 to 150 m in width and have nearly vertical walls 1 to 20 m high (Figs 14.12 and 14.15b). The incised channel can extend down-fan from the apex for tens to hundreds of metres. Smaller forms may be present within incised channels, including terraces or debris flow plugs with relief of 0.5 to 1.5 m (Fig. 14.12d). Smaller-scale (≤0.5 m high) erosional forms such as rills or boulder deposits usually are present in this channel (Figs 14.12 and 14.13b). Clast-poor debris flows may also be present, producing a smoothed channel floor (Fig. 14.12b).

Many constituent morphological features on a fan have less than 2 m of relief and a lateral extent of several tens of metres. Rock avalanche tongues and clast-rich debris flow lobes and levees produce an irregular morphology, particularly in the proximal fan, with relief commonly of 0.5 m to 1.5 m (Fig. 14.10). Individual lobes may be 2 to 10 m across and extend tens to hundreds of metres in a down-fan direction (Fig. 14.10a). Jams of sheetflood boulders may also have a relief of 0.5 to 1.5 m and extend laterally for hundreds of metres. Erosive secondary forms, including gullies (Figs 14.10e and f, 14.11b, 14.13c, f, and g, 14.15c, and 14.19c) and winnowed mantles (Fig. 14.13d), may also produce features with this scale of relief and may extend laterally for several metres. In contrast, near-vertical fault scarps, developed as a result of offset of the fan sediment, can create walls up to 40 m high typically oriented parallel to and commonly occurring near the mountain front (Fig. 14.14c).

Lower-relief forms (≤0.5 m high) that extend laterally for tens to hundreds of metres also are common on fans. Rills produced by secondary erosion typically have a relief of less than 25 cm (Figs 14.13e and 14.15d). Rodent colonies may create mounds of sediment ≤50 cm high and several metres across (Fig. 14.14b). Sediment-deficient sheetfloods can produce transverse ribs 20 cm high distributed over whole fan lobes (Fig. 14.11d). Sediment-laden sheetflood and clast-poor debris flows may produce nearly smooth areas on the fan that can extend laterally for tens to hundreds of metres (Figs 14.10g, 14.11c and 14.13a). Smooth fan surfaces also can be formed by overland flow and aeolian winnowing (Fig. 14.13c and d).

Neighbouring environments may create externally induced constituent forms on the fans. For example, viscous volcanic flows such as basalt may irregularly cover fans, creating relief 0.1 to 3.0 m high and elongated parallel to fan slope (Fig. 14.19f). Aeolian sand-dune or sandsheet deposits 1 to 30 m high may migrate on to the fan, significantly altering its form (Fig. 14.19a). Coppice dunes create mounds 1 to 10 m across and 0.5 to 4.0 m high. Lateral migration by rivers may result in the erosion of distal fan sediment, leaving cuts 1 to 10 m high extending along the edge of the fan (Fig. 14.19d). Lake or marine water bodies impinging on the fan can also cause significant erosion of the fan margins or deposit shore-linear features such as spits, bars, and beach ridges (Figs 14.2c and 14.19g).

Constituent forms generally are not studied or portrayed in cross-fan or radial fan profiles because their relief (usually ≤2 m) is less than the contour interval commonly used on conventional topographic maps in mountainous terrain (typically 10 m). Constituent features such as incised channels, levees, and lobe boundaries, may be readily discernible if detailed maps with 1-m-interval contours are available (e.g. Fig. 14.20).

COMPOSITE MORPHOLOGY

The overall fan form, or composite morphology, is characterized by planview shape, the presence or absence of an incised channel, and radial and cross-fan profiles. Composite fan forms have been the subject of more study than the constituent forms because they can be identified using conventional topographic maps combined with aerial imagery.

Planview Shape and Incised Channels

The planview shape of an alluvial fan where it ideally is allowed to aggrade without lateral constrictions is semi-circular (Fig. 14.1d). Lateral constriction, however, usually occurs due to the presence of neighbouring fans, which cause the fan radii to become elongated perpendicular to the mountain front (Fig. 14.1b and c). Radial growth may also be limited by perennial lakes, marine embayments, aeolian sandsheets, or rivers that erode or overtop the distal fan. These distal environments can result in a preferential shortening of the fan radii perpendicular to the mountain front (Fig. 14.19g).

