CHAPTER 6

Humid Fans of the Appalachian Mountains

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Abstract

Alluvial fans are abundant throughout the Appalachian Mountains of the eastern United States. Most of these humid fans are small, irregularly-shaped landforms formed dominantly by debris-flow processes which occur in first or second order basins. Larger, more regular fans formed dominantly by fluvial processes also occur in the Appalachians and are best exemplified by fans along the perimeter of the Shenandoah Valley in west-central Virginia. These two fan types commonly coexist in the same region.

Fan morphology, sedimentology, and dominant depositional processes are controlled by: (1) location in the drainage network; (2) recovery rates on hillslopes; (3) source basin lithology; (4) depositional frequency; and (5) post-depositional modifications. Activity on most of these fans occurs during the incursion of tropical moisture into the region, producing locally intense rainfall. Although depositional events at a site are infrequent (typically on the order of a few thousand years) fans are activated every few years in various parts of the Appalachians.

Introduction

Alluvial fans display a variety of geomorphic styles depending largely upon the dominant depositional processes which, in turn, are controlled by climate and lithology. Kochel and Johnson (1984) provided a generalized comparison of fans formed in a variety of climates, including arid, humid glacial, humid tropical, and humid temperate, and showed that the physical characteristics of fans may vary greatly due largely to the influence of climate. Important factors that affect fan morphology include: (1) the nature of dominant depositional processes, generally whether fan sediments are delivered by fluvial processes (traction dominated transport) and hyperconcentrated flood flows, or by debris-flow processes; (2) the frequency of depositional events; (3) the rate of recovery or revegetation of hillslopes and fan surfaces following depositional events; (4) source basin lithology; (5) the degree of topographic restriction of the depositional site where fans are constructed; and (6) post-depositional modifications of fan sediments by geomorphic processes operating in the vicinity. These factors will be considered, among others, in this survey of alluvial fans formed in the humid temperate region of the Appalachian Mountains in the United States.

Alluvial fans are widespread, significant landforms in piedmont regions of the Appalachian Mountains from New England to North Carolina (Figure 6.1). Appalachian fans occur in two distinct geomorphic styles. Relatively small fans occur predominantly in high relief, low order

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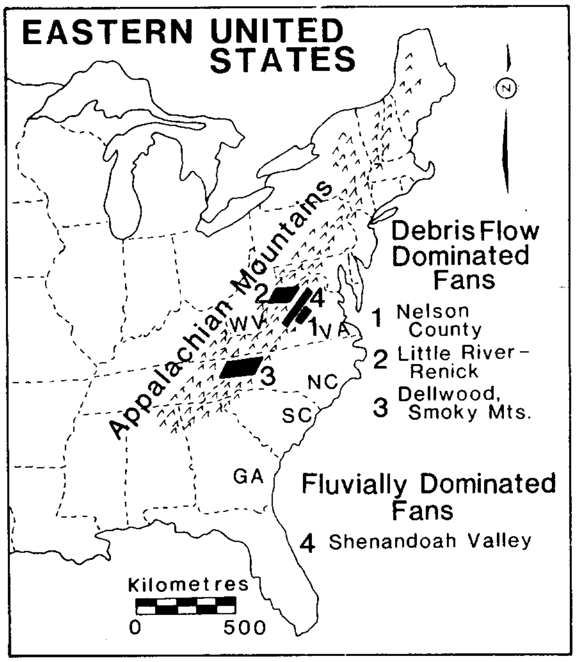

Figure 6.1. Map of the eastern United States showing the location of the major Appalachian Mountain study areas discussed in the text

drainage basins widespread throughout the Appalachian Mountains. These small fans are dominantly constructed by infrequent episodes of debris-flows and/or debris avalanches (Kochel and Johnson, 1984). They are active today under Holocene climatic conditions and will be termed 'debris-flow dominated' fans or debris fans in this paper.

The other geomorphic style of Appalachian fan appears to be largely relict and is presently undergoing a phase dominated by dissection. Holocene activity appears to be confined to fan channels which account for only a minor fraction of the fan's surface area. These will be termed 'fluvially-dominated' fans here because they are composed mostly of braided stream deposits and hyperconcentrated flood sediments of the type described by Costa (1988) and Smith (1986). Fluvially-dominated fans are larger than debris fans and may record periods of extensive fan progradation under climatic conditions somewhat different than the present. Alternatively, some of the differences from debris-flow dominated fans may be related to varying sediment yields from their respective basins due to differences in lithology or hydrology in the basin upstream from the fan.

This paper will present a brief regional view of the characteristics of humid fans in the Appalachians. The bulk of the paper, however, will describe models for the two geomorphic fan styles and discuss the climatic, geomorphic, and sedimentological variables that may explain variations in these fans. The models for the fluvially-dominated fans and debris-flow dominated fans will be developed by discussing selected sites that exemplify traits of each fan style where sufficient field work has been done to elaborate on their geomorphic and sedimentological attributes (Figure 6.1, boxed sites). The model for the debris fans will be based largely on numerous Holocene fans studied in west–central Virginia (Kochel and Johnson, 1984), east–central West Virginia (Hack and Goodlett, 1960), and in western North Carolina (Mills, 1982a,b, 1983, 1987). The fluvial fan model will be based on the extensive pre-Holocene fans that occur in an 80-km belt along the western flank of the Blue Ridge Mountains in the Shenandoah River valley of west–central Virginia.

Debris-flow Dominated Fans

The most widespread style of alluvial fan in the Appalachian Mountains is constructed dominantly by debris-flow/debris-avalanche processes. Debris fans occur in all piedmont settings along the Appalachians. Most debris fans exhibit geomorphological and sedimentological evidence of repeated depositional activity by debris-flow processes throughout the Holocene, including historical times. Appalachian debris avalanches can be triggered by initial failure at many sites on the slope (Williams and Guy, 1973) and continue rapidly downslope until the valley floor is intersected (Figure 6.2). At the valley floor, debris-avalanche sediment is either deposited as a hummocky, poorly-sorted mass at the slope base, or mixed with sufficient runoff from tributary channels to

