PLEISTOCENE AND HOLOCENE COLLUVIAL FANS AND TERRACES IN THE BLUE RIDGE REGION OF SHENANDOAH NATIONAL PARK, VIRGINIA

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INTRODUCTION

The bedrock geology of the Blue Ridge in central Virginia has been the subject of numerous studies for over a century (e.g., Keith, 1894a and b; King, 1950; Gathright, 1976; Rader and Evans, 1993; Southworth and Brezenski, 1996, and contained references for a general review). The Proterozoic and Paleozoic history of the Blue Ridge has been interpreted on the basis of the bedrock evidence. However, there is no comparable preserved record of post- Paleozoic rocks available for interpretation of Mesozoic and Cenozoic history. Knowledge about the late Cenozoic history of the region, including the processes responsible for the development of the present landscape is much more problematic and speculative.

The spatial data contained in this report encompasses the Shenandoah National Park and surrounding Blue Ridge from Front Royal to Waynesboro, Virginia (figure 1). The study provides a portrait of the physiography and principal bedrock formations, and describes the large colluvial and alluvial deposits in the region that are of Quaternary age. The synthesis of the compiled data of these deposits in conjunction with related research, including pollen, isotopic and fission track studies from soils, regolith, and bedrock will help establish the history of the Pleistocene and Holocene landscape development of the Blue Ridge.

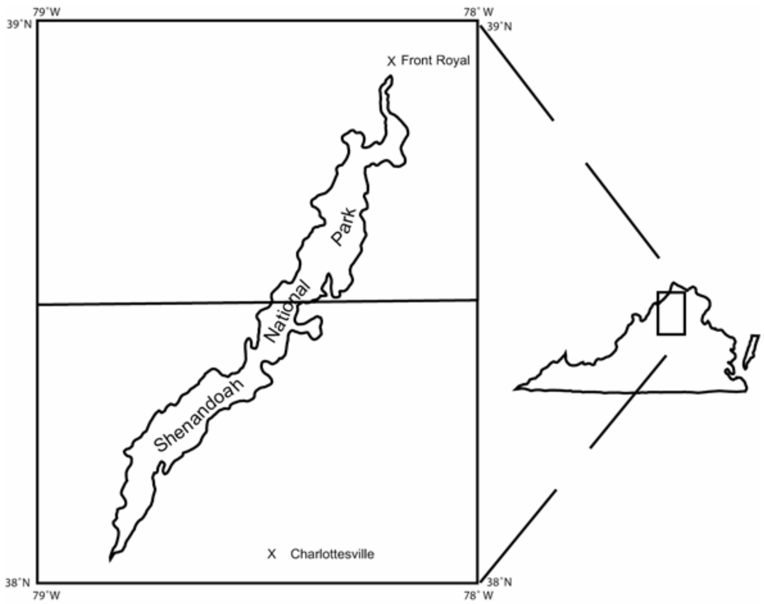

FIGURE ONE: LOCATION MAP SHOWING THE AREA OF STUDY AND SHENANDOAH NATIONAL PARK IN NORTH-CENTRAL VIRGINIA

The objective of this report and the contained spatial data sets is to emphasize the relationship between physiography, bedrock, and principal surficial deposits. The spatial data sets are layers of information that have been compiled using the same projection as the Front Royal and Charlottesville, Virginia 30 by 60-minute 1:100,000-scale maps. In the text the spatial data layers are either mentioned separately, or collectively, as "the area of study". Four layers of information are used:

- Layer one contains political boundaries (county lines and the boundaries of Shenandoah National Park), hydrologic data, and place names used in the text of the report.

- Layer two is derived solely from the digital elevation models (DEMs) used by the U. S. Geological Survey for elevation control for the production of 1/24,000-scale 7.5' topographic maps within the Front Royal and Charlottesville, Virginia quadrangles. The DEM pixel size is 30 x 30 meters and the resulting image is illuminated from the northwest quadrant.

- Layer three is a compilation of the bedrock geology and is largely based on a publication of (1) the Geology of Shenandoah National Park (Gathright, 1976); (2) geologic maps published by the Virginia Division of Mineral Resources for the counties of Albemarle (Nelson, 1962), Greene and Madison (Allen, 1963), Page (Allen, 1967), Rockingham (Brent, 1960), and Warren (Rader and Conley, 1995); (3) quadrangle geologic maps published by the Virginia Division of Mineral Resources for Front Royal (Rader and Biggs, 1975); Waynesboro East and Waynesboro West (Gathright and others, 1977); Grottoes (Gathright and others, 1978a); Crimora (Gathright and others 1978b); Madison (Bailey and others, in press) and Old Rag Mountain (Hackley and Tollo, in press); (4) a summary geologic map of Clarke, Frederick, Page, Shenandoah, and Warren Counties (Rader and others, 1996); (5) Geology of the Elkton area, Virginia (King, 1950); as well as (6) supplementary field work and observations by the authors for this report.

- Layer four is a compilation of surficial deposits taken from (1) published reports and maps listed above; (2) mapping at 1/24,000-scale in Albemarle County (Morgan and others, 2000), and the 7.5' quadrangles of Madison, Fletcher, Swift Run Gap, and Stanardsville (Eaton and others, 2001a) and Old Rag Mountain (Morgan and Eaton, in press: and (3) by unpublished 1:24,000-scale mapping by the authors in the Thornton Gap, Washington, Bentonville, Chester Gap, Big Meadows, Browns Cove and Crozet, VA 7.5' quadrangles.

PHYSIOGRAPHY

The Blue Ridge in the study area is a prominent NE-SW trending range, and is the eastern-most prominent range in the Appalachian Mountains in Virginia. In plan view the Blue Ridge is neither linear nor sinuous, but rather is extremely irregular with numerous outlying ridges, promontories and recesses. Streams on the eastern flank have cut deep ravines into the ridge and drain into narrow, alluvium-floored valleys. Major recesses on the western flank are covered with thick alluvial accumulations of sand and gravel. Depending on the extent of outlying ridges, the Blue Ridge in the mapped area varies in width from 3 miles near Waynesboro, to 19 miles near Stanley.

The general elevation of the range is best compared with the elevation of the South Fork of the Shenandoah River that flows northeastward parallel to the Blue Ridge. Near the northern boundary of the study area, the confluence of the North and South Forks of the Shenandoah River at Front Royal has an elevation of 152 m (500 ft) above sea level; nearby, the gaps in the range have an average elevation of 512 m (1,680 ft) and peaks are low with a general elevation of 792 m (2,600 ft). Further south and upstream at Luray, the South Fork of the Shenandoah has an elevation of 232 m (760 ft) above sea level. The gaps have a general elevation of 844 m (2,770 ft) and peaks an average elevation of 1,116 m (3,660 ft), including the highest peaks in the area with elevations of 1223 m (4,011 ft, Stony Man) and 1,234 m (4,050 ft, Hawksbill). Southward, the combination of peak and gap elevations declines slightly and the rising elevation of the Shenandoah River decreases the relative elevation, or relief, of the ridge. Near the southern boundary of the mapped area at Waynesboro, the river has an elevation of 396 m (1,300 ft), gaps an average elevation of 621 m (2,040 ft) and peak heights are only 860 m (2,820 ft) above sea level. Thus, within the area of study, the relative elevation difference, or relief, between ridge and valley floor is always in excess of 305 m (1,000 ft) and can be as much as 1006 m (3,300 ft).

STRATIGRAPHY

The following is a brief summary of description, distribution, and structure of the older rocks of the Blue Ridge within the study area. In the most general way, the eastern flank of the Blue Ridge is underlain by quartzo-feldspathic rocks which are part of an extensive Grenville-age terrane. The majority of summits of the Blue Ridge are underlain by greenstones designated as the Catoctin Formation of latest Precambrian age; the western flank and some summits are underlain by siliciclastic rocks of Lower Cambrian age; the lowlands making up the Shenandoah and Page Valleys to the west are underlain by limestones, dolomites, and shales of Cambrian and lower Ordovician age. The entire package has been interpreted as the western limb of a major anticlinorium (Espenshade, 1970; Mitra and Lukert, 1982) with the Catoctin resting unconformably on a basement of granitic rock with both bedding and foliation of the Catoctin dipping gently to the southeast. The Chilhowee Group, primarily siliceous metaclastics, rests conformably on the Catoctin, but is sharply overturned on the west flank, resulting in bedding and foliation that dip steeply to the southeast. The more resistant rocks of the Chilhowee Group form flatiron and hogback ridges along the western margin of the ridge.

