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Boulder Streams, Debris Fans, and Pleistocene Climate Change in the Blue Ridge Mountains of Central Virginia[1]

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ABSTRACT

The west slope of the Blue Ridge mountains in central Virginia is a polygenetic landscape containing interglacial and periglacial features. This paper proposes a general model relating the distribution and origin of hillslope and toeslope Quaternary landforms to climatically influenced geomorphic processes. Two generations of interglacial debris fans in the study area differ in their degree of soil development and clast weathering. Boulder streams, which clog debris flow chutes for the upper debris fans, are interpreted as solifluction features formed during successive periglacial episodes. Growth of the boulder streams and associated talus slopes can influence the magnitude and frequency of debris flows and fan formation during interglacials.

Introduction

Many recent geomorphic studies in the Appalachians south of the glacial border demonstrate the influence that climate has had on changes in landscape processes. Features used as evidence for periglacial processes operating in this area during cold episodes of the Quaternary, reviewed by Clark and Ciolkosz (1988), include frost-shattered soils and rocks (e.g., Lietzke and McGuire 1987), patterned ground (e.g., Clark 1968), solifluction lobes (e.g., Delcourt and Delcourt 1985), and some colluvial deposits (e.g., Eargle 1977) and boulder streams (e.g., Mills 1988; Shafer 1988). In the southern and central Appalachians, analyses of Quaternary vegetation (Delcourt and Delcourt 1981) and radiocarbon dates from the bases of Holocene debris flows, suggest that debris fans formed due to catastrophic rainfall events principally during interglacial episodes (Kochel 1987) or perhaps during the lateglacial-interglacial transition (Delcourt 1980; Mills 1986).

In this paper we analyze an area where the development of periglacial landforms (boulder streams) influenced the growth and history of interglacial landforms (debris fans of multiple ages). Because boulder streams and debris fans are common features throughout the unglaciated Appalachian highlands, their presence within the same drainage system may provide valuable clues about both the history of Quaternary climate changes and the hazards of debris avalanche in this region.

Site Description

The study area is located 20 km south of Waynesboro, Virginia between Back Creek and the Blue Ridge divide (figure 1). This site is representative of geomorphic settings present along many stretches of the western flank of the Blue Ridge in the central Appalachians. Greenstone and metasedimentary rocks of the Catoctin and Harpers formations underlie the hillslopes; bedrock shear planes and bedding dip 40°–50° to the southeast (Bartholomew 1977). Northwest-facing hillslopes descend from as high as 1160 m elevation to <500 m in approximately 1.7 km. Although footslopes and ridge crests have been cleared for agriculture at various times in the past, all of the area except for the valley floor is currently covered by deciduous forest.

Methods

Landform boundaries (figure 2) initially delineated on aerial photography were field-checked. Surficial materials associated with each landform type were

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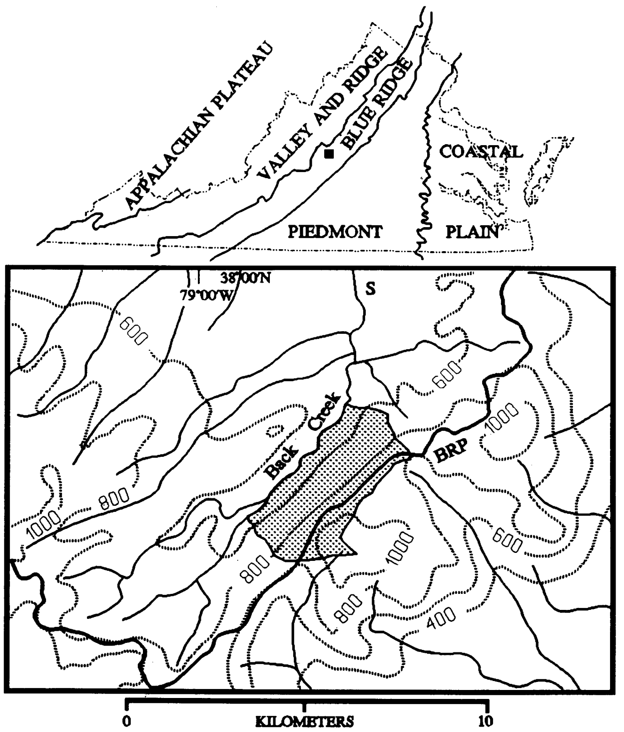

Figure 1. Location of study area (shaded) in relation to physiographic provinces. Elevation contours in meters. S: village of Sherando. BRP: Blue Ridge Parkway.

