AN EXPERT REPORT ON

GEOLOGIC HAZARDS IN THE KARST REGIONS OF VIRGINIA AND WEST VIRGINIA

Investigations and Analysis Concerning the Proposed Mountain Valley Gas Pipeline

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Executive Summary

The proposed corridor of the Mountain Valley Pipeline (MVP) passes through a significant area of karst as it crosses the mountainous Valley and Ridge Province (the Appalachian Fold Belt) in Summers and Monroe counties, West Virginia and Giles, Craig, Montgomery, and Roanoke counties in Virginia. Karst is a landscape that is formed by the dissolving of bedrock. Severe karst can create hazards for structures that are built on or across it. The environment, both on the surface and in the subsurface, is more easily degraded in karst than in most other terrains. Karst poses severe constraints on engineering, construction, and maintenance of large-scale structures built upon it or across it. Moreover, the karst in this mountainous region is much different than that in other areas. Siting a pipeline through the Appalachian karst poses significantly greater hazards than in karst areas where the terrain has lower topographic relief.

Karst is a critical factor in siting and management of a high-pressure gas pipeline such as the one proposed. However, other potential hazards such as land instability, weak soils, and potential seismicity are also highly significant in this region. When two or more of these elements act together, the resulting environmental threat from the pipeline is compounded and exacerbated.

The conclusion of this report is that the karst and associated hazards constitute a serious incompatibility with the proposed pipeline. The effect of these threats on the emplacement and maintenance of the line, as well as the potential hazards of the line on the natural environment, renders this region as a ‘no-build’ zone for the project.

Report Contents

The first two sections of this report are included as a summary of karst and its occurrence in the central Appalachian region. The first section provides a brief overview of the nature of karst and how it works as a system, including sinkholes, caves, integrated groundwater flow networks, and the inseparable relation between surface water and groundwater. The second section describes attributes of karst specific to the region of concern, namely the geologic fold belt constituting the central Valley and Ridge Province of Virginia and West Virginia.

Environmental issues and concerns relative to the proposed pipeline are identified and discussed in detail in the third section. Groundwater contamination is a concern related to construction of the pipeline as well as to its operation. Sinkhole collapse may occur where groundwater patterns are altered and in fill used in burying the pipe (the process of suffosion). Erosion of denuded land is likely, and steep slopes underlain by weak soils may become unstable and lead to soil creep and landslides. The threat of this hazard is exacerbated within the Giles County Seismic Zone, an area of enhanced seismic risk that is traversed by the propose pipeline. Allogenic water (flowing on impermeable rocks in the uplands before it reaches soluble rock below) as well as relatively pure water originating from ridge crests may be compromised in quantity and quality by the presence of the pipeline before it reaches the karst in the lowlands.

A long corridor, cutting a swath through these sensitive terrains may create extensive zones of land instability, collapse, flooding, siltation, and disruption of natural flow paths of surface and ground water. Caves, some of which have been designated as significant by public agencies and speleological organizations, may be intersected, thus compromising hydrologic and ecologic systems. The most dramatic negative results would occur where two or more hazards act in unison or result in a cascading series of events.

Geologic Hazards

The Mountain Valley Pipeline application is deficient and inadequate because it fails to address significant environmental hazards that would be created by the pipeline, if constructed as proposed. It fails to address geologic hazards that occur within areas in or near the proposed corridor and their potential impacts on the pipeline itself. Geologic hazards that are not adequately addressed by the application include:

- *Groundwater Contamination*: Karst terrains are uniquely vulnerable to augmented groundwater contamination owing to the nature of the groundwater aquifers that form in such areas. Thousands of people living in these potentially impacted areas depend on groundwater to supply their homes. The risk of severe groundwater contamination is increased during construction and may occur should a pipeline rupture in this karst terrain.

- *Vulnerability of Groundwater Recharge:* Allogenic recharge areas (where surface water from steep, upland mountain slopes enters karst aquifers at the base of those slopes) are especially vulnerable to disruption owing to hydrologic alterations that would be caused by the construction of the pipeline.

- *Enhanced Potentials for Surface Collapse:* Construction of the pipeline in mountainous terrain would likely alter hydrologic flows by channelizing subsurface waters. Should the pipeline trench intersect with below-ground karst features, results would include enhanced potential for collapse in the karst.

- *Accelerated Erosion:* Pipeline construction on steep slopes will remove native vegetation, cut into steep slopes, alter soils via compaction, remove surface soil over the pipeline trench and access roads, and will thus create potential for accelerated erosion.

- *Slope Instability:* Unconsolidated geologic material present throughout the area on steep slopes should not be considered as stable. Movement of such materials, especially if stimulated by excess rainfall or by seismic activity, can be expected to threaten the integrity of the proposed pipeline. Over half of the preferred route from Monroe to Roanoke counties has slopes that are 20 percent grade or greater. Almost 20 percent of the slopes along this route are 35 percent grade or greater.