Quartzo-feldspathic rocks in the Blue Ridge are of igneous origin. They consist of granitic gneiss, and both massive and gneissic charnockite, and are of Grenvillian age (Aleinicoff and others, 1993, Burton and others, 1994). Paragneisses have not been described in the mapped area. Studies of these rocks have been carried out for more than a century with early work by Keith (1894b) mapping in the Harpers Ferry vicinity, and with descriptions of hypersthene granite by Jonas (1934) from central Virginia. Bloomer and Werner (1955) published a general review of granitic rocks in the Blue Ridge of central Virginia, and subdivided them into the massive charnockites (their Pedlar Formation) and layered gneisses (their Lovingston Formation), as well as several minor units of monzonite and granite (Marshall Formation and Old Rag Mountain Granite, respectively). Geologists conducting more recent mapping at 1:24,000-scale have not found these divisions useful (Bartholomew and Lewis, 1984; Sinha and Bartholomew, 1984; Bailey and others, in press; Hackley and others, in press). Bloomer and Werner's formation names were not adopted on the most recent geologic map of Virginia (Rader and Evans, 1993). Within the area of study, charnockites are more abundant along the western margin of the Grenville basement, but granite and biotite orthogneisses also occur (Hackley and others, in press; Bailey and others, in press).

Within the area of study, Hackley and others (in press) have defined a suite of rocks with charnockite affinity, defined here as a coarse-grained dark rock containing hypersthene, both with and without almandine garnet, and the absence of biotite. These rocks are prominent in the central and western-most part of the Blue Ridge near contacts with the overlying Catoctin Formation. At lower elevations, the terrain is underlain by granitic biotite gneiss; coarse grained, lighter in color, and with prominent compositional layering. A distinctive light colored quartz-microcline granite is found but restricted to Old Rag Mountain and the proximal surrounding area (Hackley and others, in press).

Absolute age determinations of these rocks give dates ranging from 1,050 to 1,160 mybp (Aleinikoff and others, 1993). Greenschist facies metamorphism during the Paleozoic has retrograded most of these rocks, although nearly pristine unaltered rocks can be found in places. Hypersthene and biotite are replaced by chlorite and magnetite; and feldspar by a fine-grained mesh of muscovite. Numerous occurrences of mylonitic rocks along faults form wide shear zones and are of late Paleozoic age.

For this study, all of the quartzo-feldspathic rocks of Grenville age have been designated as a single unit in the area of study. All of these rocks weather initially to sandy loam, have similar slopes and aspects, and contribute regolith (boulders and cobbles) to debris flows and finer material to alluvial fans. During a major storm in 1995 in Madison and Greene Counties, debris flows were triggered over a broad area between the Robinson and Conway Rivers in areas underlain by rocks described previously as Pedlar Formation and Lovingston Gneiss (Allen, 1963). Remnants of late Pleistocene and Holocene debris-flow deposits rest unconformably on massive units, as well as layered gneisses. Compositional or textural differences in these rocks did not preferentially influence sites of debris-flow initiation, a conclusion also reached by study of a similar debris-flow event in 1969 in Nelson County, immediately south of this area of study (Morgan and others, 1999b).

Quartzites, conglomerates and siliceous slates of the Swift Run Formation unconformably overlie the granitoid rocks of the Grenville basement. The formation crops out in discontinuous lenses; thickness rarely exceeds 61 m (200 ft) thick and is more commonly only about a meter thick. The heterogeneous nature of the formation, grading rapidly from quartzites into slates, is characteristic. The formation is absent in the stratigraphic section in many places in the area of study, and similar lithologic units are present interbedded in the overlying Catoctin greenstones and tuffaceous rocks. The formation was described by Keith (1894a) and Furcron (1934), and the type section at Swift Run Gap was named by Jonas and Stose (1939). Reed (1955) interpreted the formation to have been deposited in the valleys and streams of a terrane underlain by an eroded and exposed granitic basement, thus accounting for its discontinuous and heterogeneous nature. Gathright (1976) noted that the formation contains volcanic detritus and that similar rocks are interbedded with the overlying Catoctin Formation. For the purposes of this report, the Swift Run Formation is grouped with the Catoctin Formation in the spatial data of layer three; the Swift Run underlies a very small part of the area of study, and its geomorphic expression is dominated by the overlying Catoctin Formation.

The Catoctin Formation is a tholeitic flood basalt, metamorphosed to the greenschist facies, and consists of multiple flows, agglomerates, and interbedded tuffaceous slates with a maximum thickness of about 610 m (2,000 ft) within the area of study. The formations is a major ridge former cropping out along almost the entire length of the Blue Ridge in central and northern Virginia as well as on the eastern limb of the Blue Ridge anticlinorium along ridges named Catoctin Mountain (in Maryland), Hogback Mountain (northern Virginia) and the Southwest Mountains (Albemarle County, Virginia). It has been the subject of numerous investigations, for example, Keith

(1894a), Furcron (1934), Jonas and Stose (1939), Reed (1955), Reed and Morgan (1971), and more recent studies by Badger and Sinha (1988) and Badger (1992, 1993).

The predominant lithology of the Catoctin Formation is a fine grained, dense greenstone. Constituent minerals are chlorite, albite and actinolite, and frequently with relict pyroxene. Remnants of columnar jointing are found in many places along the Blue Ridge, indicating subaerial extrusion, although pillows and pillow breccias of subaqueous origin crop out at several localities. Highly brecciated rocks along the base of flows and amygdular greenstone are also common. Veining and partial replacement by irregular masses of epidote and quartz are also characteristic. The age of the Catoctin has been considered to be late Proterozoic or Lower Cambrian. Badger and Sinha (1988) have assigned an age of 570 mybp to the Catoctin Formation based on Sr isotopic evidence.

The combined Swift Run and Catoctin Formations depicted in layer three underlies most of the higher sections of the Blue Ridge, and is nearly continuous from the ridge summit near Front Royal south to the summit near Waynesboro. The topography along the ridge crest has gentle slopes relative to the more easily eroded granitic rocks or breaks between lava flow units. These discontinuities between formations or within the Catoctin Formation constitute the most abrupt topographic changes within the area, and are the loci of most waterfalls in the Blue Ridge.

The Chilhowee Group of conglomerate, silicious slate, and quartzite formations overlies the Catoctin Formation and is of Early Cambrian Age. Similar to the Catoctin, there is an extensive literature describing the Cambrian silicious rocks that crop out on the west side of the crystalline massifs of the Blue Ridge and related older rocks from Tennessee, north through Pennsylvania. Arthur Keith (1894b) mapping in the Harpers Ferry area of Virginia, West Virginia, and Maryland described these rocks and divided them into a lower Weverton Formation, a sandstone; the Harpers Formation, a shale; and the Antietam Quartzite. Subsequent work largely builds on Keith as well as on revisions by Jonas and Stose (1939) and Stose and Stose (1946). The formations defined in the Harpers Ferry vicinity are useful for characterizing rocks in the Blue Ridge, although the Harpers Formation is a silicious slate or phyllite, interbedded with quartzite throughout most of the area of study. King (l950) made careful descriptions of these rocks in the vicinity of Elkton, Virginia, and his charts and maps provide the best guide available for these rocks in the central Blue Ridge.

The Weverton Formation is a conglomerate, sandstone, and phyllite unit with lenticular beds nearly conformable to the underlying Catoctin. Gathright (1976) reports that the Weverton was deposited on an erosional surface with as much as 100 feet of relief in places. The formation is easily identified by the common occurrence of quartz pebbles in an iron stained matrix. Thickness varies from 31 to 152 m (100 to 500 ft). The overlying Harpers Formation is a thick (approximately 610 m (2,000 ft)) monotonous sequence of quartzose phyllites, quartzose schists, with sparse lenses of quartzite. Trace fossils are present throughout much of the formation, the most common of which are scolithus (worm) tubes, present in the cleaner quartzite lenses. The Antietam Quartzite is a prominent ridge former on the western flank of the Blue Ridge consisting of lenses of clean, white, cross-bedded quartzite, and is 213 to 305 m (700 to 1,000 ft) thick. Scolithus tubes are abundant throughout much of the formation.

The rocks of the Chilhowee Group in the areas of study are compiled in layer three as a single unit because of common compositional and weathering characteristics. These highly silicious rocks disintegrate into thin, acidic loamy soils and support a forest of pine, oak, and mountain laurel. The terrain underlain by the Chilhowee rocks have almost no history of agricultural use prior to the establishment of Shenandoah National Park. The alternating quartzite/slate sequences of the Chilhowee rocks result in ledge, hogback, and flat iron ridges. The thicker, more continuous quartzite lenses support the more prominent ridges and these usually are a part of the Antietam Quartzite.

The Tomstown Dolomite of Lower Cambrian age overlies the Chilhowee Group and underlies the low rolling and forested region between the Blue Ridge and the South Fork of the Shenandoah River. The formation was named and described by Stose (1906) and described in some detail in the Elkton area by King (1950). Outcrops in the area of study are quite limited because of extensive weathering, and because the formation is extensively overlain by surficial deposits of gravelly and bouldery alluvium. The absence of exposures is deceptive; King (1950) was able to obtain enough drilling records to allow him to conclude that the Tomstown occupies a belt 305 to 610 m (1,000 to 2,000 ft) wide between outcrops of the Antietam and the Waynesboro Formation in the Elkton area. The formation consists of fine-grained light gray dolomite with a relatively large percentage of shale and clay-rich carbonate. Weathering of this formation is intense, leading to thick deposits of residual clays and karst topography.

