CHAPTER SIX

Occurrence of Small-Scale Debris Fans in Sandstone Landscapes of the Central Appalachians: Fan Preservation as a Function of Erosional Accommodation Space

ABSTRACT

Fans in the central Appalachians provide a valuable record of humid-regime process, climate change and debris-flow recurrence interval. The first step in analyzing this record is delineation of conditions conducive to fan preservation. Comparative geomorphic analysis is presented for three study areas in the central Appalachians: the Fernow Experimental Forest, Tucker County, West Virginia; the North Fork basin, Pocahontas County, West Virginia; and the Little River basin, Augusta County, Virginia. Each area is underlain by strata of the upper Devonian Acadian clastic wedge. Mapping (1:9,600) of small-scale debris fans and morphometric analysis yield results that elucidate local controls on fan accommodation at the watershed scale.

Debris fans are comprised primarily of gravel diamicton and are dominated by debris-flow processes. Map units are delineated according to fan-surface morphology and height above channel grade. Debris fans are classified as either simple or compound. Simple fans are characterized by single map unit types, with surfaces graded to active channels or positioned at heights ranging from 2 to15 meters. Compound fans are characterized by complex map patterns and inset fan-terrace relationships. Composite fan surfaces range in area from 2.0×10^2 to 6.5×10^4 m^2, with a mean of 3.9×10^3 m^2. Debris fans are preserved at tributary junctions, with greater than 75% occurring at the intersections of first- or second-order channels with higher order trunk streams.

Critical morphometric parameters for the Fernow, North Fork, and Little River areas include, respectively: **(1)** total basin area (km^2) = 17.6, 49.3, 41.5; **(2)** drainage density (km^{-1}) = 4.2, 3.3, 4.7; **(3)** ruggedness = 2.5, 1.7, 3.9; **(4)** Shreve magnitude = 139, 287, 380; **(5)** tributary junction frequency (km^{-2}) = 9.0, 5.8, 9.1; **(6)** maximum valley width (m) = 120, 180, 290; **(7)** total valley bottom area (km^2) = 0.76, 1.86, 3.09; **(8)** total fan area (km^2) = 0.115, 0.212, 0.508; **(9)** fan area to total basin area ratio = 0.006, 0.003, 0.012; and **(10)** fan frequency (km^{-2}) = 2.0, 1.0, 2.8. The greater drainage density, valley width, and tributary-junction frequency at the Little River dramatically increase the volume of fan deposits in storage.

Three modes of fan accommodation are recognized in the central Appalachians: valley erosion (at tributary junctions), pediment erosion, and piedmont-karst solution. Mode of accommodation is driven by intra-montane erosion and controlled by local bedrock geology. Optimum conditions for fan preservation under the valley-erosion mode, the focus of this study, include: (1) high drainage density, (2) high tributary-junction frequency, (3) steep low-order channels, (4) high valley-width expansion rates, (5) wide high-order channels, and (6) steep, colluvial hillslopes prone to debris flow. Fan-accommodation mechanisms outlined in this study provide an important research model for locating watersheds with high fan-preservation potential.

INTRODUCTION

Alluvial fans occur in diverse climo-tectonic settings, and represent critical sites of sediment routing in mountainous watersheds. Fan storage within the fluvial system favors conditions where sediment supply exceeds transport capacity (Harvey, 1990). Although the alluvial fan literature is voluminous, traditional research is spatially biased towards the arid southwestern United States (Leece, 1990). Fans in the central Appalachians provide a valuable record of humid-regime process, climate change, and debris-flow recurrence interval (Mills, 1983; Kochel and Johnson, 1984; Kochel, 1987, Eaton and others, 1997); however, relatively few studies have been completed in this region. In addition, Appalachian fans occur in hazard-prone footslope areas that are sites of increasing development (Kochel, 1992). Fan analysis provides a fundamental tool for regional hazards assessment.

The first step in systematic fan analysis is identification of watersheds that preserve a depositional record. This task requires a necessary understanding of sediment delivery mechanisms, fan morphology, and geomorphic conditions conducive to fan preservation. This paper focuses on the latter two elements through comparative analysis of three watersheds underlain by the Acadian clastic wedge. These areas include the Fernow Experimental Forest, Tucker County, West Virginia; the North Fork basin, Pocahontas County, West Virginia; and the Little River basin, Augusta County, Virginia (Figure 6-1). The conditions for fan preservation outlined in this paper provide an important research model for future workers to use in identifying potential areas of study.

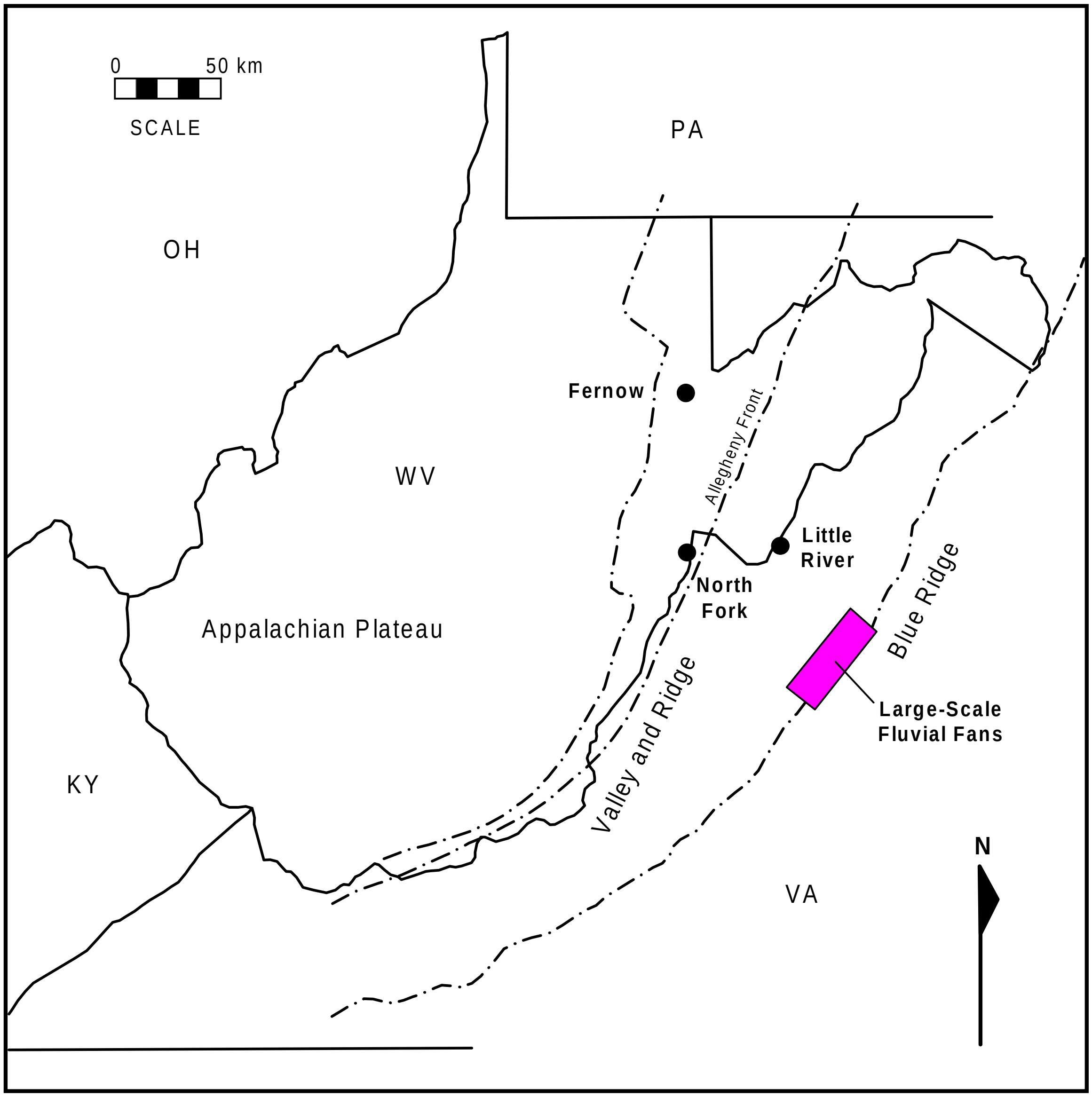


Figure 6-1. Physiographic map of the central Appalachians. Locations include: "Fernow" - Fernow Experimental Forest, Tucker County, West Virginia; "North Fork" - North Fork basin, Pocahontas County, West Virginia; and "Little River" - Little River basin, Augusta County, Virginia. Physiographic base map from Kulander and Dean (1986). Hatched box shows location of large-scale fluvial fans as described by Kochel (1990). See text for discussion.

GENERAL SETTING

Physiography

The Fernow Experimental Forest lies in the Allegheny Mountain section of the unglaciated Appalachian Plateau province, 40 km west of the Allegheny structural front (Figures 6-1 and 6-2). The area occupies 19 km^2 of Monongahela National Forest and surface elevation ranges from 533 to 1,112 m (1748 to 3647 ft) AMSL. The North Fork area also lies in the Allegheny Mountain section, but only 4 km west of the Allegheny structural front (Figure 6-1). The 50 km^2 area has surface elevations ranging from 853 to 1,386 m (2800 to 4546 ft) AMSL. The Little River basin occupies 40 km^2 in the Valley and Ridge province of central Virginia, 40 km east of the Allegheny structural front (Figure 6-1). Mountain slopes are steep with elevations ranging from 500 to 1340 m (1680 to 4397 ft) AMSL.

The climate of all three areas is classified as humid continental (Lockwood, 1985). Average yearly precipitation ranges from 1450 mm (57 in) at the Fernow area to 1000 mm (40 inches) at the Little River. Regional weather systems are directed primarily from the west, with mid-latitude frontal systems and large-scale cyclonic disturbances common (Hirschboeck, 1991). The region is sporadically prone to torrential rainfall associated with the extratropical-phase of hurricanes (Colucci and others, 1993) and terrain-locked convective clusters (Michaels, 1985; Smith and others, 1996). High-magnitude precipitation is the driving mechanism for catastrophic slope failure and flooding in the central Appalachians (Jacobson and others, 1989a).

Soils in all three areas are similar and commonly form on bedrock hillslopes mantled with colluvium and residuum. Hillslope soils are composed of channery silt loams and stony to very stony silt loams (Mesic Typic Dystrochrepts; Losche and Beverage, 1967; Hockman and others, 1979; Natural Resources Conservation Service, in press). Valley-bottom soils are comprised of poorly-developed Fluvents that are reworked during flood events. Each area is heavily forested by deciduous, coniferous, and mixed-forest communities (Core, 1966; Braun, 1950; Hack and Goodlett, 1960).

Bedrock Geology

The study areas are underlain by upper Paleozoic sedimentary strata that have been moderately deformed into broad and open folds (Cardwell and others, 1969; Rader and Evans,

Figure 6-2. Overview of the Fernow study site. Photo is representative of the forested, humid-mountainous landscape of the central Appalachians. Field of view is approximately 2 km.

1993). Exposed strata range in age from late Devonian to early Pennsylvanian. In ascending order, these units include the Devonian Foreknobs Formation, the Devonian Hampshire Formation, the Mississippian Price Formation, the Mississippian Greenbrier Group, the Mississippian Mauch Chunk Group, and the Pennsylvanian Pottsville Group (terminology after Cardwell and others, 1968; Dennison, 1970; and Kammer and Bjerstedt 1986). Significant portions of each study area are underlain by sandstones and shales of the Acadian clastic wedge, a mega-facies that encompasses the Foreknobs, Hamsphire, and Price formations. Greater than 75% of the North Fork and Little River areas are underlain by nonmarine facies of the Hampshire Formation. The Hampshire accounts for approximately 60% of surface exposures at the Fernow area. Although there is local variation, structure of the three areas is remarkably similar in that folds are broad and open, with dips less than 10 degrees. Erosionally resistant sandstones of the Price Formation are notable ridge formers.

Surficial Geology

Surficial deposits in the unglaciated central Appalachians are mapped according to a four-fold classification including age, origin (genetic process), landform, and material (texture) (Taylor and others, 1996; Taylor, Chapter 5, this volume). Large-scale landform units include hillslope and valley-bottom features. Hillslopes are subdivided into ridges, hollows, noses, and side slopes. Valley-bottom landforms include channels, floodplains, terraces, fans, and aprons. Hillslope deposits are comprised of colluvial and residual boulder diamicton. Footslope areas and low-order tributaries are sites of fan and apron deposits. Floodplain sequences are composed largely of imbricated coarse-grained gravel facies. Mills and others (1987) provided a comprehensive overview of the surficial processes and deposits in the Appalachian region.

