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Quaternary deposits and landscape evolution of the central Blue Ridge of Virginia

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Abstract

A catastrophic storm that struck the central Virginia Blue Ridge Mountains in June 1995 delivered over 775 mm (30.5 in) of rain in 16 h. The deluge triggered more than 1000 slope failures; and stream channels and debris fans were deeply incised, exposing the stratigraphy of earlier mass movement and fluvial deposits. The synthesis of data obtained from detailed pollen studies and 39 radiometrically dated surficial deposits in the Rapidan basin gives new insights into Quaternary climatic change and landscape evolution of the central Blue Ridge Mountains.

The oldest depositional landforms in the study area are fluvial terraces. Their deposits have weathering characteristics similar to both early Pleistocene and late Tertiary terrace surfaces located near the Fall Zone of Virginia. Terraces of similar ages are also present in nearby basins and suggest regional incision of streams in the area since early Pleistocene–late Tertiary time. The oldest debris-flow deposits in the study area are much older than Wisconsinan glaciation as indicated by 2.5YR colors, thick argillic horizons, and fully disintegrated granitic cobbles. Radiocarbon dating indicates that debris flow activity since 25,000 YBP has recurred, on average, at least every 2500 years. The presence of stratified slope deposits, emplaced from 27,410 through 15,800 YBP, indicates hillslope stripping and reduced vegetation cover on upland slopes during the Wisconsinan glacial maximum.

Regolith generated from mechanical weathering during the Pleistocene collected in low-order stream channels and was episodically delivered to the valley floor by debris flows. Debris fans prograded onto flood plains during the late Pleistocene but have been incised by Holocene stream entrenchment. The fan incision allows Holocene debris flows to largely bypass many of the higher elevation debris fan surfaces and deposit onto the topographically lower surfaces. These episodic, high-magnitude storm events are responsible for transporting approximately half of the sediment from high gradient, low-order drainage basins to debris fans and flood plains.

Keywords: Landscape evolution; Blue Ridge Mountains; Terraces; Debris flows; Stratified slope deposits

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1. Introduction

The study of the sedimentology, stratigraphy, and pedology of surficial deposits is essential for understanding the climatic and geomorphic history of a landscape. In the central and southern Appalachian region of the eastern United States, pristine surficial outcrops are few due to the combination of abundant rainfall, intensive weathering, and a thick mantling of vegetation. Most surficial deposits are poorly exposed, thin, and discontinuous. The scarcity of sites makes correlation among multiple drainage basins difficult and limits the interpretation of past geomorphic processes. These factors have severely limited researchers in their capacity to develop chronologies of Pleistocene landscape evolution in the central Appalachians.

A catastrophic storm in June 1995 that struck the Blue Ridge Mountains in central Virginia provided a rare opportunity to study numerous fresh exposures of surficial deposits. Over 775 mm (30.5 in.) of rain fell in 16 h during the storm, referred to as the Madison County storm in this study (Wieczorek et al., 2000); and the deluge triggered more than 1000 slope failures (Fig. 1). Stream channels and debris fans were deeply incised, exposing deposits of earlier mass movement and fluvial events (Eaton and McGeehin, 1997). Thirty-nine radiocarbon dates were obtained from buried paleosols and organic-rich deposits. Pollen data collected from two of the radiocarbon sites were used to reconstruct plant communities and climate at the time of deposition. The synthesis of data obtained from detailed studies of radiometrically dated surficial deposits in the Rapidan basin gives new insights into Quaternary climatic change and landscape evolution of the central Blue Ridge Mountains.

2. Regional setting

The study area (~ 600 km^2) is located in the Blue Ridge physiographic province in western Madison and Greene Counties (Fig. 2). The Rapidan River and its major tributaries (Robinson, Conway, and South Rivers) originate in the eastern flanks of the Blue Ridge Mountains of central Virginia and together serve as the southern headwaters of the Rappahannock River. The topography of the region is irregular; many subsidiary ridges extend several miles away from the Blue Ridge summits, and separate well-defined low-order tributary networks. Local relief varies between 120 and 1170 m, and slopes in headwater basins commonly exceed 30°.

The geology of the region initially was mapped and described by Allen (1963); and more recent

Fig. 1. Debris flows triggered by the June 1995 Madison County storm denuded numerous upland drainages of western Madison and Greene Counties, Virginia. Photo is of Kirtley Mt., 3 km southwest of Graves Mill.

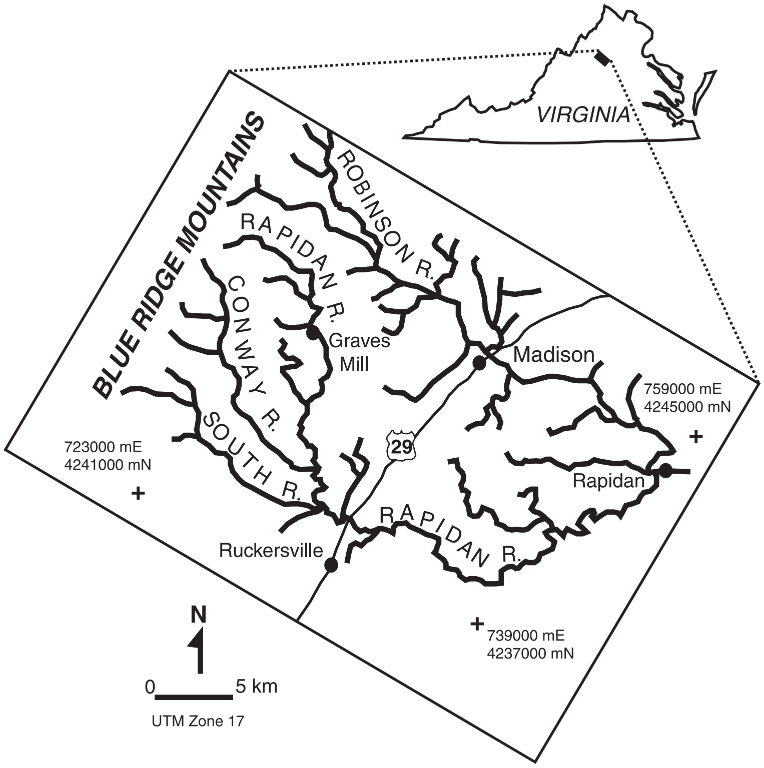


Fig. 2. Location map of the study area.

summaries of the bedrock geology have been published by Gathright (1976), Rader and Evans (1993), and Bailey et al. (2001). The oldest mapped bedrock within the study area is quartzo-feldspathic rock of mostly granitic composition. Allen (1963) mapped these rocks as the Pedlar, Lovingston, and Marshall formations. These rocks originated as a series of igneous intrusions that later were deformed and recrystallized about 1 BYBP during the Grenville Orogeny. The granitic rocks were intruded by diabase dikes about 570 MYBP that presumably acted as conduits for the basaltic volcanic flows that comprise the Catoctin Formation. The Catoctin Formation unconformably overlies the granitic rocks and includes basalt lava flows with prominent columnar jointing, volcanic ash, and agglomerates. All of these rocks were altered by metamorphism and deformation during the Paleozoic Era. The granitic intrusions were retrograded, and pyroxene was replaced by amphibole and chlorite. The basalt was altered to greenstone composed of albite, chlorite, epidote, and minor amphibole. Well-defined faults and shear zones cut all rock units in many places, and foliation is prominent and obscures bedding in the greenstones and siliclastic rocks.

