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CONTROLS ON FORM, PROCESS, AND SEDIMENTOLOGY OF ALLUVIAL FANS IN THE CENTRAL AND SOUTHERN APPALACHIANS, SOUTHEASTERN U.S.A.

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ABSTRACT

The most prominent Cenozoic deposits in the Appalachians are alluvial fans. Some fans occur at the junction of tributary and master valleys, but others are many times longer than the width of the master valley and instead occupy the lower end of the tributary valley. Most fans are composed of clay-rich debris-flow deposits, the main exception being fans along the southeast margin of the Great Valley in the central Appalachians. The latter fans, which include the largest in the province, occur where source areas are high in quartzite and piedmont slope angles are comparatively low. These fans appear to consist largely of upper-flow-regime waterlaid deposits and hyperconcentrated-flow deposits. The primary source of sediment for the debris-flow fans is shallow translational slides that occur in colluvium or residuum during rare, catastrophic rainstorms and continue downslope as debris flows. An increased rate of frost weathering and hillslope erosion due to Quaternary glacial climates may have an important, if periodic, effect on Appalachian fans. The most important secondary processes on all studied fans are intense chemical weathering, which greatly modifies the older deposits, and stream erosion along the fan margins.

In some areas, fans appear to be better developed where their tributary basins are underlain by more-resistant bedrock that supplies large boulders to the mountain piedmont. The morphometric relations between fan area and basin area, and between fan slope and basin area, are similar to those reported for fans in other regions, although weak in areas where fan size and shape are highly constrained by topography. Maximum boulder size on fans generally shows only a weak relation to distance from the divide or to slope, presumably because the boulders are moved largely by debris flows rather than by water flows.

Mapping of fan surfaces using relative-age criteria yields information on the evolution of fans. "Telescopic" fans, dominated by entrenching headwater drainage, inset paired terraces, and fan progradation, appear to be less common in this region than elsewhere. Instead, evolution by piedmont-drainage capture appears to be more common on the largest fans. On some other fans, however, a third type of development, involving the lateral migration of streams heading in the uplands, appears to dominate.

INTRODUCTION

The greater part of research on alluvial fans has been carried out in arid and/or tectonically active regions (e.g., see reference list in Blair and McPherson, 1994a). The concentration of fan research in such areas runs the risk of confusing essential characteristics of fans with those that stem from the particular environmental settings of the fans. It is therefore of interest to compare fans from arid and/or tectonic regions with those in regions characterized by humid climate and a low rate of tectonism. Appalachian fans provide an opportunity for such a comparison. Kochel and Johnson (1984) previously made a comparison between Appalachian fans and those in other areas. The present study updates this comparison in the light of additional data and changing ideas about fan genesis.

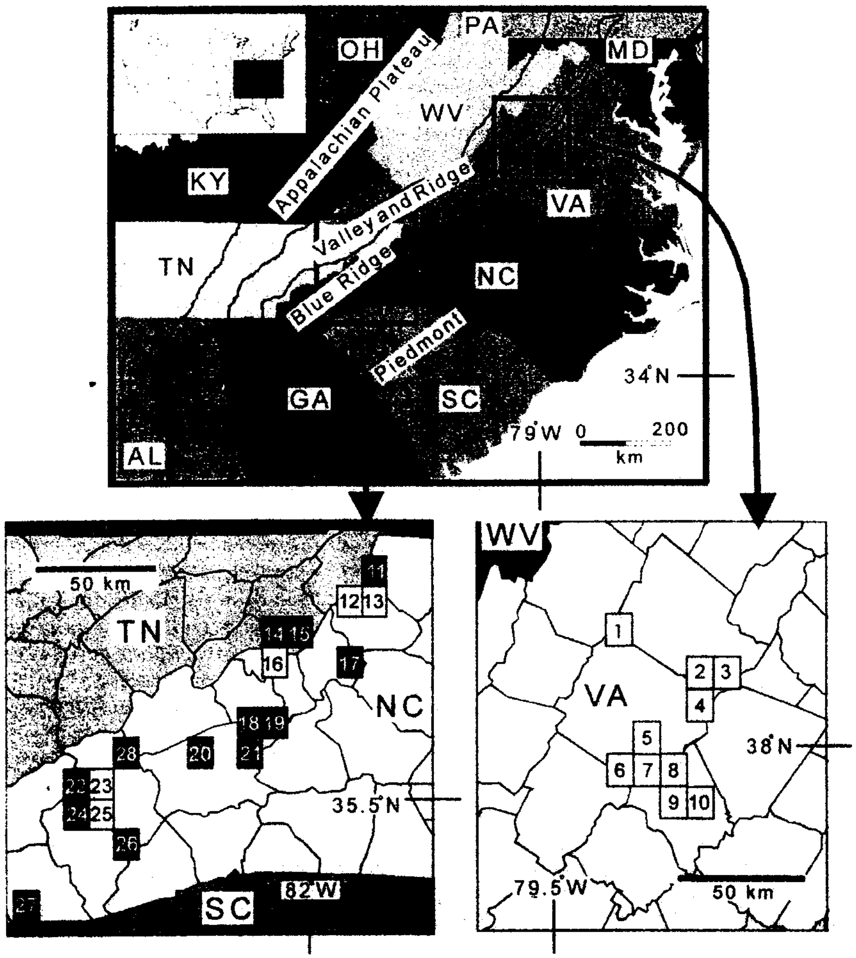

Figure 1. Index map to 7.5-minute quadrangles referred to in text. Unshaded quadrangles are primary locations of fan data discussed in paper; shaded quadrangles are locations of additional data from mountain piedmonts. Virginia quadrangles are: 1 = Reddish Knob, 2 = Grottoes, 3 = McGaheysville, 4 = Crimora, 5 = Stuarts Draft, 6 = Vesuvius, 7 = Big Levels, 8 = Sherando, 9 = Horseshoe Mountain, 10 = Lovingston. North Carolina/Tennessee quadrangles are: 11 = Baldwin Gap, 12 = Sherwood, 13 = Zionville, 14 = Iron Mountain Gap, 15 = White Rocks Mountain, 16 = Bakersville (location of Roan Mountain), 17 = Grandfather Mountain, 18 = Mount Mitchell, 19 = Celo, 20 = Weaverville, 21 = Montreat, 22 = Bunches Bald, 23 = Dellwood, 24 = Sylva North, 25 = Hazelwood, 26 = Sam Knob, 27 = Prentiss, 28 = Fines Creek. State symbols: AL = Alabama, GA = Georgia, KY = Kentucky, MD = Maryland, NC = North Carolina, OH = Ohio, PA = Pennsylvania, SC = South Carolina, TN = Tennessee, VA = Virginia, WV = West Virginia.

The central and southern Appalachian Mountains form a broad arc in the eastern United States that sweeps from the glacial border in Pennsylvania southwestward to Alabama. This study deals chiefly with the Blue Ridge province, and immediately adjacent provinces, in the states of North Carolina and Virginia (Fig. 1). North Carolina contains the highest peaks in the Appalachians, with several exceeding 2000 m in altitude; in central Virginia, the highest peaks in the province have altitudes little more than half this amount. The bedrock is metamorphic rocks of Precambrian and Paleozoic age. Mean annual temperatures reported for mountain weather stations in this province are in the range of 8° - 12° C, although temperatures on the higher peaks are probably somewhat cooler. Mean annual precipitation ranges from 1200 - 2000 mm. Pre-settlement vegetation consisted mainly of hardwood forest, with spruce-fir forest at the highest elevations.

Alluvial fans on mountain piedmont slopes constitute the most prominent Cenozoic deposits in the unglaciated Appalachian Mountains. These deposits attracted the attention of the first geologists to encounter them, primarily bedrock mappers. In the Great Smoky Mountains, for example, fans were noted and briefly described by Hamilton (1961), Hadley and Goldsmith (1963), King (1964), and Neuman and Nelson (1965). More than 30 fans were included on Hadley and Goldsmith's (1963) map of the Dellwood quadrangle, North Carolina. The first geomorphologists to study these features were Hack (1960, 1965) and Hack and Goodlett (1960) in the central Appalachians and Michalek (1968) in the southern Appalachians.

One of the main differences between arid/tectonically active areas and the present study area is in the sediment production rate of the basins feeding the fans. In the Appalachians, the relatively low uplift rate necessarily limits the sediment that can be produced by erosion, and the sediment on the mountain piedmonts is correspondingly thin. Hack (1960) and Mills (1983), in fact, have interpreted some mountain piedmonts in the Blue Ridge province as pediments (in the sense of Rich [1935], in which pediments may be covered with a substantial thickness of deposits, rather in the more common sense of a nearly bare bedrock surface). However, although the piedmonts as a whole may resemble Rich's (1935) pediments, many of the individual deposits on the piedmonts are actually small alluvial fans.

The most prominent alluvial fans in the central and southern Appalachians are located in the Blue Ridge province or in the Valley and Ridge province immediately to the northwest of the Blue Ridge, and previous studies have concentrated on these fans (Fig. 1).

SETTINGS AND TYPES OF FANS

A common setting for alluvial fans in nonglacial, nontectonic areas is at the junction between tributary-stream and master-stream valleys, where fans prograde from tributary mouths onto the floor of the master valley, the size and shape of fans being controlled by the width of the latter. In the Appalachians, most stream valleys are narrow, so that most fans in this setting are small, with radii less than 0.3 km (C in Fig. 2). The largest fans in the Appalachians, however, with radii reaching 5 km, also are found in this setting. These fans have prograded from the western slope of the Blue Ridge Mountains into the wide Great Valley of the Valley and Ridge province; superb examples occur in the southern Shenandoah Valley of Virginia (Kochel and Johnson, 1984; Kochel, 1990; Whittecar and Duffy, 1992). At this location, mountains capped by metamorphic quartzite abut lowlands underlain by limestone and shale. Kochel (1990) noted that the terrain here is similar to the setting of intermontane fans in the northern Rocky Mountain region, and the size and slope of fans here are indeed more similar to fans in the western United States than are most other Appalachian fans.

Most small- and medium-sized fans in the Appalachians, however, do not occur at the junction of a tributary and a master stream, but rather occupy the lower portion of the tributary valley above the junction. (A and B in Fig. 2). Such fans have been called "intrabasinal" (Mills, 1982), because they occupy the lower end of the fan drainage basin rather than an area

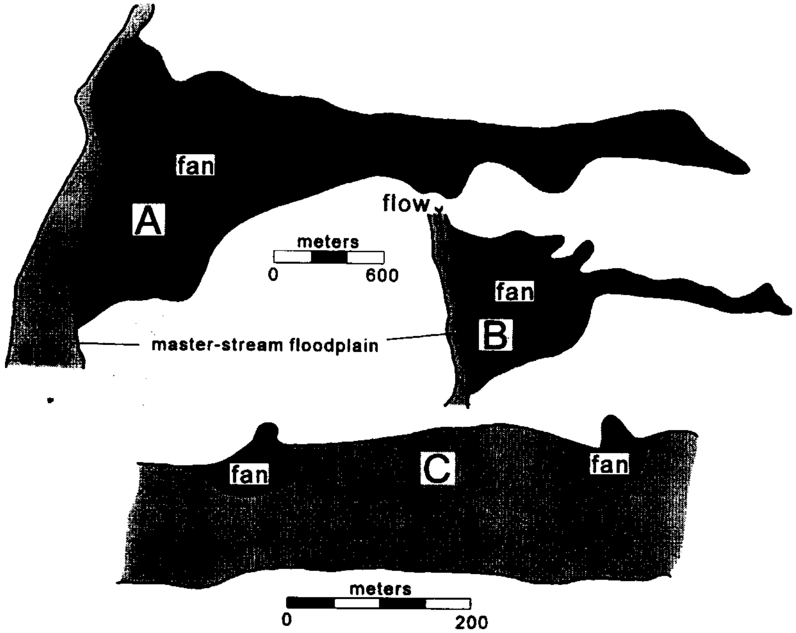

Figure 2. Plan view diagrams of fans at tributary-master stream junctions (C, from Hack and Goodlett 1960, Fig. 26, Reddish Knob quadrangle) vs. intrabasinal fans (A, from Bakersville quadrangle, North Carolina; B, from Dellwood quadrangle, North Carolina).

Table 1. Ratio of fan length to master-stream width.