- *Weak Soils:* Even if in the absence of such extreme weather or seismic events, soils on steep slopes can be subject to the slow and persistent downslope movement known as "soil creep". This would threaten the integrity of underground structures such as pipelines, especially where those structures run parallel to a slope. Soils on steep slopes should not be considered as stable. Several soil groups are high in plasticity and shrink-swell characteristic, resulting in poor drainage and low bearing strength that can induce downslope movement.

- *Seismic Risks:* The proposed route of the pipeline passes through an area with a history of severe seismic activity and enhanced seismic risk as determined by recent geophysical studies. A major seismic event would clearly threaten the integrity of the pipeline. However, even moderate seismic activity, in combination with other conditions, such as karst, severe slopes, and weak soils, pose elevated risks. By extension, in karst areas, the quality of groundwater may be threatened as well.

The above hazards occur as a direct result of the terrain typical to the region being traversed by the proposed pipeline corridor. Multiple geologic hazards are inherent to karst in mountainous regions such as that of concern here. Because of their potential to interact synergistically, they cannot be mitigated by engineering practice. For these reasons, large karst systems must be avoided during pipeline construction.

Examples of Geologic Hazards and Potential Interactions

Much of the pipeline corridor would encounter karst as it passes through the area that is the focus of this report. There are many specific locations where karst features are within or perilously close to the corridor. Four specific examples have been selected as important in order to illustrate cumulative environmental hazards that cannot be mitigated through engineering and construction practice:

- **Milepost 181-195 segment, in Monroe County:** The proposed pipeline crosses numerous interacting karst features, including springs providing allogenic recharge, sinkholes, caves, and a sinking stream. Within this segment, the corridor ascends the northern flank of Peters Mountain where it encounters steep slopes and unstable soils in an area of enhanced seismic risk and where numerous springs discharge waters that are essential to residences, community water supplies, and a commercial bottling facility.

- **Milepost 208-210 segment in Giles County:** Dye traces have documented multi-mile groundwater transport through karst aquifers and with extensive caves. The pipeline is proposed to cross Sinking Creek at a point where its waters have begun to descend into subsurface channels, within an area that is well populated, with numerous homes that depend on karst aquifers for household waters. The pipeline is proposed to enter this area after descending a long and steep mountain slope with potentially unstable soils within the Giles County Seismic Zone of enhanced risk from earthquakes.

- **Milepost 213-214 segment in Giles County:** The pipeline is proposed to cross a cave that is approximately 3000 feet in length, contains water, is inhabited by significant biota, has been designated as a cave conservation site, and is near the surface with little overlying bedrock. Furthermore, the proposed corridor crosses over the cave and runs along a slope within potentially unstable soils. This would threaten the integrity of the pipeline if soil slippage were to occur. The site is within the Giles County Seismic Zone.

- **Milepost 220-226 segment in Montgomery County:** The proposed corridor crosses an area known as the "Mt. Tabor Karst Sinkhole Plain" - perhaps the most intensive karst terrain along the entire route, and associated conservation areas. Several dye tracings have documented the interconnected nature of karst areas and caves within this area. Along this segment, the corridor is proposed to pass through two cave conservation areas, a natural area preserve, and a major segment of the karst plain where scores of large, compound sinkholes are present at the surface. As a result, MVP has proposed an alternate corridor for study in this area. However, a greater length of alternate proposed corridor passes through cave conservation areas than would the original proposed corridor. Both proposed corridors pass through the watershed of areas containing sinkholes that have been shown by dye traces to provide discharge into the primary spring of the Mill Creek Springs Natural Area Preserve that discharges into Mill Creek, a tributary of the North Fork of the Roanoke River. This is a short distance upstream from where it serves as habitat for a federally protected fish, the logperch. Furthermore, both proposed corridors pass through steep slopes that would threaten the integrity of the pipeline within a significant cave conservation area. This area is also populated, with numerous homes that draw household waters from karst aquifers and have no access to alternative water supplies.

The above examples were specifically selected for this report to illustrate potential environmental problems along the corridor. There are many other examples of interacting geologic hazards over the entire length of the corridor within karst. This is typical of the entire region.

Conclusions

There are serious problems imposed by geologic and hydrogeologic constraints along the route of the Mountain Valley Pipeline. They fall into two basic categories: (1) the impact of the geologic setting on constructing and safely maintaining the pipeline and (2) the environmental impacts of the pipeline on the land that it would pass through.

As discussed in this report, the predominant geologic aspects are:

- Karst
- Hydrogeology
- Slope Stability
- Soil
- Seismicity

Although each of these five topics has serious specific considerations that have not been addressed by the applicant, the greatest concern is that all five topics are interrelated and are not mutually exclusive. These geologic attributes and the geologic risks are typical to the region and operate as **a system.** Therefore, they should not be merely evaluated on an individual basis.

Siting a pipeline through the Appalachian karst poses significantly greater hazards than in areas where the terrain has much lower topographic relief, and lacks similar geologic hazards. Steep slopes promote a profound influence of the pipeline on soil stability, erosion, and groundwater.