Regolith mantles most of the landscape. It is thickest on debris fans and in hollows and thinnest on planar and convex-shaped hillslopes. Most of the soils in the study area are derived from transported material as a result of mass movement on steep slopes or close to streams. In the study area, the soil orders developed from the regolith are primarily Ultisols, Inceptisols, and Entisols (Elder and Pettry, 1975). Ultisols are found on high river terraces, debris fans, and residual upland surfaces. Inceptisols occupy mountainous slopes, low river terraces, and historically inactive debris fans. Entisols are located on steep mountain slopes, historically active debris fans, and river flood plains.

3. Early Quaternary landforms and deposits

The oldest surficial landforms present in the Rapidan valley are fluvial terraces (Fig. 3). They are the most prominent landforms on the valley floor and are traceable for ~ 160 km from the Fall Zone at Fredericksburg to the confluence of Kinsey Run and the Rapidan River (Dunford-Jackson, 1978; Howard, 1994). Similar surfaces are also present in the nearby Robinson, Conway, and South River valleys. The highest surface is the most extensive and would form a nearly continuous, horizontal plane 25–30 m above the active flood plain through the upper Rapidan River valley if it were not for its advanced stage of dissection. The high terraces are straths and have a thin veneer of weathered alluvium (0.1–2 m) overlying a deep saprolite that can exceed 30 m in thickness (Eaton, 1999). Approximately a third of the mapped terraces show traces of rounded cobbles on the surface, indicative of fluvial transport. The other terrace surfaces have been stripped of alluvium, leaving behind large flat exposures of bedrock or thin alluvial soils. Pre-Wisconsin debris flow deposits overlie terrace seg-

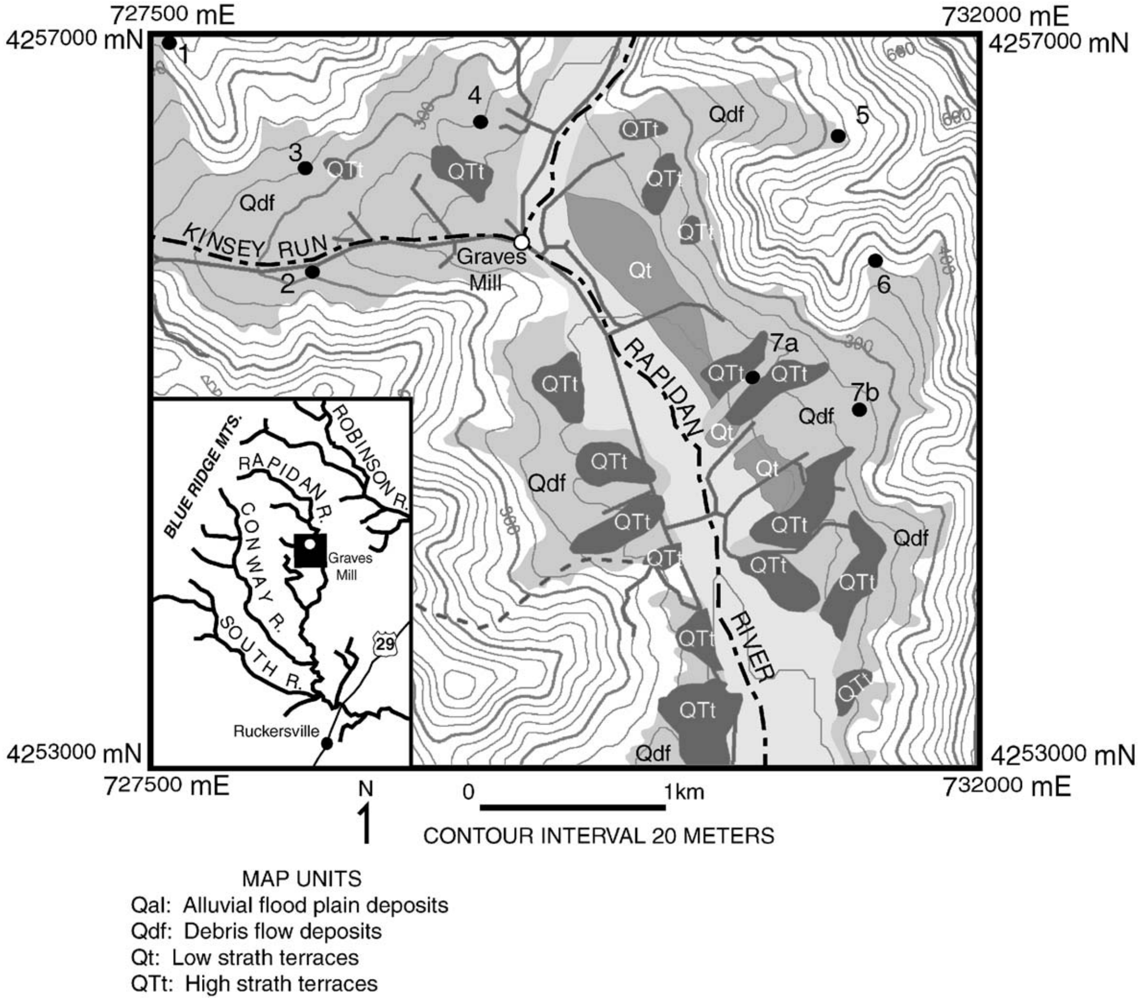


Fig. 3. Surficial geology of the Graves Mill area (modified from Eaton et al., 2001b). Site 1, Kinsey Run stratified slope deposits; site 2, Kinsey Run debris flow deposits; site 3, Generals debris fan; site 4, Kulenguski debris fan; site 5, Lillard debris flow deposits; site 6, Rhodes stratified slope deposits; sites 7a and 7b, Rhodes debris fan.

ments near the margins of tributaries that drain into the Rapidan.

The soils on most of the high terraces are of the Dyke and Braddock series, both characterized by 2.5YR to 10R Munsell colors, thick argillic horizons, and deeply weathered granitic clasts. The Dyke series is a clayey, mixed, mesic, typic Rhodudults; and the Braddock series is a clayey, mixed, mesic, typic Hapludults (Elder and Pettry, 1975). As many as three lower flights of terraces are present in the basin and the soils were collectively mapped as the Unison series, classified as a clayey, mixed, mesic, typic Hapludults (Elder and Pettry, 1975) with slightly less clay and rubification than the Dyke and Braddock series.