Location	Mean	Std Dev	n
Colorado River, Grand Canyon (Webb *et al.*, 1989)	0.88	0.27	3
Little River, VA (Reddish Knob quadrangle) (Wilson, 1987)	0.49	0.22	3
Sherando quadrangle, VA (Whittecar and Ryter, 1992)	1.97	0.54	4
Shenandoah Valley, VA - North (Crimora, Grottoes, McGaheysville quadrangles) (Simmons, 1988)	1.31	0.51	6
Shenandoah Valley, VA - South (Big Levels, Stuarts Draft, Vesuvius quadrangles (Simmons, 1988)	2.52	0.56	3
Nelson County, Virginia (Lovingston, (Horseshoe Mt quadrangles) (Wilson, 1987; Kochel, 1990)	6.60	0.77	4
Hazelwood quadrangle, NC (Barber Orchards) (Mills and Allison, 1994)	7.91	2.14	4
Bakersville quadrangle, NC (Roan Mountain) (Mills, 1983)	9.21	5.40	9
Dellwood quadrangle, NC (Mills, 1982; Mills and Allison, 1994)	5.07	3.53	16

beyond the basin mouth, as in the case of the classical alluvial fan. Wilson (1987) summarized the settings of fans in the Appalachians and found that, except for the largest fans, which occur in the very wide valleys of the Shenandoah drainage basin, tributary-junction fans tend to be much smaller than the "intrabasinal" fans.

The two settings discussed above can be distinguished quantitatively by comparing the radial length of the fan to the width of the master valley. The mean ratios of fan radial length to master valley width for a number of areas, including some outside the study area, are shown in Table 1. Ratios that are below or not greatly above 1.00 indicate that the master valley can laterally accommodate all or a large part of the fan. Areas in which fans can be accommodated wholly or largely within the valley include those in the Grand Canyon, Arizona (Webb et al., 1989), Little River, Virginia (quadrangle 1 in Fig. 1; Hack and Goodlett, 1960), and the northern study area in the southern Shenandoah Valley (quadrangles 5, 6, and 7 in Fig. 1; Wilson, 1987). These are locations in which fans are small or master valleys are wide. In contrast, several Appalachian fan locations show ratios greatly above 1.00. The fans at Roan Mountain (Bakersville quadrangle; quadrangle 16 in Fig. 1), for example, show lengths that exceed nine times the width of the valley into which the fans feed. Obviously, only a small part of such fans can be contained within the master valley.

Fans can also be distinguished by the dominant types of sediment they contain. Appalachian fans have been dichotomized into "debris-flow dominated" versus "fluvially dominated" (Kochel, 1990) and into "debris fans" vs. "alluvial fans" (Whittecar and Ryter, 1992a, 1992b; Whittecar and Duffy, 1992). In these terms, most fans in this region are debris-flow dominated or debris fans. The predominantly waterlaid fans are confined chiefly to the Great Valley of the Valley and Ridge province, particularly the broad Shenandoah Valley in Virginia (quadrangles 2 - 7 in Fig. 1).

PRIMARY AND SECONDARY PROCESSES ON FANS

Blair and McPherson (1994a) defined primary processes as those responsible for transporting sediment from the drainage basin to the fan and secondary processes as those that modify fan sediments in the intervals of time between depositional episodes. Primary and secondary processes on Appalachian fans are basically similar to those reported for fans in arid and/or tectonically active areas, although the relative importance of specific processes differs because of the low slopes and high rate of chemical weathering that characterize the Appalachians. In particular, sediment-gravity processes that supply sediment to the fans show differences. Blair and McPherson (1994a) list rockfalls, rock avalanches, gravity slides, debris flows, and water flows under this category. In the central and southern Appalachians, most sediment is supplied to fans by shallow translational slides in colluvium or residuum, particularly in hollows, which subsequently transform into debris flows (e.g., Williams and Guy, 1973). Rockfall onto the heads of fans is rare, for two reasons. First, cliffs are relatively restricted in the Appalachian Mountains. Second, rangefront slopes above the heads of fans are generally fairly low. As a consequence, slopes sufficiently steep to generate rockfalls rarely abut fans, but occur farther up the mountain, separated from the fan by slopes of intermediate steepness. Likewise, rock avalanches are relatively rare in this region. Although large bedrock landslides do occur in the Appalachians (e.g., Schultz, 1986; Schultz and Southworth, 1989), they are uncommon and do not appear to be an important means of supplying rock debris to fans. Schultz and Southworth (1989), for example, reported that there was no substantive evidence for historical movement of the bedrock landslides they studied. This finding contrasts with the thousands of debris flows that have occurred in the Appalachians during the 20th century alone (e.g., Williams and Guy, 1973; Gryta and Bartholomew, 1983). It is likely, however, that Pleistocene periglacial climates have had a strong effect on fans. An increased erosion rate on hillslopes due to deeper freeze-thaw cycles may have greatly increased the volume of hillslope colluvium in basins tributary to fans, although exactly when this debris would be delivered to the fans is unclear. Eaton and others (1997) and Eaton (1999), for example, suggested that during glacial intervals the importance of debris-flow processes may have decreased while that of slope wash increased. Whittecar and Ryter (1992a, 1992b) suggested that during glacial intervals the upper parts of basins tributary to basins may have been clogged by the increase in the formation of talus and boulder streams, thereby reducing the sediment supplied to fans. Both these effects would thus decrease the amount of sediment transported to the fans during glacial intervals, while at the same time increasing the volume of sediment in the basin ultimately available for delivery to the fans, even though the actual delivery might not occur until after the glacial interval.

Intense chemical weathering in the Appalachians due to comparatively high rainfall and temperature (at least during interglacial climates - see Cleaves, 1989) produces large amounts of residuum (e.g., Pavich, 1986). Cohesive clay-rich debris flows resulting from the failure of this material on slopes make up the main form of deposition on most Appalachian fans (e.g., Mills, 1986; Mills and others, 1987; Kochel, 1987; Whittecar and Ryter, 1992a). An exception is the Shenandoah-Valley fan type. The drainage basins of these fans are underlain chiefly by quartzite, and consequently are deficient in clay. As a result, these fans are dominated by fluid-gravity flows (Kochel, 1990; Kochel and Johnson, 1984; Simmons, 1988).

Secondary processes on fans, like primary processes, differ in relative importance from those fans studied elsewhere. Surficial reworking by water occurs in both areas, but is probably less frequent on Appalachian fans because streams are generally confined to fan margins during times between the rare depositional episodes. Lateral erosion along the flanks of the fans by these marginal streams, however, constitutes an important secondary process, as discussed below. Bioturbation is probably much more important on Appalachian fans owing to the natural presence of dense hardwood forest combined with relatively low sediment-deposition rates. Although the abundance of large clasts in the deposits prevents some types of bioturbation, uprooting of trees by wind, in particular, disrupts sedimentary structures. Weathering and soil development are also probably more important on Appalachian fans, owing to high rates of chemical weathering and the relative thinness of the sediments. In some areas even Holocene fan surfaces show development of Ultisols (Mills and Allison, 1995a), excepting those surfaces activated in historical times. On mid- to early Pleistocene fan remnants, intense chemical weathering can greatly increase clay contents and decompose clasts as deep as 10 meters below the surface; thinner deposits may therefore be highly weathered all the way to their base (e.g., Mills and Allison, 1995a, 1995b).

CONTROLS ON FAN PROCESSES

Five factors that strongly influence the major sedimentary processes and deposits of alluvial fans are: a) lithology and splitting characteristics of the bedrock underlying the drainage basin, b) shape and evolution of the drainage basin, c) neighboring environments, d) climate, and e) tectonism (e.g., Blair and McPherson, 1994a). Each of these is discussed below in the context of Appalachian fans.

1) Drainage Basin Lithology

Blair and McPherson (1994a) found that the regolith of basins must contain a certain minimum clay content in order for debris-flow deposition to be important on alluvial fans. At the other end of the spectrum, however, there may be a maximum regolith clay content for the occurrence of debris flows. Jacobson et al. (1993) reported that extremely clay-rich regolith in the Appalachians, such as that which forms on shale bedrock, is destabilized not by short, intense rainfalls but by long-duration low-intensity rainfall. Slope failures are mainly slides and slumps that commonly transform into earth

flows, but not debris flows. Debris flows, in contrast, tend to occur in basins with coarser, more-permeable regolith which fails mainly under the influence of high-intensity rainfalls (see Kochel, 1990, for an account of the association between debris flows and intense rainfall events). Thus, there is an optimum range of regolith clay content, with values below and above resulting in debris flows being uncommon. In the Appalachians, basins that lack debris flows due to low clay contents appear to be confined mainly to quartzite bedrock; those lacking flows due to excessively high contents are confined mainly to shale bedrock. Most other bedrock types in this region apparently produce regolith with a clay content conducive to debris flows. In contrast, in drier regions, bedrock types besides quartzite may produce clay-deficient regolith. Blair and McPherson (1994a) note, for example, that in arid regions, granite and gneiss yield little clay and silt, whereas shale, mudstone, and volcanic rocks yield abundant fines. In the Appalachians and in other humid areas, however, many igneous and metamorphic rocks are quite vulnerable to chemical weathering, and may yield regoliths rich in clay. (Actually, the main factor in the production of clay-rich regolith is probably the ratio of chemical weathering to physical weathering and erosion. An area characterized by humid climate and active tectonics, for example, might have a rate of chemical weathering equal to that of the Appalachians, but the much greater rate of hillslope erosion associated with tectonically active areas would produce larger amounts of coarse debris.) Also, in dry or tectonically active areas, there is probably rarely a problem with clay contents in regolith being too high for the occurrence of debris flows.

Fans are by no means ubiquitous on mountain piedmonts in the Appalachians. Many areas lack significant fan development, despite the presence of relief comparable to that in areas with well developed fans. One factor that appears to be associated with the presence of well developed fans is the presence of abundant large boulders. A characteristic of the bedrock that may be important for Appalachian fans is the size and durability of boulders supplied by the drainage basin. (Durability is as important as initial size, as some bedrock initially splits into large boulders, but the boulders subsequently disintegrate close to their source.) There are at least two different effects of boulders that might favor fan development. First, debris flows and their relatively voluminous deposits appear to be necessary for fan development in many parts of the Appalachians. (Some evidence for this association is provided by my observation that basins underlain by shale, in which debris flows are rare, are seldom associated with prominent fans.) Basins with numerous large boulders too large to move by fluid-gravity transport are likely to accumulate sediment until a catastrophic rainfall moves the sediment out in the form of a debris flow. Hence, large boulders may be significant for fan formation because they increase the relative importance of debris flows for sediment transport in the drainage basin. Second, boulders may directly promote fan growth by armoring the fans. Large boulders, once delivered to gently-sloping footslopes, are difficult to subsequently remove by water flows. Further, the protective effect of large boulders helps prevent stream dissection, thereby preserving the morphology of the fan. The effect also inhibits the erosion of fan toes by master streams. The protective effect of boulders is probably a somewhat more important factor in the Appalachians than in arid/tectonically active areas because of the very low ratio of primary sedimentation rates to secondary process rates in this region.

To test the hypothesized effect of boulders on fans, maximum clast size (MCS), defined as the mean intermediate diameter of the five largest clasts, was measured at a large number of mountain piedmont sites both with and without fans (clasts in the latter sites were located in channels and hollows). In Figure 3, MCS is plotted against distance from the divide. The areas with fans are distinguished from the areas without fans. (Sites in hollows upstream from fans are included with the fan data). Although a Student's t-test showed that the two groups are not significantly different in size at the $p < 0.05$ level, of the 37 sites with maximum clast size larger than 200 mm, only 4 lack fans, which suggests that although large boulders are not re-

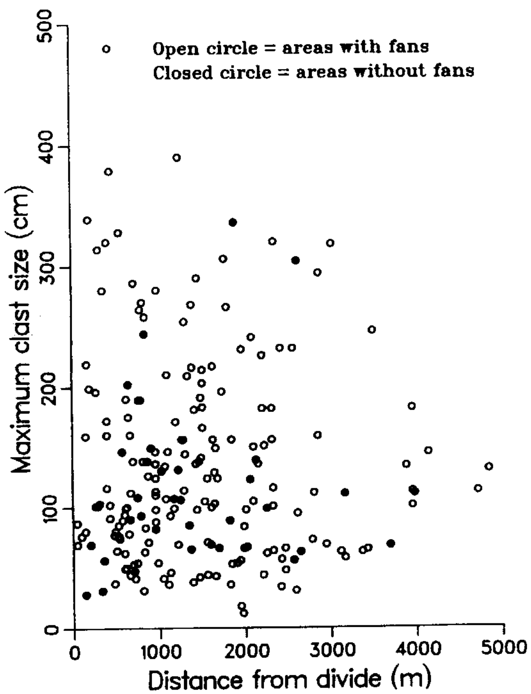

Figure 3. Maximum clast size (intermediate diameter) vs. distance from drainage divide for areas with fans vs. areas without fans in the North Carolina Blue Ridge province. (Data from old fan surfaces were excluded, because weathering has decomposed many of the surface boulders.)

quired for fan development, they do favor the presence of fans. The possible relation of boulders to fan size and form is discussed in the following section.

