GEOLOGIC HAZARDS OF VIRGINIA

Author contacts

L. Scott Eaton, Department of Geology and Environmental Science, James Madison University, Harrisonburg, VA 22807, eatonls@jmu.edu

R. Craig Kochel, Department of Geology, Bucknell University, Lewisburg, PA 17837, kochel@bucknell.edu

David A. Hubbard, Jr., Virginia Department of Mines, Minerals and Energy's Division of Mineral Resources, 900 Natural Resources Dr., Suite 500, Charlottesville, VA 22903, david.hubbard@dmme.virginia.gov

Fiorella V. Simoni de Cannon, Department of Chemistry and Biochemistry, George Mason University, Fairfax, VA 22030, FSIMONIDECANNON@lmi.org

Douglas G. Mose, Department of Chemistry and Biochemistry, George Mason University, Fairfax, VA 22030, dmose@gmu.edu

INTRODUCTION: AN OVERVIEW OF GEOLOGIC HAZARDS OF VIRGINIA

L. Scott Eaton

In the United States, natural hazards are annually responsible for hundreds of deaths, disruption of commerce, destruction of homes and infrastructure, and billions of dollars in disaster aid (USGS, 2007). The U.S. Geological Survey includes earthquakes, floods, hurricanes, landslides, tsunamis, volcanoes, and wildfires as natural hazards. Although the number of lives lost to natural hazards each year generally has declined, the economic cost of major disaster response and recovery continues to rise. Each decade, property damage from natural hazards events doubles or triples. The United States is second only to Japan in economic damages resulting from natural disasters (USGS, 2007).

Geologic hazards, a subset of natural hazards, are defined as a geologic condition or phenomenon, natural or brought about by human activity, that represents a threat to human life, welfare, and property (Neuendorf et al., 2005). In the Commonwealth, the threat of natural hazards continues to increase as more rural counties become suburbanized. In 2005, three of the top ten fastest growing counties in the United States were in Virginia (Christie, 2006). Loudoun County's population increased nearly 60% from 2000 to 2006, making it the fourth fastest-growing county in the United States (Francis, 2007). Additionally, sparsely populated regions of Virginia are not immune to geologic hazards. The remnants of Hurricane Camille in 1969 resulted in landslides and flooding that killed over 150 people in Nelson County, equating to approximately 1% of the county population. Other geologic hazards, although not as energetic, pose risk[1] to humans and property. For example, many rural counties in western Virginia have extremely high radon gas concentrations, and counties in karst regions can be at risk of sinkhole collapse and groundwater contamination. Regardless of the population density, recognizing these potential hazards in the Commonwealth, and disseminating the information to its citizens is of utmost importance.

[1] Throughout the section on radon, the term *risk* is used to mean the possibility of unwanted, adverse consequences to human life, health, property, or the environment. (Source: The Society for Risk Analysis, www.sra.org.)

The Virginia Department of Emergency Management lists geologic hazards within the Commonwealth as including landslides, flooding, subsidence from sinkholes and mining, radon, shoreline erosion, earthquakes, and soil movement. This chapter focuses on the first four of the listed topics; the topics of shoreline erosion, earthquakes, and subsidence from mining are addressed in other chapters of this volume. Soil movement, including the processes of frost heave and expandable soils, are notably present in Virginia, and are discussed in the Soils of Virginia chapter of this volume.

LANDSLIDE AND FLOODING HAZARDS IN VIRGINIA

L. Scott Eaton and R. Craig Kochel

INTRODUCTION

Landslides and flooding events pose a threat to both property and life throughout the United States. Annually, landslides cause approximately $3.5 billion in damage (valued in year 2001 dollars), and kill between 25 and 50 people annually, primarily from rock falls, rock slides, and debris flows (USGS, 2006). Flooding is even more costly in the loss of life and property, where over $6 billion in property damage and 140 deaths occur annually. Virginia experienced 13 flood-related federally declared disasters between 1996 and 2005, during which 12 hurricanes tracked across the state, including Fran, Bonnie, Floyd, Isabel, Jeanne, and Dennis (VDEM, 2007). Surprisingly to some, Virginia has experienced several of the most catastrophic geomorphic flooding events in the history of the United States. Two floods in recent memory that were notorious for their intensity and destructiveness are the Hurricane Camille event in Nelson County in 1969, and the Rapidan flood in Madison County in 1995 (Fig. 1). In Nelson County, nearly 1% of the County's population perished in this deluge; 113 confirmed dead with 39 missing, and damages amounting to more than $1.4 billion. In Madison County, the loss of life was limited to one fatality; and destruction of property reached $110 million. Geologically, these storms are remembered for accomplishing over a thousand year's worth of erosion in a single day, and for altering mountain front landscapes to a degree rivaling anything observed in the nation since European settlement (Eaton et al., 2003a,b). Rainfall in both of these events reached approximately 760 mm (30 in) in a day, and the resulting peak discharges of streams rank among the largest in the nation, based on the USA maximum flood envelope (Fig. 2). Virginia's geographic position as a common collision zone between extratropical and tropical air masses; and a wide distribution of orographic-triggering mechanisms on the slopes of the Appalachians (Michaels, 1985) combine to give Virginia one of the most dramatic hydroclimatic flood-producing terrains in the eastern USA.

Flooding has the potential to occur across Virginia. Notably, slow moving coastal storms, such as Northeasters, can cause widespread disturbances to seaside communities, as evident by the Ash Wednesday storm of 1962 (e.g., Zhang et al., 2002). Chincoteague Island experienced the brunt of this storm, where a combination of northeasterly winds from a stalled low pressure system and a tidal surge further enhanced from spring tide conditions, impacted the island community. This event still remains the largest flood to impact Chincoteague Island in recent memory. Coastal flooding is important, and is addressed in the chapter on Coastal Processes and Offshore Geology in this volume.

Occasionally, large geographic areas of Virginia are inundated by storms of both tropical and extratropical origins, including Hurricane Agnes in 1972 and Hurricane Fran in 1996. These storms were most remembered for their impact on the lowlands, where many communities were flooded by steadily rising water from mainstem rivers and large tributaries. Generally, these large storms bring periods of steady precipitation over several days, and usually allows citizens to seek shelter as flood waters are predicted to rise. In contrast, the scenario that continues to be of increasing concern is storms that are less predictable, intense, of long duration, and have the ability to strike rapidly in mountainous terrain and trigger landslides. While the authors do not want to minimize the importance of flooding in the lowlands or along the coastline, this section examines the real and largely unrecognized hazards created by the combination of 1) heavy, prolonged rainfall; 2) steep mountainous topography of the central Appalachians; and 3) the encroachment of human development onto these landslide hazard areas. Specifically, this section of the paper examines both the geologic and practical considerations of catastrophic flooding and landslides, and how they affect human activity in the Commonwealth of Virginia.

STORM-GENERATED DEPOSITS AND LANDFORMS IN VIRGINIA

The term *landslide* is a general expression for the downslope movement of rock, soil, or artificial fill under the influence of gravity. Specifically, mass movements can be broadly categorized as slides, flows, or heaves (Carson and Kirkby, 1972). In slides, cohesive blocks of rock or soil move along a well-defined failure surface, and minimal internal disruption of the material takes place while in motion. In comparison, flows move entirely by differential shearing within the material, and no clear failure plane can be defined at the base of the moving mass (Ritter et al., 2002). Debris flows are a subset of this class, and includes a complex group of gravity-induced rapid mass movements that contain a variety of grain sizes from boulders to clay; and have sediment concentrations that range from 70 to 90% by weight (Costa, 1988) (Fig. 3).

In Virginia, geomorphic processes responsible for transporting sediment from steep, mountainous terrain to alluvial fans and valley bottoms include water floods (streamflows), debris flows, and hyperconcentrated flows, the latter defined as streamflows carrying 40 to 70% of sediment by weight (Costa, 1988) (Fig. 3). All types of flow processes have been documented in Virginia, but there appears to be some regional geologic factors that promote dominance of one process over the other, and the resulting alluvial fan types. In general, the fans along the western slopes of the Blue Ridge (i.e., eastern margins of the Shenandoah Valley) tend to be dominated by streamflow processes; whereas those of the interior and eastern Blue Ridge, along the flanks of Massanutten Mountain, and the western Appalachian front tend to be dominated by debris flows (Fig. 4). These distinctions are based on stratigraphy and morphology of the landforms. The formative processes and resulting landforms appear to be both a function of the watershed hydrology, basin lithology, and the lateral accommodation space for the deposits.

The western flank of the Blue Ridge is bordered by extensive sand and gravel of fluvial origin that form a nearly continuous apron, or bajada, between the Blue Ridge and the low, hilly ground stretching to the Shenandoah River or its tributaries (Fig. 4). Gravel deposits were described by King (l950) in the Elkton vicinity, and more broadly by Hack (l965). More detailed studies have been undertaken by Kochel and Johnson (1984), Kochel (1987, 1990, 1992), Duffy (1991), Kite (1992), Whittecar and Duffy (1992, 2000), Morgan et al. (2003), Wieczorek et al. (2006); 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° from the mountain front to the Shenandoah River (Fig. 4). The sharp demarcation of bedrock resistance that exists between the siliciclastic-based mountains and the carbonate lowlands allows these fans to grow unrestricted, in the lateral sense, into the Shenandoah Valley. These fans are comprised of imbricated, well-sorted quartz arentite gravels and sands, display a broad fan shape in plan view, and range in area from approximately 2 to 10 km^2 (Simmons, 1988) (Fig. 5). The aerial extent of the fans is proportional to the drainage basin area, similar to the fans in the southwestern Unites States (Mills et al., 1987). Typically, fan thickness is greatest in the mid-fan region, but overall fan thickness varies depending upon vertical accommodation space from the dissolution of underlying carbonates, that is strongly influenced by the dip of the carbonate bedrock underlying the fans (Simmons, 1988). The older fans have collapsed into the karst so that accumulations of alluvial deposits commonly reach 30 m (100 ft) (King, 1950); and drill records reveal that they can be as much as 180 m (600 ft) thick in places (Simmons, 1988). Some debris flow sediments are common in the proximal areas of these fans, but most of the fans are formed by streamflows and hyperconcentrated flows. Watersheds feeding these fans are typically larger than those directly producing debris flows (e.g., basins draining the eastern flank of the central Blue Ridge (Kochel, 1990)), and thereby able to dilute sediment yields with enough water volume to retard debris flow transport. Flash floods of significant magnitude are historically common on these fans, as exemplified in the floods produced by the remnants of Hurricanes Juan (1985), Fran (1996), and, most recently, Isabel in 2003 (Fig. 6).

In contrast, debris fans have drainage basins that are usually smaller and steeper than fans formed by streamflow (Fig. 7). Fan shapes are often irregular (Kochel 1987, 1990) because of their restricted lateral accommodation space, having formed within rocks of low solubility in the high-relief mountain regions of the Blue Ridge and the western Appalachian front. In the Blue Ridge, debris fan slopes average 5-17°, and are composed of poorly-sorted sediments that range in size from boulders of several meters in diameter to clay (Eaton et al., 2003a). These deposits are relatively thin (several meters thick), and possess both matrix-supported and clast-supported units (Fig. 7). Stratification of these units is usually lacking, but the boundary between individual deposits is typically sharp. Paleosols are partially preserved at some contacts between these units, indicating a period of quiescence of debris flow activity sufficiently long enough to create soil profiles. Lower magnitude floods are usually incapable of remobilizing the largest of the material, leaving it to weather in-situ or to be remobilized by the next event of similar or greater magnitude.

Fans and associated landforms in montane and mountain-front areas appear to be little impacted by frequent low magnitude storm events. Rather, these landforms which include boulder berms, boulder bars, boulder levees, and fan sediments are only altered by extreme high magnitude events of low frequency like those mentioned previously in this paper. In these steep environments, thousands of years of geomorphic work occurs episodically during a single event. Measurements from the 1969 and 1995 events suggest that the long-term transport of sediment from the mountains to the lowland floodplains is episodic; that is nearly half of the sediment that would normally be expected be transported gradually over a few thousand years is moved by a single event (Eaton et al., 2003b). Episodic, high magnitude events appear to be the dominant agents of landscape change and geomorphic work in mountain regions (e.g., Hack and Goodlett, 1960; Wolman and Miller, 1960; Williams and Guy, 1973; Kochel, 1987; Jacobson et al., 1989; Miller, 1990; Eaton et al., 2003b).

RECENT HISTORY OF COUPLED FLOODING AND MAJOR LANDSLIDE ACTIVITY

Numerous storms that produced torrential rain and associated flooding have struck the Commonwealth. Four storm events between 1949 through 1995 were intense enough to produce significant numbers of landslides, primarily debris flows, which modified the landscape, damaged property, and in most cases took lives. Two of the storms impacted the central Virginia Blue Ridge, whereas the other two affected the Valley and Ridge province along the West Virginia–Virginia border near the central Shenandoah Valley. What is noteworthy about all four of these storms in both the Valley and Ridge and Blue Ridge provinces is that catastrophic flooding was generated by a variety of extreme weather conditions, rather than by exclusively hurricanes. The most infamous of these was Hurricane Camille. In the late evening of August 19, 1969, the remnants of Hurricane Camille crossed the Blue Ridge from the west, collided with a southeastward-advancing cold front, and stalled in the rugged foothills of Nelson County, Virginia. As much as 711 mm (28.0 in) of rain fell over a 7–8 hour period during the early morning hours of August 20 (Camp and Miller, 1970), although one unofficial reading of nearly 1020 mm (40.2 in) of rainfall was made at a single locality (Simpson and Simpson, 1970). The deluge triggered thousands of debris flows and killed more than 150 people, and still ranks as Virginia's most costly natural disaster (Fig. 8).

Not all of these events, however, were hurricane derived. In contrast, the June 27, 1995 storm centered over the Rapidan River basin in Madison County developed from the combination of a stalled cold front and westward-flowing, moisture-laden air moving toward the eastern slopes of the Blue Ridge Mountains (Smith et al., 1996). Maximum rainfall totals for the storm system reached 775 mm (30.5 in) during a 16 hour period (Wieczorek et al., 2000). The deluge triggered more than 1000 debris flows, and flooding in the region was catastrophic (Fig. 9). Major flooding from this event also affected the North Fork of the Moormans River in western Albemarle County, located 45 km southwest of the Rapidan Basin. The rainfall exceeded 279 mm (11.0 in) (Morgan and Wieczorek, 1996), but may have been as great as 63 mm (25 in) (Carlton Frazier, 1996, pers. comm.). Nearly 100 debris flows were documented in the basin. This same storm also impacted a third area near Buena Vista, where over a dozen debris flows were mobilized and entered the Maury River (Sas and Eaton, 2006a). Unfortunately, no rainfall estimates exist for this cell of the storm. Both the 1969 and 1995 storms rank near the edge of the USA maxima flood envelope (Fig. 2), illustrating the extreme flash flood index potential (i.e.; Beard, 1975) of the Blue Ridge Province (Fig. 2).

West of the Blue Ridge, catastrophic storms struck the Valley and Ridge province along the West Virginia–Virginia border in 1949 and 1985 (Fig. 1). In both storms, nearly all of the fatalities were from flooding in the lowlands rather than from debris flow impacts. The June 1949 storm was the result of convective storm cells limited to only a few mountainous basins in Augusta and Rockingham Counties. The torrential rainfall produced as much as 229 mm (9.0 in) of rainfall in western Virginia and 380 mm (15.0 in) in eastern West Virginia (Stringfield and Smith, 1956), and triggered dozens of debris slides and flows (Hack and Goodlett, 1960). In contrast, the November 1985 storm covered a much larger area, and was noted for rainfall at a moderate intensity and a long duration of three days. The storm produced as much as 250 mm (9.8 in) of rain, and was dominated primarily by two low-pressure systems and, to a lesser extent, the remnants of Hurricane Juan (Colucci et al., 1993). This storm initiated thousands of debris flows and occurred over the same region as areas affected by the 1949 deluge. Large-scale flood events are typically associated with debris flow-producing events and may affect significant areas downstream of the mountainous region along piedmont rivers. For example, the 1969

Nelson County flood produced one of the largest discharges in the past 400 years on the James River at Richmond.

