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Quartzite terrains, geologic controls, and basin denudation by debris flows: their role in long-term landscape evolution in the central Appalachians

Abstract A large storm in 1995 that impacted the central Blue Ridge Mountains of Virginia triggered over a thousand debris flows, which deeply incised stream channels in zero-, first-, and second-order basins underlain primarily by granite, metabasalt, and quartzite. This event provided an opportunity to gain insight into geologic controls on debris-flow initiation and rates of basin denudation. Intensive investigations in quartzite terrain indicated that well-developed joints provide for rapid infiltration of rainwater and thus affected debris-flow initiation. Possible mechanisms of slope failure include (1) elevated rates of fracture recharge in steep valleys and/or (2) bedrock bedding planes. Fracture recharge may serve to substantially increase rock pore pressure during high intensity rainfall, especially when coupled with antecedent moisture. The quartzite bedrock tends to break into orthogonal blocks due to jointing. Statistical analysis shows the presence of a minimum of two joint populations that serve as bedrock controls on lateral erosion. Resistant bedding planes, parallel to slope, control vertical erosion below a finer-grained layer of saprolite. The combination of increased recharge and joint orientations in quartzite basins are likely the main factors resulting in the highest measured values of basin denudation from debris flows, relative to other lithologies, in the central Appalachians. Additionally, these joint and bedding planes produce a topographic signature at all scales and, therefore, are an important factor controlling long-term landscape evolution.

Keywords Rock control · Debris flow · Quartzite · Denudation · United States of America · Virginia · Rockbridge County

Introduction

In the central Appalachians of Virginia, debris flows are a significant process in transporting sediment from steep, mountainous terrain to low gradient streams. Landscape modification is traditionally quantified by the volume of sediment transported during an event, also known as 'geomorphic work' (Wolman and Miller 1960) or by the ability of an event to affect the shape or form of a landscape, termed 'geomorphic effectiveness' (Wolman and Gerson 1978). Whereas infrequent, large magnitude flooding events appear to contribute only nominally to geomorphic work in low-gradient environments (e.g., Wolman and Miller 1960; Moss and Kochel 1978), researchers report that catastrophic floods and associated debris flows are significant agents in transporting sediment in the mountainous terrain of the Appalachians (e.g., Kochel 1987, 1988; Jacobson et al. 1989; Miller 1990; Eaton et al. 2003). Although the recurrence of debris-flow activity of individual mountain basins is infrequent (every 2200 to 3500 years; Kochel 1987; Eaton and McGeehin 1997), their activity is responsible for approximately half of the long-term denudation in granitic terrain of the Blue Ridge Mountains (Eaton et al. 2003).

Understanding the bedrock controls on basin denudation due to debris flows is important for developing more realistic models of bedrock lowering and for developing geomorphic-transport laws (Dietrich et al. 2003; Stock and Dietrich 2006; DeLong et al. 2007). Roering et al. (2005) demonstrate the importance of bedrock structure and lithology on the topographic signature of deep-seated, large landslides in the Oregon Coast Range. Although these landslide processes are larger in scale when compared to those occurring in the Appalachians, the links among bedrock structure, rock type, and basin denudation are similar.

This research examined the influence of lithology and bedrock structures on basin denudation and landscape evolution in the central Appalachians. Our objectives were to (1) assess the effects of rock type and structural controls on sediment yield from debris flows originating from basins of varying rock type and (2) demonstrate the statistical relationship between the locus of debris-flow initiation and bedrock structures in quartzite terrain.

Regional and geologic setting

The Blue Ridge Mountains is a prominent NE–SW trending range and is the easternmost prominent range in the Appalachian Mountains in Virginia (Fig. 1). In plan view, the Blue Ridge is neither linear nor sinuous but rather is extremely irregular with numerous outlying ridges, promontories and recesses. Streams on the eastern flank have cut deep ravines into the hillsides and drain into narrow, alluvium-floored valleys. Major recesses on the western flank are covered with thick alluvial accumulations of sand and gravel. On both sides of the Blue Ridge, many of the streams empty onto alluvial and debris fans. In the most general way, the eastern flank of the Blue Ridge is underlain by quartzo-feldspathic granitic and gneissic rocks which are part of an extensive Precambrian-age terrain. The majority of summits of the central Blue Ridge are underlain by metabasalts designated as the Catoctin Formation of latest Precambrian age; and the western flank and some summits are underlain by siliciclastic rocks, primarily quartzite of Lower Cambrian age.

The quartzite terrains are of particular interest to this study for two reasons; first, minimal research exists in Virginia on debris-flow denudation in this rock type; and second, a storm in 1995 triggered 53 individual failure events in quartzite terrain along the western margins of the central Blue Ridge. The study area (~50 km^2) is located in eastern Rockbridge County, Virginia (Fig. 1) and is drained by low-order tributaries to the Maury River, which flows into the larger James River near Glasgow, Virginia. The topography of the region is steep, with well-defined low-order tributary networks that converge to make parallel drainage

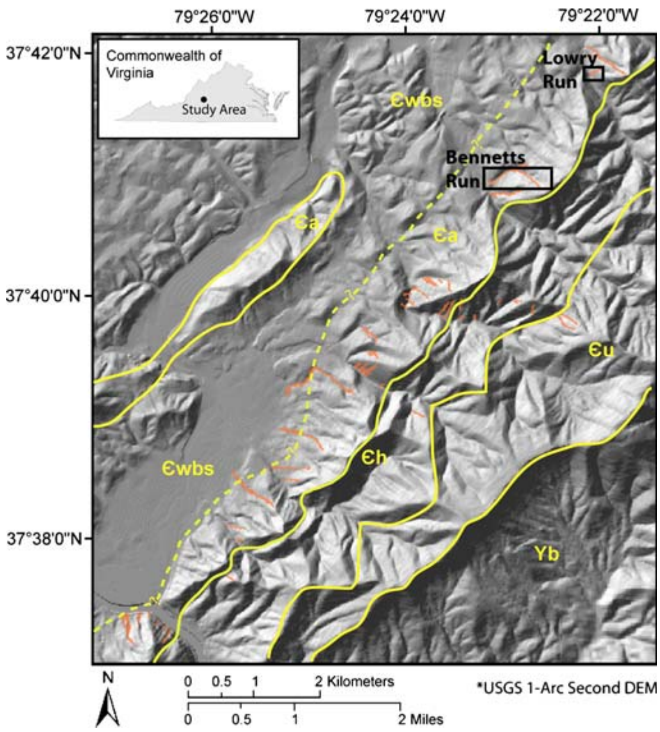

Fig. 1 Hillshade map showing study area in Rockbridge County, Virginia. Debris-flow tracks are indicated by *red areas*. Approximately 40 debris flows initiated in shown region during a NE tracking storm in June 1995. *Ꞓwbs* Waynesboro limestone; *Ꞓa* Antietam quartzite; *Ꞓh* Harpers metasediments; *Ꞓu* Unicoi metasediments; *Yb* Blue Ridge Basement/Charnokite and gneiss. *Black boxes* show locations of debris flows where basin denudation was measured