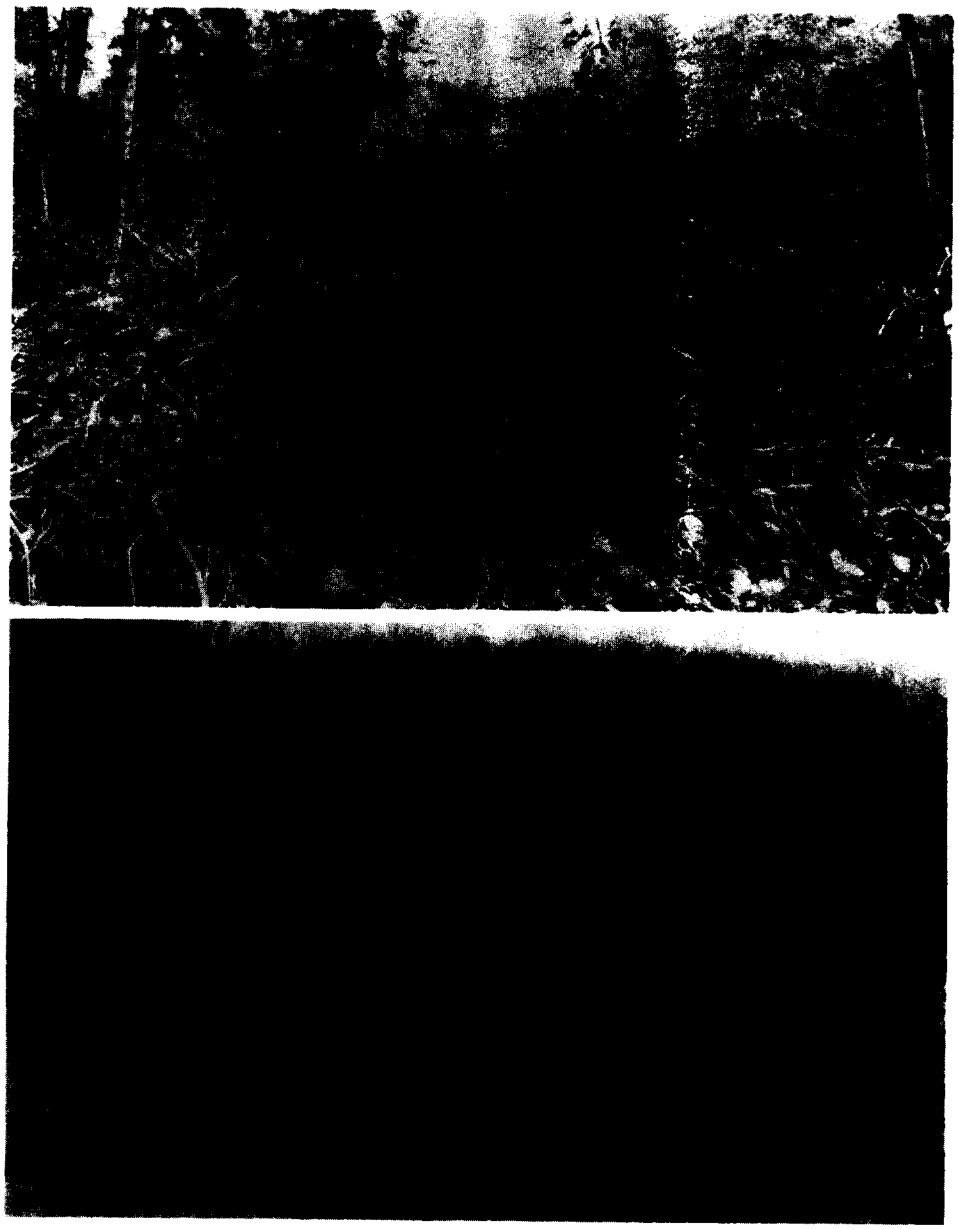

Figure 6.2. Appalachian debris avalanches: (A) Avalanche chute and uppermost portion of debris fan formed in August, 1984, on Anakeesta Ridge in the Smoky Mountains, Tennessee. Note the abrupt margins separating the area of complete denudation from the undisturbed forest. The entrained colluvial sediment cover varied in depth from less than 1 m along the chute edges to 2 m in the central hollow (photo taken in 1985); (B) Three debris avalanche scars coalescing at the apex of an irregular debris fan in Nelson County, Virginia, caused by Hurricane Camille rains in 1969 (photo taken in 1981). The coarsest boulders were deposited on the fan apex and make up the hummocky terrain at the base of the bedrock-floored chutes. Debris from the 1969 flows thins rapidly away from the apex. The fan surface slopes at about 13°

continue across debris fans as debris-flow or hyperconcentrated flood-flow.

GEOMORPHOLOGY AND DEPOSITIONAL PROCESSES

Debris-flows and Climate

Systematic records indicate that Appalachian debris-flows have been numerous over the last 50 years (Table 6.1). Episodes of debris avalanching have invariably been caused by intense rainfall events. Synoptic weather patterns associated with these storms indicate that most debris-flow-producing storms can be directly linked to the incursion of warm, moist tropical air masses over the mountains between May and November. Most of the large debris-flow events have been caused by the remnants of hurricanes or tropical storms (such as Camille in 1969 and Juan in 1985). Other high intensity rains have been produced by convective storms along the interface between extratropical systems and tropical air, intensified by interactions with the mountains.

The heavily-forested slopes of the Appalachian Mountains are generally quite stable under most rainfall and snowmelt conditions. Figure 6.3 provides an idea of the rainfall magnitude necessary to produce widespread debris-flows on these slopes: the lower line probably represents a threshold of minimum rainfall intensity necessary to cause debris-flows in the Appalachians for various storm durations. However, caution should be used in interpreting relationships like these because the data are subject to considerable error for several reasons. First, the relationship of declining intensity with duration is partially a function of physical limits inherent in meteorological conditions (Caine, 1980). Second, there may be significant error in the rainfall data: many of these points are from non-recording rain gauges, hence a storm may be given a 24-hour duration because the gauge was checked only once a day, while the rainfall may have accumulated over a much shorter duration. Additional problems result because

Table 6.1. Major historical appalachian debris-flows

Date	Location	Rainfall Data Amount (cm)	Duration (hrs)	Source*	Reference
8/4–5/38	Webb Mt., TN	28–38	4	T	Moneymaker, 1939
8/17–18/40	Watauga, TN	–	–	T–H	U.S.G.S., 1949
8/17–18/40	Grandfather Mt., NC	–	–	T–H	U.S.G.S., 1949
8/17–18/40	Radford, VA	–	–	T–H	U.S.G.S., 1949
6/17–18/42	Northcentral, PA	90	12	?	Eisenlohr, 1952
6/17–18/49	Little River, VA	24	3–4	T	Hack and Goodlett, 1960
6/17–18/49	Petersburg, WV	40	24	T	Stringfield and Smith, 1956
9/1/51	Smoky Mts., NC–TN	10–20	1	T	Bogucki, 1970; 1976
6/30/56	Cove Creek, NC	30	1	T	Bogucki, 1970
8/19–20/69	Nelson Co., VA	80	8	T–H	Williams and Guy, 1973
8/19–20/69	Spring Creek, WV	10–40	8	T–H	Schneider, 1973
8/10/76	Dorset Mt., VT	10	6	T–H	Ratte and Rhodes, 1977
6/19–20/77	Johnstown, PA	25–30	–	ET	Pomeroy, 1980
8/10–11/84	Smoky Mts., TN	10	24	?	this study
Various dates	Adirondack Mts., NY	–	–	–	Bogucki, 1977
Various dates	White Mts., NH	–	–	–	Flaccus, 1958

*T = demonstrable tropical air mass
T–H = hurricane
ET = extratropical cyclone
? = difficult to determine

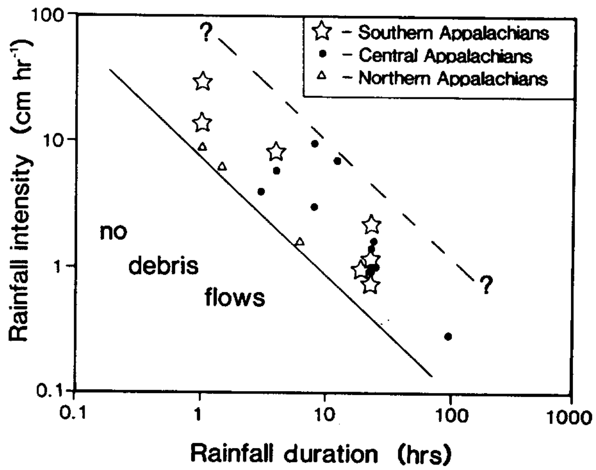

Figure 6.3. Intensity-duration relation for major debris-flow producing storms in the Appalachians. Debris-flows occur at lower rainfall intensities as the duration of the storm increases. See discussion in text. Data were compiled from the following sources: Bogucki, 1970, 1976, 1977; Costa, unpublished; Eisenlohr, 1952; Eschner and Patric, 1982; Hack and Goodlett, 1960; Moneymaker, 1939; Neary and Swift, 1984; Patric, 1981; Pomeroy, 1980; Ratte and Rhodes, 1977; Schneider, 1973; Stringfield and Smith, 1956; Williams and Guy, 1973

rain gauges often were not at the sites of the debris-flows and great spatial variation is common in mountainous terrain during intense rainfalls. In particular, gauges are seldom at high elevations where the debris-flows originate, hence they usually fail to record the orographically elevated rainfall amounts. Third, considerable spread in the data is expected due to differences in antecedent moisture conditions and due to lithological factors.

The threshold of rainfall required to initiate debris-flows in the Appalachians varies with lithology, vegetation, and topography. However, catastrophic rainfall is required to produce significant slope failures in these areas where slopes and source basins are typically covered by mature forest. Only catastrophic storms are capable of sufficiently elevating pore pressures at the soil–bedrock interface, or within the soil, on these steep slopes with thin colluvial cover, to produce a debris avalanche. An example of the kind of storm capable of initiating extensive debris-flow activity on Appalachian fans is Hurricane Camille of 1969. Camille dumped over 70 cm of rain in less than 8 hours on parts of Nelson County, Virginia (Williams and Guy, 1973; Kochel and Johnson, 1984). This intense storm resulted from the combined effect of the hurricane remnants moving over the Blue Ridge from the southwest, collision with an extratropical frontal system moving into the area from the northwest, orographic effects, and the addition of moisture from strong southeasterly winds originating from another tropical storm off the southeast coast of the United States (Schwarz, 1970).

Other severe rainfall events capable of producing debris-flows and catastrophic floods in the Appalachians have been the result of hurricane landfall, but many have also been simply associated with tropical moisture. The most severe storms of this class are referred to as 'terrain locked' storms (Lee and Goodge, 1984) or Appalachian convective clusters (Michaels, 1985). The key ingredient in these storms is the uninterrupted supply of warm, moist tropical air such as occurs with the light southeasterly winds common in the Appalachian piedmont. When these moist winds are orographically lifted over the Appalachians, and, if they encounter weak upper-air steering currents, then convective storms of great proportions and intensity may result (Michaels, 1985). Currently, weather records indicate that such intense storms are relatively rare in the Appalachians. However, when one considers the relatively low density of recording weather stations and the localized nature of these intense events, it seems likely that many go undetected. They may in fact be much more common than officially recorded. An increased network of rainfall gauges is needed in mountainous terrain to better understand these processes.