The presence or absence of a prominent incised channel on the proximal part of the fan is another important feature of the composite fan morphology. Such channels extend the fan's radial length by acting as conduits for water flows and sediment-gravity flows, positioning the active depositional lobe farther from the mountain front than on fans lacking incised channels. Their presence results in greater travel distances for primary processes, promoting fan extension by lobe progradation. Incised channels, therefore, are more likely to be present and have greater length on fans with progressively longer radii.

Radial Profiles

The radial fan profile is probably the most significant feature of the composite morphology inasmuch as it is a measure of the slope affecting sedimentary flows down the fan surface. The two main factors controlling the average slope and variations in slope along the radial profile are (a) the dominant processes operative on the fan and (b) the sediment size available for fan construction. The composite radial profile reflects the types of processes that build the fan inasmuch as differences in the physical properties of each process gives rise to deposits with varying slopes (Blissenbach 1954). Freefall accumulations such as talus form the steepest slopes, typically between 30 and 40° (Fig. 14.21). Freefall material mixed with other sediment-gravity flow types such as debris flows, rock avalanches, and gravity slides, create fan slopes ranging from 10 to 30° (Fig. 14.21). Clast-rich debris flows or bouldery sheetflood deposits more typically build fans with slopes between 5 and 15°, whereas fans dominated by sandy, pebbly, and cobbly sheetflooding or clast-poor debris flows have the lowest slopes, about 2 to 6° (Fig. 14.21). Distal accumulations such as sandskirts decrease the average fan slope, as do incised channels that promote aggradation in a progressively more distal direction (e.g. Drew 1873).

Another important factor in determining a fan's radial slope is the size of the sediment used to construct the fan (Tolman 1909, Blissenbach 1952). A direct relation exists between fan slope and gravel

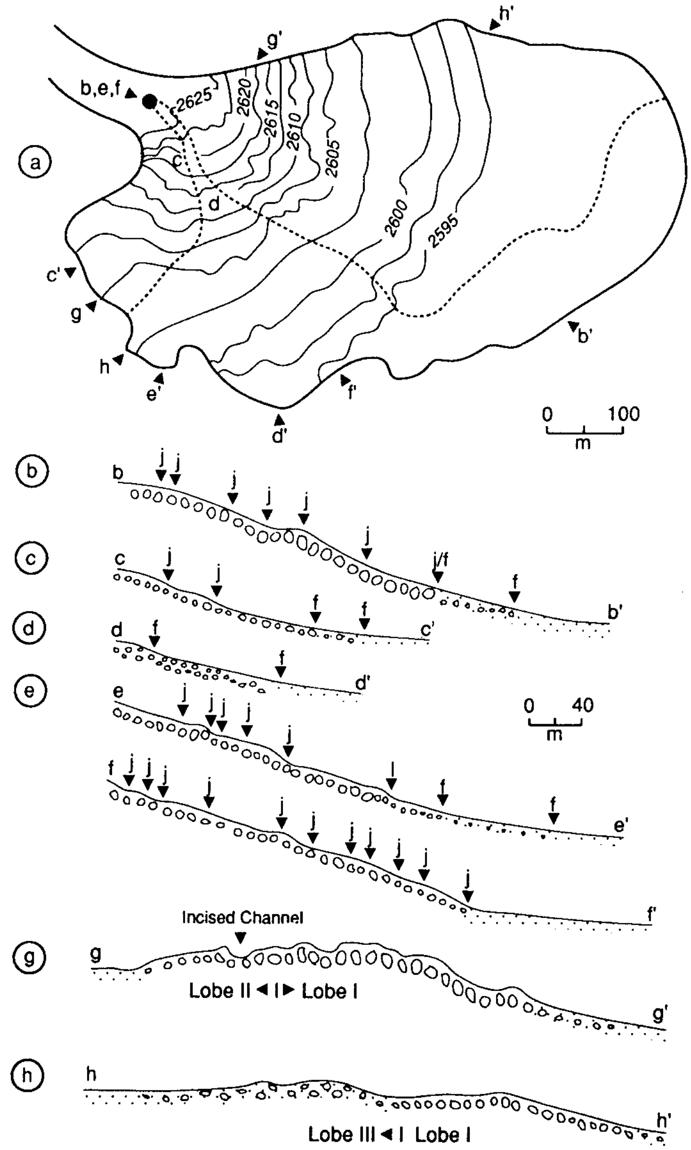

Figure 14.20 Radial and cross-profiles of lobes and transects of the Roaring River alluvial fan, with some constituent forms labelled (after Blair 1987a). Arrows point to segment boundaries, which are caused by boulder-log jams (j), facies changes (f), or lobe boundaries (l). Vertical exaggeration of the profiles is 2.5.

size, with fan slope increasing as grain size increases. The depositional slope of a fan sector underlain by boulder deposits, therefore, is greater than that of a fan sector underlain by pebbles or sand. An example of this relation is the sheetflood deposits of the Roaring River fan (Blair 1987a). The slope of this fan is 6 to 10° where underlain by boulders, 4 to 6° where fine boulders and cobbles are present, 2 to 4° in the sandy pebble gravel sector, and 1.4 to 2.0° in the distal sandskirt region (Fig. 14.20).