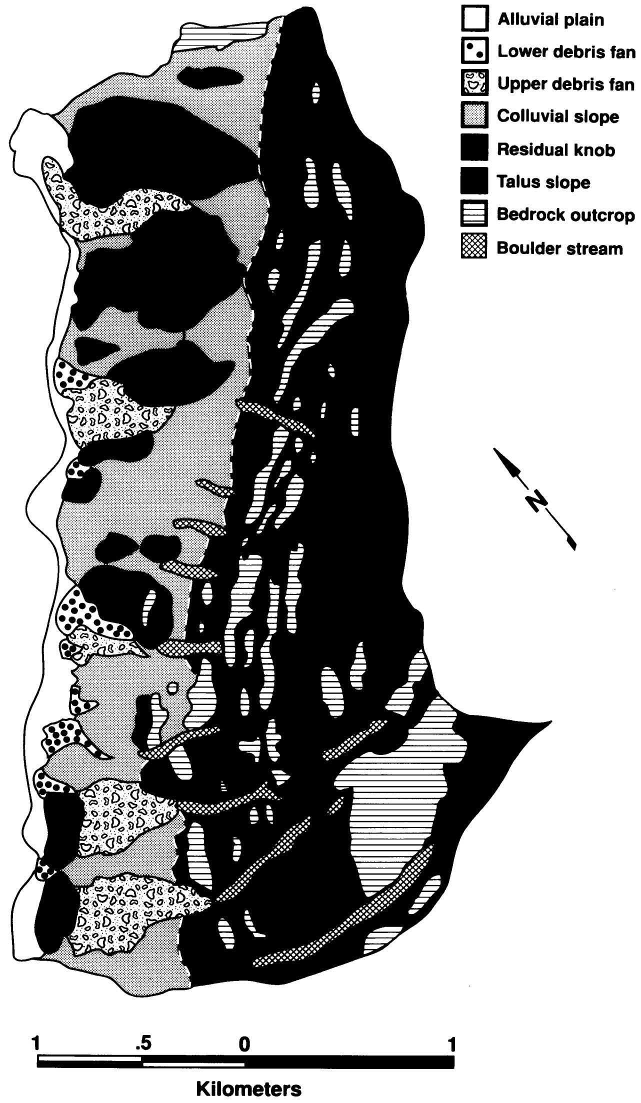

Figure 2. Map of landforms in study area.

described in stream bank exposures and shallow excavations.

Cross-sectional profiles of four boulder streams were surveyed along stretches where the width, relief, and slope gradient are relatively consistent. On these profiles, we estimated the largest probable thickness of a boulder stream deposit (H_{MAX}) as the depth from the peak of convexity to the lowest point of the underlying valley floor, determined by projection of the valley walls beneath the boulder stream.

Boulder stream fabric, defined by AB planes of tabular clasts, was measured within 3 m radius sample areas at 10 sites located on four boulder streams. Poles to planes were plotted and contoured on a stereonet to determine orientation and strength of fabric (figure 3).

Debris fan surfaces and materials were analyzed at eight sites, selected randomly from all fans present in the area, for Munsell hue, clay percentage, and iron content of debris matrix in Bt horizons, and clast weathering rind thickness in the upper 1 m of sediment. Sampling sites were chosen near the crest of the convex surfaces, where presumably the least amount of erosion has taken place since deposition. Iron content of debris matrix was determined using a sodium dithionite extraction method for all free iron (Jackson et al. 1986). The clay content determined represents the percentage clay of the <2 mm fraction of the debris matrix (Gee and Bauder 1986).

