The Debris Flows of Madison County, Virginia

Oblique aerial view (to northwest) of debris flow chutes and flood deposits from the June 27, 1995 flood at Kinsey Run, near Graves Mill

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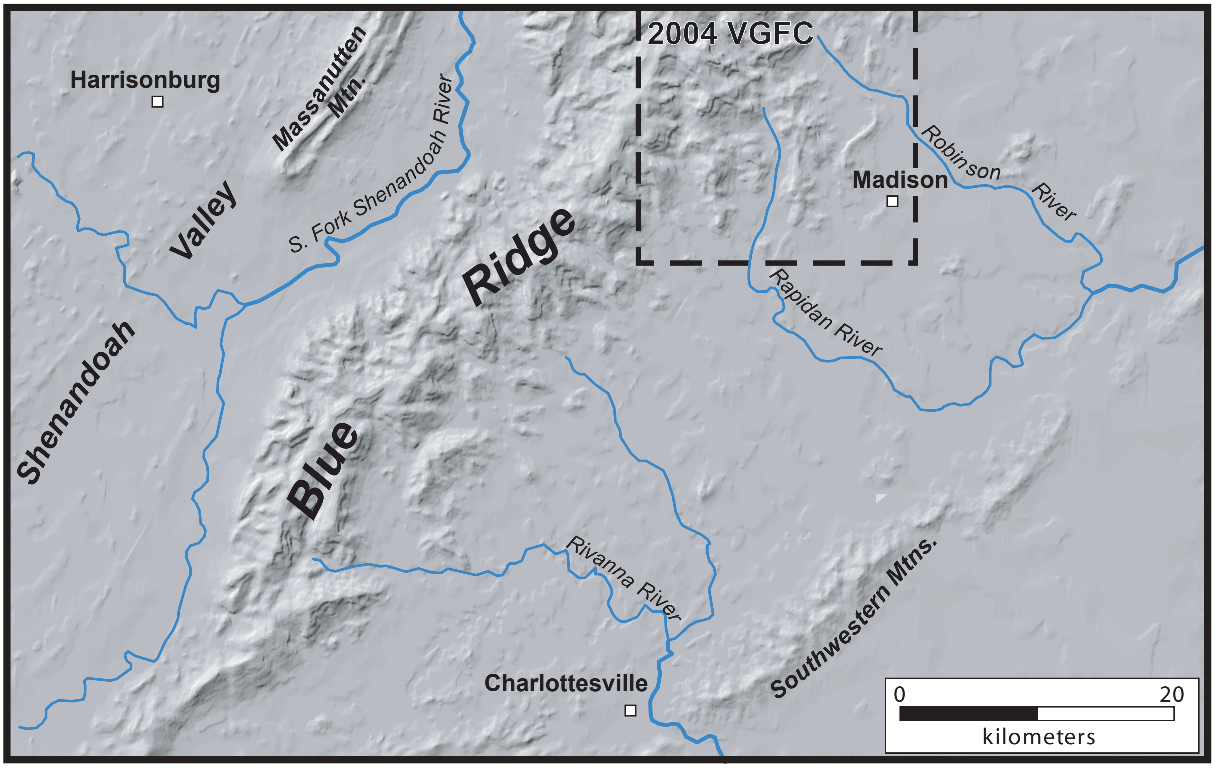


Figure 1. Shaded DEM of the Charlottesville 1:100K quadrangle with major geographic features.

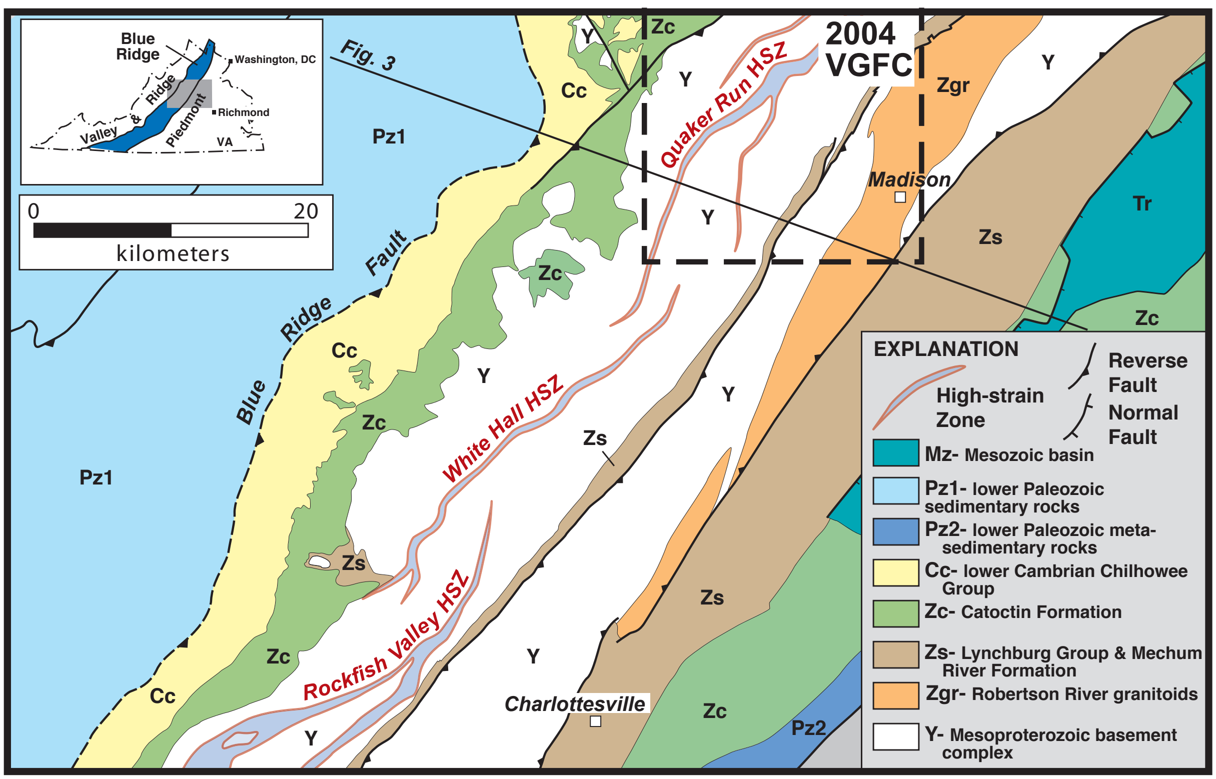


Figure 2. Generalized geologic map of the Charlottesville 1:100K quadrangle. Data from many sources.

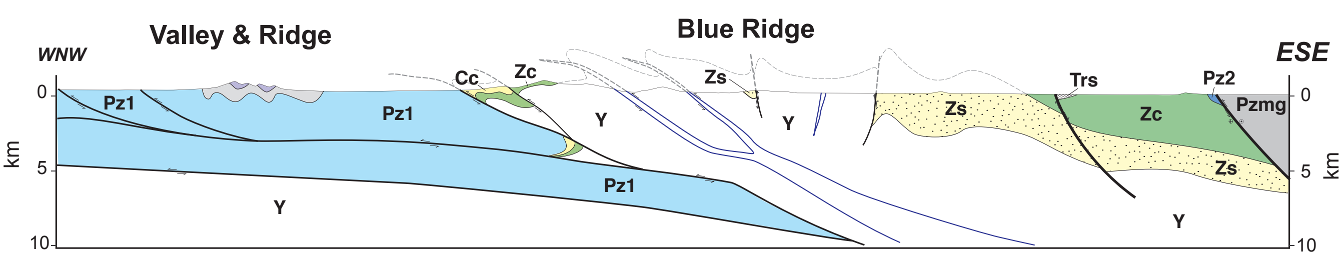


Figure 3. Generalized geologic cross section across the Blue Ridge anticlinorium in Madison County

"Ignorance is preferable to error; and he is less remote from the truth who believes nothing, than he who believes what is wrong."
Thomas Jefferson, *Notes on the State of Virginia* (1787)

Introduction

Geology has experienced tremendous changes in content and focus over the last several decades. Topics that were once considered peripheral in scope or belonging to other disciplines (e.g. geomorphology, soils, hydrology) are increasingly being integrated into research and have become important components of geology curricula. Geologists are commonly asked to investigate complex problems that require an understanding of soils, engineering, and hydrology. The current literature illustrates how increasing collaboration among experts from different geologic disciplines is being used to answer multifaceted research questions.

The 2004 Virginia Geological Field Conference combines both traditional and applied geology to investigate some of the larger questions concerning the geologic history and landscape evolution in the Blue Ridge Mountains of north-central Virginia. The catalyst for our research in Madison County was the June 27, 1995 storm that devastated the region; the destruction of private and public property was enormous. Thousands of debris flows were triggered by this storm, some moved at velocities greater than 60 kilometers per hour (40 mph), and mobilized large quantities of sediment. In the steep upper reaches of stream valleys, debris flows scoured and exposed large sinuous bedrock outcrops, while on adjoining fans and floodplains sediment was deposited (cover photo).

Erosion from this storm produced a number of remarkable exposures of both bedrock and older surficial deposits. Surficial exposures have yielded a wealth of information concerning the Quaternary history of debris flow activity, climate in the region, and the nature of modern geologic hazards. Newly exposed bedrock reveals much about the Paleozoic and Proterozoic tectonics of the Blue Ridge. Over the last nine years, geologists from a number of institutions have used these exposures to study the surficial and bedrock geology at a level of detail not generally obtainable in Virginia. These studies have dramatically improved our understanding of Blue Ridge geology.

The Blue Ridge Mountains form the easternmost range in the central and southern Appalachians. In north-central Virginia, the Blue Ridge forms a 10-20 km wide range characterized by significant topographic relief and a single high crest with elevations in excess of 1200 m (Fig. 1). In Madison County, the east side of the Blue Ridge is drained by the Robinson and Rapidan Rivers, tributaries streams to the Rappahannock (Fig. 1). The Blue Ridge geologic province is wider than the physiographic Blue Ridge and forms a broad anticlinorium that exposes Mesoproterozoic basement rocks (Fig. 2 & 3). This year's field conference has four planned stops in the Madison area and each will include components of both surficial and bedrock geology (Fig. 4).

Acknowledgements

This field conference has been made possible by the kindness and generosity of many people in Madison County. In particular we wish to thank the Aylors, Randall, Rodney and Ruth Lillard, Jimmy Graves, and General Bob and Nicki Jenkins. Over the past eight years a small army of undergraduates from James Madison University, the College of Willliam & Mary, and Bucknell University have completed thesis research in the Madison area. Their labors, in both the field and laboratory, have borne fruit; as their research is substantive and greatly improved our understanding of Blue Ridge geology.

We thank our colleagues, Ben Morgan, Gerry Wieczorek, Scott Southworth, Craig Kochel, Alan Howard, Dick Tollo, John Aleinikoff, Mick Kunk, Nick Evans, Bill Henika, and David Spears for informative discussions concerning Blue Ridge geology. Adam Forte and Pablo Yanez put an extraordinary effort into the preparation of this guidebook. It could not have been finished without you. Thanks.

We also wish to thank our parents, who long ago graciously tolerated our outdoor adventures in the Blue Ridge and encouraged our early interests in geology. It finally amounted to something!

The Storm of June 27, 1995

Detailed discussions of the June 27, 1995 storm and related events are presented in Smith and others (1996), Wieczorek and others (2000), and Eaton (1999). The widespread flooding and debris flow activity that impacted western Madison and Greene Counties was the result of multiple storms with high rainfall intensity and duration. The region had received ample antecedent rainfall, ranging from 75 to 170 mm (3.0 to 6.7 in), 5 days prior to the June 27 storm, thus increasing the moisture content of regolith and saprolite. A cold front stalled east of the Blue Ridge Mountains where a moist southerly tropical air mass met a northerly polar air mass (Goldsmith and others, 1995). From 2 to 6 a.m. on June 27, residents reported continuous rain. After a brief hiatus, continuous heavy rain resumed around 10 a.m. and lasted until 4 p.m. During this 14-hour period, rain fell with extreme intensity for several hours, initiating over 1000 debris flows in an area of 130 km^2. The maximum rainfall total was in Graves Mill, where two residents measured 770 mm (30.5 in) of rainfall during this storm (Fig. 5). The highest rainfall intensity was measured near Kinderhook, 1 km west Kirtley Mountain, where 180 mm/hr (7.1 in/hr) fell during 35 minutes, equivalent to 300 mm/hr (11.8 in/hr).

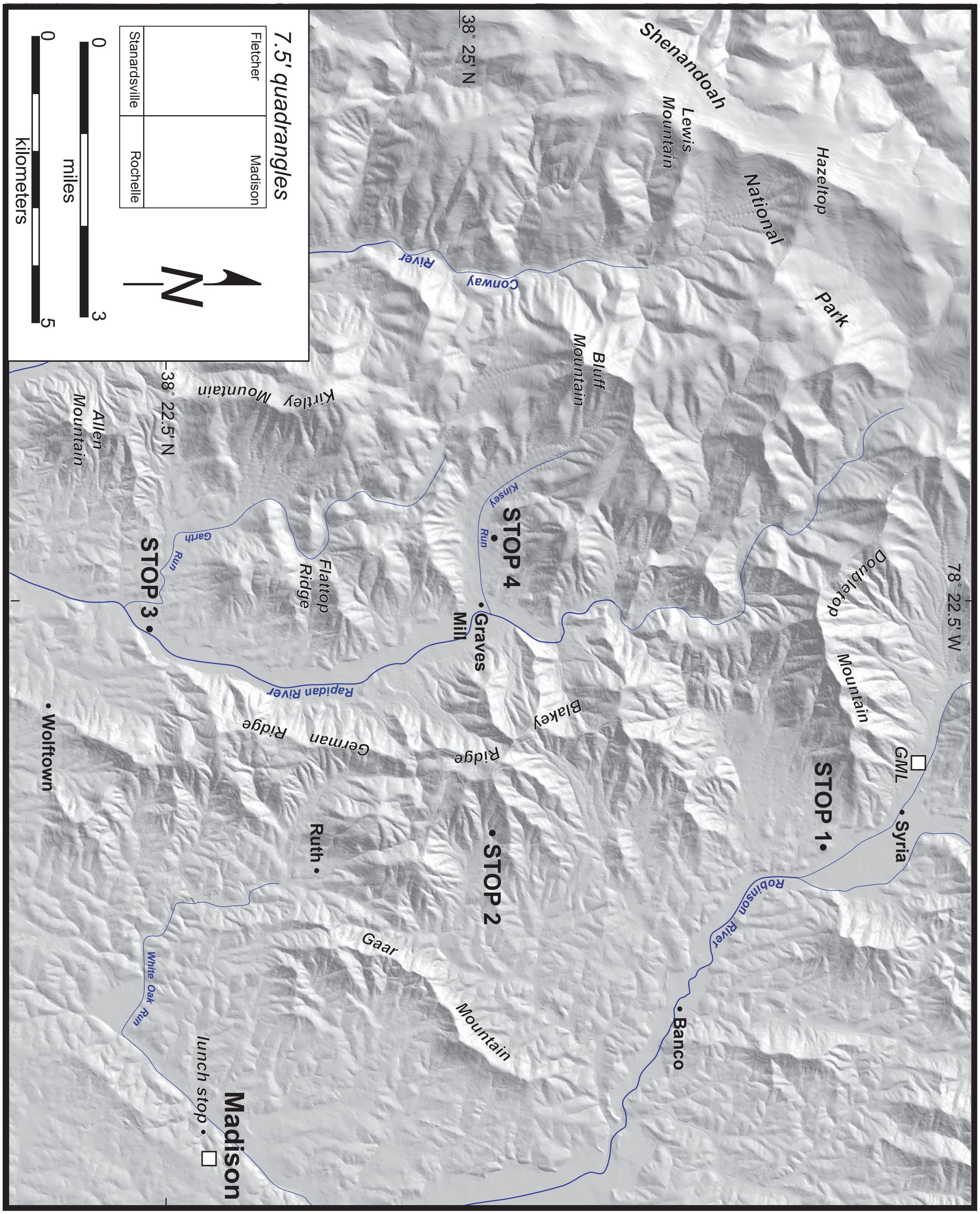


Figure 4. Shaded DEM of the Madison area with field trip stops marked.