Further to the west a belt of shale-rich rock, the Waynesboro Formation, underlies the lower areas between the Blue Ridge and the South Fork of the Shenandoah River. Like the Tomstown Dolomite, the Waynesboro Formation has very few outcrops, and is usually limited to small ledges of shale. Most of the area occupied by this formation is covered by Quaternary gravel deposited in alluvial fans. Neither the Tomstown Dolomite nor the Waynesboro Formation has a prominent topographic expression and, for the purposes of this study, these formations are compiled as a single unit in layer three.

Well developed residual soils and saprolite are characteristic of much of the Piedmont and eastern Blue Ridge Provinces (Pavich, 1989), and to the west in the Shenandoah Valley. To the west, drilling records have revealed zones of intense weathering and accumulation of residual materials that characterizes the buried Tomstown and Waynesboro Formations (King, 1950). On the eastern flank of the Blue Ridge, saprolite formed from granitic rock is exposed in gullies at the apices of debris-flow fans at a point of sharp inflection of the slope, typically from about 12 degrees to 18 degrees or more. Presumably, a residual weathered zone extends from this inflection point under the debris-flow fans away from the mountain front. However, saprolite is largely absent from steeper slopes and summit exposures of the Blue Ridge. Gullies and small canyons in the higher elevations of the Blue Ridge reveal either fresh bedrock capped by a thin layer of residual soil or by slightly weathered colluvium, suggesting that the processes of physical weathering and erosion have proceeded at a substantially faster rate than chemical alteration and dissolution of the mineral constituents of the several formations.

STRUCTURE

The Blue Ridge in Virginia forms the western limb of the Blue Ridge/South Mountain Anticlinorium, a complex fold structure extending from southernmost Pennsylvania to central Virginia. The structure is topographically defined with the eastern limb variously named Catoctin Mountain in Maryland, the Bull Run Mountains in Fauquier and Prince William Counties, Virginia, and the Southwest Mountains in Albemarle County, Virginia. Although the northward plunging structure has a broadly straightforward explanation, the results of small scale folding and faulting, as well as topographic effects, make the pattern of outcrops of the various rock types on the west limb of the anticlinorium quite complex (see for example, Southworth and Brezinski's (1996) structure sections and 1:24,000-scale geologic map in the vicinity of Harpers Ferry, West Virginia). The Catoctin/Swift Run Formations are exposed unconformably over the Grenville quartzo-feldspathic rocks at higher elevations, usually above 610 m (2,000 ft), and dip gently to the east and southeast. On the west side of the anticlinorium, the Catoctin Formation and overlying formations are overturned. The more resistant members of the Chilhowie Group form hogbacks and flatirons and usually dip steeply to the southeast. Prominent cross-faulting further complicates the pattern so that in the vicinity of Front Royal, basement rocks are thrust further to the west, overriding the Chilhowee Group rocks. The Stanley fault, which passes through Thornton Gap, wraps around the west side of the Blue Ridge and south to the town of Stanley. Movement on this fault has shoved the older granitic rock structurally over the Catoctin Formation so that in places the granitic rocks are now juxtaposed or faulted against the Chilhowee Group rocks on the west side of the Blue Ridge. In these areas, for example east of Luray, Virginia, granitic rocks rather than Catoctin Formation underlie the summit of the Blue Ridge and also crop out on the western slopes.

The principal folding and faulting associated with the Appalachians were completed by the end of the Paleozoic Era. Faulting associated with Mesozoic grabens was localized east of the Blue Ridge, but a broad regional area must have experienced arching and uplift, supplying sediment into the Mesozoic basins. The area of the Blue Ridge may have been eroded to near sea level by the end of the Mesozoic. Preliminary work on fission track studies by Naeser and others (2002) indicate that the Blue Ridge began a continuous slow uplift starting in the late Paleozoic and continued through the Cenozoic. Rocks originating from west of the Shenandoah Valley that contain zircon and apatite mineral grains with fission tracks are present in coastal plain sediments of Miocene age, indicating that the ancestral Shenandoah and Potomac River systems were draining through the Appalachians eastward to the Atlantic from that time to the present. (Naeser and others, 2002). By virtue of an extended period of uplift, there is no sedimentary record in the area of study within the Blue Ridge from either the Mesozoic or Cenozoic Eras except for the fragmentary occurrences of colluvial and alluvial deposits on stream terraces and footslopes. These are all apparently of Quaternary and Holocene age, and are the subject of the remainder of this report.

SURFICIAL DEPOSITS

The summit of the Blue Ridge has extensive areas of outcrop as well as mountain-top detritus and shallow colluvial deposits. The detritus is almost certainly a product of degradation of bedrock by action of ice wedging in the subsurface and other periglacial processes during colder climatic periods in the late Pleistocene. The detritus is most conspicuous in sparsely vegetated block fields and talus sheets underlain by quartzites of the Antietam and Harpers Formations. One talus stream near Blackrock, located in the southern part of Shenandoah National Park, shows many characteristics of a rock glacier (Eaton and others, 2002). These quartzites produce extensive block fields that grade into slope and talus deposits, rock streams, and clusters or jumbles of balanced rocks, present as tors along ridge crests and summits. These features are also widespread in areas underlain by the Catoctin Formation and by granitic rock. For example, occurrences of extensive block fields and talus composed of Catoctin Formation boulders are found in the upper headwaters of the Rapidan River. Tors, balanced rocks, block fields and talus composed of granitic rock are found on Old Rag Mountain. A few of the block fields and talus sheets are as much as 500 m (1,640 ft) in longest dimension, but most block fields and talus rarely exceed a few acres in area. Colluvial deposits of slope wash, both stratified and unsorted, occur throughout the area, and are usually several meters thick in outcrops along banks of streams. The slope wash is interpreted to be the result of solifluction of soils and weathered bedrock during periglacial conditions. Fragments of rock within the slope wash are within a clayey matrix and show a well-defined dip that parallels the surrounding slope. These deposits contain charcoal with C^{14} ages that range from 13,000 to greater than 50,000 ybp (Eaton and McGeehin, 1997). Outcrops of slope wash are difficult to find due to the combination of winter frost action and vegetation cover. Field work conducted for this study noted that seeps or springs often indicate the presence of slope wash deposits; the high clay content in the matrix makes the slope wash relatively impermeable and favors formation of a perched water table.

The surficial deposits compiled in the area of study are limited to river terraces, and colluvial and alluvial fan deposits. Mountain-top detritus and slope wash colluvium are widespread at higher elevations in the Blue Ridge but are not shown on the accompanying map because of the small scale of the deposits.

STRATH TERRACES AND ASSOCIATED DEPOSITS ON THE EASTERN FLANK OF THE BLUE RIDGE

Terraces on the lower Rappahannock and Rapidan Rivers have been mapped by numerous workers and are depicted on the Fredericksburg, VA 1:100,000-scale quadrangle map by Mixon and others (2000). A well-defined sequence of Pliocene-Pleistocene terraces extend along the Rappahannock across the Coastal Plain. These become substantially smaller upstream in the Piedmont Province, although fragmentary terraces have been traced to Culpeper, Virginia, located a few miles east of the study area. These terraces in valleys of piedmont rivers as mapped by Mixon and others (2000) are constructional terraces consisting of gravel, sand, clay and silt in well-graded, gently sloping beds that flank the river. Gravels include greenstone, vein quartz, and quartzite.

The floodplains of small streams and rivers draining the eastern side of the Blue Ridge within the study area are flanked by numerous terraces. Although the terraces are scattered from north to south along the mountain front, they are more widespread to the south in the area around Crozet where they define a broad pediment. These terraces differ from those on the lower Rappahannock in that they are strath terraces composed of quartzo-feldspathic bedrock and saprolite, capped by transported soils and rotted gravels. They are most easily identified by the topography of the beveled hills adjacent to flood plains that slope gently downstream. At least two flights of terraces can be identified in most of the stream basins. The topographic contour interval of 40 feet precludes easy determination of more subtle elevations of terrace flights of low relief above the streams. Correlation of terraces among stream drainages is not practicable with the available data. The set of high strath terraces is by far the most extensive and was once probably continuous along most of the major streams prior to fluvial dissection. Terrace surfaces are often as much as 37 m (120 ft) above the adjacent active flood plains. A small number of terraces that were identified show little relationship to the present drainage patterns and may be relicts of much earlier drainage systems. Further downstream, strath terraces have a decreasing elevation above streams and gradually merge into the topography of the surrounding Piedmont.