patterns prior to their confluence with the Maury River. Local relief varies between ~220 and 670 m, and slopes in headwater basins commonly exceed 30°. The area is underlain by conglomerate, siliceous slate, and quartzite formations of the Chilhowee Group (Bloomer 1941; Rader and Evans 1993; Spencer 2000a, b). The Antietam Formation, the uppermost formation of the Group, is a prominent ridge former on the western flank of the Blue Ridge consisting of lenses of clean, white, cross-bedded quartzite and ranges in thickness from 213 to 305 m. The Antietam contains trace fossils throughout much of the formation, the most common of which is Skolithos linearis (worm tube), present in the cleaner quartzite lenses. The alternating quartzite/slate sequences of the Chilhowee rocks result in ledge, hogback, and flat iron ridges. The thicker, more continuous quartzite lenses support the more prominent ridges primarily composed of the Antietam Quartzite. The steeply dipping beds in some locations contribute to the ruggedness of the upland topography. The debris flows studied initiated in zero- and first-order drainages on slopes >28°.

Materials and methods

Debris flows in Rockbridge County were initially documented by stereoscopic aerial photographic interpretation using photos flown after the 1995 storm and by communications with the US Forest Service on debris-flow activity (Tom Collins, personal communication, 2004). These actions narrowed our field examination to 9 of the 53 debris flows in the region. After initial field reconnaissance in 2005, we selected two basins (Bennetts Run and Lowry Run) containing debris flows that were representative of the regional characteristics of run-out length, slope morphology, and areas of erosion/deposition.

The volume of eroded sediment was measured in the two basins. Basin denudation was defined as the total volume of material removed by debris flows divided by the area of the basin. Volume losses were calculated by reconstructing the pre-erosional slopes adjacent to the debris-flow path and measuring a cross-sectional area as described by Shroyer (1997). Cross-sectional depths were measured from a string line spanning across the width of the failure and measuring to the eroded surface at width intervals of 1 m. Measurement of the debris flow in Bennetts Run (Fig. 1) included 16 cross-sections at intervals of 60 m through the thalweg. The smaller flow located on Poplar Cove (Fig. 1) required a total of six cross-sections at 30-m intervals through the thalweg. The volume of material removed was calculated by averaging each value of depth with the upstream value of depth measured laterally across the width of the failure. These averages were then summed and multiplied by the distance between each cross-section. The sum of these values yielded the total volume of material removed by erosion. The basin area was measured from 7.5 minute US Geological Survey topographic quadrangles by using a planimeter. Quantification of soil development, including rubification and solum development, was conducted using methods outlined by Markewich et al. (1989).

The orientation of joints and bedding planes was measured using a Brunton compass. Selection of measured planes depended upon available exposures of bedrock within the debris-flow track. Bedding planes were differentiated from joint surfaces using primary sedimentary structures, such as cross-bedding and trace fossils of Skolithos linearis. Failure direction was delineated using field data and aerial photography, and the direction was determined using geographic information systems (GIS) software.

The Fisher test was used to determine the statistical correlation within the joint data. The Fisher test utilizes the von Mises distribution for spherical directional data (calculated eigenvectors) to determine the significance (within a 95% confidence interval) of variance within the sample (Davis 2002). Essentially, if the initial test for variance results in a critically high value of R/n, then the null hypothesis of a uniform distribution is rejected. R is defined as the magnitude of the resultant vector and n is the sample population. If the total dataset is truly bimodal, then the critical value of R/n can yield a misleading resultant because it is based on the size of the total population. The effects that bimodal distributions have on these types of directional statistics can be alleviated by using an azimuthal doubling method assuming there are no lurking variables (Davis 2002). We employed the azimuthal doubling method to assess the effect bimodality on error of the Fisher test for variance.

After the initial test, a post hoc test of variance is performed on each sample subset to determine the statistical significance of each subset to detect the presence of any misleading results of the initial test for variance. Selection of the sample subset depended upon three-dimensional contouring of the data and visual approximation to include or exclude poles within a subset. Poles were excluded only if their removal from the sample was warranted based on field observations or the quality of the measurement. The three-dimensional contours represent the calculation of a concentration parameter (k). The k value represents the average density of data within a 2% contour interval.

Results and discussion

Influence of bedrock weathering on slope failure

A debris flow is a flow-like slope movement containing colluvium, sand, clay, and organic debris mobilized when regolith is sufficiently saturated (Hungr et al. 2001). The slope failures studied here are best described as debris flows in their general morphology; however, some specific distinctions should be made to clarify the exact nature of failure. Well-defined layers of saprolite are found in upper and middle reaches of the debris path. Resistant bedrock planes are observed at each initiation site (Fig. 2). Between the 1995 debris-flow event and when the study began in 2005 the head escarpment continued to erode, obscuring the full extent of bedrock exposure. However, the depth of saprolite, intact bedrock, and regolith exposure along lateral escarpments suggest that bedrock exposure is relatively continuous at the initiation sites. The presence of saprolite overlying an intact bedrock plane indicates that these slope failures initiate as landslides or debris slides that quickly translate into debris flows. As the initial debris flow continues downslope, bedrock exposure becomes increasingly discontinuous.