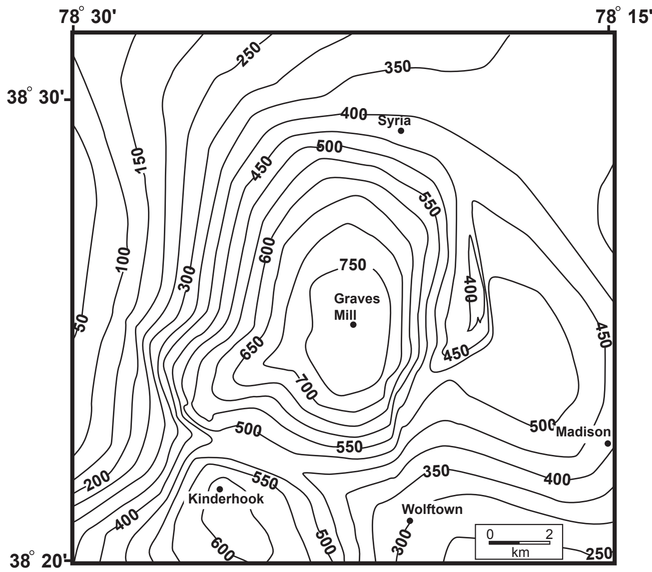


Figure 5. Rainfall contours (mm) from June 27, 1995 storm in Madison County (from Wieczorek and others, 2000).

The storm was not limited to this region. Later that evening the North Fork of the Moormans River in western Albemarle County, located 45 km southwest of the Rapidan Basin, was also affected by the storm system. The rainfall exceeded 279 mm (11 in.) (Morgan and Wieczorek, 1996), but may have been as great as 635 mm (25 in.) (Carlton Frazier, 1996, pers. com.). Nearly 100 debris flows were documented in a much smaller area (13 km^2) relative to the Rapidan Basin (100 km^2). The debris-flow surges partially filled the Sugar Hollow Reservoir, and had the potential for compromising the dam had not water been manually released prior to the arrival of the flows. The storm also affected the western slopes of the Blue Ridge near Buena Vista, and triggered nearly a dozen debris flows. Unfortunately, little is known about the rainfall totals for this region, as no rain gages were present at the time of the storm.

Surficial Geology

Overview

The Rapidan River and its major tributaries (Robinson, Conway, and South Rivers) originate in the eastern flanks of the Blue Ridge Mountains in north-central Virginia (Fig. 1 & 4). 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°.

Much of the landscape is mantled by regolith. 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 from streams deposits. The soil orders developed from the regolith are primarily Ultisols, Inceptisols, and Entisols (Elder and Pettry, 1975). Ultisols occur 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 floodplains. Eaton and others (2001a) produced surficial geologic maps of the Fletcher, Madison, and Stanardsville 7.5' quadrangles and these maps are compiled in Figure 6.

What follows is an overview of the dominant landforms and surficial deposits in the Rapidan basin and the north-central Blue Ridge Mountains. Although time will not allow us to visit all of these features, references documenting the location of these deposits are provided for future field excursions.

Blockfields and boulder streams

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). 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 preferential orientations of boulders in the headwaters of the Blue Ridge suggest widespread Pleistocene periglacial activity (Fig. 7). In general, wherever frost heaving is prominent, tabular stones within the regolith tend to be vertically oriented (Washburn, 1979). Researchers have mapped numerous sites that contain these features (e.g., Whittecar and Ryter, 1992; Morgan, 1998; Eaton and others, 2001b). Recent work by Eaton and others (2002) at Blackrock summit, Shenandoah National Park, noted a prominent blockfield that contained a series of benches and escarpments, as well as boulders oriented with their long axis oriented parallel to the slope (Fig. 7). They attributed this morphology to solifluction processes similar to features found in southern and central Pennsylvania, proximal to the margins of late Pleistocene glaciation.

The significance of these features is that much of the regolith in the Blue Ridge may be relict; that is, it likely formed during late Pleistocene conditions. Mapping conducted by Eaton and others (2001a) in upland mountain hollows showed most channels are filled with sediments that range in size from small cobbles to boulders exceeding 6 m in length. The pervasiveness of blockfields and boulder streams that remain unmodified in the present landscape indicate little Holocene modification and, therefore, are relict of colder climates. Other workers have made similar conclusions on the genesis of many of the Appalachian landforms (e.g., Clark and Ciolkosz, 1988; Delcourt and Delcourt, 1988; Braun, 1989; Ciolkosz and others, 1990; Gardner and others, 1991; Ritter and others 1995).

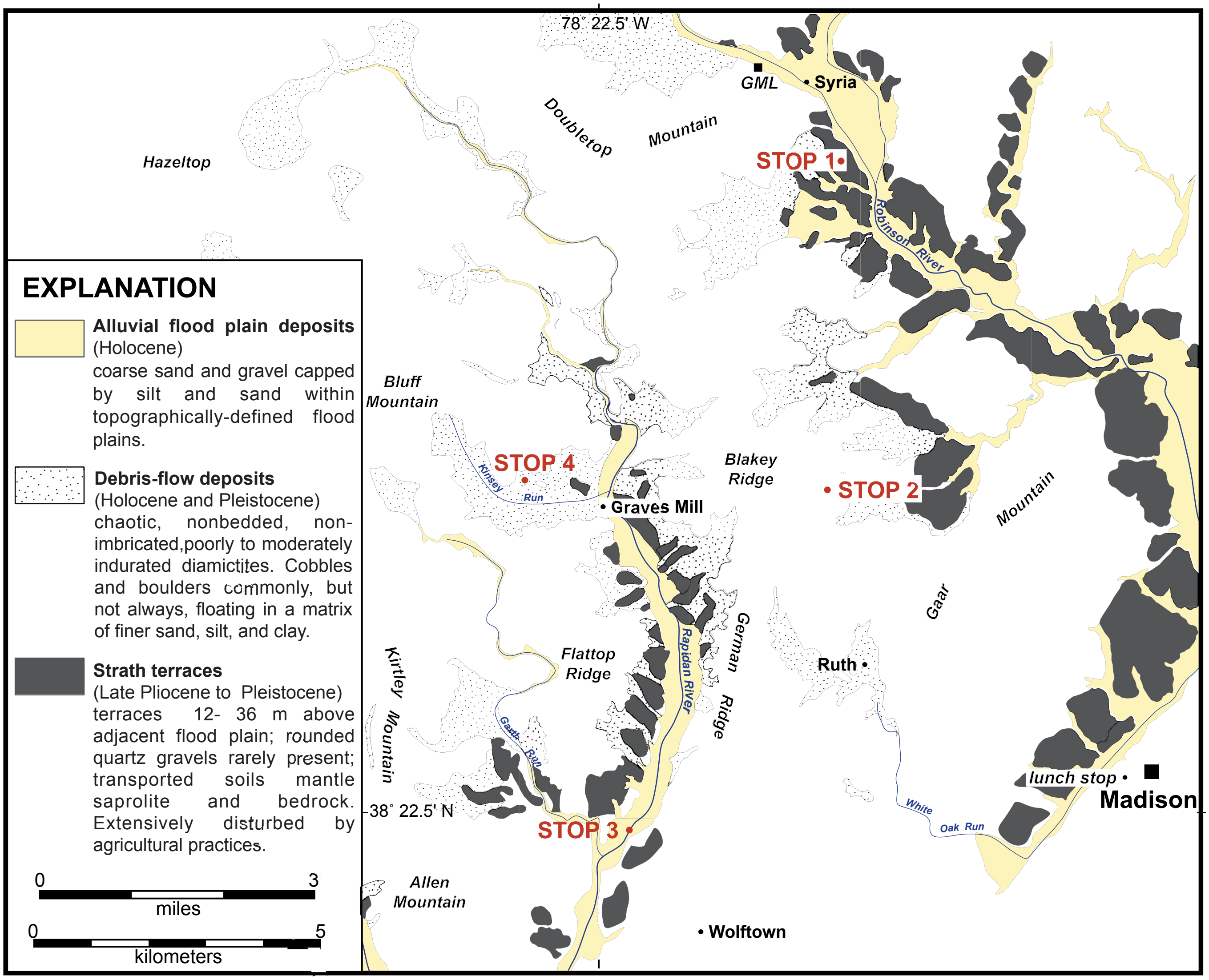


Figure 6. Generalized surficial geologic map of the Madison area. Modified from Eaton and others (2001a).

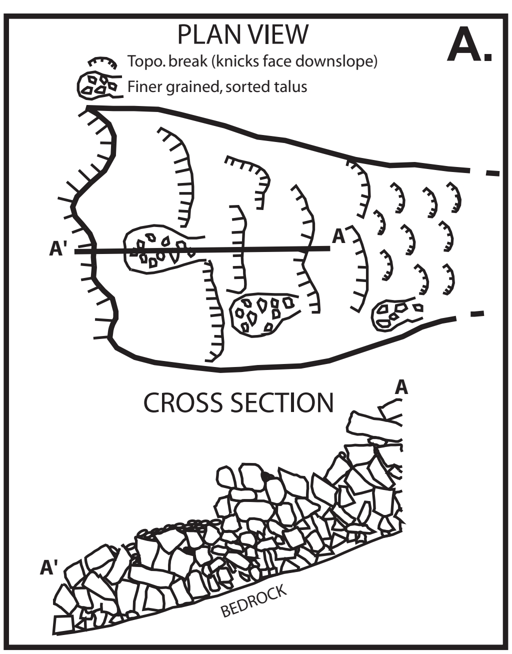
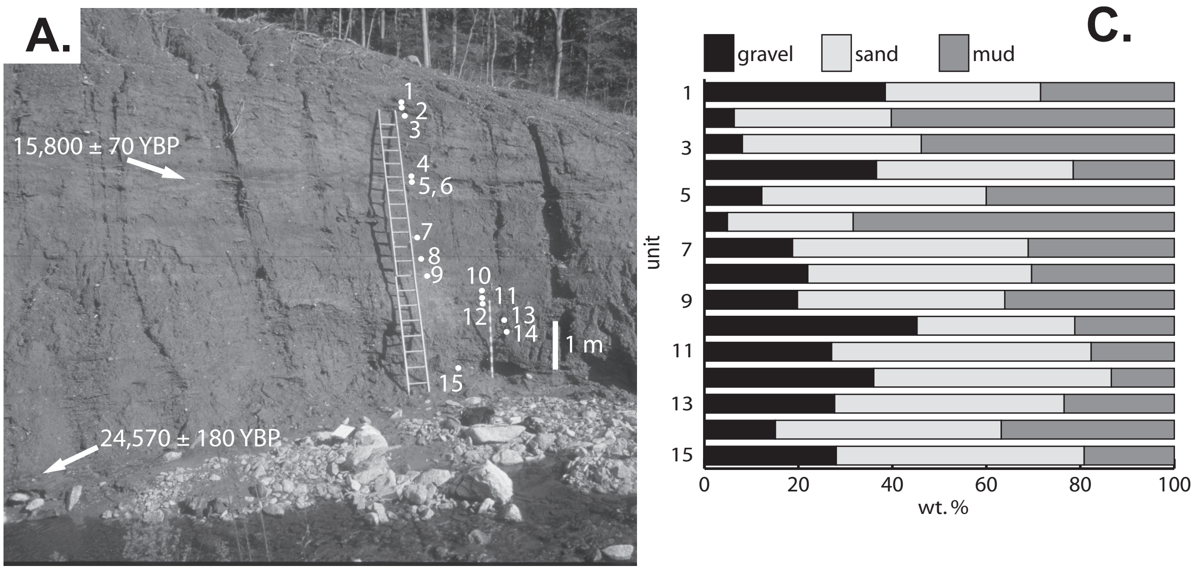


Figure 7.
A. Plan and cross section schematic views of the topography at Blackrock, Shenandoah National Park (from Eaton and others, 2002). B. View towards northeast of upper, widest part of block slope at Blackrock, Shenandoah National Park. Block slope is approximately 175 m in width, and mean volume of boulders is 0.8 cubic m.

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 and others, 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. Prior to the June 27, 1995 storm, most of these studies had taken place in the unglaciated terrain of Pennsylvania (e.g., Jobling, 1969; Sevon and Berg, 1979; Clark and Ciolkosz, 1988; Gardner and others, 1991). The storm exposed these previously unknown deposits throughout the upper Rapidan, Robinson, and Conway River basins. Because of time constraints, our trip will not include a stop to view these deposits. However, their pervasiveness throughout the basin warrants discussion here, and their locations are documented in Eaton and others (2003b).