Hurricane Camille was perhaps one of the best examples of the combined influence of terrain locking and tropical moisture, resulting in the production of hundreds of debris-flows in the central Appalachians in 1969. Extensive debris avalanching in this area of concentrated rainfall resulted in numerous debris-flows onto debris fans that many workers had considered to be

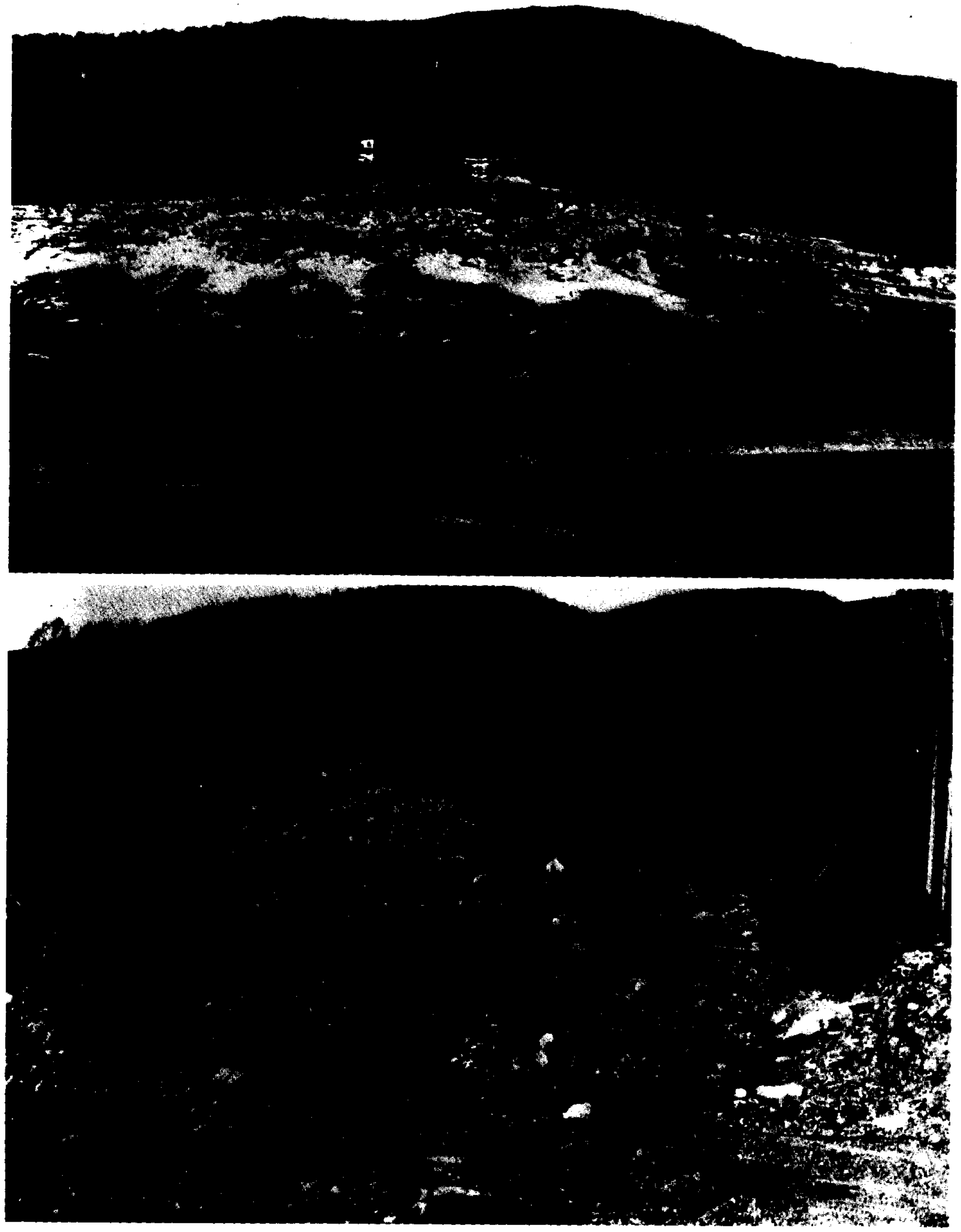

Figure 6.4. Examples of debris fans activated in 1969 in Nelson County, Virginia. (A) Coarse boulders and broken trees spread in a fan shape where debris-flows could spread out in an unconfined valley along Muddy Creek; (B) More typical confined valley where an elongated debris fan was covered by poorly-sorted, bouldery debris. This fan surface in Davis Creek was fully forested before 1969. (Photos reproduced by courtesy of Virginia Division of Mineral Resources)

relict features of past climates (Figure 6.4). Between 30% and 70% of the fan surfaces in Nelson County, Virginia, experienced erosional or depositional activity from this event.

Fan Morphology

Appalachian debris fans are small, typically less than 1.0 km^2 in area, and usually occur in first or second order basins near drainage divides. Because of their basin head locations, debris fans are laterally constrained by valley walls and tend to be irregular or elongate in plan view, rather than displaying typical fan shape (Figure 6.5). Variations in debris fan shape appear to be controlled by: (1) bedrock resistance; (2) bedrock structure and its effect on stream order; and (3) grain-size of the debris deposited on the fan. Debris fans developed in areas of uniformly resistant rocks tend to be the smallest and have the most irregular shape. These fans generally form in highly confined, narrow valleys and are exemplified by fans in Nelson County, Virginia, a region underlain by granite–gneiss of the Lovingston Formation (Kochel and Johnson, 1984). Debris fans in Little River basin in western Virginia (Hack and Goodlett, 1960) have been built on to the floodplains of stream valleys of significantly higher stream order. Low order tributaries enter high order axial valleys due to the trellis drainage pattern developed in response to differential erosion of the folded sandstones and shales underlying the area. Little River fans appear to be affected little by floods in the main axial valley because of armouring by their exceedingly coarse debris.

Debris fans in the Dellwood, North Carolina region tend to be elongate, but less constrained and larger than their Virginia counterparts (Hadley and Goldsmith, 1963; Mills, 1982a,b, 1983). Mills (1982a, 1987) noted that the Dellwood fans are segmented. His studies of the weathering characteristics of these fans (Mills, 1982b) indicated that the segments represented a continuum of fan building episodes attributed to piracy processes similar to those described by Rich (1935). Piracy and preservation of older fan segments concomitant with renewed fan sedimentation at lower levels attests to the reduced lateral confinement of the Dellwood fans compared to those in Nelson County. Due to the restricted nature of fan depositional areas in Nelson County, subsequent episodes of fan building usually result in destruction of most remnants of earlier fans.

The dependency of debris-fan size upon topographic confinement is evident in Figure 6.6A. Bull (1964) described a well-defined relationship between fan area and basin area for fans where debris-flow processes are important in a semiarid region of the southwestern United States. Exponents of this relationship averaged between 0.8 and 1.0 (Bull, 1964). In contrast, the exponent for the relationship between fan area and basin area of Nelson County fans is about 0.2 with a low standard deviation. This indicates the severe topographic constraint and shows that fan area is relatively constant regardless of basin area. Mills (1987) reported exponents of 0.6, but with a high standard deviation of 0.53, for Dellwood fans showing that, although constrained, these fans vary considerably.

Most Appalachian debris fans are relatively thin: typically these deposits are less than 30 m thick. Fan profiles are generally very steep, averaging 10° to 17° compared to slopes of 4° to 5° for the fluvially dominated fans common along the western slopes of the Blue Ridge in the Shenandoah Valley of Virginia. The thin deposits and steep profiles of these debris fans is attributable largely to the dominance of debris-flows as their major depositional process. Transportation of coarse clasts by Bingham fluids and debris-flow processes (Johnson, 1970) yields considerably steeper depositional slopes than are observed on fans where deposition is dominated by fluvial processes. Similar ranges of depositional slopes of debris-flow dominated fans have been reported from southwestern Canada by VanDine (1985).