2) Drainage-basin Form

The major difference between the drainage basins of fans in arid/tectonically active areas and those of Appalachian fans is the relative lack of steep slopes in the latter, which reduces the contribution by rockfall, rock avalanches, and large rock slides to the sediment budget. The average slope is still fairly high, however, and combined with the narrow V-shaped valleys, flash-flood potential in the basins is high. Feeder channel sediment-storage capacity is probably a less important factor than in arid or tectonically active basins, because the volume of regolith on the valley walls, which can be mobilized into debris flows, commonly is relatively abundant.

3) Neighboring environments

In Appalachian basins, the longitudinal master stream occupying the valley into which the fans are feeding marginally is very important. Because the valleys in the Appalachians are narrow, the marginal fans are susceptible to pronounced erosion at their distal margins, and cut terraces may be produced on the toes of abandoned fan segments. In the broad Shenandoah Valley, a complicated interdigitation of fan and master-stream deposits occurs at the fan toes (Mason, 1992).

4) Climatic Effects

Climatic effects include precipitation and temperature, and the effects of these factors on vegetation. Precipitation is sufficiently high and temperature sufficiently moderate to maintain dense forests throughout the Appalachians, at least during the Holocene (e.g., Delcourt and Delcourt, 1981). Two effects of vegetation, bioturbation and weathering, have been discussed above. Another effect, as pointed out by Greenway (1987), is that vegetation increases the shear strength of regolith, allowing hillslopes to stand steeper than they would otherwise. This is probably a particularly important effect in the densely forested Appalachians. The recurrence interval of storms capable of producing hillslope failure is probably much longer than it would be in the absence of trees, so that debris flows, although less frequent, probably are more voluminous than they would be otherwise. As much of the material in most Appalachian fans appears to consist of debris-flow deposits, it is likely that storms with intensities below that needed to set off debris flows contribute little sediment to fans.

Minor climatic changes, such as those that have occurred during the Holocene, have been shown to have a significant impact on alluvial fans in dry regions (e.g., Wells *et al*, 1987; Bull, 1991). These changes affect fan deposition by means of their effect on hillslope runoff and sediment yield, via effects on vegetation cover and permeability of hillslope surfaces. Such variations seem unlikely to affect Appalachian fans, for several reasons. First, although minor climatic changes may affect the dominant types of trees, drainage basins would remain completely forested. Second, solid sediment yield from forested Appalachian basins in the absence of significant slope failures generally is small (e.g., Dils 1957), and, as discussed above, such water-laid sediment probably is insignificant in the deposition of most Appalachian fans. Third, in dry regions sediment-laden runoff may transform into debris flows downhill; in forested Appalachian drainage basins, debris flows rarely form in this manner but result almost exclusively from slope failure in saturated regolith. Thus, changes in hillslope runoff and sediment yield would have little effect on fan deposition.

The effect of major climatic changes, specifically the alternation of glacial and interglacial climates during the Quaternary, is more problematic. Is fan building more prominent during glacial or interglacial climates? Earlier investigators, noting that fans presently appear to be inactive, considered them to be relicts of the late Wisconsinan glacial interval (e.g. Hadley and Goldsmith, 1963; Michalek, 1968). Kochel and Johnson (1984) and Kochel (1987), however, demonstrated with radiocarbon dates that most of the debris flows on small fans in Nelson County, central Virginia, are of Holocene age. As a possible explanation of this age, Kochel (1987) pointed out that, based on paleovegetation reconstructions by Delcourt and Delcourt (1981, 1984), the average position of the summer polar front was well south of central Virginia, which would block tropical moisture from reaching the mountains of central Virginia and triggering the intense rainfalls necessary for extensive debris slides. Subsequently, Kochel (1990) showed that in the further-south North Carolina Blue Ridge, from which the summer polar front retreated several thousand years earlier, postglacial debris-flow deposition on fans had begun by 16 ka.

More recent studies, however, which have obtained dozens of radiocarbon dates from fans in Madison County, Virginia (Eaton and McGeehin, 1997; Eaton and others, 1997; Eaton, 1999), suggest a more complicated picture, with a number of deposits being much older than 16 ka. In addition, Morgan and others (1997) point out that fan stratigraphy is extremely complicated and difficult to interpret, as a given debris flow usually covers only part of a fan, and old deposits may be scoured away by younger events. Other considerations make understanding the effect of climate even more uncertain. For example, the mean annual temperature even in the southern Appalachians is estimated to have been lowered as much as 15° C during glacial maxima (e.g., Delcourt, 1979), with an average lowering in the southeastern U.S. of 10°-12° (Webb and others, 1993). Treeline, the maximum altitude at which trees grow, was consequently lowered to 1000-1500 m, depending on latitude, so that large parts of the fan drainage basins in the Blue Ridge probably lacked forest cover. Even if the basins remained completely covered with tundra vegetation, the lack of tree roots would decrease slope stability and thereby decrease the threshold of rainfall intensity necessary to set off debris slides. Presumably, more-severe freeze-thaw activity would have increased surficial debris on hillslopes. These effects promoting debris flows, however, may have been offset by the paucity of tropical air masses and a tendency to arid climates during glacial maximums. One possibility is that debris-flow deposition was particularly intense just at the transition from glacial to interglacial climates. Some evidence for this interpretation is provided by Delcourt's (1980) study of terraces along the Little Tennessee River. Delcourt found massive alluviation, and by implication, colluviation, to be concentrated at the Pleistocene/Holocene transition. Knox's (1972) model for arid/humid climate transitions, at which large pulses of sediment to streams occur, might well apply here. In any case, discussion of the effect of glacial/interglacial climatic effects on Appalachian fans will remain speculative until fan deposits are much more extensively dated.

5) Tectonic Effects

Blair and McPherson (1994a) point out that without continued tectonism, fans may be minor and short-lived features. The intraplate setting of the Appalachians implies that the uplift that maintains relief is the isostatic response to denudation (Pavich, 1985). Such uplift is epeirogenic, so that differential erosion must accompany the uplift in order to maintain the local relief necessary for fan development. This uplift, at least averaged over long time periods, is much slower than most tectonic uplift. For example, net vertical uplift rates average 1-3 cm/1,000 yr on the Atlantic Coastal Plain of North and South Carolina (Cronin, 1981), whereas rates in tectonically active areas may exceed 10 m/1,000 yr. The relatively low uplift rate of the Appalachian region necessarily limits the sediment that can be produced by erosion, which in turn influences fan development.

There may be evidence of changing uplift rates through time on some Appalachian fans. Whittecar and Duffy (1992) noted that in their study area in the Shenandoah Valley, Quaternary deposits are somewhat less extensive than much-older, probably Tertiary fan deposits, and hypothesized that the more-extensive Tertiary deposits might reflect accelerated uplift of the Appalachian region during the Miocene, as inferred by Poag and Sevon (1989) based upon stratigraphic records of offshore sediments.

FORM AND SIZE OF FANS

In contrast to classical alluvial fans in the Basin and Range province, the size and shape of fans in the Appalachians generally are much more constrained by the surrounding topography, owing to their "intrabasinal" settings. The most unconstrained are the waterlaid fans produced by streams debouching into the Shenandoah Valley from the Virginia Blue Ridge (Fig. 4A; Quadrangles 2-7 in Fig. 1). These fans are similar in both morphology and sedimentology to many of those of the western United States. They are the largest in the Appalachians, and are composed of clast-supported gravels believed to be upper-flow-regime sheetflood and hyperconcentrated-flow deposits. Fan thickness can exceed 200 m (Kochel, 1990). Whittecar and Duffy (1992) provide a more-complete discussion of these fans.

The next less-constrained fans are those at Roan Mountain (Bakersville quadrangle) (Mills, 1983; Figs. 4B and 5A) and Barber Orchards (Hazelwood quadrangle), (Mills and Allison, 1994; Fig. 5B), both in North Carolina; these fans occur in large embayments in the mountain front. These are smaller and less regular than the Shenandoah fans, and they are composed primarily of bouldery debris-flow deposits, with a total thickness generally much less than those of the Shenandoah fans. Still more constrained are the fans of Dellwood quadrangle, North Carolina (Fig. 4C) and Nelson County, Virginia (Figs. 1 and 4D). Although

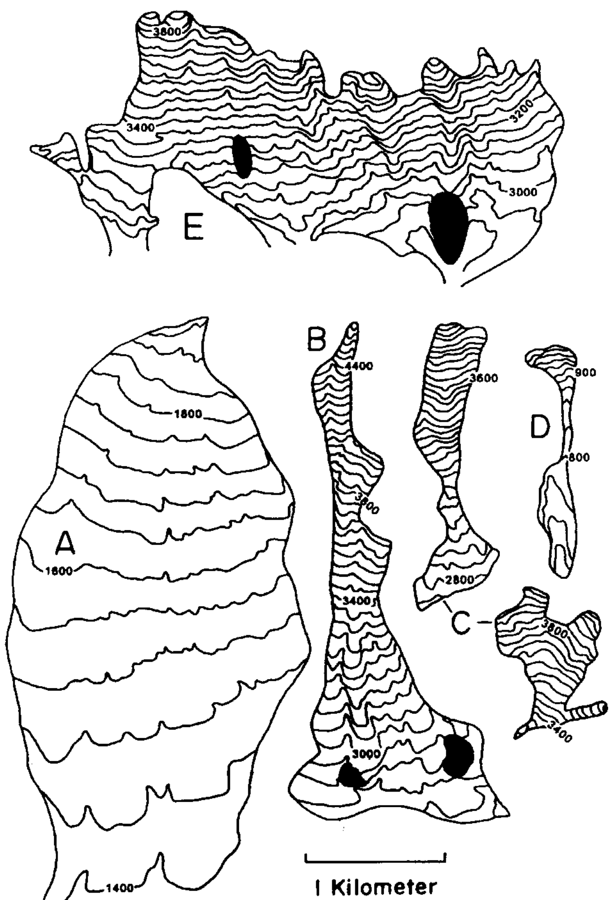

Figure 4. Examples of Blue Ridge fan topography. Downslope direction is to bottom of page. Contour interval is 40 ft (12.2 m) for A, B, C, and E, and 20 ft (6.1 m) for D. Altitudes (in feet) are given for selected contours. Black indicates areas of saprolite or bedrock outcrops. Fans are from the following locations: A. Big Levels and Stuarts Draft quadrangles, Virginia, western Blue Ridge and Shenandoah Valley; B. Bakersville quadrangle, Roan Mountain, North Carolina; C. Dellwood quadrangle, southeastern Great Smoky Mountains, North Carolina; D. Horseshoe Mountain quadrangle, Nelson County, Virginia; E. Zionville quadrangle, Rich Mountain, North Carolina. Modified from Mills *et al.* 1987.

some of these fans resemble sections of cones, (e.g., Fig. 5C), many are quite irregular in form. Fan width in some cases decreases rather than increases downslope, and some fans have multiple feeder channels (Fig. 4C). These somewhat anomalous characteristics stem from the pronounced topographic constraint and the intrabasinal setting of the fans. Additional small fans have been mapped by Gryta and Bartholomew (1983) in the Sherwood quadrangle, North Carolina (e.g., Fig. 5D). The fan examples discussed to this point have discrete forms;