In general, these deposits exposed from the 1995 flood have rhythmic layers of clast-supported and matrix-supported platy, angular, pebble-sized rock chips aligned parallel to the slope of the hillside (Fig. 8). Individual layers within the deposits are typically thin (~0.1 m thick), 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. 6 & 8) (Eaton, 1999; Eaton and others, 2001b). The 1995 flood exposed 6.5 vertical meters of stratified slope deposits with individual



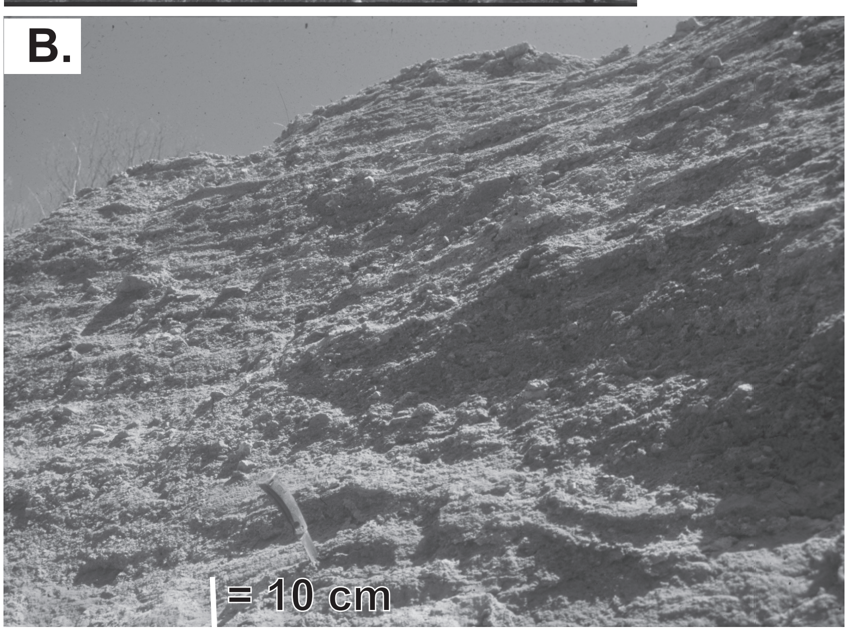


Figure 8. Stratified slope deposits, Kinsey Run, Graves Mill. A. Overview of site. B. close up oblique view of individual beds. C. particle size analyses of prominent beds (From Eaton and others, 2003b).

beds that are laterally continuous for a minimum of 50 m. The deposit is thickest at the downslope end adjacent to the modern channel and gradually thins upslope. The Kinsey Run site has numerous, thinly bedded (2 to 5 cm) units that dip 7-12˚, subparallel to the hillslope. The matrix surrounding the chips consists of sand, sandy loam, and loam. Munsell soil colors are dominantly 10YR, 5Y, and 2.5Y (brown-to-yellow brown) hues. The units are poorly sorted and chiefly grain supported; however, matrix supported pebbles do occur.

The timing and rate of deposition of these stratified slope deposits were determined by radiocarbon dating. At the Kinsey Run site, 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/1000 yr. 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 rates of accumulation were found at a second site, and are documented in Eaton and others (2003b).

The late Wisconsinan ages of the stratified slope deposits in the Rapidan basin indicate 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 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 (e.g., Litwin, 2004; Smoot, 2004).

Debris fans and flows

Debris fans are prominent geomorphic features along the eastern flank of the Blue Ridge in central Virginia (Fig. 6). 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 & Range province of the western United States and in the eastern Shenandoah Valley of Virginia (King, 1950). Most of the debris fans in the study area 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, whose episodic failures serve as the sources for the fan deposits (Fig. 9). 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, commonly 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 (Fig. 9). Deposits from multiple flows can create substantial fans that coalesce in aprons along the base of mountain slopes.

In the Rapidan basin, maximum fan exposures of 4 m were observed in the 1995 scour zones near the apices (Fig. 10). 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; and the complete disintegration of granitic clasts in some of the flows suggests emplacement ages of hundred of thousands of years (Fig. 11). Work by Eaton and McGeehin (1997) and Eaton and others (2001) included 39 radiometric carbon dates that originated from debris-flow, slope-wash, and fluvial deposits and paleosols in the study area. This research indicates a recurrence interval of debris-flow activity of approximately 2500 yr since the onset of the Wisconsinan glacial maximum.

Figure 9. Photo of Kirtley Mountain, March 1996. Dashed line approximates the boundary between debris flow chutes and debris fans .

Figure 10. Prehistoric debris flow deposits exposed in Deep Hollow fan. Bedrock-debris flow contact is marked by person's hand. This site was reclaimed by the NRCS within a few months following the storm.

Several debris fans have been the focus of intense study following the June 27, 1995 storm (Daniels, 1997; Eaton, 1999; Eaton and others, 2001b; Scheidt, 2001). Studies of soil profile development on several 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. One debris fan located 1.3 km WNW of Graves Mill, referred to as the Generals Fan in this study, consists of at least five distinctive weathering surfaces that range in age from modern to 0.5 MYBP; and is discussed in detail at Stop 4 of this field guide.

Although the field trip will not examine the fans on the west side of the Blue Ridge, they are of interest as they are strikingly different in morphology and process in comparison to fans situated on the eastern flank. The western flank of the Blue Ridge is bordered by coalescing alluvial fans comprised of extensive gravels and sands of fluvial origin. The fans are best developed from Waynesboro north to Luray (Fig. 1). These landforms are broad in plan view, and extend with gentle slopes of usually less than 6 degrees from the mountain front to the South and Shenandoah Rivers. They are almost entirely made up of detritus from the Cambrian Chilhowee Group, especially the more resistant quartz arenites of the Antietam Formation. The fans grade over the Tomstown Dolomite and Waynesboro Formation, and older fan surfaces are degraded due to extensive solution and karstification. As the fans collapse into the karst, alluvial deposits commonly reach thicknesses of 30 m (100 ft); drill records reveal that they can be as much as 53 m (175 ft) thick in places (King, 1950). This geologic situation is fortuitous for those seeking high yielding water wells, as demonstrated by the numerous aqua-loving industries situated along the western slopes of the Blue Ridge. Morgan and others (2003) discuss these fans in more detail.

River terraces and alluvial deposits

The oldest surficial landforms present in the Rapidan valley are fluvial terraces (Figs. 6 & 12). They are the most prominent landforms on the valley floor and are traceable for ~160 km from the Fall Zone

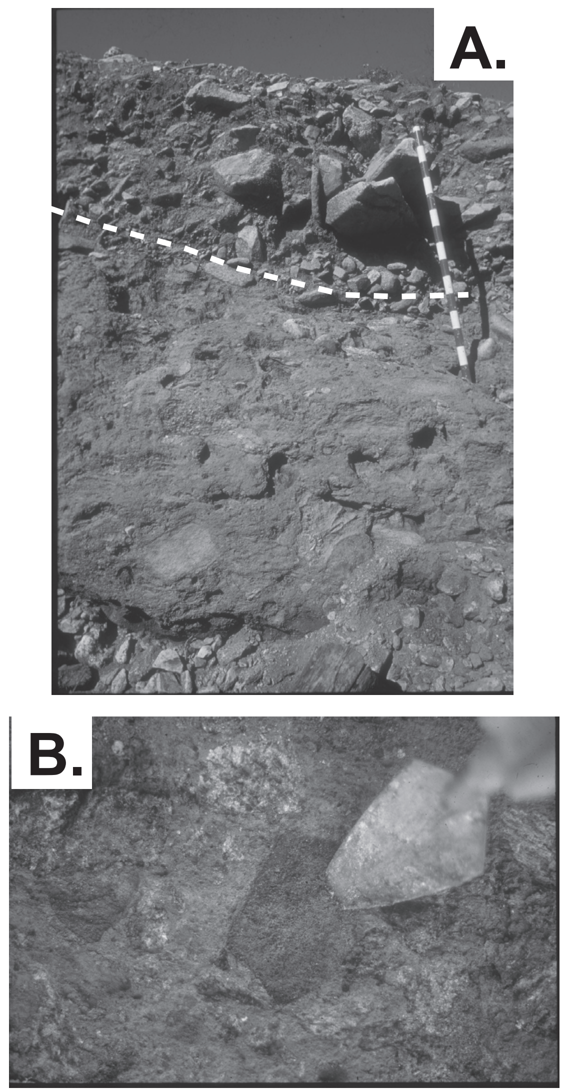


Figure 11. Debris flow deposits exposed by the June 1995 storm. A. Dashed line shows boundary between two prehistoric debris flow deposits; the clastsin the basal unit have weathered to saprolite. B. Trowel easily penetrates granitic clast.

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 segments 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 and others (1993) and by Markewich and others (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 MYBP to 5.3 MYBP (Howard and others, 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 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 and others (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 and others, 2001b).

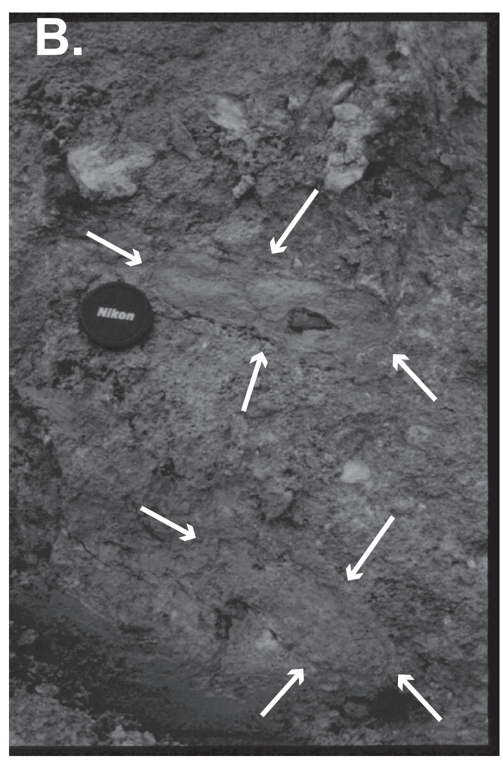


Figure 12. A. House and farm buildings reside on one of the high terrace surfaces present in the Rapidan basin. Note the debris flow chutes still visible on Kirtley Mountain. Photo is taken from the Rt. 662 bridge, Stop 3 of this field guide (Photo by C.L. May, 2003). B. In situ weathered terrace gravels (outlined by arrows) exhumed in a borrow pit near Graves Mill, ~1 km upstream of terrace surface shown in A.

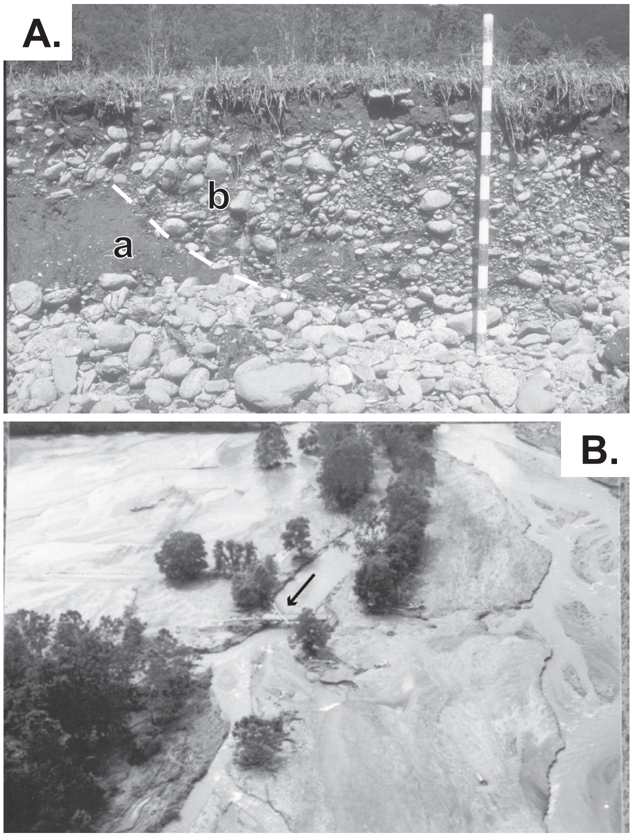


Figure 13. A. Rapidan alluvial deposits near the Rt 676 Bridge. Organic-rich soil (a), (1550 +/- 50 YPB) is truncated by a channel fill deposit (b) prior to the 1995 storm. Scale is in decimeters. B. Rapidan River, 1 km downstream of Graves Mill during the recession of the June 27, 1995 flood. Arrow denotes the remnants of the Rt. 676 bridge (view is upstream). Note the braided pattern of the channels following the event. This pattern resumed again during Hurricane Fran (Sept. 1996). The system has been repeatedly anthropogenically 'restored' to a single narrow channel and continues to be unstable.

Floodplains and alluvial deposits

Alluvial deposits mantle most of the low gradient stream valleys draining the Blue Ridge. Channel deposits consist of cobbles and pebbles that are clast-supported and imbricated, and overlain by overbank deposits of fine gravel, sand, silt, and clay (Fig. 13a). Rather than a simple time-stratigraphic sequence, this pair of strata is produced by the meandering of the stream scrolling across the floodplain, scouring previous alluvial deposits, and leaving a track of channel material that is overlain by later overbank deposits during periods of flooding. Streams draining the uplands pass through debris-flow fans that are gradually merged into the flood plain sequence so that the more distal parts of the fans are overlain by slack water deposits. The distal parts of the debris-flow fan are commonly modified by later flooding so that the boundary between debris-flow fan and alluvial channel sediment is partly overlain by slack water deposits.

In the Rapidan basin, streams draining bedrock and debris fan deposits broaden out into well-developed floodplains that have been extensively modified by agricultural practices. Most major streams such as the Robinson, Rapidan, Conway, and South Rivers have been straightened and deepened (channelized) to increase the agricultural potential of the floodplain. Furthermore, the alluvial deposits are dissected by numerous drainage ditches and tiles. Generally speaking, landowners have very precise ideas and needs concerning where the streams are supposed to flow and move strenuously to correct deviant behavior caused by major floods. In an attempt to minimize flooding on personal property, landowners have straightened many stream courses, stripped off vegetation in the riparian zones, built dikes, lined channels with boulders, and smoothed out the streambed riffles. Most of these attempts have proven disastrous, and have drastically increased the flooding potential down stream for their neighbors. Preliminary evidence suggests that prehistoric floodplains near the mountain front were choked with gravel and probably braided by numerous, short-lived, shallow stream channels. The movement of gravel and cobbles into the floodplain probably took place during episodic flooding throughout the late Pleistocene and Holocene. A substantial supply of sediment may have been derived from highland areas that were subjected to periglacial conditions with minimal vegetative cover during the late Pleistocene (Bradley, 1999). The sediment filled low lying areas east of the Blue Ridge creating a number of enlarged flood plains proximate to the Blue Ridge such as those on the Robinson, Hazel, Thornton, and Covington Rivers.