The radial fan profile also can be modified by erosional or depositional processes related to adjacent environments. Shoreface erosion by Walker Lake, for example, has steepened the distal part of some of the fans in this valley from 3.6° to 7.8° (Fig. 14.19g). In contrast, deposits by shoreline processes on parts of the neighbouring fans have lowered the

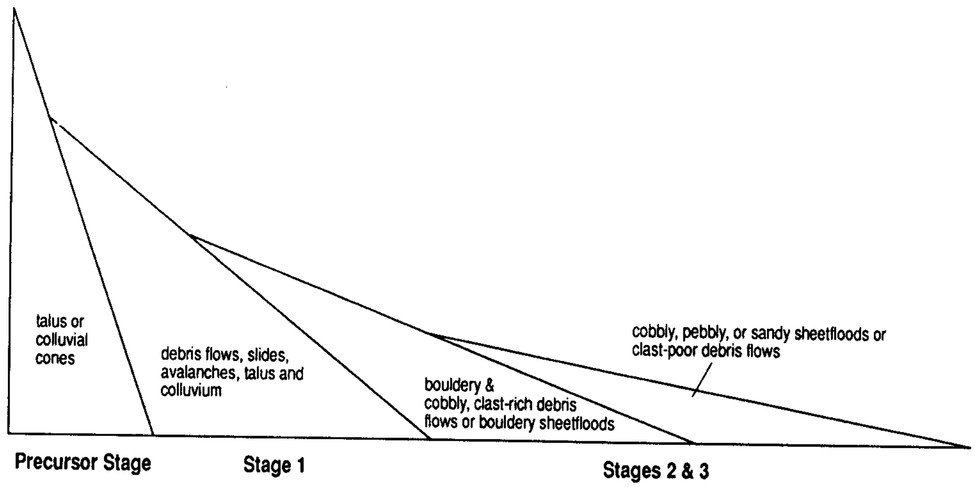

Figure 14.21 Schematic diagram of the slopes, drawn with a 2× vertical exaggeration, of various associations of primary processes commonly operative on alluvial fans. Depositional slopes increase towards the left, fan radii lengthen towards the right, and knickpoints decrease in elevation towards the right. Stages refer to the common depositional and morphological evolutionary schemes that fans ideally follow as they increase in size.

average fan radial slope or made it more irregular.

The radial profile of a fan not modified by neighbouring environments displays one of the following three styles: (a) a relatively constant slope, (b) a distally decreasing slope, which gives rise to a concave-upwards geometry, or (c) a segmented slope (Figs 14.5 and 14.20). Constant slopes are typical of fans in which only one primary process type is operative and where there is no marked decrease in grain size down-fan. The debris flow dominated fans of Death Valley demonstrate this relationship (Fig. 14.5). In contrast, fans with pronounced downslope decreases in grain size, such as from boulders to sand, are characterized by radial profiles with a concave-upwards geometry associated with distally decreasing slope values. The profile may be accentuated by radial variations in process type, such as from rock avalanche deposits in the proximal fan to sheetflood deposits in the distal fan.

Segmented fans are those with radial profiles characterized by two or more sectors, each with a constant slope angle, but with values that differ from the adjoining sectors, decreasing down fan (Bull 1964a). This profile type is similar to a distally decreasing one except that slopes change in value at inflection points rather than in an exponential fashion. Development of segmented profiles has been attributed to either a change in slope of the feeder channel caused by rapid and intermittent tectonic uplift of the mountains, base level change, or climate change (Bull 1964a). In the case of the western Fresno County fans, Bull (1962) favoured a change in channel slope due to uplift of the drainage basin. In contrast, segmentation of the radial profiles of fans in Death Valley has been attributed to tectonic rotation of the fans themselves (Hooke 1972). Blair (1987a), who was able to construct radial profiles of the Roaring River fan with the constituent forms identified, demonstrated that radial profile segmentation on this fan resulted from intrinsic causes, including (a) simply crossing from one fan lobe to the next along profile, (b) crossing from one constituent form to another along profile, or (c) from inflections in slope caused by sharp, down-fan changes in sediment size (Fig. 14.20). The same types of intrinsic sedimentological causes of segmentation present on the Roaring River fan may also have created this pattern on other fans where it has been attributed to the extrinsic effects of climate or tectonism (Blair 1987a).