Depositional Frequency

Inspection of Table 6.1 suggests that debris-flows are relatively frequent in the Appalachian Mountains: there have been tens of events documented during the last 50 years. Thus, the average return interval for a debris-flow event

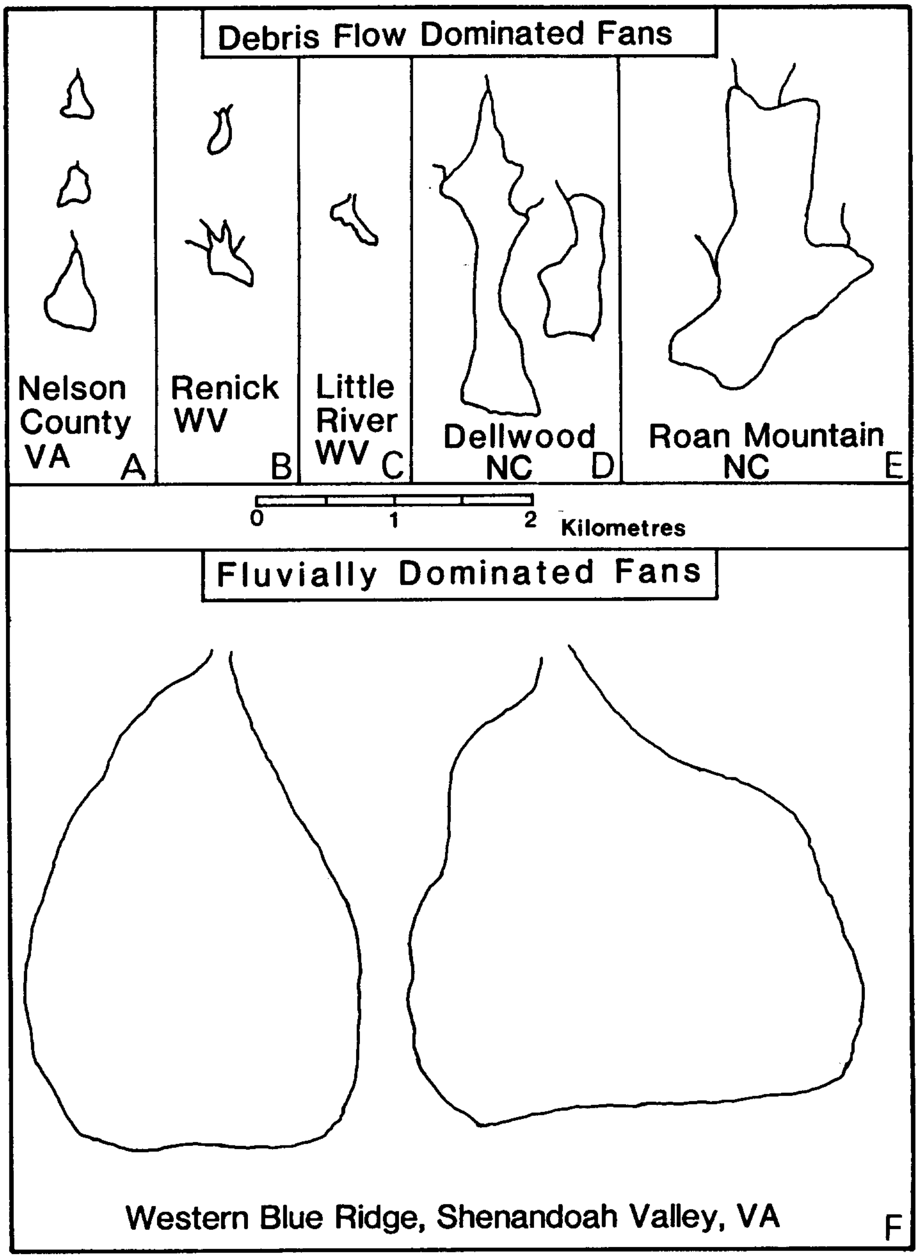

Figure 6.5. Comparative maps of debris-flow dominated fans and fluvially dominated fans. Debris fans are extremely irregular and variable in size, but considerably smaller than the fluvial fans in the eastern Shenandoah Valley. (A) Fans in Davis Creek and Ginseng Hollow, Nelson County, Virginia (from Kochel and Johnson, 1984, and this study; (B) Fans in the vicinity of Renick, West Virginia (from Wilson, 1987); (C) Fan 770 in Little River, Virginia (from Hack and Goodlett, 1960); (D) Examples of fans near Dellwood, North Carolina (from Mills, 1982b); (E) Typical fan at Roan Mountain, North Carolina (from Mills, 1983); (F) Two examples of unconfined, fluvially dominated fans near Waynesboro, Virginia, in the Shenandoah Valley

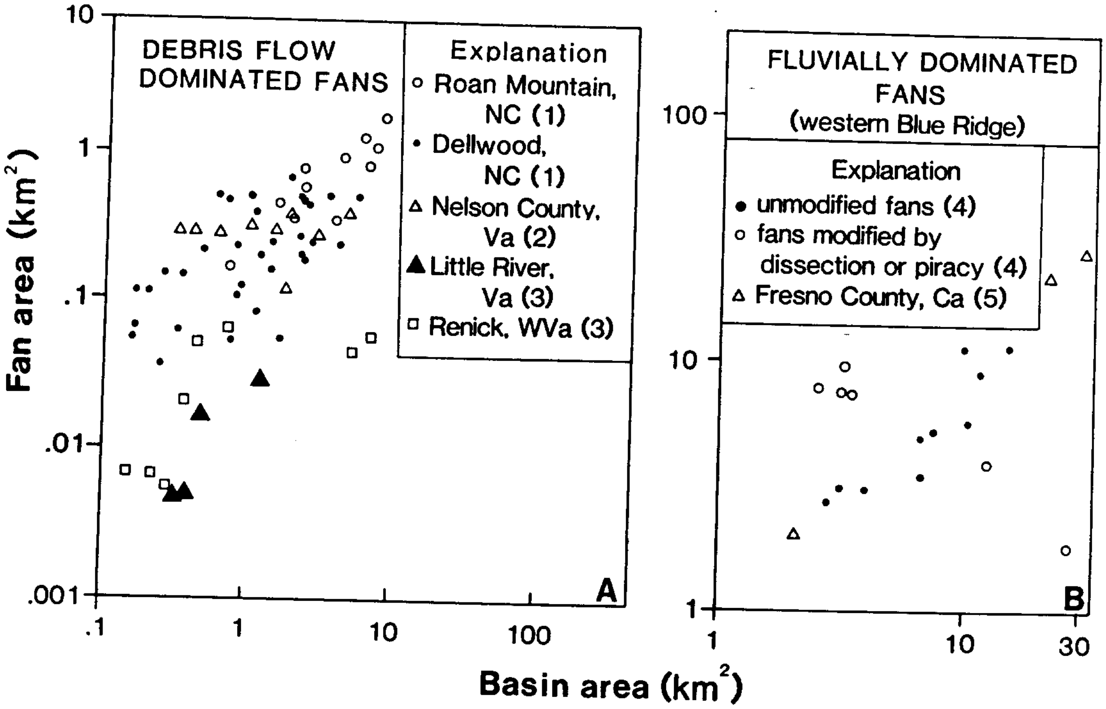

Figure 6.6. Relation of fan area to drainage basin area upstream from the fan apex. (A) Appalachian debris-flow dominated fans discussed in text. Note the ill-defined relation for the confined fans in Virginia and West Virginia and the somewhat better relation for less confined fans in North Carolina. Data sources: (1) Mills, 1987; (2) Kochel and Johnson, 1984; (3) Wilson, 1987; Simmons, 1987; (B) Appalachian fluvially-dominated fans in the Shenandoah Valley. A well-defined relation exists for most sites except those marked by open circles. These fans have been altered after their formation by erosional processes and/or piracy. Note how near the trend reported for fans in California the Virginia fans plot. Data sources: (4) Kochel and Johnson, 1984; Simmons, 1988; (5) Bull, 1964

somewhere in the Appalachians is in the order of every five to seven years. In addition, many debris-flows probably have gone unrecorded due to their association with terrain locked storms that have occurred in particularly remote areas. However, when the recurrence intervals of debris-flows on specific fans are considered, their frequency appears to be very low. Kochel and Johnson (1984) were successful in obtaining samples of palaeosols developed on fans in Davis Creek, located in Nelson County, Virginia, for radiocarbon dating. They found that at two separate sites, only three or four major debris-flow events had occurred within the last 11 000 years, from which it might be inferred that the recurrence interval at any particular location of a storm like Camille is roughly 3000 to 6000 years. These long recurrence intervals may reflect, in part, the real frequency of recurrence of the special meteorological conditions required to produce such catastrophic rainfalls at a specific site.

There must also be a recovery period between events for revegetation to occur and for residual colluvial regolith to accumulate once again before a subsequent rainfall can trigger another debris-flow. Subsequent rains that occur before such recovery is complete would result in sheetwash and flash flooding on the fan, but the likelihood for slope failures and debris-flows would be minimal. Lenses of moderately well-sorted sand and fine gravel occur in some Nelson County and Dellwood fans and may record floods that occurred between debris-flow events. Testimony to the importance of the temporal ordering of events and their associated geomorphic effects is available by comparing the results of successive storms that occurred in 1969, 1972, and 1985 in the same area of Virginia. Extensive and widespread rainfall occurred in conjunction with Hurricane Agnes in 1972 and with Hurricane Juan in 1985, resulting in larger floods on the James River (to which these areas are tributary) than was produced by the Camille storm in 1969. However, no significant debris-flows resulted from these later storms in the Nelson County area devastated in 1969. Part of the reason for the paucity of debris-flows in the latter storms was due to the lower intensity and longer duration of rains in 1972 and 1985 than in 1969. However, the Juan flood did trigger numerous debris-flows in 1985 in areas not affected previously by Camille. This suggests that most of the potentially unstable material had been released by Camille and hillsides had not recovered sufficiently by 1985 to result in slope failures in these areas. Similar observations were made by Newson (1980) in a comparison of the geomorphic effects of two large storms in Great Britain.