The high strath terrace deposits of the Rapidan River have weathering characteristics similar to both the early Pleistocene and late Tertiary surfaces of the Fall Zone and Inner Coastal Plain of Virginia as described by Howard et al. (1993) and by Markewich et al. (1990). The clay content, Munsell colors, and weathering characteristics of the Dyke and Braddock soil series, are similar to pedological characteristics of the Paleudult soils on the Fall Zone terraces dated 3.4 to 5.3 MYBP (Howard et al., 1993). In contrast, the Dyke and Braddock series have a greater rubification and clay content than Hapludult terrace soils at the Fall Zone dated 700 KYBP to 1.6 MYBP. Although different parent materials could be a factor, correlation of soils from the Fall Zone to the Blue Ridge suggests that the highest terrace surfaces in the study area may be early Pleistocene to late Tertiary in age.

Previous research has postulated that the high terrace surface as well as similar terraces in nearby basins may be topographically correlative to late Tertiary terraces in the Coastal Plain (Dunford-Jackson, 1978), but further research is needed to substantiate this claim. Mixon et al. (2000) have traced Tertiary surfaces from the Fall Zone to Culpeper, 60 km downstream of the study area. Even if the surfaces in the upper Rapidan River basin topographically align with those in the Coastal Plain, regional incision may not have been contemporaneous throughout the entire basin. The upper terrace surfaces clearly predate the Wisconsinan glaciation, and the pedogenesis of the soils suggests a minimum age of 0.5 MYBP (Eaton et al., 2001a).

Numerous debris fans grade onto the Rapidan terrace and flood-plain surfaces. The degree of soil pedogenesis on these fan surfaces indicates that some of these deposits predate the Wisconsinan glaciation and may be nearly as old as the river terraces. Munsell colors of some deposits are 2.5YR, maximum clay contents reach 72%, and weathered granitic cobbles are easily sliced with a trowel (Daniels, 1997; Kochel et al., 1997; Eaton et al., 2001a). The deposits occur in both topographically low and high fans (Eaton, 1999). One debris flow deposit containing charcoal was >50,000 YBP (Fig. 3, site 5), and its degree of weathering suggests it is pre-Illinoian in age. Similarly, Mills and Allison (1995) estimated the age of soils developed on Appalachian debris fans in western North Carolina, which have slightly less pedogenesis than the oldest Rapidan fans, to be up to several hundred thousand years.

4. Late Quaternary landforms and deposits

4.1. Blockfields and boulder streams

The late Pleistocene has been documented as a time of intense mechanical weathering and denudation in the Appalachian highlands (e.g., Clark and Ciolkosz, 1988; Mills and Delcourt, 1991). Reduced vegetation cover and increased frost action activity on hillslopes enhanced mechanical weathering, creep, and solifluction processes. The presence of blockfields, boulder streams, and the orientations of boulders in the headwaters of the Rapidan basin suggest widespread Pleistocene periglacial activity. In general, wherever frost heaving is prominent, tabular stones within the regolith tend to be vertically oriented (Washburn, 1979). One blockfield site located near the Rapidan headwaters (elevation 1000 m) is comprised of tabular slabs of the Catoctin Formation that exhibit vertical orientations and is of probable periglacial origin. Morgan (1998) and Eaton et al. (2001b) have mapped numerous blockfields and boulder streams in the upper Rapidan basin that contain clasts with vertical orientations. Similarly, Whittecar and Ryter (1992) documented blockfields in the Blue Ridge 70 km SW of the Rapidan basin and noted clusters of vertically oriented, tabular boulders and cobbles in small, steeply inclined mountainous basins.

Mapping conducted by Eaton et al. (2001b) in zero-, first-, and second-order hollows not modified by the 1995 storm showed most channels are filled with sediment that range in size from small cobbles to boulders that exceed 6 m in length. Most of these features were classified as boulder streams. The pervasive presence of blockfields and boulder streams that remain unmodified in the present landscape indicate little Holocene modification and, therefore, relict of colder climates. Other workers have made similar conclusions on the genesis of many of the Appalachian landforms (Clark and Ciolkosz, 1988; Delcourt and Delcourt, 1988; Braun, 1989; Ciolkosz et al., 1990; Gardner et al., 1991; Ritter et al., 1995).

4.2. Talus and tors

At elevations above ~ 667 m (2200 ft), the summits and shoulders of the Blue Ridge are mantled with a thin, blocky colluvium (Morgan, 1998; Eaton et al., 2001b). In the Fletcher, VA, 7.5′ quadrangle, scattered talus deposits are widely interspersed with colluvium. Rock streams are well developed within many Rapidan first-order tributaries. The origin of the talus and rock streams is controversial (for an extended discussion, see Mills, 1988). Tors cap several ridge summits in the western edge of the basin. The balanced rocks as well as chimneys and spires at the summits are typical of periglacial tors described in Great Britain and elsewhere (Ballantyne and Harris, 1994). These are the product of mechanical weathering and denudation characteristic of conditions imposed by a periglacial climate during the Pleistocene Epoch in the Blue Ridge (Eaton, 1999).

4.3. Stratified slope deposits

The term ‘stratified slope deposits’ refers to a broad category of sediment deposited along side slopes in which stratigraphic units are differentiated by sorting, grain size, and/or particle orientation (Gardner et al., 1991). Although stratified slope deposits have been widely documented in the European literature (e.g., Guillien, 1951; Ballantyne and Harris, 1994) they have received until recently only minimal attention in the Appalachians. Jobling (1969) described a deposit of rhythmically bedded shale clasts along a hillslope exposure in Pennsylvania. He interpreted the deposit as *grèzes litées* and proposed solifluction as the mechanism of emplacement. Sevon and Berg (1979) and also Gardner et al. (1991) provided descriptions of shale-chip rubble deposits in Pennsylvania that have descriptions similar to the Rapidan basin sites. Clark and Ciolkosz (1988) noted that similar slope deposits have been found as far south as northern Virginia. Similar deposits were observed in a steep, north-facing hollow in Nelson County, central Virginia exposed by debris flows during the 1969 Hurricane Camille flood (Alan Howard, University of Virginia, personal communication, 1995) and in the Great Smoky Mountains National Park (Scott Southworth, U.S. Geological Survey, personal communication, 1995).