At present the floodplains are extensively used for agriculture. Although not practical given the current land use, braided fluvial channels on these floodplains would allow conveyance of flood water during storms, with minimal impact on the landforms. This process was observed following the 1996 Hurricane Fran flood that struck the Graves Mill area only a year after the larger 1995 flooding event. The areas on the Rapidan that had been shaped to a linear, deep, wide, single channel morphology were returned to their immediate post-flood morphology: multichannel flow and wide, shallow channels. In contrast, stream reaches that were left undisturbed following the 1995 flood showed little or no change as a result of the subsequent flooding, as they were already adjusted for larger flows. These observations indicate that the anthropogenically-modified stream systems are unstable, and have great potential for failure during floods that produce near, or exceed bankfull flow, which occur approximately every 1 to 3 years (Eaton, 1999). Subsequent observations made since 1995 indicate that these approximately annual floods continue to blow out channels and require further anthropogenic modification (Figure 13b).

Bedrock Geology

In central and northern Virginia, the Blue Ridge geologic province forms a broad anticlinorium (Figs. 2 & 3) that developed as basement thrust sheets were imbricated and the overlying cover rocks folded during northwest-directed crustal shortening in the middle to late Paleozoic. Mesoproterozoic basement rocks are exposed in the core of the anticlinorium (Figs. 2 & 3). Neoproterozoic to early Paleozoic metasedimentary and metavolcanic cover rocks crop out on the anticlinorium flanks and in fault-bounded inliers (Figs. 2 & 3).

In Madison County the basement complex consists of a suite of ~1,030 to 1,180 Ma granitoids and granitoid gneisses that formed in the middle and lower crust during the long-lived Grenville orogeny (Bailey and others, 2003; Tollo and others 2004a, b). Grenvillian rocks were intruded by granitoids of the Robertson River batholith between 700 and 735 Ma (Tollo and Aleinikoff, 1996). Robertson River granitoids form dike-like plutons that were emplaced during regional extension. Rift-related arkosic rocks of the Swift Run Formation, Mechum River Formation, and Lynchburg Group were deposited in a series of basins that received sediment from source areas exposing Grenvillian and Robertson River granitoids (Schwab, 1974; Wehr, 1986; Bailey and Peters, 1998). Neoproterozoic metasedimentary units are overlain by the voluminous metabasalts of the ~570 Ma Catoctin Formation (Badger and Sinha, 1988; Aleinikoff and others, 1995). The Catoctin Formation is exposed on both the western and eastern limbs of the anticlinorium (Fig. 2 and 3). Catoctin flood basalts extruded during a second successful phase of Neoproterozoic rifting and by the early Cambrian the Iapetus Ocean had opened to the east of the Blue Ridge. In the western Blue Ridge, shallow marine siliciclastics of the Chilhowee Group were deposited on the North American edge of Iapetus.

During collisional tectonic events in the middle to late Paleozoic, all units in the Blue Ridge were deformed and metamorphosed to varying degrees. Many of the basement rocks and most of the overlying cover sequence display a penetrative foliation that typically strikes NE-SW and dips to the southeast. Blue Ridge rocks were faulted over early Paleozoic rocks of the Valley & Ridge province during the late Paleozoic Alleghanian orogeny (Evans, 1989). The total shortening across the Blue Ridge province is at least 50% (Mitra, 1977; Evans, 1989; Bailey, 1994). The Blue Ridge anticlinorium is ~40 km wide, however prior to deformation, rocks that would become the western and eastern limbs were separated by over 80 km. The youngest rocks in the Blue Ridge are Mesozoic diabase dikes related to the distal effects of rifting associated with the opening of the Atlantic Ocean. Rocks exposed in the Blue Ridge province provide evidence of a long complex history involving multiple episodes of both continental rifting and collisional tectonics.

This year's field conference will visit exposures in western Madison County and focus primarily on the basement complex (Fig. 14). Allen (1963) recognized four basement formations in Greene and Madison counties: these included the Lovingston, Marshall, Old Rag, and Pedlar Formations. Recent workers have not mapped formations within the basement complex in the Virginia Blue Ridge; rather Mesoproterozoic units are distinguished on the basis of rock type, cross cutting relations, geochemistry and modern U-Pb geochronology. Field relations are discussed in Bailey and others (2003), Tollo and others (2004a, b). Tollo and others (2004a, 2004b) present detailed petrological, geochemical and geochronological data.

In the Madison 7.5' quadrangle, Bailey and others (2003) recognized five basement units that include a suite of older (>1180 Ma) granitoid units that were intruded by younger (1030–1060 Ma) granitoid units (Figs. 14, 15, & 16). The oldest unit in the Madison area is a dark gray, fine- to medium-grained garnetiferous gneiss (**Ygn**) that is exposed as small (<1 km^2) inliers within younger rocks (Fig. 14). A composite felsic pluton (**Ylg**) that includes fine- to medium-grained leucocratic gneiss, coarse-grained granitic gneiss, and leucogranitic pegmatite crops out to the northwest of the Mechum River belt and southeast of the Quaker Run high-strain zone (Fig. 14). U-Pb ages from zircons in the coarse-grained granitic gneiss suggest a crystallization age for this pluton at 1,183±11 Ma (Tollo and others, 2004a); making it the oldest rock (for the time being) in the Virginia Blue Ridge dated using modern geochronologic methods. These rocks commonly display a foliation characterized by aligned feldspar and quartz aggregates that developed under high temperature conditions (>600° C) during Grenvillian orogenesis prior to the intrusion of the younger granitoid suite (~1,030 to 1,060 Ma).

Older Mesoproterozoic rocks are intruded by 1) charnockite (**Ych**), 2) biotite-bearing granitoid (**Ybg**), and 3) coarse-grained alkali feldspar granite (**Yaf**). The charnockite (**Ych**) crops out over a large area in the mountainous parts of western Madison County (Figs. 14 & 16) and is characterized by primary pyroxene ±hornblende, a low SiO_2 content (58-61%), and is typically massive. Tollo and others (2004b) obtained a U-Pb zircon age of 1,050±8 Ma for this unit. The biotite-bearing granitoid and gneiss (**Ybg**) is a heterogeneous unit that crops out to the southeast of the Quaker Run high-strain zone (Fig. 14). This unit commonly displays a greenschist facies (Paleozoic) fabric and metamorphic biotite forms up to 20% of this unit. Preliminary U-Pb zircon data indicates this unit may be one of the youngest in the Blue Ridge with a crystallization age of ~1,030 Ma (Tollo, pers. com. 2004). Two small bodies of alkali feldspar granite (Yaf) crop out near Ruth (Fig. 14). The mineralogy and chemistry of this unit is similar to the 1,060±5 Ma Old Rag granite exposed 20 km to the north (Tollo and others, 2004b; Hackley and Tollo, in press). Interestingly, **Ylg** and **Yaf** are compositionally similar (leucogranites),

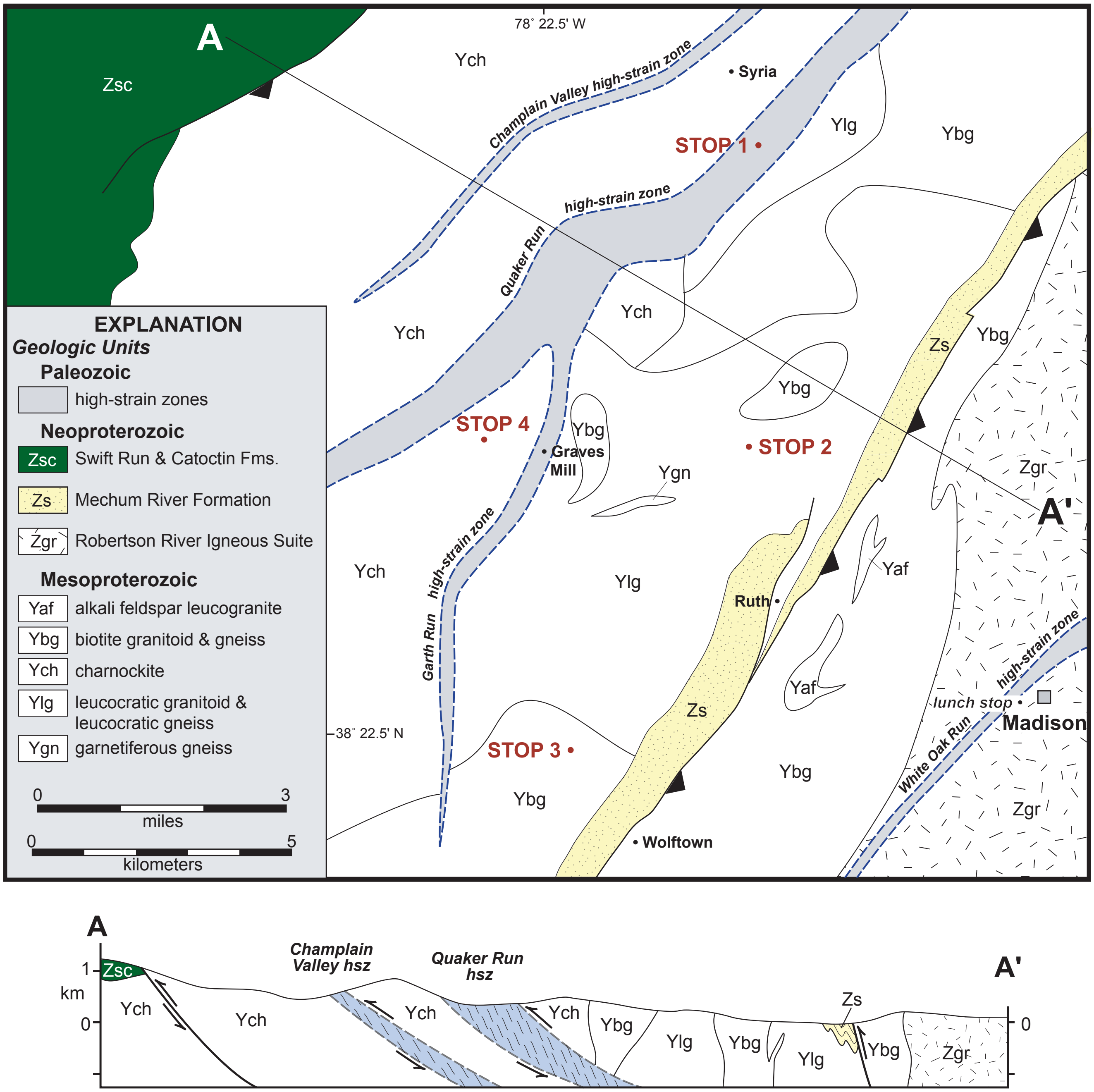


Figure 14 & 15. Generalized bedrock geology and cross section of the Madison quadrangle. Data from Bailey and others (2003) and Tollo and others (in press).

yet separated in age by over 100 Ma indicating that leucogranite generation occurred multiple times during Grenvillian orogenesis.

In Virginia, the Blue Ridge basement complex is cut by a network of high-strain zones (Figs. 2, 3, 14, & 15) (Mitra, 1977; Bartholomew and others, 1981; Bailey and Simpson, 1993). Individual high-strain zones form anastomosing, NE-SW striking belts of mylonitic rock, 0.5 to 3 km thick, that dip moderately to the southeast. In the northwestern part of Madison County, the Champlain Valley and Quaker Run high-strain zones cut the basement complex. These zones are characterized by protomylonite, mylonite, and rare ultramylonite derived from massive charnockitic rocks and granitic gneisses. Lenses of weakly foliated to massive charnockite occur within the high-strain zones. Asymmetric structures consistently record top-to-the-northwest (hanging wall up/ contractional movement) sense of shear. The northwest-directed movement (reverse) across these Blue Ridge high-strain zones accommodated crustal shortening in the Paleozoic. In essence, the development of high-strain zones in the Blue Ridge enabled the relatively stiff basement complex to shorten, while cover rocks (e.g. the Catoctin Formation and Chilhowee Group) were folded.

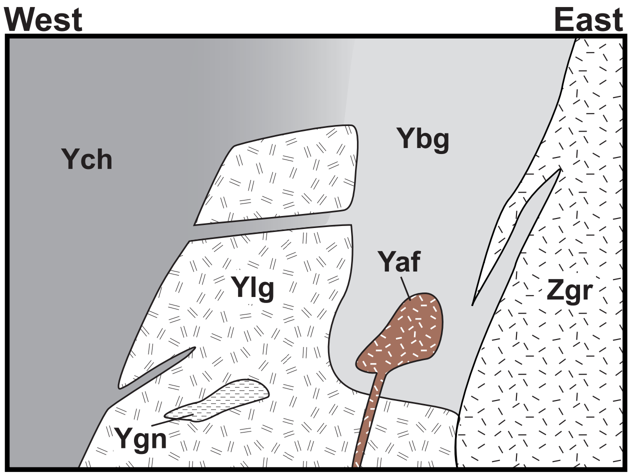


Figure 16. Contact relations between units in the Blue Ridge basement complex, Madison 7.5' quadrangle. **Zgr**- Robertson River Igneous Suite, **Yaf-** Coarse-grained alkali feldspar granite, **Ybg**- biotite granitoid gneiss, **Ych**- charnockite, **Ygn-** garnetiferous gneiss, **Ylg-** leucocratic granitoid gneiss. From Bailey and others (2003).

The total displacement across individual basement high-strain zones is modest (~1-2 km) and they do not form regional terrane boundaries (Berquist and Bailey, 2001; Bailey, 2003). These mylonitic rocks formed at the greenschist facies (~350˚-400˚ C) under conditions where fluid enhanced chemical reactions were common (Bailey and others, 1994). The age of metamorphism, ductile deformation and high-strain zone movement is poorly understood (middle to late Paleozoic based on scant cooling age data). We are currently analyzing a suite of samples from the Madison area (collaborative research with Michael Kunk at the U.S. Geological Survey) and expect to have a much better understanding of Blue Ridge thermochronology within the next year.

STOP 1-
Strath terrace overlooking the Robinson River Valley

Overview

We begin our excursion by examining one of the oldest surficial landforms present in the Robinson River valley and comment briefly on the nature of the topography and the bedrock.