SEDIMENTOLOGY

Appalachian debris-fans are composed of very poorly-sorted sediments that range in size from boulders several metres in diameter to clay. These deposits occur as both matrix supported and clast supported units, depending upon the amount of water that was mixed with the debris as the flow travelled across the fan surface. Most of the fans observed in the Nelson County area of central Virginia are matrix supported (Kochel and Johnson, 1984), while those described by Hack and Goodlett (1960) in western Virginia are generally clast supported. Deposits in the southern Appalachians (Dellwood and Roan Mountain, North Carolina) are generally dominated by clast supported bedding, although matrix supported units are common. Sediment supply to the fans may differ between areas due to significant differences in source basin lithology, weathering processes, and basin hydrology. The coarse, matrix-free nature of fans in western Virginia may be due to their occurrence in folded sedimentary rocks dominated by resistant sandstones which yield only thin soils composed of sandy loam. Nelson County debris fans have a more readily available supply of matrix because of the thicker, clay-rich soils formed on the granitic rocks of central Virginia.

The hydrology of floods in these two areas may also play an important role in the nature of sedimentation on these debris fans. The volume of runoff associated with debris-flows in the first order basins in Nelson County may be considerably less than the amount available from similar unit rainfalls in the higher order basins of Little River in western Virginia. Debris-flows in higher order basins generally contain larger amounts of water; thus, hyperconcentrated sediment flows may dominate over debris-flows in these areas. A systematic survey of the hydrologic, climatic, and lithologic controls on central Appalachian fans is currently in progress and will address these questions.

Stratification in Appalachian debris fan deposits is lacking, but contacts between units are generally sharp. Individual units are thick, ranging from a few tens of centimetres to 2 m. Palaeosols are partly preserved at some of the contacts between debris-flow units, indicating that considerable time had elapsed between successive debris-flows during which significant soil formation occurred. Because each stratum in a debris fan is produced by a discrete flood event, their textural characteristics tend to differ greatly. As a result, abrupt changes in texture are common in vertical sections through these deposits. Abrupt changes in weathering characteristics and mineralogy of the sediments is also common due to weathering processes and the great differences in age that normally exist between successive strata (Kochel and Johnson, 1984).

Sedimentary structures are virtually absent in Appalachian debris-flow deposits, aside from occasional occurrences of weakly imbricated clasts and reverse grading. Surface features such as debris levees have been observed at a number of sites in photographs taken immediately after the 1969 flows, but are generally lacking. Hack and Goodlett (1960) described numerous levees, boulder lobes, and channels in the Little River area associated with the flood of 1949 in western Virginia. These forms persist today as well as similar features produced by older debris-flows at those sites. Floodplains downstream from the Little River debris fans exhibit extremely irregular surface topography dominated by boulder levees and abandoned channels produced by earlier flows (Figure 6.7). Lower magnitude floods are incapable of redistributing this coarse material in the fluvial system. Hence, material generated by debris-flow remains as a lag deposit on the downstream floodplain until an event of similar magnitude occurs that is competent to entrain the coarse sediment again. An example of this kind of event was the Hurricane Juan flood of November, 1985. The Juan flood caused considerable erosion and deposition on valley floors in eastern West Virginia and western Virginia and was also of sufficient intensity to cause significant numbers of debris-flows (Kochel and others, 1987).

Debris fans studied in Virginia and North Carolina show very little change in their sediments from proximal to distal reaches. These deposits are generally thickest and extremely coarse at the fan apices where the coarsest debris avalanche material is deposited as a hummocky mass (see Figure 6.2B). Most debris-flow units change little in thickness and grain size downfan from this region. The lack of change can be explained because material is carried by debris-flows which retain their competence throughout their travel over the small debris fans. There is little opportunity for sorting to occur before the material is deposited in valley bottom streams marginal to the distal parts of the fans (Costa, 1984).

AGE RELATIONSHIPS AND GEOMORPHOLOGY

Fans in topographically confined areas such as those in Nelson County, Virginia, appear to have been largely constructed during the Holocene Epoch. Radiocarbon dates of the basal debris-flow units resting upon bedrock at each of three localities in Virginia studied in detail indicate that the oldest fan deposits were deposited about 11 000 yr B.P. (Kochel and Johnson, 1984). This date corresponds approximately with the period when palynological data (Watts, 1979; Delcourt and Delcourt, 1984) indicate that the summer position of the polar front had retreated sufficiently far north after the late Wisconsinan glacial maximum to allow tropical moisture to reenter the central Virginia region (Kochel, 1987). It is unlikely that debris-flow activity occurred here as a major process during the glacial intervals of the Pleistocene Epoch because the atmospheric circulation would then have been unfavourable for the movement of significant tropical air masses into the region (Bryson, 1966; Bryson *et al.*, 1970).

Episodes of debris fan deposition probably occurred throughout the Quaternary Period in Virginia during interglacial intervals. Evidence of the earlier fans is limited because subsequent fan building in these confined valleys probably destroyed older deposits. Evidence of pre-Holocene fans exists in several wider valleys like Ginseng Hollow (Figure 6.8A) where there was enough room for the Holocene fan to form adjacent to the older fan. Here, the Holocene fan, including deposits from the Camille event, is entrenched into an older fan. The older fan remnant (Figure 6.8B) appears to be significantly older than the Holocene fan on the basis of weathering indices.

Debris fans described by Mills (1982a; 1983) in the Roan Mountain and Dellwood areas of North Carolina exhibit multiple ages based upon recognition of fan segments preserved at various topographic levels and relative differences in weathering. Fluvial incision of the fans generally occurs along fan margins between debris-flow events. Subsequent debris-flows follow the incision, and so extend fans laterally and at a lower elevation in a manner similar to that described for terrace formation and piracy in piedmont regions (Rich, 1935; Ritter, 1967). The most recent episode of fan construction by debris avalanching is represented by the lowest topographic segment on these fans.

During 1985 we conducted a survey of fans in North Carolina and sampled organic materials for radiocarbon dating. The basal debris-flow units of the most recent segments of several fans in the Dellwood area were sampled to determine when the current phase of debris avalanching began.

Figure 6.7. Examples of irregular floodplain topography in areas affected by debris-flows upstream. These are from Little River, Virginia, and have been modified by the flood of 1949 (Hack and Goodlett, 1960). (A) Stepped floodplain surface showing boulder berm at left; (B) Segmented boulder levees and abandoned channels on floodplain surface

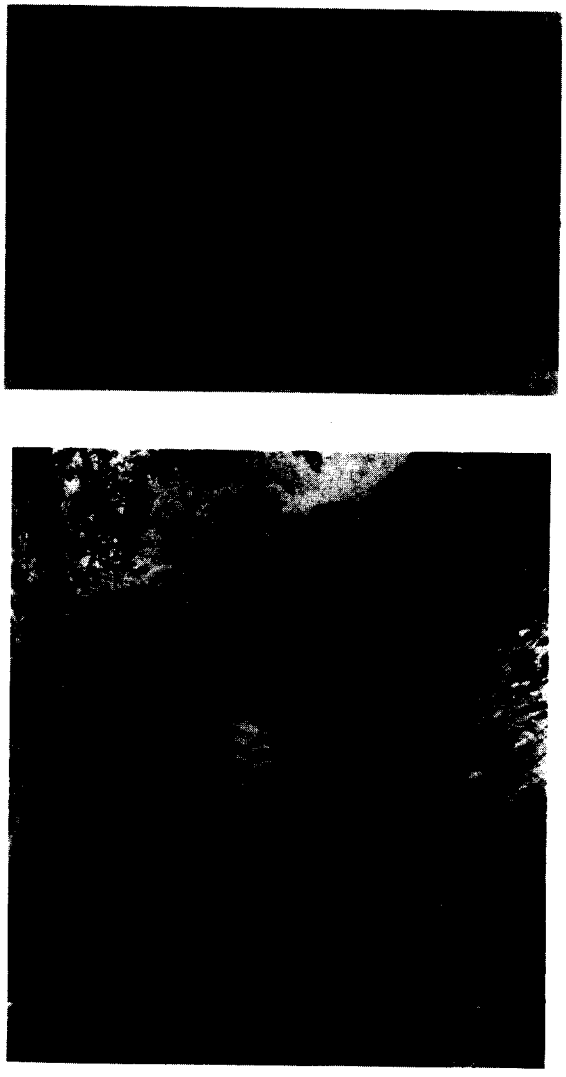

Figure 6.8. Ginseng Hollow in Nelson County, Virginia, is a site where relatively little valley confinement has resulted in the preservation of a pre-Holocene fan remnant, now dissected with an incised Holocene fan. (A) Oblique aerial photo shows the older fan, on which an orchard is located. The lower fan was totally covered by debris-flow sediment in 1969; (B) Thick, oxidized, red soil developed on clast-supported sediment in the higher, older fan. Exposure is just opposite the house near the fan apex. These clasts are extremely rotted from a long period of intense weathering, indicating a Pleistocene age