Cross-fan Profiles

Cross-fan profiles, in contrast to radial profiles, are a poorly studied characteristic of the composite fan morphology. They generally have an overall plano-convex geometry, although variations exist. Cross-profiles from the upper part of the fan, for example, have greater amplitude than those from the lower fan (Fig. 14.4). The height of the cross-profiles may vary between fans due to differences in relief caused by changes in the grain size or the operative

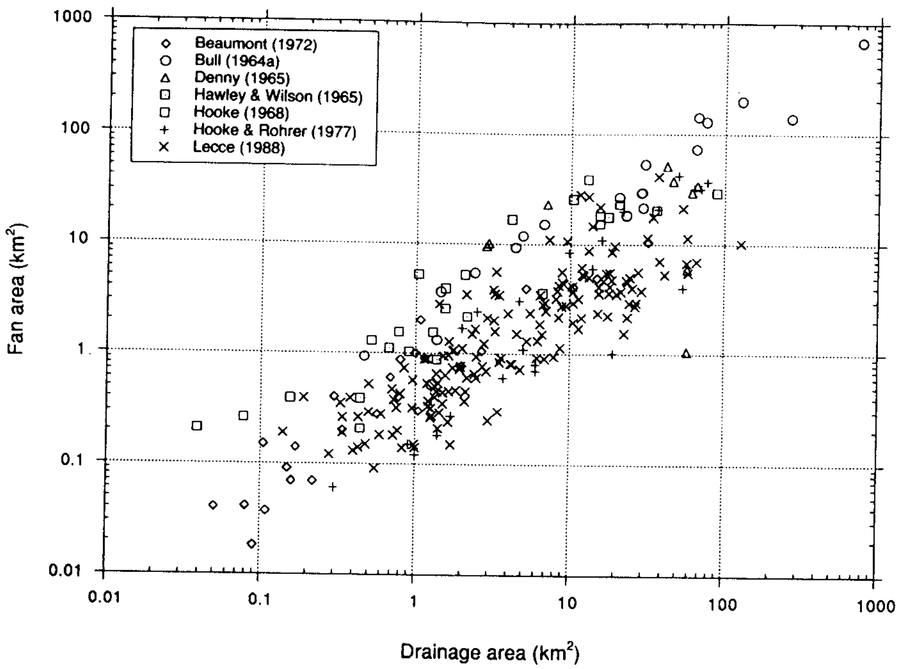

Figure 14.22 Log–log plot of drainage basin area versus fan area based on a compilation of data from published sources.

depositional process. Irregularities also may be caused by constrictive or erosive lateral environments (Fig. 14.4). Although essentially unstudied, cross-profiles also differ between fans as a result of the variable distribution of the constituent forms. On the Roaring River fan, for example, cross-profiles are asymmetric due to the spatial distribution of the lobes (Fig. 14.20). Variations in texture within individual lobes on this fan, such as in Lobe I, also cause irregularities in this cross-profile, as does the position of the incised channel.

MORPHOMETRIC RELATIONSHIPS BETWEEN ALLUVIAL FANS AND THEIR DRAINAGE BASINS

RELATIONSHIP BETWEEN FAN AREA AND DRAINAGE BASIN AREA

The most widely compared features of the composite fan and its drainage basin are their respective planview areas, which have a positive correlation (Fig. 14.22) (Bull 1962, 1964a, 1977, Denny 1965, Hawley and Wilson 1965, Hooke 1968, Beaumont 1972, Hooke and Rohrer 1977, French 1987, Lecce 1988, 1991). The association of small fans with small drainage basins and large fans with large drainage basins is intuitively obvious since the movement of sediment from the drainage basin to the fan serves to increase both the size of the fan and the size of the drainage basin. The relationship usually is given quantitatively as

$$A_f = cA_d^n$$

where A_f is the area of the fan, A_d is the area of the drainage basin, and c and n are empirically determined constants. The exponent n varies from 0.7 to 1.1, whereas c is even more erratic, ranging from 0.1 to 2.2 (Harvey 1990). Attempts also have been made to isolate the effect of variables on this relationship, usually with conflicting results. For example, Bull (1964a, b) concluded in his study of western Fresno County fans that drainage basins underlain by erodible lithologies such as shale produce larger fans per unit of drainage basin area than basins 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 drainage basin area where derived from very resistant bedrock such as quartzite.