The Terraces

Our vantage point at Stop 1 is situated atop a river terrace (Eaton and others, 2001b). These terraces are arguably the most prominent landforms on the valley floor in the upper Robinson, Rapidan, Conway, and South River valleys. In the upper Robinson basin, they are easily traceable for ~8 km from Graves Mountain Lodge to Banco, and are readily seen on both sides of the highway from the State Highway leading from Banco to Graves Mountain Lodge (Fig. 4 & 6). The highest surface is the most extensive and would form a nearly continuous, horizontal plane 25-30 m above the active floodplain throughout the basin 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. Other terrace surfaces have been stripped of alluvium, leaving behind large flat exposures of bedrock or thin alluvial soils. During reconnaissance for this field trip, cobbles were collected in a recent excavation for a house foundation at Stop 1. The cobbles, 5 to 15 cm in diameter, are rounded to subrounded, and extensively weathered. The soils mapped here are the Dyke series (clayey, mixed, mesic, typic Rhodudults), characterized by 2.5YR to 10R Munsell colors, thick argillic horizons, and deeply weathered clasts (Elder and Pettry, 1975). Although particle size analysis has not been conducted for this site, other Dyke soil series in the proximal Rapidan basin (Stop 4) have clay contents that exceed 70% (Eaton and others, 2001a). This value is striking when compared to the low concentrations of clay (<5%) present in the active channel and floodplains of these rivers. A cosmogenic Beryllium date taken from the Dyke series soil profile at Stop 4 suggests an age of approximately 500,000 YBP. In summary, these data indicate that these high terrace surfaces have been stable for hundreds of thousands of years.

Bedrock

Low outcrops of mylonitic charnockite in the Quaker Run high-strain zone are poorly exposed on the slopes below this strath terrace (Fig. 14). The southeast-dipping Quaker Run high-strain zone is one strand in an anastomosing set of high-strain zones that cut the Blue Ridge basement complex in Virginia. The high-strain zone is characterized by heterogeneously deformed mylonitic rocks. The footwall is underlain primarily by massive 1,050±8 Ma charnockite (**Ych**) (exposed to the northwest on Doubletop Mountain), whereas the hanging wall block (to the southeast) includes massive charnockite and variably deformed biotite-bearing granitoid gneiss and leucogranite gneiss (**Ybg**, **Ych**, **Ybg**). At this location the Quaker Run high-strain zone is approximately 1 km thick and displacement is estimated to be 1 km±0.5 km (Berquist and Bailey, 2001).

STOP 2-
Debris fan and chute, Aylor Farm

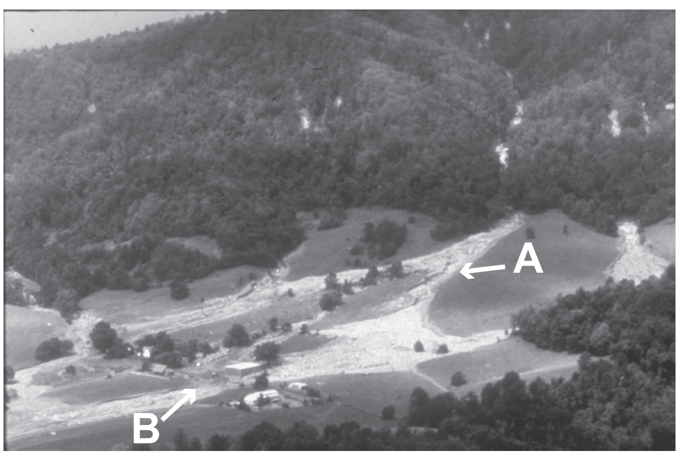
The Debris Fans

The Aylor fan, named after the owners of this property, is the first of two fans we will see during our excursion. The aerial photograph in Figure 17 was taken a few days after the June 27, 1995 storm and clearly shows the impact of the event upon the fan and the Deep Hollow basin. Debris flow deposits were ~2 m thick at location A (Fig. 17); floodwaters emerging from the chute scoured and exposed prehistoric debris flow deposits of >5 m thick near the fan apex. At this site two distinct debris flow deposits are present (Fig. 17, location B), the basal debris flow unit contains saprolitized cobbles and boulders.

This fan has been the focus of two undergraduate theses under the direction of Craig Kochel at Bucknell University. A cursory examination of the fan surface suggests homogeneity in both its soils and the timing of deposition. Research by Daniels (1997) and Scheidt (2001) examined soil pedogenesis throughout the fan, yielding a minimum of 4 surfaces of differing ages (Fig. 18). One soil pit was located on the QF1 surface; clasts were almost completely weathered. In contrast, two soil pits were situated on the QF2 surface. Both pits contained clasts that were only moderately weathered, where weathering rinds were approximately 2 cm thick. Soils of both QF1 and QF2 contained argillic horizons at approximately 80 cm from the surface, and maximum clay contents reached 40%. What is striking is the apparent surface homogeneity between the QF1 and QF2 pits, in that one would be led to believe that both of these surfaces represent the same period of debris flow activity. However, the soils and clast weathering data suggest otherwise, in that these surfaces represent differing ages of activity. This afternoon at Stop 4, our trip will examine a more extensively studied fan environment where soils are a necessity for deciphering the landscape history.

The combination of persistent efforts to remove the 1995 storm deposits from the fan, combined with the return of indigenous and introduced lush vegetation has masked the majority of the evidence of debris flow activity that occurred here just nine years ago. The strongest remaining signatures of this event persist above the fan apices, where steep stream channels were excavated of most sediment via debris flows, leaving behind exposed bedrock for the enjoyment of structural geologists and petrologists. At the bedrock channel sites, there is strong evidence indicating that rock channels were mantled with regolith for an extended period prior to the storm event. Several of these outcrops contain numerous small void spaces, most of <1 cm wide, interpreted as dissolution sites of feldspar crystals. One model suggests that these were removed by hydrolysis from continual contact with percolating groundwater traveling along the bedrock-regolith contact.

It unclear how rapidly these debris flow chutes and channels will be refilled by regolith. Based on other sites impacted by debris flows in the Appalachians, the recovery is in the order of hundreds, if not a few thousands, of years given current Holocene conditions. The recovery rate is a significant and practical issue, in that most of the streams impacted by the June 27, 1995 storm continue to display flashy properties, including those downstream of direct debris flow modification. The absence of regolith and veg-



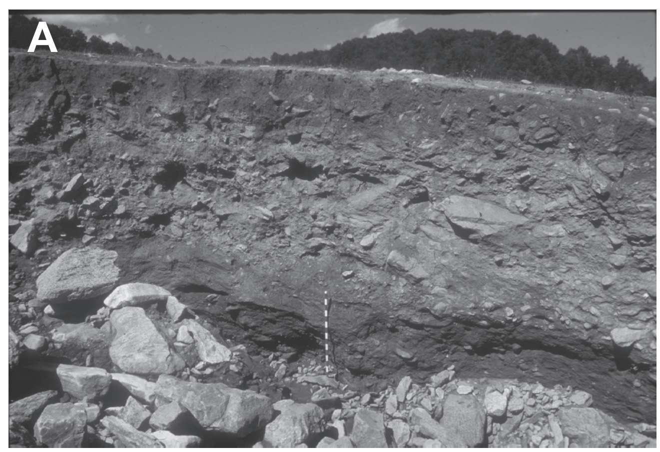


Figure 17. Deep Hollow debris fan. Letters depict photo locations. Scale is in decimeters. Site A shows the stratigraphy of older debris flow deposits. Site B documents debris flow deposition from the June 1995 storm.

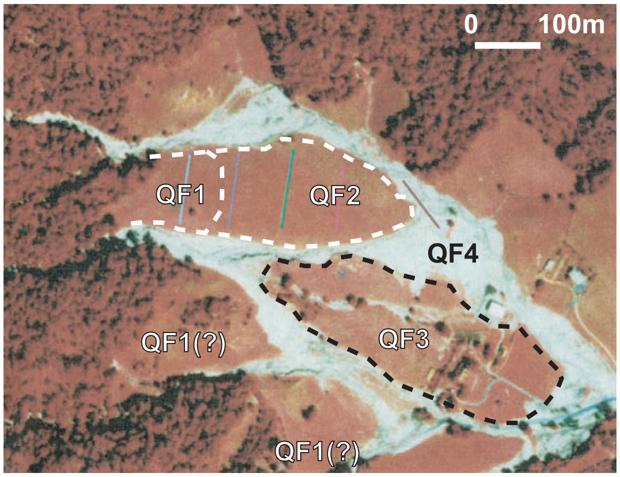


Figure 18. Approximate boundaries (dashed lines) of fan surfaces, Deep Hollow. Solid lines are the locations of geophysical surveys, documented in Daniels (1997).

etation removes the properties of infiltration and surface roughness, thereby increasing the rate at which water is fed into upland stream channels. These events affect the peak discharge and lag time by increasing the rate at which water is transferred from the uplands into the valley floor. Although data is lacking to support this hypothesis, a higher frequency of exaggerated peak flows could alter the dominant channel morphology of these streams, as high flows will almost certainly increase the channel cross sectional area to reflect dominant bankfull discharge.

We have one additional thought concerning this site. With respect to what has been observed at the fan apices over the last 9 years, already both indigenous and exotic species of plants have incrementally encroached upon the bedrock channel, as well as dropping their detritus of leaves and othe plant matter on the channel floor, providing a positive feedback mechanism for the establishment of additional vegetation. However, the same cannot be said of storm-exposed bedrock at the initiation sites of the debris flows, near the headwaters of these basins. Bed shear stress is affected by channel slope, and these steep, upland surfaces have been notably slower in revegetating due to the highly erosive environment. One proximal analog is Nelson County, struck by Hurricane Camille in 1969. Many of the sites in steep upland tributaries that were scoured to bedrock continue to look just as bare despite 35 years of time. It is hoped that the geological community will begin the long-term documentation of the recovery at these sites while they continue to remain fresh.

Bedrock

This large exposure has proven seminal to our understanding of the Blue Ridge basement complex in the Madison area as crosscutting relations among several units and deformation fabrics are well displayed (Fig. 19). The dominant rocks at this exposure are part of a composite felsic pluton that includes: coarse-grained to megacrystic, leucocratic granite gneiss (**Ylg1**), weakly foliated, medium-grained leucogranite gneiss (**Ylg2**), and leucogranite pegmatite (**Ylg3**). These rocks are characterized by white to gray alkali feldspar, blue-gray quartz with minor plagioclase and biotite. At the base of the outcrop a ~10 to 15 cm-thick dike of leucogranite pegmatite (**Ylg3**) is deformed into a series of tight folds with rounded hinges. The surrounding leucogranite gneiss (**Ylg2**) has a weak foliation that strikes ~070˚, dips steeply to the N, and is axial planar to the folded dike. Simple line-length restoration of the dike indicates ~70% shortening in a NNW-SSE direction. Although the medium-grained gneiss was also deformed the fabric is only weakly developed indicating that static recrystallization at high temperatures occurred after deformation. This high-temperature foliation is well developed in the coarse-grained leucocratic granite gneiss (**Ylg1**) and is commonly overprinted by a foliation with abundant aligned micas.

At the larger exposure, 20 m up the outcrop, a 30 to 50 cm-thick dike of fine- to medium-grained biotite granodiorite (**Ybg**) intrudes all of the leucocratic granitoids (Fig. 19). This dike clearly post dates the high-temperature deformation recorded in the leucogranitoids. The biotite granodiorite contains a mineral assemblage similar to the widespread ~1,030 Ma biotite-bearing granitoid gneiss (**Ybg**). The high-temperature deformation fabric is present in the older suite of Grenvillian granitoids (**Ygn**, **Ylg**) and developed prior to the widespread plutonic activity between 1,065 and 1,030 Ma.

The basement units are cut by a NE-striking, ~5 m wide dike of porphyritic hornblende metagabbro (**Zm**) (Fig. 19). The metagabbro is composed of actinolitic hornblende, extensively altered plagioclase, epidote, and chlorite. The dike is part of a suite of mafic to ultramafic igneous rocks that intrude Blue Ridge basement and Neoproterozoic metasedimentary units in the central and eastern Blue Ridge (Weiss, 2000). The dike may be related to ~570 Ma Catoctin volcanism or an earlier pre-Catoctin pulse of Neoproterozoic of mafic magmatism.

A number of discrete high-strain zones cut all basement units in this exposure. These zones range from the mm-scale to tens of cm thick. Where discernible mineral elongation lineations plunge obliquely downdip. The apparent offset, as illustrated on the subhorizontal outcrop surface, is dextral. However, there clearly was out-of-section movement as well. The mineralogy and microstructures in the high-strain zones are consistent with formation under greenschist facies conditions and are interpreted to result from Paleozoic contraction.