In the study area, these deposits have rhythmic layers of clast-supported and matrix-supported platy, angular, pebble-sized rock chips aligned parallel to the slope of the hillside (Fig. 3, sites 1 and 6). The deposits are typically thin (~ 0.1 m thick) (Fig. 4b), and are exposed at the base of planar or slightly concave shaped hillslopes. The most extensive stratified slope deposit documented in the study area is the Kinsey Run debris fan site in the upper Rapidan basin (Fig. 4) (Eaton, 1999; Eaton et al., 2001b). The 1995 flood exposed 6.5 vertical meters of stratified slope deposits with individual beds that are laterally continuous for a minimum of 50 m (Fig. 4a). The deposit is thickest at the downslope end adjacent to the modern channel and gradually thins upslope. Another site is located on a small Rapidan River tributary near the Rhodes farm, 0.5 km south of Graves Mill (Fig. 3, site 6). The deposits there are 1.9 m thick and are overlain by three debris flow units. Individual units are laterally continuous for at least 20 m. Both the Kinsey Run and Rhodes sites have numerous, thinly bedded (2 to 5 cm) units that dip 7–12°, subparallel to the hillslope.

The clasts at both sites consist mainly of pebble size material of highly sheared gneiss, greenstone, and vein quartz. Cobbles are few in number, and boulders are notably absent. The clasts are generally tabular in dimension and angular to subangular, largely due to the combination of strongly developed foliation, short transport distance, and weathering along discontinuities. The median pebble dimensions are 5 cm (long axis) by 4 cm (intermediate axis), much finer grained than debris flow deposits. The maximum clast size generally does not exceed 12 cm. The matrix consists of sand, sandy loam, and loam (Fig. 4c). Munsell soil

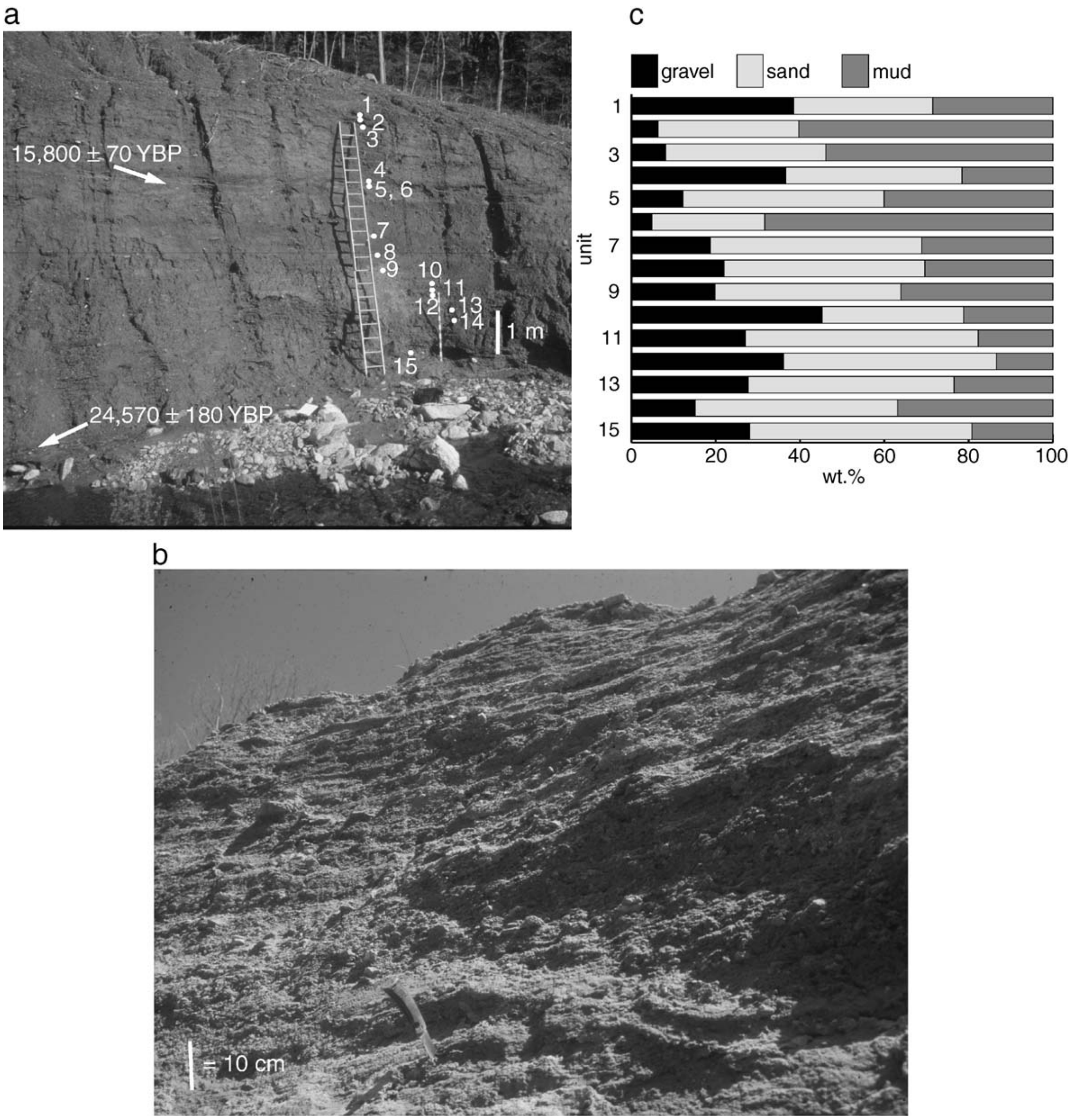


Fig. 4. Stratified slope deposits, Kinsey Run, Graves Mill. (a) Overview of site; (b) close up oblique view of individual beds; (c) particle size analysis of prominent beds.

colors are dominantly 10YR, 5Y, and 2.5Y hues. The units are poorly sorted and chiefly grain supported; however, matrix supported pebbles were observed. Particle orientation is subparallel to the hillslope.

The timing and rate of deposition of these stratified slope deposits were determined by radiocarbon dating. At Kinsey Run (Fig. 4a), 6.5 m of slope deposits formed between 24,570 and 15,800 YBP, indicating an average accumulation rate of at least 74.1 cm/l000 years. An additional meter of slope deposits overlies the 15,800 YBP unit; and some of the topmost layers may have been removed by the 1995 and earlier storms, so accumulation may have continued until the end of the Pleistocene.

Similar accumulation rates of stratified slope deposits were observed at the Rhodes site. Slope activity began as early as 27,410 YBP and continued up to 24,450 YBP, and then was interrupted by a debris flow event, which radiocarbon dates of debris flow deposits suggest a basin-wide event (Eaton et al., 2001b). During the 2960 years of slope wash deposition activity, 1.59 m of sedimentation occurred, giving an average accumulation rate of 53.7 cm/1000 years.