The majority of strath terraces have surfaces that are either stripped entirely of the alluvial cap or are covered only by transported soils and a few partially disintegrated cobbles of vein quartz and greenstone. The soils found on most of the terraces are of the Dyke Series and Braddock Series, both characterized by deep red (2.5YR to 10 R Munsell colors), thick argillic horizons, and deeply weathered clasts of granite. The Dyke Series is a clayey, mixed, mesic, typic Rhodudult. The Braddock Series is a clayey, mixed, mesic, typic Hapludult (Elder and Pettry, 1975).

The higher strath terrace deposits of the Rapidan River have weathering characteristics similar to both the early Pleistocene and Late Tertiary deposits of the Fall Zone and Inner Coastal Plain of Virginia as described by Howard and others (1993). The clay content, Munsell colors, and weathering characteristics of the Dyke and Braddock soils series, Rhodudult and Hapludult respectively, are similar to pedological characteristics found in the Paleudult soils of the Fall Zone terraces dated 3.4 mybp to 5.3 mybp. In contrast, the Dyke soil series has a greater rubification and clay content than the Hapludult terrace soils at the Fall Zone (7,000 ybp to 1.6 mybp) (Howard and others, 1993). Although different parent materials could be a factor, correlation of soils from the Fall Zone to the Blue Ridge suggests that the higher terraces in the study area are early Pleistocene to late Pliocene in age.

A high terrace on Kinsey Run in the Fletcher, VA 7.5' quadrangle was trenched and revealed two distinct deposits overlying saprolitized gneiss (Eaton and others, 2001b). The upper unit had a 1.0 meter thick argillic horizon, a 2.5 YR Munsell color, and a clay content of 72 percent. The lower unit has an argillic horizon of 0.8 meters, a

10R Munsell color and a clay content of 40 percent. A cosmogenic beryllium date of this surface suggests an age greater than 500,000 ybp (Pavich, USGS, written communication). All *in situ* boulders are extensively saprolitized.

FLUVIAL DEPOSITS AND TERRACES ON THE WESTERN FLANK OF THE BLUE RIDGE

The western flank of the Blue Ridge is bordered by extensive gravels and sands of fluvial origin that form a nearly continuous bajada between the Blue Ridge and the low, hilly ground stretching to the Shenandoah River. The gravel deposits were described by King (l950) in the Elkton vicinity, and more broadly by Hack (l965). Hack’s general map of the Shenandoah Valley at 1:250,000-scale labeled these deposits as alluvium on terraces. More detailed studies have been undertaken by Kochel and Johnson (1984), Kochel (1987, 1990, 1992), Duffy (1991), Kite (1992), Whittecar and Duffy (1992), and by thesis studies of Bell (1986) Wilson (1987), Simmons (1988) and Mason (1992). Together these studies have demonstrated that an extensive plexus of alluvial fan deposits extend with gentle slopes of usually less than 6 degrees from the mountain front to the Shenandoah River. The fans are almost entirely made up of detritus from the Chilhowee Group, especially the more resistant quartzites of the Antietam Formation, and they largely cover the Tomstown Dolomite and Waynesboro Formation. The Tomstown Dolomite has undergone extensive solution and karstification and has been an unstable substrate during the deposition of alluvial fans. The older fans have collapsed into the karst so that accumulations of alluvial deposits commonly reach 30 m (100 ft); drill records reveal that they can be as much as 53 m (175 ft) thick in places (King, 1950).

Alluvial fan deposits are well-developed along the flanks of the west slope of the Blue Ridge from Waynesboro north to Luray. They are especially prominent in filling the valley floors of the large re-entrants in the Blue Ridge in the areas around Elkton and Luray. They are present in at least two distinct topographic levels that have been interpreted as terraces of the Shenandoah River (Bell, 1986). In the area of study, data for the alluvial fans on the western flank have been compiled to depict two separate surfaces or terraces, in addition to the modern flood plain of the South Fork of the Shenandoah River.

The modern streams and rivers draining the Blue Ridge are currently incising the alluvial deposits. Although there is ample evidence that these streams overtop their banks during floods, there is no evidence that slack water deposition is taking place on the alluvial surfaces, or that bouldery deposits are accumulating at the present time. From Waynesboro north to the town of Shenandoah, the streams draining the Blue Ridge have narrow flood plains that are deposited on older alluvial fan material. Further to the north, the alluvial fan deposits are incised increasingly deeper by streams that penetrate through the deposits into bedrock, resulting in minor or no flood plain. From the town of Shenandoah north to Front Royal, all of the streams flow over bedrock before reaching the South Fork of the Shenandoah. In this area, the alluvial fan deposits become increasingly fragmentary, occupying smaller areas on hilltops, and are almost completely removed by erosion at the northern boundary of the study area.

Incision of the alluvial fan deposits by modern streams coupled with terrace development by action of the South Fork of the Shenandoah River has divided the rolling lowland into lobes that can be interpreted as discrete depositional fans (see for example, Bell, 1986; and Kochel, 1992, fig. 7). Although some of the lobes may be the result of depositional accumulation from single drainages, the depositional history has been extremely complex and the modern streams are cutting into a plexus of older alluvial deposits. The present topographic lobes owe more to the modern incision pattern than to earlier patterns of deposition.

Cross sections of the alluvial deposits are very limited. King (1950) was able to document longitudinal sections of the deposits based on drill records. His sections show alluvial deposits of gravel as much as 53 m (175 ft) thick lying over residual clay (or saprolite) derived from the Tomstown dolomite that in places is as much as 61 m (200 ft) thick. However, his descriptions of older and younger gravels fail to differentiate them into discrete units based on weathering, soil development, depositional fabric or other criteria.

A spectacular exposure of multiple units in the alluvial deposits is exposed on an eroded bluff along Meadow Run near Crimora, Virginia, and was described by Sherwood and others (1987) and by Whittecar (1992). Elements or parts of the stratigraphic succession exposed at this outcrop occur in alluvial deposits in other places along the western flank of the Blue Ridge and lend credence to the use of this single locality as a regional model for these deposits. Figure 2 is taken from Whittecar (1992) with several modifications based on the present state of exposure. The deposit was divided by Sherwood and others (1987) and by Whittecar into 13 units, although several of these (4 and 5) were not exposed during field work in the autumn of 2002. Unit 1 is a saprolite formed on the Tomstown Dolomite and is overlain by Units 2 and 3, both of which are intensely saprolitized, enriched in clay, and highly oxidized. Despite extensive alteration, these units contain sufficient fabric to show that they originally consisted of clast-supported rounded pebbles of quartzite, evidence of an alluvial sequence. Bedding in the units is well-defined and parallel to the contact with the underlying residual saprolite. The steep dips of 40 to 45 degrees of these units is remarkable and interpreted to be the result of collapse after formation due to extensive leaching of carbonate from the underlying dolomite. Units 4 and 5 were not visible in 2002 but according to Whittecar, the units were deformed, but less than Units 2 and 3, and represent an upward fining sequence of coarse gravels overlain by finer-grained overbank deposits. Unit 6 can be traced across the outcrop and consists of coarse cobbles and gravel. Depositional evidence such as imbricate structures are largely absent, perhaps due to tree growth disrupting the fabric and jacking individual cobbles out of the original position. This is especially evident at the contact with the overlying unit 7 that is a sandy slackwater deposit. At that contact, trains of cobbles from Unit 6 locally disrupt the contact and “intrude” into the slackwater deposits, apparently pushed into place by tree growth. The principal evidence for the alluvial origin of Unit 6 is the round cobbles and moderate-to-good sorting, and the paucity of a finer matrix. Similar open work, clast-supported fabrics can be identified in the cobbles forming the low banks of the modern stream.

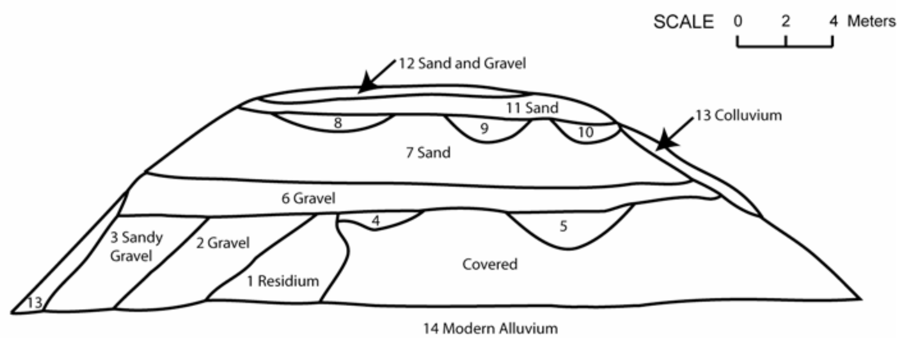

FIGURE TWO: STRATIGRAPHY OF ALLUVIAL DEPOSITS EXPOSED ON MEADOW RUN

Unit 7 is a sand sheet formed from overbank flooding and was formed from multiple flood events. Its 3 m (10 ft) thickness is remarkable and, if widespread, represents a period of aggradation very different from the present regime characterized by entrenchment of the alluvial sequence. The sand sheet is crossed by three channels (Units 8, 9 and 10) that are filled with coarse cobbles. The three channels may actually be portions of the same meandering channel. These are overlain by a thin sand sheet, Unit 11, and a sandy sheet with loose cobbles and pebbles, Unit 12. Whittecar also lists the colluvium and sediments in the modern stream floor as additional Units 13 and 14.