The ages of surficial deposits in the study areas have not been dated directly, however regional chronologies suggest that colluvium is in part Late Pleistocene (>10 Ka) while alluvium is mostly Holocene in age (<10 Ka) (Kochel, 1987; Jacobson and others, 1989b; Behling and others, 1993). A convective storm in June of 1949 caused widespread slope failure, debris flow, and flooding in the Little River watershed (Hack and Goodlett, 1960). Debris fans and slide scars generated by that event are a conspicuous component of the present-day landscape (Osterkamp and others, 1995; Taylor, Chapter 4, this volume). All three study areas were geomorphically impacted by record flood discharges associated with complex cyclonic interaction in November of 1985.

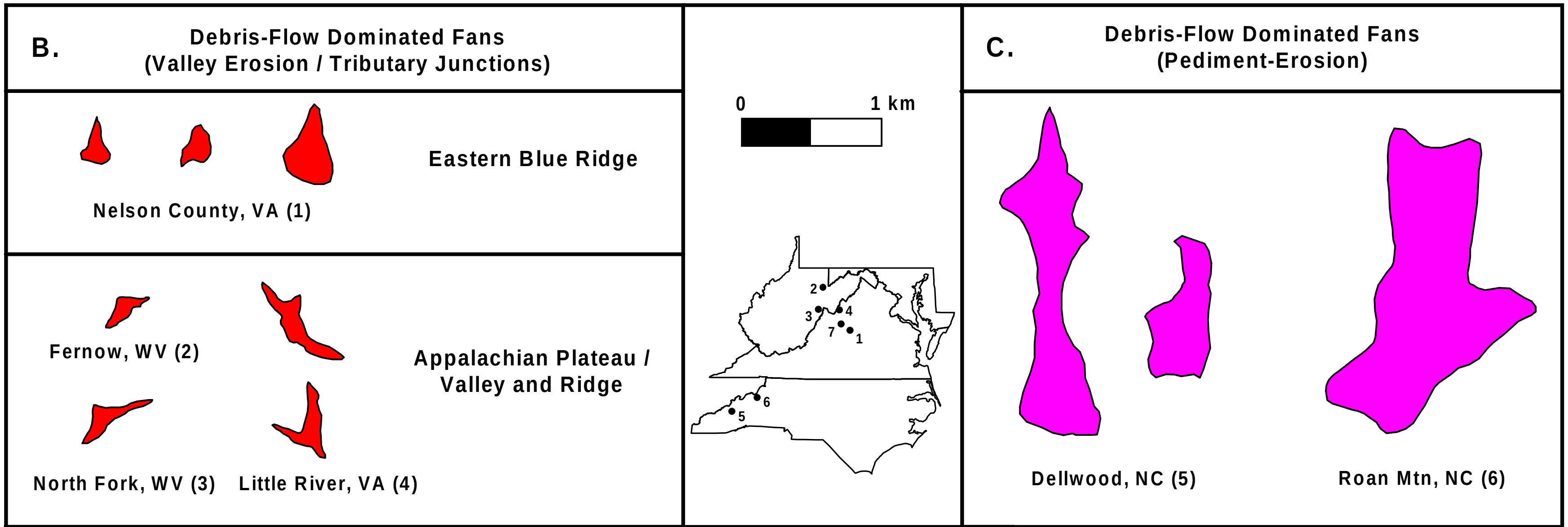
APPALACHIAN FANS

Previous Work

Kochel (1990) provided a summary of humid-temperate fans in the central Appalachian region. Fans are classified as either fluvially-dominated or debris-flow dominated, depending upon the primary style of depositional process. For the purposes of brevity, Kochel's (1990) two classes are subsequently referred to as "debris fan" and "fluvial fan", respectively. Most Appalachian fan research has been conducted in crystalline bedrock landscapes of the Blue Ridge province (Mills, 1982, 1983; Kochel and Johnson, 1984; Kochel, 1987; Mills and Allison, 1995a,b,c; Liebens and Schaetzl, 1997; Eaton, 1999). Significant work in the Shenandoah Valley is limited to the eastern portion where Paleozoic carbonate rocks are in contact with Blue Ridge crystalline rocks (Hack, 1965; Bell and Kite, 1987; Simmons, 1988; Kochel, 1990; Duffy, 1991; Whittecar and Duffy, 1992). Very few investigations have been completed farther to the west in sandstone terrain of the Appalachian Plateau and Valley and Ridge provinces (Hack and Goodlett, 1960; Wilson, 1987; Tharp, unpublished report). The present study focuses on comparative analysis of debris-fan deposits in the western sandstone landscapes.

Fluvial Fans

Fluvial fans are spatially restricted to the west flank of the Virginia Blue Ridge, where they debouch eastward into the Shenandoah Valley (Figures 6-1 and 6-3a; Kochel, 1990). These large-scale fans range up to 10's of square kilometers in area and coalesce to form an extensive bajada along the mountain front. Hack (1965) originally mapped these features as combination fan, pediment, and terrace deposits. Kochel and Johnson (1984) identified proximal to distal fan facies, with transport processes ranging from mixed hyperconcentrated-debris flow to tractive bedload. Sedimentary facies are characterized by well-stratified, cross-bedded sand and gravel. Clast-supported, boulder to pebble gravel decreases in grain size with distance from apex. Fluvial fan deposits have accumulated to several hundred meters thickness in response to karst solution



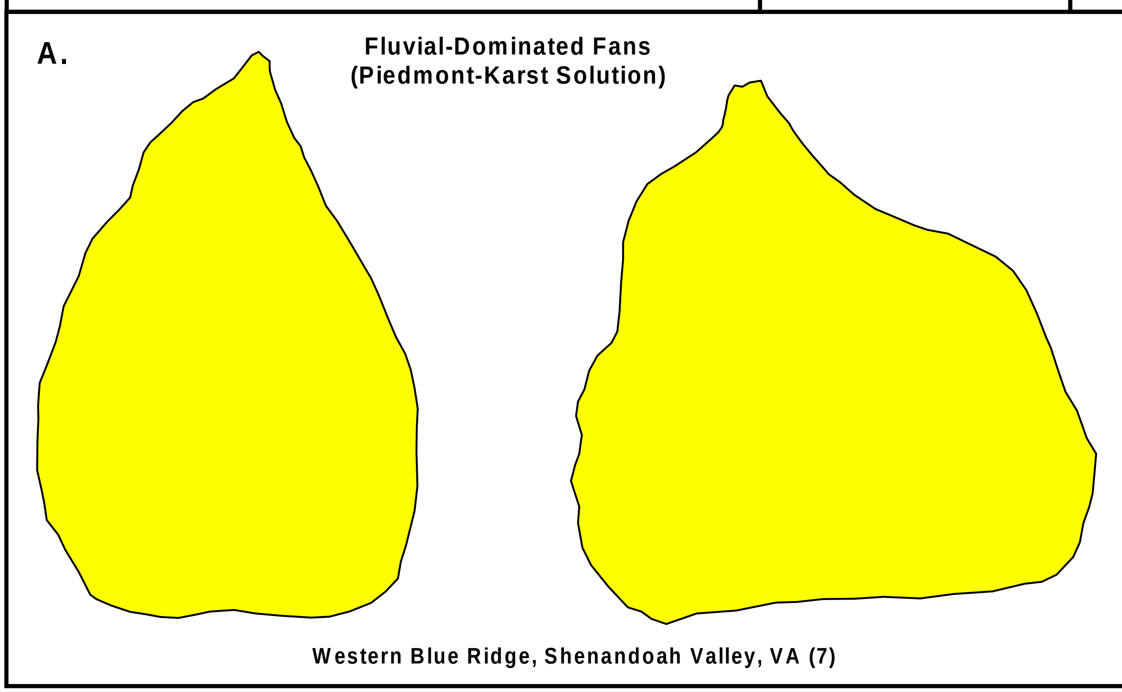


Figure 6-3. Scale comparison of fan types recognized in the central Appalachians (after Kochel, 1990). Source of fan accommodation listed in parentheses. Fan shapes are derived from the following sources: Nelson County, VA - Kochel and Johnson (1984); Roan Mountain, NC - Mills (1983); Dellwood, NC (Mills, 1982); western Blue Ridge, VA (Kochel, 1990); Fernow, North Fork, Little River - this study. Refer to numbered site locations on base map. See text for discussion.

of Lower Paleozoic limestone (Hack, 1965). Whittecar and Duffy (1992) used relative age dating techniques to identify a mosaic of young, intermediate, and old age fan surfaces. They speculated that the oldest fan surfaces are at least 1 Ma. Kochel (1992) noted that fluvial fans are presently experiencing incision and likely represent relict deposition by braided fluvial systems.

Debris Fans

Debris fans are ubiquitous throughout the central Appalachian region, and are associated with low-order drainage basins in erosion-dominated landscapes (Figure 6-3b; Kochel, 1990). These landform elements are characterized by small-scale (< 1 km^2), irregularly shaped deposits that commonly occur at valley intersections. Low-order to high-order stream junctions provide the optimum topographic expansion necessary for fan development. Debris fans are constructed primarily by a combination of debris-slide and debris-flow processes in steep mountain watersheds. Sedimentary facies are characterized by poorly sorted, crudely-stratified diamictons, with lesser amounts of clast-supported gravels (Kochel, 1992). In the Appalachian Plateau, Remo (in preparation) mapped spectacular debris fans containing clast-supported, sandstone boulders up to tens of meters in diameter. Complex internal stratigraphy suggests that many fans are constructed by multiple, episodic debris-flow events (Kite, 1987). Thicknesses range up to 20 meters, but are commonly less than 10 meters. Similar fan occurrences were documented in other regions by Wells and Harvey (1987), Benda and Dunne (1987) and Kellerhals and Church (1990). These features are also termed "debris cones" or "alluvial cones" elsewhere in the literature (Hack and Goodlett, 1960; Harvey, 1986; Leece, 1990; Oguchi, 1997).

Mills (1982, 1983) identified a variation of debris-flow dominated fan in the Blue Ridge of North Carolina. He employed the terms "fan-pediments" and "piedmont-cove deposits" to describe the occurrence of debris-flow facies overlying erosionally-bevelled saprolite along mountain footslopes (Figure 6-3c). Crudely stratified diamicton deposits attain thicknesses of 20 to 30 meters. In comparison to the small-scale fans described above, this larger-scale variety is similarly irregular in shape, but range up to several square kilometers in area.

Historic debris-flow events have activated numerous fans throughout the central Appalachian region (Hack and Goodlett, 1960; Williams and Guy, 1973; Bogucki, 1976; Neary and others, 1986; Clark, 1987; Wieczorek and others, 1996). High-magnitude, low-frequency precipitation is the driving mechanism for slope and fluvial processes in mountain watersheds (Jacobson and others, 1989a; Kochel, 1992). Costa and Jarrett (1981) argued that storms release proportionally larger volumes of water in small basins. High rainfall intensities, coupled with steep colluvial slopes, promote slope instability and debris flow. Based on radiocarbon dating, Kochel (1987) estimated debris-flow recurrence intervals of 3000-4000 years on Holocene fans in the Virginia Blue Ridge. He postulated that incursion of tropical cyclones at the Holocene interglacial transition triggered debris-flow delivery of periglacial colluvium to fans. More recent radiocarbon work by Eaton and McGeehin (1997) support the 3000-year recurrence interval estimates; however, their debris flow ages extend well into the Late Pleistocene. Eaton (1999) suggested that periglacial climates are capable of spawning debris flow in the Blue Ridge, and alternatives to Kochel's (1987) process-response model are warranted.

Study Areas

Systematic surficial mapping was completed at each study area, and forms the basis for the fan analysis presented herein (Taylor, Chapters 2, 3, 4; this volume). Debris fans in the study areas are small scale (<0.1 km^2), irregularly shaped deposits composed of poorly sorted gravel and gravel diamicton (Figure 6-4; Table 6-1). The depositional facies are similar to those described by Kochel and Johnson (1984) along the east flank of the Blue Ridge (Figure 6-3b). Debris fans likewise occur at tributary junctions of low-order streams. Inset fan relationships are common, with fan surfaces both at present channel grade and at heights of greater than 15 meters (Figures 6-5 and 6-6). Hack and Goodlett (1960) made similar observations at the Little River area. Age data are not available for fans; however, weakly to moderately developed weathering rinds are noted on sandstone clasts associated with higher-level terraces. Based on limited fan exposure, deposits are characterized by hard framework clasts and an absence of well-defined soil horizons. Mills and Allison (1995b) noted that these types of fan deposits are the most common in the Appalachians and speculated that they are no older than Late Pleistocene. Recent chronosequence work in the Blue Ridge suggests that fan surfaces increase in age with height above channel grade (Mills and Allison, 1995a,b,c; Liebens and Schaetzl, 1997). It is likely that similar relationships apply to areas included in this study; however, relative age dating techniques have yet to be tested.