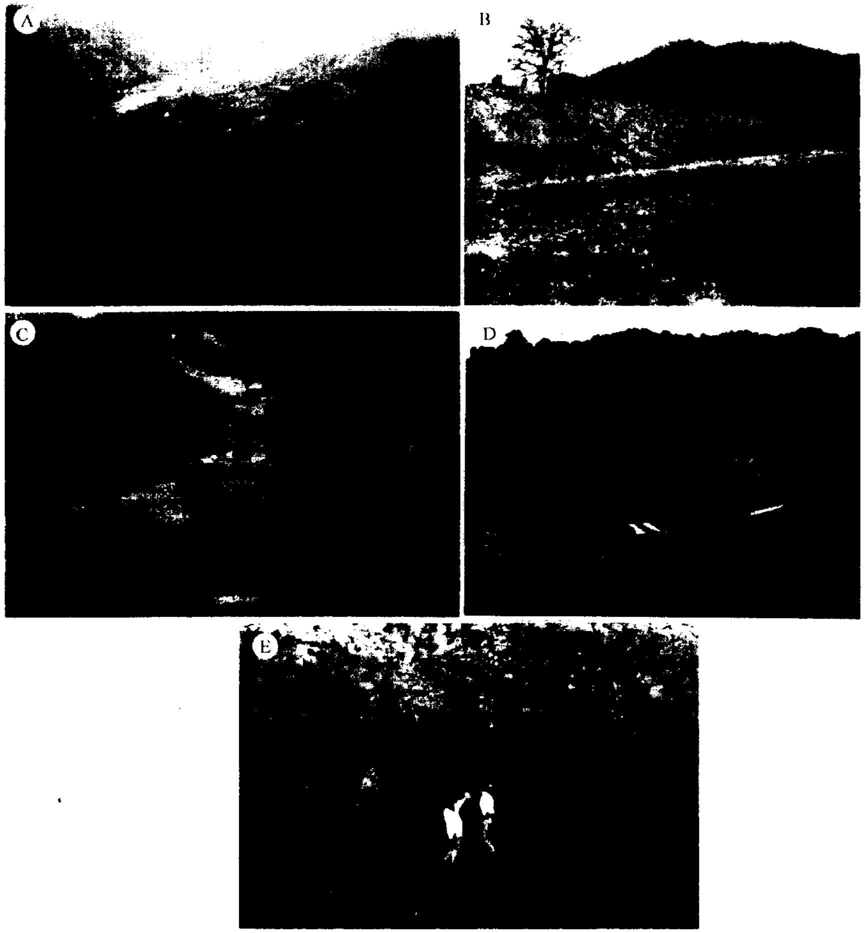

Figure 5. Examples of alluvial fans in the North Carolina Blue Ridge province. A. West flank of Roan Mountain (Bakersville quadrangle) showing complex of relatively large fans; west is to left. B. Fan in Hazelwood quadrangle, looking upslope; younger fan surface in foreground, older, higher fan surface in middle ground. C. Small fan in Fines Creek quadrangle. D. Small fan in Sherwood quadrangle. E. Exposure of fan deposits on west slope of Rich Mountain, Zionville quadrangle, showing sediments several meters thick overlying saprolite. Note sharpness of contact.

other fans occur as continuous aprons along mountain footslopes, as illustrated by the west slope of Rich Mountain, North Carolina (Fig. 4E). To some extent, these fans may be considered analogous to bajadas, although the fact that the deposits are only several meters thick in many locations (e.g., Fig. 5E) also suggests an analogy to pediments.

In the southwestern United States, log-log regression equations of the form $A_f = c\ A_d^n$ (where A_f is fan area and A_d is drainage-basin area) yield values of the exponent n that are generally between 0.7 and 1.1 and values of c between 0.1 and 2.2 (Blair and McPherson,

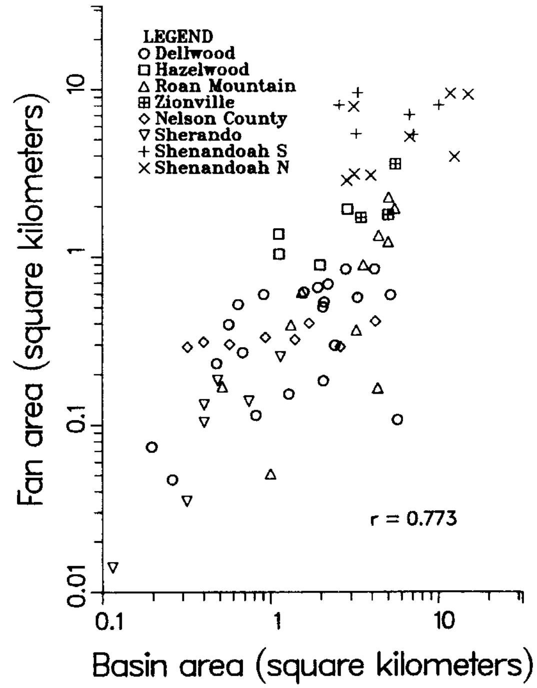

Figure 6. Plot of fan area versus basin area for Blue Ridge fans. Note that within some individual areas, such as Nelson County, there is little or no correlation.

1994a), and in many cases the log-log correlations are fairly high. In the Blue Ridge province, fan-basin area correlations have been found to be very low for some areas (e.g., Kochel and Johnson, 1984; Simmons, 1988), apparently owing to 1) the topographic constraint of fans, and 2) the small range of fan size in some areas. A plot of data for fans throughout the Blue Ridge area, however, shows a fairly good relation (Fig. 6), with a log-log correlation (*r*) of 0.773. For the plot in Figure 6, an equation of $A_f = 0.229\ A_d^{1.08}$ is found. The values of c and n are thus within the ranges reported for the southwestern United States. The low value of c (0.229) indicates that in the Blue Ridge province the ratio of fan area to basin area is small relative to ratios usually seen in the Southwest. This could result from the low rate of sediment production in the Appalachians relative to tectonically active areas, but it probably also reflects the topographic constraint that limits the size of fans. These two factors are closely related, for if the volume of sediment in small, deposits will be thin and thus more affected by topography.

A question addressed by many authors is the effect of drainage-basin lithology on the size and form of alluvial fans. Bull (1962) and Hooke (1968) reported that drainage basins underlain by rock types which are less resistant to erosion tend to produce alluvial fans larger in area than do basins with more-resistant rock types, the idea being that basins with less-resistant rocks produce more sediment per unit area. In contrast, in the White Mountains of eastern California, Lecce (1991) found that larger fans are produced by basins underlain by more resistant rocks. His explanation involved the valleys associated with rock type. In basins underlain by resistant rock types, trunk streams flow in

Table 2. Slopes of Blue Ridge fans.

Location and reference	n	Mean slope	Standard deviation
Dellwood quad, North Carolina (Mills, 1982)	34	0.184	0.064
Hazelwood quad, North Carolina (Barber Orchards) (Mills, unpub. data)	4	0.159	0.013
Bakersville quad, North Carolina (Roan Mountain) (Mills, 1983)	13	0.137	0.042
Zionville and Sherwood quads, NC and TN (Mills, unpub. data)	3	0.107	0.032
Shenandoah Valley, VA - North (Crimora, Grottoes, McGaheysville quads) (Simmons, 1988)	8	0.027	0.008
Shenandoah Valley, VA - South (Big Levels, Stuarts Draft, Vesuvius quads) (Simmons, 1988)	7	0.028	0.008

steep, narrow canyons with little sediment in storage; most sediment is delivered to the fan apex. In basins underlain by erodible rock types, however, valley floors are wide and much sediment is stored along the trunk stream canyons, so that less sediment reaches the fan apex. Storage of sediment also is somewhat greater on valley side slopes, which are gentler in areas of erodible rock than in areas of resistant rocks. It seems probable that these competing effects of lithology are present in most drainage basins. Where the sediment-production factor is dominant, basins with erodible lithologies produce larger fans than basins with resistant lithologies. Where the sediment-storage factor is dominant, however, basins with erodible lithologies produce smaller fans.

In the Appalachians, Hadley and Goldsmith (1963) and Hack (1965) reported that fans tend to have greater areas where basins are underlain by more resistant rocks. Similarly, Simmons (1988) found that in the Shenandoah Valley of Virginia, drainage basins underlain by high percentages of less-resistant rock types have fans with smaller areas than do those with high percentages of the resistant Antietam Formation quartzite. Besides the effect suggested by Lecce (1991), this relation may also derive in part from the fact that the area of alluvial fans depends partly upon the resistance of the deposits to subsequent erosion. As clasts from basins underlain by resistant rocks commonly are larger as well as more resistant to erosion than those from basins underlain by less-resistant rocks, the deposits also are more resistant to secondary erosion. The armoring effect of the resistant clasts on a fan should be most dramatic where the contrast between the erosional resistance of the rocks in the upland basin and the piedmont slopes upon which they come to rest is greatest. In the Shenandoah Valley (Hack 1965), quartzite clasts overlie shale bedrock. In the Great Smoky Mountains (Hadley and Goldsmith, 1963), resistant metasandstone and metaconglomerate boulders of the Great Smoky Group overlie the much less-resistant Pigeon Siltstone or Roaring Fork Sandstone on lower mountain flanks. In the Dellwood quadrangle of the eastern part of this mountain range, however, a statistical study by Mills (1982) found essentially no relation between the type of bedrock in the drainage basin and fan area. On the other hand, in the northern Great Smokies, where the metasandstone and metaconglomerate of the Great Smoky Group have much thicker bedding than in the eastern part of the range, fans have much greater area than in the Dellwood quadrangle.

Fan slope has been studied by many researchers (Blair and McPherson, 1994a, 1994b). Table 2 shows mean overall fan slopes for several study areas in the Blue Ridge province. Note that the slopes on the waterlaid fans (Shenandoah areas) are much lower than those on the debris-flow dominated fans. This difference may result from two factors. First, debris-flow fans generally have somewhat steeper slopes than fans deposited mainly by water flows because flows of Bingham fluids (debris flows) require steeper slopes for movement than do water flows (Johnson, 1970). Second, the waterlaid Shenandoah fans and their drainage basins are much larger than those of the debris-flow fans, and inverse relations between drainage-basin area and stream slope and between fan area (or fan length) and fan slope has been recognized for some time (e.g., Hack, 1957; Anstey, 1965) (although, to be sure, the causal relation between these two variables remains unclear). Figure 7 shows a plot of the mean fan slopes against mean drainage-basin area, compared to an envelope showing the range of similar plots for fan studies in other regions. All points plot within the envelope, indicating that Appalachian fans do not differ from fans in other parts of the world in this regard. Note that the points representing the debris-flow dominated fans plot higher in the envelope (relatively steep slopes) and those representing the waterlaid Shenandoah fans plot near the lower boundary of the envelope (relatively low slopes). An uncertainty concerning the interpretation of the slopes of thin fans is that the slope of the underlying bedrock and saprolite may have been controlled by processes that predate the fans, so that fan surface slope may only partly reflect depositional processes.

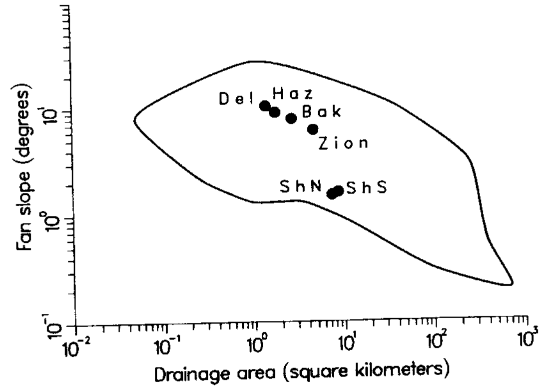

Figure 7. Plot of mean fan slopes vs. mean drainage-basin areas. Envelope shows range of values for arid-region fans (envelope from data compilation by Blair and McPherson 1994a). Del = Dellwood quadrangle; Haz = Hazelwood quadrangle; Bak = Bakersville quadrangle; Zion = Zionville quadrangle; ShN = northern Shenandoah Valley fans (Crimora, Grottoes, and McGaheysville quadrangles); ShS = southern Shenandoah Valley fans (Big Levels, Stuarts Draft, Vesuvius quadrangles).