Blue quartz is particularly common in the leucogranitic rocks at this exposure. Blue quartz is blue only in reflected light and brownish in transmitted light. The color results from Rayleigh scattering due to submi-

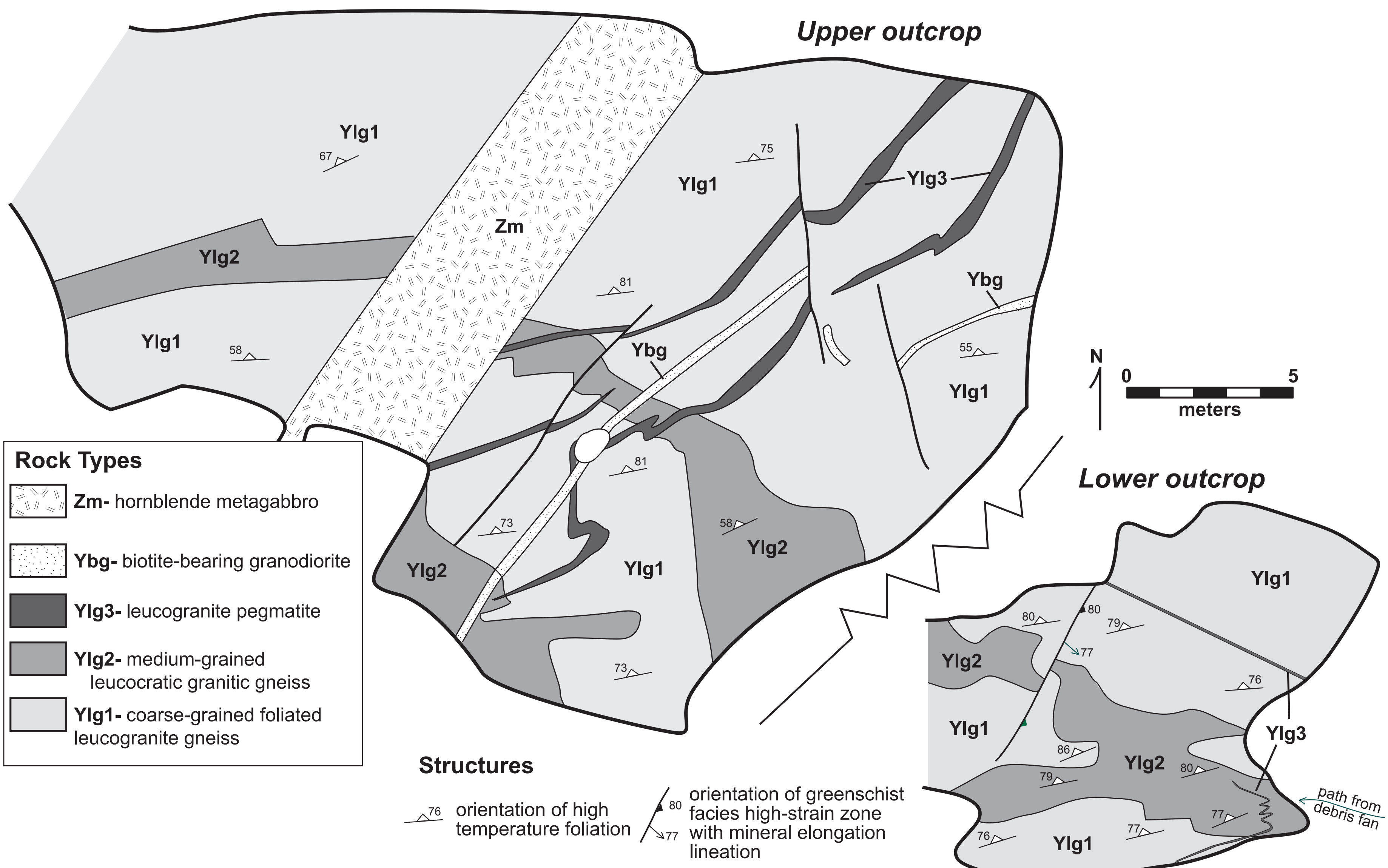


Figure 19. Geologic map of exposures in debris flow chute on the Aylor farm.

crometer-sized crystals of Fe-Ti oxide in the quartz lattice (Nord, unpublished data as cited in Herz and Force, 1984; Zolosenky and others, 1988). Blue quartz is a distinctive character of many basement rocks in the Blue Ridge and is likely the consequence of the relatively high Ti-content of these rocks and the high-temperature conditions associated with Grenvillian magmatism and metamorphism. Milky white quartz (and chlorite) occurs in fractures at the outcrop and is interpreted to have formed in the Paleozoic. Systematic fracture measurements at this outcrop and over the entire Madison area indicate a complex distribution of joints in the basement complex (Mager and Bailey, 2004).

LUNCH STOP-
Madison Picnic Shelter

Our primary goal at this stop involves satisfying our hunger pangs, however bedrock is exposed to the southeast of the picnic shelter. These rounded outcrops, heavily stained with biologically mediated Fe- and Mn-oxides, expose alkali feldspar syenite of the Neoproterozoic Robertson River Igneous Suite (Bailey and others, 2003; Tollo and Lowe, 1994). The rock is typically massive, contains abundant alkali feldspar with minor quartz and hornblende, and is cut by mm-thick high-strain zones. The town of Madison sits atop a low, northeast-trending ridge that parallels a linear segment of White Oak Run (Fig. 4). Allen (1963) mapped a normal fault at the base of this scarp. Knight and Bailey (1999) demonstrated that heterogeneously deformed, amphibolite facies mylonitic rocks are common on both sides of the scarp and suggested that this high-strain zone developed during Neoproterozoic crustal extension.

Northwest of Madison, the Robinson River has an unusually wide floodplain (up to 2 km in width). Downstream of the confluence with White Oak Run, the floodplain contracts and passes through a bedrock gorge created by a bedrock bluff that serves as a high flow discharge barrier. During both the June 1995 storm and the Hurricane Fran storm of 1996, the lower part of the Robinson River valley was inundated by 2 to 3 meters of water. The inability of the discharge to efficiently pass through the gorge created backwater, resulting in nearly a half meter of fine grain deposition in the floodplain (Fig. 20). The origin of this bedrock scarp is unclear, but may be structurally controlled by differences in fracture density in the bedrock.

STOP 3-
Rapidan River floodplain at St. Rt. 662

Introduction

The traverse from our lunch stop at Madison to Stop 3 takes us from the Robinson River basin and into the Rapidan River basin. At Wolftown we descend into the upper Rapidan Valley and into the region that experienced catastrophic flooding from the June 27, 1995 storm. Our vantage point at Stop 3 affords an excellent opportunity to photograph the debris flow

Figure 20. Slack water deposits from the June 1995 storm near the confluence of the Robinson River and White Oak Run. Note the debris trapped at the top of fence posts, indicating the minimum flooding depth. Note unofficial emblem of the Virginia Commonwealth (No Trespassing sign) for scale.

chutes still visible on Kirtley Mountain. The objectives of this stop include: 1) an overview of the meteorology and hydrology of the June 1995 storm; and 2) a discussion of the role of debris flows in terms of denudation and sediment transport in steep mountainous terrain.

Stream Discharge

Unfortunately, no direct measurements of discharge were made at this site during the flood. The floodplain was inundated by 2 to 3 m of water, and most of the crops in the floodplain to the north of Stop 3 were destroyed. Rainfall totals here were estimated as 400 mm (16 in) during the storm. The nearest gaging station on the Rapidan River is located at Ruckersville, 27 km downstream from the basin headwaters and 10 km southwest of this stop. Direct measurements of stream discharge at the Ruckersville station were made throughout the duration of the early storm and through the first part of the late storm, until it was destroyed in the mid afternoon by high flow. Fortunately, the Virginia Department of Environmental Quality videotaped the rise and fall of the floodwaters of the late storm at Ruckersville, and reconstructed the stream discharge from recording the temporal changes in the high water marks during the storm. Figure 21 displays both the hydrograph and gage height for June 27. Baseflow at the Ruckersville gaging station from midnight to 03:00 was 9 m^3s^{-1} (gage height (H) of 0.6 m). Flood stage from the early storm rose to a maximum discharge of 436 m^3s^{-1} (H=4.36 m) at 06:30. Discharge then fell to a minimum of 153 m^3s^{-1} (H=2.83 m) by 11:00, down by a third of the earlier flood peak, before receiving the next wave of water from the late storm.

The volume and rate of change of discharge resulting from the afternoon storm dwarfed the flow volumes caused by the morning storm. Following the decrease in discharge from the early storm (153 m^3s^{-1}

(H=2.83 m) by 11:00), flow jumped to an estimated maximum of 3,000 m^3s^{-1} (H=9.51 m) by 14:00. The largest change in discharge and gage height was between 12:30 to 13:00, corresponding to an increase in discharge of 1,348 m^3s^{-1}, and an increase of 3.66 m in a mere half hour (Fig. 21). The US Rt. 29 bridge was submerged by several meters of water during the peak discharge.

The magnitude of this storm dwarfs the median June stream discharge for the Rapidan River. Historical flow data indicate the median flow rate for late June is 1.6 m^3s^{-1}. The Rapidan storm flow peaked at 3,000 m^3s^{-1}, or an 190,000% increase from the median flow rate. The total volume of flow resulting from the storm is estimated at 8.73 x 10^7 m^3; the first storm contributed 0.84 x 10^7 m^3, and the second storm contributed 7.89 x 10^7 m^3 (Smith and others, 1996). The historical median total volume for this same time period is 2.0 x 10^5 m^3, two orders of magnitude less than the Rapidan storm total.

The unit discharge at Ruckersville, that is the discharge per unit area of basin, was 10.2 $m^3s^{-1}km^{-2}$. This peak discharge places the event very near the upper limits of the envelope curve of flood discharge, a plot of maximum historical peak discharges with respect to basin area (Costa, 1987), for the eastern United States (Fig. 22). The Ruckersville gaging station is shown as a solid triangle in Figure 22; and it should be noted that this site is substantially downstream from the areas hardest hit by the torrential rainfall. Only 305 - 330 mm (12-13 in) of rain fell from the two storms at the Ruckersville gaging station; roughly a third of the maximum total received in the upper Rapidan basin. The unit discharge certainly was greater farther upstream of the gaging station near Graves Mill. Although its true value remains unknown, extrapolation of the data from sites below Graves Mill suggests that peak discharge in the upper Rapidan may lie on the national flood discharge envelope curve. To verify this assertion, creative methods were used to project these values. Using rainfall data from Morgan and others (1997) (Fig. 5), we estimated the total volume of water that fell upon the upper Rapidan by multiplying the basin area by the estimated precipitation totals. Most of the precipitation fell over a 14-hour period; this allowed for data conversions from units of volume to units of mean discharge, where discharge is volume of water per time. The symbols depicted as "x" in Figure 22 show these estimated values.

Finally, the peak storm discharge in the upper Rapidan basin was crudely estimated by examining the difference between the mean storm and peak storm discharges of two gaging stations downstream of the headwaters. The Culpeper gaging station, 136 km downstream of Graves Mill, reported that storm peak discharge was 1.4 times greater than storm mean discharge. The Ruckersville station, 21 km downstream of Graves Mill, showed peak discharge was 3.6 times greater than the mean storm flow. This relationship suggests that differences between mean and peak discharges increase with position towards the headwaters. Based on the findings at the Ruckersville gaging station, these estimates tenuously suggest that peak discharges in the upper Rapidan basin may be as much as 4 times greater than the calculated storm mean discharge. If these assumptions are correct, the Rapidan flood plots as open boxes in Figure 22, just below the limits of the national flood envelope curve.

Many have noted the similarity between the Rapidan storm and the Hurricane Camille-Nelson County storm of 1969. Both storms produced rainfall totals of ~30 in (760 mm) and subsequent catastrophic flooding, denudation of mountain hollows and slopes, and unprecedented loss of property. Discharge data show that where the basin area is less than 300 km^2, the Rapidan storm produced an equal, if not greater discharge per unit basin area than the Hurricane Camille storm (Fig. 22). The Ruckersville data point of

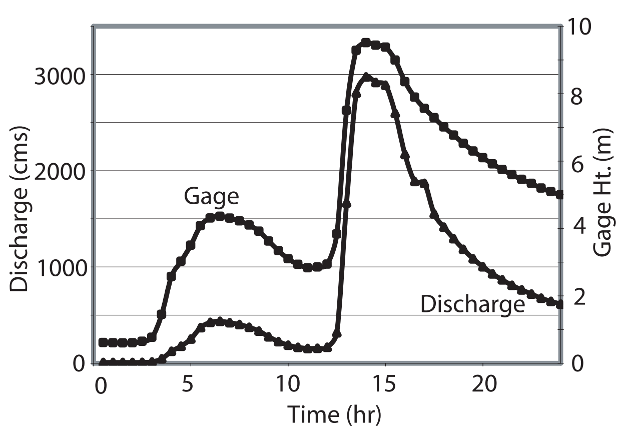


Figure 21. Time vs. Discharge and Gage Height of the Ruckersville Gaging Station, Rapidan River, June 27, 1995.

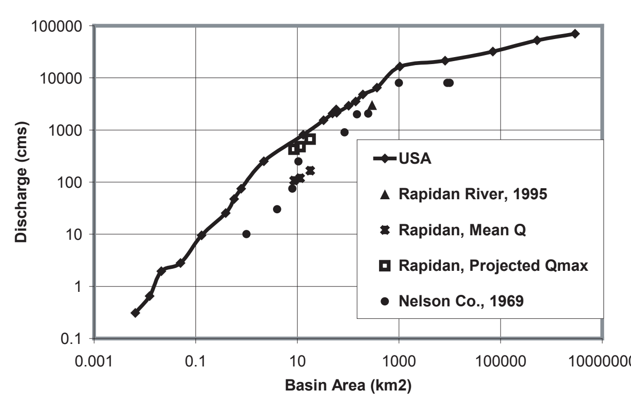


Figure 22. Flood envelope curve for United States, including discharge values for Hurricane Camille (Nelson County), and the Rapidan Storm.

the 1995 flood lies on the envelope of the Hurricane Camille flood. The three other Rapidan flood data points, which represent the estimated mean flood discharge for the 14 hours of precipitation rather than peak flow, plot on or slightly above the Camille storm curve, depending on the construction of the line. If the "4 fold rule" difference between peak and mean storm discharge observed at Ruckersville holds true in the upper Rapidan basin, peak discharge per basin area would have been greater for the Rapidan storm than for the Camille storm.

Debris flows and landscape evolution

Stop 3 is a good place to speculate on the role of catastrophic events in sculpting the Blue Ridge landscape. For decades geologists have debated the effectiveness of catastrophic storms in modifying the landscape. Landscape modification has traditionally been quantified by the volume of sediment transported during an event (geomorphic work; Wolman and Miller, 1960) or by the ability of an event to affect the shape or form of a landscape (geomorphic effectiveness; Wolman and Gerson, 1978). Researchers have found that large-magnitude, infrequent events transport only a small fraction of the total annual sediment load in large, lower-gradient river basins (e.g., Wolman and Miller, 1960; Moss and Kochel, 1978). In low-relief landscapes such as the Piedmont, debris flows are rare, both because of low slope gradients and relief, and because of lesser orographic forcing of extreme rainfall. In contrast, studies of smaller mountainous river basins have documented that large-magnitude events are effective in transporting sediment and denuding the landscape (Hack and Goodlett, 1960; Williams and Guy, 1973; Kochel, 1987, 1988, 1990; Jacobson and others, 1989; Miller, 1990; Eaton, 1999; Eaton and others, 2003a) and that a significant amount of long-term denudation is achieved during these events. Several components are needed to elucidate this question of the effectiveness of catastrophic storms in denuding the landscape: 1) frequency of debris flow activity, 2) long term denudation rates, and 3) denudation from catastrophic storms. A more detailed discussion of this topic can be found in Eaton and others (2003a).

The frequency of debris flow activity in the Blue Ridge is in the order of one event every few thousand years (Kochel, 1987; Eaton and others, 2003b). The question remains of how much of the denudation over geologic time is attributed to catastrophic flooding. In Nelson County (Fig. 23), Kochel (1987) estimated an average debris-flow frequency of approximately 3500 yr. Using data from Judson and Ritter (1964), the estimated "long-term" mechanical (suspended and bed load) denudation rate in Nelson County is 2.6 cm/k.y.; therefore, 9.1 cm of mechanical denudation would occur during a 3500 yr period (Fig. 24). In contrast, the 1969 Hurricane Camille storm denuded the landscape on average 4.3 cm (Williams and Guy, 1973), or 47% of the expected 9.1 cm of denudation over a 3500 yr period (Fig. 24). In summary, nearly half of

Figure 23. Debris flows in Nelson County triggered by the remnants of Hurricane Camille (Photo courtesy: Virginia Division of Mineral Resources).