Taken as an analogue for the regional deposition of alluvial sediment, the exposure on Meadow Run as well as fragmentary exposures elsewhere in the area of study suggests that deposition of alluvium has been periodic over an extended, but unknown age. Several major conclusions can be drawn from the fragmentary picture that is available.

The high angle dips of strata and weathering of older deposits are evidence of a landscape that collapsed into extensive karst developed in the underlying Tomstown Dolomite. Evidence for this has been given by King (l950) and Bell (l986) and by the exposures on Meadow Run. However, younger sediment was not so severely affected. Sand layers in alluvial deposits exposed in numerous road cuts, stream banks, and the younger units at Meadow Run are horizontal or near horizontal, all evidence that the major period of karst development was before the youngest deposits. However, the propagation of sink holes through the overlying mask of alluvial gravels and the thickness of these deposits suggests that at least some dissolution of the underlying dolomite is ongoing, resulting in at least minor modification of the present day surface.

Boulder and cobble sizes in the higher level alluvial deposits (Units 6, 8,and 11 in Meadow Run, Figure 2) rarely exceed 0.5 m in longest dimension, and are similar to those moved by modern streams draining the western flank of the Blue Ridge during periods of flooding, such as Meadow Run, Payne Run, Madison Run, Big Run, and

Hawksbill Creek. The very large blocks of quartzites from the Harpers and Antietam Formations present in block fields on the upper slopes of these drainages commonly exceed one meter and not infrequently 3 meters (Eaton and others, 2002). These large blocks have not been carried down slope onto the alluvial deposits, a process that would require debris-flows during a major rain storm. This suggests that the alluvial deposits making up the foot slopes of the western Blue Ridge were not built during major, prehistoric storms, but built by streams having a hydrologic capability similar to modern streams draining the same area.

The alluvial deposits are not only incised by modern streams, but the distal parts of the deposits have been planed off by the Shenandoah River and form distinct lower terraces. In the area of study, these deposits are divided only into a higher and lower terrace set, allowing for the possibility of several flights of terraces within each set (see for example, Bell's discussion, 1986). As pointed out earlier, the incision of the alluvial fan deposits is greater in the northern part of the area. This suggests that changes in the base level of erosion of the South Fork of the Shenandoah have been a major factor in the regional destruction of the alluvial deposits. Evidence for radical change or lowering of that base level is (1) the high topographic level of the alluvial deposits such as those exposed at Meadow Run relative to the modern flood plain of the South Fork of the Shenandoah River; (2) development of distinct terrace levels; and (3) progressive, continuous change of base level in the Shenandoah River as evidenced by the increasing degree of incision of surfical deposits to the north and their nearly complete destruction at the latitude of Front Royal.

In describing the Meadow Run exposure, Whittecar (1992) observed that the time of deposition of the alluvial deposits, and the more regional terrace construction was not known, a problem that persists to the present. A substantial but unknown length of time must have elapsed between the saprolitized and collapsed alluvium (Units 2 and 3 at Meadow Run) and the overlying, flat-lying flood and slack water deposits. Extensive weathering and rubification of the lowest and oldest units suggests a Pliocene or early Pleistocene age, but that is conjectural.

These studies document the presence of older alluvial fan deposits and terraces on both flanks of the Blue Ridge. There are some similarities, but more generally, there are profound differences between these deposit groups. Both flanks have prominent terraces and both are strath, or cut terraces. The eastern terraces are cut into bedrock and the western are cut into the older alluvial deposits derived from the Blue Ridge, although admixture on the lowest western terraces with alluvial material deposited by the Shenandoah River is also present. Thus, both flanks of the Blue Ridge show a regional readjustment to base levels of erosion that is probably but not certainly, a late Pliocene or Early Pleistocene event. Both sets of terraces and related alluvial deposits show best development in the south and central parts of the study area and both progressively become more and more negligible to the north and are nearly absent at the latitude of Front Royal.

Alluvial materials on the west flank are eroded relative to the base level of the Shenandoah River that flows north to the Potomac, then southeast to the tidal estuary of the Potomac, a distance of approximately 240 km (150 mi) (for example, from Grottoes, Virginia to Washington, DC). Streams draining the eastern flank reach the Virginia tidewater area in half the distance (for example, from the headwaters of the Rapidan to Fredericksburg, Virginia), suggesting that removal of detritus from the eastern flank should proceed with substantially greater efficiency than on the western side.

The alluvial deposits and terraces on the western flank are armored with cobbles of quartzite that show great resistance to weathering, whereas the alluvial deposits that cap the strath terraces on the eastern flank consist of granite cobbles and scarce vein quartz cobbles. These have nearly completely disintegrated and most terraces on the eastern side are stripped of all but a thin cover of transported soil. Terraces armored with quartzite have great durability, and west-to east through-going drainages such as the James River have prominent terraces capped with quartzite cobbles derived largely from the Antietam Formation. By contrast, terraces and associated deposits on the eastern flank are evident primarily from their relict morphology and older, red soil sequences and saprolite.

The substrate for the two sets of terraces contrasts sharply. The older alluvial deposits along the western flank have sagged and collapsed into a karst terrain. Longitudinal sections of colluvium from mountain front to the Shenandoah River obtained by drill records from the Elkton area (King, 1950, fig.16) show an overall thickening in the central parts of the gravel deposits in three of his four sections. Subsequent deposition appears to have been only slightly modified by continued or renewed karstification.

DEBRIS-FLOW DEPOSITS

Diamictons of boulders and cobbles that appear to be suspended in, or floating in a matrix of sand, silt, and clay form deposits that fill the lower reaches of many of the stream valleys and hollows draining the Blue Ridge. These constructional features are formed by debris flows and are commonly referred to as debris-flow fans. Deposition in narrow valleys influences their actual form so that a fan-like aerial distribution, commonly associated with arid environments in the western United States, is almost never realized (Kochel, 1990). Fans that were deposited down major stream valleys such as the Rapidan, Conway, South, Moormans, and Hughes Rivers are often partially eroded, and remnants of these fans form terraces. Debris-flow deposits or fans in the Blue Ridge typically are several tens-to-hundreds of meters wide and rarely exceed more than a few kilometers in length. The deposits may be more than 30 m (98 ft) thick near their distal margins (Daniels, 1997); they progressively thin up gentle slopes of 6 to 12 degrees and merge into sporadic clast-supported debris along streams with gradients steeper than 12 degrees. The colluvial soils and moderate slopes of the debris-flow fans allow for good drainage of cold air and moisture and are attractive for farming, especially for hay and pasture, as well as for orchards and more recently, vineyards. Early settlers in the area were attracted to living and farming on the debris-flow fans because of gentle slopes and lack of bedrock; the now forested fans reveal numerous stonewalls, terrace walls, and stone piles, evidence of the extraordinary labor of the settlers to create orchards and pasture.

Almost all of the debris-flow fans in the study area are constructed from granitic debris or granitic debris mixed with clasts of greenstone. As quartzo-feldspathic rocks crop out on most of the slopes of the eastern side of the Blue Ridge, most of the debris-flow fans also occur on the east side. In those places where major faults have thrust the granitic rocks westward so that they form the crest and slopes of the western side of the Blue Ridge, debris-flow fans are also common (for example, the west slope of the Blue Ridge from Thornton Gap, south to Tanners Ridge). Although the Catoctin Formation occupies much of the elevated terrain in the Blue Ridge, debris-flow fans composed dominantly of Catoctin Formation rocks are not common. The Moormans River is the only major drainage within the study area that flows through extensive outcrops of Catoctin Formation and the riverbanks and those of many first and second order tributaries contain numerous small debris-flow fans and debris-flow terraces. The Weverton and Harpers Formations supply blocks of quartzite and finer material derived from siliceous slates to a few small debris-flow deposits that cover valley floors underlain by the Harpers Formation; debris-flow deposits are distinctly less abundant to absent in most of the terrain underlain by the Chilhowee Group.