The ages of the stratified slope deposits in the Rapidan basin bracket the late Wisconsinan glaciation and suggest that the Blue Ridge, located about 400 km south of the Wisconsinan glacial border, experienced permafrost conditions. Deposition probably was continuous even as climate cooled during the late Wisconsinan glacial maximum because there is no observable evidence of fossil soil horizons or variations in weathering of pebbles in the deposits. The deposits provide critical information about the amount of vegetation covering the slopes and about the prevailing climatic conditions. Some researchers propose continuous, uninterrupted bedding is indicative of a vegetation-free surface during stratified slope deposit formation (Sevon and Berg, 1979; DeWolf, 1988), suggesting that the upland central Blue Ridge landscape (>300 m) was relatively free of vegetation from 27.4 KYBP to at least 15.8 KYBP. However, work by Hétu and Gray (2000) documented frost coated clast flow deposits

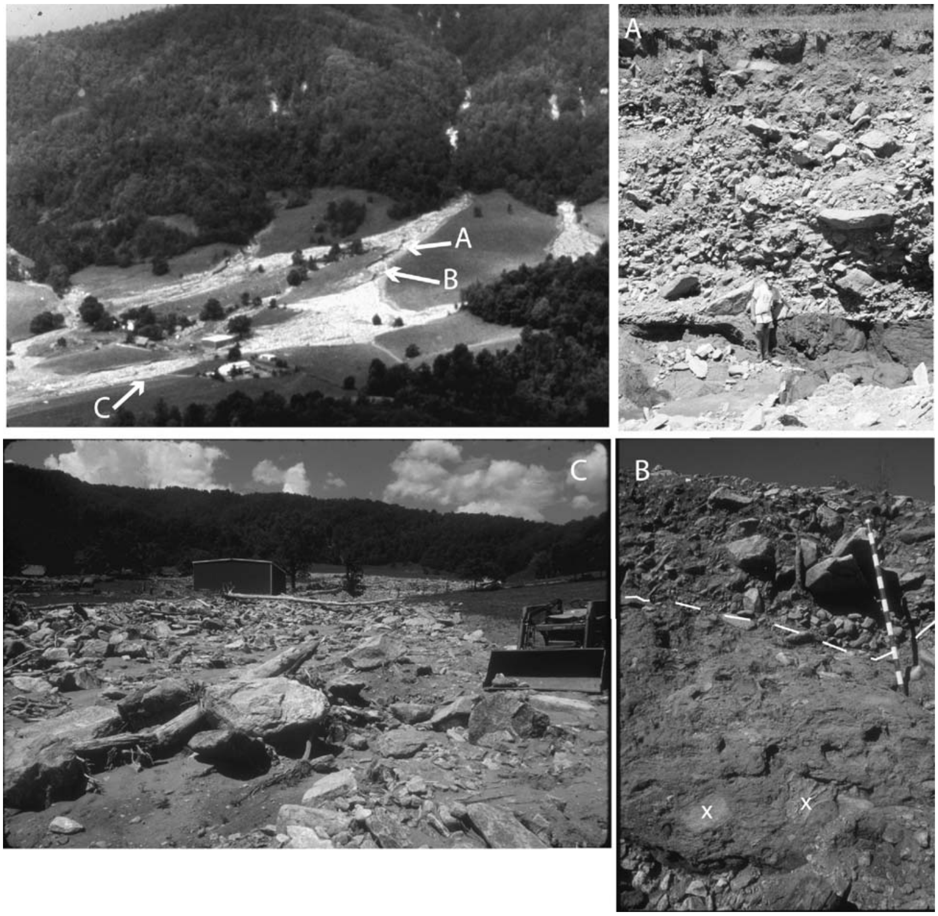


Fig. 5. Deep Hollow debris fan, located 4 km east of Graves Mill. Letters depict photo locations. Scale is in decimeters. Sites A and B show the stratigraphy of older debris flow deposits. Person's hand rests on saprolite-debris flow contact in site A. Note the advance stage of weathering of the basal debris flow deposit of site B as demonstrated by the outlines of disintegrated granitic clasts (marked "x"). Site C documents debris flow deposition from the Madison County storm.

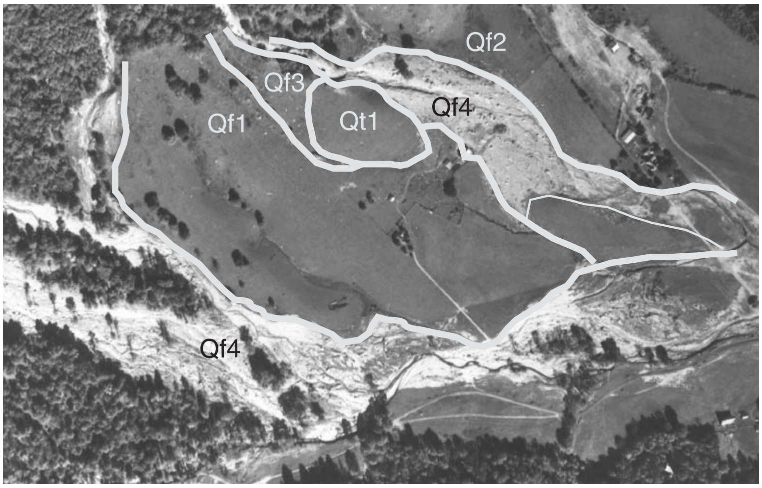


Fig. 6. Multiple debris fan surfaces at the Generals Fan site, Graves Mill. The distinctive weathering surfaces range in age from modern to a minimum of 0.5 MYBP.

forming in the presence of forest cover in southeastern Quebec. Detailed palynological and sedimentological research currently in progress in the Rapidan basin will help clarify the relationship between hillslope processes in the Blue Ridge and vegetation cover during the late Wisconsinan glacial maximum.

On upper slopes in the Rapidan basin, late Wisconsinan slope deposits are exposed in ravines created by the 1995 debris flows and in eroded bluffs on the Rapidan River. In many of these outcrops, these deposits lie directly on bedrock or on saprolite. This suggests that many localities the Blue Ridge were largely denuded of colluvium before the onset of late Wisconsinan glacial maximum.