HAZARDS AND DEVELOPMENT ON FANS IN VIRGINIA

Overview

Several aspects of debris flows in the mountainous terrain of Virginia make them especially problematic, resulting in potentially dangerous situations for humans. First, the recurrence of debris flows at an individual site is episodic over the span of several thousand years, but occurs somewhere across the whole of the southern and central Appalachians approximately every 5-10 years. Second, steep slopes in mountainous terrain tend to focus human development on the fans rather than neighboring hillslopes. Third, when events do occur they are typically catastrophic, impacting significant parts of the fan surface. Finally, there has been an increasing trend of suburban sprawl targeting mountain-front developments in piedmont areas such as the episodically-active fans in Virginia. Comprehension of these factors is essential for assessing the level of risk associated with development on alluvial and debris fans in the Appalachians.

Recognition of Debris Fans and Debris Flow Frequency

Debris fans are ubiquitous mountain-front landforms along the eastern slopes of the Virginia Blue Ridge and the western Appalachian front. Prior to the Hurricane Camille (1969) and Rapidan storm (1995) events, debris fans in Virginia were not recognized as active landforms due to the combination of their atypical fan morphology; and that they are commonly forested or cultivated as orchards, thus disguising their presence. Recent geomorphic mapping illustrates the location of debris fans, and the high frequency of debris fans that have not experienced historic activity along segments of the Blue Ridge (e.g., Eaton et al., 2001) (Fig. 10). Radiometric dating of these fan surfaces shows a history of late Pleistocene and Holocene activity; and they will likely see similar catastrophic events in the future. In basins where mountain hollows are filled with colluvium, and the fan deposits show a paucity of recent debris flow activity, it is even more likely the conditions are primed for debris flows when the next intense rainfall occurs in their contributing mountain watersheds. These are the sites where considerable suburban development is occurring and will likely continue in the future.

Recent work on Virginia debris fans activated in the 1969 and 1995 storm events provide pertinent information on the long-term recurrence intervals of these events (Kochel and Johnson, 1984; Eaton and others, 2003a, b). Figure 11 depicts radiocarbon-dated debris flows in Madison County. Return intervals for debris flows vary between 1,800 – 3,000 years at-a-site. Similar debris flow return intervals were found in Nelson County (Kochel, 1987). The presence of debris flows occurrence during the Holocene post-glacial climate is reasonable warning that they are active processes capable of generation by modern hydroclimatic conditions; and not relicts of a former climate. A fact worth noting is that while at-a-site recurrence intervals are measured in millennial timescales, significant historic debris flow events have occurred somewhere in Virginia once each decade, and throughout the Appalachians on average of every three years (Eaton et al., 2003a; Clark, 1987). Thus, the hazard and risk of debris flows increases significantly as development spreads to new locations throughout Virginia and the Appalachians. Another factor to consider is that conditions capable of producing debris flows occur even more frequently at a site than the 1,800 – 3,000 year interval as suggested, because a significant recovery period is necessary to refill the hillslope hollows and stream channels with colluvium so that there is ample material available for mobilization by the next intense rainfall (Fig. 12). A good example of the importance of event ordering is illustrated by the succession of storms in Madison County in 1995, and Hurricane Fran in 1996. The 1995 event produced over 1,000 debris flows, whereas not a single debris flow resulted from up to 432 mm (17 in) of rain from the remnants of Hurricane Fran in 1996 (Eaton, 1999). The possibility exists that all of the unstable hillslope colluvium was mobilized in 1995, as many of the debris flows in 1995 were triggered around this threshold rainfall value. In contrast, the 1996 event produced massive runoff from recently exposed bedrock slopes evacuation by debris flows in 1995; and resulted in major floodplain and channel morphological changes downstream from the fans. Similar contrasts in geomorphic response to subsequent rainfalls were also observed in Great Britain by Newson (1980). Interestingly, in 2003 Hurricane Isabel delivered up to 513 mm (20.2 in) of rain near Waynesboro (Wieczorek et al., 2006). This region had no historic record of debris flow activity in the past, and no debris flows or large scale slope failures were observed from Hurricane Isabel. Perhaps not enough time has passed in this part of the Blue Ridge to refill the hollows with sediment to the critical threshold required to mobilize debris flows; or that the triggering threshold of rainfall/duration may not have been exceeded.

The level of risk from debris flow hazards can be reduced by detailed bedrock and surficial mapping of the geomorphic landforms within the landscape (e.g., Eaton et al., 2001;

Mills et al., 2005; Heller and Eaton, 2010). This knowledge can assist in alerting land managers and home owners of the potential risks of debris flows and flooding. Figure 10b depicts surficial mapping of the Graves Mill area on the Rapidan River, and shows numerous dwellings residing on debris fans that were activated during the 1995 storm. Fortunately, only several of the homes were destroyed and loss of life was minimal. Based on the growth trends in Virginia, surficial mapping will become increasingly important as more of the fans are considered for developed.

GEOLOGIC FACTORS INFLUENCING DEBRIS FLOW LOCATION AND FREQUENCY

Although rainfall events like those in 1969 and 1995 are likely to result in widespread debris flow activity, the distribution of debris flows in these areas compared to spatial patterns of rainfall does not perfectly correlate; suggesting that there are other factors such as geologic structure that may exert an influence on the localization of debris flow activity. Several investigators examined nearly 50 debris flows triggered by the Camille 1969 event in Nelson County (Terranova, 1987; Terranova and Kochel, 1987; Gryta and Bartholomew, 1989). They found that the morphology of slope failures varied according to hillslope orientation and its intersection with structural elements in the granite-gneiss bedrock (Fig. 13). The research noted that where slope aspect coincided with dominant foliation and joint strikes and dips, residual soils around the margin of failure scarps showed sandier soils of lower cohesion compared to sites where slope aspects did not parallel structural lineations. Kochel (1987) suggested that the more cohesive, clay-rich soils reflected areas of lower frequency of debris flow activity. Jurgens (1997) conducted a similar survey of three hollows in Madison County and concluded that areas where foliation and major joint trends coincided had significantly more debris flows than other regions with similar rainfall. Figure 14 is an example of this asymmetry. Here, the dominant foliation and a dominant joint plane both dip toward the southeast. Debris flow scars are seen on these southeast-facing slopes, whereas no debris flows occurred on the northwestern slope of Kirtley Mountain, or on the northwestern slope of the small drainage to its west. In another study, Sas and Eaton (2006a) examined geologic controls of slope failures from the 1995 debris flows in Rockbridge County and found preferential failure along joint and bedding planes. In summary, these studies indicate that bedrock geologic mapping may prove quite useful in delineating regions of highest risk for debris flow in areas where a variety of slope orientations occur, such as in major topographic hollows common in the Blue Ridge Province.

RAINFALL THRESHOLDS

One of the applied products that is beginning to emerge from debris flow research are threshold curves that document the level at which rainfall intensity and duration are sufficient to mobilize debris flows. Wieczorek et al. (2000) determined a minimum continuous rainfall intensity-duration envelope for the granitic-gneissic terrains of the central Blue Ridge, including sites impacted from the 1969 and 1995 storms. The threshold curve indicates that sustained intensities of 70 mm/hr for 2 hours, 50 mm/hr for 4 hours, 40 mm/hr for 6 hours, and 25 mm/hr for 12 hours are sufficient for triggering debris flows in the Blue Ridge of central Virginia. The research notes that the Blue Ridge has the highest recognized rainfall thresholds when compared to other studied regions, including Puerto Rico, Hawaii, and the San Francisco Bay area. Possible explanations for the high values may include high permeability and storage capacity of the thick regolith. It also appears that these intensity-duration threshold curves are probably rock type dependent. One site in the Blue Ridge near Waynesboro received 513 mm (20.2 in) of rainfall in less than 24 hours during Hurricane Isabel, clearly placing this event above the threshold curve (Wieczorek et al., 2006). The small basin is underlain by highly fractured quartzite bedrock, and its regolith may be more conducive to efficiently storing and expelling into the subsurface rainwater to minimize slope failures. As more automated weather stations are activated and are able to report rainfall data in near real-time format, scientists and emergency officials will hopefully have a greater ability to forecast the potential for debris flows during the course of a storm.

CONSIDERATIONS FOR WATERSHED PLANNING AND MANAGEMENT

Since the seminal work of Wolman (1967) and Leopold (1968), it has been recognized that land use can have significant impacts on the nature of water runoff and sediment yield to stream channels and floodplains. Suburban development into remote mountain watersheds will undoubtedly increase runoff rates, and hence increase the unit hydrograph for rainfalls of most recurrence intervals. Major debris flow events like that of the Rapidan event in 1995 can also significantly alter runoff characteristics for decades after the event. Bedrock, primarily exposed in headwater streams from debris flow events, can increase the routing efficiency of streams and changes in channel morphology in large rivers may reduce their conveyance efficiency, such that water is routed more rapidly from the mountain streams and drains more slowly from the lowland and valley bottom streams. Conversations with people residing along the Rapidan River indicate that significant floods now occur in the Rapidan watershed from lower magnitude rainfall events than those prior to June 1995 (i.e., Randall Lillard, Douglas Graves, 2006, pers. comm.). A prime example is the volume of runoff from Tropical Storm Fran in September 1996, when discharges nearly equaled that of 1995 but from half of the rainfall in 1996 (Fig. 15). In addition to problems of flooding, there is an increased volume of coarse bedload in transport during flows following the 1995 debris flow event. Sediments released from the slopes in 1995 are now being flushed through mid-and-downstream reaches of the Rapidan River by subsequent floods like the 1996 event and other smaller floods. Culverts that were replaced from the 1995 event were quickly overwhelmed by the bedload transport in 1996 along many of the tributaries of the Rapidan (Eaton, 1999). These examples highlight the importance of factoring in significant adjustments in water and sediment fluxes when designing upgrades or replacements to infrastructures following a major disturbance within a watershed.

Similarly, changes in discharge and sediment yield need to be incorporated into the planning of stream restoration projects in a system-wide basin-scale approach. Stream channel geometry is greatly influenced by discharge and sediment delivered to the channel from the upstream watershed. Changes in land use (e.g., channelization, deforestation) and by major geomorphic events such as debris flows will result in downstream adjustments in channels that often require decades to re-establish equilibrium. A stream restoration project on the Rapidan River near Graves Mill is a prime example of the kinds of problems than can occur when these issues are not taken into account in project design. First, the Rapidan River has been channelized multiple times for agricultural and transportation purposes since the region was first settled in the late 1700s, thus altering its system from a multiple-channel braided pattern to a single meandering channel. Channels transporting large quantities of coarse bedload are better served by braided courses with wide and shallow channels to maximize bed shear stress. Thus, when large supplies of sediment are delivered to the Rapidan during major floods and debris flow events, the channel reverts back to its braided condition, resulting in valley-wide inundation, scour, and deposition. This happened in 1995 and again in 1996 (Fig. 15) (Eaton, 1999). Exposures of the floodplain uncovered during these events revealed numerous wide and shallow paleochannels that were likely the high-flow anabranches of the Rapidan prior to channelization following European settlement. In 2002 the Virginia Department of Transportation initiated a restoration project on a reach of the Rapidan River, 1 km south of Graves Mill, to help maintain the course of the river under the State Route 767 bridge. Within a year a major stream avulsion had occurred because the restored channel was not designed to transport the higher supply of bedload the reach was receiving, largely due to the continued adjustments to the 1995 debris flow event (Fig. 16). Most natural channel design projects do not account for long-term adjustments that may be occurring in streams due to past land use and/or major geomorphic changes. Kochel et al. (2005) observed a failure rate of more than 70% for natural channel design projects in North Carolina after experiencing their first significant flood.

LANDSLIDES AND TRANSPORTATION

Road construction on steep hillslopes can increase landslide susceptibility by 1) adding weight to the slope with fill material; 2) steepening the slope on both cut and fill surfaces; 3) removing support of the cutslope; and 4) rerouting and concentrating drainage water (see review by Sidle et al., 1985). Increased landslide susceptibility from roads can impact downslope and downstream areas, and interrupt transportation. The literature shows that landslide hazards along transportation corridors in the central Appalachians are numerous (e.g., Watts and Whisonant, 1992; Sas and Eaton, 2006b; Douglas et al., 2007; Lantham et al., 2007). Some of the larger landslide events in the central Appalachian region in recent memory include large rockslides along the Interstate 40 corridor in 1985 (Winchester, 1985) and debris flows originating from road fill failures along the Blue Ridge Parkway from Hurricanes in 2004 (Sas and Eaton, 2006b). These road-related landslides often have a larger volume and can increase the risk of debris flows to downstream areas (May, 2002). Recent advances in remote sensing and terrain analysis are likely to increase the ability of scientists and land managers to detect high risk areas along transportation corridors.

CLIMATE CHANGE

Because of the common linkage of floods and debris flows with tropical storms, the concern about global climate change could be significant in the evaluation of flood hazards for Virginia. If tropical storm frequency increases in the mid Atlantic, or if the hurricane tracks are altered so that these storms collide with the central Appalachians, a higher frequency of debris flow events may result in some locations in Virginia. Kochel (1987) suggested that debris flow activity in the Appalachians could be correlated to the retreat of the polar front as the Pleistocene climate waned; although Eaton et al. (2003a) found activity since the Last Glacial Maximum. What is not known is, if discrete warming trends that occur as documented in the Blue Ridge pollen record (Litwin et al., 2001) may also correlate to these debris flow events. It is clear from Clark's (1987) research that more debris flow events have impacted the southern Appalachians, presumably from their closer proximity to tropical air masses and steep, mountainous terrain. Whether or not these events become more common from south to north over time as the incursion of tropical air masses would likely have become increasingly common is still undetermined, but worthy of further investigation.

KARST HAZARDS IN VIRGINIA

David A. Hubbard, Jr.

INTRODUCTION

Karst is a terrain that develops by the action of water with soluble bedrock and characteristically features karren, sinkholes, caves, and subsurface drainage. Soluble bedrock that has developed karst in Virginia occurs in all five of the major physiographic provinces: in Pliocene indurated shelly sand of the Yorktown Formation of the Coastal Plain province; in Cambrian to Ordovician marble and limestone of the Piedmont and Blue Ridge provinces; in Cambrian to Mississippian-age limestone, dolostone, gypsum, and salt in the Valley and Ridge province; and as the Mississippian limestone in the Appalachian Plateaus province. The most significant karst in the Commonwealth, and the focus of this discussion, extends over twenty-six counties in the Valley and Ridge physiographic province (Fig. 17). Karst mapping of the Valley and Ridge province defined areas of karst by carbonate and non-carbonate rock boundaries and sinkholes

(Hubbard, 1983, 1988, 2001). Approximately 48,800 sinkholes were remotely sensed using stereographic interpretation of low-altitude aerial photography and are plotted on the three karst maps. Because Virginia karst is a cover karst, wherein a mantle of soil and sediment covers most of the solutional patterns of bedrock (karren), sinkholes are the most readily observable surface feature. The natural processes active in karst result in some phenomenon recognized as hazards: subsidence, sinkhole flooding, and the recharge of karst groundwater aquifers with contaminated surface water. Unfortunately, land-use modifications in karst may induce changes to the local hydrology than can trigger and exacerbate these hazards.

KARST HAZARDS

Three phenomena that are commonly recognized as karst hazards are subsidence, sinkhole flooding, and the recharge of the aquifer by surface waters. Each of these hazards is the result of natural processes and water-rock interactions in karst. Historically, the hazard of greatest concern to karstland residents is catastrophic sinkhole collapse.

Subsidence Hazards

Water-rock interactions in a landscape underlain by soluble bedrock, which may range from 60 to 99 percent soluble, almost guarantee that subsidence will occur. Anecdotal evidence suggests that most people who reside in karstlands are relatively at ease with existing sinkholes that gradually deepen or slowly grow in extent; and many are undaunted by sudden collapses within alluviated subsidence features. However, residents are concerned when un-patterned catastrophic sinkholes develop without warning; particularly at locations without a previous history of cover subsidence. The collapse of bedrock into cave passages is relatively rare in karst, as the soils and sediments that mantle bedrock in a covered karst can temporarily span enlarging soil-bedrock interface voids that form at epikarst drains. These voids may expand beyond the strength of the arching soils and catastrophically fail to the surface of the landscape and form a sinkhole (Fig. 18).

The soluble bedrock surface is not equally exposed to water, so most dissolution occurs along preferred flow paths at the bedrock surface and within rock partings and fractures. The solutional patterns of the bedrock, both on exposed surfaces and under soil or sediment cover, are known as *karren*. Unfortunately, the preferred flow paths hidden by covering sediments are not necessarily mirrored by the landscape surface. Most water flow is not along surface drainage features, but along channels eroded on the covered bedrock surface and in the solution-enlarged partings and fractures, known as conduits and caves, within the bedrock. Some subsidence sinkholes are the result of the direct dissolution of the bedrock and form by the gradual letdown of cover materials over periods of human life-spans.