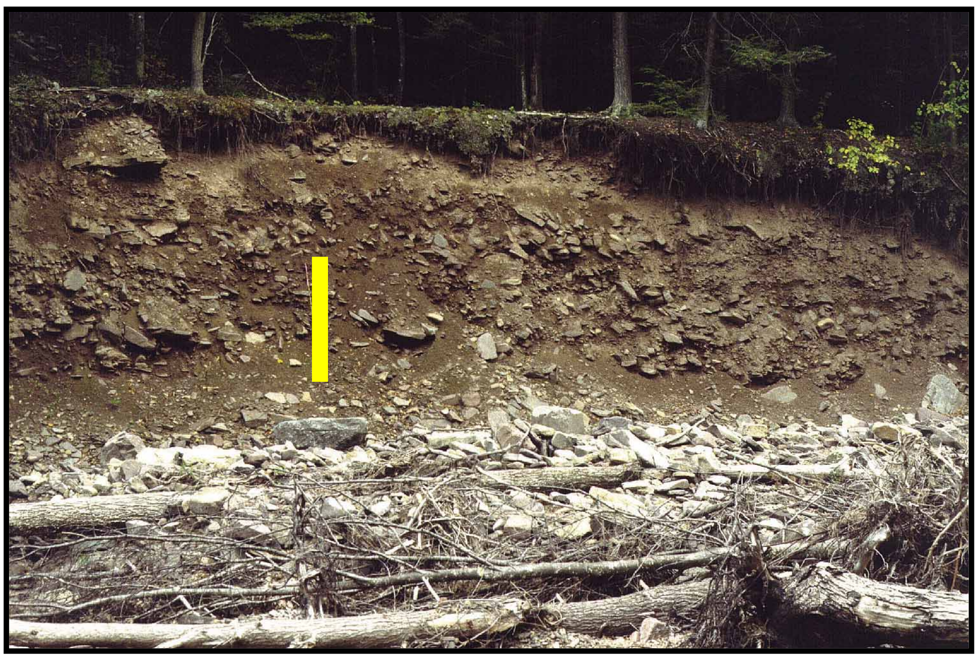


Figure 6-4. Photo showing example of complex internal stratigraphy from a 5 to 6 m fan terrace in the central Appalachians. Note abundance of cobble- to boulder-diamicton and crude stratification. Yellow bar is 2 m.

Table 6-1. Results of Clast-Size Analysis for Three Debris Fans at the Little River Area (from S. Tharp, unpublished data).

Fan ID*	Fan Facies#	Grain Size Distribution					
		%Boulders	%Cobbles	%Pebbles	%Sand	%Silt	%Clay
LR-73	pD	0	18.59	49.86	23.12	6.13	2.3
	p-cD	2.89	21.06	47.97	20.98	4.75	2.35
	gD	N/A	N/A	N/A	N/A	N/A	N/A
	p-bD	N/A	N/A	N/A	N/A	N/A	N/A
	c-pD	6	29.27	37.93	16.8	7.66	2.34
	c-bD	15.12	20.2	41.67	15.28	5.9	1.82
	b-cD	20.3	26.22	30.07	15.53	5.85	2.03
	bD	N/A	N/A	N/A	N/A	N/A	N/A
	G	27.47	28.19	18.73	16.86	5.44	3.31
	pG	N/A	N/A	N/A	N/A	N/A	N/A
	cG	0	53.18	32.44	10.35	3.82	0.23
	snd-slt	0	0	12.96	53.57	23.18	10.29
LR-90	pD	0	7.67	53.49	21.61	14.48	2.7
	p-cD	7.17	13.59	39.84	26.65	1.71	2.04
	gD	10.33	27.33	27.91	24.35	7.88	2.21
	p-bD	N/A	N/A	N/A	N/A	N/A	N/A
	c-pD	0.74	17.68	41.66	27.49	9.75	2.69
	c-bD	0	18.95	36.8	26.53	12.63	5.1
	b-cD	23.73	26.47	25.43	19.93	3.4	1.05
	bD	36.49	16.95	20.23	16.49	8.11	1.72
	G	1.39	19.13	46.86	24.48	5.68	2.47
	pG	0	3.98	61.24	24.87	7.17	2.74
	cG	N/A	N/A	N/A	N/A	N/A	N/A
	snd-slt	0	0	7.59	51.16	27.49	13.77
LR-97	pD	0	23.82	44.06	23.22	7.09	1.81
	p-cD	12.11	29.43	31.54	18.06	6.7	2.16
	gD	N/A	N/A	N/A	N/A	N/A	N/A
	p-bD	9.8	20.61	37.08	21.49	7.37	3.65
	c-pD	6.66	19.19	38.21	26.96	6.52	2.47
	c-bD	15.5	40.39	24.34	14.88	4.05	0.84
	b-cD	11.85	32.41	24	23.52	5.72	2.5
	bD	N/A	N/A	N/A	N/A	N/A	N/A
	G	20.09	25.37	21.7	23.62	6.68	2.54
	pG	N/A	N/A	N/A	N/A	N/A	N/A
	cG	N/A	N/A	N/A	N/A	N/A	N/A
	snd-slt	0	0	19.2	66.23	10.61	3.96

* This study
# p = pebble, c = cobble, b = boulder, snd = sand, slt = silt, D = diamicton, G/g = gravel

LR-73 = South Fork Little River (Virginia-North State Plane-ft:1797196, 270258)
LR-90 = North Fork Little River (Virginia-North State Plane-ft: 1798187, 276823)
LR-97 = North Fork Little River (Virginia-North State Plane-ft: 1796512, 278259)

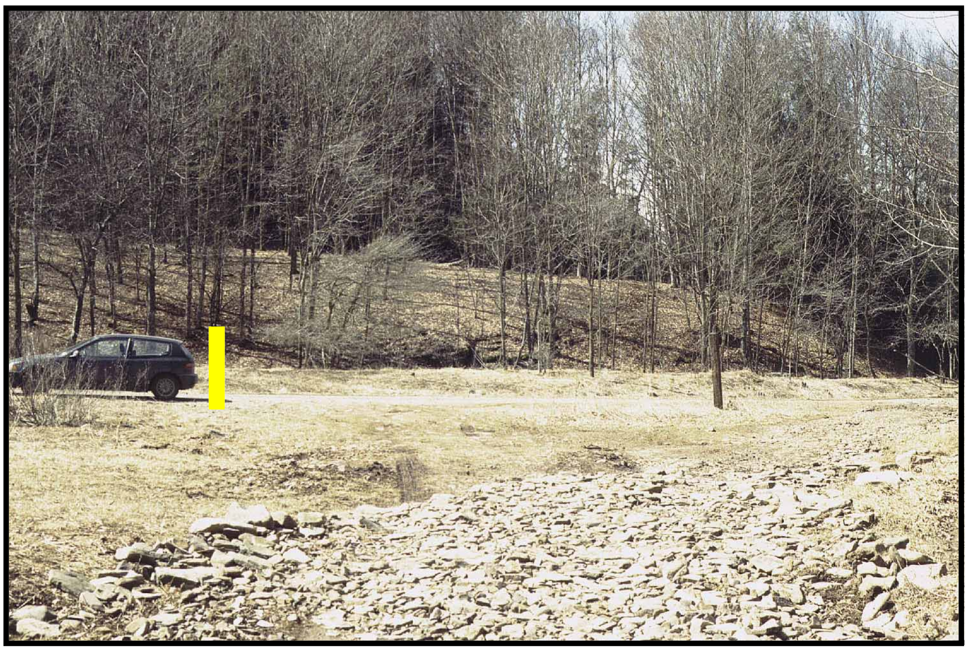


Figure 6-5. Photo showing example of 5 m fan terrace (Qf2) in the central Appalachians. Debris-fan tributary channel is in the forground. Master channel lies beyond field of view on photo right. Yellow bar is 2 m.

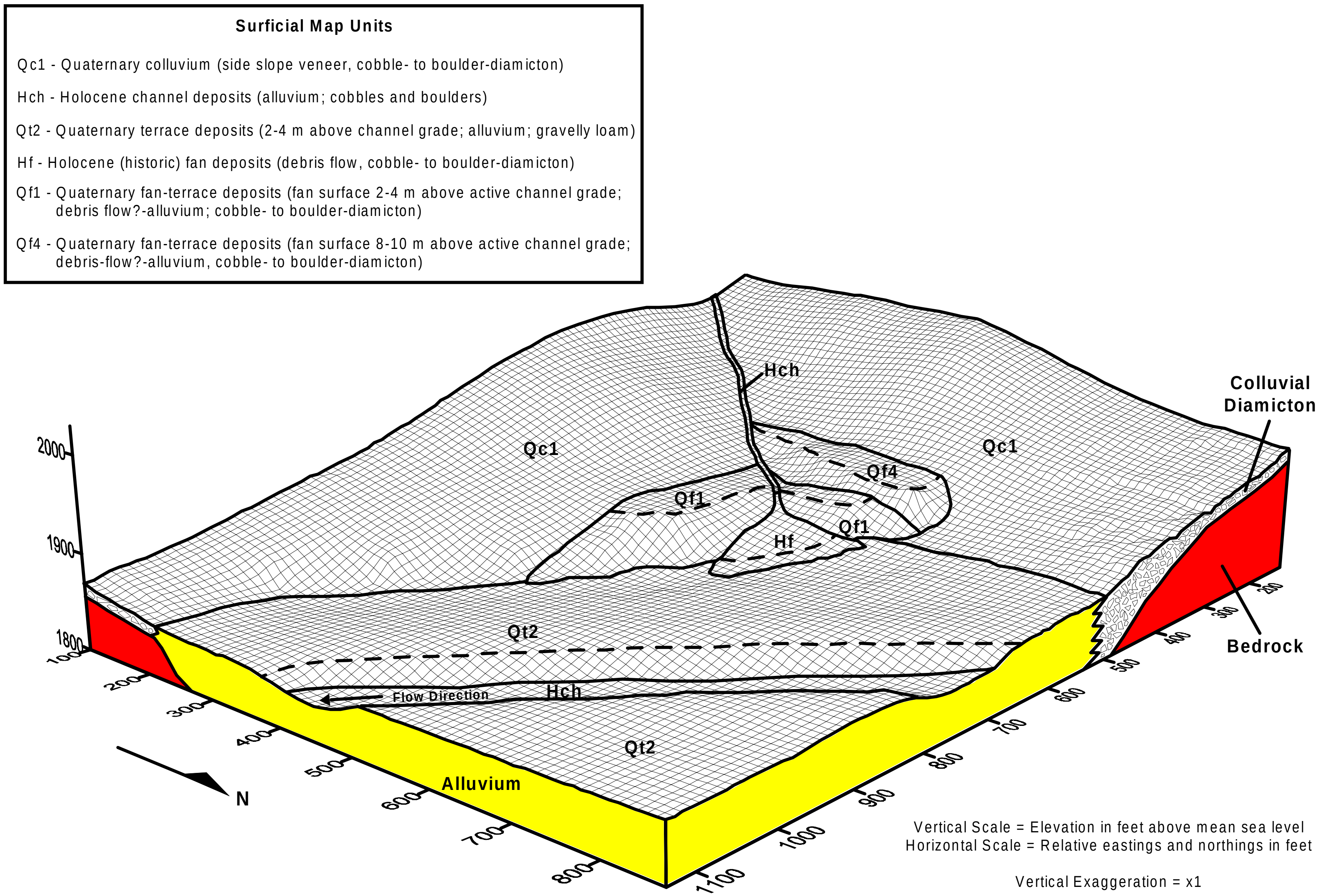


Figure 6-6. Generalized block diagram illustrating inset fan-terrace relationships in the central Appalachians.

Arid Fan Comparison

Classic arid-climate fans occur at the intersection between upland drainage basins and tectonically-controlled mountain fronts. Flow expansion at the edge of the front results in an unconfined fan-shaped deposit. Debris flow, hyperconcentrated flow and normal streamflow are the primary sediment delivery mechanisms (Blair and McPherson, 1994). Episodic deposition, faulting, and fluvial incision result in abandonment of fan surfaces and creation of a complex mosaic of morphostratigraphic units (Denny, 1967). Fan surfaces are typically segmented with varying longitudinal slopes along tectonically-active mountain fronts (Hooke, 1968). Arid-environment fans are very sensitive to climate change and depositional processes have been modulated by variable precipitation levels throughout the Quaternary (Bull, 1991).

By comparison, small-scale debris fans in the central Appalachians occur primarily within the upland drainage basin proper, rather than at well-defined mountain fronts (Figure 6-7). Mills (1983) pointed out that arid fans are mainly products of depositional processes whereas Appalachian fans are accommodated by erosion within low-order basins. Thus, fan-sediment storage is largely a function of basin morphometry in forested mountain watersheds. Basin morphometry is in turn controlled by variations in bedrock geology (Hack, 1957).