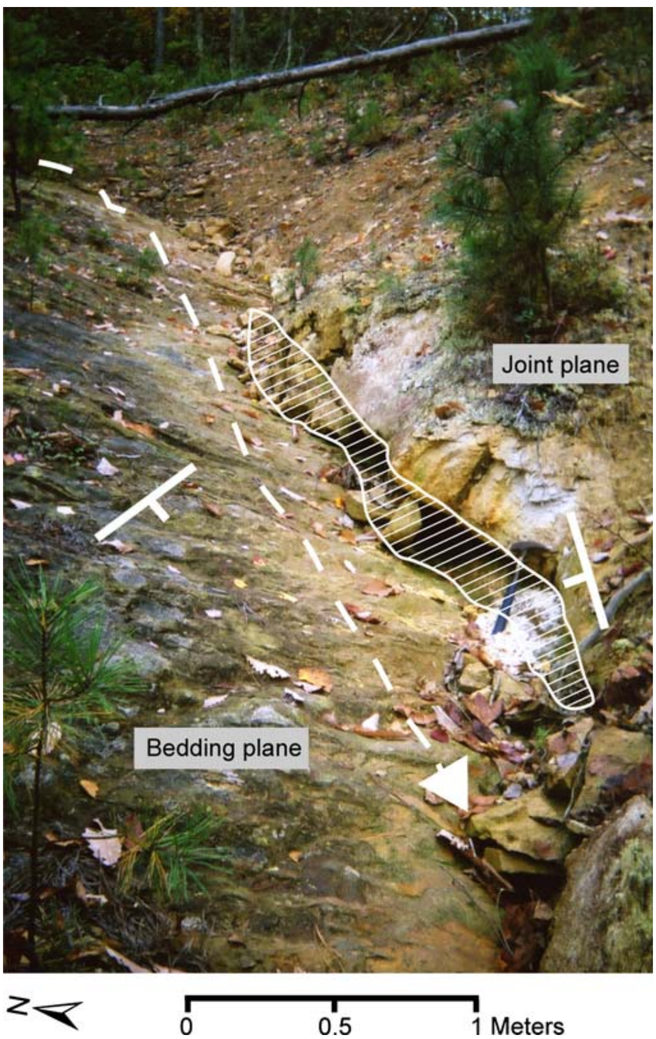

Fig. 2 Initiation site of debris flow demonstrates bedrock structure controls. *Hachured area* indicates eroded layer of saprolite (i.e., the material composing the initial landslide). *Strike/dip symbols* show orientations of high-angle wedge failure planes. *Dashed line* shows debris-flow track

The bedrock exposed at the failure initiation sites possessed sedimentary structures including the trace fossil Skolithos linearis, which are preserved in sediments of uniform grain size. It is likely that this is a stratigraphically continuous unit based on the depth of saprolite developed on top of the resistant failure surface. The authors suggest that the high density of Skolithos in the resistant layer and lack thereof in the saprolite leads to a greater erosional resistance due to decreased pore space and infiltration capacity in the tightly spaced sediments within the wormholes. Furthermore, the trace fossils provide a greater rheologic strength, and the tightly spaced sediments within the wormholes decreases pore space and infiltration capacity.

Comparison of denudation in a quartzite terrain to other lithologies

A comparison of basin denudation values reported for 12 basins in Virginia and West Virginia (from values reported in Eaton et al. 2003) showed that the two basins we investigated, which are underlain by quartzite, have significantly higher values (Fig. 3a).

Previously, the greatest value reported for a clastic basin was in West Virginia, where basin lowering from a debris-flow event was 2.15×10^{-3} m (Cenderelli and Kite 1998). The highest value of basin denudation calculated in Rockbridge County was nearly two orders of magnitude greater, 1.30×10^{-1} m. Patterns of erosion and deposition are similar for both of these basins (Cenderelli and Kite 1998). In the upper two thirds of the debris-flow track, erosion is dominant, and in the lower third, deposition is dominant. Cenderelli and Kite (1998) describe four zones within impacted basins: "an upper failure zone, a middle transport zone, a lower deposition zone, and a scour zone immediately beyond the debris-flow terminus." Additionally, they described the presence of hyperconcentrated-flow deposits in stream channels. Stream channels in Rockbridge County show similar deposits from prehistoric activity, where well-weathered, poorly to moderately imbricated cobbles are supported in a red, clay-rich matrix. Hyperconcentrated stream deposits are likely to have existed in this region directly following the 1995 event; however, their record was not preserved, as much of the material was reworked during subsequent storms in the 10 years leading up to this study.

Sediment yields due to erosion from debris flows occurring in sandstone, siltstone, and shale lithologies in West Virginia range from 3,300 to 20,900 m^3 (Fig. 3b) with respective basin areas of 1.78 and 17.48 km^2 (Table 1). Comparable sediment yields of 2,447 and 25,185 m^3 were measured in Rockbridge County. However, basin areas are smaller, 0.28 and 1.94 km^2, respectively. These relatively small basin areas may provide one explanation for such high calculated values of basin denudation where sediment yields are comparable to other basins. The effects of stream order draining these basins were not assessed in this study. Numerous slope failures from regions outside of Rockbridge County initiated in fourth- or fifth-order drainages, whereas the basins within Rockbridge County initiated in zeroth- and first-order drainages. Despite differences in basin size, geologic processes exist that may enhance erosion and allow for greater basin denudation in basins of relatively small areas. Specifically, the authors suggest that structural controls on failure mechanisms and on lateral and vertical erosion likely explain this phenomenon.