In contrast, collapse sinkholes result from erosion of soil and sediment covers at epikarst drains, (the interval between the mostly unaltered bedrock and the topsoil), and may be catastrophic in their failure. The water-rock processes of karst that sculpt this dominantly erosional landscape are sensitive to the stability of climatic and land-use conditions. Because the degree of activity of water-rock processes largely is veiled by the mantle of soil and sediment, these unstable terrains are mistakenly perceived as inactive or stable. Extreme weather events, including droughts, and land-use changes that result in changes to the local hydrology can trigger and exacerbate subsidence hazards.

To help assist the risk of rapid subsidence, government officials have used subsidence susceptibility mapping, primarily a GIS tool used by planners, to designate or model site suitability for development. From the most simplistic perspective, areas of dense sinkhole populations are more likely to experience future sinkhole formation than karst without existing sinkholes. However, research suggests that the greatest influence in future sinkhole formation is not the past land-use, nearest sinkhole, nearest stream, etc.; rather, most new sinkholes form in response to very recent land-use changes in drainage volumes and flow-paths (Hubbard, 2003). Hubbard noted that sinkholes frequently form over an existing epikarstic drain, and the subsequent surface collapse is accelerated by alteration of the localized drainage volume or flow-path of surface runoff. The additional volume of water provides a positive feedback situation, which scours out sediment within the void and contemporaneously increases the conduit size, thus allowing for greater flow capacity. The covered subsurface drain is gradually enlarged and leads to the subsequent collapse of the soil mantle.

Sinkhole Flooding Hazards

Throughout most of the Commonwealth, sinkhole flooding is a minor hazard. Sinkholes, blind valleys, and losing surface streams are input points for surface water, especially storm-generated runoff, to enter groundwater conduits of the karst aquifer. All karst sinkholes are drained by solution-enlarged flow-paths that lead to the karst aquifer, or to base-level streams and rivers. Under normal hydraulic conditions, most sinkholes serve as drains for surface water runoff and subsurface water, draining along the soil-bedrock interface, to access the karst aquifer. There are three conditions under which sinkholes and other karst depressions flood (Fig. 18). The first two conditions are characterized by under-drainage occurring at lesser rates than drainage into the sinkhole, whereas the final condition is one of back-flooding due to high-head pressures in the groundwater conduits under-draining the sinkhole. The first condition typically occurs during exceptional precipitation events whereby surface water run-off topographically funneled to sinkholes greatly exceeds the subsurface drain's capacity to transmit water to the karst aquifer. This type of flooding is usually temporary and represents a lag or ponding of drainage. The second condition is usually due to a change in the land-use and results from increased sediment yield in the development of the area topographically draining to a sinkhole, and the partial choking of the sinkhole drain by sediment. Under such circumstances, storm-generated runoff can pond in the sinkhole due to the reduced efficiency of the sediment-clogged drain. This condition is usually further complicated by a secondary effect of land-use change, an increase in surface runoff. Most anthropogenic induced land-use modification creates more runoff by changes in vegetation, soil compaction, and the application of impermeable surfaces such as roofs and pavements. Increased runoff to a sediment-clogged sinkhole drain greatly enhances sinkhole ponding. Sedimentation from such ponded waters, which may carry additional sediment to the sinkhole, tends to increase the period of ponding. The third type of sinkhole flooding is caused by a non-passive back-flooding phenomenon and truly is a flooding hazard. This type of flooding occurs when the under-draining conduit or cave system is overwhelmed by down-system sinkhole drainage during an exceptionally large precipitation event. Under this situation, flow of water from other sinkholes downstream in the conduit system results in high head pressures reversing conduit flow. Water resurges from the sinkhole drain and floods the sinkhole. Under these circumstances, a sinkhole may not only flood, but water may fill and overflow from the sinkhole and create additional flooding of other adjacent sinkholes or lowlands.

Karst Aquifer Contamination Hazards

The most pervasive karst hazard is of aquifer contamination by recharge of polluted surface waters. Perhaps the greatest hazard in Virginia karst is the routing of highway run-off to sinkhole drains. Not only does this type of design contribute heavy metals, road salts, nutrients, bacteria, and hydrocarbons carried in highway run-off (Stephenson and Beck, 1995) to aquifer recharge, but such designs assure that hazardous materials and other potential contaminant cargos that are transported along highways are potential aquifer contaminants (Hubbard, 1999). Data from both the U.S. Department of Transportation and the Environmental Protection Agency indicate that highway transportation of hazardous materials is a relatively high-risk industry (Padgett, 1993). Crop and livestock operations can pollute karst groundwater directly by sinkholes, as well as through diffuse non-point source entry of bacteria, leaching nutrients, pesticides, or other contaminants (Berryhill, 1989; Boyer and Pasquarell, 1994, 1999). Some of the contaminants that have degraded Virginia’s karst aquifers include: the leachate of improperly disposed wastes; and spills or leaks of petroleum products, herbicides, solvents, fertilizers and poultry waste, sheep and cattle dip, sewage, and milk (Hubbard and Sterrett, 1994).

HAZARD MITIGATION AND REMEDIATION

The successful mitigation and remediation of karst hazards is problematical due to the out-of-sight nature of the water-soil-rock processes that form karst and its attendant hazards. That karst in an unstable terrain, and that land-use changes to it generally enhance hazard realization, does not bode well for the idea of hazard mitigation. Although the basic concepts for hazard mitigation and remediation are presented in the following sections, most mitigation and remediation in karst addresses the manifestations of the hazards and solutions to stop and correct subsidence, flooding, and aquifer pollution. Successful mitigation and remediation is more likely accomplished through professionals experienced with karst hazards, and the use of appropriate methodologies that address the site-specific processes and conditions.

Subsidence Hazard Mitigation and Remediation

Catastrophic sinkhole collapse is undoubtedly the hazard of greatest concern to karstland residents. The most commonly recognized land-use triggers of sinkhole collapse are water-well drilling and increased run-off. In most situations where water-well drilling induces one or more sinkholes, three conditions are present: 1) a water level is encountered above bedrock; 2) a saturated mud-seam (a mud-filled cave), is intercepted at some depth in the bedrock; and 3) the driller "blows mud" to develop a water-filled void in the saturated mud-fill. The cause of ground failure is the creation of an open water-filled void in rock and its failure through overlying rock and soil straight to the surface. Most catastrophic karst sinkholes do not involve rock failure. Collapse sinkholes are formed when voids at the soil-bedrock surface fail through the sediment-soil cover to the ground-surface. When the groundwater level is above the soil-bedrock interface, saturated cave fills have continuity within the cave to the saturated sediment above the sediment covered cave entrance. Most caves are presently entrance-less or are not enterable, and probably not recognized by humans. In the folded and faulted carbonates of Virginia's Valley and Ridge province, extensive mud seams may wind through bedrock to a sediment covered-rock opening within hundreds of feet of the well-head. When groundwater is shallower than bedrock, drillers should avoid blowing-out saturated mud-seams.

Increased run-off is the other most commonly recognized cause of new sinkhole collapses. Extending drainage outflows as far from buildings as possible will reduce the risk of new sinkhole formation near structures. Increases in run-off and new flow paths trigger more rapid growth of soil voids at epikarst drains, which form new sinkholes as the voids extend in size beyond critical soil strength and progressively collapse to the land surface.

The best way to remediate a collapsed sinkhole, and not induce additional new sinkholes, is to excavate the feature to the bedrock surface and build a reverse filter that bridges the rock throat of the drain so that material cannot wash into the drain, but subsurface water can continue to drain. An aggregate size too large to fit into the bedrock drain is used as a base. Successively finer aggregate, that is too coarse to fit in the voids between clasts in the underlying layer, is used in adjacent layers to construct a stable filter that allows water to pass, but prevents voids from forming and collapsing. Methods utilizing materials that can erode into under-draining conduits may undergo further subsidence. Grout plugs that are not emplaced on bedrock may undergo settling as the underlying soil is eroded into under-draining conduits.

Effective grout sealing of a solution-enlarged epikarst drain restricts groundwater movement, which may create addition problems. Subsoil water that previously drained at this site may collect and saturate adjacent soils, or propagate new sinkholes proximal to the site by moving along the soil/bedrock interface into adjacent epikarst drains and enhances void expansion and collapse. In rare circumstances, grout sealing may extend into the under-draining cave system, resulting in back flooding of up-system sinkholes drained by the grout-occluded conduit.

Sinkhole Flooding Hazard Mitigation and Remediation

Sinkhole flooding can be mitigated by reducing the amount of run-off flowing to the sinkhole, and by eliminating siltation and sedimentation problems in these drainage features. Whereas most individuals that work and/or reside in karst landscapes understand that building within a closed contour feature may lead to flooding, the presence of large complex sinkholes and blind valleys, many of which extend more than a half-kilometer in length in Virginia, can make the recognition and delineation of potential flood zones extremely difficult. The modification of sinkhole drains, also referred to as dry wells and drainage wells, to better accommodate surface water run-off and minimize sinkhole flooding, may result in new sinkhole formation and non-passive back-flooding of other sinkholes adjacent or remote to a remediated site. This type of modification commonly contributes to groundwater contamination of karst aquifers by enhancing recharge of contaminated surface waters.

Karst Aquifer Contamination Hazard Mitigation and Remediation

Karst aquifer contamination is the most extensive and serious karst hazard in Virginia. The folded and faulted nature of the sedimentary rocks in the Valley and Ridge province can compromise thin shale and other thin non-carbonate beds as potential aquitards that would normally partition carbonate sequences into separate aquifers in less tectonically-affected sedimentary sequences. The first step in the mitigation of a karst groundwater contaminant is to determine the source and stop the flow of the contaminant. This concept may be much easier to state than to implement. Karst aquifers in dense, low primary porosity carbonate and evaporite rocks are principally composed of conduits that are difficult to intercept by drilling. Investigators unfamiliar with karst commonly interpret the absence of a contaminant at a newly drilled monitoring well as evidence that a contaminant is contained, or that the plume is limited to up-gradient of the uncontaminated well. Drilling into the right conduit is akin to the proverbial search for a needle in a haystack. Tracers, commonly dyes, are utilized in tracking karst aquifers and determining the routes of contaminants. In karst, the question is not *did the contaminant move*, but *where did it go?* Existing water wells and springs are common monitoring points to determine flow paths, which may demonstrate surprisingly rapid transport.

Contaminant remediation in karst aquifers generally is more complicated than in homogeneous aquifers. Remedial technologies have continued to advance in the past few decades. In-situ treatment by biodegradation can be effective, as can extractive methods. Extremely toxic and refractory organic contaminants that can destroy aquifer resources remain problematic. Karst aquifer contamination sites are contaminant and site specific, and their remediation is beyond the scope of this summary. Complexities include the nature of the contaminants in terms of density, solubility, stability, toxicity, volubility, reactivity with rock and sediment as well as complexities of the nature of the particular karst aquifer (Freeze and Cherry, 1979; Fetter, 1988).

The contamination of karst aquifers continues as land is shifted from agricultural to residential, commercial, and industrial land-uses. Perhaps the most significant contaminant disasters involve tanker releases of hazardous and toxic cargoes along Virginia's karstland highway corridors. A major initiative is needed to trace and map the run-off flow routes from Interstate Highways and other major transportation routes through Virginia karst. Such a project could enable the development of early warning communication systems for emergency responders to alert groundwater users along major hazardous and toxic transportation corridors; and could alleviate the potential of avoidable waterborne lethal exposures and poisonings.

SINKHOLES OTHER THAN KARST

Non-karst collapse sinkholes typically form by two processes: 1) soil piping, or 2) collapse of anthropogenically-made voids, such as underground mines. Numerous examples of these failures exist in the Commonwealth. Examples of sinkholes resulting from underground mine failures exist in karst rocks such as salt, gypsum, and carbonate rocks. The failure processes probably include some degree of dissolution of the host rock, but blast damage, existing fractures, weak strata above ceilings, excessive ceiling spans, and robbed pillars are more likely the critical culprits in these failures (Figs. 20a,b). Most historic mines were not designed for longevity and post-mining failures are inevitable at many of these underground mines. An example of a subsurface mine failure in a non-karst setting is this coalfield sinkhole shown in Fig. 21, , which resulted from the collapse of coalfield workings.

RADON HAZARDS IN VIRGINIA

Fiorella V. Simoni de Cannon, Douglas .G. Mose, and L. Scott Eaton

INTRODUCTION

Naturally occurring radioactive radon gas (Radon-222) is always present in the air that we breathe (Lowder, 1985). However, indoor radon in high levels has been a recent addition to the list of natural health hazards that pose serious risk to human health and property value. Radon has always been present in air, water and soil, but in 1924 Ludwig and Lorenser postulated radon as an important factor in lung cancer (Samet, 1994). By the mid 1960s, many reports of lung cancer mortality among U.S. uranium miners emerged (e.g., Wagoner et al., 1965; Sevc et al., 1976; Kunz and Sevc, 1978; Harley, 1984, 1989; Proctor, 1995; NAS, 1999). The focus of the problem was transferred from miners to the general public in the 1980s, when a home in Pennsylvania was found to have radon levels over 600 times the threshold level recommended by the Environmental Protection Agency (Lafavore, 1987). The elevated concentrations at this site as well as other localities throughout the United States created nationwide concern of radon, and initiated a series of state and federal programs to assess and understand the problem (Gunderson and Wanty, 1991).

In 1994, the National Toxicology Program (NTP) of the U.S. Department of Health and Human Services first listed radon in its *Seventh Annual Report on Carcinogens*. In 1999, the National Academy of Sciences BEIR VI (BEIR-Committee on the Biological Effects of Ionizing Radiation) Report concluded that radon is the second leading cause of lung cancer after smoking (NAS, 1999). Today, NTP (2005) lists radon in its *11^{th} Annual Report on Carcinogens* as a known human carcinogen based on evidence of carcinogenicity in humans presented by the Agency for Toxic Substances and Disease Registry (ATSDR) and by the International Agency for Research on Cancer (IARC). In the United States, it is estimated that radon causes between 15,000 to 22,000 deaths from lung cancer each year. That is, approximately 12% of all lung cancer deaths are linked to radon exposure (NAS, 1999). By U.S. Environmental Protection Agency (US-EPA) (2005) estimates, indoor radon causes lung cancer fatalities in hundreds of Virginia residents each year.

Radon concentrations in air are measured in picoCuries per liter (pCi/L). By definition, a Curie is the rate of decay of one gram of radium, that is, 37 billion decays per second (Cohen, 1989). Because this is a very large quantity, radioactivity in the environment is usually measured in units of one millionth of a millionth of a Curie (10^{-12} Curie), or a picoCurie (pCi). In effect, in a room with a radon concentration of 1 pCi/L, two alpha-particles would be emitted about every minute from radon atoms per liter of air (Brookins, 1990). While the US-EPA (2006) has established 4 pCi/L as a general guideline for maximum acceptable indoor radon concentration when buying a home, it established 2 pCi/L as the limit for people living in a home. It also recommends testing all homes and urges mitigating action by increasing ventilation and preventing soil gas entry into the home. The average home in the U.S. has an indoor radon concentration of

1.3 pCi/L; the average outdoor radon concentration is 0.3 pCi/L (Cohen, 1989; UNSCEAR, 2000; US-EPA, 2006).

VARIATION IN RADON CONCENTRATION

Uranium is a naturally occurring radioactive element that is present in varying concentrations in all rocks and soils throughout the United States. Studies in Virginia and other states show that particular geologic units and the soil above these units are associated with elevated indoor radon concentrations (Mose and Mushrush, 1997a; Mose and Mushrush, 1999). For example, granite has relatively high uranium content and so granite and granitic soil tend to generate more radon than do other geological materials (Brookins, 1990).

Indoor radon concentrations can vary in response to weather on hourly, daily, and seasonal time scales. The most important weather factors are wind, barometric pressure changes, and soil moisture changes (Mose et al., 1992a,b; Mose and Mushrush, 1997b). Of all the weather variables, a change in soil moisture is the most important. As precipitation infiltrates and saturates the surface horizons of the soil profile, the saturated zone temporarily serves as a confining unit and is effective at slowing the release of gases from within the profile. Therefore, on rainy days the wet soil around a home slows the rate at which radon is released into the atmosphere, thus increasing its concentration in the profile around a home relative to non-precipitation days. Conversely, on hot sunny days the soil is dry, allowing the release of soil gases through the surface horizons into the atmosphere; and less radon is available in the soil for potential migration into the home.