Landforms in Study Area

Talus Slopes, Colluvial Slopes, and Residual Knobs. Talus slopes consist of very coarse (average >30 cm diameter), highly angular boulders and cobbles produced by physical weathering of fractured greenstone and metaconglomerate outcrops. The mature forest cover with undisturbed trees and the steep, uniform slopes formed of tightly

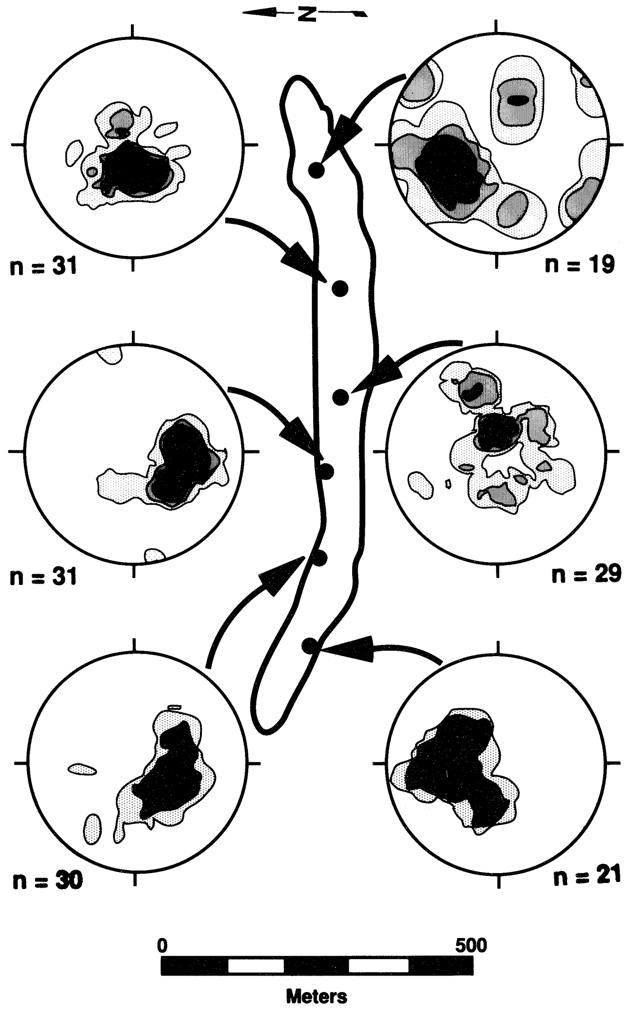

Figure 3. Fabric of tabular boulders (poles to AB planes) along the most southerly boulder stream in field area (see figure 2). Stereonets are rotated so that downslope is towards bottom of page. Values are percentage for total data set: Black = >20%; dark gray = 15–20%; light grey = 10–15%; pattern = 5–10%. N for site is listed below stereonet.

wedged clasts indicate little or no recent talus movement.

Talus grades downslope into matrix-supported colluvium (>1 m thick) that blankets lower slopes of the ridge and many low-order drainage basins. The position of colluvium in the hillslope system suggests that it is mainly a product of talus formation and weathering, with some subsequent transportation. Numerous hillslope hollows store thick colluvium. Small hilltops underlain by residuum and thin colluvium (<1 m thick) are present along the lower flank of the ridge.

Patterned ground and solifluction lobes were not observed on hillslopes in the study area; if originally present they may have been obscured by tree throw or by erosion, farming, or other anthropogenic disturbances.

Boulder Streams. Boulder streams in the study area are composed of a mix of both tabular and blocky clasts that range from 20 cm to 3 m in diameter. No matrix is observable at the surface of the deposits. Located in low-order drainages between the zone of greatest hillside convexity and lower slopes where debris fans have formed, these features are typically between 20 m and 30 m wide and 200 m to 1000 m long. In upper reaches where many outcrops of bedrock cross the valley bottom, boulder stream slopes usually decrease above the outcrop and increase below. At their upper ends, boulder streams commonly grade into talus and increase in width. Small boulder streams may meet at valley junctions to form larger boulder streams. Notably, no head scarps or erosional chutes were present upslope from any boulder streams in the study area. Boulder stream surfaces are chaotic and display no compression ridges or swales.