DEBRIS FAN ANALYSIS

Methodology

Surficial data were compiled on 1:9,600 base maps, digitally converted from 7.5-minute quadrangles. The 1:9,600 scale proved very effective for the delineation of meso-scale landforms in the study areas (Kite and others, 1998). County soil surveys, air photos, and aerial videography supplemented standard field methods. The final map products were compiled in a vectorized GIS format using AutoCAD (Autodesk, 1992), Idrisi (Clark Labs, 1997), and ArcView (Environmental Systems Research Institute, 1996). Table 6-2 presents a summary of fan-related map units.

Digital elevation models (U.S. Geological Survey 30-meter DEM), vectorized topographic maps, and surficial map coverages were analyzed by GIS techniques. Debris fans and fan drainage areas were numbered by site (Figure 6-8). Analytical parameters include: fan

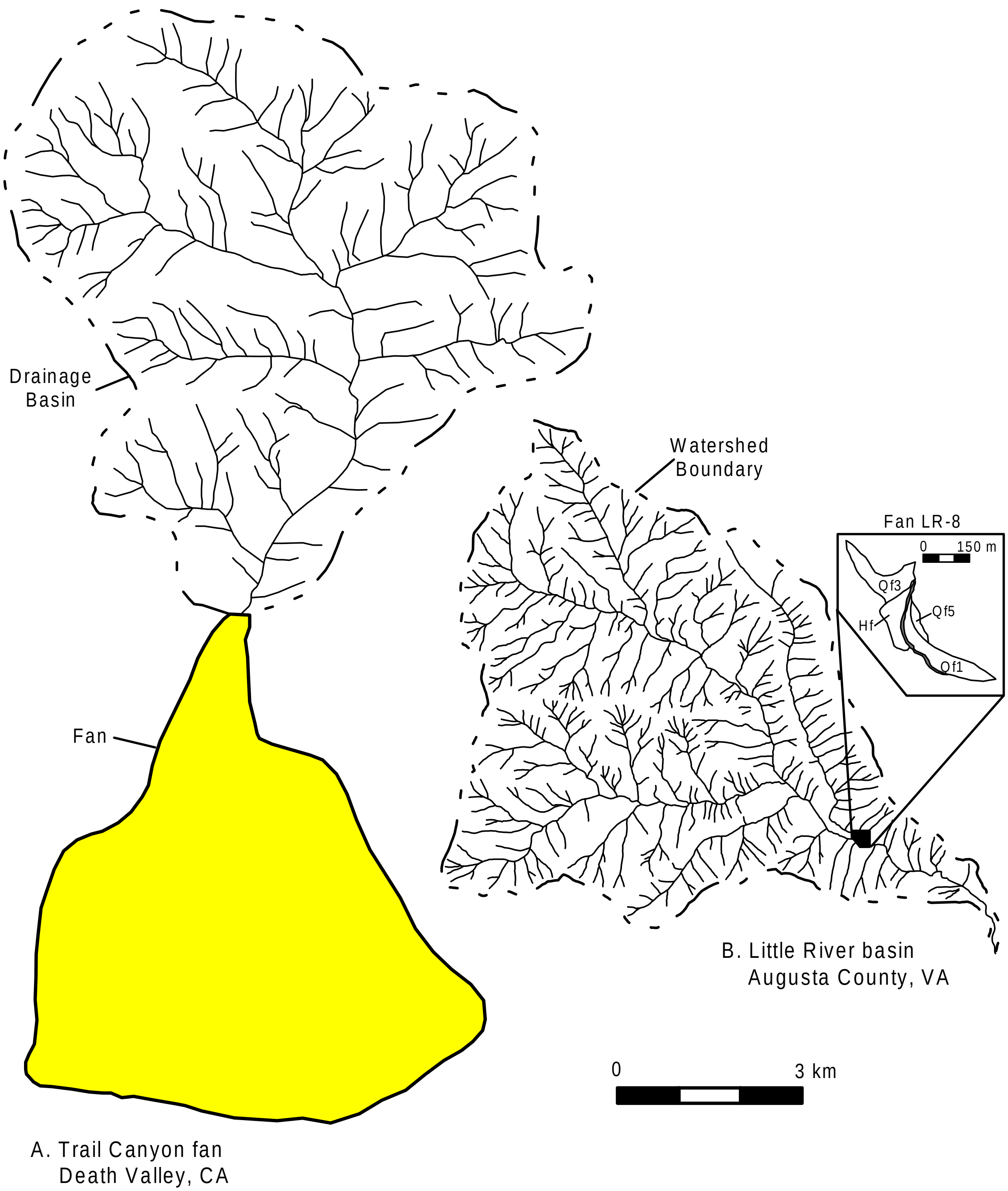


Figure 6-7. Scale comparison of debris fans at the Little River basin with an arid alluvial fan at Death Valley, California. The Trail Canyon fan map is from Blair and McPherson (1994).

Table 6-2. Explanation of Fan-Related Map Units Recognized at the Study Sites (from Taylor and Kite, 1997; 1998; and 1999).

Map Unit Label	Map Unit Description	Age	Origin (Process)	Landform	Material (Texture)	Comments
Hch	Holocene Channel Alluvium	Holocene	Alluvium	Channel and Narrow Floodplain	Cobbles-Boulders and Pebbly Loam (rounded to subrounded)	Fluvial channel deposits associated with first- to sixth-order streams. Unit includes channel alluvium and portions of adjacent floodplain too small to map at the given scale.
Hf	Holocene (Historic) Fan Deposits (undissected)	Holocene	Alluvium - Debris Flow(?)	Fan	Cobbles and Boulders, Gravel Diamicton	Historic fan deposits commonly associated with first- to second-order hollows at stream-tributary junctions. Identified by fresh deposits, disturbed and buried vegetation.
Qf	Quaternary Fan Deposits (undissected)	Quaternary (Undiff.)	Alluvium - Debris Flow(?)	Fan	Cobble- to Boulder-Diamicton with Silty Loam Matrix (subangular to rounded)	Fan deposits commonly associated with first-order hollows at stream-tributary junctions. Identified by older tree stands and lack of fresh appearance.
Qf1	Quaternary Fan-Terrace Deposits (2.0 to 4.0 m surface)	Quaternary (Undiff.)	Alluvium - Debris Flow(?)	Fan	Cobble- to Boulder-Diamicton with Silty Loam Matrix (subangular to rounded)	Entrenched fan surfaces commonly located at stream tributary junctions. Diamicton may be crudely stratified with imbricated gravely-loam facies.
Qf2	Quaternary Fan-Terrace Deposits (4.0 to 6.0 m surface)	Quaternary (Undiff.)	Alluvium - Debris Flow(?)	Fan	Cobble- to Boulder-Diamicton with Silty Loam Matrix (subangular to rounded)	Entrenched fan surfaces commonly located at stream tributary junctions. Diamicton may be crudely stratified with imbricated gravely-loam facies.
Qf3	Quaternary Fan-Terrace Deposits (6.0 to 8.0 m surface)	Quaternary (Undiff.)	Alluvium - Debris Flow(?)	Fan	Cobble- to Boulder-Diamicton with Silty Loam Matrix (subangular to rounded)	Entrenched fan surfaces commonly located at stream tributary junctions. Diamicton may be crudely stratified with imbricated gravely-loam facies.
Qf4	Quaternary Fan-Terrace Deposits (8.0 to 10.0 m surface)	Quaternary (Undiff.)	Alluvium - Debris Flow(?)	Fan	Cobble- to Boulder-Diamicton with Silty Loam Matrix (subangular to rounded)	Entrenched fan surfaces commonly located at stream tributary junctions. Diamicton may be crudely stratified with imbricated gravely-loam facies.
Qf5	Quaternary Fan-Terrace Deposits (>10.0 m surface)	Quaternary (Undiff.)	Alluvium - Debris Flow(?)	Fan	Cobble- to Boulder-Diamicton with Silty Loam Matrix (subangular to rounded)	Entrenched fan surfaces commonly located at stream tributary junctions. Diamicton may be crudely stratified with imbricated gravely-loam facies.

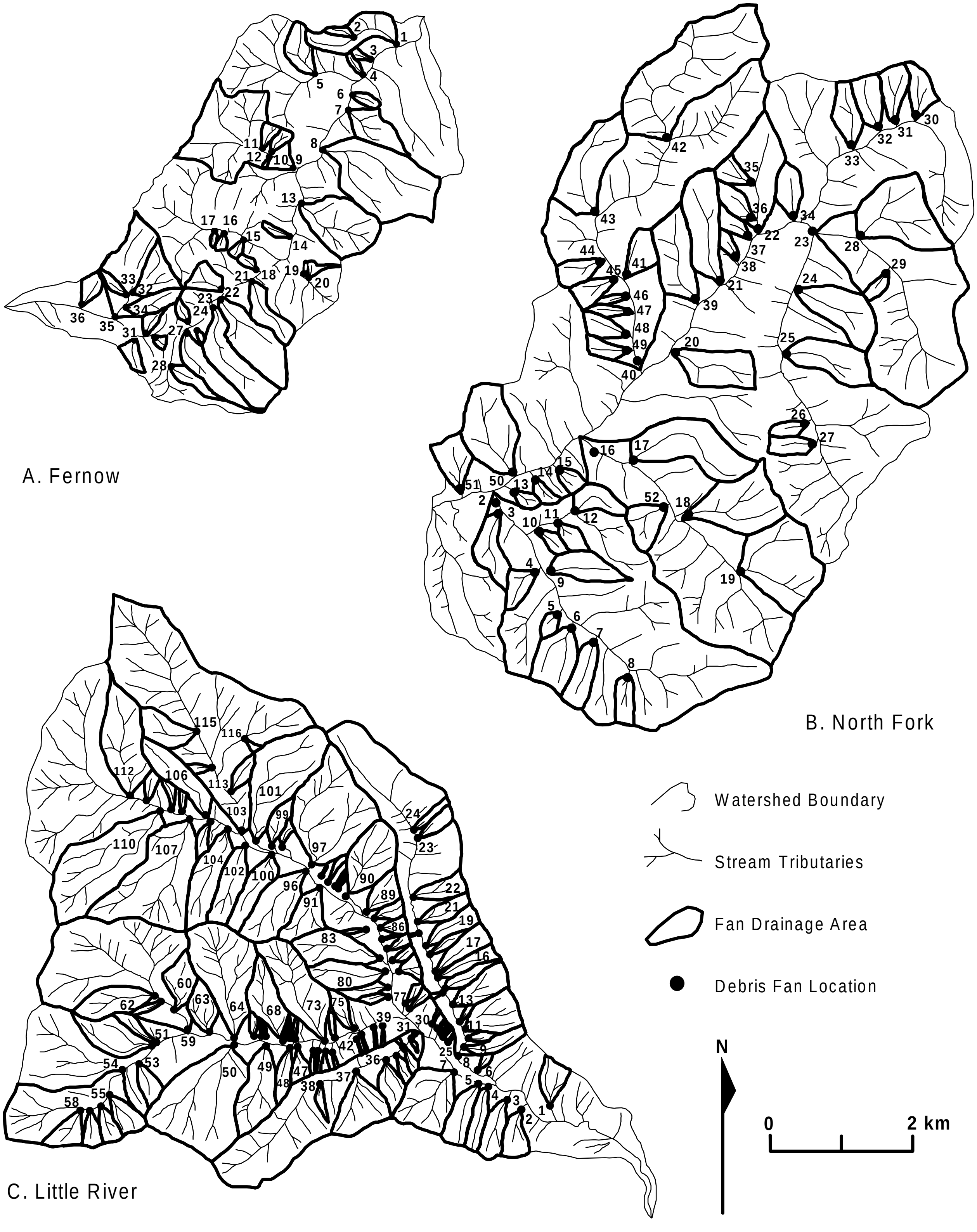


Figure 6-8. Map showing debris fan locations and fan drainage areas; Fernow, North Fork, and Little River study areas.

frequency, map-unit composition, fan type (simple vs. compound), surface area, drainage area, tributary-junction type (Strahler order), width of receiving valley, slope of fan tributary, and slope of receiving valley. A standard suite of watershed-scale morphometric parameters (Horton, 1945) were also computed for each area (Table 6-3), with tributaries identified by the contour-crenulation method (Strahler, 1957).

Results

Fan map units are delineated according to fan-surface morphology and height above channel grade (Table 6-2). Debris fans are classified as either simple or compound. Simple fans are characterized by single map-unit types, whereas compound fans include complex map patterns with inset fan-terrace relationships. Fan terraces represent preserved segments that are otherwise dissected by tributary channels following deposition. Figure 6-9 illustrates the variety of fan types and shapes recognized at the study areas. The most notable observation is that these small-scale debris fans lack the classic semi-conical shape of arid fans. Fans commonly display a width-to-length ratio greater than 1.0 relative to the principal transport direction. Limited growth in the axial direction is largely controlled by narrow valley widths of the receiving channel. Feeder channels incise higher-level fan terraces, with sediment delivery to lower segments, or directly into the master tributary. Debris fans are most commonly preserved at tributary junctions, with greater than 75% occurring at the intersections of first- or second-order channels with higher order trunk streams (Figure 6-10). Frequency plots of simple vs. compound fans reveals that the Little River has a significantly higher percentage of compound-inset fans compared to the Fernow or North Fork (Figure 6-11).