It is clear from the data plotted in Fig. 14.22 that there is a general trend of increasing fan area with

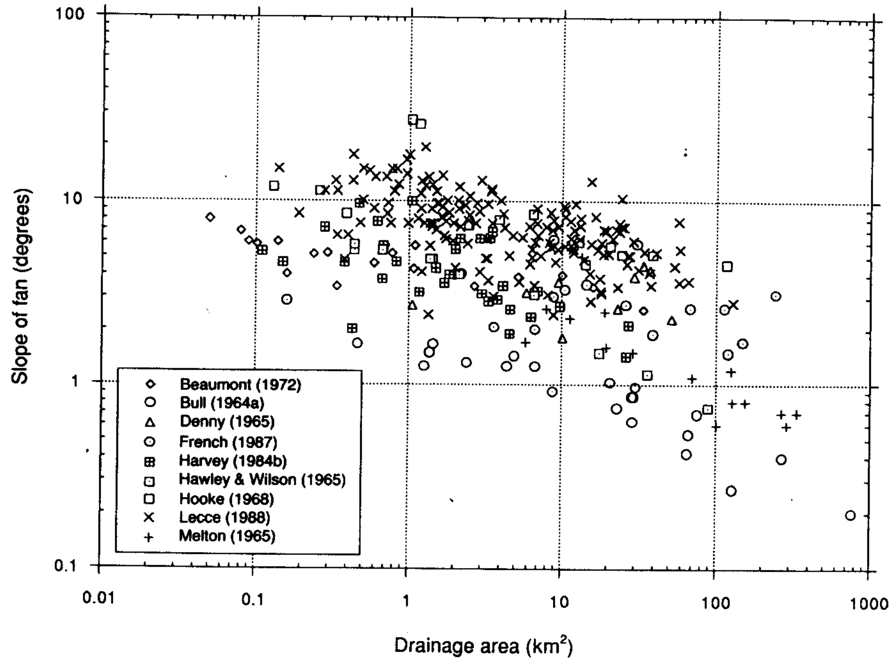

Figure 14.23 Log–log plot of average fan slope versus drainage basin area based on a compilation of data from published sources.

drainage basin area. The wide scatter of the data, however, indicates that this relationship is exceedingly more complex than has been suggested. First, there is an obvious problem of whether the assumption of comparing only the planview areas of three-dimensional features has mathematical merit (Lustig 1965). Second, it should not be surprising that this relationship is more complex than portrayed when the multitude of variables affecting the fan area and drainage basin area are considered. Variables such as drainage basin relief and altitude, fan relief and depth, stream piracy in the drainage basin, tectonic beheading of fans, the operative sedimentological processes, the effects of inherited and local structures or geological discontinuities, the drainage basin bedrock lithology, the degree of aerial constriction of the fans, and the interplay of environments that border the fans all combine to greatly influence fan area and drainage basin area.

FAN GRADIENT VERSUS DRAINAGE BASIN SIZE

Drew (1873) observed that fans with relatively large drainage basins had lower average slopes than those with smaller drainage basins. This relation has been quantified by others during the last 30 years (e.g. Bull 1962, 1964a, Denny 1965, Hawley and Wilson 1965, Melton 1965, Hooke 1968, Beaumont 1972, French 1987, Harvey 1987, Lecce 1988, 1991) and is demonstrated by a plot of the average fan slope versus the drainage basin area (Fig. 14.23). This relationship reflects the greater storage capacity of larger drainage basins and its effect on primary process types active on the fan. Also, fans with progressively longer radii have progressively lower slopes due to the distal progradation of active depositional lobes via a progressively elongating incised channel. The wide scatter of the compiled data (Fig. 14.23) reveals, however, that there are other variables not accounted for in this plot. As previously discussed, drainage basin area is not a good proxy for the volume of the material eroded from the drainage basin. Moreover, the multitude of variables such as bedrock geology and the relief in the drainage basin can have an important impact on the operative primary processes and size of liberated sediment, and these factors directly affect average fan slope. Thus, like the fan area versus drainage basin area plot, the average fan slope versus drainage basin area plot serves to demonstrate an obvious trend but does not account for the details of the system.