The mechanism of radon entry into buildings is well understood. Large to microscopic wall and floor cracks, floor and wall penetrations (wires, pipes, sump holes) and floor-to-wall corner joints are all common entry points. A negative atmospheric pressure in a home relative to the soil produces a soil-to-home pressure gradient that draws radon in through entry points in soil-facing walls and floors. Atmospheric pressure in a home can also be reduced by furnace combustion, ventilation devices, and the stack effect (the rising and escape of warm air from the upper floors of the building) during cold winter months. This negative pressure draws radon into a home from the underlying soil.

Mose and Mushrush (1988, 1997b; Mose et al., 1991) found that variations in home construction are related to indoor radon levels in homes with otherwise similar weather and geology. That is, factors related to home construction affect indoor radon levels. For example, they found that higher indoor radon tends to occur in homes with basements, probably because homes with basements have more soil-touching entry points for radon, a more pronounced stack effect, and lower air pressure relative to the surrounding soil than no-basement homes (i.e., homes without a basement or with a crawl space). The authors note that basements with concrete block walls tend to have higher indoor radon concentrations than basements with poured concrete walls, probably because concrete blocks are likely to be more permeable and to develop more fractures. The research also documents that homes with electrical heating systems (heat pumps) tend to have higher indoor radon than homes with combustion heating systems, probably because a fuel-burning furnace significantly removes home air for combustion, which pulls in low-radon air from outside the home.

WATERBORNE RADON AND CANCER

The pores between the grains of soil and the cracks in rock usually contain a mixture of air and water (Brady and Weil, 1996). Often, a radon atom will come to rest in the water and remain there (Wilkening, 1990). In many homes in Virginia, domestic water is drawn through a water well from underground sources. Surface water (e.g., from a water reservoir) normally has radon concentrations too low to measure (less than 100 pCi/L), but ground water tends to accumulate radon generated within the groundwater aquifer (Hess et al., 1982; Nazaroff and Nero, 1988; Gosink et al., 1990; Mose and Mushrush, 1997a). Radium is also in groundwater, but because radium is not as soluble as radon, the concentration of radon is usually 10-1,000 times the concentration of radium dissolved in ground water (Milvy and Cothern, 1990; Mose et al., 1990; Mose and Mushrush, 1997b).

Waterborne radon enters the air in a home primarily as bursts of radon released into the air by mechanical sprays during a shower or by the heating and agitation of water that occur during laundering, washing, and cooking (Mose et al., 2005). All of these contribute to an increase in indoor radon concentration. Hess et al. (1982) first reported that indoor radon levels can be correlated with concentrations of radon in the water supply, suggesting that in a typical home about 1 pCi of radon per liter would be added to indoor air from the outgassing of water containing 10,000 pCi/L of radon. Many subsequent studies have used this 1:10,000 ratio, though in small homes the ratio may be as low as 1:100 (Mose et al., 2005) This can be a problem in Virginia homes where the waterborne radon is sometimes as high as 10,000 pCi/L.

The ingestion of radon-enriched and RDP (radon decay product)-enriched water may also be a serious health concern. Gosink et al. (1990) reported that radon ingested from drinking well water is not rapidly eliminated by metabolic respiration and can remain in the body for 12 hours depending on physical activity. During this time interval, radium, radon, and RDPs carried by ingested water can move through the body and may produce an effect at cancer prone sites (Mose and Mushrush, 1997b).

RADON IN VIRGINIA

According to Schumann (1993), the rock types and overlying soils that are most likely to cause indoor radon problems in the U.S. are carbonaceous shales, sandstones, certain fluvial sediments, phosphorites, carbonate rocks, uranium-rich granitic rocks, metamorphic rocks of granitic origin, and sheared and faulted rocks. Those least likely to produce indoor radon problems are marine quartz sandstone, non-carbonaceous shales and siltstones, and silica-poor metamorphic and igneous rocks. However, localized uranium deposits cause exceptions within all these categories and can produce high-radon concentrations in homes. Within the Commonwealth of Virginia, the varied geology in each of the geologic provinces creates different radon potentials, and these conditions are examined further in the following text.

Coastal Plain

The Coastal Plain of Virginia is underlain largely by fluvial and marine sediments that date from the Cretaceous to the Late Holocene, and many of these sediments were deposited in beach or near shore environments. Under these conditions, quartz (which contains essentially no uranium) is chiefly the residual surviving product of the intense mechanical and chemical weathering (Gundersen et al., 1992). The uranium-bearing minerals are mostly dissolved and the uranium is carried away. This process is thought to explain the general trend of low indoor radon readings in the Coastal Plain (i.e., most houses tested in this area have concentrations of less than 4 pCi/L). Interestingly, some small areas have shown high indoor radon, possibly due to accumulations of less-weathered river-deposited sediments. Higher values were also found in samples originating from phosphatic fossil units and glauconitic sands in the Aqui, Brightseat, and Calvert Formations in Maryland and Virginia (Otton, 1992). In one extreme example, the Yorktown Formation had an average radon concentration of 1050 PCi/l, and Goodwin et al. (1989) suggests that fossilized whale bones in the formation may be the source of the radon. Additionally, heavy mineral deposits in the Virginia Coastal Plain have also created localized high values of radon (Gundersen, 1993).

Mose and Mushrush (1987) first reported on the comparatively low indoor radon measurements characteristic of the Coastal Plain in 1987. The US-EPA reports the average indoor radon concentrations from 1986-1989 were <1 pCi/L for most parts of the Outer Coastal Plain (Gundersen et al., 1992), and that indoor radon measurements from the Inner Coastal Plain averaged 2.3 pCi/L. Earlier, Berquist et al. (1990) found similar trends within Virginia in his study of radon potential with respect to geologic province, finding that the probability of a house exceeding 4 pCi/l in the Coastal Plain is less than 10%. He attributed the fact that homes on the Outer Coastal Plain tend to have the lowest indoor radon due to 1) the deep burial of uranium-bearing basement rocks as the clastic wedge of sediments thickens to the east; and 2) the largely weathered nature of the sediments residing in the Coastal Plain. In summary, it appears that with the exception of localized elevated radon concentrations, the Coastal Plain has the lowest potential of the provinces for radon.

Piedmont and Blue Ridge Provinces

In contrast to the Coastal Plain, the complexity and varied geology found in the Piedmont and Blue Ridge provinces creates a patchwork of high and moderate zones of concentrated radon. The region is underlain by Proterozoic and Paleozoic igneous and metamorphic rocks that have undergone differing levels of metamorphism and structural deformation; and also include sedimentary and contact metamorphic rocks deposited or emplaced during Mesozoic rifting. The literature originating from both Virginia and the larger mid Atlantic region indicates that granites, pegmatites, and monazites have the greatest propensity to contain trace amounts of uranium (e.g., Grauch and Zarinski 1976; Mose and Mushrush, 1987; Gundersen and Wanty, 1991). In general, several known localities exist in the province have elevated levels of radioactivity. These sites include 1) the inner Piedmont and Goochland Terrane; 2) plutons northwest of Fredericksburg (Neuschel et al., 1971); and 3) the region near Spotsylvania (Neuschel, 1970) (Fig. 22). Very high uranium concentrations have been documented in the Petersburg Granite near Richmond (Baillieul and Dexter, 1982), the Maidens Gneiss of the Goochland Terrane near Powhatan (Krason et al., 1988), the Old Rag Granite in Rappahannock County (Baillieul and Daddazio, 1982), the Crozet Granite in Albemarle County (Baillieul and Daddazio, 1982), and the Swanson Uranium deposit near Pittsylvania County (Halladay, 1987). Gundersen (1993) provides an excellent review on the numerous plutons throughout the Commonwealth that also have elevated concentrations of uranium and the potential for radon.

Regional metamorphism (heat, pressure, and chemically active fluids) can produce conditions conducive to the segregation and concentration of radioactive minerals. Within the Piedmont and Blue Ridge, the foliated metamorphic rocks, including phyllites, schist and gneisses, have the potential to contain radioactive minerals (e.g., allanite, monazite, zircon, and titanite). One of the best studied examples of the above conditions is in northern Virginia, where researchers document very high aerial radioactivity, soil-gas radon, and indoor radon levels are associated with the Peters Creek Schist in Fairfax County (Mose et al., 1988a,b; Otton et al., 1988; Schumann and Owen, 1988). Additionally, sheared fault zones have been found to be generating high amounts of radon. Mylonitization of the rock can increase the radon levels through 1) a volume loss and grain size reduction of uranium accessory minerals, thereby leaving the rock enriched in uranium; and 2) the foliation imparted on the rock during shearing increases the permeability, allowing the introduction of uraniferous fluids and gases into the shear zone (Gundersen, 1991). Several Piedmont sites that report high radioactive anomalies or the presence of uranium are in shear zones (e.g., Baillieul and Dexter, 1982; Halladay, 1987; Gundersen, 1991) Additionally, some of the highest indoor radon concentrations documented in the United States have been within shear zones (Gundersen et al., 1987, 1988; Smith et al., 1987; Henry et al., 1991).

Postdating the regional Paleozoic metamorphism of the Piedmont and Blue Ridge are the rocks of the Mesozoic basins (Fig. 22). In numerous locations, these rocks, chiefly siltstones, sandstones, and conglomerates, were transformed to uranium-enriched hornfels when they were locally metamorphosed by igneous intrusions. When faulting occurred as best seen in the Danville and Richmond basins, zones of high-uranium mylonites were created (Gundersen, 1993). Particular geological units now known to be higher than average in uranium include the Manassas Sandstone of the Culpepper Basin, the Cow Branch Formation of the Danville Basin (Gundersen et al., 1992), and hornfels in the Culpeper basin (Otton et al., 1988; Schumann and Owen, 1988). Also known as high-uranium units are black shales in the Mesozoic basins (e.g., the Cow Branch Member, the Balls Bluff Siltstone, the Catharpin Creek Formation, the Waterfall, Turkey Run, and Midland Formations, the upper portions of the Danville basin lacustrine sequence, and the Vinita Beds Member of the Tuckahoe Formation). All appear to have locally elevated uranium (J.P. Smoot, USGS, oral comm.).

In general, the Inner Piedmont and Goochland Terrane subprovinces have the greatest potential for radon (Fig. 22). Goodell (1989) reports that homes in the Piedmont have a 30% probability of high radon values, with local values exceeding 50% in homes located in dark gray phyllites, graphite schists, slates, and hornfels, many of which likely fall within these two subprovinces. Homes located in the Mesozoic basins have radon values equivalent to the rest of the Piedmont (Goodell, 1989).

Valley and Ridge and Appalachian Plateau Provinces

The rocks of the Valley and Ridge geologic province of Virginia include Paleozoic sedimentary rocks dominated by the carbonates, shales, and sandstones that have been folded and faulted. Similar are the rocks present in the Appalachian Plateau province, with the addition of bituminous coal and a minimal amount of structural deformation to the rocks. In both provinces, the dark shales and soils derived from carbonate and dark shale bedrock show the highest concentrations of radon in the province (e.g., Schultz et al., 1992; Gundersen, 1993). In general, most carbonate rocks have low concentrations of uranium, but the residual soils developed from the underlying bedrock are commonly elevated in uranium. Research by Schultz et al. (1992) in the Great Valley of West Virginia suggest that the deepest, most mature soils have the highest radium and radon concentrations, presumably from the dissolution of the carbonates and the concentration of base metals, including uranium. Elevated concentrations of soil-gas radon have been found in the Elbrook, Conococheague, and Beekmantown formations, all of which are interbedded limestones and dolomites; and in soils underlain by the Martinsburg Formation, characterized by zones of dark shales (Schultz et al., 1992). Gundersen (1993) reports the findings of aerial radiometric data in Virginia (Texas Instruments Incorporated, 1980), where uranium anomalies are associated with Devonian black shales to which the Martinsburg belongs. Specifically, the anomalies were present in 1) the sandstones and shales of the Chemung Formation; 2) shale and sandstone of the Hampshire Formation; 3) sandstone, shale, and coal of the Pocono Formation; 4) limestone and shale of the Greenbrier Group; and 5) with some of the Pennsylvanian sandstones, shales, and coals, where the upper Devonian-Pennsylvanian sandstone units in Virginia have only local areas of high radioactivity (Baillieul and Daddazio, 1982; Gundersen, 1993). Additionally, the enlargement of fractures and cave systems would likely increase the advection of radon, although Schultz et al. (1992) found no increase in radon concentration with respect to proximity to fractures, joints, or faults in the Great Valley.

The numerous studies listed previously indicate that some localities in the Valley and Ridge contain some of the highest concentrations of radon in the Commonwealth. Additionally, Goodell (1989) found the highest probabilities of radon exceeding the threshold value in the Valley and Ridge, where they average 50%, with values exceeding 70% in houses located on black or dark gray shales. In general, the US-EPA has designated the Valley and Ridge as having a high potential for radon (Fig. 22).

RADON POTENTIAL MAPS FOR VIRGINIA

The preceding section illustrates the general usefulness of geologic maps for providing a good first approximation of delineating areas that may have the presence of radioactivity. However, the previous research mentioned shows the heterogeneity of radon concentrations within a geologic province, and even within a specific rock formation. These studies illustrate some of the shortcomings of only relying on geologic maps or soil surveys for predicting the levels of radioactivity, as anomalies are often missed. Several factors that limit the usefulness of geologic maps include 1) uranium is usually not uniformly distributed in each geologic unit shown on maps; 2) generalized geologic maps may not show fault zones, which can be enriched in uranium; 3) fault zones may be soil covered and inconspicuous to bedrock mappers, leading to their omission on geologic maps; and 4) the complexity of the soil physics that cannot be measured by mapping. In short, geologic maps alone can, at best, be used to produce generalized radon-risk maps.

Most radon potential maps such as those developed by the U.S. Geological Survey (USGS) for the US-EPA are very dependent on geological maps. The US-EPA in cooperation with the USGS published Open-File Report 93-292, titled Geologic Radon Potential of EPA Region 3, which includes Virginia (Schumann, 1993). The purpose and intended use of this report was 1) to help identify areas where states can target their radon program resources; 2) to provide guidance in selecting the most appropriate building code options for areas; and 3) to provide general information on radon and geology for each state for federal, state, and municipal officials dealing with radon issues. In this report (EPA Region 3), the radon potential map is based on countywide generalizations of the bedrock geology. The map is also based on a database of indoor radon measurements to verify the report's conclusions. The EPA's national indoor radon database consisted of about 100,000 home-tests, of which about 1,100 measurements were from the

Commonwealth of Virginia. The EPA map is also based on a consideration of aeroradioactivity.

As a follow up to the USGS Geologic Radon Potential study, the US-EPA (2006) published a series of Radon Zones Maps, including one for Virginia (Fig. 22). They developed three tiers of potential radon zones derived from the results of their national radon survey program in conjunction with the USGS. The zones show areas with a high, an intermediate, or a low percentage of homes with an indoor radon problem (Fig. 22), where:

- **Zone 1** has the highest indoor radon potential and shows counties where untested homes probably have an average indoor radon level greater than 4 pCi/L;
- **Zone 2** has moderate indoor radon potential and shows counties where untested homes probably have an average indoor radon level between 2 and 4 pCi/L;
- **Zone 3** has the lowest indoor radon potential and shows counties where untested homes probably have an average indoor radon level less than 2 pCi/L.

Homes possessing elevated levels of radon have been documented in all three zones; and serves as a reminder that these maps are generalized and should only be used as a first approximation of radon potential. These maps were only intended to aid in the resource-allocation-decision-making-process of national, state, and local organizations as radon-resistant building codes are implemented (US-EPA, 2006).