Basal units generally dated between 16 000 yr B.P. and 18 000 yr B.P. Older dates in the range of 22 000 yr B.P. to 25 000 yr B.P. were also obtained for several debris-flow layers in fans of the Dellwood area. This indicates that, although debris-flow activity may have been retarded during glacial maxima, it may have still been possible occasionally for tropical moisture to invade the southernmost regions of the Appalachians in North Carolina and Tennessee. Historical debris-flows have not been observed in the Dellwood or Roan Mountain areas of North Carolina, but have been frequent in the neighbouring Smoky Mountains of Tennessee and North Carolina. In the Smoky Mountains, radiocarbon dating indicates that major debris-flows occur at a site on average about once every 400 to 1600 years, which is considerably more frequent than farther north, in the Nelson County area in Virginia.

Fluvially Dominated Fans

At certain sites within the Appalachian Mountains, extensive alluvial fans occur that appear to be largely composed of sediments deposited dominantly by tractive bedload transport mechanisms in braided streams. The most widespread and well exposed of these fluvially dominated fans occur along the western flank of the Blue Ridge Mountains in the southeastern Shenandoah Valley of Virginia (Figure 6.1). These deposits were identified by Hack (1965) in his reconnaissance geomorphic mapping of the Shenandoah Valley. He labelled them undifferentiated terrace, pediment, and fan sediments but did not conduct detailed studies of these features.

The gravels along the western Blue Ridge are deposited in distinctly fan-shaped geometries (Figure 6.5F), they exceed 200 m in thickness in some areas, and they can be linked to upstream source basins. They will be called fluvial fans in this paper. Their distal reaches are graded to the various terrace levels of streams following the axis of the Shenandoah Valley, such as South River and South Fork Shenandoah River. These fans formed at the topographic break that marks the abrupt change in lithologic resistance encountered by streams issuing from the Blue Ridge. Basin headwaters are underlain by resistant lithologies that include Precambrian crystalline rocks and basalts and lower Cambrian quartzites, while the southeastern Shenandoah Valley is underlain by a thick section of weak, steeply-dipping Cambro-Ordovician carbonate rocks. Fan progradation occurred as coarse bedload was rapidly deposited by competent streams in flood as they left the confines of high gradient, narrow mountain channels and spread out onto the rolling, carbonate piedmont areas.

GEOMORPHOLOGY AND DEPOSITIONAL PROCESSES

Fan Morphology

Appalachian fluvial fans are restricted in their occurrence to areas where there are distinct highland source areas bordered by extensive lowland basins, like the situation in the southern Shenandoah Valley (Figure 6.9A). This type of geomorphic setting is not unlike the settings of intermontane fans located in the northern Rocky Mountain region of western Montana.

The fans along the Blue Ridge are considerably larger than Appalachian debris fans, ranging between $2\,km^2$ and $18\,km^2$. Although they have typical fan shapes in plan view, fans have often merged to create an extensive alluvial apron or bajada along the mountain front. Individual fan boundaries can generally be determined from studies of topographic maps and field checking because the fans are bounded by streams draining along their margins. Recent dissection has made the exact location of all fan boundaries uncertain in some cases. Figure 6.6B illustrates that the relationships between basin area and fan area is much better developed than for most debris fans. The area relationship is very similar to that described for arid fans by Bull (1964), as shown by the exponent of approximately 0.7. This reflects the absence of topographic constraints upon areal fan growth, unlike the situation of debris fans formed in basin head areas.

Most of the fluvial fans are fed by streams of the third or higher order, whereas most of the debris fans in Nelson County occur at the base of first order channels. The higher order basins along the Blue Ridge can therefore collect greater volumes of runoff which are more conducive to normal fluvial or hyperconcentrated flood-flows rather than to debris-flows. Blue Ridge basins are underlain dominantly by the resistant quartzite of the Antietam Formation, limiting the supply of fine-grained sediment necessary for the production of debris-flows. The combination of increased catchment area and decreased matrix availability relative to the nearby debris fans in

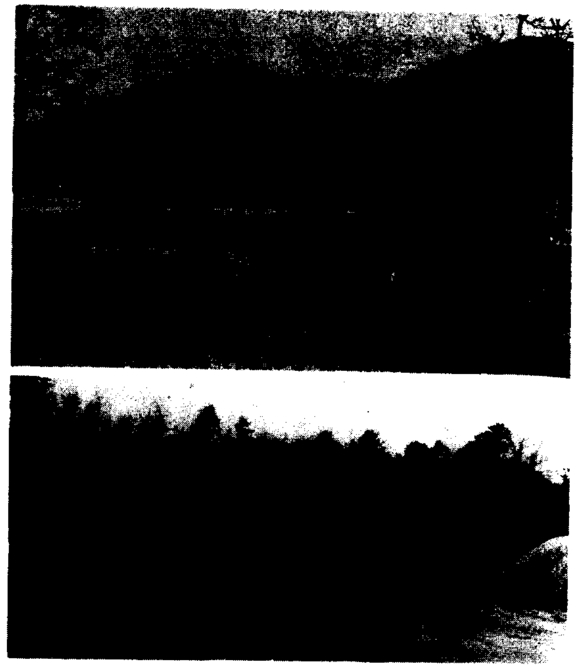

Figure 6.9. Morphology of Shenandoah Valley alluvial fans. (A) View on a fluvially dominated fan a few kilometres north of Vesuvius, Virginia. Note the extensive scree slopes higher on the Blue Ridge Mountains and the sharp break in slope between colluvial slopes and the fan surface. The fan surface slopes toward the lower left at about 4°. Photo was taken at upper mid-fan; (B) View of the wall of a manganese quarry near the apex of a fan about 15 km southwest of Waynesboro, Virginia. Lines drawn on the photo indicate the approximate boundaries of the upper, unweathered gravel, the lower, weathered gravel, and the carbonate residuum (see Figure 6.11A for details of the stratigraphy). The tree in front of the outcrop is about 6 m tall

Nelson County, Virginia, may explain the absence of debris-flow processes on these fans.

Longitudinal profiles of the fluvial fans along the Blue Ridge show much gentler gradients than those that occur on debris fans in Virginia and elsewhere in the Appalachians, averaging 4° to 5°. The lower gradient reflects the dominance of fluvial tractive transport rather than debris-flow modes of sediment transport onto these fans. Fan thickness is highly variable, but is generally much greater than that observed in debris-fans. Drillers' logs indicate that it is not uncommon for these fluvial fans to contain up to 250 m of gravel in the mid-fan and distal regions. Manganese quarry wall exposures show that proximal gravel thickness generally averages between 10 and 25 m Figure 6.9B).

Depositional Processes and Climate

Mature forests with well-developed soils occur on the fluvial fan surfaces today, suggesting that they have not received any appreciable depositional activity on their surfaces during late Holocene time. Mature spodosols occur everywhere on the fan except in the active channel areas, which account for less than 2% of the fan surface. Therefore, it appears that active sedimentation on these fans is either relict from past climates (i.e. Pleistocene) or occurs with such rarity that extensive soil formation has occurred since the last depositional events. Support for the former hypothesis was provided by observations made of the impact of Hurricane Juan rainfall of November 1985. Five-day rainfall totals from Juan exceeded 30 cm in many parts of the Blue Ridge, resulting in extensive flooding in basins tributary to the fans and in downstream areas along South River and Shenandoah River. Geomorphic effects of these floods were significant, but generally limited to channel widening, channel scour, and bar reorganization within the confines of the narrow floodplains of the streams along the margins of the large fans (Kochel, 1988). The fan surfaces themselves were unaffected by this flood. The recurrence interval of the rainfall for the Juan storm was estimated at between 50 and 100 years (Virginia State Climatology Office, personal communication, 1986) and the resulting flood on the major rivers in the area was about a 100 year flood. Therefore, it is unlikely that rainfalls expected in the present climatic regime can contribute substantially to fan development in these areas.