GENERAL FAN TYPES

Despite the inherent complexities, alluvial fans can be grouped into two types on the basis of the dominant operative primary processes and the resultant constituent and composite fan morphologies. Each of these two types can further be subdivided based on the relevance of secondary reworking by overland flows.

TYPE I ALLUVIAL FANS

Type I fans are constructed principally of cohesive clast-rich and clast-poor debris flows, which may or may not have an active incised channel in their upper segment (Fig. 14.8b). Colluvial slides, bedrock slides, rock avalanches, and rockfalls may also be active primary processes. The main constituent forms include lobes and levees of clast-rich debris flows and smoothed surfaces of clast-poor debris flows. Lobate or irregular masses from gravity slides, rock avalanches, or rockfalls may be present locally. The average slope of these fans varies from 5 to 15°, with radial profiles most commonly maintaining a constant slope. More steeply dipping colluvial cones are present in the proximal fan area.

Due to the low recurrence interval of the debris flow activity on Type I fans, surfaces away from the active depositional lobe and even the active depositional lobe itself widely display the effects of secondary processes. Dominating the secondary processes are the surficial winnowing of the exposed debris flow tops by overland flow and wind to produce gullies, rills, or a hummocky gravel mantle. Gullies and rills are present if the maximum clast size is cobbles or pebbles; a hummocky mantle of winnowed deposits results if boulders are present. A braided distributary pattern commonly results from this secondary erosion.

Type I fans are produced in deserts from drainage basins underlain by bedrock that weathers to produce sufficient matrix clay. Such bedrock includes pelitic metamorphic rocks, sedimentary rocks containing shale interbeds, and most volcanic rock types. Weathering of these lithologies under desert conditions also produces boulders, cobbles, pebbles, silt, and clay, but little sand. Distal sandskirts, therefore, usually are not present and sand interbeds in the proximal part of the fan are absent. Boulders are relatively small unless interbeds of more brittle clasts such as carbonate or quartzite are present in the drainage basin. Drainage basins are relatively steep and mantled by colluvium. Examples of this fan type are the South Badwater fan in Death Valley and the Dolomite fan in Owens Valley, California (Figs 14.1d and 14.10). Sand may locally be present in minor amounts in the debris flows of Type I fans where granitic plutons have intruded the low-grade metamorphic, volcanic, or shaley terranes. An example of this scenario is the Deadman Canyon fan of Walker Lake, Nevada (Fig. 14.1c).

The extent of secondary reworking of the debris flows in a Type I fan typically is minor, resulting in a stratigraphic record characterized dominantly of stacked debris flows separated by minor winnowed gravel lags produced mainly by rill or gully erosion. The drainage basin conditions of some debris flow dominated fans, in contrast, are conducive to the production of minor to catastrophic, sediment-deficient overland flows capable of extensively winnowing previously deposited debris flows, particularly in proximity to the fan apex or intersection point. This scenario develops where fan drainage basins are especially large, or where clay production in the drainage basin is retarded due to the bedrock lithology. The resultant effect at the fan site is the extensive winnowing of fine sediment from the primary debris flows by secondary overland flows, creating a stratigraphy characterized by interbedded debris flows, coarse, non-sorted gravel lags with common outsized clasts, and bedded granules and pebbles. Examples of this fan type are the Furnace Creek, Trail Canyon, and Hanaupah fans of Death Valley, California (Fig. 14.1a). This distinctive debris flow dominated fan type is designated Type IB, in contrast to debris flow dominated fans characterized by minimal secondary reworking and designated Type IA.

TYPE II ALLUVIAL FANS

Fluid-gravity flows and their waterlain deposits are dominant on Type II fans (Fig. 14.8a). Hyperconcentrated sheetfloods and incised channel flows are common, whereas rockfall, rock avalanche, and non-cohesive debris flow deposits may be present locally. Incised channels typically contain cobbles and boulders, whereas sheetflood deposits vary in grain size from boulders to sand in a down-fan direction. Sandy interbeds are common in the gravelly sheetflood deposits. A prominent sandskirt rims the lower part of the fan where neighbouring environments detrimental to its preservation are not present. Primary constituent forms in the proximal fan include the incised channel and non-cohesive debris flow or rock avalanche levees. The fan surface in general is relatively smooth, especially in contrast to Type I fans. The average slope of the Type II fan is between 2 and 8°, with a progressive down-fan lessening of slope corresponding to a reduction down-fan in grain size. The resultant radial pattern is either concave-upwards or segmented.