SUMMARY

The diversity of Virginia's geology, geography, and climatic setting, when combined with its rapidly increasing population, has created an environment prone to geologic hazards. The primary hazards include lowlands flooding, landslides and debris flows in steep terrain, subsidence from sinkholes in karst areas, and radon gas emissions into homes. Nationwide, flooding is the leading weather-related killer in the U.S., costing an average of $3.7 billion annually; and flooding is the cause of 90 percent of all natural disaster damage, excluding agricultural losses due to drought. In Virginia, combined flooding and landslides are responsible for the greatest loss of life and property in recent history. These hazards are created by the combination of 1) heavy and prolonged rainfall; 2) steep mountainous topography of the central Appalachians; and 3) the encroachment of human development onto these flood-prone landscapes. The hazard of sinkhole development is primarily found in terrain underlain by carbonate rock. Geomorphic processes active in karst result in subsidence, sinkhole flooding, and surface water recharge of groundwater aquifers. Human induced changes to the local hydrology can trigger and exacerbate subsidence, flooding, and groundwater contamination hazards. Successful mitigation and remediation of karst hazards require mitigation that address the karst processes. In addition to land surface processes, radon is also a risk in Virginia. Radon is a naturally occurring radioactive gas formed as a decay-product of uranium, a radioactive element that is a known human carcinogen. Radon may accumulate inside a home due to a number of factors, including rock and soil types, weather conditions, soil moisture levels, construction style of the home, and from negative air pressure inside a home. Radon is present in varying concentrations in nearly all rocks and soils throughout the U.S., but has a tendency to be highest in granitic rocks, dark marine shales and limestones, and environments that have been severely structurally deformed. All five geologic provinces contain specific formations that have elevated concentration of radon. The provinces of the Valley and Ridge, as well as the Piedmont show a greater propensity for high radon concentrations in homes. Current radon potential maps are useful as a first approximation for assessing radon concentrations, but more data of in-situ radon concentrations and detailed geologic mapping are necessary to assess the radon levels of individual dwellings.

ACKNOWLEDGEMENTS

Virginia Division of Geology and Mineral Resources colleague James A. Lovett graciously provided the photograph of the sinkhole associated with an underground gypsum mine. The authors express their appreciation for the helpful comments and suggestions offered on this manuscript by colleagues Christine May, Karen Hostettler, and William Lassetter. Funding for radiocarbon dates was provided by the U.S. Geological Survey.

REFERENCES

Baillieul, A., and Daddazio, P.L., 1982, National Uranium Resource Evaluation of the Charlottesville quadrangle, Virginia and West Virginia: U. S. Department of Energy, National Uranium Resource Evaluation Report PGJ/F-114 (82), 46 p.

Baillieul, A., and Dexter, J.J., 1982, Evaluation of uranium anomalies in the Hylas zone and northern Richmond basin, east-central Virginia: *in* Goodknight, C.S., and Burger, J.A., eds., Reports on investigations of uranium anomalies: U. S. Department of Energy, National Uranium Resource Evaluation Report GJBX-222 (82). 97 p.

Beard, L.R., 1975, Generalized evaluation of flash flood potential. Austin: Univ. Texas Center Water Res. Tech. Rpt. CRWR-124., p. 1-27.

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

Berquist, C.R., Jr., Cooper, J.M., and Goodwin, B.K., 1990, Radon from Coastal Plain sediments, Virginia: Preliminary results: Geological Society of America, Abstracts with Programs, v. 22, no. 2, p. 4-5.

Berryhill, W.S., Jr., 1989, The impact of agricultural practices on water quality in karst regions, *in* Beck, B.F., ed., Engineering and Environmental Impacts of Sinkholes and Karst, Proc. Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. St. Petersburg Beach, FL. A.A. Balkema, Rotterdam, p. 159-164.

Boyer, D.G., and Pasquarell, G.C., 1994, Agricultural land use impacts on karst groundwater quality. American Water Resources Association, Proceedings of the Symposium on Effects of Human-Induced Changes on Hydrologic Systems, p. 791-799.

Boyer, D.G., and Pasquarell, G.C., 1999, Agricultural land use impacts on bacterial water quality in a karst groundwater aquifer. Journal of the American Water Resources Association, 35(2): 291-300.

Brady, N.C., and Weil, R.C., 1996, The nature and properties of soils: Prentice Hall, New Jersey.

Brookins, D., 1990, The indoor radon problem: Columbia University: New York.

Camp, J.D., and Miller, E.M., 1970, Flood of August, 1969 in Virginia: U.S. Geological Survey Water Resources Division Open-File Report, 120 p.

Carson, M.A., and Kirkby, M., 1972, Hillslope form and process. London: Cambridge University Press.

Christie, L., 2006, 100 fastest growing counties, CNNMoney.com http://money.cnn.com/2006/03/15/real_estate/fastest_growing_US_counties/index.htm

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.

Cohen, B.L., 1989, Radon, a homeowner's guide to detection and control: Consumers Union, New York.

Colucci, S.J., Jacobson, R.B., and Greco, S., 1993, Meteorology of the storm of the November 3–5, 1985, in West Virginia and Virginia, *in* Jacobson, R.B., ed., Geomorphic studies of the storm and flood of November, 1985, in the upper Potomac and Cheat River basins in Virginia and West Virginia: U.S. Geological Survey Bulletin 1981, p. B1–B31.

Costa, J.E., 1988, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. *in* Baker, V.R., Kochel, R.C., and Patton, P.C., (eds) Flood Geomorphology, p. 113-122., John Wiley, New York.

Douglas, T.J., Wooten, R.M., Gillon, K.A., Bauer, J.B., 2007, Geohazards and transportation aspects of sulfidic rock in North Carolina, (abs.): 7th Technical Forum, Geohazards in Transportation in the Appalachian Region, Asheville, NC.

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., Morgan, B.A., and Blair, J.L., 2001, 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., 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.

Fetter, C.W., 1988, Applied Hydrogeology. Merrill Publishing Company, Columbus, OH, 592 p.

Francis, D., 2007, Census: Loudoun among nation’s fastest-growing counties since ’00, The Examiner, http://www.examiner.com/a-632648~Census__632648~Census__Loudoun_among_nation_s_fastest_growing_counties_since__00.html

Freeze, R.A., and Cherry, J.A., 1979, Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 p.

Goodell, H.G., 1989, The geology of radon hazard in Virginia: Virginia Journal of Science, v. 40, no. 2, p. 81.

Goodwin, B.K, Berquist, C.R., Jr., Whitesell, T.E, and Cooper, J.M., 1989, Radon in the sediments of the central Virginia coastal plain, Virginia Journal of Science, v. 41, no. 2, p. 91.

Gosink, T.A., Baskaran, M., and Holleman, D.F., 1990, Radon in the human body from drinking water: Health Physics, v. 59, p. 919-924.

Grauch, R.I., and Zarinski, K., 1976, Generalized descriptions of uranium-bearing veins, pegmatites, and disseminations in non-sedimentary rocks, Eastern United States: U.S. Geological Survey Open File Report 76-582, 114 p.

Gryta, J. J, and Bartholomew, M.J, 1989, Factors influencing the distribution of debris avalanches associated with the 1969 Hurricane Camille in Nelson County, Virginia, Special Paper: *in* Schultz, Arthur P; Jibson, Randall W (eds.), Landslide processes of the Eastern United States and Puerto Rico, Geological Society of America Special Paper, v. 236, p.15-28.

Gundersen, L.C.S., 1991, Radon in sheared metamorphic and igneous rocks: *in* Gundersen, L.C.S., and Wanty, R.B., (eds) , Field studies of radon in rocks, soils, and water, U.S. Geological Survey, Bulletin 1971, 334 p.

Gundersen, L.C.S., 1993, Preliminary geologic radon potential assessment of Virginia: *in* Schumann, R.R. (ed.), Geologic radon potential of EPA region 3: Delaware, Maryland, Pennsylvania, Virginia, and West Virginia, U.S. Geological Survey Open-File Report 93-292-C, p. 146-184.

Gundersen, L.C.S., Reimer, G.M., and Agard, S.S., 1987, Geologic control of radon in Boyertown and Easton Pa. [abs.]: Geological Society of America, Abstracts with Programs, v. 19, no. 2.

Gundersen, L.C.S., Reimer, G.M., and Agard, S.S., 1988, The correlation between geology, radon in soil gas, and indoor radon in the Reading Prong, *in* Marikos, M.A., and Hansman, R.H. (eds.), Geologic causes of natural radionuclide anomalies: Proceedings of GEORAD conference, St. Louis, MO, United States Apr. 21-22, 1987, Missouri Department of Natural Resources, Special Publication 4, p. 91-102.

Gundersen, L.C.S., Schumann, R.R., Otton, J.K., Dubiel, R.F., Owen, D.E., and Dickinson, K.A., 1992, Geology of Radon in the United States: *in* Gates, A.E., and Gundersen, C.S. (eds.), Geologic Controls on Radon, Geological Society of America Special Paper 271, p. 1-16.

Gundersen, L.C.S., and Wanty, R.B., 1991, Field studies of radon in rocks, soils, and water. U.S. Geological Survey, Bulletin 1971, 334 p.

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.

Halladay, C.R., 1987, The Swanson uranium deposit, Virginia: A structurally controlled, U-P albitite deposit: *in* Proceedings of the International Atomic Energy Agency Meeting, Uranium Resources and Geology of North America, Saskatoon, Saskatchewan, Canada, IAEA-TECDOC-500, p. 519.

Harley, N.H., 1984, Radon and lung cancer in mines and homes: New England Journal of Medicine, v. 310, p. 1525.

Harley, N.H., 1989, Environmental Lung Cancer Risk from Radon Daughter Exposure: *in* Risk assessment of environmental and human health hazards: a textbook of case studies, Paustenbach D., ed., Wiley: New York, 1989, p. 612-630.

Heller, M., and Eaton, L.S., 2010, Surficial Geologic Map of the Elkton West Quadrangle, Virginia: Virginia Division of Geology and Mineral Resources Publication Open File Report 10-2, 1:24,000 scale.

Henry, M.E, Kaeding, M.E., and Monteverde, D.H., 1991, Radon in soil gas and gamma-ray activity of rocks and soils at the Mulligan Quarry, Clinton, New Jersey: *in* Gundersen, L.C.S., and Wanty, R.B., (eds.) , Field studies of radon in rocks, soils, and water, U.S. Geological Survey Bulletin 1971, 334 p.

Hess, C.T., Weiffenbach, C.V., and Norton, S.A., 1982, Variations of airborne and waterborne Rn-222 in houses in Maine: Environment International, v.8, p. 59-66.

Hubbard, D.A., Jr., 1983, Selected karst features of the northern Valley and Ridge province, Virginia. Virginia Division of Mineral Resources, Publication 44, one sheet.

Hubbard, D.A., Jr., 1988, Selected karst features of the central Valley and Ridge province, Virginia. Virginia Division of Mineral Resources, Publication 83, one sheet.

Hubbard, D.A., Jr., 1999, Highways in Virginia karst: Resource and hazard considerations. 50th Annual Highway Geology Symposium & TRB Karst Meeting, Proc. & Field Trip Guide, 13-22.

Hubbard, D.A., Jr., 2001, Selected karst features of the southern Valley and Ridge province, Virginia. Virginia Division of Mineral Resources, Publication 167, one sheet.

Hubbard, D.A., Jr., 2003, Use of regional sinkhole mapping for sinkhole susceptibility maps, *in*, Beck, B.F., ed., ASCE Geotechnical Special Publication No. 122, p. 61-71.

Hubbard, D.A., Jr. and Sterrett, R.M., 1994, Ground-water contamination in Virginia karst: Case studies (abs.). Program and Abstracts, 37th Annual Meeting of the Association of Engineering Geologists, Williamsburg, VA, p. 49.

Jacobson, R.B., Miller, A.J., and Smith, J.A., 1989, The role of catastrophic geomorphic events in central Appalachian landscape evolution: Geomorphology, v. 2, p. 257–284.

Jurgens D.M., 1997, An investigation of the controls of slope stability in the 1995 debris flows of Madison County, Virginia. BS thesis, Bucknell University, Lewisburg, Pennsylvania, 34 p.

King, P.B., 1950, Geology of the Elkton area, Virginia: U. S. Geological Survey Professional Paper 230, 82 p.

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.

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. *in* Gravels and Conglomerates, E. Koster and R. Steel, (eds.) Canadian Society of Petroleum Geologists Memoir 10, p. 109-122.

Kochel, R C., Miller, J.R, Lord, M., and Martin, T., 2005, Geomorphic problems with in-stream structures using natural channel design strategy for stream restoration projects in North Carolina, Abstracts with Programs, Geological Society of America, vol.37, no.7, p. 329.

Krason, J., Johnson, S.S., Finley, P.D., and Marr, J.D., Jr., 1988, Geochemistry and radioactivity in the Powhatan area, Virginia: Virginia Division of Mineral resources Publication 78, 60 p.

Kunz E., and Sevc J., 1978, Lung cancer mortality among uranium miners (methodological aspects): Health Physics, v.35, p.579.

Lafavore, M., 1987, Radon: The invisible threat: Rodale Press, Pennsylvania, 256 p.

Latham, R.S., Wooten, R.M., Witt, A.C., Gillon, K.A., 2007, Big slow movers: a look at weathered rock slides in western North Carolina: (abs.), 7th Technical Forum, Geohazards in Transportation in the Appalachian Region, Asheville, NC.

Leopold, L.B., 1968, Hydrology for Urban Land Planning – A Guidebook on the Hydrologic Effects of Urban Land Use, U.S. Geological Survey Circular 554, 18p.

Litwin, R.J., Morgan, B.A., Eaton, L.S., Wieczorek, G.F., and Smoot, J.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.

Lowder, W.M., 1985, Part One - Radon: Overview, in Indoor Air and Human Health: *in* Gammage, R.B. and Kaye, S.V., (eds.), Lewis Publishers: Michigan, p. 39-41.

Mason, J.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.

May, C.L., 2002, Debris flows through different forest age classes in the central Oregon Coast Range: Journal of the American Water Resources Association 38(4), p. 1097-1113.

Michaels, P.J., 1985, Virginia climate advisory: Charlottesville, University of Virginia, v. 9, no. 2, 30 p.

Miller, A.J., 1990, Flood hydrology and geomorphic effectiveness in the central Appalachians: Earth Surface Processes and Landforms, v. 15, p. 119–134.

Mills, H.H., Campbell, E., Floyd, J., Hibbits, H., and Williams, S., 2005, Preliminary Surficial Geologic Map of the Grottoes Quadrangle, Virginia, Division of Mineral Resources Open File Report 05-05.

Mills, H.H, Brakenridge, G.R., Jacobson, R.B., Newell, W.L., Pavich, M.J., and Pomeroy, J.S., 1987, Appalachian mountains and plateaus, DNAG, Decade of North American Geology; Geological Society of America., Boulder, CO.

Milvy, P., and Cothern C.R., 1990, Scientific background for the development of regulations for radionuclides in drinking water; *in* Cothern, C.R., and Rebers, P.A., (eds.), Radon, radium and uranium in drinking water, Lewis Publishers, Michigan, p. 1-16.

Morgan, B.A., and Wieczorek, G.R., 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.

Morgan, B.A., Eaton, L.S., and Wieczorek, G.R., 2003, Pleistocene and Holocene colluvial fans and terraces in the Blue Ridge region of Shenandoah National Park, Virginia, U. S. Geological Survey, Report: OF 03-0410, 25 p., 1 Sheet.

Mose, D.G., and Mushrush, G.W., 1987, Correlation between indoor radon and geology in VA and MD: Geological Society of America, Abstracts with Programs, v. 19, p. 779.

Mose, D.G., and Mushrush, G.W., 1988, The effect of home construction on indoor radon in Virginia and Maryland: Environment International, v.14, p. 223-230.

Mose, D.G. and Mushrush, G.W., 1997a, Carcinogenic risk associated with radon-enriched well water: Energy Sources, v.19, p. 705-713.

Mose, D.G., and Mushrush, G.W., 1997b, Variable spatial and seasonal hazards of airborne radon: Atmospheric Environment, v. 31(21), p. 3523-3530.

Mose, D.G., and Mushrush, G.W., 1999, Influence of local geology on the concentration of indoor radon in Maryland: Energy Sources, v. 21, p. 715-721.

Mose, D.G., Mushrush, G.W., and Chrosniak, C., 1990, Radioactive hazard of potable water in Virginia and Maryland: Bulletin of Environmental Contamination and Toxicology, v. 44, p. 508-513.

Mose, D.G., Mushrush, G.W., and Chrosniak, C., 1991, Seasonal indoor radon variations related to precipitation: Environmental and Molecular Mutagenesis, v. 17, p. 223-230.

Mose, D.G., Mushrush, G.W., and Chrosniak, C., 1992a, A two-year study of seasonal indoor air radon variations in southern Maryland: Environmental Pollution, v. 76, p. 195-199.