Composite fan surface areas range from 2.0×10^2 to 6.5×10^4 m^2, with a mean of 3.9×10^3 m^2 (Table 6-3). Critical quantitative parameters for the Fernow, North Fork, and Little River areas include, respectively:

Table 6-3. Summary of Morphometric Data for Watersheds, Valley Bottoms, and Debris Fans at the Fernow, North Fork, and Little River Areas.

	Ref. I.D.[1]	Morphometric Parameter	Fernow[2]	North Fork	Little River
Watershed Morphometry	a	Drainage Order (Strahler)	5	5	6
	b	Basin Area (km^2)	17.62	49.27	41.48
	c	Drainage Density (km^{-1})	4.24	3.26	4.66
	d	Basin Relief (km)	0.586	0.533	0.828
	e	Ruggedness **(c*d)**	2.486	1.737	3.856
	f	Total No. of First-Order Tributaries (Shreve Magnitude)	139	287	380
	g	Total No. of Stream Segment Intersections	158	284	377
	h	Tributary Junction Frequency (km^{-2}) **(g/b)**	8.97	5.76	9.09
	I	Stream Frequency (km^{-2})	12.14	7.79	12.08
Valley Bottom Statistics	j	Maximum Valley Width (m)	120	180	290
	k	Total Valley Bottom Area (km^2)	0.76	1.86	3.09
Fan Morphometry	l	Total No. of Fans	36	51	116
	m	Total Fan Area (km^2)	0.113	0.165	0.486
	n	Total Fan Drainage Area (km^2)	8.24	30.51	35.42
	o	Average Fan Area (m^2)	3203.0	4165.0	4378.0
	p	Average Fan Drainage Area (km^2)	0.229	0.819	0.305
	q	Average Fan Basin Slope (m/m)	0.30	0.28	0.37
	r	Ratio: Slope of Fan Tributary / Slope of Receiving Tributary	5.20	7.40	9.90
	s	% Total Basin Area Occupied by Valley Bottom **(k/b)**	4.31	3.78	7.45
	t	% Valley Bottom Occupied by Fans **(m/k)**	14.87	8.87	15.73
	u	Ratio: Total Fan Area / Total Basin Area **(m/b)**	0.006	0.003	0.012
	v	Fan Frequency (km^{-2}) **(l/b)**	2.04	1.04	2.80
	w	Ratio: Total Fan Area / Fan Drainage Area **(m/n)**	0.014	0.005	0.014
	x	Ratio: Fan Drainage Area / Total Basin Area **(n/b)**	0.468	0.619	0.854

1. Ref. I.D. = reference letter used in text discussions and parameter derivations (in parentheses).

2. The Fernow site includes both the Elklick Run and Stonelick Run sub-basins.

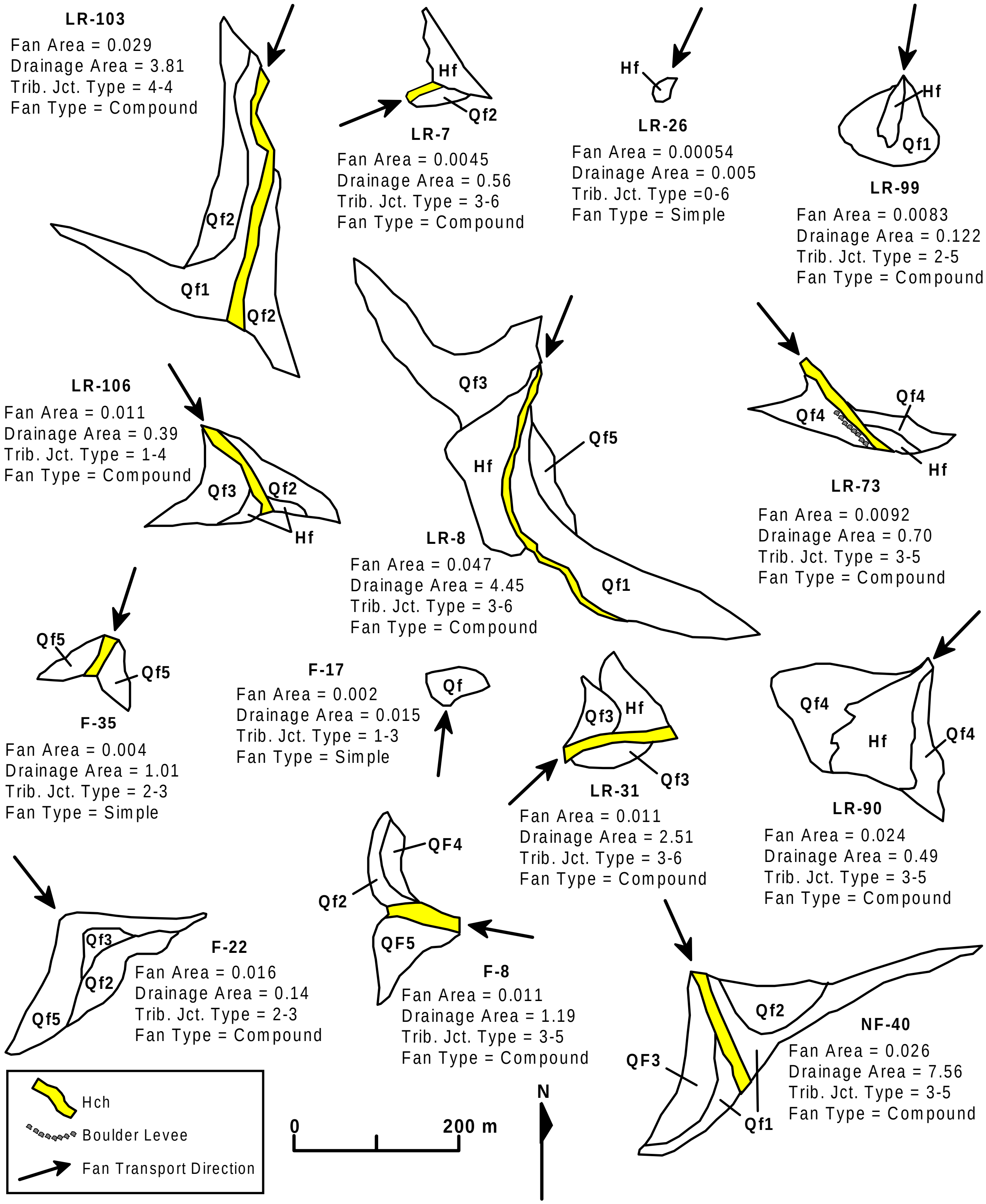


Figure 6-9. Examples of debris fan morphology recognized in this study. Surficial map units are as follows: Hch = Late Holocene channel alluvium, Hf = historic fan deposits (at grade), Qf = Quaternary fan deposits (at grade), Qf1 = Quaternary fan-terrace deposits (2-5 m surface), Qf2 = Quaternary fan-terrace (4-6 m), Qf3 = Quaternary fan-terrace (6-8 m), Qf4 = Quaternary fan-terrace (8-10 m), Qf5 = Quaternary fan-terrace (>10 - 15 m). Areas are listed in sq. km. Other codes include: F = Fernow, NF = North Fork, LR = Little River; Trib. Jct. Type = tributary junction according to Strahler stream order (e.g., 1-3 = 1st order-3rd order tributary junction). Refer to Figure 6-8 for fan locations.

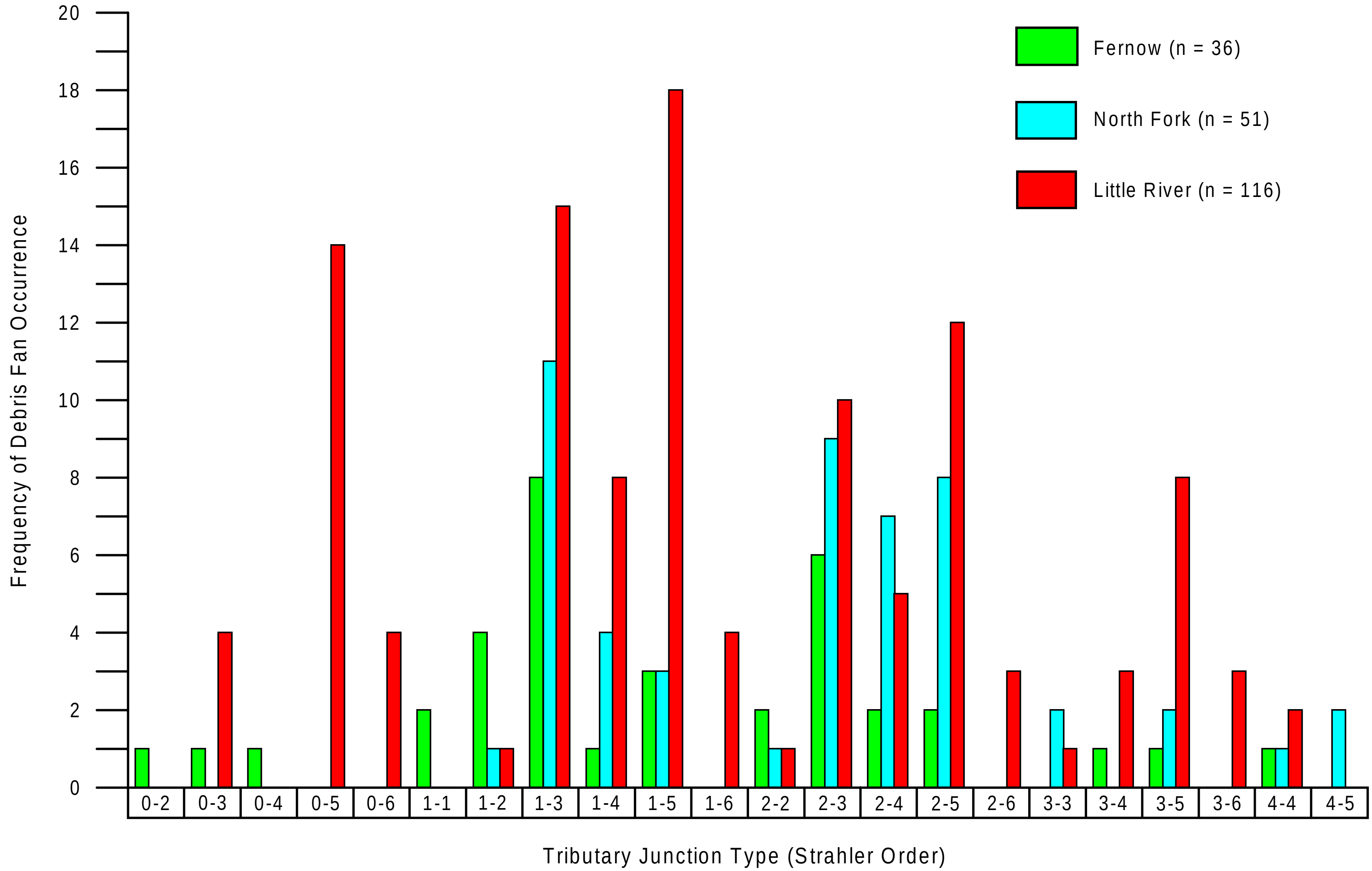


Figure 6-10. Frequency distribution of debris-fan occurrence at a given stream tributary junction type (Strahler order) for the study areas. The junction type code refers to Strahler stream order intersections (e.g. 1-4 = 1st order - 4th order intersection). Zero-order tributaries are hollows (*sensu* Hack and Goodlett, 1960) without well-defined channels.