During a major flood and debris-flow event in Madison County in 1995, debris-flow deposits were extensively scoured to reveal a complex stratigraphy of older debris-flow deposits interbedded with slope wash colluvium and minor alluvium. All of the larger debris-flow deposits that were incised were found to be composite with stratigraphy giving evidence for a history of multiple events. Sufficient charcoal was obtained from these deposits, and C^{14} dates provide evidence that the area has been undergoing debris-flow deposition from greater than 50,000 ybp (the limit of C^{14} age determinations) to the present, with the majority of dated deposits ranging from 13,000 to 26,000 ybp (Eaton and McGeehin, 1997; Eaton, 1999; Eaton and others, 2001a). Deposits older than 50,000 ybp have lower clast populations, greater rubification, and a clay-rich matrix. Some deposits were noted with as much as 80 percent clay, much of which is pedogenic. Catoctin greenstone in the older deposits have well-developed weathering rinds of about 2 to 4 mm (Eaton and others, 2001b). Granitic cobbles are often completely weathered and rounded. Primary minerals are extensively altered and cementation is moderate. The debris-flow deposits younger than 35,000 ybp show minimal or no weathering rinds, and deposits consisting primarily of granitic cobbles have a lower clay content. These deposits are only slightly cemented and clasts are easily dislodged. Holocene debris flow deposits of granitic clasts have from 2 to 3 percent silt and clay (percent finer than 0.004mm) in an otherwise sandy matrix (Wieczorek and others, 2000). The Holocene deposits are highly permeable due to the sand-rich, clay-poor matrix, are extensively oxidized, and consequently contain scarce or no charcoal for dating. There is virtually no cementation of the fabric. All of the debris-flow deposits composed of clasts from the Chilhowee Group are sand-rich and are highly oxidized with no recovered charcoal. By contrast, debris flows comprised of Catoctin clasts on the Moormans River have a clay-rich matrix and abundant preserved charcoal.

Preliminary studies of *in situ* cosmogenic isotopes, ^{10}Be and ^{26}Al, on 21 boulders in a debris fan near Graves Mill (Bierman and others, 2002) support and extend the ages of debris flows in the Madison, Virginia area. Model exposure ages of boulder samples range from 7,000 to 140,000 ybp with clusters of dates at 18,000, 30,000, 67,000 and 140,000 ybp. Use of these model ages is qualified inasmuch as the amount of inherited nuclides in the boulders is not known and also the amount of surface erosion of the boulders removing the accumulated nuclides is not known.

The majority of ages determined for debris flows in the Madison County area are late Pleistocene, a time of extreme climate instability in the Blue Ridge (Litwin and others, 2001). Permafrost conditions in the higher ridges resulted in generation of mountain-top debris during cold intervals; the debris was flushed out by violent storms as the climate “flickered” between cold and warm. The debris-flow fans created during the late Pleistocene are currently being incised. The incision of small streams draining the fans creates a characteristic “wavy” or undulating contour pattern that can be easily identified on topographic sheets, even those with 40-foot contours. Older fans are nearly boulder free on the surface and are identified primarily by surface morphology. These fans are usually modified by extensive agriculture. Younger fans have surfaces with partially buried boulders within a soil matrix that supports forest and limited use for pasture. The youngest fans are extremely stony, with tangential clasts often piled with clast-on-clast contact and are never cultivated. The Holocene debris-flow events have been mining out debris created during colder intervals, and deposits from these events are principally in the channels of the incised older fans. The sediment supply for the Holocene debris-flow events, including the 1995 storm and accompanying landslides, is not derived from a steady state process of weathering and filling of hollows in which a balance is maintained between sediment accumulation and catastrophic removal. The longer term evolution of these slopes appears to be one of periodic and catastrophic removal of older colluvium from the upper slopes of the Blue Ridge, and a tendency for a gradual return to Pre-Pleistocene conditions marked by continuous weathering and gradual removal of soil derived from weathered bedrock.

The 1995 convective storms that struck the Blue Ridge area of central and southern Virginia caused extensive flooding and debris-flow activity in three areas of Shenandoah National Park and one in the George Washington National Forest near Buena Vista, Virginia. The area between the Robinson and Conway Rivers in Madison County and on the Moormans River in Albemarle County, both in the study area, were the most affected by the storms. On the morning and early afternoon of June 27, as much as 700 mm (30 inches) of rain fell in a small area of about 130 km^2 in Madison County, resulting in an excess of 1000 debris flows (Morgan and others, 1999a; Wieczorek and others, 2000) in an area entirely underlain by granitic rock. On the same evening, a smaller storm struck the Moormans River area (Morgan and Wieczorek, 1996) and rain in excess of 292 mm (11.5 inches) fell in a two-hour interval. Approximately 100 debris flows and debris slides were generated by the storm in this area underlain by Catoctin Formation.

In the Madison area, debris flows were generated on slopes of approximately 30 +/- 4^{o} as debris slides, usually became fluid within a few tens of meters, and entrained as much as 90 percent of final volume during descent to flood plains of the Rapidan, Robinson, and Conway Rivers. Super elevation, measured on the channels of several of the debris-flow chutes, indicates that velocities obtained were as much as 24 m/sec in the upper channel and decreased to 8 m/sec near the flood plain (Wieczorek and others, 2000). A large partial failure of a rotated block of soil with tilted trees was observed at only one site and ground fractures above failure sites were not observed. Approximately two thirds of the failure sites were within hollows, the remainder generated on planar or outwardly convex slopes. Scouring of the chutes and proximal portions of older debris-flow deposits was extensive with channels incising as much as 8 m into colluvium and saprolite.

In the Moormans River area, debris-slides were generated on slopes between 20 and 30 degrees, and evidence of down slope entrainment and fluid behavior was less conspicuous than in the Madison area. Ground cracking, slumping, and partially failed sites were common. Debris-slides moved directly down-slope from failure sites on noses and hollows of the slopes bordering the Moormans River. These combined in the Moormans River to create a major debris flow that partially filled upper end of the Sugar Hollow Reservoir in a series of five or more surges. The debris flow profoundly eroded the bed and side walls of the Moormans River, shearing off the sides of older debris-flow terraces, and exposing vertical cuts in the colluvium of as much as 10 m high. The fresh exposures revealed a complex stratigraphy of debris flows and slope wash deposits emplaced between 36,000 ybp and the present (Morgan and Wieczorek, 1996).

Debris flows in the central and southern Appalachian Mountains are not uncommon events. Clarke (1987) has documented 51 historical debris-flow events in the area between 1844 and 1985. This is probably a subset of the actual number because the area was sparsely populated during most of that time, and major storms that may have triggered debris flows in the uplands produced down stream events that were widely observed and recorded only as floods. During the past half-century, storms resulting in debris flows in the Appalachian Mountains of Virginia and West Virginia have been documented by Hack and Goodlett (1960), Williams and Guy (1973), Jacobson (1993), Morgan and Wieczorek (1996), Morgan and others (1999a, 1999b, 2000) and by Wieczorek and others (2000). The historic recurrence interval of these storms over this broad area has been from ten-to-fifteen years.

In the Madison area, the time of occurrence of prehistoric debris flows has been documented by dating charcoal and carbon fragments incorporated within debris-flow deposits (Eaton and McGeehin, 1997; Eaton and others, 2003a). The distribution of ages through the C^{14} data set that ranges from 35,000 ypb to the present is not uniform and the recurrence interval can be calculated using all or several subsets of the data. The resulting recurrence estimates range from 2,000 to 2,500 years, using the entire data set, for debris flows recurring at a given site similar in size to the Madison or Moormans areas affected by the 1995 storm.

Eaton and others (2003b) have used the recurrence interval of 2,500 years and the sediment moved in three small drainage basins during the 1995 storm together with the regional denudation rates (Judson and Ritter, 1964) to calculate the effectiveness of debris-flow erosion in regional denudation. They have found that debris-flow erosion accounts for at least 47 percent, nearly half, of the regional denudation caused by physical removal of material from slopes of the Blue Ridge.

ALLUVIAL DEPOSITS

Alluvial deposits cover the floors of many stream valleys draining the Blue Ridge. Commonly these channel deposits consist of cobbles and pebbles that are clast-supported and imbricated, and overlain by slack water deposits of fine gravel, sand, and silt. Rather than a simple time-stratigraphic sequence, this pair of strata is produced by the meandering of the stream scrolling across the flood plain, 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 eastern flank pass through debris-flow fans that are gradually submerged into the flood plain sequence so that the more distal parts of the fans are overlain by slack water deposits (e.g., the South and Robinson Rivers). The distal parts of the debris-flow fan are often extensively modified by later flooding so that the boundary between debris-flow fan and alluvial channel gravels and cobbles, both all or partly overlain by slack water deposits, is completely gradational.

On the eastern slope of the Blue Ridge, streams drain granitic bedrock and the alluvial deposits broaden out into well-developed flood plains that have been extensively modified by agricultural practices. Most major streams such as the Thornton, Robinson, Rapidan, Conway, and South Rivers have been channeled to increase the agricultural potential of the flood plain. The alluvial deposits are dissected by numerous drainage ditches. Local landowners and farmers have very precise ideas about 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 flood plain 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. 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 flood plains are extensively exploited for agriculture. Braided fluvial systems on these flood plains 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 "restored" 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. Floods of this magnitude occur in the area approximately every 1 to 3 years. (Eaton, 1999).