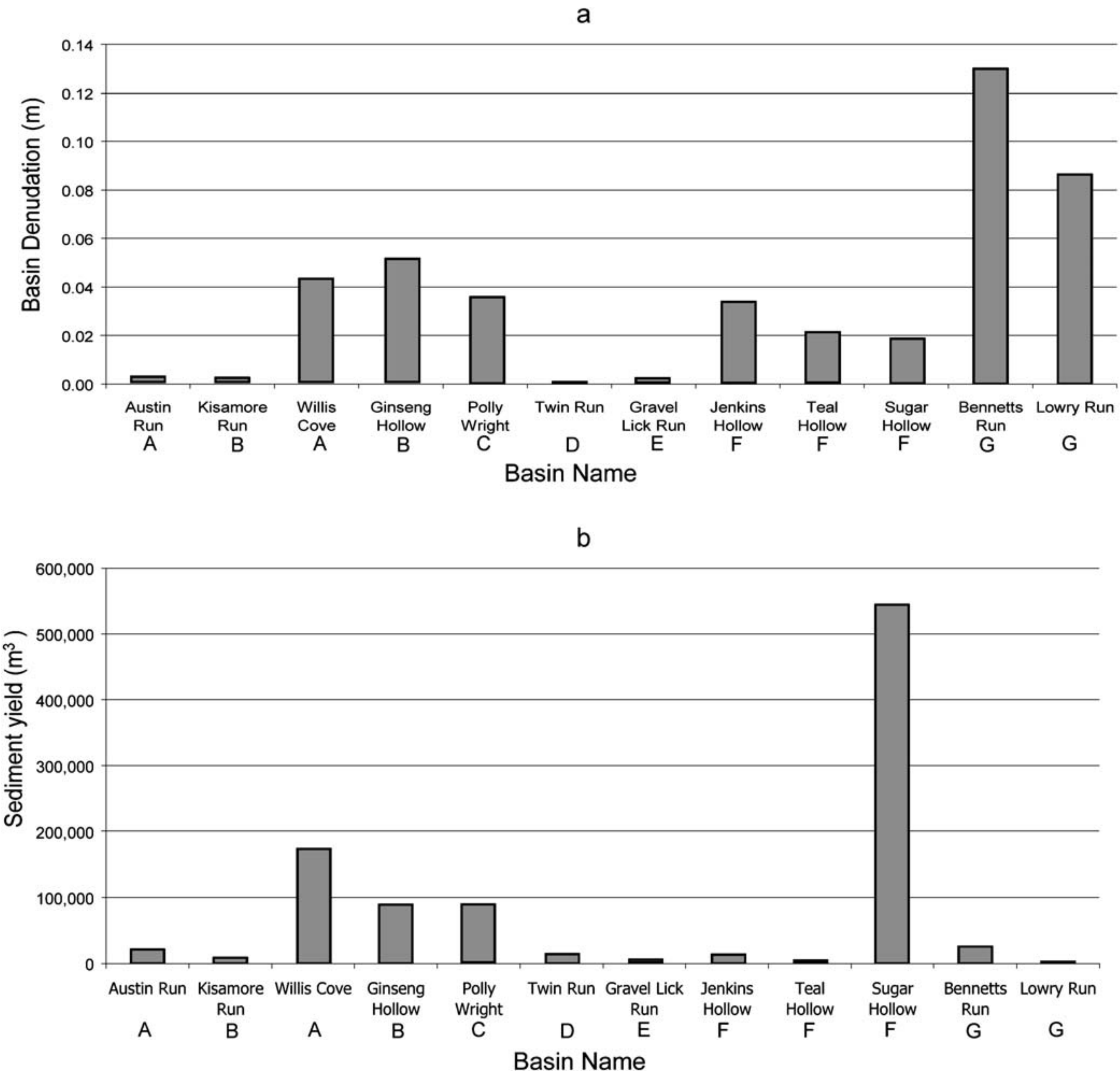

Fig. 3 **a**, **b** Graphs showing basin denudation (**a**) and sediment yield (**b**) compared to basins of various lithologies. The small basin areas of Bennetts Run and Lowry Run may explain why their values of basin denudation are comparably high. However, Bennetts Run has the fifth greatest value of sediment yield of the compared basins. This high volume of sediment removed by debris flow, given a comparably much smaller basin area, is likely explained by structural controls on erosion. *Letters below basin names* refer to rock types: *A* quartz sandstone; *B* siltstone–shale–sandstone; *C* gneissic granodiorite–greenschist dike; *D* orthoquartzite; *E* argillaceous sandstone; *F* gneiss–granite–schists; *G* quartzite

Structural controls

Outcroppings of quartzite were observed at the failure apex, on the lateral escarpments in the upper two thirds of the debris-flow tracks, and in the channel thalweg. Planar bedrock features located at the initiation sites demonstrate that these debris flows begin as landslides or debris slides. Bedrock failure planes were observed in all slope failures but were particularly pronounced in nine debris flows with run-out distances >0.7 km in length. The units acting as failure planes are likely to be stratigraphically correlative across the strike of the mountain belt. Observations of (1) dense sedimentary packing and density of fossil occurrence in failure planes and (2) a lack of these characteristics in overlying units suggest interdependence between sedimentology, weathering, and decoupling of resistant and nonresistant units. Beds overlying the failure plane are saprolitic and are only preserved on lateral escarpments adjacent to initiation sites. The fissile nature of the contact between the slide plane and failure blocks is due to the relative resistance and nonresistance to weathering of the units, assuming no appreciable difference in groundwater characteristics within the ~1 m total thickness of these units. Additionally, 83% of slope failures initiate at 430±30 m in elevation. We suggest that the similarities in the elevations of initiation sites is not only an effect

Table 1 Summary of basin denudation, rainfall and lithology

Event year	Basin	Drainage area (km^2)	Sediment yield (m^3)	Basin denudation (cm)	Storm Rainfall (mm)	Lithology
1949	Austin Run[a]	9.71	20,900	0.22	229–380[g]	Quartz sandstone
1949	Kisamore Run[a]	5.01	8,500	0.17	229–381[g]	Siltstone–shale–sandstone
1969	Willis Cove[b]	4.08	173,488	4.25	250[h]	Quartz sandstone
1969	Ginseng Hollow[b]	1.75	88,727	5.07	250[h]	Siltstone–shale–sandstone
1969	Polly Wright[b]	2.47	87,707	3.55	250[h]	Gneissic granodiorite–greenschist dike
1985	Twin Run[a]	17.48	13,900	0.08	711[i]	Orthoquartzite
1985	Gravel Lick Run[a]	1.78	3,300	0.19	711[i]	Argillaceous sandstone
1995	Jenkins Hollow[c]	0.40	13,364	3.34	775[j]	Gneiss–granite–schists
1995	Teal Hollow[c]	0.12	2,492	2.08	775[j]	Gneiss–granite–schists
1995	Sugar Hollow[d]	29.50	544,000	0.92[f]	775[j]	Gneiss–granite–schists
1995	Bennetts Run[e]	0.19	25,185	12.99	213[k]	Quartzite
1995	Lowry Run[e]	0.03	2,447	8.63	213[k]	Quartzite

(Adapted from Eaton et al. 2003) Comparison of basin denudation, rainfall, and lithology for basins in Virginia and West Virginia. The highest value of basin denudation, measured in the Bennetts Run debris flow, is associated with bedrock joints acting to control erosion.

[a]Cenderelli and Kite 1998

[b]Williams and Guy 1973

[c]Springer et al. 2001

[d]Eaton 1999

[e]This study

[f]Minimum estimated value

[g]Stringfield and Smith 1956

[h]Colucci et al. 1993

[i]Camp and Miller 1970

[j]Smith et al. 1996

[k]National Oceanic and Atmospheric Administration 1995

of the height of precipitable air mass but is related to the location of unstable, well-developed saprolite. Saprolite exposure and colluvial covering on failure planes are attributed to the backstepping of the failure apex due to long-term weathering processes, including frost action and surface erosion.

The resultant vector of pole-to-plane orientations (R/n=0.98) indicates a high correlation between the measurements of these bedding planes. The value of n=15 appears to violate an essential assumption of most statistical tests which require a minimal value of n=30 for the null hypothesis to be worthy of testing. However, the effect on error propagation of low n values in Fisher statistics appears to be small (Whitney and Merrill 1974).

Joint planes are the dominant control on lateral erosion within the upper two thirds of the debris-flow track. Two distinct populations of joints, one coinciding with the southeast escarpment, the other with the northeast escarpment, were observed in the field. Since these joints are genetically related, there was no need to analyze them separately even though their distribution appears to be bimodal. The bimodality of this sample population would increase the margin of error by 1–2° only if there was a variable acting to violate the assumption that these joints are genetically related.