4.4. Debris fans and flows

Debris fans are prominent geomorphic features along the eastern flank of the Blue Ridge in central Virginia. The narrow stream valleys typical of much of the eastern flanks of the Blue Ridge prevent the formation of a classical fan-like morphology in plan-view (Kochel, 1990) seen, for example, in the basin and range province of the western United States; and in the Shenandoah Valley of Virginia (King, 1950). Most of the debris fans are elongated longitudinally and convex in cross section. Blue Ridge debris fans occur at the bottom of steep, weakly dendritic mountainous hollows and at the base of planar slopes,

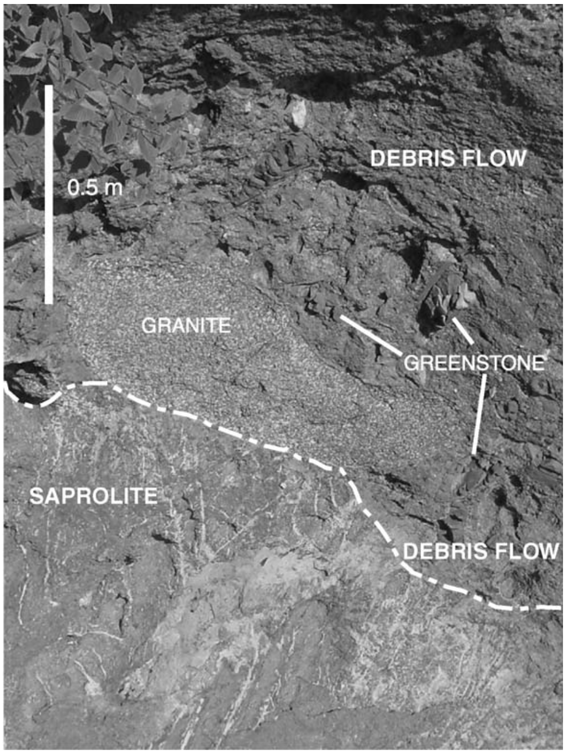
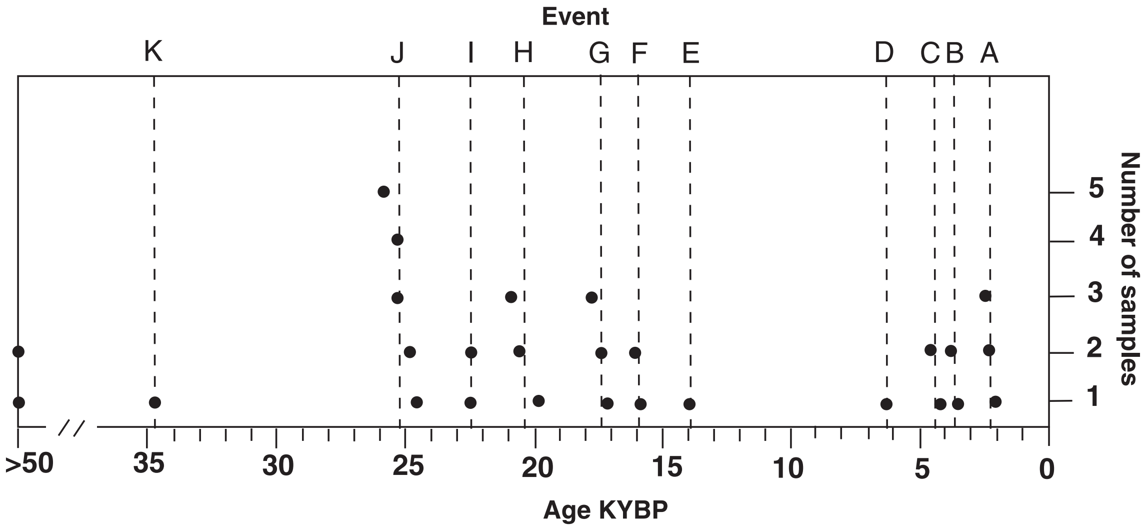


Fig. 7. Deeply weathered granite and greenstone boulders and cobbles in Qt1 surface, Generals Fan.

whose episodic failures serve as the sources for the fan deposits (Fig. 5). Many of the fans are dissected by multiple, entrenched, minor streams, and form an easily recognizable pattern of contours on topographic maps. Debris flows originating from hollows and planar slopes travel rapidly downslope, often excavating loose colluvium down to firm bedrock. The downstream transition from debris flow chute to debris fan is generally abrupt and associated with a decrease in gradient, ranging from 17–45° in colluvial hollows to 6–11° on debris fans. Deposits from multiple flows can create substantial fans that coalesce in aprons along the base of mountain slopes (Fig. 5).

In the Rapidan basin, maximum fan exposures of 4 m were observed in the 1995 scour zones near the apices (Fig. 5A,B). Seismic refraction and ground resistivity surveys on the main body of several fans in the upper Rapidan basin suggest that thicknesses may exceed 30 m (Daniels, 1997). Extensive scour within debris flow chutes resulting from storms on the Rapidan and Conway Rivers expose multiple debris flow deposits generally interbedded with slope wash deposits. Fragments of wood and charcoal in these deposits yield radiocarbon dates of late Wisconsinan glacial maximum. Radiocarbon dates from charcoal found in two weathered debris flow deposits indicated an age of >50,000 YBP (Fig. 3, site 5).

Several debris fans have been the focus of intense study following the Madison County storm (Daniels, 1997; Eaton, 1999; Eaton et al., 2001a; Scheidt, 2001). Studies of soil profile development on five debris fan surfaces show a mosaic of deposits of varying ages emplaced by episodes of fan entrenchment, deposition, and abandonment over hundreds of thousands of years (Fig. 6). One debris fan located 1.3 km NWW of Graves Mill, referred to as the Generals Fan in this study (Fig. 3, site 3), consists of at least five distinctive weathering surfaces that range in age from modern to 0.5 MYBP (Fig. 6). The surface distinctions were based on marked changes in soil rubification, clay content, surface and



Event

	K	J	I	H	G	F	E	D	C	B	A
		25,860±120									
		25,290±90									
		24,910±120		19,760±110	17,120±80						2080±50
>50,000		24,650±120	22,350±80	20,470±110	17,560±70	15,990±70			4240±50	3700±50	2240±50
>50,000	34,770±690	24,570±180	22,430±100	20,660±70	18,920±60	16,430±80	13,990±60	6520±60	4450±60	3880±50	2430±60

Fig. 8. Ages of 11 debris flows in the upper Rapidan basin. Recurrence of debris flows was approximately every 2500 years (Eaton, 1999). The small circles represent samples from debris flow deposits, and their respective dates are listed in the table. Each vertical dashed line is interpreted as a discrete debris flow event.

subsurface boulder frequency, and thickness of the argillic B horizon (Eaton et al., 2001a); and ^{10}Be cosmogenic dates of the soil profiles (Milan Pavich, U.S. Geological Survey, personal communication, 2001).

The oldest surface of the Generals Fan, denoted as Qt1, is mapped as the Dyke soil series, a Hapludult (Fig. 6). Unlike the four younger surfaces at this site, Qt1 is totally devoid of boulders exposed at the surface. However, the Qt1 deposit contains cobbles in a localized basal debris flow unit that show advanced stages of disintegration and lies unconformably over saprolite (Fig. 7). The thickness of the B horizon exceeds 1.5 m. The maximum clay content is 72%, and Munsell colors are 2.5YR-10R (Eaton et al., 2001a). Additionally, the Qt1 surface is noticeably lower in gradient ($<3°$) than the others, suggesting a terrace landform rather than a fan. An unpublished ^{10}Be cosmogenic date of the soil profile suggests a minimum age of 0.5 MYBP of this surface (Milan Pavich, U.S. Geological Survey, personal communication, 2001). Four other studied debris fans in the Rapidan basin also have Qt1 surfaces that contain strikingly similar pedogenic characteristics to the Generals Fan (Daniels, 1997; Scheidt, 2001) and may all be of the same age.