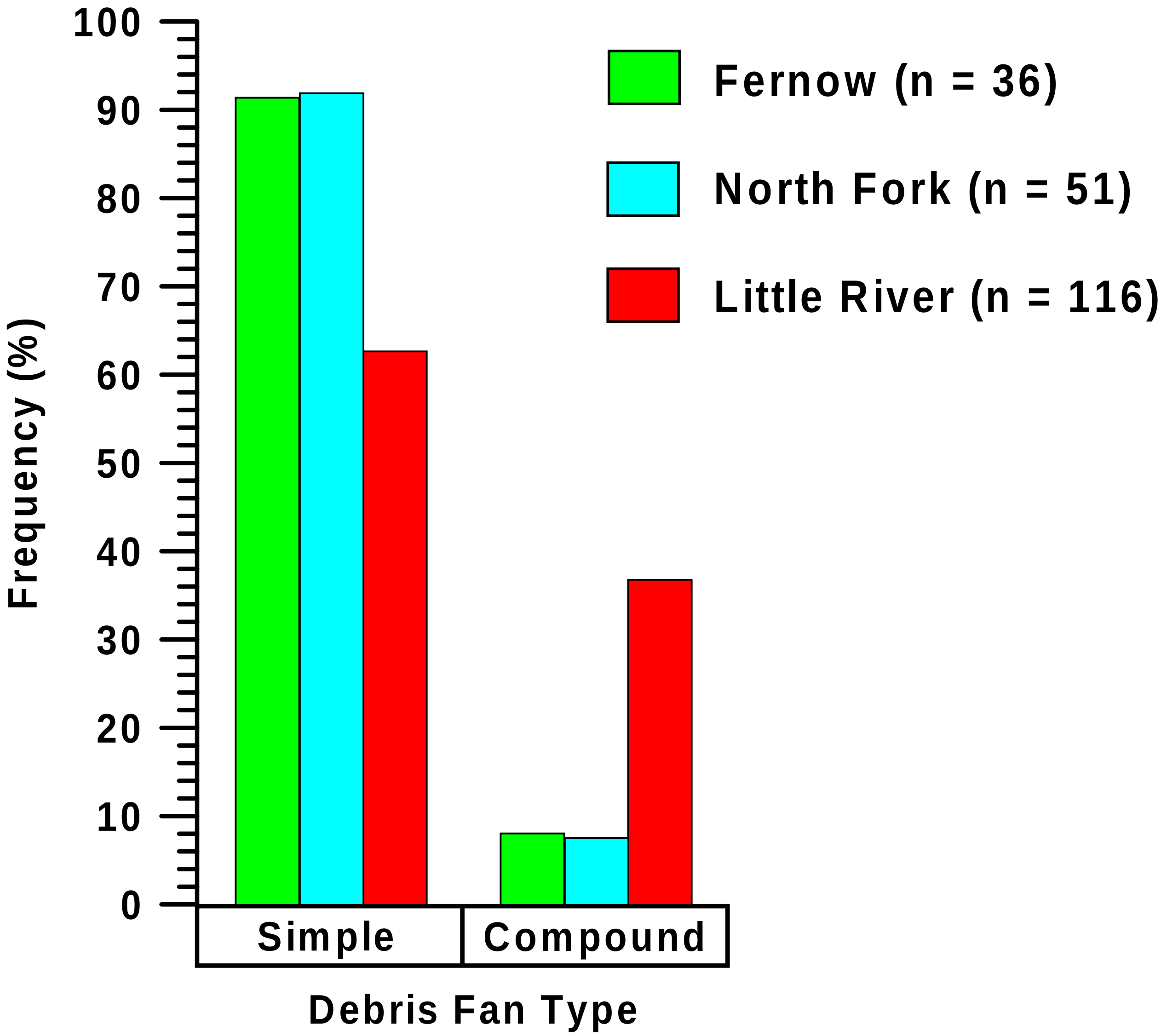


Figure 6-11. Percent frequency distribution of fan type (simple vs. compound) at the Fernow, North Fork, and Little River areas.

1. total basin area (km^2) = 17.6, 49.3, 41.5;
2. drainage density (km^{-1}) = 4.2, 3.3, 4.7;
3. ruggedness = 2.5, 1.7, 3.9;
4. Shreve magnitude = 139, 287, 380;
5. tributary junction frequency (km^{-2}) = 9.0, 5.8, 9.1;
6. maximum valley width (m) = 120, 180, 290;
7. total valley bottom area (km^2) = 0.76, 1.86, 3.09;
8. total fan area (km^2) = 0.115, 0.212, 0.508;
9. fan area to total basin area ratio = 0.006, 0.003, 0.012; and
10. fan frequency (km^{-2}) = 2.0, 1.0, 2.8.

The data in Table 6-3 indicate that compared to the other two areas, Little River is a steep, rugged watershed with significantly higher drainage density and higher percentage of valley-bottom area. Accordingly, Little River also has the highest volume of fan deposits in storage (refer to Taylor, Chapter 8, this volume). This relationship is supported by qualitative observations made while field mapping, particularly with respect to the large number of fan polygons noted in the Little River area. Comparatively, the Little River consistently shows greater values in the categories of valley-bottom area, number of fans, and total fan area.

Bull (1964) related fan area to drainage area for study sites in central California. He empirically determined a positive power-function fit with the following form:

(Equation 1) $$A_f = c(A_d)^n$$

where A_f is fan area and A_d is source basin drainage area. Bull's (1964) n values ranged from 0.8 to 1.0 for California fans. The coefficient c varied as a function of bedrock geology. Following Bull's (1964) approach, Figure 6-12 presents a fan area-drainage area plot for the study areas. The drainage area exponent (n) is 0.23, 0.34, and 0.51 for the Fernow, North Fork, and Little River, respectively. Correlation coefficients (R) range from 0.40 to 0.74. Combined data yield an n value of 0.39 and an R value of 0.60. In a similar analysis of Blue Ridge debris fans, Kochel (1990) concluded that low n values document the restricted nature of fan growth in narrow valleys. Regardless of the amount of source-basin area, restricted storage space precludes a corresponding increase in fan size. Factors controlling variability of fan accommodation are discussed below.

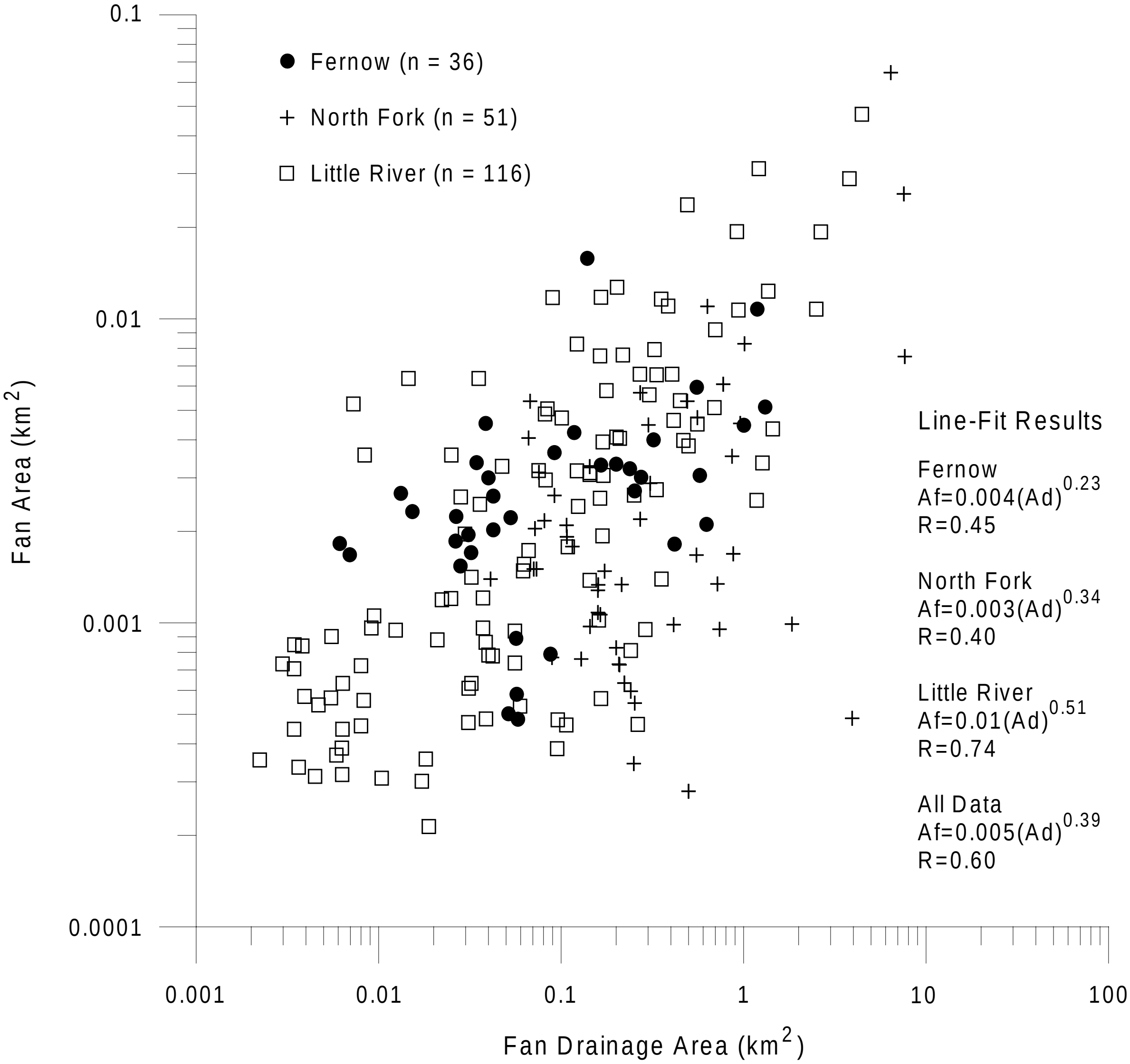


Figure 6-12. Log-log plot of fan drainage area (km^2) vs. fan area (km^2) for small-scale debris fans at the Fernow, North Fork and Little River areas. Power-function fits for the data are shown at lower right. Greater values for drainage-area exponent and correlation coefficient at the Little River result from increased valley-bottom width and erosional accommodation space.

DISCUSSION

Critical factors that affect fan morphology in the Appalachians include: (1) source basin lithology (resistant vs. non-resistant), (2) depositional process (debris flow vs. fluvial), (3) topographic configuration at the depositional site (degree of constriction), and (4) post-depositional modification by fluvial processes (lateral and vertical incision) (Kochel, 1990). Topographic configuration and depositional modification relate to the fan accommodation space provided by watershed erosion processes. The above results suggest that compared to the other areas, geomorphic conditions at the Little River are more conducive to fan storage. The less frequent occurrence of debris fans at the Fernow and North Fork suggests that these fluvial systems are more effective at routing sediments out of the watershed.

Local Fan Accommodation

Since debris fans occur mainly at valley intersections, it is reasonable to hypothesize that fan accommodation area is largely a function of valley width and tributary-junction frequency. The wider the valley bottom and greater the number of stream-segment intersections, the greater the accommodation area available for fan storage. Miller (1994) observed that in narrow valleys, tributary fans constrict main stem flow, producing greater shear stress and negative feedback in the form of lateral fan erosion. Thus, wider valley bottoms provide the necessary accommodation space to promote fan development and sediment storage. To test this hypothesis, valley width was plotted as a function of channel distance at the study areas (Figure 6-13). The Fernow is associated with the narrowest valley bottoms and lacks significant correlation between the two parameters ($R<0.3$). In contrast, the North Fork and Little River display a positive linear relationship with slopes of 0.011 and 0.021, respectively ($R = 0.87$ and 0.91). The slope of the linear regression in Figure 6-13 represents the rate of valley width increase per unit channel distance from divide, and is here referred to as "valley-width expansion rate". The Little River is associated with the highest values of maximum valley width, valley-width expansion rate, drainage density, tributary-junction frequency, fan frequency, average fan area, and percent compound fans (Table 6-3, Figure 6-13). Wide valleys, coupled with a high number of tributary intersections, provide numerous storage sites for fan deposits. These observations support the