Each variable (i.e., bedding, joints, and chute azimuth) was tested individually (initial test) and then together (post hoc; Table 2). All sample populations passed their initial and post hoc tests for variance with a value of R/n well above the respective critical value. Margins of error are minimal, with all possible values of R/n falling within the 95% confidence interval.

Figure 4 shows a compiled rose diagram of the pole-to-plane joint population, the pole-to-plane bedding population, debris-slide chute azimuth, and mean vectors (θ). The failure direction is

Table 2 Results of statistical analysis shows a correlation between debris-slide chute azimuth and orientation of bedrock structures in Antietam Quartzite

Data type	Sample size, n	Mean resultant vector, R/n	Critical value of R/n	Concentration parameter, k	Mean vector, θ (degrees)	±Error about θ (degrees)
Initial test						
Joint plane	54	0.47	0.23	1.87	333	17
Bedding plane	15	0.98	0.41	51.47	134	4
Chute azimuth	53	0.64	0.23	2.71	290	12
Joint/bedding	69	0.42	0.23	1.70	350	16
Post hoc test						
Joint/chute	107	0.49	0.16	1.95	306	11
Bedding/chute	68	0.40	0.23	1.64	281	17
Joint/bedding/chute	122	0.40	0.16	1.64	304	13

All resultant vectors and respective margins of error are within a 95% confidence interval. Refer to Fig. 4 for related rose diagram.

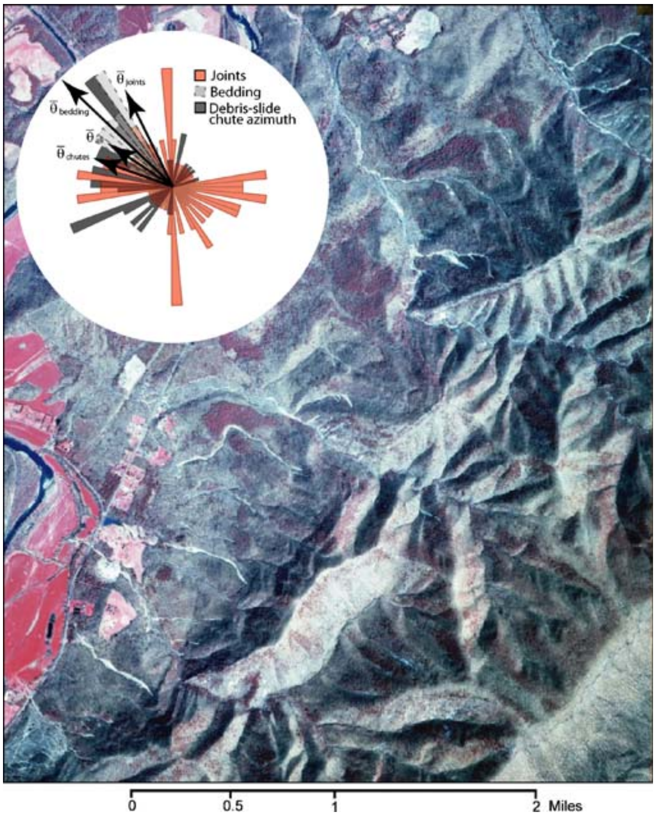

Fig. 4 Rose diagram of joint planes, bedding planes, and debris-slide chute azimuths on aerial photo of study region. All data pass initial and post hoc Fisher tests for preferred orientation of structures and debris-slide chute azimuths. Roses displayed with a 10% bin size and all calculations are within a 95% confidence interval. Statistical and field data agree with conclusion that bedrock structures facilitate pore pressure increases and are associated with high values of basin denudation. *Aerial photograph* shows debris-flow scars as linear, white features oriented NW–SE. See Table 2 for results of statistical analysis. (θ=mean vector)

roughly parallel to the dip direction and along azimuth with the bedding plane population. The chute azimuth also falls between each of the joint populations even where it is not correlated with bedding. In general, the statistical correlation within each pole-to-plane population, combined with the close spread of mean vectors and minimal margins of error, strongly suggests structural control of the debris-flow track.

The structural data coupled with field observations demonstrate that the joint and bedding planes in these failures have a high-angle, wedge-like geometry. Similar morphologies were observed in other mass-wasting processes in quartzite lithologies (Lee 1989; Vaughn 1997; and Volk 2000). These structural controls are likely facilitating the high basin denudations measured in this region, given that these high-angle wedge failures allow for deep incision by debris flows and have the potential to mobilize large volumes of rock and regolith.

A three-dimensional visualization provides compelling evidence to support this statistical analysis (Fig. 5). This visualization was constructed in ArcScene™ by draping aerial photographs over a 30-m Digital Elevation Model (DEM). Topographic signatures of bedding (in a strongly asymmetric anticlinorial structure) and joint planes were delineated using Computer Aided Drawing (CAD) techniques and were guided by field observations and stereoscopic, aerial photograph interpretation. These structures are pervasive at all topographic magnitude scales, including debris-flow initiation sites (1 m scale; Fig. 6a showing bedding plane at initiation site), mountain hollows (10^1–10^2 m scale; Fig. 6b showing joints and bedding planes) and in large erosional valleys (10^3 m scale; Fig. 6c showing outcrop in valley).

Previous studies of geologic controls in debris flows

Over the course of five decades, Virginia and West Virginia have experienced several catastrophic storms that triggered debris flows (Eaton et al. 2003), most notably the Hurricane Camille storm of 1969 and the Rapidan storm of 1995. Whereas Hurricane Camille triggered debris flows within granite–gneiss terrain, the Rapidan storm had slope failures that occurred in basins of varying rock types, including granite–gneiss, quartzite, and metabasalts. Despite the differences in rock type, similarities among the basins include: (1) statistical correlation of failure direction to bedrock structures (Gryta and Bartholomew 1989; Jurgens 1997; Sas and Eaton 2006), (2) rainfall as the primary triggering mechanism of debris-flow initiation (Wieczorek et al. 2000), (3) failures originated in zero- and first-order hollows, and (4) failures occurred at the interface of bedrock and regolith where pore pressures were the greatest (Kochel 1987; Williams and Guy 1973; Springer et al. 2001).