The Blue Ridge fans appear to be undergoing a phase of active dissection today. Modern floods seem to be transporting sediment in fan channels toward and beyond the distal portions of the fans. Current geomorphic processes appear to be actively degrading these fans along the Blue Ridge Mountains. The coarse sediment delivered from the resistant upland basins on to the fans has armoured the fan surfaces and streams subsequently have shifted to the fan margins (Hack, 1965). The shift of fan drainage to the lateral margins could have resulted from a number of processes, including: (1) armouring of the channels with resistant lithologies from the mountains; (2) lateral forcing due to exceedingly rapid aggradation near the fan axis; and (3) entrenchment long after the main period of active fan aggradation had ended. Present streams appear to be eroding these fans very slowly along their margins, carrying sediment from the fans to the axial streams along the Shenandoah Valley. Recent studies by Simmons (1988) showed that the Juan flood was competent to move all sizes of sediment available in the active channels. In addition, the distal portions of some of the fans have been truncated by lateral migration by valley axis streams such as South River, indicating that these fans were formed earlier than others graded to lower levels and not truncated (Figure 6.10).

SEDIMENTOLOGY

Unlike the discrete event-dominated stratigraphy of Appalachian debris fans, there does not appear to have been lengthy periods of inactivity during the deposition of sediment in these fluvially-dominated fans. Two major episodes of fan building can be discerned from the observation of extensive exposures of fan gravels in quarry walls (Figure 6.9B). These episodes are separated by a well-developed and laterally extensive palaeosol (Figure 6.11A) which represents a significant

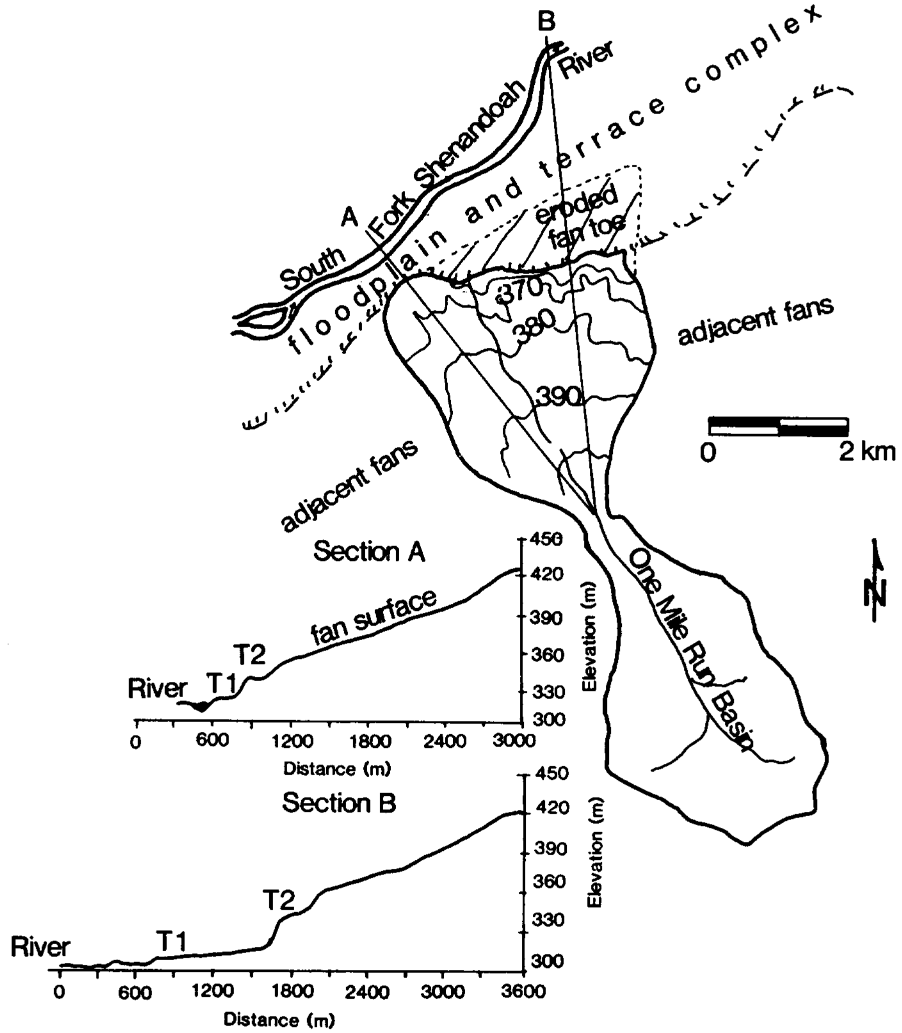

Figure 6.10. Topographic sketch map and longitudinal cross-sections of a fan in the Shenandoah Valley between Waynesboro and Elkton. Evidence of the old age of this fan includes its being graded to a high terrace level and post-depositional dissection. Erosion by the South Fork of the Shenandoah River has removed a significant portion of the northern toe of this fan. This can be seen clearly by comparing the two fan profiles. Fans appear to be of varying ages along the eastern Shenandoah Valley because others are graded to lower terrace levels

hiatus in fan building. No radiocarbon dates have been obtained from these fans, but observations of clast weathering indicate that the lower gravels are very old. Gravels above and below the palaeosol are dominantly clasts of resistant Antietam Quartzite. The upper gravels are extremely rigid and show little disintegration. Weathering rinds on the upper gravels are virtually absent. The lower quartzite gravels, however, are sometimes ghosts that can be penetrated with a dull knife or broken by hand and disaggregated into sand. The extreme disintegration of quartzite clasts below the palaeosol indicate a Pleistocene or perhaps even Tertiary age for the lower gravels. The older period of fan progradation appears to have been more extensive because the younger gravels have extended only to approximately the lower mid-fan region.

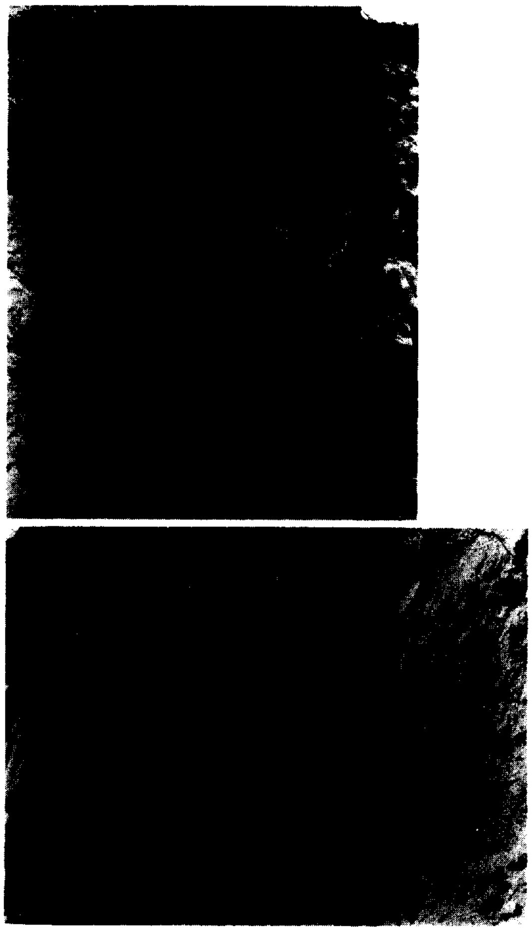

Figure 6.11. Stratigraphy of Shenandoah Valley alluvial fans. (A) View of a quarry wall exposure near the apex of a fan 15 km southwest of Waynesboro (see Figure 6.9B for stratigraphic context). Material above the person's head is unweathered upper gravels composed of imbricated clasts of Antietam Formation quartzite. A well-developed spodosol occurs at the fan surface, covered with mature forest. The lower gravel is intensely weathered, although not all the clasts have been decomposed to sand. The upper 50 to 70 cm of the lower gravel contain a well-developed palaeosol that can be recognized on many fans. Person's hand rests on the palaeosol; (B) Example of the gently dipping, horizontal stratification common in the thick upper gravels of the mid-fan region. This site is in a quarry near Vesuvius. Note the alternating layers of poorly-sorted gravel and moderately well-sorted sand. Gravels display strong imbrication perpendicular to palaeoflow direction

The sedimentology of the fluvial fans along the western slopes of the Blue Ridge is considerably different than that observed in the debris fans found throughout the Appalachian Mountains. The fluvially-dominated fans exhibit well-defined stratification dominated by thick, horizontal beds. These gravels are generally better sorted than debris fan sediments, but are still poorly sorted. Individual beds vary considerably in their relative sorting (Figure 6.11B), from poorly-sorted gravels to well-sorted sand. Large-scale channel cut-and-fill structures are also common in these deposits. Cobbles generally show well-developed, unidirectional imbrication of the type common in fluvial deposits formed by tractive processes, with long axes oriented normal to palaeoflow direction. Sediment size is variable ranging mostly from sand to small boulders rarely over 0.5 m in diameter. These sediments are considerably finer-grained than debris fan sediments. They can be entrained on gentler slopes than required for the transportation of coarser grained sediment observed in the debris fans.