Where best-developed, boulder streams in the study area have convex cross-sectional profiles with relief of as much as 2 m. Estimated thicknesses are as great as 6.1 m; at the sites profiled, surface slopes are 17°–19° (table 1). These estimates are similar to estimated thicknesses of other boulder streams in Virginia (e.g., Mills 1988).

Boulder stream snouts are rarely well defined and usually appear as a down-valley gradation, ≥10 m wide, from a broad and continuous mound of angular boulders to elongate, discontinuous patches of bouldery alluvium. The end of one boulder stream extends downslope onto the apex of a debris fan.

Tabular boulders on these boulder stream surfaces commonly exhibit a strong fabric with AB planes inclined upslope at shallow dips. This imbrication can be difficult to recognize visually in the field, due to the numerous blocky boulders present. Stereonets from six sites scattered along

Table 1. Values of boulder stream morphometric parameters and basal shear stress

Site	H_{MAX} (m)	Width (m)	Slope (α) (deg)	τ_{yz} (bars)
1	6.1	31.0	18.8	.4
2	3.7	21.7	18.2	.2
3	2.5	42.0	17.1	.2
4	3.4	25.0	18.2	.3

Note. $\tau_{yz} = \rho g H_{MAX} \sin\alpha$ where $\rho_{(est)} = 1.8$ g/cm^3 (Warhaftig and Cox 1959).

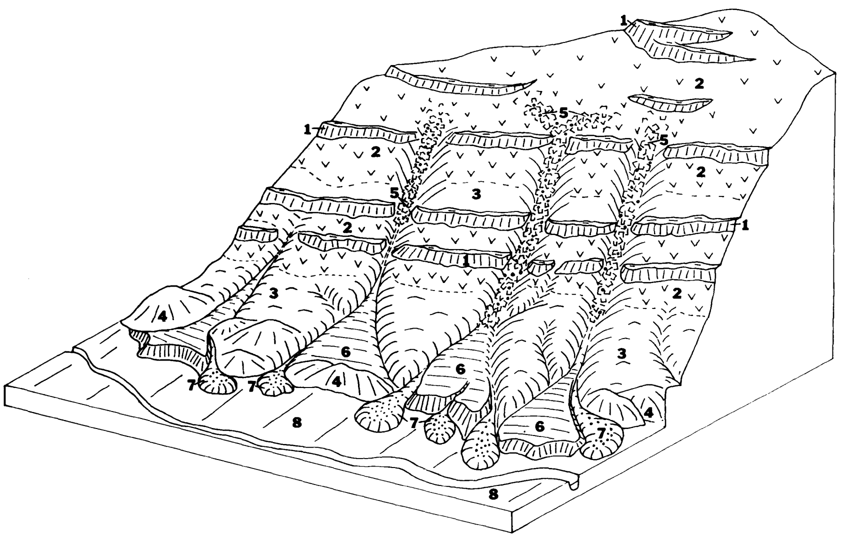

Figure 4. Diagrammatic sketch showing position of landforms common in the portion of the central Viginia Blue Ridge examined in this study. 1: bedrock outcrops; 2: talus slopes; 3: colluvial slopes; 4: residual knobs; 5: boulder streams; 6: upper debris fans; 7: lower debris fans; and 8: floodplain with channel. See figure 2 for map of landforms.

one boulder stream (figure 3) illustrate the range of fabric strength and orientation present across most of the boulder stream surfaces measured in the study area. Although not illustrated on figure 3, clusters of on-edge tabular boulders and cobbles are common along the higher-elevation portions of many of the boulder streams.

Debris Fans. Debris fans in the study area consist of subangular pebbles, cobbles, and boulders up to 3 m in diameter supported by a silty-to-sandy matrix. All of the grain sizes (boulders-to-clay) and clast lithologies observed on fan surfaces and in excavations apparently were reworked from talus and colluvial deposits upslope.