In a study that followed the Hurricane Camille event in Nelson County, Virginia, Gryta and Bartholomew (1989), and Kochel and Johnson (1984) found that penetrative rock fabrics in the granite–gneiss bedrock, including foliation and compositional layering, are associated with ~10% of all chute azimuths of debris avalanches

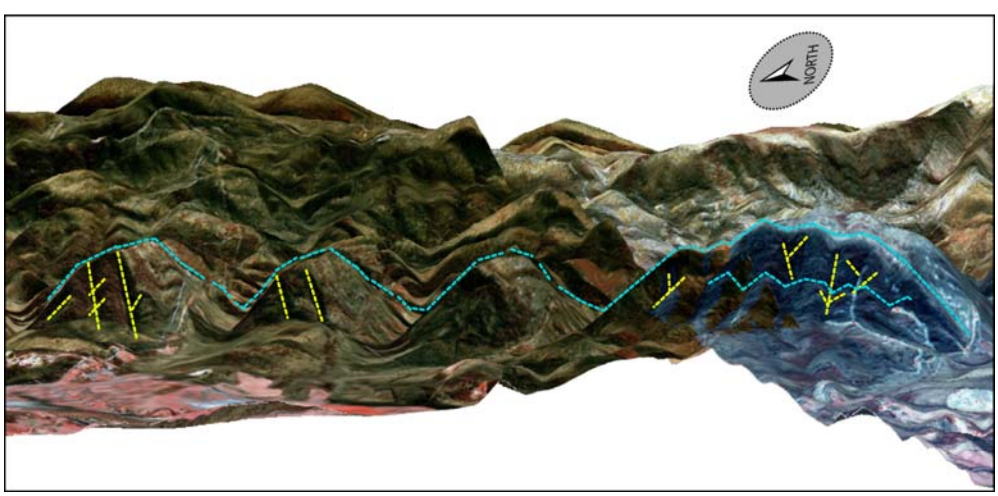

Fig. 5 Three-dimensional scene showing relationships between topography and rock structure. The morphometry of erosional valleys is strongly controlled by bedding and joint planes. *Bedding dips to the west* at approximately between 30 and 40°. Topographic trace pattern of joints is ubiquitous at scales ranging from meter to kilometer. Visualization created using ArcScene™ by draping aerial photos over a 30-m DEM. *Blue dashed lines* topographic trace of bedding; *yellow dashed lines* topographic trace of joints (note: no vertical exaggeration; some distortion occurs during rendering in two-dimension)

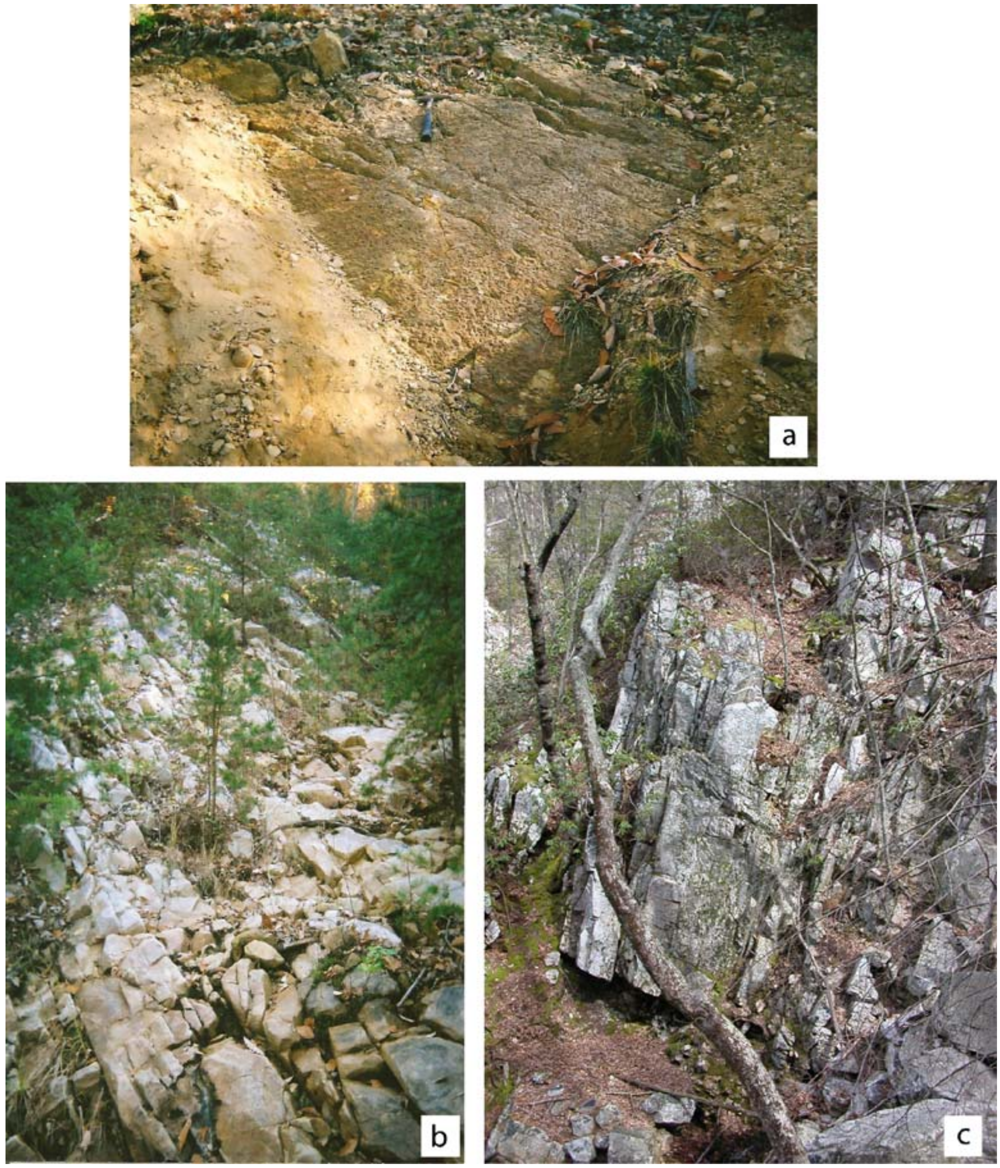

Fig. 6 **a** Photo showing bedding failure-plane at initiation site. Joint planes are exposed outside of photo view. Bedding and joint planes are controls on topography at all scales. Debris flows are the mechanism by which these structures are exposed. These structures in turn control the extent to which debris flows can erode through the regolith. Debris flows have a significant influence on long-term landscape evolution given the episodic nature of debris flows in the region, the role of geologic controls, and extensive basin denudation due to debris flow. **b** Joint and bedding planes exposed by debris flow several hundred meters from initiation site. Exposure of joint planes is more extensive along lateral escarpment, and bedding is more intact through thalweg. **c** Joint and bedding planes exposed in large erosional valley. A debris-flow track is ~60 m from outcrop shown in photo. Outcrop shows evidence of long-term exposure to chemical weathering

from the 1969 storm. Nearly 2% of all chute azimuths that followed a preferred orientation of failure did not correlate with penetrative rock fabrics. Although jointing was not directly studied, the 2% could be attributed to structures such as joints. They also found that ~88% of chute azimuths correlated with factors besides penetrative fabrics. However, this result does not necessarily mean that there was no influence of bedrock controls within these basins, only that the rock fabric variable was not statistically significant when compared to rainfall, topography, and local variations in lithology. The highest values of precipitation in this region showed a high correlation to preferred chute azimuth and thus was the primary factor influencing preferential failure azimuths. Nevertheless, the correlation of chute azimuth to dip direction of rock fabrics strongly suggests a secondary control of bedrock structures.