Deposition of modern debris on the Generals Fan occurs on surface Qf4. It is topographically the lowest and grades into the modern flood plain. The surface shows an absence of pedogenic development due to episodic Holocene disturbances, including the 1995 Madison County flood (Daniels, 1997; Kochel et al., 1997; Eaton et al., 2001a; Scheidt, 2001). The stream that transports debris to Qf4 has incised through higher, older debris fan surfaces, denoted as Qf3, Qf2, Qf1, and Qt1 (Fig. 6). Some of these older surfaces are correlative among fans; for example, the Kulenguski and Rhodes fans (Fig. 3, sites 4 and 7) show similar pedogenic and geochemical properties in the Qf3, Qf1, and Qt1 surfaces (Scheidt, 2001; Scheidt and Kochel, 2001). Other surfaces do not appear to correlate with other fans in the basin, such as the Qf2 surface of the Generals Fan. The combination of the highly erosive nature of some debris flow events, narrow stream valleys, and local control of deposition and erosion by channel bends and tree jams makes preservation of a complete record of debris flow activity unlikely.

4.5. Debris flow frequency

Until recently, knowledge of the recurrence interval of debris flow activity in the central Blue Ridge was limited. Kochel (1987) estimated that the debris flow recurrence interval in small stream basins in western Nelson County, VA, ranged from 3000 to 4000 years. The analysis was based on five radiocarbon dates obtained from three debris fan and one flood plain deposits in the small drainage basin of Davis Creek; the oldest radiocarbon age of a debris flow deposit was dated as early Holocene. In the Rapidan basin, radiometric dating of organic-rich deposits exposed

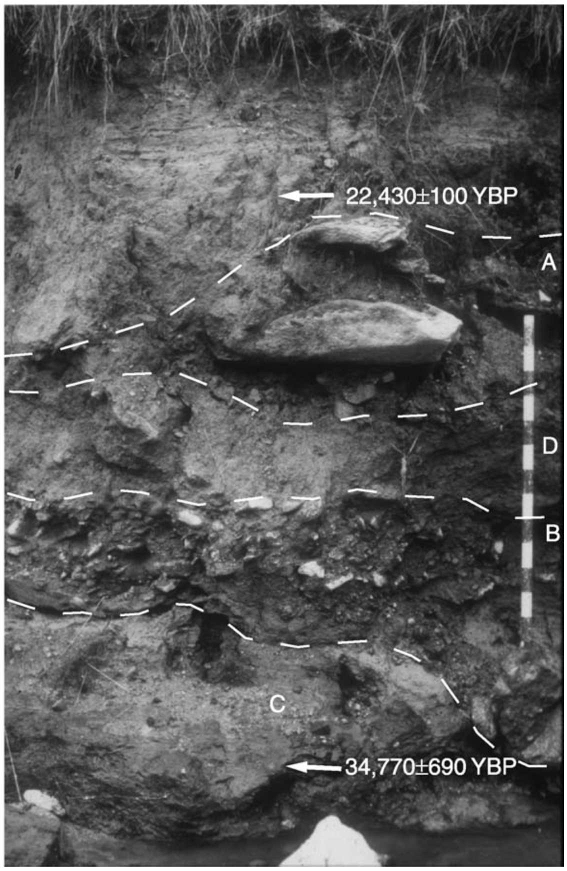


Fig. 9. Lower Kinsey Run debris flow deposit, site 2 in Fig. 3. Organic peat deposit (C) dated 34,770 ± 690 YBP is overlain by two debris flows (A and B) and fluvial sands (D) that were emplaced before 22,430 ± 100 YBP. The sedimentology and lithology of the debris flows indicates each originated from separate hollows. Scale is in decimeters.

by the Madison County storm show debris flow activity extending into the late Pleistocene (Fig. 8). The oldest organic materials exceeded 50,000 YBP. These materials were collected from basal debris flow deposits; one located in the Kirtley Mountain debris flow fan west of Graves Mill (Fig. 1), and the second in the Lillard debris fan (Fig. 3, site 5). Wood originating from the top of a 0.7-m-thick organic, peat deposit (Fig. 3, site 2) was dated at 34,770 YBP and is directly overlain by two debris flow deposits (Fig. 9, units A and B). The next youngest sample related to a debris flow event was dated at 24,910 YBP. This event impacted numerous first- and second-order basins in the Rapidan basin. After this event through 13,990 YBP, at least five separate debris flow events are recorded over a 10,880-year period, or a frequency of one event every 2200 year (Eaton and McGeehin, 1997). No radiocarbon dates were obtained from 13,990 through 6520 YBP. At least five debris flow events have occurred since 6520 YBP, including the 1995 flood, or one event every 1600 years. If the entire period from 25,000 YBP to the present is considered, debris flow activity has on average recurred in the upper Rapidan basin at least every 2500 years (Fig. 8).

5. A model of landscape evolution

The geologic record preserved in surficial deposits in the central Blue Ridge is greatly restricted because the area has been one of uplift and denudation since well before the end of the Cenozoic. However, the remnants of these deposits do provide insight into the evolution of the landscape during the Quaternary. The lateral extent of the high strath terraces suggests that the rivers draining the eastern slopes of the Blue Ridge had broad flood plains that may have been two to three times the width of the modern flood plains. After stream incision, the older flood plains were preserved as strath terraces along all of the major streams within the study area. Factors that may explain the causes of incision include climatic change, tectonics, and stream piracy; and future research is needed to elucidate this problem.

The relatively wide and flat valley floor of these rivers east of the Blue Ridge Mountain front suggests that the stream level in these reaches have been stable throughout the late Quaternary. The presence of numerous local bedrock exposures along the system indicates that the rivers have never incised much deeper than their present level. Additionally, the local presence of deeply weathered debris flow deposits at or near the level of present drainage on debris fans also suggests that late Quaternary fluvial downcutting has been modest. A few debris fans, such as the Generals Fan (Fig. 6), are deeply entrenched at their apices so that some highly weathered fan units are well above present drainage, but many others are not. In the latter cases, the bedrock and debris flow deposits exposed at and near the channel beds are commonly deeply saprolitized. These deeply weathered fan-head deposits, such as the Qt1 surface of the Generals Fan (Figs. 6 and 7), could possibly be correlative with the high strath terraces 25–30 m above present river level, but this correlation would imply that fans have built outward to accommodate the subsequent river dissection without appreciable change in elevation of the fan apices. By contrast, the fresh bedrock exposed in the debris flow tracks in the mountain fronts suggests that downcutting of the steeper mountain hollows has been episodic through the Quaternary.