The above discussion considers only the overall fan slopes. Generally, slopes on fans decrease in the downstream direction. However, the longitudinal profile is commonly not smooth and concave-upward, but consists of a series of straight profiles, becoming successively gentler downstream. Similar radial profiles can be seen on Appalachian fans (Fig. 8). Bull (1964a, 1964b) referred to fans with such profiles as segmented fans, and suggested that in the Basin and Range province segmentation resulted from intermittent uplifts or perhaps climatic change. However, other factors than those discussed by Bull can probably account for segmentation. For example, Blair (1987) found that segmentation on the Roaring River fan in Rocky Mountain National Park, Colorado, produced by the 1982 Lawn Lake flood, resulted from intrinsic causes such as crossing from one fan lobe to the next along profile or downslope breaks in clast size. In the Appalachians, Duffy (1991) noted that the breaks in slope along radial profiles correlate well with the boundaries of different aged deposits, with steeper slopes associated with younger deposits, although why

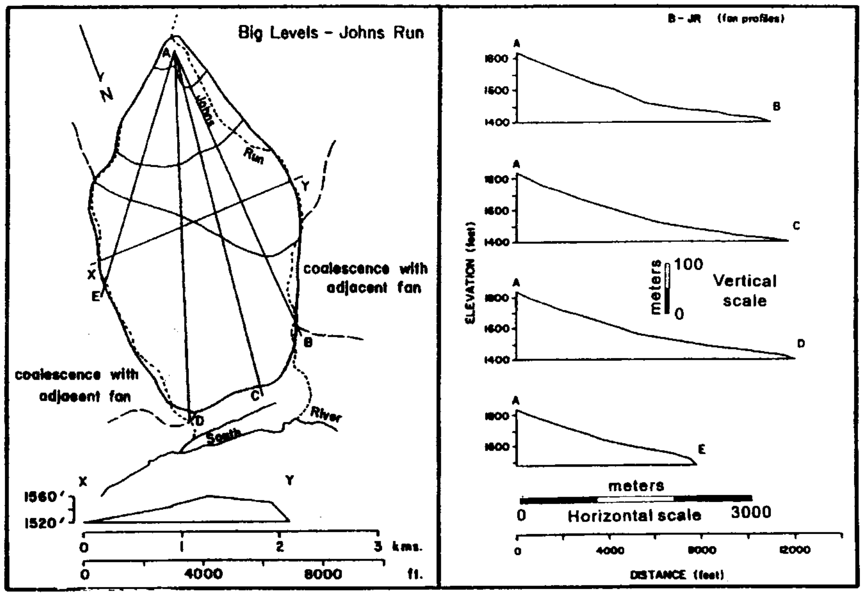

Figure 8. Examples of radial profiles of the segmented Johns Creek fan (Big Levels quadrangle; from Simmons 1988).

this relation should exist is unclear.

As with fan size, researchers have attempted to relate fan slope to drainage basin lithology. Bull (1964a), for example, found that fans derived from basins underlain by fine-grained sedimentary rocks are 33 to 75% steeper than fans derived from sandstone basins. Simmons (1988) found some evidence to support this concept in the Shenandoah Valley, in that the steepest overall slopes are generally associated with basins containing a larger percentage of the Hampton Formation, a relatively weak rock unit consisting of siltstone and arkosic sandstone. On the whole, this is a difficult hypothesis to test in the southern Blue Ridge (i.e, North Carolina), where bedrock formations show relatively small differences in resistance to erosion. However, the hypothesis seems unlikely to be true, as basins with highly resistant bedrock are likely to produce large boulders which require steep slopes to export and move across the downslope fan, either because a greater tractive force is required to move the clasts, or because debris flows are required to move the clasts, and debris flows produce fans with relatively steep slopes.

SEDIMENTOLOGY AND STRATIGRAPHY OF FANS

The sedimentology and stratigraphy of Appalachian fans has received relatively little attention, owing to the general lack of exposures and visible bedding. The most obvious dichotomy in fan sedimentology and stratigraphy within the Blue Ridge province is between the waterlaid fans on the southeastern side of the Great Valley in the central Appalachians and the debris-flow dominated fans elsewhere.

1) Waterlaid Fans

These fans have received the most study along the western flank of the Blue Ridge Mountains in the southeastern Shenandoah Valley of Virginia (Hack, 1965; Kochel and Johnson, 1984; Simmons, 1988; Kochel, 1990; Duffy, 1991; and Whittecar and Duffy, 1992). Simmons (1988) and Kochel (1990) provide the most detailed account of the sedimentology, and their observations are summarized below. These observations have been confined to a small number of localities, however, and therefore must be considered preliminary.

Commonly the fans show several major units, each several meters thick, separated by paleosols (B horizons only). Proximal facies show poor sorting, although better than that shown by debris flows, with clast sizes ranging from coarse sand to boulders exceeding 3 m in diameter. The only primary sedimentary structures are a crude planar bedding and slight imbrication of the largest clasts. Mid-fan (i.e., between proximal and distal) facies show generally poor sorting in major units that contain layers of cobbles, gravel, and sand (Fig. 9A). Individual layers within major units, however, may be well sorted. Alternating layers of poorly sorted gravel and moderately well sorted sand are common. The largest clasts are 1 m in diameter, although much of the coarse material ranges from 0.25 to 0.50 m. At some locations, clay-rich deposits occur; these deposits may have been laid down in lakes between fan lobes, although no modern examples of such lakes occur. Sedimentary structures include fairly continuous stratification inclined gently down fan, with individual beds ranging from 0.8 to 2.5 m in thickness. Many of these beds show normal grading. Radial exposures commonly display numerous uniform sand beds and layers of well sorted pebbles. Clast imbrication is well developed. Transverse exposures show overlapping channel-fill deposits containing lenses of uniform sand and concentrated, well sorted pebbles. Channel cross sections appear to have widths that exceed 100 m and depths of 1-2 m. The distal facies is composed largely of horizontal, well sorted sands, with some exposures showing interbedded gravels (Fig. 9B). Gravel becomes less extensive in the down-fan direction.

These sequences are interpreted to have been deposited chiefly by fluid-gravity flow, for the following reasons. Debris flows appear to be rare, confined to the uppermost portions of the proximal fan region, where there is some difficulty in distinguishing them from colluvium. Hyperconcentrated flows, however, may be somewhat more common. Costa (1988) reported that hyperconcentrated flows show weak horizontal stratification or are massive; they show weak or no imbrication, and both normal and reverse grading. According to Smith (1986), gravel-dominated hyperconcentrated flow deposits are poorly sorted, clast supported, and often show normal grading. Lenses of stratified sand do not occur. Deposits generally matching these characteristics are common in the proximal facies.

The large majority of deposits in these fans are clearly water laid. Kochel (1990) attributed these deposits to a "braided stream" origin, but subsequently has stated (personal communication, 1995) that he actually meant to convey simply that the deposits on the fans are largely waterlaid. The deposits, in fact, generally have characteristics consistent with upper-flow-regime deposits that have been documented as sheetflood sequences (Blair, 1987; Blair and McPherson, 1994a, 1994b). In contrast, rippled and cross-bedded sands, lower-flow-regime structures that are abundant in braided streams, are rare here.

Fan thickness appears to increase to a maximum in the mid-fan region and then gradually thin until the fans merge with high terraces of the master streams. The waterlaid fans generally do not show evidence of lengthy periods of inactivity between individual depositional events, unlike the debris-flow dominated fans. However, three major episodes of fan building can clearly be discerned from the observation of extensive exposures of fan gravels in quarry walls in the Stuarts Draft area. Deposits from each of these episodes are separated by a laterally extensive paleosol, which indicates a substantial hiatus in fan deposition. This stratigraphy is discussed by Kochel and Johnson (1984), Kochel (1990), Duffy (1991), and Whittecar and Duffy (1992).

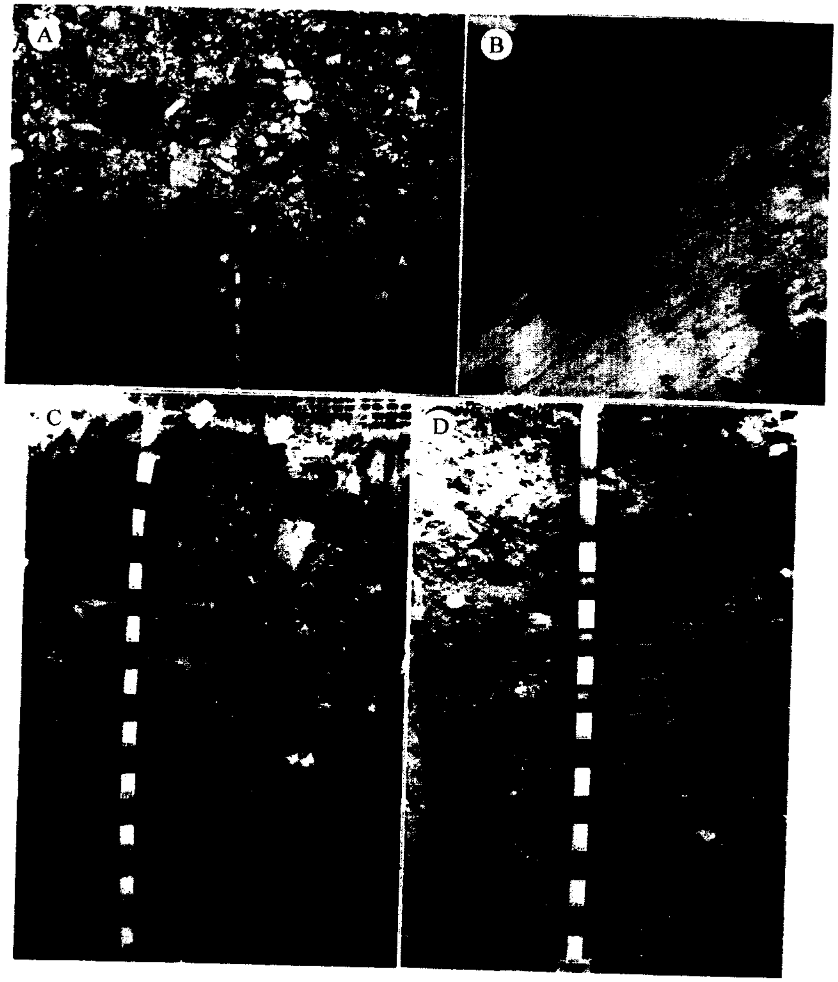

Figure 9. Vertical cuts in alluvial fans. A. Mid-fan facies of waterlaid fan in the Great Valley, showing poorly sorted coarse gravel (Conners quarry, Stuarts Draft quadrangle, Virginia). Marks on rod are at 10-cm intervals. B. Distal facies of waterlaid fan in the Great Valley (Vesuvius quarry, Vesuvius quadrangle, Virginia; photograph supplied by R. C. Kochel). C. Deposits of a young debris-flow-dominated fan, west flank of Roan Mountain (Bakersville quadrangle, North Carolina). Marks on tape are at 10-cm intervals. Deposit is clast-supported, although coating of the exposed clast surfaces by fines, promoted by the high clay content (35%), gives the impression that it is matrix-supported. Reddest Munsell hue is 7.5YR. D. Deposits in an old debris-flow-dominated fan, south flank of Roan Mountain (Bakersville quadrangle, North Carolina). Marks on tape are at 10-cm intervals. Excavation is in very old abandoned fan deposit, where intense weathering presumably has destroyed most of the metamorphic clasts in the upper 2 m, although "ghosts" of large clasts are present near the bottom of the exposure. Light-colored mottles about two-thirds of the way from the top are characteristic of highly weathered sediments in this region. Reddest Munsell hue is 2.5YR.

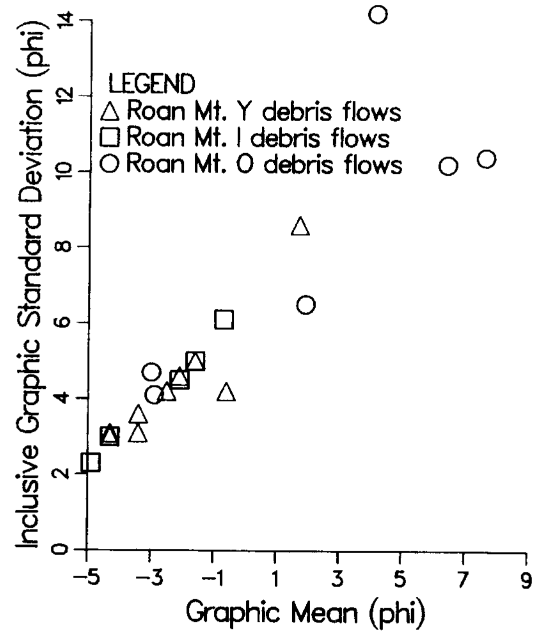

Figure 10. Inclusive Graphic Standard Deviations vs. Graphic Mean for fan debris-flow deposits at Roan Mountain, Bakersville quadrangle, North Carolina. Studied samples were approximately 10 kg in weight and included clasts up to 256 mm in intermediate diameter. Data are from Mills and Allison 1995a.