Two groups of debris fans exist in this area. Fans within each group have very similar topographic positions, amounts of erosion along their sides and toes, and degrees of soil development. "Upper" debris fans, the highest and largest in the study area, carpet footslopes at the mouths of the largest valleys tributary to Back Creek (figures 2 and 4). Surfaces on these fans are broadly convex in cross-section, commonly slope downhill 10° to 18° (table 2), and only occasionally are dissected by small valleys. Upper fans near the modern floodplain of Back Creek often have very steep-sided, concave meander scars eroded into their toes. "Lower" debris fans display convex toes and upper surfaces and

Table 2. Data from soil profiles and surface slopes on debris fans and analysis of variance (upper fans vs. lower fans)

Site	Max. Clay (%)	Max. Fe (mg/g)	Aver. Rind Width[b] (mm)	Min. Hue (YR)	Slope (deg)
Upper Fans					
1	32	2.10	6	5	10.8
2	33	1.97	10	2.5	17.2
3	40	2.01	8	2.5	17.7
4	42	2.87	12	2.5	15.1
Mean	37	2.24	9.0	3.1	15.2
s.d.	4.3	.37	2.2	1.1	2.7
Lower Fans					
1	25	1.78	4	7.5	10.8
2	22	1.49	6	5	14.5
3	26	1.57	3	5	15.1
4	23	1.57	4	5	15.1
Mean	24	1.60	4.3	5.6	14.7
s.d.	1.6	.11	1.1	1.1	2.7
ANOVA					
$F_{\text{CALCULATED}}$	22.9[a]	8.0[a]	11.0[a]	8.0	.5

[a] Difference between upper and lower fans significant at 95% confidence level.
[b] $n = 30$.

overlap the floodplain of Back Creek. Surface slope angles on lower fans (10° to 15°) are very similar to those measured on upper fans (table 2), but the lower fans are not dissected by valleys.

Steep-sided small valleys line the edges of most upper fans (figure 4). These valleys can extend uphill to the apex of each upper fan where some merge with the larger valley that descends to the fan. Because these small valleys lead downhill to the apexes of the lower fans, they appear to be the source of debris present on the lower fans. Thus the valleys probably were incised both by relatively frequent channel erosion and by infrequent debris flows that originated along the margins of the upper fans and, in some cases, farther uphill.

Hockman et al. (1977) mapped all soils on these fans as Typic Hapludults and did not differentiate fan surfaces. However the color and distribution of clay and iron in the soil profiles (table 2) differ markedly between the two groups of fans (Ryter 1989). Prominent argillic horizons in upper fan soils have consistently higher percentages of total soil clay, which often increase between 30 to 100 cm depth and peak between 32–40%. Lower fan soils show only a slight increase of subsoil clay with maximum values of 22–26%. Both total and peak soil iron concentrations also display similar patterns; upper fan soils may have up to 2.0–2.9 mg/g but lower soils have 1.5–1.8 mg/g. Redder colors of the upper fan soils, typically 2.5YR versus 7.5YR, also reflect these differences. ANOVA results (following Davis 1986) indicate that the soil profiles analyzed formed on two different populations of fan surfaces (table 2).

Weathered greenstone clasts in the upper 1 m of lower fans are very competent and resistant to breakage, while greenstone cobbles in the upper 1 m of upper fans can be easily broken or even dissected with a shovel during excavation. Average weathering rind thicknesses are 9.0 mm on upper fan greenstone clasts, but only 4.3 mm on lower fan clasts (table 2).

Interpretation of Geomorphic Processes

We considered four possible processes of formation for boulder streams in the study area: (1) rock glacier flow, (2) simple gravity processes, (3) periglacial influence, and (4) debris flow activity. Using analyses developed by Warhaftig and Cox (1959), Ryter (1989) determined that Blue Ridge boulder streams are too thin to have been rock glaciers moved by viscous flow. Even though their slopes are seldom steeper, active rock glaciers are commonly much thicker (50–100 m) and generate basal shear stresses an order of magnitude greater than those on these boulder streams (table 1) (Warhaftig and Cox 1959). Based on the criteria developed by Mills (1988), simple gravity processes (toppling; rolling) were also eliminated; instead, the slope angles of the stable, interlocked surfaces of the boulder streams in our study area indicate that they were formed by either periglacial or debris flow processes.