The pervasiveness of surficial deposits derived from periglacial processes indicates that many of the landforms in the Blue Ridge are relict of a colder Pleistocene climate and are currently being modified by Holocene processes. Other workers have made similar conclusions about the genesis of many of the Appalachian landforms (Clark and Ciolkosz, 1988; Delcourt and Delcourt, 1988; Braun, 1989; Ciolkosz et al., 1990; Gardner et al., 1991). The late Pleistocene was a time of intense mechanical weathering and denudation in the Appalachian highlands (e.g., Clark and Ciolkosz, 1988; Mills and Delcourt, 1991). Pollen studies conducted in the central Appalachians document changes in both climate and vegetation during the late Pleistocene (e.g., Shafer, 1988; Webb et al., 1993). The pollen assemblages of one site in the upper Rapidan (Fig. 3, site 2; Fig. 9) dated 34,770 YBP indicate that the mean July temperature was $\sim$ 19 C, compared to the current mean of 23 C (R. Litwin, U.S. Geological Survey, personal communication, 1998). Substantial changes in vegetation and temperature occurred during the succeeding 10,000 years, where a 24,570-YBP site contains pollen assemblages (Fig.

3, site 1; Fig. 4a) that project the mean annual temperature at ~ 17 C and conditions had become increasingly drier.

Reduced vegetation cover and increased cycles and intensity of frost action on hillslopes enhanced mechanical weathering, creep, and solifluction processes. Of the undisturbed drainages, substantial amounts of regolith currently rest on hillslopes and in zero-, first-, and second-order basins (Morgan, 1998; Eaton et al., 2001b). During the late Pleistocene, debris flows delivered some of the sediment to the valley floors and aided in progradation of the fans. Pleistocene fan progradation was documented at the Rhodes site where the topmost paleo flood plain unit, radiocarbon dated 17,760 YBP, is overlain by multiple debris flows (Fig. 3, site 7a). Other debris-fan exposures showing similar degrees of weathering, topographic position, and sedimentological sequences were noted and are probably associated with late Wisconsinan debris fan progradation.

The onset of a warmer climate during the Holocene terminated periglacial processes, presumably lowering the rate of mechanical weathering and transportable sediment. The sparsely covered slopes were gradually covered by deciduous vegetation, thereby increasing the stability of the hillslopes (Delcourt and Delcourt, 1988). The reduction of the sediment supply to the fluvial system probably initiated stream incision through the Pleistocene-age debris fans, allowing Holocene debris flows to bypass many of the higher elevation fans and deposit onto Holocene fans that grade into the modern flood plain. Inspection made of low-order streams following the Madison County storm indicated that the sediment comprising the debris flows was largely derived from Pleistocene-age deposits. In short, Holocene debris flow processes appear to be mining the Pleistocene deposits.

Debris flow activity is a significant factor in sediment transport and the long-term denudation in the Blue Ridge uplands. Work by Eaton (1999) and Springer et al. (2001) indicates that nearly half of the long-term sediment transport in the upland areas of the Blue Ridge occurs during extreme events. Basins studied by Springer et al. (2001) were denuded an average of 3.3 cm during the Madison County storm (e.g., a basin of 92,000 m^2 loses 2497 m^3 of sediment, yielding 2.7 cm of denudation). Using regional denudation rates of solid and chemical loads by Judson and Ritter (1964), 27% of the long-term denudation projected for a period of 2500 years (12.1 cm) occurred in a single event. If only the solid load is considered (5.1 cm/2500 years) (Judson and Ritter, 1964), then 65% of the long-term mechanical denudation occurred in a single event. Similar observations were made following the Hurricane Camille event in Nelson County, VA, where 47% of the long-term mechanical denudation occurred in 1 day (Eaton, 1999). These data support earlier suggestions that high-magnitude events significantly modify upland landscapes (Kochel, 1987; Jacobson et al., 1989; Miller, 1990).

These studies appear to contradict findings of other workers (e.g., Wolman and Miller, 1960; Moss and Kochel, 1978) that document high-magnitude, low-frequency events transport only a small fraction of the total annual sediment load, or geomorphic work. However, these studies were conducted primarily on larger, low-gradient rivers. The following model is proposed to address the differences in observed geomorphic work with respect to event magnitude and stream gradient throughout the Appalachian geomorphic system, where low-order drainages are dominated by steep gradients and coarse bedload streams.

Much of the sediment stored in low-order basins is too coarse to be moved during annual bankfull flood stage. Traverses through undisturbed Blue Ridge drainages show most hollows are choked with large boulders that have little chance of being mobilized by the bankfull flows (Fig. 10a). The majority of the material is exported down to the debris fans and mountainous flood plains only by episodic debris flows with return intervals measured in thousands of years (Fig. 10b). Once the material is deposited onto flood plains or debris fans, bankfull flows gradually rework and transport the sediment from areas of storage to the lower gradient Piedmont and Coastal Plain streams. Sediment that is too large to mobilize remains in situ until another high-magnitude event occurs or weathering and comminution can sufficiently reduce the particles to a transportable size.

Other workers (e.g., Kochel, 1988; Jacobson et al., 1989; Miller, 1990) suggested similar models in which high-magnitude events significantly modify upland landscapes; however, each lacked the quantitative data necessary to definitively test their hypoth-

Fig. 10. (a) Cripple Creek, located in Nelson County, is typical of many first- and second-order tributaries in the Blue Ridge Mountains of Virginia. Note the abundance of cobbles and boulders. (b) An unnamed tributary of the upper Rapidan River denuded to bedrock and purged of boulders following the Madison County storm. Note the elevated water mark on the right bank relative to the left bank due to high debris flow velocities (superelevation).

eses. This model differs slightly from one developed by Kochel (1987) following his research in Nelson County, 90 km to the southwest of the Rapidan basin. He proposed that debris flow processes in the Blue Ridge are largely Holocene events, based on a dearth of Pleistocene radiocarbon dates of excavated debris fan and flood plain deposits. The data show the age of the oldest debris flow deposit as early Holocene (10,510 ± 190 YBP), suggesting that the climate may have ameliorated sufficiently to permit the incursion of tropical air masses into the central Appalachians. However, his field investigations were hampered by massive post-storm modification of the study area prior to his study, limiting his efforts to three debris fan sites, and only five radiocarbon dates. Following the work in the Rapidan basin, it is the authors' opinion that debris flow deposits of late Pleistocene age are also present in Nelson County, but were obscured within several years from subsequent seasonal mass wasting and flood events, and rapid revegetation of the regolith slopes.

Future questions that remain to be answered include documenting denudation rates of upland Appalachian landscapes, and quantifying the geomorphic effectiveness and magnitude of debris flow activity during the late Pleistocene. Studies of future events, and closer examination of current periglacial mountainous terrain will aid in this discussion.

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