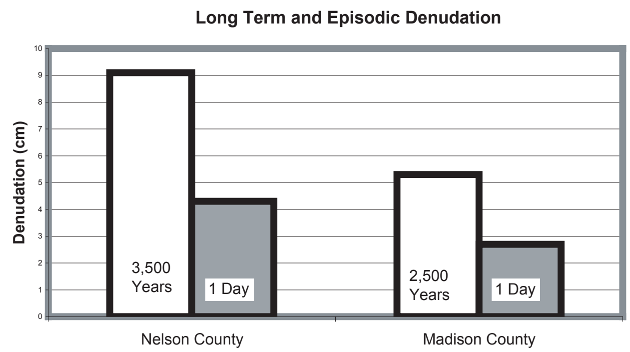


Figure 24. Long term and episodic denudation of mountainous streams impacted by debris flows.

the "long-term" denudation is attributable to one day of debris-flow activity. Similar trends were noted in the Rapidan basin. For the 1995 Madison County storm, the projected basin-denudation rate attributed to mechanical load is 2.1 cm/k.y. (Judson and Ritter, 1964), or 5.3 cm for the 2500 yr increment between debris flows (Eaton, 1999). During the Madison County storm an average of 3.3 cm was removed from the studied basins, i.e., 63% of the denudation expected over a 2500 yr period (Fig. 24).

In the Appalachians, and probably other mountainous terrains located in humid-temperate climates, the role of high-magnitude events on geomorphic effectiveness and landscape evolution has arguably been underestimated. The presence of coarse bedload stored in upland channels, porous regolith that mantles the slopes, and densely vegetated terrain marginalizes the effectiveness of frequent, low magnitude storms in mobilizing sediment. In contrast, high magnitude events trigger debris flows, which incise streams, export sediment from the uplands, and deposit regolith onto debris fans or into lowland stream channels and floodplains (Fig. 25). Many of the upland channels impacted by debris flows seen on Kirtley Mountain and other locations have been slow to recover; they continue to maintain a greater hydraulic geometry than required for frequent, low magnitude storms.

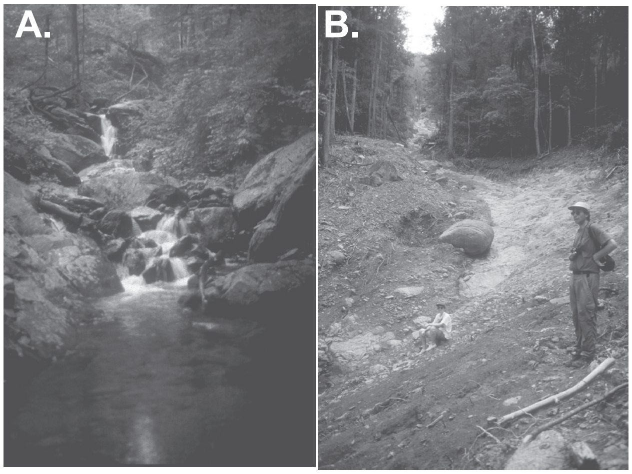


Figure 25. A. Cripple Creek, located in Nelson County, is typical of many first-and second-order tributaries in the Blue Ridge Mountains of Virginia. Note the abundance of cobbles and boulders in storage. B. An unnamed tributary of the upper Rapidan River denuded to bedrock and purged of boulders following the June 1995 storm. Note the elevated water mark on the right bank relative to the left bank due to high debris flow velocities (superelevation). Modified from Eaton and others (2003b).

Throughout much of the Appalachians, the ubiquity of specific landforms and deposits; including debris fans and levees, boulder bars and terraces, remarkably wide linear alluvial valleys that originate at the terminus of debris fans, and single-channel floodplains that become braided during catastrophic flooding all suggest that geomorphic work and effectiveness in mountainous terrain is achieved largely by high-magnitude, infrequent events. The presence of extensive blockstreams and periglacial deposits (not seen on this trip) additionally suggests that many of the landforms present in the Blue Ridge are relicts and are unrelated to Holocene processes.

Bedrock Geology

Rocks exposed on the slopes across the Rapidan River are foliated biotite-bearing granitoid gneisses (**Ybg**) (Fig. 14). To the north, the leucocratic granitoid gneiss (**Ylg**) crops out on German and Blakey Ridges (Fig. 14). Charnockite (**Ych**) is well exposed in the debris flow chutes on the eastern flank of Kirtley Mountain (Fig. 14).

STOP 4-
Generals Debris Fan & Chute

Introduction

From Stop 3, our traverse up the Rapidan Valley passes by a series of strath river terraces, located to the west (left side) of the highway (Fig. 4 & 6). Their general descriptions are outlined in the surficial geology section of the guidebook. Along this stream reach, most of the terraces are highly dissected, as first and second order streams that emerge from the uplands have incised through these surfaces, leaving them to resemble rounded knobs rather than planar landforms. Soils on the high terraces were mapped as the Dyke and Braddock Series. 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 village of Graves Mill marks the point where the relatively broad valley of the upper Rapidan basin narrows considerably, coinciding with confluence of the Rapidan and Kinsey Run, a major tributary (3rd order stream) of the system (Fig. 4 & 6). The Kinsey Run valley is flanked on both sides by a plexus of debris fans, whose geology suggests a long and complex history of activity. Upon initial examination, these landforms do not resemble the 'typical' debris fans found in the western United States (e.g. Death Valley), where fans are broad in both their length from the mountain front and cross sectional width. Along the eastern flank of the Blue Ridge, the narrow nature of mountainous stream valleys limits the accommodation space for fan formation, or the ability for fans to 'spread out' transversely to the direction of flow. This limitation leads to deposits appearing as debris 'wedges' rather than the classical fan shaped in plan view, and tends to minimize the 'long term' preservation of deposits. The Kinsey Run debris fan is one of the largest fans in length and width in the Rapidan basin, thereby allowing greater preservation of the deposits than other sites in this region.

Our time today will not allow us a trip up the Kinsey Run debris fan (cover photo). However, the site is situated entirely in Shenandoah National Park and is worth a separate hike. Figure 8 depicts a surficial outcrop that is interpreted by workers as periglacial in origin; and an extended discussion is found in Eaton and others (2003b). Figure 26 shows a superelevation site near the fan apex where one debris flow surge ran up the right side of the channel 16 meters

Figure 26. Superelevation site created by debris flows duringthe June 1995 storm. Arrows depict the maximum elevationsto which water and debris reached during the debris flow surges. The high water mark on the right bank is 16 m higher than the left bank, suggesting maximum debris flow velocities of ~20 m/s (45 mph).

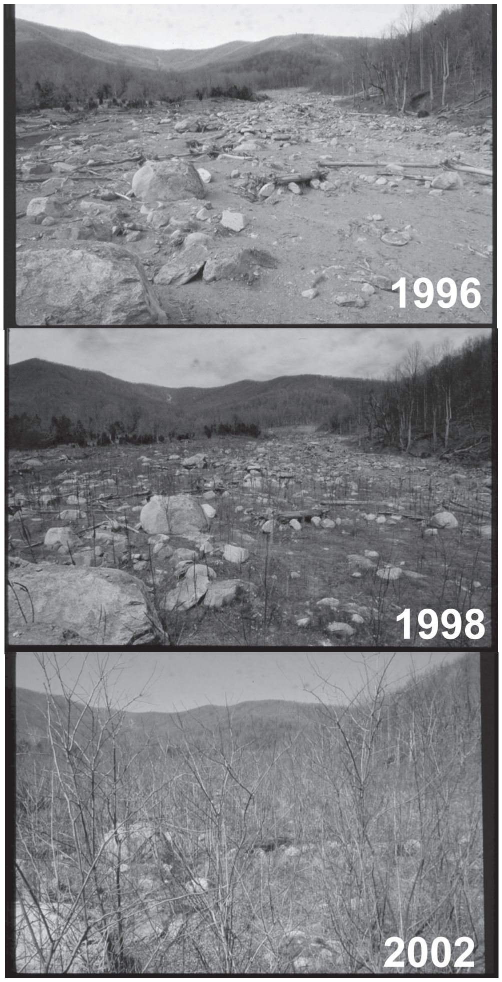


Figure 27. Revegetation of Kinsey Run debris fan, site 7. Photos are a part of a series of 15 sites along the fan that are photographed annually during the late winter to docment subtle changes in the landscape. The two large boulders in the lower left corners serve as good reference points.

Figure 28. Large boulder situated on the Generals Fan. Its emplacement continues to be debated.

relative to the left at a velocity of 20 m/s (45 mph). Figure 27 illustrates the rapid regrowth of vegetation since 1995 of the lower fan of Kinsey Run.

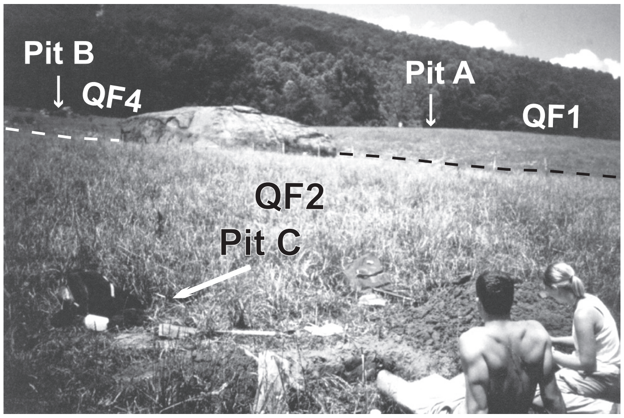
The Generals Fan

The landforms of primary interest at this stop are a series of coalescing debris fans that contain deposits emplaced during the 1995 storm, to as old as ~500,000 YBP. The site is referred to as the Generals Fan in honor of the owner, General Bob Jenkins (retired Air Force), and his wife, Nicki. From State Route 662, the fan appears nearly homogenous with the exception of a single trail of large boulders that lead from the woods to the back of the Jenkins' house, one exceeding ~19 meters in length. Investigations conducted by Daniels (1997), Eaton and others (2001a), and Scheidt and Kochel (2001), suggest that this and other debris fans in the vicinity are the result of multiple episodic events of debris flow activity throughout the Quaternary.

Stop a. Large boulder of charnockite (**Ych**) (Fig. 28). Students from past field trips have fondly named this rock Big Bertha due to its girth. Using cosmogenic Beryllium dating methods, Bierman and others (2002) determined an exposure age for Bertha as ~136,000 YBP. Uncertainty exists concerning the process responsible for the emplacement of the Bertha. Hypotheses include debris flow, solifluction, and rock fall processes, or perhaps in situ bedrock.

The next two sites illustrate the complexity of the Generals Fan based on differences in soil development within debris flow deposits. The rock type providing the parent material for the debris flow is a charnockite, containing alkali feldspar, quartz, plagioclase, and orthopyroxene (Gilmer, 1999, Bailey and others, 2003). Debris flow deposits from the 1995 storm showed Munsell colors of 10YR (brown), and a matrix of mostly sand, with a clay content of a meager 3 percent. During periods of quiescence, these fan deposits will undergo weathering and soil pedogenesis, thereby increasing the thickness of the B Horizon (zone of accumulation) as well as increasing the clay content, and strengthen the degree of oxidation as manifested by the redness of the profile. The following two sites exhibit this progression of soil pedogenesis.

Stop b. Soil chronosequence studies (that is, a comparison of soil development and age among multiple sites) from soil augering and trenching of the Generals Fan (Eaton and others, 2002) revealed debris-flow deposits of markedly different ages. Figure 29 shows the location of the two soils pits we will examine today labeled as "A" and "B". Pit B is situated on the youngest prehistoric surface, labeled QF4, in the midst of numerous large protruding boulders, suggesting "recent" activity of Holocene/Late Pleistocene age. Figure 30 depicts our interpretation of the soil horizon breaks for profile B, including two distinct debris-flow deposits. This site has a 1.6 m thick debris-flow deposit with a solum (meaning combined A and



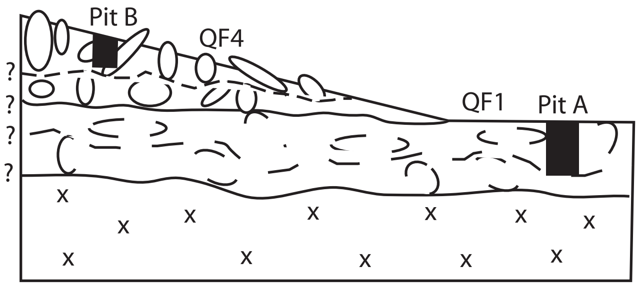


Figure 29. View of three fan surfaces and pit locations on the Generals Fan. Schematic diagram depicts interpreted stratigraphic relationships between the QF4 and QF1 surfaces as viewed from the photo location.

B Horizons thicknesses) thickness of 0.9 m, Munsell colors of 5YR (reddish brown), and an argillic horizon that contains 29 percent clay. There is some question concerning the precise age of the fan surface. The basal debris flow contains a buried organic-rich soil at its top, yielding a radiocarbon age of 18,490±60 YBP, indicating the approximate timing of debris flow activity. However, Beryllium dating of boulders proximal to this site yielded values ranging from 49,000 YBP to 109,000 YBP, suggesting a greater antiquity of this surface. At the time of this publication researchers had not yet resolved this discrepancy (Bierman and others, 2002). Our original research included a total of 5 trenches placed throughout the Generals Fan. Although our time does not allow us to examine each site, data from Pit C (surface QF2) are presented in Figure 30.

Stop c. In contrast to the relatively young debris fan surface at stop b, the soils of Pit A (surface QF1) typifies many of the oldest fan deposits seen in the Rapidan. Upon initial glance, it appears that this surface and the previous surface (QF4) upslope are the same. Yet, they are not. This trench reveals two distinct debris-flow deposits distinguished by a greater concentration of cobbles in the lower deposit, as well as two distinct clay bulges shown in Figure 27. The upper debris flow deposit has a 1.0 m thick argillic horizon, a 2.5YR Munsell color (red brown), and a clay content of 72 percent (keeping in mind that our modern day debris flow deposit has less than 5 percent clay). The lower unit has an argillic horizon that exceeds 0.8 m, a 10R Munsell color (red), and a clay content of 40 percent. A cosmogenic Beryllium date obtained from the soil profile suggests an age of approximately 500,000 YBP. Surface boulders are notably absent from the site, and nearly all in-situ cobbles are extensively saprolitized. Interpretations of how these surfaces are interconnected are shown in Figure 29. If the weather conditions allow, we will view the contact between the basal debris flow deposit and saprolitic bedrock as shown in Figure 31.