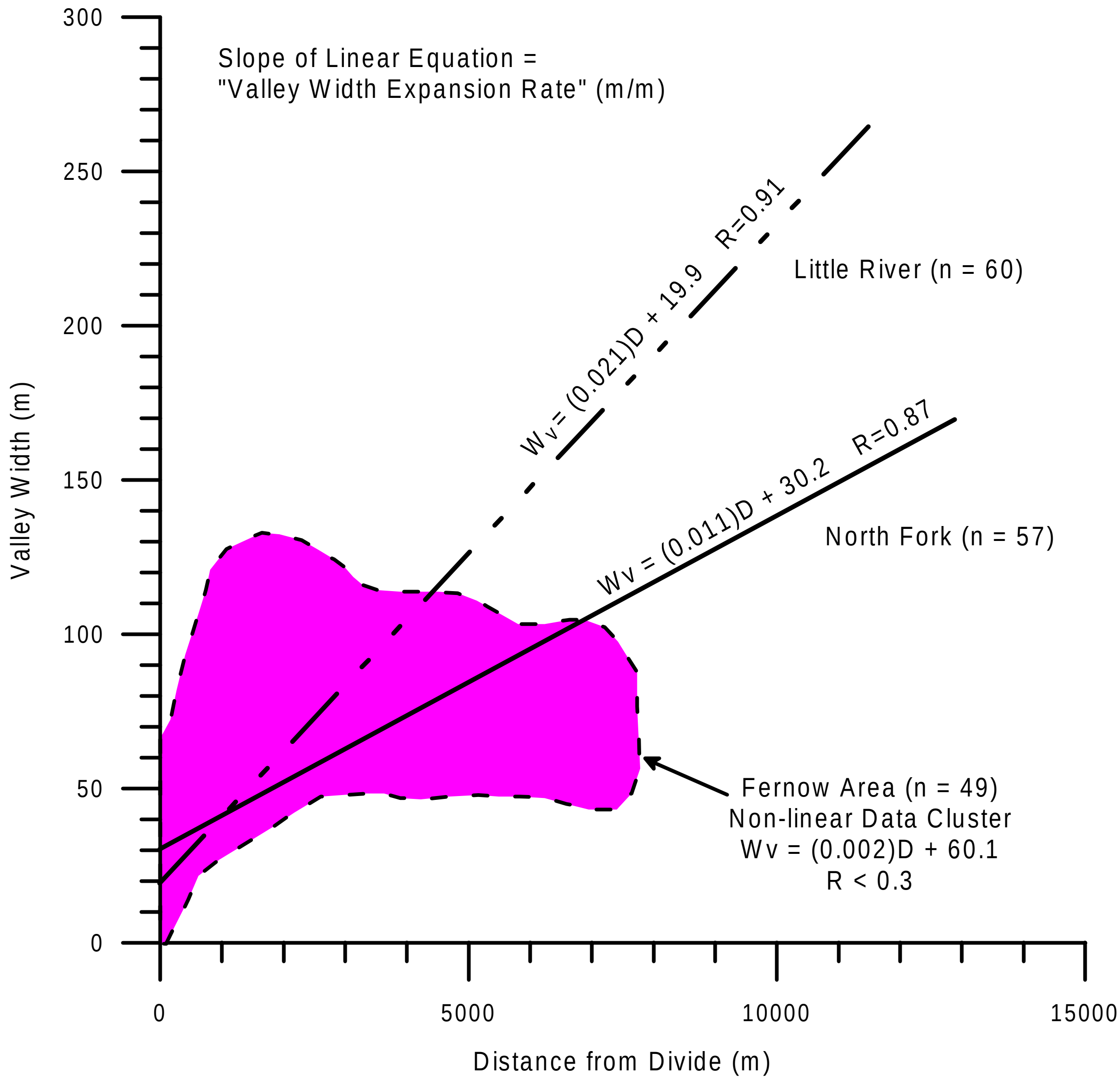


Figure 6-13. Linear regression summary from scatter plot of longest channel distance from divide (m) vs. valley width (m). Note the constricted valley width trend at the Fernow area and the relatively high rate of valley-width expansion at Little River.

contention that valley width and tributary-junction frequency are the primary factors controlling debris-fan accommodation. The optimum conditions for fan preservation include:

1. high drainage density,
2. high tributary junction frequency,
3. steep low-order channels,
4. high valley-width expansion rates,
5. wide high-order channels, and
6. steep, colluvial hillslopes prone to debris flow.

The critical valley-width thresholds necessary for fan preservation are assessed by a log-log plot of fan area versus valley width (Figure 6-14). The plot reveals that, for fan areas greater than 100 m^2, the threshold envelope of fan preservation is described by the power function:

(Equation 2) $$A_f=1.8W_v^{1.57}$$

where A_f is fan area (km^2) and W_v is valley width (km). The threshold equation defines a line, above which valleys are too narrow and constricted to allow fan preservation. This relation defines the minimum valley width required to provide storage space for a fan of a given size. The data distribution also suggests that large fans require wide valleys, but small fans may occur in both narrow and wide valleys. Thus, valley width does not necessarily dictate fan size, just the accommodation space necessary for preservation.

Valley-width morphometry also controls the power-function relation between fan area and drainage area. Figure 6-15 illustrates a plot of exponent "n", from Equation 1 above, versus maximum valley width and valley-width expansion rate. Although the sample population is limited to the three study areas, the graphs illustrate a strong, positive linear relationship between exponent n and valley-width morphometry ($R = 0.99$). Following Kochel's (1990) interpretation that higher n values signify less constriction of fan growth, the data suggest that wider valleys promote stronger morphometric correlation between fan area and source drainage area in the central Appalachians.

Influence of Bedrock Geology

Bull (1964) discussed the effects of source area lithology on fan area. He found that, for a given drainage area, fans derived from less resistant bedrock terrain are larger than fans derived

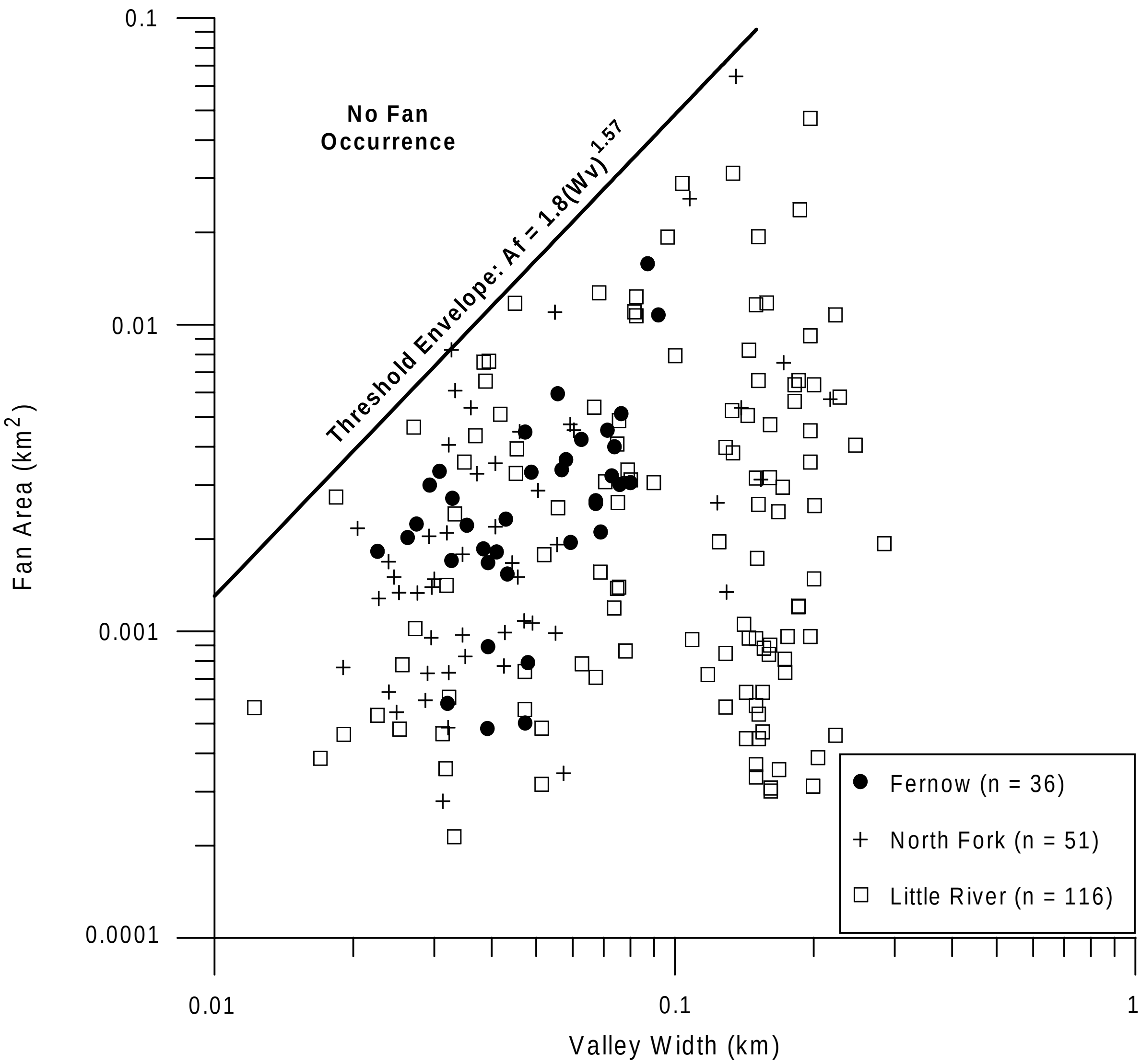
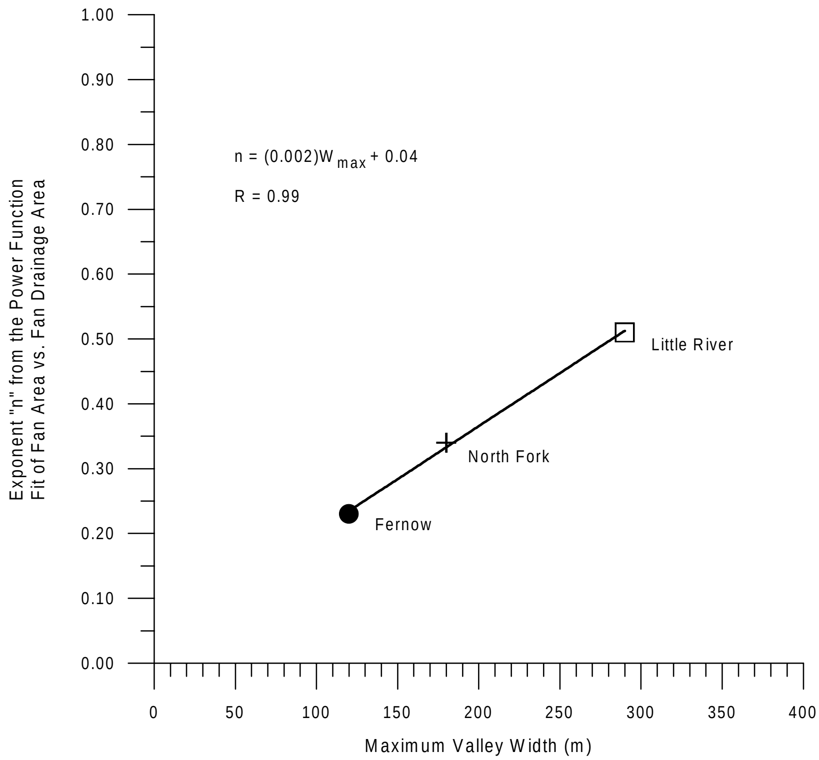


Figure 6-14. Log-log plot of valley width (km) vs. fan area (km^2) for the Fernow, North Fork and Little River areas. The threshold envelope suggests that for a given fan area greater than 0.001 km^2, there is a critical valley width, below which, fans are not preserved.



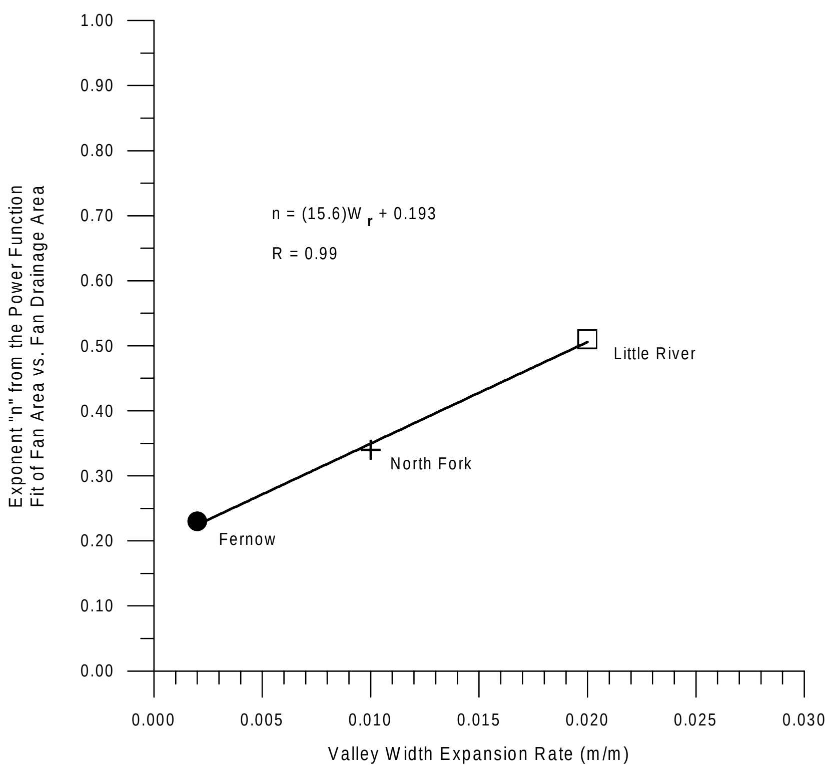


Figure 6-15. Plots of exponent "n" from the relation $A_f = c(A_d)^n$ vs. maximum valley width (m) and valley-width expansion rate (m/m), respectively. Exponent "n" values are derived from Figure 6-12. The plots suggest that valley width is the primary factor controlling growth of debris fans.

from more resistant lithology. This relation suggests that more easily eroded bedrock will yield a greater volume of sediment to fan storage compartments. Similar bedrock controls on fan morphometry are evident in the central Appalachians. Figure 6-16 is a comparison of fan area-drainage area data for debris fans in the Appalachian Plateau, Valley and Ridge, and Blue Ridge provinces. For a given drainage area (> 0.1 km^2), Blue Ridge fans are notably larger than those in the Appalachian Plateau and Valley and Ridge. Exponent n values from Equation 1 are 0.59 and 0.44, with correlation coefficients of 0.70 and 0.62, respectively. The data suggest that Blue Ridge crystalline rocks are associated with landscapes that provide greater fan accommodation and promote larger fan sizes. Sandstone lithofacies relationships in the upper Devonian Acadian clastic wedge are interpreted as the primary factor controlling differences in gross watershed morphology between the Fernow, North Fork, and Little River study areas (Taylor, Chapter 7, this volume).