2) Debris-flow Dominated Fans

These fans, in contrast to the waterlaid fans, are composed throughout of very poorly sorted sediment ranging in size from coarse boulders to clay. Although some earlier workers (e.g., Michalek, 1968) believed these sediments to be solifluction deposits, for the most part researchers today consider them to be debris flow deposits, based on their sedimentological similarity to modern debris flows on Appalachian fans. The deposits occur as both matrix-supported and clast-supported units, presumably depending upon the water content of the emplacing flow, the degree of surface winnowing, and the position of the deposit within an individual debris flow (e.g., bouldery levees and flow fronts vs. main body of the flow). The degree of weathering also affects clast content, as clasts decompose with increased weathering; this effect is primarily important on old abandoned fan surfaces. Considering only young, relatively unweathered deposits, most of the Nelson County, Virginia, fans are matrix supported (Kochel and Johnson, 1984), whereas those in North Carolina include both types (Mills, 1983, 1986; Mills and Allison, 1994, 1995a; Figs. 9C and 9D). Sedimentary structures are rare in Appalachian debris-flow deposits, except for occasional occurrences of weakly imbricated clasts and reverse grading (Kochel, 1990). Bioturbation probably does not account for the lack of sedimentary structures, as modern flows on fans also lack these structures (e.g., Williams and Guy, 1973; Kochel and Johnson, 1984).

The Graphic Mean and Inclusive Graphic Standard Deviation (Folk and Ward, 1957) from 20 samples taken from soil pits on fans at Roan Mountain, North Carolina, show that mean size decreases and sorting decreases (i.e., Inclusive Graphic Standard Deviation increases) as surface age increases (Fig. 10). This reflects the increase in fines and decomposition of clasts produced by increasing amounts of weathering. These findings suggest that for research on fan sedimentology, attention should be confined to younger, relatively unweathered deposits.

Measurements of clast long-axis orientations have shown that debris flows generally have weak fabrics (e.g., Mills, 1991). Few clast orientations have been measured in Appalachian fans. One study in the Dellwood quadrangle, North Carolina, showed a tendency for an alignment of clast long axes in a downslope direction, but with great variation in the consistency of orientation (Mills, 1986). Such fabric is compatible with a debris-flow origin.

Stratification in Blue Ridge debris flow deposits generally is lacking, but contacts between units may be sharp. Individual units range from a decimeter to several meters in thickness. Paleosols (generally only the B horizons) are partly preserved at some contacts, indicating substantial time intervals between deposition of the units. Because each stratum in fan deposits is produced by a discrete flood event, their textural characteristics may differ greatly, resulting in abrupt changes in textures in vertical sections (Kochel and Johnson, 1984; Kochel, 1990). On the other hand, where overlying deposits have a similar texture and no paleosol is present, distinguishing individual debris flows may be difficult or impossible.

Surface features such as debris-flow levees were observed following the 1949 Little River flood (Hack and Goodlett, 1960) and after the 1969 Hurricane Camille storm (Williams and Guy, 1973), but are generally rare on fans, probably as a consequence of subsequent erosion. In addition, on many of the fans in the Appalachians, farming has probably obscured such features. Debris-flow-dominated fans generally show little change in texture from proximal to distal reaches. Fan thickness is not great, rarely exceeding 30 m, and often is only a few meters (e.g., Fig. 5E).

Kochel and Johnson (1984), Wilson (1987), and Kochel (1990) have obtained a number of radiocarbon ages from fans in Nelson County, Virginia, and Dellwood quadrangle, North Carolina. Generally, the samples consisted of disseminated organics and many of these failed to supply the desired amount of carbon for dating. In addition, despite techniques to remove carbonate and humic acid, some contamination with carbon from modern plants seems likely. Nevertheless, such dates provide the best estimate of fan age. In Nelson County, six radiocarbon ages combined with distinctive characteristics of some of the fan units make it possible to correlate fans, as well as provide an estimate of the recurrence interval of catastrophic floods that produce aggradation on these small fans. The fan stratigraphy shows a record of at least three debris-flow events comparable in magnitude to the 1969 event caused by Hurricane Camille, the oldest at about 11 ka. This suggests a recurrence interval on the order of 3 - 4 ka (Kochel and Johnson, 1984; Kochel, 1992). More recent work on fans in Madison County, Virginia, suggests a similar interval of about 2 ka (Eaton and McGeehin, 1997; Kochel and others, 1997; Eaton, 1999).

In the Dellwood quadrangle, North Carolina, Wilson (1987) and Kochel (1990) obtained 10 radiocarbon dates from 5 fans. They ranged from 1 ka to 25 ka, although the oldest ages, obtained from one cut, showed age inversion, with the 25 ka age underlain by an age of 17 ka. Sampling locations were on fan surfaces that were mapped as "young" or "intermediate" on the basis of relative-age criteria. The oldest consistent ages are in the 16-18 ka range. Because of the problem of contamination with modern organic matter, probably the latter ages should be considered minima.

The most extensive dating of debris-flow dominated fans in the Appalachians has been made possible by the catastrophic storm of June 27, 1995, in Madison County, Virginia. (Wieczorek and others, 1995, 1996; Morgan and others, 1997, 1999). Incision of fans by storm runoff exposed dozens of organic-rich layers that have been radiocarbon dated (Eaton and McGeehin, 1997; Eaton and others, 1997; Eaton, 1999). Dates range from 2 ka to more than 51 ka. As discussed above, interpretation

of the fan stratigraphy is difficult because of its complexity, and the large number of ages aids, but does not resolve, the interpretation problem.

The dating of "old" fan surfaces by means of radiocarbon is probably not possible. The red soils suggest that all of the original carbon in the soil has been oxidized, and even if original carbon were present the age of these surfaces very likely exceeds the range of radiocarbon dating. Based on ages estimated by comparison of sediment weathering intensity to weathering intensity of dated deposits elsewhere (e.g., Whittecar and Duffy, 1992; Mills and Allison, 1995a, 1995b), older fan surfaces probably have ages in the hundreds of thousands of years. A layer of fines in one very old fan remnant at Rich Mountain, North Carolina, was found to have reversed magnetism, indicating an age of at least 780 ka. The magnetization appears to reside in secondary hematite produced by weathering rather than in original magnetite grains, so that, including the time necessary to accomplish deep, intense, weathering, a minimum age on the order of 1 Ma is more likely (Mills and Allison, 1995b). Paleomagnetism can rarely be measured in fan sediments, however, owing to their high gravel content, and so this method is unlikely to find wide applicability. Cosmogenic isotope dating may aid in the dating of fan surfaces, although there is the problem that most clasts probably had a long exposure history before they became incorporated into the fan.

3) Boulders on Fans of the Southern Blue Ridge Province

Many investigators have related the size of transported clasts on fans to the fan form, particularly slope. Exactly which particle-size parameter optimally predicts fan slopes is unclear, but it very likely involves the coarse fraction. In this study the parameter measured was maximum clast size (MCS), defined previously. The primary reason for choosing this parameter was practical. In most cases it was necessary to sample fan material at or near the ground surface. Most fan surfaces in the study area have been highly modified by human activity (such as by removing clasts from fields) so that the original surface particle-size distribution of the coarse fraction can no longer be determined. On many fan surfaces, however, most of the largest clasts are still present, if not in the field then in gravel piles or fences. Maximum clast size is also an appropriate parameter to study because it is closely related to the dynamics of fluid-gravity deposition on fans or pediments. Assuming that the source area contains a range of clasts sizes that extends above the maximum size that a stream is capable of transporting, the maximum clast size at a given reach of the stream is indicative of the maximum velocity and depth of flow in that reach (e.g., Bradley and Mears, 1980; Costa, 1983). With regard to debris flows, no comparable calculations are possible, but the presence on a fan surface of a boulder clearly too large to be carried by the largest floods obviously suggests the action of a debris flow (e.g., Costa, 1984).

Although most researchers have measured mean or median clast size, there is also a body of data on maximum clast size on fans. Blissenbach (1952) and Bluck (1964), for example, found that the maximum particle size along the radial profile of alluvial fans in the southwestern United States paralleled the slope of the fan surface, both showing an exponential decline with distance. Kesel (1985) and Kesel and Lowe (1987) reported a similar finding for humid-tropical fans (although, according to Blair and McPherson 1994b, the "fans" of the latter authors are better classified as gravelly river deposits). Kesel and Lowe (1987) also suggested that fans which show little or no regular decrease in clast size downfan may be dominated by debris flows. Certainly this seems a reasonable inference. Work by Cenderelli (1994), for example, showed little if any downstream decrease in maximum clast size along modern debris-flow tracks in West Virginia, and recent reconnaissance on fans in Madison County, Virginia, that received debris flows during storms of June, 1995, suggests a similar finding (Kochel, personal communication, 1996).

For the present study, maximum clast size (MCS) was measured at more than 200 locations on mountain piedmonts and associated uphill slopes in the Blue Ridge province of North

Carolina. Figure 11A is a plot of distance from the most-distant point on the drainage-basin divide against MCS for 92 sites on the surfaces of young- or intermediate-age fans. (Distance from the divide rather than distance from fan apex was used owing to the problem of multiple feeder channels on some fans. Old fan surfaces were not included owing to the reduction of clast size by weathering that often occurs in this setting.) As can be seen, there is essentially no correlation between these variables. A plot of local slope against MCS shows a significant ($p < 0.05$) low correlation (Fig. 11B). These results are misleading to a degree, however, combining as they do fans on different lithologies and terrains. Correlations improve when they are computed for individual study areas. Correlations for each fan study area with at least six measurements are shown in Table 3. These results show that in some areas there is a tendency for clast size to decrease with distance and to increase with steeper slopes, but that generally this tendency is weak, probably reflecting the dominance of debris-flow processes on these fans. It should be noted that correlation coefficients can be raised somewhat by including MCS measurements made in streams and hollows upslope from the fans, as clasts in these upslope settings are almost always larger than those on the fans themselves.

Figure 11C shows a plot of gradient index (SL) against MCS. The gradient index is the local slope multiplied by the distance from the divide (Hack, 1973), and is of interest in this setting because it is roughly related to stream power. Stream power is defined as discharge times slope (e.g., Chang, 1998), and both the upstream drainage area and the distance to the divide can be used as proxies for the discharge of a given recurrence interval. As can be seen, the correlation between SL and MCS is stronger than that between slope and MCS. Figure 11D shows that if only the streams in piedmont areas are considered (including both those on fans and those not on fans), the correlation between MCS and SL is higher than that on fans; this result probably stems from the lesser role of debris flows in moving boulders in stream channels than on fan surfaces.

Kesel and Lowe (1987) compared MCS-slope relations on alluvial fans from different areas. In Figure 12, the MCS measurements from this study have been plotted on a diagram modified from Kesel and Lowe (1987). As can be seen, the maximum clast sizes in the Blue Ridge province are as large as those on most other fans. The slopes, however, are somewhat higher than those on other fans, probably a consequence of the fact that the fans here are smaller, and have smaller drainage basins, than the other fans. (Again, the "fans" of Kesel, 1985, and Kesel and Lowe, 1987, as well as those of Boothroyd and Nummedal, 1978, are better classified as high-gradient gravelly rivers, according to Blair and McPherson, 1994b. If this interpretation is accepted, Figure 12 shows a comparison among different high-energy piedmont environments, rather than strictly among fans.)

EVOLUTION OF APPALACHIAN FANS

Blair and McPherson (1994a) proposed a four-stage evolutionary scenario for arid-region fans. The precursor stage is a talus or colluvial cone at the base of a newly created slope. In

Table 3. Correlation between MCS and distance from divide and between MCS and local slope for individual study areas.

Study Area	n	MCS vs. Distance	MCS vs. Slope
Dellwood quad, NC	35	-0.349*	0.572*
Hazelwood quad (Barber Orchards), NC	7	-0.874*	0.843*
Bakersville quad (Roan Mountain), NC	26	-0.318	0.318
Zionville and Sherwood quads, NC	19	-0.351	0.113

* indicates significance at the p < 0.05 level.