Although the pattern of the short-axis tabular boulder fabric we measured is common to both solifluction and debris flow deposits (Mills 1988), the many small patches of clasts with nearly vertical fabric along the upper reaches of several boulder streams indicate frost heave processes and a solifluction origin (e.g., Shafer 1988). Variations in the strength and direction of the short-axis fabrics may reflect many factors, including undulations in the underlying bedrock surface; gravity effects along the sides of boulder streams with strongly convex cross-sections; shearing between portions of a boulder stream creeping downslope at different rates; and a transition from higher to lower elevations in the number and intensity of freeze-thaw cycles.

Slope angles and texture of boulder streams in the study area (17°–19°) (table 1) are similar to bouldery debris flow deposits reported elsewhere in the Appalachians (e.g., Hack and Goodlett 1960; Williams and Guy 1973). However, several landforms diagnostic of debris flows are not associated with the boulder streams in the study area. Instead of having an erosional chute and head scar typical of debris avalanche sites (Clark 1987), study area boulder streams widen at their tops and grade into broad talus slopes lying immediately downhill of cliffs or mantling hillcrests. Continuous for hundreds of meters, usually convex in cross-profile, and relatively uniform in thickness, these boulder stream deposits do not resemble most debris deposits, which usually are discontinuous and may exhibit levees, berms, or accumulations upstream of obstructions (e.g., Hack and Goodlett 1960; Kite and Linton 1987). From these analyses and the similarities in morphology and sedimentology of these deposits to other boulder streams ascribed to periglacial processes (e.g., Michalek 1968; Godfrey 1975; Mills 1988; Shafer 1988), we conclude that the boulder streams in the study area resulted from solifluction and related processes of creep during episodes of periglaciation.

Debris fans in the study area are very similar in sedimentology and morpholology to those found in Nelson County, Virginia, which were either built or enlarged in 1969 during the Hurricane Camille catastrophic rainfall (Williams and Guy 1973; Kochel and Johnson 1984). Such fans form over many thousands of years due to multiple slope failures and debris flows during high-magnitude, low-frequency events, principally caused in this area by storms associated with tropical air masses (Clark 1987; Kochel 1987). Soil development on fans and lack of erosional scars in hillslope hollows suggests that neither the Camille precipitation, centered approximately 10 km to the south, nor any other historical storm generated significant effects in the study area (also see Gryta and Bartholomew 1989).

No stratigraphic or morphologic evidence exists to suggest that relatively fine-grained, matrix-supported colluvium moved onto fans in the study area via solifluction lobes. Thus we infer that debris fans are primarily humid-temperate features formed during or after lateglacial-interglacial transitions when the retreat of polar air masses during the summer permitted an uninterrupted flow of tropical air into the area (Delcourt 1980; Delcourt and Delcourt 1981; Kochel 1987).

Timing of Geomorphic Processes

The dominant hillslope processes in the study area can be related to climatic conditions common during the Late Pleistocene in the central and southern Appalachians (e.g., Watts 1983). During periglacial episodes, frost shatter, solifluction, and accelerated creep would create a large amount of talus and form boulder streams. Boulder streams in the study area were probably reactivated during the Late Wisconsinan, but could have moved during many of the previous glacial maxima. Humid-temperate interglacial conditions induce chemical weathering of talus and colluvium, accumulation of colluvium in hillside hollows, more frequent catastrophic rainfall events, and the subsequent formation of debris fans.

Geomorphic and pedologic distinctions between the upper and lower fans indicate the fan surfaces have notably different ages. The upper fans could be considered older simply on the basis of their more dissected surfaces and toes. Comparisons of soil profile and clast weathering characteristics permit order-of-magnitude estimates of the ages of geomorphic surfaces. The degree of argillic soil development and clast weathering present on the upper fans resembles that commonly present on glacial or interglacial deposits at least 10^5 years old but perhaps $<10^6$ years old (e.g., Follmer 1982; Levine and Ciolkosz 1983; Markewich et al. 1987). Upper fans that have boulder streams clogging the debris chutes uphill of the fans or overlapping their apexes certainly predate the Late Wisconsinan glacial, the latest probable period of boulder stream growth. Thus we estimate the age of the upper fan surfaces to be approximately 10^5 years old ("Sangamon" interglacial) or older. Based on their weak argillic soils, their lobate and relatively uneroded shapes, and their highly competent clasts, the most probable age of the lower fan surfaces is Holocene (no older than approximately 10^4 years).