Streams draining the western slope of the Blue Ridge pass through steep walled valleys underlain by the Chilhowee Group rocks with only minor colluvium and alluvium preserved along stream courses. Velocity of streams such as the Paine, Madison, and Big Run apparently increases as the streams pass through the narrow valleys carved into the Antietam Formation. In these areas, the streams flow on bedrock and all sediment is bypassed to the west onto the floodplains of streams draining into the South Fork of the Shenandoah River. As noted earlier, floodplains of these streams draining the western flank of the Blue Ridge are resting on older fan deposits between the mountain front and the Shenandoah River in the southern part of the study area. North of the town of Shenandoah, the flood plains of prominent streams such as Hawksbill, Overall, and Jeremy Run do not extend to the Shenandoah River, and the streams drain on exposed bedrock at the juncture with the Shenandoah.

REFERENCES

Aleinikoff, J.N., Walter, Marianne, Lyttle, P.T., Burton, W.C., Leo, G.W., Nelson, A.E., Schindler, J.S., and Southworth, C.S., 1993, U-Pb zircon and monazite ages of Middle Proterozoic rocks, Northern Blue Ridge, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 25, no. 2, p.2.

Allen, R.M., 1963, Geology and Mineral Resources of Greene and Madison Counties: Virginia Division of Mineral Resources Bulletin 78, 102 p.

Allen, R.M., 1967, Geology and mineral resources of Page County: Virginia Division of Mineral Resources Bulletin 81, 78 p.

Badger, Robert, 1992, Stratigraphic characterization and correlation of volcanic flows within the Catoctin Formation, central Appalachians: Southeastern Geology, v. 32, p. 175-195.

Badger, Robert, 1993, Fluid interaction and geochemical mobility in metabasalts; an example from the central Appalachians: Journal of Geology, v. 101, p. 85-95.

Badger, R.L., and Sinha, A.K., 1988, Age and Sr isotopic signature of the Catoctin volcanic province – implication for subcrustal mantle evolution: Geology, v. 16, p. 692-695.

Bailey, C.M., Berquist, P.J., Mager, S.M., Knight, B.D., Shotwell, N.L., Gilmer, A.K., and Griffith, W.A., in press, Bedrock geologic map of the Madison quadrangle and parts of Brightwood, Madison Mills, and Rochelle quadrangles, Virginia: Virginia Divion of Mineral Resources

Bartholomew, M.J., and Lewis. S.E., 1984, Evolution of Grenville massifs in the Blue Ridge geologic province, southern and central Appalachians, *in*: Bartholomew, M.J., and others, editors, The Grenville Event in the Appalachians and related topics: Geological Society of America Special Paper 194, p. 229-254.

Bell, A.M. 1986, Morphology and stratigraphy of terraces in the upper Shenandoah Valley, Virginia: M.S. Thesis, West Virginia University, Morgantown, 160 p.

Bierman, P.R., Pavich, Milan, Eaton, L.S., and Finkel Robert, 2002, The boulders of Madison County [abs.]: Geological Society of America Abstracts with Program, v. 34, p.

Bloomer, R.O., and Werner, H.J., 1955, Geology of the Blue Ridge region in central Virginia: Geological Society of American Bulletin v. 66, pp. 579-606.

Brent, W.B., 1960, Geology and Mineral Resources of Rockingham County: Virginia Division of Mineral Resources Bulletin 76, 174 p.

Burton, W.C., Aleinikoff, J.N., Southworth, C.S., and Lyttle, P.T., 1994, Grenvillian history of intrusion and deformation, northern Blue Ridge, Virginia [abs.]: Geological Society of America Abstracts with Programs, v. 26, no. 4, p. 5-6.

Clark, G.M., 1987, Debris slide and debris flow historical events in the Appalachians south of the glacial border *in* J.E. Costa and G.F. Wieczorek, (eds), Debris Flows/Avalanches: Process, Recognition and Mitigation: Geological Society of America Reviews in Engineering Geology, Vol. VII, p. 125-179.

Daniels, N., 1997, The role of debris flows in landscape evolution in the Blue Ridge Mountains, Madison County, Virginia: Senior Thesis, Bucknell University, 78 p.

Duffy, D.L., 1991, The geomorphology of alluvial fan deposits on the west flank of the Blue Ridge, Augusta County, Virginia: M.S. thesis, Old Dominion University, Norfolk, VA, 118 p.

Eaton, L.S., 1999, Debris flows and landscape evolution in the Upper Rapidan Basin Blue Ridge Mountains, Central Virginia: Ph.D. Thesis, University of Virginia, 154 p.

Eaton, L.S., and McGeehin, J.P., 1997, Frequency of debris flows and their role in the long term landscape evolution in the central Blue Ridge (abstr.) Geological Society of America Abstracts with Programs, v. 219, no. 6, p. 410.

Eaton, L.S., Morgan, B.A., and Blair, J.L., 2001a, Surficial geology of the Fletcher, Madison, Stanardsville, and Swift Run Gap 7.5-minute quadrangles, Madison Greene, Albemarle, Rockingham and Page Counties, VA: U. S. Geological Survey Open File Reports 01-92, 4 maps 1:24,000-scale.

Eaton. L.S., Wieczorek, G.F., and Morgan, B.A., 2001b, Weathering characteristics and Ages of debris-flow deposits at Graves Mill, VA [Abs.]: Geological Society of America, Abstracts with Programs, v. 33, no. 2, p. 59A.

Eaton, L.S., Wieczorek, G.F., Morgan, B.A., McKnown, A.W., Smoot, J.P, and Litwin R.J., 2002, Periglacial slope-processes and deposits in the Blue Ridge Mountains of Central Virginia [abs.]: Geological Society of America Abstracts with

Programs, v. 34 p.
Eaton, L.S., Morgan, B.A., Kochel, R.C. and Howard, A.D., 2003a, Quaternary deposits and Landscape evolution of the central Blue Ridge of Virginia: Geomorphology, v. 1351, p. 1-16.
Eaton, L.S., Morgan, B.A., Kochel, R.C. and Howard, A.D., 2003b, Role of debris Flows in long-term landscape denudation in the central Appalachians of Virginia: Geology, v. 31, p. 339-342.
Elder, J.H., and Pettry, D.E., 1975, Soil Survey of Madison County, Virginia: USDA, Government Printing Office, Washington, D.C., 143 p.
Espenshade, G.H., 1970, Geology of the northern part of the Blue Ridge anticlinorium *in* Fisher, G.W., and others, eds. Appalachian geology: New York, Interscience Publishers, p. 199-211.
Furcron, A. S., 1934, Igneous rocks of the Shenandoah National Park area: Journal of Geology, v. 42, p. 400-410.
Gathright, T.M., 1976, Geology of the Shenandoah National Park, Virginia: Virginia Division of Mineral Resources, Bulletin 86, 93 p.
Gathright, T.M., Henika, W.S., and Sullivan. J.L., III, 1977, Geology of the Waynesboro East and Waynesboro West quadrangles, Virginia: Virginia Division of Mineral Resources, Publication 3, 53 p.
Gathright, T.M., Henika, W.S., and Sullivan, J.L., III, 1978a, Geology of the Grottoes quadrangle, Virginia: Virginia Division of Mineral Resources Publication 10, text and 1:24,000-scale map.
Gathright, T.M., Henika, W.S., and Sullivan, J.L., III, 1978b, Geology of the Crimora quadrangle, Virginia: Virginia Division of Mineral Resources Publication 13, text and 1:24,000-scale map.
Hack, J.T., 1965, Geomorphology of the Shenandoah Valley, Virginia and West Virginia and origin of the residual ore deposits: U. S. Geological Survey Professional Paper 484, 84 p.
Hack J.T., and Goodlett, J.C., 1960, Geomorphology and forest ecology of a mountain Region in the central Appalachians: U. S. Geological Survey Professional Paper 347, 66 p.
Hackley, Paul, and Tollo, Richard, in press, Bedrock geologic map of the Old Rag Mountain, Virginia quadrangle: Virginia Division of Mineral Resources
Howard, J.L., Amos, D.F., and Daniels, W.L., 1993, Alluvial soil chronosequences in the Inner Coastal Plain, central Virginia: Quaternary Research, v. 39, p. 201-213.
Jacobson, R.B., editor, 1993, Geomorphic studies of the storm and flood of November 3.5, 1995, in the Upper Potomac and Cheat River Basins in West Virginia and Virginia: U. S. Geological Survey Bulletin 1981.
Jonas, A.I., 1934, Hypersthene granodiorite in Virginia: Geological Society of America Bulletin, v. 46, p. 47-60.
Jonas, A.I., and Stose, G.W., 1939, Age relation of the Precambrian rocks in the Catoctin Mountain-Blue Ridge and Mount Rogers anticlinoria in Virginia: American Journal of Science, v. 237, no. 8, p. 575-593.
Judson, S., and Ritter, D.F., 1964, Rates of regional denudation in the United States, Journal of Geophysical Research, v. 69, p. 3395-3401.
Keith, Arthur, 1894a, Geology of the Catoctin belt: U. S. Geological Survey 14th Ann.