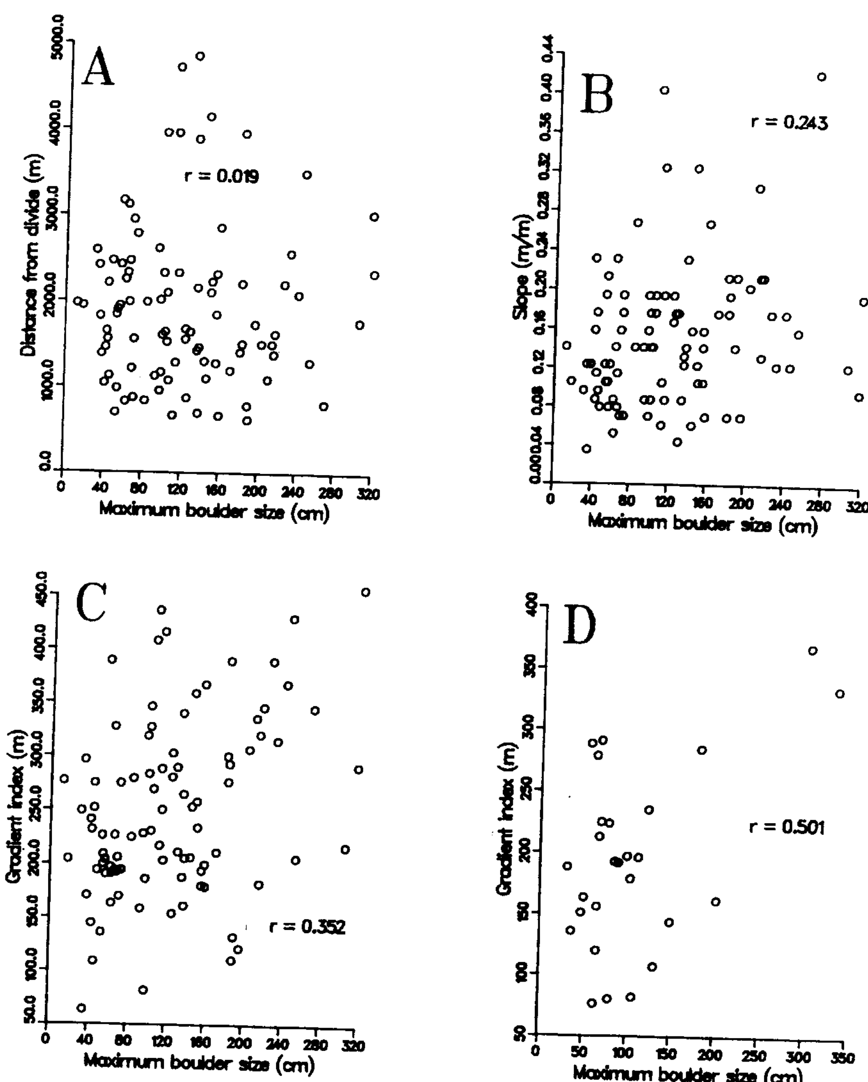

Figure 11. Plots of maximum boulder sizes on mountain piedmonts of the North Carolina Blue Ridge. A. Distance from divide vs. maximum boulder size for young and intermediate-age fan surfaces. B. Local slope vs. maximum boulder size for young and intermediate fan surfaces. C. Gradient index (SL; defined for a given point on a stream as the local slope times the horizontal distance from the point to the most distant point on the basin divide) vs. maximum boulder size for young and intermediate fan surfaces. D. Gradient index (SL) for footslope streams, including areas with and without fans. All correlations are significant (p≤ 0.05) except for A.

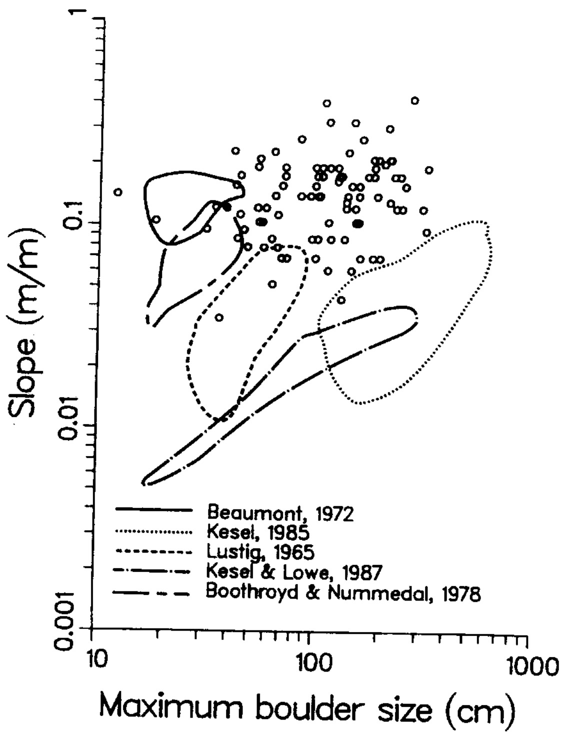

Figure 12. Slope vs. maximum boulder size for young and intermediate fan surfaces in the North Carolina Blue Ridge province compared to maximum sizes from other areas. Open circles show data from present study and envelopes are from Kesel and Lowe 1987.

Stage 1 (incipient fans), these cones acquire a more fan-like shape through the addition of mass-wasting products other than freefall material; where weathering produces adequate clay in the drainage basin, the fans consist mainly of debris flow and winnowed debris-flow deposits. Fans dominated by waterlaid deposits also occur. Slopes become lower, and fans extend farther outward from the mountain front, but rarely more than 0.5 km. Stage 2 is characterized by the development of more gentle average radial slopes (3° to 15°) resulting from a reduced input by all mass wasting processes except debris flow. Radial lengths of fans are greater than those of Stage 1, but commonly less than 3 km. Stage 3 is characterized by radial enlargement by the progradation of active depositional lobes outward from a progressively lengthening incised channel. Stage 3 fans commonly are 2 to 10 km long, with slopes of 2° to 8°. The unique feature of this stage is the development of a prominent incised channel that confines debris flows and water flows near the fan apex so that they cannot spread out, thus bypassing the upper fan to be deposited on the distal parts of the fan.

Development of fans in the Appalachians shows variation from the above ideal scenario. First, fans here rarely start as talus/colluvium cones. The heads of fans commonly are hundreds of meters, even kilometers, downslope from mountain slopes steep enough to provide material for such cones. Rather, fan heads occur below zero-order (i.e., lacking a stream channel) or first-order valleys that supply debris only during catastrophic rainfall. Stage 1 thus appears to be the earliest stage of development for Appalachian fans. Second, the progradation of active depositional lobes outward by means of a progressively lengthening incised channel appears to be uncommon. The upland perennial streams associated with Appalachian fans most commonly flow along fan margins, not across the fans. Further, where such streams do flow across fans, they do not have intersection points; rather, they are incised the full length of the fan, and sediments carried in them are not deposited at the fan terminus, but rather are removed from the system. Deposition appears to occur only during catastrophic storms, when flows overtop channel banks because of plugging and spread across the fan surface.

Pleistocene periglacial climates may also play an important role in the evolution of Appalachian fans. As discussed above, cold climates may have large effects on both the generation of sediment in the tributary basin and the transport of sediment across the fan. Nevertheless, it is still likely that deposition occurs mainly during catastrophic storms, although the frequency of such storms and the volume of sediment moved may vary greatly according to the stage of the Quaternary climatic cycle.

Fan-evolution scenarios can be inferred from maps showing the distribution of fan surfaces of different ages, whether determined by numerical or relative methods. In the Appalachians, fan mapping has been done chiefly in relative terms, using techniques such as soil-profile development and clast weathering (e.g., Mills, 1983; Whittecar and Duffy, 1992; Whittecar and Ryter, 1992a, 1992b; Mills and Allison, 1994, 1995a, 1995b). Several fan-evolution models have been inferred in this manner by previous investigators. Idealized versions of these are discussed below.

Dorn (1988) proposed a model involving radial lengthening by means of an incised fan channel, as follows. An initial fan lobe is aggraded. A stream channel then incises through the entire length of this lobe, so that sediment from the uplands now bypasses the initial fan surface and a new fan lobe is built downstream from the first. Subsequently, the new lobe is incised, and the process repeats. As the locus of deposition continues to shift downfan, the upfan surfaces are thus abandoned. The resulting fan pattern shows older fan surfaces to be nearer the fan head. In addition, successively younger fan surfaces are arranged adjacent to one another, reflecting the stair-stepped ordering of the terraces. Typically the terraces are paired (Fig. 13A). This arrangement of surfaces has been called a "telescopic" fan (Blissenbach, 1954, p. 180). This model is compatible with the sequence proposed by Blair and McPherson (1994a), although the latter sequence may also involve other activity, as discussed below.

An alternative pattern, in which fan-surface age is arranged concentrically, with age decreasing toward the fan apex (Fig. 13B), was described by Bull (1964) for alluvial fans in western Fresno County, California. Bull attributed this pattern to intermittent uplift of the mountain front, which increases stream gradients above the fan apex and thereby results in the deposition of a new fan segment of steeper slope on the upper part of the preexisting fan. Whittecar and Duffy (1992), however, have pointed out that in the Appalachians such a pattern, at least for fans with ages extending into the Tertiary, could also reflect a decrease in tectonic activity. Greater sedimentation during times of higher uplift rates probably would build more extensive fans than during times of lower uplift rates. Hence, a period of lower uplift rates following a period of higher might well produce a younger, smaller fan segment that covered only the upper part of the preexisting fan, thereby producing a map pattern similar to that in Figure 13B. Whittecar and Duffy (1992) point out that the Shenandoah Valley fans show this pattern to some extent, although it is not the dominant pattern.

A third scenario of fan development was suggested by Hack (1960, 1965) for waterlaid fans along the west side of the Shenandoah Valley, Virginia. In this setting, upland streams carrying coarse loads from the resistant rocks of the highlands have steeper gradients than do streams heading on the piedmont that carry fine loads. Because of this difference in gradient, piedmont streams commonly flow at lower elevations than subparallel upland streams. As a

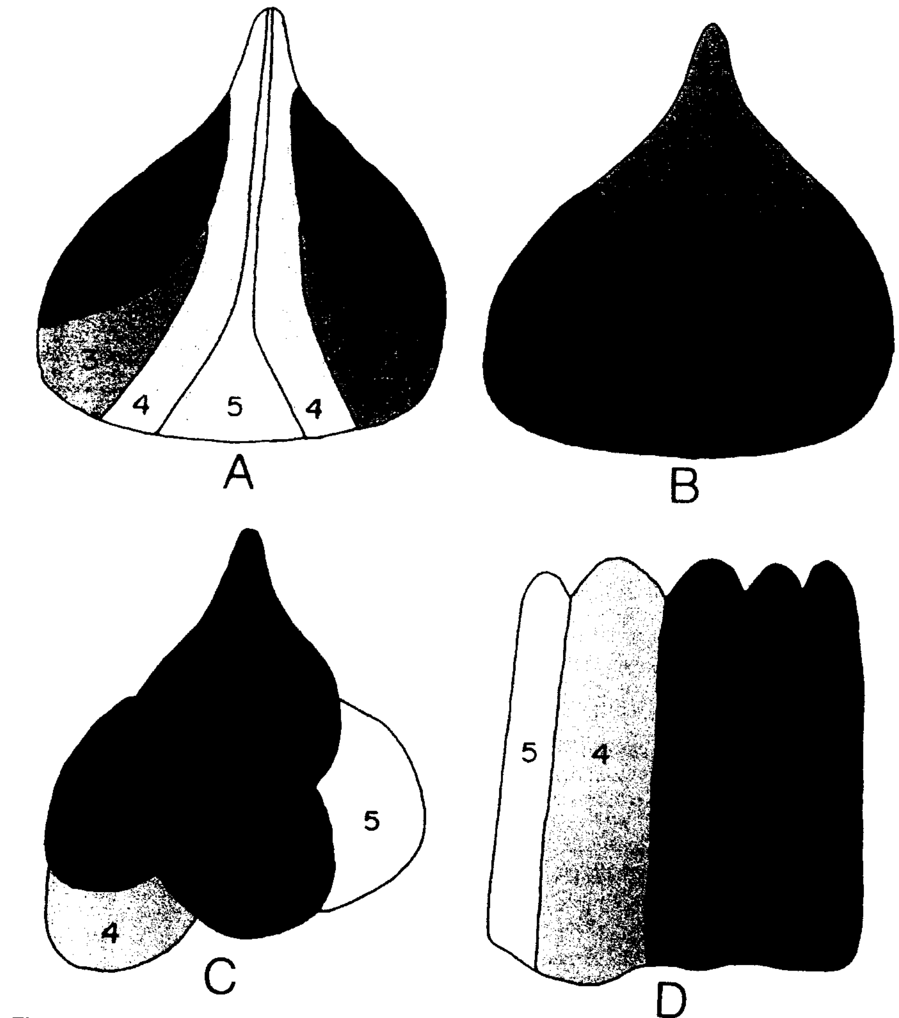

Figure 13. Four hypothetical map patterns produced by different fan development scenarios. Fan surfaces labeled 1 are the oldest in each case. A. "Telescopic" fan pattern produced by fanhead incision and unidirectional fan progradation. B. Concentric pattern with decreasing surface age toward apex. C. Random fan pattern produced by piedmont stream capture. D. Pattern produced by lateral stream migration. Scenarios are discussed in text.