Jurgens (1997) examined structural controls of debris-flow initiation during the Rapidan storm of 1995 in Madison County, Virginia. The basins are chiefly granite–gneiss in lithology. She found that there was an average debris-flow path azimuth of 110–120° and that 19 of the 20 sites studied had foliation or jointing as a significant control on debris-flow track orientation. Although other factors including soil gradation, clay content, and slope morphology also account for variance about the average chute azimuth, structural controls are the dominant variable controlling erosion.

A third study inventoried debris flows from the 1995 storm within the Moormans River basin in Albemarle County, Virginia (Morgan and Wieczorek 1996). Their map shows an asymmetry of debris flow and debris-slide activity within the basin, where the southeast-facing channels have largely failed compared to the stable northwest-facing channels. The basin is underlain by metabasalt that has a strong regional foliation in this area that also dips to the southeast (L. S. Eaton, unpublished data). Although the evidence presented here is somewhat speculative, it does suggest a likely structural control on failures at this site.

Slope processes in quartzite terrains

Lee (1989), in his investigation of the Cambrian Cheshire Quartzite in Vermont, finds that orthogonal jointing in bedrock is the main factor contributing to slope movement, mainly rockslides and topples, during freeze–thaw cycles and heavy rainfall. Freeze–thaw mechanisms are the main focus of his study and were determined to be the dominant mechanism leading to failure. Lee (1989) states that the joint systems act to "rapidly drain" percolating water because the pressure within the joints is atmospheric, and the erosive force of the water is limited to removal of alteration products along fractures. However, numerous studies (e.g., Patton and Deere 1971; Reid and Iverson 1992; and Volk 2000) elucidate the mechanical effectiveness of groundwater flow in bedrock with regard to local porosity/conductivity contrasts and flow in fracture networks.

Patton and Deere (1971) note that cleft-water (i.e., water existing in rock discontinuities such as joints and fractures) pressures vary widely within a basin-scale fracture network and that these differences lead to slope instability by increasing pore pressures between joint or bedding discontinuities. Modeling shows that layered materials with contrasting values of conductivity increase the potential for slope failure by one to four orders of magnitude (Reid and Iverson 1992). Long-term mass rock creep, increased cleft pressures, and slope parallel structures were controlling factors leading to a large landslide in the Kuncha Quartzite in central Nepal (Volk 2000). Volk concluded that the resulting wedge-like failure was ultimately the consequence of a catastrophic rainfall event despite the influence of protracted rock creep due to gravitational sliding along weak bedding planes.

Vaughn (1997) observed "well-defined bedrock chutes" within the aptly named debris-flow impacted basin, Slide Canyon, along the Wasatch Front, Utah. Slide Canyon is underlain by the Cambrian Tintic Quartzite. Although climate, elevation, and land use differ between this location and Rockbridge County, similarities in geologic controls are apparent. Topographic signatures of bedding planes are visible in aerial photographs and in a DEM of this region. Additionally, debris flow or debris-slide scars are evident in valleys