FAN ACCOMMODATION MODEL

The relationships derived from this study, combined with previous work, permit development of a model for three styles of Appalachian fan accommodation (Figure 6-17). In increasing order of accommodation, these modes include: (1) valley erosion (at tributary junctions), (2) pediment erosion, and (3) piedmont-karst solution. The most ubiquitous form of fan accommodation is that of the valley erosion (tributary junction) type (Figure 6-17a). Accommodation space is controlled by drainage density and valley-width morphometry. The valley-erosion mode is prevalent throughout much of the Appalachian Plateau, Valley and Ridge, and Blue Ridge. The pediment-erosion process involves beveling of footslopes along retreating mountain fronts (Figure 6-17b). Mountain-front retreat provides a gently sloping surface that accumulates debris-flow deposits with time. Crystalline bedrock terrain of western North Carolina best exemplifies the piedmont-erosion model. Piedmont-karst solution processes are restricted in occurrence to the west flank of the Virginia Blue Ridge where Paleozoic carbonates are in contact with metamorphic lithologies (Figure 6-17c). The three modes of fan accommodation are driven entirely by landscape erosion, and contrast markedly with fault-controlled accommodation mechanisms in the southwestern U.S. (Figure 6-17d). Thus, fan accommodation in the humid Appalachians results from long-term intra-montane valley erosion,

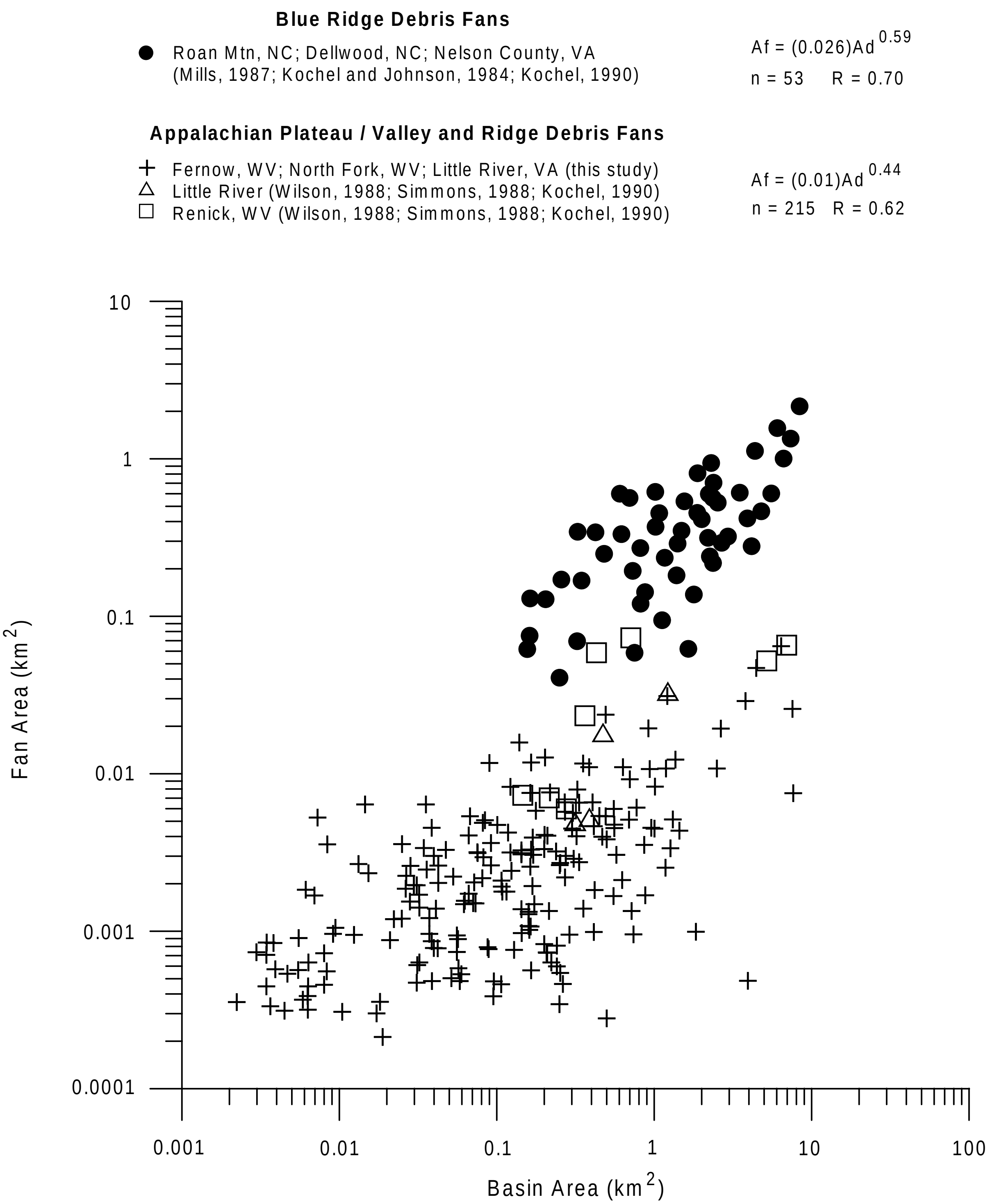


Figure 6-16. Comparison of fan area - drainage area relationships between crystalline bedrock landscapes of the Blue Ridge and sandstone terrain of the Appalachian Plateau and Valley and Ridge. Note larger fan sizes in the Blue Ridge, see text for discussion (after Kochel, 1990).

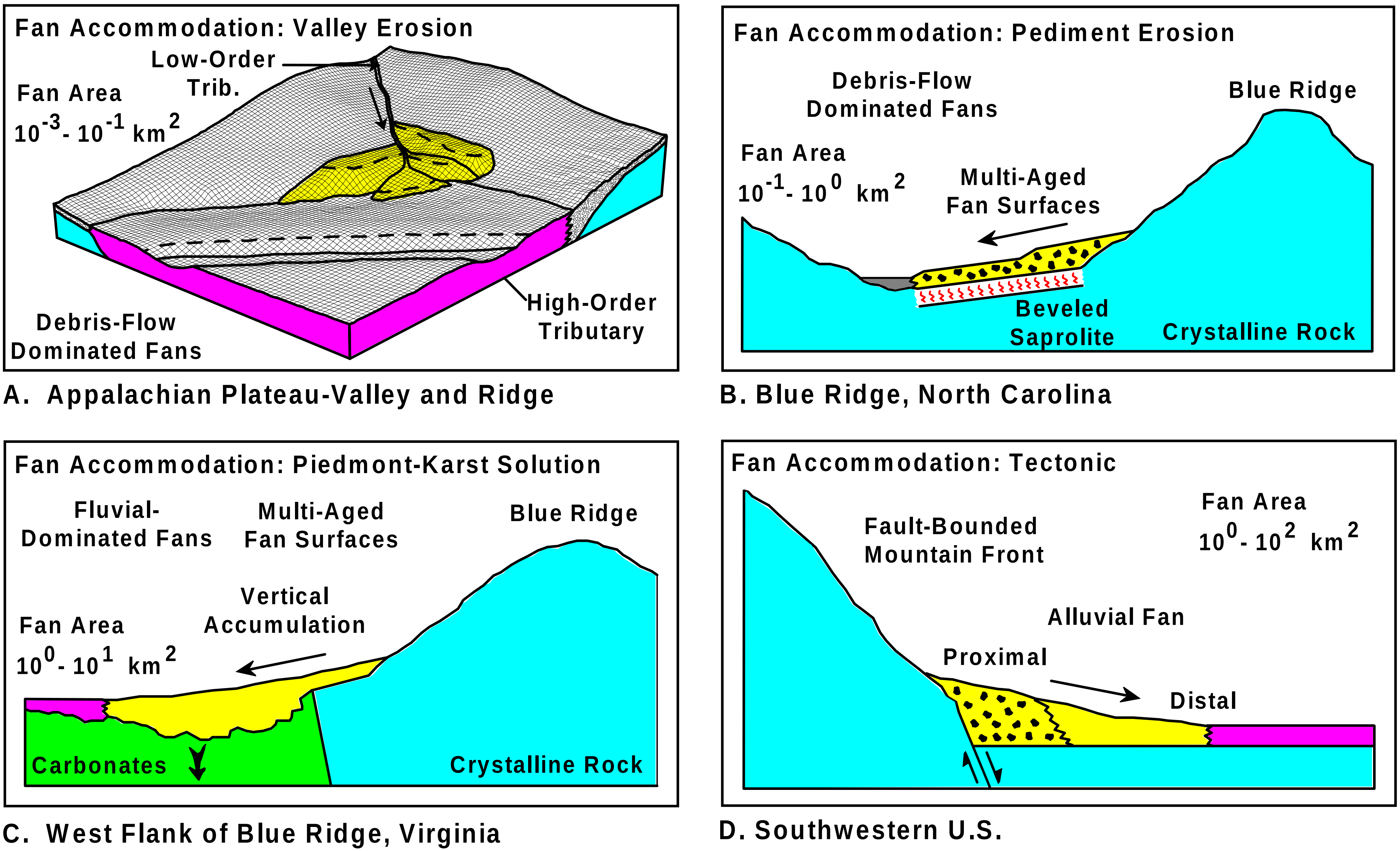


Figure 6-17. Diagrammatic illustration of the modes of fan accommodation recognized in this study (not to scale). Fan accommodation diagrams are arranged in increasing order of magnitude. Southwestern U.S. fans modeled after summary discussions provided by Ritter and others (1995) and Blair and McPherson (1994). Diagrams B and C for the Blue Ridge are derived from Kochel (1990), Whittecar and Duffy (1992), Mills (1983) and Mills and Allison (1995a,b,c).

rather than tectonic relief. Given that regional Appalachian erosion rates are estimated at 0.04 mm yr^{-1} (Hack, 1980), the only tectonic requirement is that isostasy provide altitude sufficient to maintain active erosion processes over time spans of 10^6 to 10^7 years.

Greater fan-accommodation space should increase residence time of deposits on the landscape. Consequently, as accommodation space increases from intra-montane valley erosion to pediment erosion to piedmont-karst solution; the ages of fan deposits are expected to increase accordingly. Following this line of reasoning, some of the oldest fan deposits in the Appalachian landscape should be located along the Blue Ridge in central Virginia and western North Carolina. This concept is favorably supported by the chronosequence work of Mills (1982), Kochel (1987), Whittecar and Duffy (1992), and Mills and Allison (1995 a,b,c). With respect to age relationships at the areas included in this study, the lack of well-developed paleosols suggests that valley-bottom sediments are removed from storage on time scales of 10^3 to 10^4 years. Kochel (1990) noted that 1949 debris-flow deposits at the Little River were unaffected by record discharges in the 1985 flood event. Many fans are armored with coarse bouldery debris that will likely remain in storage until comminuted by weathering. This observation, coupled with the high number of compound fans and terraces, suggests that valley-bottom deposits at the Little River are older than those at the Fernow or North Fork. This hypothesis remains to be tested with relative and numerical age-dating techniques.

SUMMARY AND CONCLUSION

Comparative geomorphic analyses at three central Appalachian watersheds yield results that are useful in deciphering local controls on fan preservation. Three modes of fan accommodation are recognized: (1) valley erosion (at tributary junctions), (2) pediment erosion, and (3) piedmont-karst solution. The three modes of fan accommodation are driven by intra-montane erosion, and contrast markedly with fault-controlled tectonic mechanisms in the southwestern United States.

In the valley erosion model, debris fans are most commonly preserved at tributary junctions of low-order and high-order channels. The optimum conditions for fan preservation include: (1) high drainage density, (2) high tributary junction frequency, (3) high valley-width expansion rates, (4) steep low-order channels, (5) wide high-order channels, and (6) steep, colluvial hillslopes prone to debris flow. Sandstone lithofacies relationships play a significant role in controlling gross watershed morphology.

An important climate and debris-flow record is most certainly preserved in central Appalachian debris fans. Fan-accommodation mechanisms outlined in this study provide an important research model for locating watersheds with high fan-preservation potential. Excavation, drilling, and numerical dating techniques will be required to decipher this record.

DOCUMENT LINKS: Contents Chapter 1 Chapter 2 Chapter 3
Chapter 4 Chapter 5 Chapter 6 Chapter 7 Chapter 8 References Cited