result, capture by the piedmont streams often occurs, followed by alluviation as the new upland streams build up their slopes sufficiently to carry the coarse load they have acquired. Once the profiles become steepened, these streams too become subject to capture by piedmont streams flowing at lower elevations. Rich (1935) earlier suggested a similar process for the evolution of pediments, as did Denny (1967) later for the development of segmented alluvial

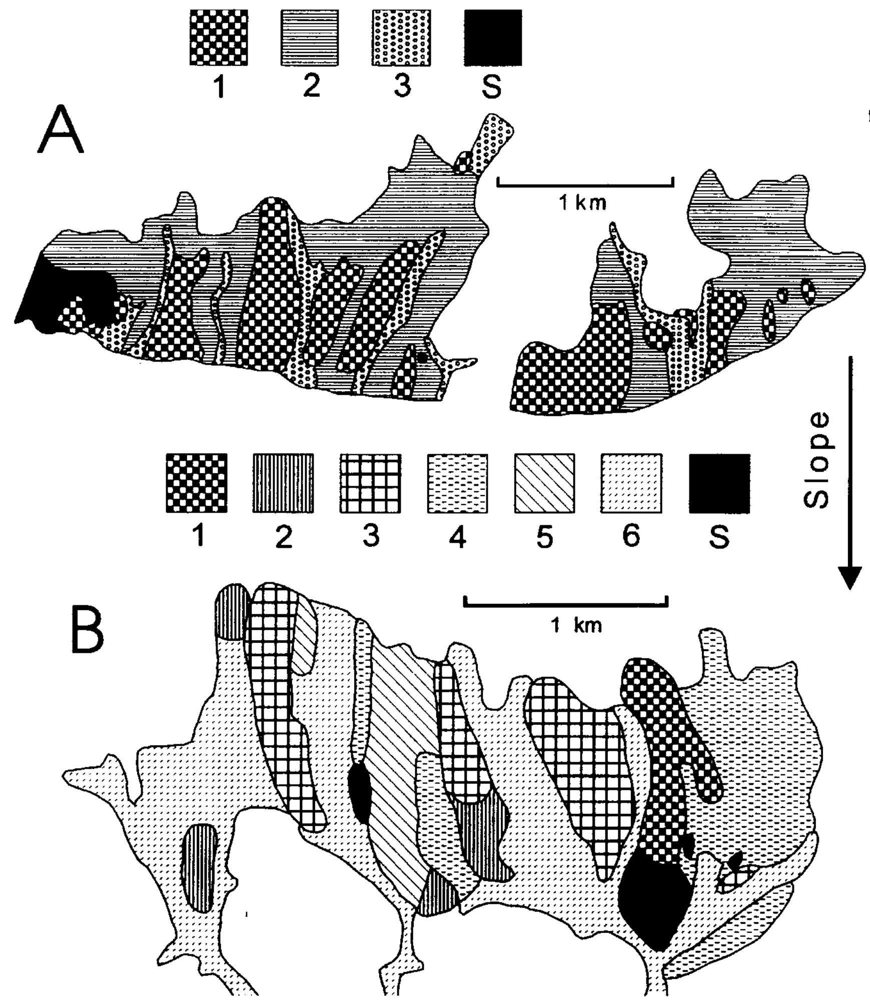

Figure 14. Example of fans that may illustrate the lateral-migration scenario. A. Northwest slope of Pinnacle Ridge (Hazelwood quadrangle; modified from Mills and Allison 1994, Fig. 3). B. West slope of Rich Mountain (Zionville quadrangle; modified from Mills and Allison 1995b, Fig. 2). Numbers refer to relative ages of fan surfaces, with 1 being oldest. The Rich Mountain fans were divided into 6 relative-age classes, whereas the Pinnacle Ridge fans were divided into 3 classes. "S" indicates saprolite.

fans. The resulting fan pattern (Fig. 13C) consists of a series of more or less randomly arranged fan lobes (although the fan may show overall progradation). The Shenandoah Valley fans (Whittecar and Duffy, 1992) and some other larger Blue Ridge fans (Mills, 1983) show such a pattern.

Other fan maps from the Blue Ridge area suggest a fourth scenario for the evolution of fan complexes. In some areas, many fan surfaces are elongate downslope, approximately parallel to the streams heading in the uplands, with fairly constant widths. The cross-slope order of surface ages is essentially random. Figure 13D shows an idealized example of this pattern and Figure 14 shows actual fan maps that resemble this example. This pattern, together with observations on the present erosional activity of fan streams, suggests that the processes responsible for abandoning a fan surface and establishing another at a lower level operate chiefly in the cross-slope direction. Apparently, new fan surfaces are created by a process of stream entrenchment accompanied by lateral erosion and stream migration. The lack of paired surfaces indicates that entrenchment takes place only at the margins of fan surfaces, not in the middle of the surface as would be required to produce paired terraces. The probable reason for this is that streams seem to migrate away from the margins of young surfaces toward areas that are more erodible than are the bouldery young fan surfaces (e.g., toward saprolitized bedrock, or toward highly weathered old fan remnants). A similar explanation was offered by Ritter (1967) for the lateral shifting of streams on the east flank of the Beartooth Mountains, Montana. The streams migrate away from the deposits of large, resistant upland-derived boulders in the valleys towards the nonresistant rock flanking the valleys.

The initial formation of a young fan surface is probably accomplished in a manner analogous to a strath terrace. In the present setting, the direction of stream migration is either toward (saprolitized) bedrock walls, or, more commonly, toward an older fan remnant. Lateral expansion of the young surface at the expense of the older fan remnant is facilitated by the lack of a bouldery mantle on its lower flanks so that the stream can cut laterally into saprolite. Much of the lateral erosion is probably accomplished by flows smaller than the catastrophic flows necessary to deposit or remove the bouldery sediments that mantle the fan surfaces. Eventually, the stream flanking the surface becomes permanently entrenched, turning the active surface into a relict one. The entrenched stream subsequently begins forming a new active fan surface by lateral migration; plugging by a debris flow might also cause the position of the stream to shift.

A hypothetical example of fan development illustrates this scenario (Fig. 15). In A, the stream lies to the right of a young fan surface. The stream subsequently migrates to the right, because the saprolite to the right offers less resistance to erosion than the bouldery fan deposit to the left. At B, the stream has migrated and formed a new fan surface at a lower level. Here, migration to the right is still favored, because the older fan deposit still bars migration to the left. If, however, as an alternative to B, greater downcutting occurs before formation of the new fan surface (as at B'), the older fan surface is no longer protected from lateral migration, as erodible saprolite is now exposed on its flank. At this point, the stream might by chance (perhaps because of plugging) become established to the left of the young fan surface (C), after which it would migrate to the left, establishing a third fan surface and partially removing the oldest fan surface (D). At E, the youngest surface continues to expand to the left, completely removing the oldest surface.

Although stream erosion is the major factor driving this sequence, stream "flood plains" in fact consist largely of debris flows, probably emplaced during rare, catastrophic storms. The repeated occurrence of these bouldery flows keeps the stream confined to the margins of the valley. In the terms of Blair and McPherson (1994a), this model of fan evolution is one dominated by two secondary processes: chemical weathering (which provides the erodible saprolite and decomposed old fan deposits) and stream erosion; the latter process is infrequently arrested by a catastrophic primary event, the deposition of a large debris flow.

This hypothesized sequence is probably applicable only to some fan complexes in the Blue Ridge province. In the first place, it applies mainly to intrabasinal fans. Fans at tributary/master stream junctions are likely to be short lived, and the large Shenandoah Valley fans are probably dominated by piedmont stream capture (e.g., Whittecar and Duffy, 1992). Secondly, it probably requires relatively thin fan

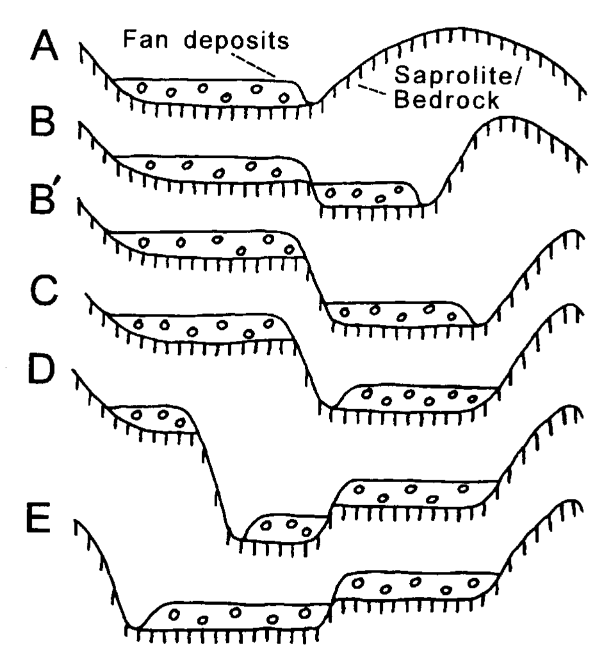

Figure 15. Hypothetical sequence of fan evolution by lateral stream migration. A substrate of saprolite or highly weathered bedrock is assumed. Time increases from top to bottom. Sequence is discussed in text.

deposits, on the order of a few meters. Concerning applicability of this model to areas outside the Appalachian region, another requirement may be the presence of thick saprolite, or at least soft bedrock, below the fan deposits.

The various fan-development scenarios discussed above are by no means mutually exclusive, and a given fan complex could show the influence of two or more of them. The piedmont-stream-capture and the lateral-migration scenarios seem to dominate in the Appalachian region. Probably both would be modulated by Quaternary climatic change owing to the variation in production of rock debris in the drainage basins and in the frequency of debris flows, but the basic tendencies would persist in both warm and cold climates.

CONCLUSIONS

A comparison of Appalachian fans with fans studied in arid and/or tectonically active settings shows similarities but also distinct differences. In size, Appalachian fans are relatively small, but their size range overlaps considerably with the size range of fans in other regions. In some areas, there appears to be a tendency for fans to be larger and better developed where tributary basins are underlain by more-resistant bedrock that supplies large boulders to fans. In form, the relations of fan area and slope to basin area, when plotted for the entire region, are compatible with those reported from other regions. Planimetric outlines of Appalachian fans are relatively irregular, reflecting greater topographic confinement and lesser thickness. The "intrabasinal" setting of many fans within the lower ends of low-order valleys also appears to be a distinctive characteristic of Appalachian fans. Segmented radial profiles are seen on some Appalachian fans, and probably result from a variety of factors.

Concerning process, deposition by debris flow seems to be even more dominant on Appalachian fans than on fans elsewhere, probably reflecting the clay-rich nature of the source materials, as well as the generally small size of the Appalachian fans. The contribution of mass-movement processes other than debris flows (such as landslides and rockfall) to fan building appears to be lower than on many previously studied fans, and probably reflects the nontectonic setting. The effect of Quaternary climatic change on fan building, however, is probably substantial. Glacial climates almost certainly increase the rate of rock-debris production in drainage basins, although whether this debris is delivered to the fans mainly during glacials, interglacials, or glacial-interglacial transitions is not yet clear.

The most distinctive secondary process on Appalachian fans is the intense chemical weathering, resulting in the presence of Ultisols on even the lowest surfaces of many fans (aided by the high clay content of fan material and the long recurrence intervals of depositional events), and the very deep weathering profiles on many high-level relict fan surfaces, with clast decomposition extending even to the base of the deposits. A further effect of this weathering is that much of the mountain piedmont is underlain by saprolite, so that fan deposits almost always rest on saprolite rather than bedrock. Stream erosion on fan margins is another important secondary process.

Appalachian fans are dominated by debris-flow deposits. The debris-flow fans contain deposits showing exceptionally poor sorting, largely reflecting the high content of fines. Maximum boulder sizes are comparable to those on fans in other regions, and generally show only a weak tendency to decrease in size in the downfan direction. Waterlaid deposits in the Appalachian fans are sparse except on the large fans in the Great Valley of Virginia, where sedimentary structures suggest that the bulk of the deposits are from upper-flow-regime water flows and hyperconcentrated flows.

The evolution of fan complexes in the Appalachians, inferred from mapping of fan surfaces according to relative age, appears to involve mainly piedmont stream capture and lateral migration of streams. The latter may be the most distinctive developmental scenario of Appalachian fans. Development of telescopic fans, with inset fans and paired terraces formed by repeated entrenchment of upland streams and progradation, appears to be less common in the Appalachians than in arid/tectonically active regions.

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