Secondary processes are dominant on Type II fans due to the relative ease of erosion of the surficial sediment and the infrequency of catastrophic primary events. The carving of rills and gullies with a braided distributary pattern by non-catastrophic overland flows is the most prevalent result of secondary erosion. Other secondary modifications include aeolian winnowing or deposition, bioturbation, soil development, and particle weathering. As with its Type I counterparts, the degree of secondary winnowing by overland flows may vary from minimal to extensive. A Type IIA designation is given to the minimal reworking case; a Type IIB designation is applied to the extensive reworking case. Unlike their Type I counterparts, this subdivision is less easy to make due to a similarity in the resulting facies types.

Type II fans are most commonly produced in deserts where the drainage basins are underlain by fractured and jointed granitic plutons and gneiss or by friable gravelly sandstone. Weathering of these rock types under desert conditions liberates sediment of all sizes ranging from coarse boulders to very fine sand. Silt and clay, however, are produced in amounts so small that debris flows are not easily generated. Drainage basin slopes are either mantled by pebbles and sand or contain partially dislodged boulders and cobbles. Flashflood or snowmelt events produce catastrophic water flows and non-cohesive debris flows from the diverse calibre of available sediment. Examples of Type II fans are the Roaring River fan in Colorado, fans derived from the Sierra Nevada in Owens Valley, California, and the fans derived from the Smith Mountains in Death Valley (Figs 14.11 and 14.12c).

ALLUVIAL FAN EVOLUTIONARY SCENARIOS

Given the considerations reviewed in this chapter and a freshly formed topographic setting conducive to fan development, such as an active normal fault along an extensional basin, the following idealized four-stage evolutionary scenario for fan development through time can be envisaged. This scenario reflects the progressive enlargement of the fan and the concomitant evolution of its drainage basin.

PRECURSOR FAN STAGE: TALUS CONE FORMATION

The first accumulations at the base of a newly created, sharp valley margin are talus or colluvial cones. Sediment is funnelled through a V-shaped fault-controlled crook that may enlarge to become a fan drainage basin. The talus cones are steep (commonly 30 to 40°) and do not extend far from the mountain front (Figs 14.9b and 14.21). Examples of this stage are the cones present along the active fault zone in south-eastern Death Valley (Fig. 14.9b). Not all talus cones will be succeeded by the development of alluvial fans; probably most will not. However, those positioned at the mountain front where sediment continues to be focused evolve to become part of an incipient fan (Fig. 14.24a).

STAGE 1: DEVELOPMENT OF THE FAN FOUNDATION (INCIPIENT FANS)

Incipient fans differ from talus cones by containing deposits of clast-rich debris flows, rock avalanches, or gravity slides in addition to the freefall material. They also bear a more fan-like shape. The slopes of incipient fans are still relatively steep (10 to 25°), but have lower slopes than those of talus cones (Fig. 14.21). A marked contrast (knickpoint) in slope angles is exhibited where the incipient fan has breached a precursor-stage cone (Fig. 14.24a). Incipient fans also extend significantly farther outward (commonly 0.5 km) from the mountain front than do the precursor talus cones (Fig. 14.24a).

A Stage 1 fan consists of debris flow and winnowed debris flow deposits with mixtures of other sediment-gravity deposits where the drainage basin bedrock weathers to produce ample clay (Type I incipient fan) (Fig. 14.24a). In contrast, where bedrock weathering produces clay-deficient sediment, the deposits consist of rock avalanche, non-cohesive debris-flow, sheetflood, and minor debris flow deposits (Type II incipient fan) (Fig. 14.24b). In either case, these deposits create the ramp-like foundation necessary for the subsequent development of fans with more common composite morphologies.

STAGE 2: DEVELOPMENT OF COMMON COMPOSITE FAN MORPHOLOGY

Stage 2 of development of either Type I or Type II alluvial fans is characterized by the creation of more gentle average radial slopes (3 to 15°) resulting from a reduced input by all mass wasting processes except debris flows. Fan construction occurs primarily as debris flows on Type I fans and sheetfloods with admixtures of non-cohesive debris flows in Type II fans (Figs 14.21 and 14.24c). Primary flows from the drainage basin issue on to the active depositional lobe either directly at or near the fan apex. The primary deposits commonly are subjected to secon-