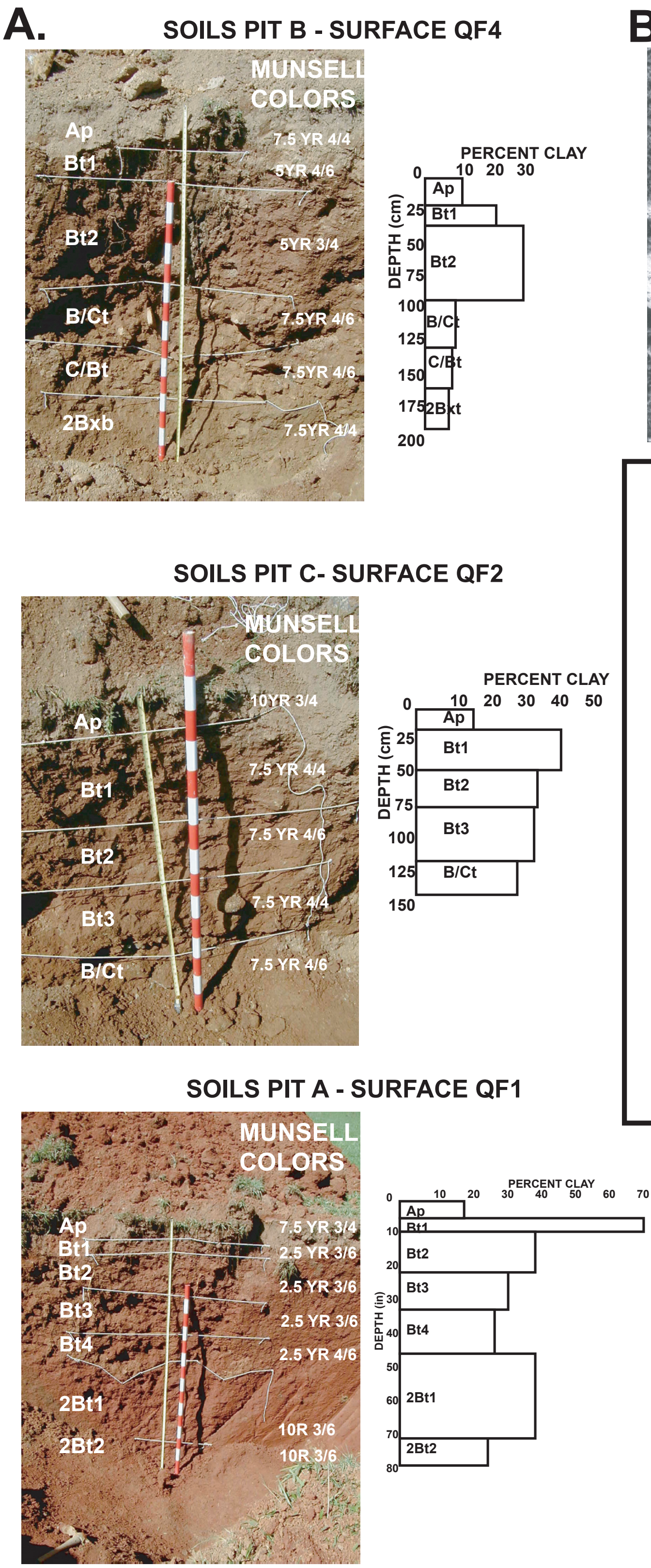
One additional note concerning this surface is its low gradient of 3 degrees, approaching the lower limit of debris fan formation. The surface extends into the Kinsey Run Valley, abruptly terminates, then drops into the modern floodplain. A similar site exists 1 km east on the Rapidan near the Randall Lillard property, and can be seen from our vantage point. Soils data from both sites are similar to deposits comprising the strath terraces seen at Stops 1 and 3, and along our traverse up the Rapidan. These debris fans may have been graded to a higher geomorphic surface that has long since been removed, leaving behind the few remnants in the form of terraces and high debris fans.

The soils and radiometric data indicate that the Generals Fan formed through repeated episodic debris flow activity over a period of hundreds of thousand of years. One possible model of activity is shown in Figure 30c. The location of debris flow deposition varies as the stream channel repeatedly swings across the fan, whose course is altered by debris blockages or subsequent stream captures. One colleague best described the process as 'a fire hose out of control'. Although this model is proposed for the Generals Fan, it is applicable to several other fans within the Rapidan and Robinson basins (Daniels, 1997; Scheidt and Kochel, 2001).

Bedrock

Charnockitic rocks (**Ych**) are well exposed in the debris flow chute above the Generals debris fan complex. At the base of the scar charnockitic rocks include porphyritic to equigranular varieties, and display a coarse (cm-scale) layering that dips NW. This layering is interpreted to be of Grenvillian age and related to fractionation and settling processes within the pluton. Thin (<10 cm) bands of pyroxene-rich cumulate (?) are present at a few locations. Tollo and others (2004b) reported a U-Pb zircon age of 1,050±8 Ma from exposures of charnockite on Kirtley Mountain (~5 km to the SSW). These charnockites are part of a large pluton that underlies the eastern slopes of the Blue Ridge in southern Madison and northern Greene Counties.

Greenschist facies high-strain zones cut the charnockitic rocks. These zones range from mm-scale to ~3 m thick, strike ~035˚, dip SE, and typically display a southeast plunging mineral elongation lineation. On the gently inclined outcrop surface these zones



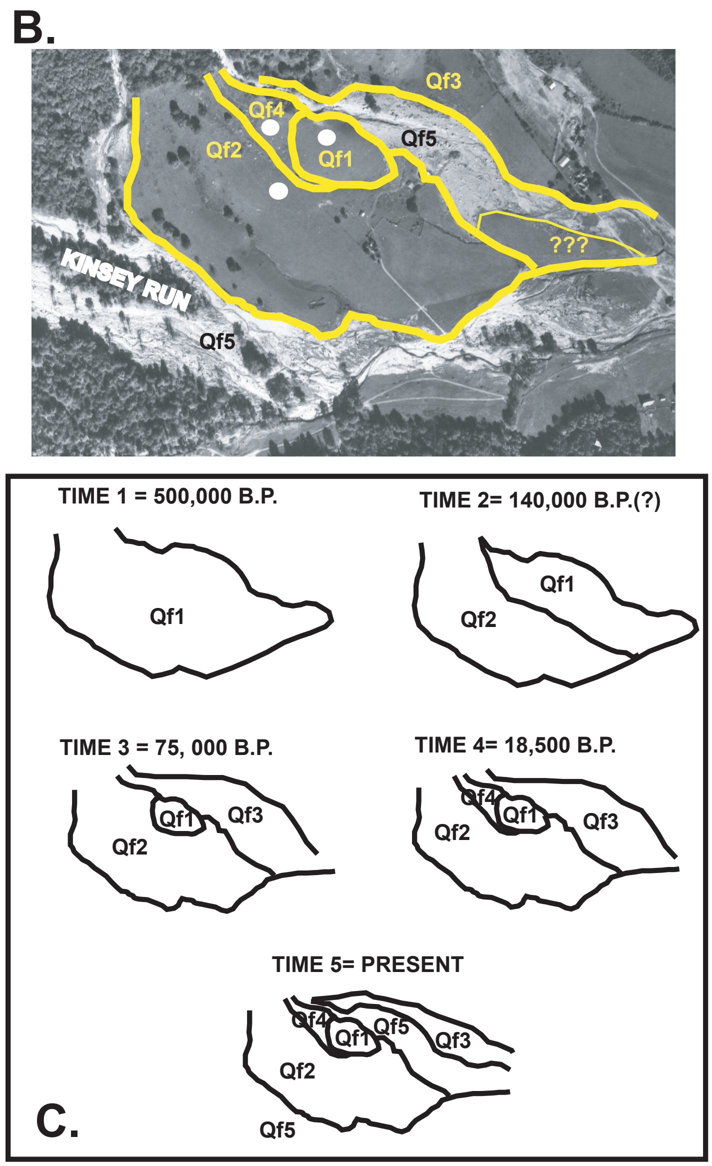


Figure 30. Summary of soils pedogenesis and fan evolution of Generals Fan, Graves Mill. Soil characteristics are documented in (A). Fan surfaces are delineated in (B). Pit locations are shown by white dots on fan surfaces. A fan evolution model is proposed in (C).

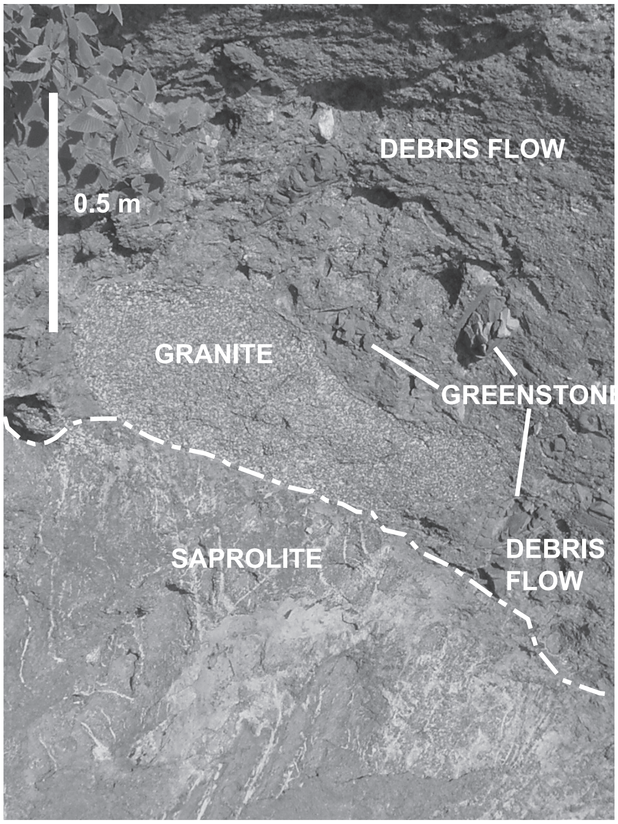


Figure 31. Deeply weathered granite and greenstone boulders and cobbles in the QF1 surface, proximal to Pit A, Generals Fan. Note the sharp contact between saprolite and the debris flow deposit.

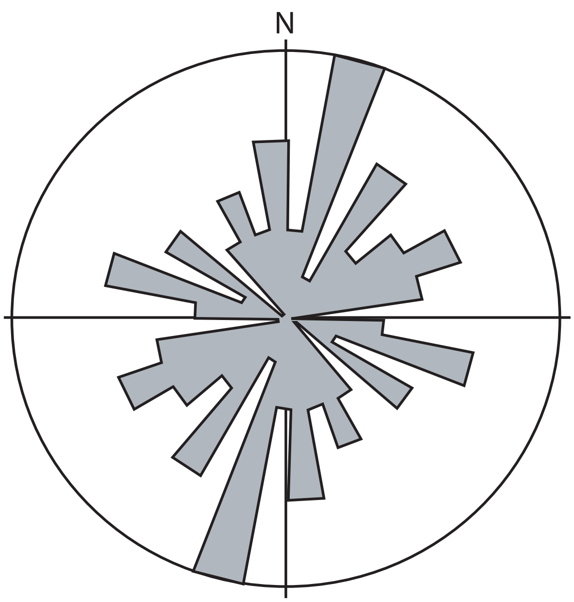


Figure 32. Rose diagram of metabasalt dike orientations from exposures in debris flow chutes in the Graves Mill area. n = 46, radius of cirle = 13% of data. (from Gilmer, 1999).

displace markers in a dextral fashion, suggesting out-of-section movement that may record a triclinic deformation symmetry (Bailey and others, 2002; Bailey and others, in press). Stop 4 is in the hanging wall of the Quaker Run high-strain zone, however at the upper reaches of this debris flow chute southeast-dipping mylonitic rocks predominate.

A strongly foliated, 0.2 to 1 m wide metabasalt dike is exposed approximately 50 meters up the exposure. High-strain zones are localized along both dike margins. Metabasalt dikes in the Graves Mill area contain abundant chlorite, actinolite, and epidote with minor amounts of albite, pyroxene, and magnetite. The mineralogy and geochemistry of these dikes are similar to metabasalts in the Catoctin Formation (exposed a few kilometers to the west). These dikes are likely feeder dikes for the overlying Catoctin flows. The orientation of exposed metabasalt dikes in the Graves Mill area is quite variable with no dominant trend (Fig. 32, Gilmer 1999).

ROAD LOG

all distances in miles

Mileage	***Cumulative***	***Directions***
	0.0	Leave Graves Mountain Lodge and turn right on St. Rt. 678.
0.9	0.9	Turn right into private drive.
0.2	1.1	Bear left then right @ Y-intersection.
0.4	1.5	Park in driveway at sharp bend. **STOP 1**. Retrace route.
0.6	2.1	Turn right on St. Rt. 678.
3.9	6.0	At stop sign, turn right on St. Rt. 231.
1.0	7.0	Turn right on St. Rt. 651.
3.0	10.0	Veer right and continue on St. Rt. 651.
0.7	10.7	Pull off road to the right and park in field. Hike up through driveway, through gate into pasture and on to **STOP 2**. Retrace route.
0.7	11.4	Stop and turn right on to St. Rt. 652.
2.3	13.7	At stop sign, turn right and continue on St. Rt. 652.
3.5	17.2	At stop sign, turn right on to U.S. Rt. 29 Business.
0.5	17.7	Turn right on Thrift Road (St. Rt. 657).
0.1	17.8	Turn right into Madison Parks & Recreation picnic area. **LUNCH STOP**. Exit parking area.
0.0	17.8	Turn left on Thrift Road (St. Rt. 657).
0.1	17.9	At stop sign, turn right on to U.S. Rt. 29 Business.
0.5	18.4	Merge right onto U.S. Rt. 29.
2.0	20.4	Turn right (at stop light) on St. Rt. 230.
3.9	24.3	Turn right on St. Rt. 662 in Wolftown.
1.5	25.8	Cross Rapidan River and park in large pullout on the right. **STOP 3**.
0.0	25.8	Turn right onto St. Rt. 662.
4.1	29.9	Bear left on St. Rt. 615 in Graves Mill.
0.5	30.4	Turn right into driveway and park. Hike up through driveway, into pasture beyond house to **STOP 4**.

End of Road Log. Return to Graves Mountain Lodge

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