The fluvially dominated fans show considerable variation in grain size and thickness from proximal to distal facies (Figure 6.12). Fan thickness appears to increase to a maximum in the mid-fan region and then slowly thin distally until the fans merge with high terraces of the axial streams of the Shenandoah Valley. Fan sediments also fine distally. Near fan apices, it is not uncommon to find an abundance of large boulders several metres in length where streams were still confined in their narrow upland canyons. Extensive deposits of quartzite scree (Hack, 1965; Hupp, 1983) occur on steep slopes above many of these fans along the Blue Ridge. Sediments in distal regions are dominated by pebble gravels, fine cobbles, and sand. Interfan areas, which probably contained small lakes, show increased percentages of sands and muds.

All of the above characteristics indicate a fluvial braided stream origin for the gravels, not unlike the modern channels seen on the fans but from streams having greater competence that allowed them to affect large areas of the fans during depositional events. Clast supported gravels, commonly found in these deposits,

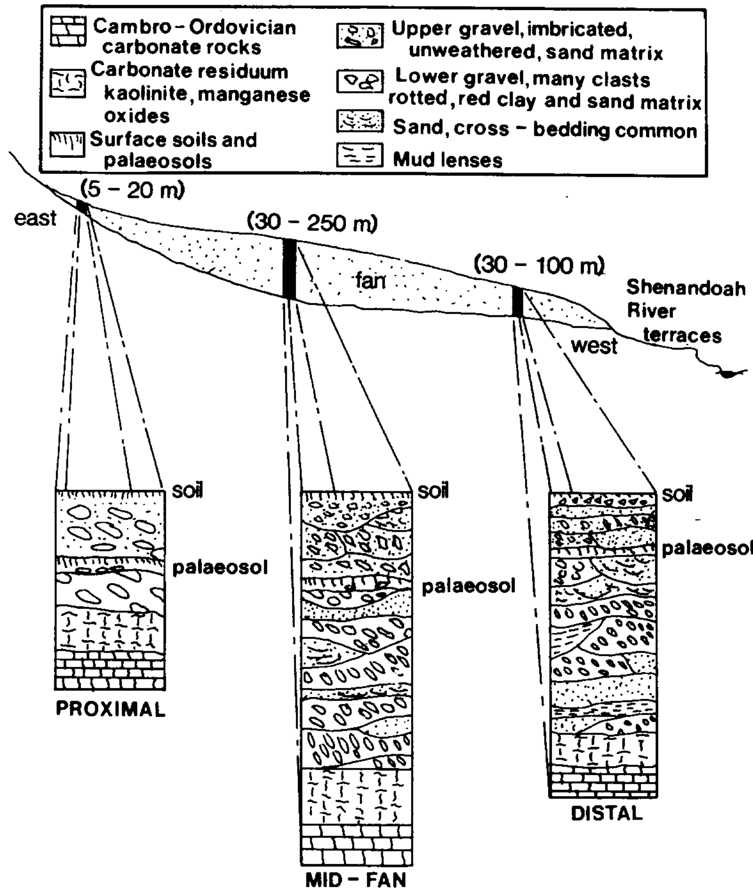

Figure 6.12. Schematic diagram of downfan variation in facies in the fluvially dominated Shenandoah Valley fans. Thicknesses in the columns are not to scale, but the range of observed or inferred (from drillers' logs) thicknesses are given in parentheses. Proximal fan facies are dominated by poorly-sorted, coarse-grained, angular to subangular bouldery material. Mid-fan facies contain interbedded sand and subrounded cobble gravel. Distal fan facies are dominated by cobble to granule gravels and well-stratified sheet sands

appear to have been deposited by hyperconcentrated flood-flows of the type described by Costa (1988) and Smith (1986). It is not unreasonable to envision hyperconcentrated flows being common in these piedmont settings, where catastrophic floods are likely to entrain large quantities of sediment. Debris-flows may be uncommon on these fans because of the lithological and hydrological controls in these basins. The lower concentration of matrix in the fan gravels may be due to lower production of muddy sediment in the source areas underlain by quartzite. In addition, much of the runoff from these basins may be lost rapidly into the subsurface in proximal fan areas. Evidence for the importance of groundwater flow through these gravels is provided by the numerous major industrial wells tapping fan gravel aquifers in distal fan areas along the eastern edge of the Shenandoah Valley.

Summary and Conclusions

Alluvial fans are important piedmont landforms along the slopes of the humid temperate Appalachian Mountains. Considerable variation exists in the morphology, sedimentology, age, and dominant depositional processes common to these fans. In general, there are two major styles of Appalachian fan based on their sedimentology and depositional processes. Debris-dominated fans are ubiquitous throughout the Appalachians and appear to have dominated Holocene fan construction in most areas. Fluvially-dominated fans appear to be restricted to special physiographic situations dictated by geologic control, best expressed along the Blue Ridge in the eastern Shenandoah Valley, and appear to be experiencing a phase of degradation today.

Debris fans occur in a range of sizes, but generally are less than 1 km^2 in area and exhibit irregular shapes due to their topographic confinement in low order tributary basins. Appalachian debris fans are composed of very poorly-sorted gravels with both matrix and clast support. The gravels occur as thickly bedded, irregular depositional units associated with individual debris-flow events. These units are typically distinct because of interevent weathering and soil formation that occur between episodes of debris-flow which tend to be separated by several thousands of years. Most debris fans contain deposits associated with historical debris-flows, but all contain evidence of repeated deposition during the Holocene. All historical debris-flows were triggered by catastrophic rainfall events apparently associated with interactions between the mountains and tropical air masses in the form of terrain locked storms and/or tropical cyclones.

Debris fans in the Dellwood and Roan Mountain areas of North Carolina appear to be less confined than their central Virginia counterparts and tend to be areally more extensive. Because of their less confined nature, multiple fan segments of varying age are generally found. Weathering characteristics and radiocarbon dates of these fans indicate that deposition has occurred to some extent at least as far back as the Late Pleistocene, but that numerous flows have occurred on their surfaces since the major climatic amelioration that began there about 16 000 yr B.P. (Delcourt and Delcourt, 1984).

Central Appalachian debris fans appear to be represented by two types, differentiated primarily on their sedimentology. Fans in central Virginia (Nelson County) are small, steep, and generally composed of matrix supported gravels. These fans are highly irregular due to constraints imposed by their location in first or second order basins. If older fan sediments did exist, they have largely been removed by the reworking by Holocene flows which commenced about 11 000 yr B.P. This date may mark the retreat of the summer polar front to the central Virginia latitude, which allowed significant tropical moisture flow, capable of producing debris-flows into the area. Fans here have formed largely as the product of debris-flows from mobilization of mud-rich colluvial soils formed on Precambrian crystalline rocks.

Western Virginia and eastern West Virginia fans occur in narrow valleys in the folded sedimentary rocks of the Appalachian Ridge and Valley province, and generally contain a greater abundance of coarse clasts derived from the erosion of source areas characterized by thin, colluvial soils developed on resistant Palaeozoic sandstones. The coarse texture of the deposits on these fans effectively armours their surfaces so that subsequent debris-flows have constructed fan segments immediately adjacent to older deposits. The western Virginia fans have prograded into higher order basins, hence are not as confined as those to the east in Nelson County.

The Shenandoah Valley of west–central Virginia exhibits the best examples of Appalachian fans that appear to have been constructed largely by fluvial processes. These fans are unconfined topographically and have prograded out across rocks of low resistance from their source basins in the Blue Ridge. The fluvial fans are significantly larger than Appalachian debris fans, are much thicker, and generally display regular fan shapes in plan view. Their sediments tend to be better sorted, well stratified, and show distinct downfan changes in facies typical of deposits dominated by fluvial tractive transport processes. Occasional less well-sorted beds occur which may be ascribed to hyperconcentrated floodflows. Debris-flow deposits were minor in the numerous exposures in these fans, perhaps due to the lack of available matrix in their resistant, quartzite-dominated source basins.

Observations of soils, clast weathering, and fan morphology suggest that the fluvial fans in the Shenandoah Valley are inactive and may have been inactive throughout much or all of the Holocene Epoch. They currently appear to be undergoing a phase of dissection. Evidence to support the dissection model was provided by the recent Hurricane Juan flood that caused extensive sediment mobilization that was confined to the channels, which occupy only a minute fraction of the fan surfaces.

Controls on alluvial fan morphology and sedimentology in the Appalachian Mountains appear to be complex. However, the major factors that account for their variation seem to be: (1) source basin lithology and weathering products, which ultimately affect depositional processes; (2) topographic confinement of the fan depositional areas; (3) source basin hydrology and morphometry; (4) regional variations in patterns of intense rainfalls; and (5) the relative frequency of depositional events of debris-flows or water flood on these fans.

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