Report, pt. 2, p. 285-395.
Keith, Arthur, 1894b, Description of the Harpers Ferry Sheet, Virginia, Maryland, West Virginia: U.S. Geological Survey Geologic Atlas (Folio no. 10) 5 p.
King, P.B., 1950, Geology of the Elkton area, Virginia: U. S. Geological Survey Professional Paper 230, 82 p.
Kochel, R.C., 1987, Holocene debris flows in central Virginia *in* Costa, J.E., and Wieczorek, G.F., (Eds.), Debris flows/avalanches: Process, recognition, And mitigation: Geological Society of America Reviews in Engineering Geology, v. 7, p. 139-155.
Kochel, R.C., 1990, Humid fans of the Appalachian Mountains, *in* Rachocki, A.H., and Church, M. (Eds.), Alluvial Fans: A field approach: Wiley, New York, p.109-129.
Kochel, R.C., 1992, Geomorphology of alluvial fans in west-central Virginia: *in* Whittecar, G.R., (Ed.), Alluvial fans and boulder streams of the Blue Ridge Mountains, west-central Virginia: Southeastern Friends of the Pleistocene, 1992 Field Trip, p.47-60.
Kochel, R.C., and Johnson, R.A., 1984, Geomorphology and sedimentology of humid Temperate alluvial fans, central Virginia. i*n* Gravels and Conglomerates, E. Koster and R. Steel, (eds.) Canadian Society of Petroleum Geologists Memoir 10, p. 109-122.
Kite, J. S., 1992, Geomorphology research in the Shenandoah Valley: West Virginia University Geology Program: in Whittecar, G.R., editor, Alluvial Fans and boulder streams of the Blue Ridge Mountains, west-central Virginia: Southeastern Friends of the Pleistocene, 1992 Field Trip, p. 113-118.
Litwin, R.J., Morgan, Benjamin, Eaton, Scott, Wieczorek, Gerald, and Smoot, Joseph P., 2001, Proxy climate evidence from Late Pleistocene Deposits in the Blue Ridge of Virginia: U.S. Geological Survey Open File Report 01-406, p. 79.
Mason, John E., 1992, Surficial geology of alluvial fans and terraces on the western Flanks of the Blue Ridge Mountains between Elkton and Port Republic, VA: M.S. thesis West Virginia University, Morgantown, WVA, 74 p.
Mitra, Gautram, and Lukert, M.T., 1982, Geology of the Catoctin-Blue Ridge Anticlinorium in northern Virginia; in: Central Appalachian Geology, American Geological Institute, NE-SE Geological Society of America 1982 Field Trip Guidebook, p. 83-108.
Mixon, R.B., Pavlides, Louis, Powars, D.S., Froelich, A.J., Weems, R.E., Schindler, J.S., Newell, W.L., Edwards, L.E., and Ward, L.W., 2000, Geologic map of the Frederick 30’ x 60’ quadrangle, Virginia and Maryland: U. S. Geological Survey, Geologic Investigations Map I-2607, 1:100,000-scale.
Morgan, B.A., and Wieczorek, G. F., 1996, Debris flows and landslides resulting from the June 27, 1995 storm on the North Fork of the Moormans River, Shenandoah National Park, Virginia: U. S. Geological Survey Open-file Report 96-503, 9 p.
Morgan, B. A., Wieczorek, G.F.,and Campbell, R.H., 1999a, Map of rainfall, debris flows and flood effects of the June 27, 1995 storm in Madison County, Virginia: U. S. Geological Survey Geologic Investigations Series Map I-2623-A, 1/24,000 scale.
Morgan, B.A., Iovine, G., Chirico, P., and Wieczorek, G.F., 1999b, Inventory of debris

flows and floods in the Lovingston and Horseshoe Mountain, VA, 7.5' quadrangles, from the August 19/20, 1969, storm in Nelson County Virginia: U. S. Geological Survey Open File Report 99-518, 9 p., map, scale 1:24,000.

Morgan, B.A., Wieczorek, G.F., and Blair, J.L., 2000, Debris-flow hazard inventory and evaluation, Albemarle County Virginia: U. S. Geological Survey Open-File Report 00-008, 13 p., map, 1:62,000 scale.

Morgan, B.A., and Eaton, L.S., in press, Surficial geologic map of the Old Rag Mountain Virginia quadrangle: Virginia Division of Mineral Resources.

Naeser, C.W., Naeser, N.D., Kunk, M.J., Morgan, B.A., Schultz, A.P., Southworth, C.S., and Weems, R.E., 2002, Paleozoic through Cenozoic uplift, erosion, stream capture, and deposition history in the Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain Provinces of Tennessee, North Carolina, Virginia, Maryland, and District of Columbia: Geological Society of America, Abstract with Programs.

Nelson, W.A., 1962, Geology and mineral resources of Albemarle County, Virginia Division of Mineral Resources, Bulletin 77, 92 p.

Pavich, M.J., 1989, Regolith residence time and the concept of surface age of the Piedmont "peneplain": Geomorphology, v. 2, p.181-196.

Rader, E.K, and Biggs, T.H., 1975, Geology of the Front Royal quadrangle, Virginia: Virginia Division of Mineral Resources, report of Investigations 45, 104 p.

Rader, E.K., and Evans, N.H, (Eds.), 1993,Geologic map of Virginia – Expanded explanation: Virginia Division of Mineral Resources, 80 p.

Rader, E.K, and Conley, J.F. 1995, Geologic map of Warren County, Virginia: Virginia Division of Mineral Resources, Publication 138, text and map scale-1:62,500.

Rader, E.D., McDowell, R.C., Gathright, T.M, and Orndorff, R.C., 1996, Geologic map of Clarke, Frederick, Page, Shenandoah, and Warren Counties Virginia: Lord Fairfax Planning District: Virginia Division of Mineral Resources, Publication 143, map scale-1:100,000.

Reed, J.C., Jr., 1955, Catoctin Formation near Luray, Virginia: Geological Society of America Bulletin, v. 66, p. 871-896.

Reed, J.C., Jr., and Morgan, B.A., 1971, Chemical alteration and spilitization of the Catoctin Greenstones, Shenandoah National Park, Virginia; Journal of Geology, v. 79, p. 526-548.

Sherwood, W.C., Campbell, F.W., Kite, J.S., and Bell, A., 1987, Surficial geology of the Central Shenandoah Valley, Virginia Geology Field Conference Guidebook, James Madison University, Harrisonburg, 43 p.

Simmons, D.W., 1988, Geomorphology and sedimentology of humid-temperate Alluvial fans along the west flank of the Blue Ridge Mountains, Shenandoah Valley, Virginia: M.S. thesis, Southern Illinois University, Carbondale, IL, 107 p.

Sinha, A.K., and Bartholomew, M.J., 1984, Evolution of the Grenville terrane in the Central Virginia Appalachians, *in*: Bartholomew, M.J., and others, editors, The Grenville Event in the Appalachians and related topics: Geological Society of America Special Paper 194, p. 175-186.

Southworth, Scott, and Brezinski, David K., 1996, Geology of the Harpers Ferry Quadrangle, Virginia, Maryland, and West Virginia: U. S. Geological

Survey Bulletin 2123, 33 p.
Stose, G.W., 1906, The sedimentary rocks of South Mountain, Pennsylvania: Journal of Geology, v. 14, p. 201-220.
Stose, A.J., and Stose, G.W., 1946, Geology of Carroll and Frederick Counties: Maryland Dept. Geology, Mines, and Water Resources, Carroll and Frederick Counties Report, p. 11-131.
Whittecar, G.R., editor, 1992, Alluvial Fans and Boulder streams of the Blue Ridge Mountains, west-central Virginia: Southeastern Friends of the Pleistocene, 1992 Field Trip, 128 p.
Whittecar, G.R., and Duffy, D.L., 1992, Geomorphology and stratigraphy of Late Cenozoic alluvial fans, Augusta Co., Virginia, *in* Whittecar, G.R. (Editor), Alluvial Fans and Boulder streams of the Blue Ridge Mountains, west-central Virginia: Southeastern Friends of the Pleistocene, 1992 Field Trip, p. 79-112.
Wieczorek, G.F. Morgan, B.A., and Campbell, R.H., 2000, Debris-flow hazards in the Blue Ridge of Central Virginia: Environmental and Engineering Geoscience, v. VI, no. l, p. 3-23.
Williams, G.P., and Guy, H.P., 1973, Erosional and depositional aspects of Hurricane Camille in Virginia, 1969: U.S. Geological Survey Professional Paper 804, 80 p.
Wilson, G.C., 1987, Debris flows and alluvial fan development in the Appalachians: M.S. Thesis, Southern Illinois University, Carbondale, Illinois