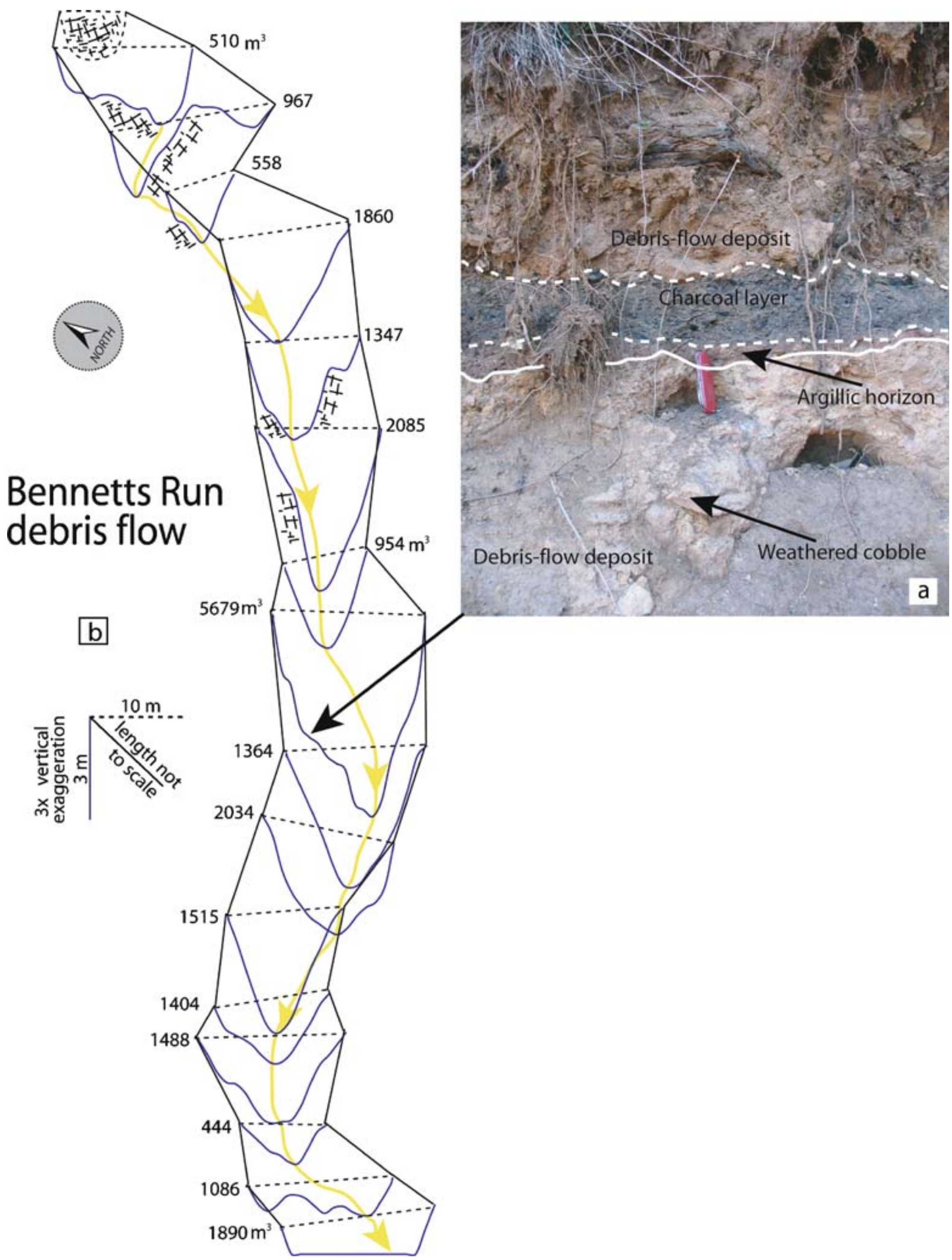

Fig. 7 **a** Photograph shows ~1 m soil sequence with chronological markers used to constrain timing of debris-flow activity. Lower deposit is likely middle to late Pleistocene, constrained by the rubification of the argillic horizon and charcoal layer. The charcoal yielded a radiocarbon age between 1640 and 1969 A.D. The older age is favored given the rubification of the debris-flow deposit above. **b** Diagram showing measured cross-sections (*blue lines*). Sediment volumes calculated from cross-section listed next to each respective section. *Schematic yellow line* follows debris-flow thalweg. The highest volumes of sediment were eroded from the middle portion of the debris-flow track. Bedrock exposure shown with hachured pattern

that have a nearly identical geometry to those in Rockbridge County. These geometries are likely due to a dense network of joints. The nature of these joints is similar to those in Rockbridge County because they are well-developed and result in a high hydraulic conductivity compared to intact bedrock (Harlow 1999).

Multiple lines of evidence from debris flows in quartzite basins investigated for this study in Rockbridge County indicate that the following factors contributed to elevated levels of pore pressure: (1) high values of conductivity contrast between the saprolite overlying the intact failure planes, (2) antecedent rainfall, (3) cleft water along joints and bedding planes, and (4) the presence of clay aquitards in joints. Initiation of debris flows within the soil–saprolite–unweathered rock interface on steep slopes is ubiquitous (e.g., Gryta and Bartholomew 1989; Springer et al. 2001), and in Rockbridge County, the high pore pressures facilitated the formation of debris slides that translated into debris flows. The rapid infiltration through the ~1 m thickness of soil and saprolite resulted in increased pore pressures along low-conductivity, bedrock planes. The antecedent rainfall of >120 mm for 4 days prior to the catastrophic rainfall event also contributed to increased pore pressures.

A mechanism that explains more localized pore pressure in concave slopes along the head escarpment is the accumulation of clays along the intersection of joint and bedding planes. During infiltration, these clays mobilize and flocculate in fractures to form an aquitard resisting the outflow of rapidly infiltrating rainwater. Soils sampled along the debris-flow track in Bennetts Run are classified as loam to clayey loam with clay fractions ranging from 5 to 22%. Using X-ray diffraction techniques, it was determined that kaolinite was the dominant clay mineral (d-spacing=7.01±0.05 Å). The clay fraction is sufficiently high to facilitate the creation of an aquitard mechanism to generate sufficient pore pressures for triggering debris flows.

The importance of debris flows in long-term landscape denudation

Studies conducted over the last several decades have helped delineate the timing and frequency of debris-flow activity in the central Blue Ridge Mountains of Virginia. Radiocarbon dating of prehistoric debris-flow deposits along the eastern flank of the central Blue Ridge indicates a recurrence interval of every several thousand years (Kochel 1987; Eaton et al. 2003). On the western flank of the Blue Ridge, our data indicate that debris-flow activity is also episodic, but their frequency of occurrence remains a question due to the uncertain age of debris-flow deposits. In Rockbridge County, a charcoal layer separating two debris-flow deposits yielded a radiocarbon date of 160±70 years B.P., indicating a recent debris flow event prior to the 1995 storm (Fig. 7a). The young age of the deposit overlying the charcoal layer seems plausible, as the unit has a poorly developed B horizon, characterized by low clay content, nominal rubification (10 YR colors, yellow-brown), and a minimal amount of clast weathering. In contrast, the debris-flow deposit underlying the charcoal unit is notably older than the upper unit, suggesting a long hiatus of activity between the two deposits. This lower deposit has a rubification index of 2.3 YR (strong red hue), higher clay content than the overlying flow, and contains numerous partially saprolitic quartzite gravels.

The gravels in this layer have a Clast Weathering Scale index value between 2 and 4, which indicates strong partial weathering of quartzite gravels. Work by Whittecar and Duffy (2000) on weathering of quartzite cobbles in Blue Ridge alluvial fans estimate their emplacement as earliest in the mid-Pleistocene. Their research concludes that transport of quartzite cobbles and boulders to alluvial fans can occur by several processes, including episodic debris flows and associated hyperconcentrated flows. The importance of these episodic events is supported by our findings, especially given the large volumes of soil and rock material eroded during these events (Fig. 7b).

In summary, the limited data presented here can be used to argue for either a long or short return interval for debris-flow activity. However, debris-flow recurrences represent a distribution of ages, and the age we report is likely to represent the low end of an extended range. Thus, the frequency of these events along the west side of the Blue Ridge cannot be established at this time. Future radiometric studies of these deposits will hopefully elucidate the debris-flow history of the area.

Conclusions

What can be learned from the episodic debris-flow activity observed during the 1995 storm is that debris flows in quartzite terrains: (1) are likely facilitated by geologic controls (i.e., lithology, structure, saprolite depth); (2) can entrain large sediment volumes from relatively small basin areas; and (3) are significant geomorphic processes in the denudation of the mountainous landscape. Structural relationships common in these debris flows are also observed in larger, mountain-scale features, indicating a scale-independent process governing erosion in the westerly dipping portions of the Antietam Quartzite. As shown in Table 1, relatively large volumes of sediment denuded by these debris flows during a single event in 1995 attest to extensive geomorphic work performed in 1 day, compared to the thousands of years required for the underlying bedrock to weather and to concentrate regolith into zero-, first-, and second-order tributaries that provide the source material for these debris flows.

Given the abundance of carefully measured, and often statistically significant, data from multiple authors, involving numerous lithologies throughout the central Appalachians, we conclude that: (1) the extensive geomorphic work performed by debris flows is dependent upon structures developed during tectonism of the middle to late Paleozoic, (2) debris flows occur episodically and are the major contributors of quartzite materials to alluvial fans, and (3) topographic signatures of debris flows indicate that-long term landscape evolution is strongly influenced by structurally controlled mass-wasting processes.

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