Mose, D.G., Mushrush, G.W., and Chrosniak, C., 1992b, Soil radon, permeability and indoor radon prediction: Environmental Geology Water Science., v. 19, no. 2, p. 91-96.

Mose, D.G., Mushrush, G.W., and Kline, S.W., 1988a, Geology and time dependent indoor radon variations in VA and MD: Geological Society of America, Abstracts with Programs, v. 20, p. 56-57.

Mose, D.G., Mushrush, G.W., and Kline, S.W., 1988b, The interaction of geology, weather and home construction on indoor radon in northern Virginia and southern Maryland: Northeastern Environmental Science, v. 7, p. 15-29.

Mose, D.G., Mushrush, G.W., and Simoni, F.V., 2005, Reduction of radon in municipal wells in Virginia and Maryland: Contaminated Soils, v. 9, p. 375-392.

NAS, 1999, Health Effects of Exposure to Radon: BEIR VI. National Academy of Sciences: Washington, D.C.

Nazaroff, W.W., and Nero, A.V., 1988, Radon and its decay products in indoor air, Wiley, New York.

Neuendorf, K.K.E., Mehl, J.P., Jr., and Jackson, J.A. (eds.), 2005, Glossary of Geology, AGI, Alexandria, VA, 779 p.

Neuschel, S.K., 1970, Correlation of aeromagnetics and aeroradioactivity with lithology in the Spotsylvania area, Virginia: Geological Society of America Bulletin, v. 81, no. 12, p. 3575-3582.

Neuschel, S.K., Bunker, C.M., and Bush, C.A., 1971, Correlation of uranium, thorium, and potassium with aeroradioactivity in the Berea area, Virginia: Economic Geology, v. 66, no. 2, p. 302-308.

Newson, M., 1980, The geomorphological effectiveness of floods; A contribution simulated by two recent events in mid-Wales: Earth Surface Processes and Landforms, v. 5, p. 1-16.

NTP, [National Toxicology Program], 2005, 11th Report on Carcinogens: National Toxicology Program, North Carolina.

Otton, J.K., 1992, Radon in soil gas and soil radioactivity in Prince Georges County, Maryland, U.S. Geological Survey Open File Report no. 92-11, 18 p.

Otton, J.K., Schumann, R.R., Owen, D.E., Thurman, N. and Duval, J.S., 1988, Map showing radon potential of rocks and soils in Fairfax County, Virginia: U. S. Geological Survey Miscellaneous Field Studies Map MF-2047, scale 1:62,500.

Padgett, D.A., 1993, Remote sensing applications for identifying areas of vulnerable hydrogeological and potential sinkhole collapse within highway transportation corridors: *in* Beck, B.F., (ed.), Applied Karst Geology, Proceedings of the Fourth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Panama City, FL. A.A. Balkema, Rotterdam, p. 285-290.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *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. 1–12.

Proctor, R.N., 1995, Cancer Wars. How Politics Shapes What We Know and Don't Know About Cancer: Basic Books, New York.

Ritter, D.F., Kochel, R.C., and Miller, J.E., 2002, Process Geomorphology, McGraw Hill, 423 p.

Samet, J.M., 1994, Health Effects of Radon in Radon: prevalence, measurements, health risks and control: *in* Nagda, N.L., (ed.), ASTM Manual Series: MNL 15, 1 Publication Code 28-015094-17, ASTM: Philadelphia.

Sas, R.J. Jr., and Eaton, L.S., 2006a, Geologic controls of basin denudation from debris flows in Rockbridge County, Virginia, Abstracts with Programs - Geological Society of America, v. 38, no.2, p. 84.

Sas, R.J. Jr., and Eaton, L.S., 2006b, Landslide Warning Action Plan: Prioritizing Areas of High Risk Along Blue Ridge Parkway Using VisiData. Eos Transactions, American Geophysical Union, 87(52), H51B-0486.

Schultz, A., Wiggs, C.R, and Brower, S.D., 1992, Geologic and environmental implications of high soil-gas radon concentrations in the Great Valley, Jefferson and Berkeley counties, West Virginia: *in* Gates, A.E., and Gundersen, L.C.S. (eds.), Geologic controls on radon, Geological Society of America Special Paper, v. 271, p.29-44.

Schumann, R. R., 1993, Geologic radon potential of EPA region 3: Delaware, Maryland, Pennsylvania, Virginia, and West Virginia, 1993, U.S. Geological Survey Open-File Report 93-292-C, 206 p.

Schumann, R. R., and Owen, D. E., 1988, Relationships between geology, equivalent uranium concentration, and radon in soil gas, Fairfax County, Virginia, U.S. Geological Survey Open-File Report 88-18, 28 p.

Sevc, J., Kunz, E., and Placek, V., 1976. Lung cancer in uranium mines and long-term exposure to radon daughters: Health Physics, v.30, p.433.

Sidle, R. C., A. J. Pearce, and C. L. O'Loughin. 1985. Hillslope stability and land use. Water Resources Monograph 11. American Geophysical Union, Washington, D.C.

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.

Simpson, P.S., and Simpson, J.H., Jr., 1970, Torn land: Lynchburg, Virginia, J.P. Bell Co., 429 p.

Smith, J.A., Baeck, M.L., and Steiner, M., 1996, Catastrophic rainfall from an upslope thunderstorm in the central Appalachians: The Rapidan storm of June 27, 1995: WaterWater Resources Research, v. 32, p. 3099–3113.

Smith, R.C., II, Reilly, M.A., Rose, A.W., Barnes, J.H., and Berkheiser, S.W., Jr, 1987, Radon: A profound case: Pennsylvania Geology, v. 18, p. 1-7.

Stephenson, J.B., and Beck, B.F., 1995, Management of the discharge quality of highway runoff in karst areas to control impacts to ground water – A review of relevant literature: *in* Beck, B.F., ed., Karst GeoHazards, Proceedings of the Fifth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Gatlinburg, TN. A.A. Balkema, Rotterdam, p. 297-321.

Stringfield, V.T., and Smith, R.C., 1956, The relation of geology to drainage, floods, and landslides in the Petersburg area, West Virginia: West Virginia Geologic and Economic Survey Report of Investigations 13, 19 p.

Terranova, T.F., 1987, Multivariate analysis of geological, hydrological, and soil mechanical controls on slope stability in central Virginia (MS Thesis), Southern Illinois University, Carbondale.

Terranova, T. F., and Kochel, R C., 1987 Multivariate analysis of factors related to debris avalanching in Nelson County, central Virginia, Abstracts with Programs - Geological Society of America, v.19, no.7, p.866.

UNSCEAR, [United Nations Scientific Committee on the Effects of Atomic Radiation], 2000, Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000 Report to the General Assembly with Scientific Annexes: Set of two volumes. United Nations: June, 2001.

US-EPA, 2006, Radon (Rn) [Online]. November 17, 2006 [cited on November 20, 2006].URL http://www.epa.gov/radon.

USGS, 2006, Flood Hazards: A National Threat, USGS Fact Sheet 2006-3026. http://landslides.usgs.gov/recent/archives/1997kinsey.php

USGS, 2007, Natural Hazards: A National Threat, USGS Fact Sheet 2006-3009. http://pubs.usgs.gov/fs/2007/3009/2007-3009.pdf

VDEM, (Virginia Department of Emergency Service), 2007, http://www.vaemergency.com/threats/flood/index.cfm

Wagoner, J.K., Archer, V.E, Lundin, F.E., Holaday, D.A., and Lloyd, J.W., 1965, Radiation as the cause of lung cancer among U.S. uranium miners: New England Journal of Medicine, v.273, p. 181-188.

Watts, C.F., and Whisonant, R.C., 1992, Slope stability problems along highway roadcuts in the Virginia Valley and Ridge Province: Geological Society of America Abstracts with Programs, v.24, no.2, p.72.

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. 6, p. 3–23.

Wieczorek, G.F., Eaton, L.S., Yanosky, T.M., and Turner, E.J., 2006, Landslide activity along Meadow Run, Shenandoah Valley, Virginia, Journal of Landslides, v. 3, p. 95-106.

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.

Whittecar, G.R., and Duffy, D.L, 2000, Geomorphology and stratigraphy of late Cenozoic alluvial fans, Augusta County, Virginia, U.S.A., Southeastern Geology, vol.39, no.3-4, p.259-279, Oct 2000

Wilkening, M., 1990, Radon in the Environment: Elsevier, New York.

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.

Winchester, P.W., Jr., 1985, Rockslide on Interstate 40 in North Carolina blocks both lanes approximately four miles from Tennessee-North Carolina state line, AEG Newsletter, vol.28, no.3, pp.16-18, Jul 1985.

Wolman, M.G., 1967, A cycle of sedimentation and erosion in urban river channels. Geogr. Annlr. 49-A:385-95.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54–74.

Zhang, K., Douglas, B., Leatherman, S., 2002, Do storms cause long-term beach erosion along the U.S. east barrier coast?, Journal of Geology, vol.110, no.4, p.493-502, Jul 2002

FIGURE CAPTIONS

Figure 1. Areas affected by debris-flow events in Virginia and West Virginia from 1949 to 1996. 1—June 17–18, 1949, storm in western Virginia and eastern West Virginia; 2—August 19–20, 1969, storm in western Nelson County, Virginia; 3—November 3–5, 1985, storm in western Virginia and eastern West Virginia; 4—June 27, 1995 storm of the Blue Ridge Mountains. Site 4a corresponds to western Madison and Greene Counties; 4b is western Albemarle; and 4c depicts eastern Rockbridge County.

Figure 2. Flood envelope curve for United States, including discharge values for Hurricane Camille (Nelson County), the Rapidan Storm (Madison County), the 1949 storm (western Virginia), and the 1985 storm (western Virginia and eastern West Virginia).

Figure 3. Rheologic classification of sediment-water flows. Vertical boundaries A, B, and C are rheologic thresholds, and are a function of grain size distribution (here assumed to be coarse, poorly-sorted mixture) and sediment concentration. Moving from left to right, boundary A marks onset of yield strength; boundary B marks sudden, rapid increase in yield strength that permits static suspension of gravel and onset of liquefaction behavior; boundary C marks cessation of liquefaction behavior. Horizontal velocity boundaries, also function of grain-size distribution and sediment concentration as well as particle density, are determined by how stress is transmitted between particles during flow (from Pierson and Costa, 1987)

Figure 4. Map of central Shenandoah Valley and Blue Ridge Mountains depicting dominant debris flow and alluvial fan types (indicated by arrows).

Figure 5a. Topographic sketch map and longitudinal cross section of an alluvial fan in the Shenandoah Valley between Waynesboro and Elkton at One Mile Run basin. Evidence of the old age of this fan includes its being graded to a high terrace level and post-depositional dissection. Erosion by the South Fork of the Shenandoah River has removed a significant portion of the northern toe of this fan. This can be seen clearly by comparing the two fan profiles. Fans appear to be of varying ages along the eastern Shenandoah Valley because others are graded to lower terrace levels.

Figure 5b. Schematic diagram of down-fan variation in facies in the fluvial dominated Shenandoah Valley fans. Thickness in the columns are not to scale, but the range of observed or inferred (from drillers' logs) thicknesses are given in parentheses. Proximal fan facies are dominated by poorly-sorted, coarse-grained, angular-to-subangular bouldery material. Mid-fan facies contain interbedded sand and subrounded cobble gravel. Distal fan facies are dominated by cobble to granule gravels and well-stratified sheet sands.

Figure 6. (A) Bankful flow from Hurricane Isabel (2003) at Meadow Run near Grottoes; and (B) the resulting coarse grained braided stream pattern downstream of figure A.

Figure 7a. Stratigraphy and sedimentology of a debris fan along the North Prong of Davis Creek, Nelson County. A) Cross sections show irregular nature of 1969 deposits across fan, resulting from shifting loci of depositional lobes. Trends in variations in texture and matrix composition with depth are useful in determining boundaries between debris flow events.
Figures 7B to 7E) Debris flow deposits exposed by the June 1995 storm in Madison County. Dashed lines shows boundary between two prehistoric debris flow deposits in photos B and D; and between saprolite and a debris flow unit in photo C. In photo E, the trowel easily penetrates a granitic clast of a debris flow deposit.

Figure 8: Debris flows and avalanches in Nelson County, Virginia, during 1969. A.) Flows deposited debris on small fans at the base of first-order hillslope channels near Lovingston. B.) Catastrophic erosion and impact forces from these flows removed some structures and devastated others (view from Davis Creek). Photos courtesy of Virginia Division of Mineral Resources.

Figure 9: Debris flows in Madison County, Virginia, from the 1995 storm. A) Two debris flows separated by 1.5 hours struck and moved a two story farm house; B) house was pushed forward by nearly 10 meters by the two events; C) large boulders deposited in 1995 on the Generals fan, located 1 km northwest of Graves Mill. Arrow denotes person for scale.

Figure 10. A) Debris flow activity on Kirtley Mountain, western Madison County, Virginia, following Madison County 1995 storm. Debris-flow activity affected and denuded numerous low-order drainages. Arrows denote houses for scale. Dashed line denotes upper margins of debris fans. B) Surficial mapping of the Graves Mill area

(Eaton et al., 2001). Landforms on the simplified map are denoted as debris fans (df), terraces (t), and floodplains (fp). The letter ‘X’ marks the location of the dwelling destroyed in 1995 and is shown in figure 9b.

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

Figure 12. A.) Cripple Creek, located in Nelson County, is typical of many first- and second-order tributaries in the Blue Ridge Mountains of Virginia. Note the abundance of cobbles and boulders. B.) An unnamed tributary of the upper Rapidan River denuded to bedrock and purged of nearly all boulders following the Madison County storm.

Figure 13. Schematic cross sections showing influence of bedrock structural characteristics on debris avalanche scar morphology. A.) Planar surfaces, where foliation and hillslope orientation are nearly normal. In these cases, failures were characterized by spalling of thin layers of bedrock along joint surfaces normal to slope. B.) Stepped surfaces, where foliation planes intersected hillslopes at small acute angles. These differences can be seen along the track of a single debris flow scar if its trend changes significantly downslope.

Figure 14. Topographic and structural controls of debris flows at Kirtley Mountain, Madison County. Note the dominant failure pattern to the southeast.

Figure 15. Figure 15. A) Rapidan River, 1 km downstream of Graves Mill during recession of the June 27, 1995 flood. Arrow denotes the remnants of the State Route 676 bridge (view is upstream). Note the braided pattern of the channels emerging from the recession of the flow. B) This pattern resumed again during Hurricane Fran (Sept. 1996). The system has been repeatedly anthropogenically modified to a single narrow channel, and continues to be unstable.

Figure 16. Avulsion of Rapidan River at the State Route 676 bridge shortly after stream restoration in 2002.

Figure 17. A collapse sinkhole that formed during a rainfall event in Austinville, Virginia in September, 1989.

Figure 18. Sinkhole flooding that extended over part of a blind valley near Harrisonburg, Virginia after a rainfall event in October, 1996.

Figure 19a. A collapse sinkhole that formed above an underground limestone mine near Lowmoor, Virginia prior to 1990.

Figure 19b. A large collapse sinkhole that formed above an underground gypsum mine in Plasterco, Virginia in November, 1984.

Figure 20. A collapse sinkhole that formed over coalfield workings in the Richmond basin, Virginia in January 2007, (DMME photograph).

Figure 21. Geologic provinces of Virginia (after Gundersen, 1993). Gray areas indicate Mesozoic basins. Numbers indicate descending levels of radon potential (after US-EPA, 2006).

Figure 1.