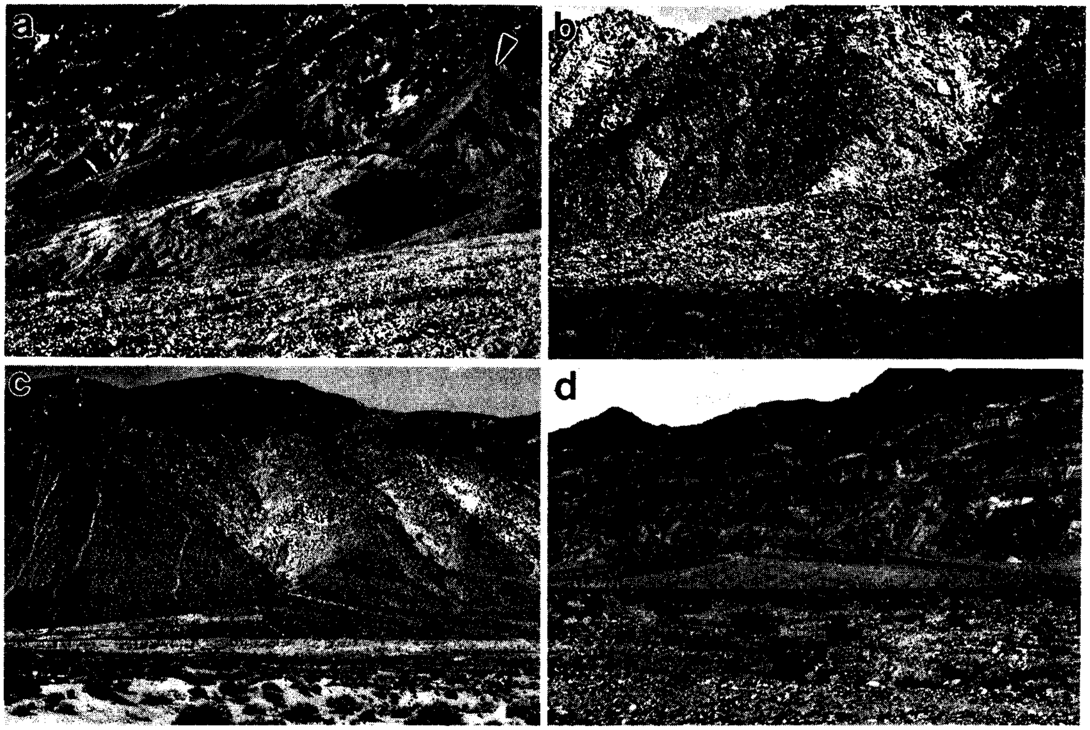

Figure 14.24 Photographs illustrating the stages of fan development. (a) View of a Stage 1 fan from Death Valley. A precursor colluvial cone (arrow) was breached during the development of this incipient fan. (b) Development of Stage 1 fan in eastern Deep Springs Valley by rock avalanche and non-cohesive debris-flow transportation from the fractured and jointed granitic bedrock of the drainage basin. (c) View of the Rifle Range fan, Hawthorne, Nevada, displaying Stage 2 development. (d) Example of Stage 3 fan development characterized by a prominent incised channel; Titus Canyon fan, Death Valley. This fan is prograding by progressive downslope movement of the active depositional lobe (light coloured).

dary processes, especially rill erosion and gullying that carve surficial braided distributary channels. Radial lengths of Stage 2 fans are greater than those of Stage 1 fans but are still relatively short, commonly less than 3 km (Fig. 14.24c).

STAGE 3: FAN PROGRADATION SCENARIOS

The third stage of development of both Type I and Type II fans is characterized by radial enlargement from the progradation of active depositional lobes outward from a progressively lengthening incised channel (Fig. 14.24d). The radii of fans in this stage are commonly 2 to 10 km long. The major primary and secondary processes operative during Stage 2 remain the same for Stage 3, including debris flows (Type I fans) and sheetfloods (Type II fans). The unique feature of Stage 3 is the development of a prominent incised channel that extends a significant distance (≥1 km) below the fan apex. This feature causes debris flows or water flows to remain confined on the upper fan, allowing for their accumulation in more distal settings. Average fan slopes are lowered to 2 to 8° due to the down-fan movement of the locus of deposition (Figs 14.21 and 14.24d).

BASIN VARIATIONS IN FAN EVOLUTION

The rate of progression through the three stages of development varies from one fan to another. The achieved stage of even neighbouring fans may differ due to variations in drainage basin features such as fracture density and relief. 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. 14.24d). This fan has a drainage basin built around a very prominent structure oriented perpendicular to the mountain front (Reynolds 1974). This drainage basin also contains