Discussion

This research provides a general model of the distribution and origin of landforms on hillslopes in the Blue Ridge mountains south of the glacial border. Elements of this model may change significantly on ridges with a different rock type, soil permeability, or hillslope hydrology. For example, hillslopes on quartzite ridges commonly have relatively large talus slopes and alluvial fans dominated by clast-supported, not matrix-supported, deposits (e.g., Bell 1986; Kochel and Johnson 1984; Duffy and Whittecar 1991). Fan sizes and processes may also be governed by the dimensions of the source drainage basin and the sensitivity of that basin to respond to meterologic events of varying magnitude.

The causes and effects of boulder stream distribution merit further study. Their occurrence may be related to rock type and structure, the form of preexisting topography, the size of talus slopes, and the length and severity of periglacial processes as controlled by altitude and aspect. The presence of boulder streams may also increase the magnitude of catastrophic events necessary to generate hazardous debris flows in a given drainage system. Thick, fine-grained colluvium that accumulates in these steep valleys and hillside hollows can fail during a massive rainfall due to increased pore water pressures (e.g., Williams and Guy 1973). Because boulder stream deposits have a much higher permeability than this colluvium, these coarser sediments would require significantly larger volumes of water for them to move downhill by the same process. Thus boulder streams might be used as indicators of modern hillslope stability in many areas of high relief in the Appalachians.

Existing data can lead to several interpretations of the causes and timing of erosional and depositional events in this study area. Several previous workers have reported toe slope deposits of different ages in the central Blue Ridge and attributed their formation to an episodic supply of sediment, possibly caused by climatic fluctuations (e.g., Mills 1982; Kochel and Johnson 1984; Sherwood et al. 1987; Kochel 1987). In the Back Creek study area, it is possible that the multiple fan surfaces were affected by climate-induced changes in the sediment supplied to Back Creek. In this model the lower fans began to form after Back Creek widened its valley bottom by eroding large volumes from the toes of the upper fans. This excavation steepened the gradient of valleys along the margins of the upper fans and provided the space needed for the lower fans to develop. Earlier, debris flow deposition on the upper fans and into Back Creek may have slowed and stopped while talus slopes and boulder streams, enlarged during successive periglacial episodes, progressively reduced the size of the fans' source areas and clogged the erosional chutes. These changes of sediment size and volume produced in the upper parts of the hillslope system could disrupt a stream's geomorphic equilibrium, which is based upon a given supply of water and sediment (Mackin 1948; Knox 1976); Back Creek may have crossed an intrinsic geomorphic threshold (Schumm 1973) and responded with the erosional event that led to the formation of the lower fans. If this widening of the valley bottom occurred during the latest (Late Wisconsinan) periglacial period, it is possible that considerable time elapsed between cessation of accretion on the upper fan and the beginning of lower fan growth. In this situation the lower fans should consist almost entirely of Holocene sediments.

An alternative hypothesis, however, is that valleys in which debris flows occur were pirated by headward erosion of the valleys incised along the edges of the upper fans. In this version of a piedmont stream-capture mechanism (Rich 1935; Mills 1983), the pirating valleys may have reached the fan apexes before, rather than after, periglacial debris overwhelmed the hillslope system. If so, the lower debris fans may contain considerable pre-Holocene sediments.

Stratigraphic analyses of the debris fans could resolve many questions remaining in this study area; such studies can provide much information about the impact of climate change upon geomorphic processes (e.g., Kochel 1987; Jacobson et al. 1989). Future geomorphic and stratigraphic research of "interglacial" fans throughout the unglaciated Appalachians should reveal the potential of both periglacial and climate-independent processes to influence landscape evolution.

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