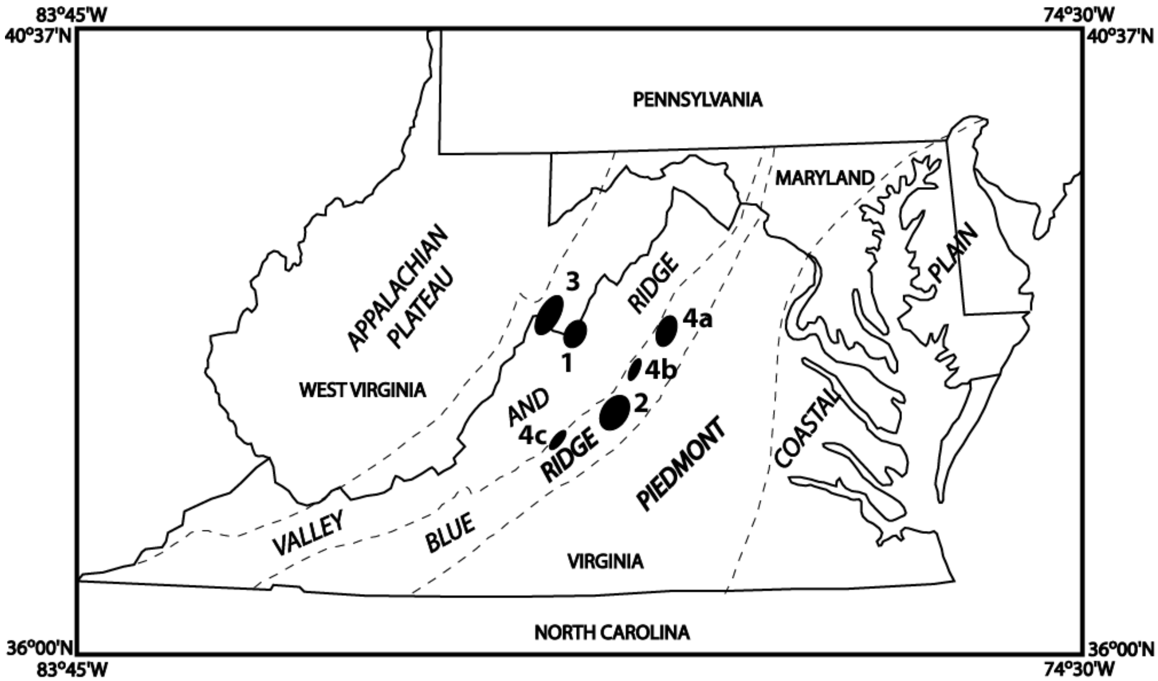


Figure 2.

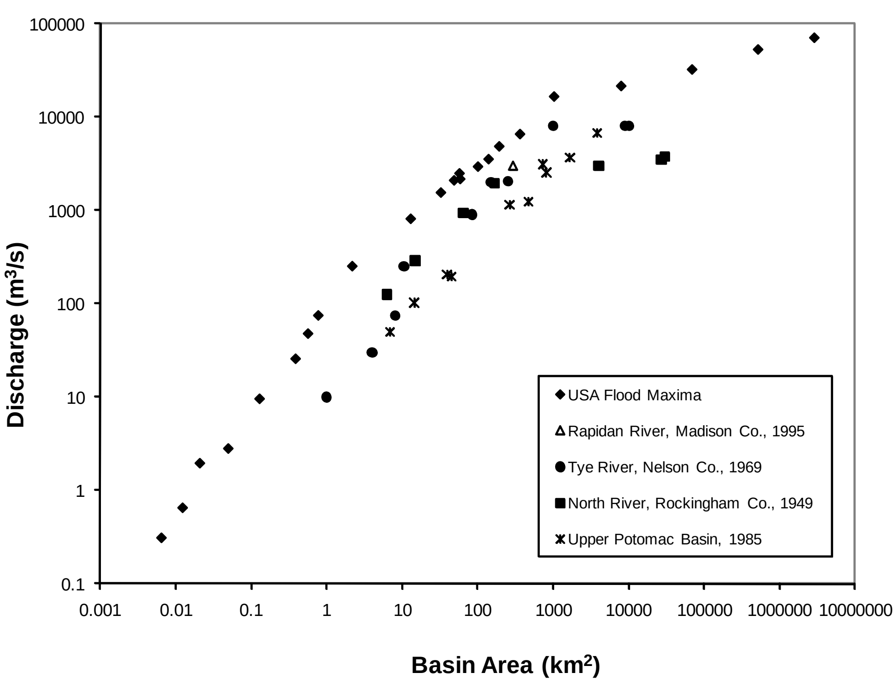
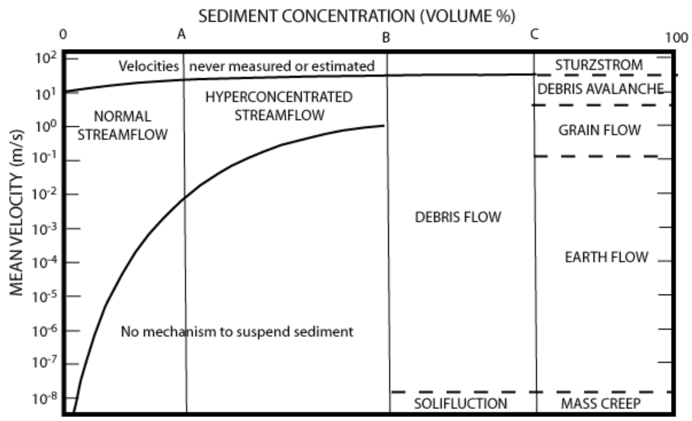


Figure 3.



FLUID TYPE	NEWTONIAN	NON-NEWTONIAN		
INTERSTITIAL FLUID	WATER	WATER & FINES		WATER, FINES, AIR
FLOW CATEGORY	STREAMFLOW		SLURRY FLOW	GRANULAR FLOW
FLOW BEHAVIOR	LIQUID	PLASTIC		

Figure 4.

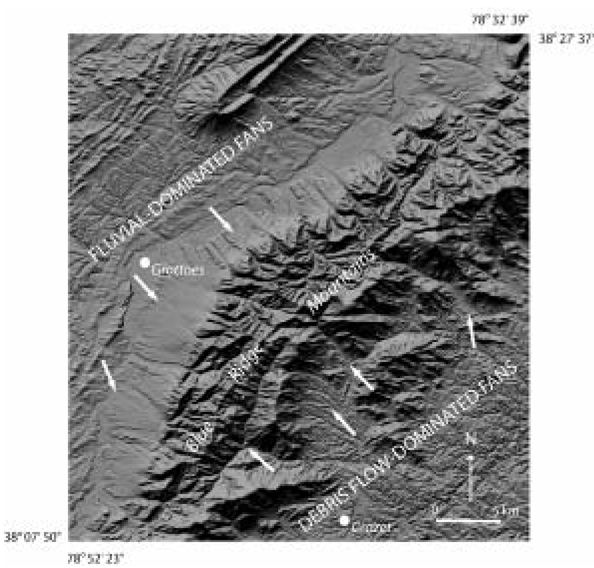


Figure 5.

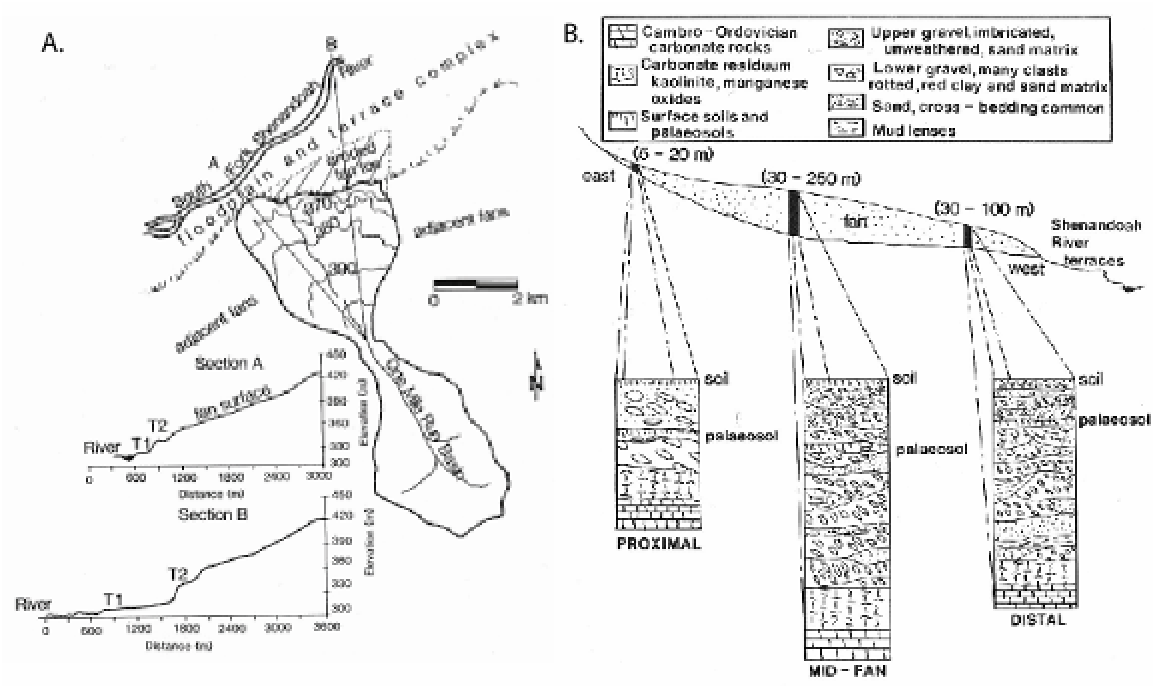


Figure 6.

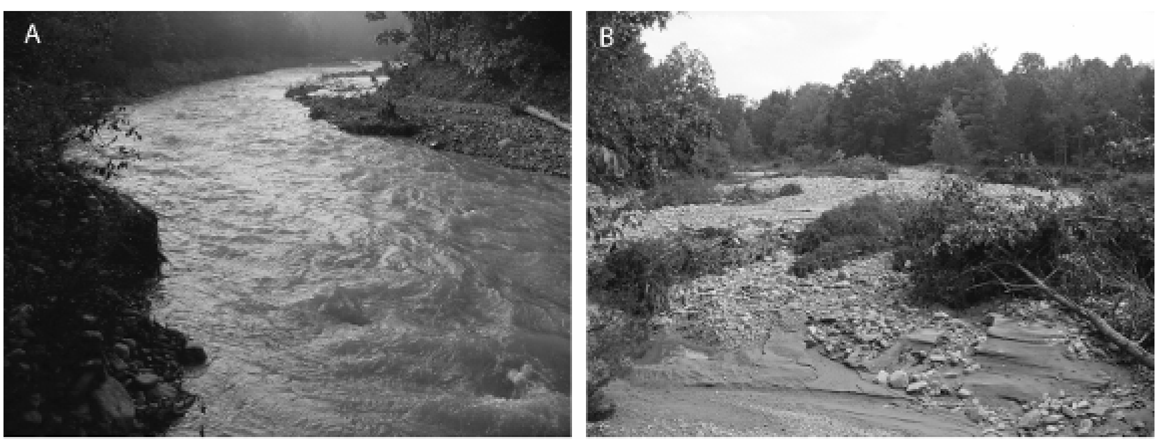


Figure 7.

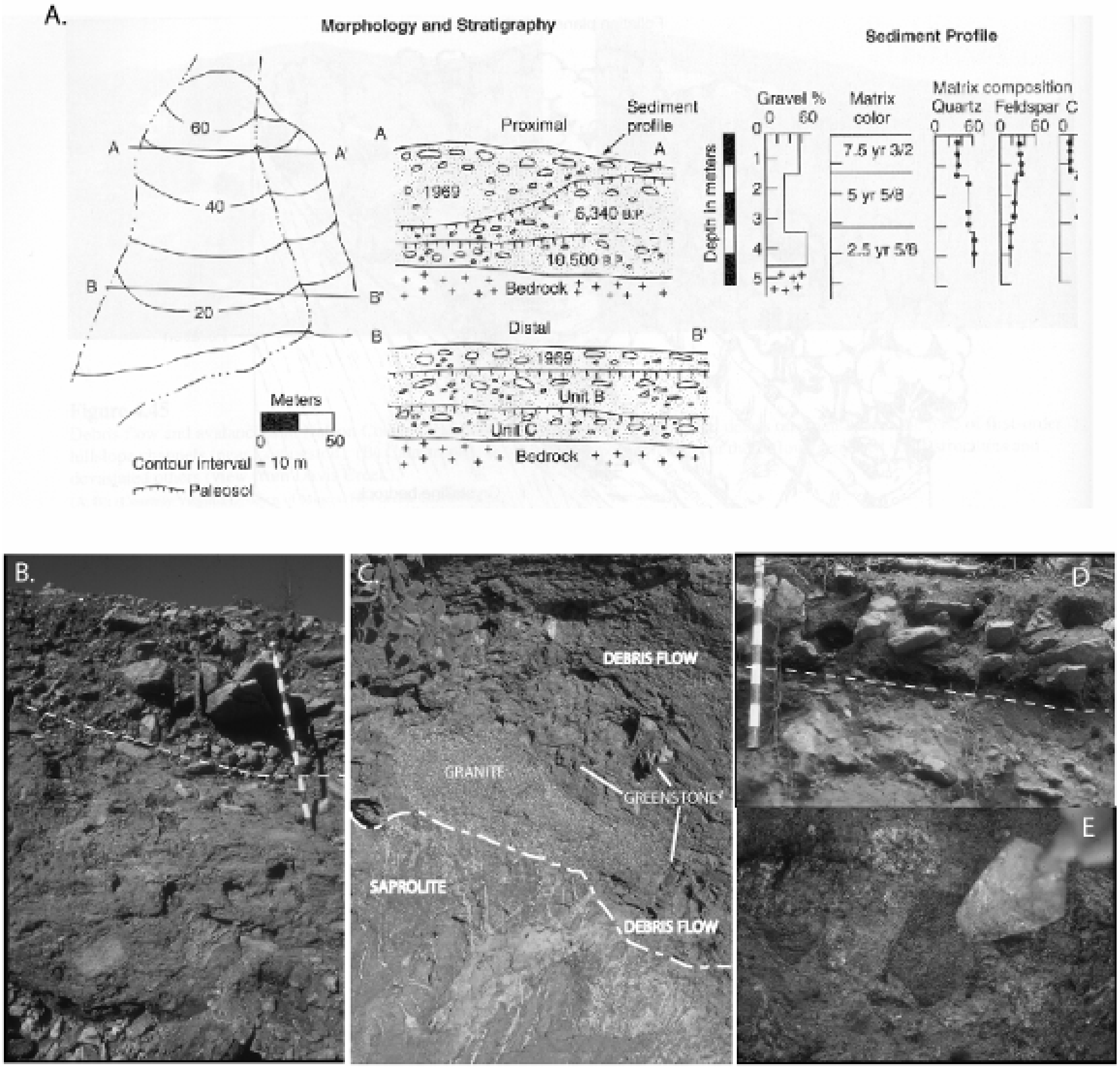


Figure 8.

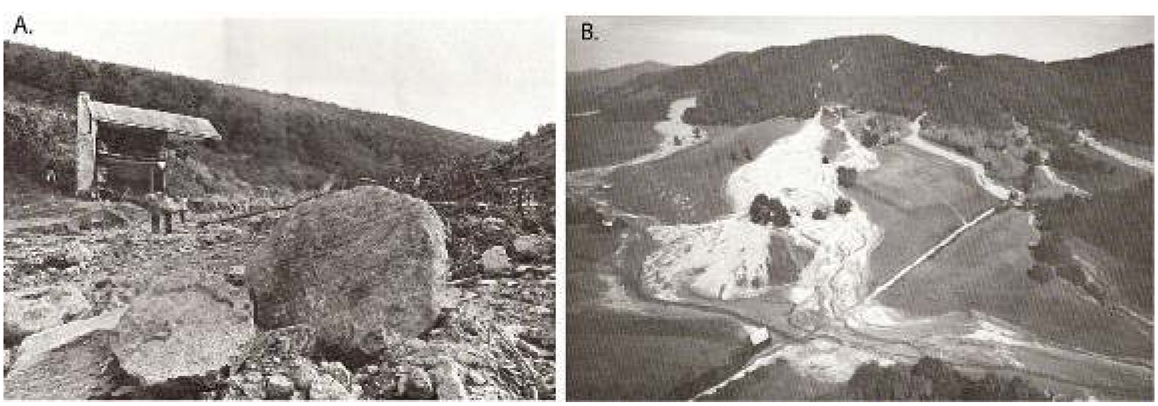


Figure 9.

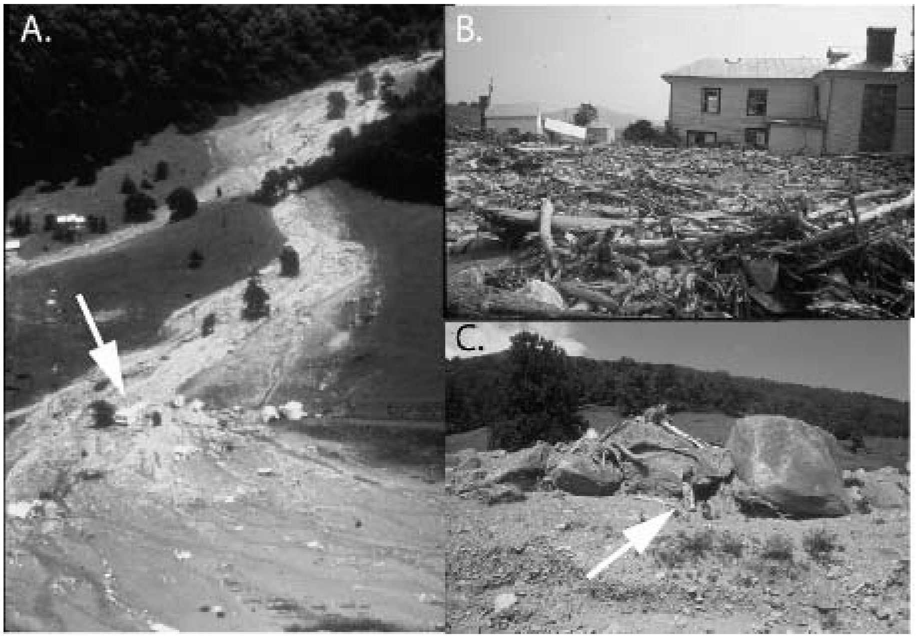


Figure 10.

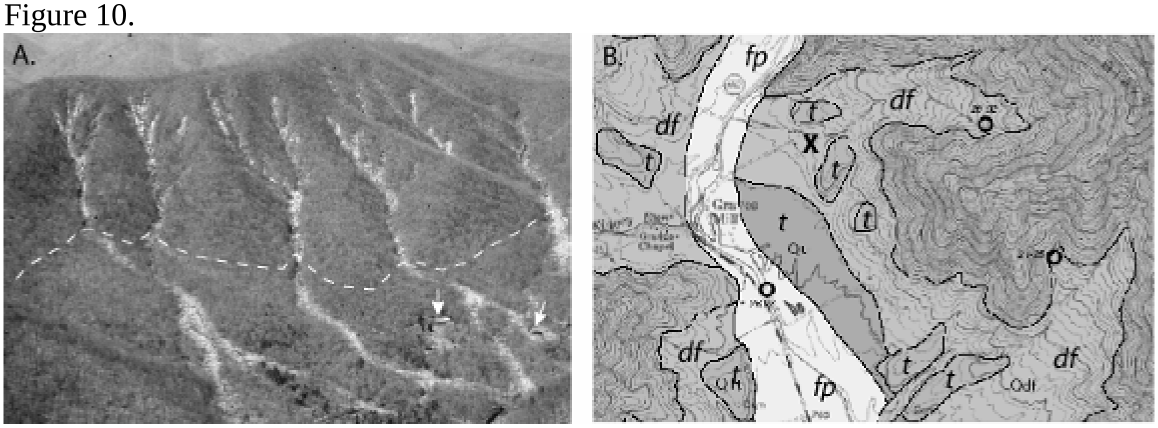
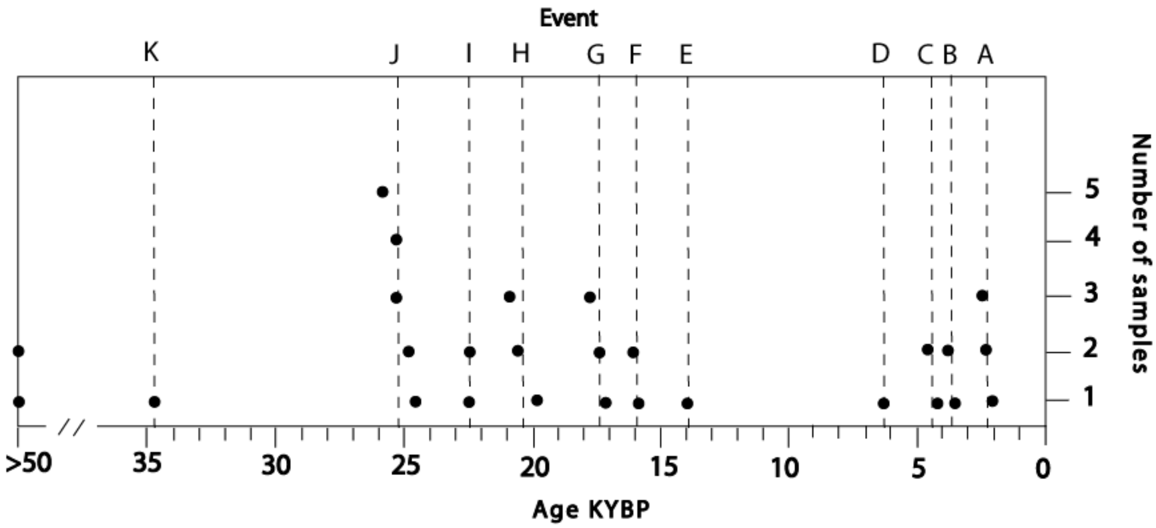


Figure 11.



Event

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

Figure 12.

Figure 13.

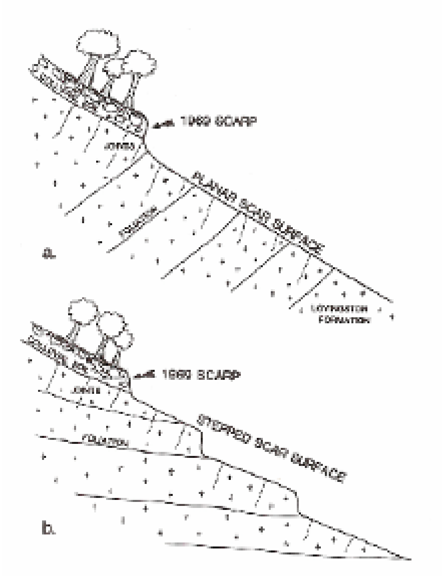


Figure 14.

Figure 15.

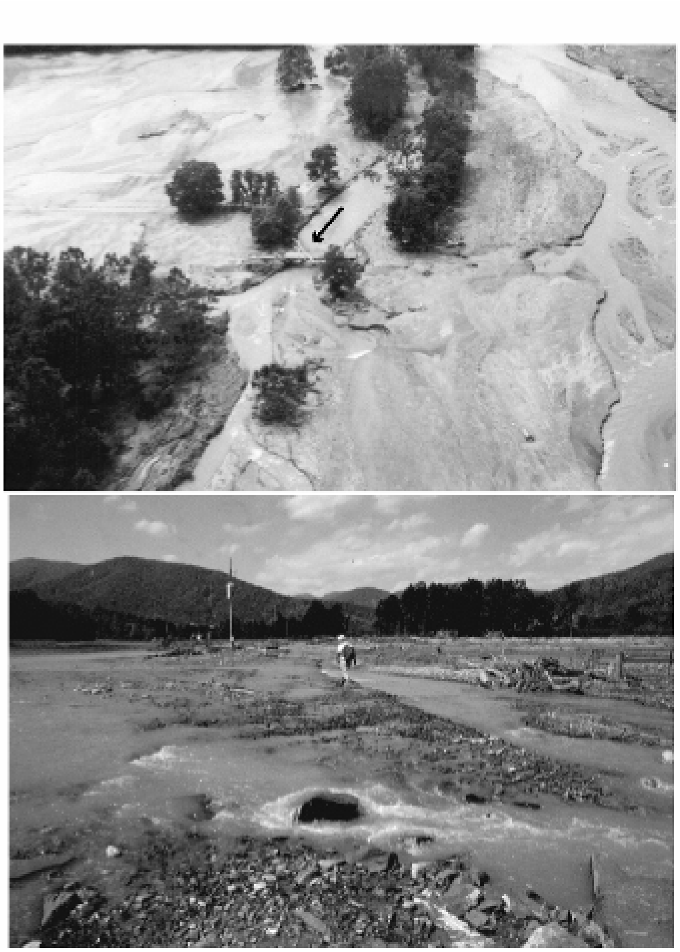


Figure 16.

Figure 17:

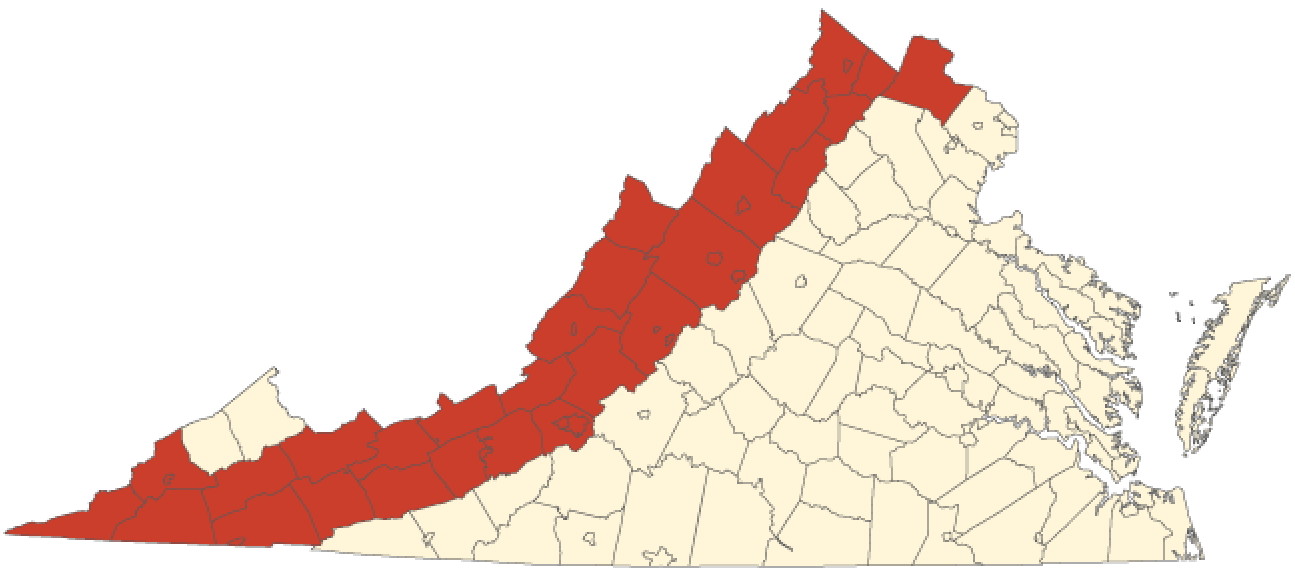


Figure 18.

Figure 19.

Figure 20.

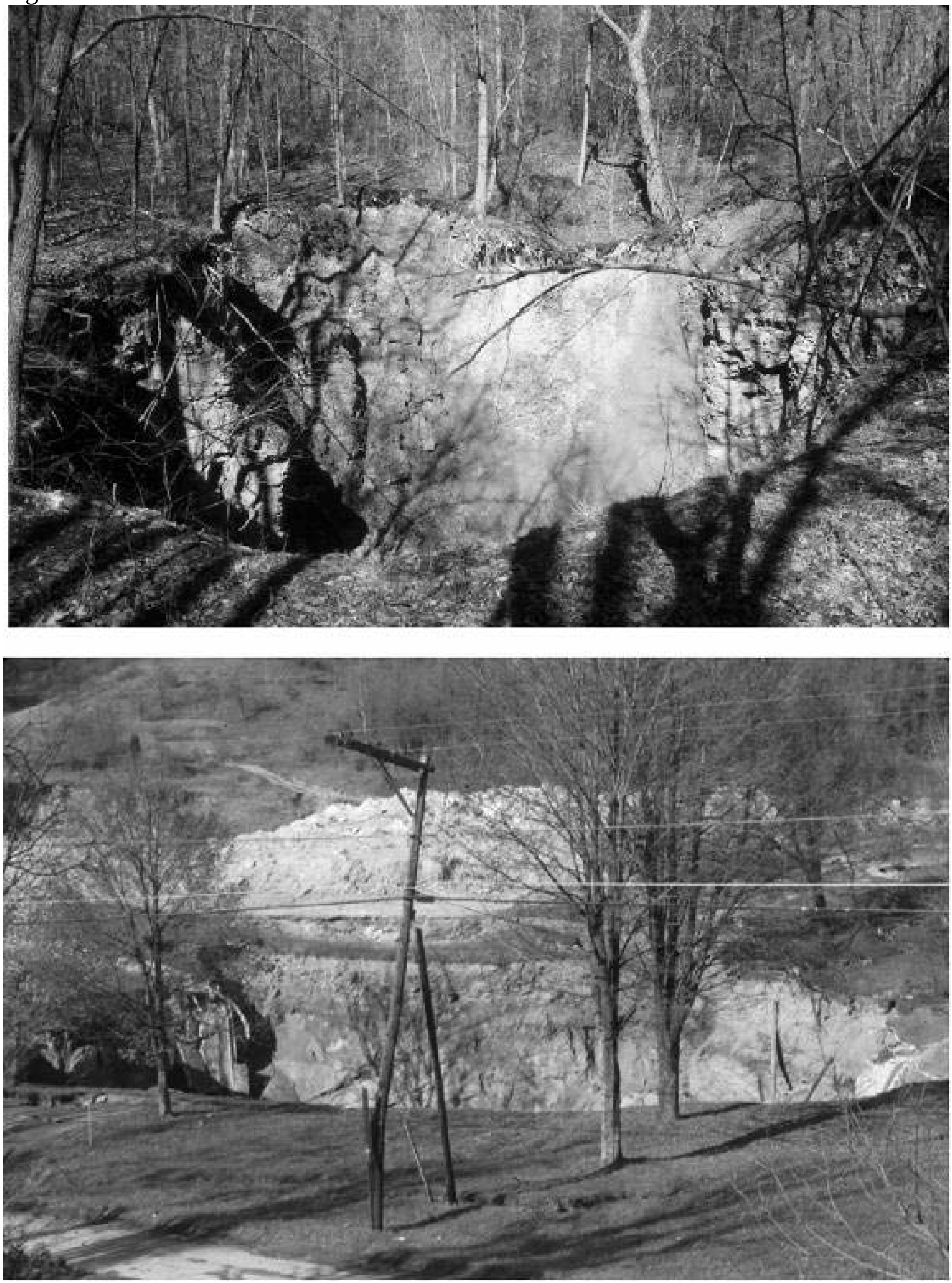
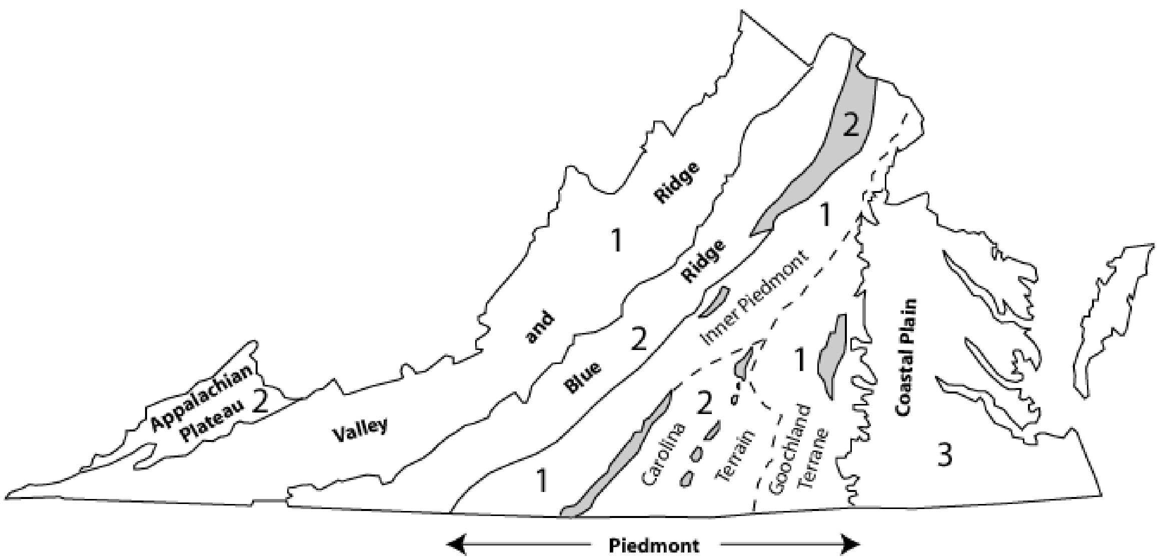


Figure 21.

Figure 22.



END OF FIGURES.