The analysis of this report unequivocally demonstrates that the Mountain Valley Pipeline cannot be safely built through the areas of Monroe, Giles, Montgomery, and Roanoke Counties that are characterized by karst terrain and steep slopes. Doing so would significantly threaten the structural integrity of the pipeline, and the ecological integrity of the surrounding environment. Many of the potential hazards are immitigable; they cannot be adequately circumvented with engineering or construction practices. The same is true should a catastrophic event occur, such as a breach of the pipeline.

Author of This Report

The author, Ernst H. Kastning, PhD, PG, has studied karst for over 50 years throughout the United States and abroad, and he has authored numerous publications on the subject. His primary expertise is karst along the entire Appalachian region extending from Alabama to New England. His résumé is appended to this report.

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Introduction

This report summarizes significant environmental impacts and risks associated with the siting the proposed Mountain Valley Pipeline (MVP) through karst terrain of Giles, Montgomery, Craig, and Roanoke counties in Virginia, Monroe County in West Virginia, and a segment of Summers County that is adjacent to Monroe County in West Virginia. The report is based on an analysis of the proposed route and information submitted to date by MVP and the following agencies: U.S. National Forest Service, Virginia Department of Conservation and Recreation, and Virginia Department of Environmental Quality. Moreover, numerous other documents have been submitted to the Federal Energy Regulatory Commission (FERC) since the announcement of the pipeline proposal. These have been authored by intervenors, local experts, and concerned citizens who have spent countless hours researching, evaluating, and commenting on potential issues brought to light by this project. These contributions and documents have been reviewed and considered in compiling this report.

The scope of this report is to assess impacts of the proposed pipeline from three perspectives: (1) geologic constraints imposed on construction and operation of the pipeline, (2) potential hazards that are posed by the geologic setting on the pipeline if it is built, and (3) potential effects of the pipeline on the natural environment during its construction and operation, especially as those potential effects can be exacerbated by geohazards.

A large part of the MVP would traverse the Appalachian Plateau and Valley and Ridge physiographic provinces. These include some of the most prolific regions of karst in the United States (Davies, 1970; Herak and Stringfield, 1972; Davies and others, 1984; Kastning, 1986; Tobin and Weary, 2004; Palmer, 2007; Weary, 2008; Palmer and Palmer, 2009). The very nature of karst in this mountainous region is much different than that in other areas. Siting a pipeline through the Appalachian karst poses significantly greater hazards than in areas where the terrain has much lower topographic relief. The specifics of these problems are discussed in detail in Sections 2 and 3 of this report.

During the various stages of FERC decision making, it is imperative that geology be a major consideration for the segment of the pipeline that crosses the mountains and valleys of the Appalachian region. The very name “Mountain Valley Pipeline” suggests that this region of major topographic relief is a significant component for the route.

The karst of the counties of West Virginia and Virginia through which the route passes has been mapped at various scales using data developed from field surveys of karst features that are visible from the surface (Miller and Hubbard, 1986; Hubbard, 1988; Kastning and Kastning, 1995). Derivative maps showing the extent of karst-prone rock in these counties in relation to the proposed route of the pipeline are in Appendix B of this report.

Geologic systems, karst included, do not stand alone - they interact. With this in mind, the concerns about karst must be evaluated in context with other geologic processes that interplay. In this report, the effects of hydrogeology (both surface and ground water), slope stability, soils, and seismicity (earthquake potential) are included where they act in unison with karst processes in ways that can, and often do, compound environmental hazards.

As it concerns karst and other geohazards, this report is organized into four sections in order to synthesize the accumulated knowledge of this landscape in the affected region and the considerable information that has been submitted to FERC to date:

> **An overview of karst.** This section includes the definition of karst, principle aspects of karst processes, and a summary of environmental factors and sensitivity typical in karstic landscapes.
>
> **Karst in the central Appalachian region of Virginia and West Virginia.** The emphasis of this section is on karst in the six-county area through which the proposed pipeline route extends.
>
> **Environmental concerns related to the Mountain Valley Pipeline.** This section specifies issues that must be addressed during the deliberative process by FERC.
>
> **Compounded hazards related to karst, slope stability, soils, and earthquakes.** This section emphasizes how geologic factors act in unison or in sequence, compounding hazards along the route, causing higher levels of impact and concern.

Important Notes to the Reader

The first two sections are for the benefit of those readers who may wish to review the meaning of karst and the hydrogeomorphic processes associated with karstic landscapes and processes (especially related to those found in the region of the proposed pipeline). Those who have a good fundamental understanding of karst and its occurrence in the Appalachian Region may wish to proceed to Sections 3 and 4 that directly address potential problems along the MVP corridor.

References are cited in this report in one of two ways. Published literature is cited by author(s) and date and is keyed to a reference list at the end of the report. Relevant unpublished reports, including submittals to FERC, are identified where applicable.

To facilitate a quick perusal or locating key points, some phrases and sentences have been emphasized in **bold font**. This is primarily the case in Sections 3 and 4 that directly address potential hazards along the pipeline corridor.

This study was initiated at the request of individuals and organizations that are local stakeholders in the FERC review process, and would be adversely affected by the eventual outcomes. They include numerous residents, scientists, and citizen groups. Many of the individuals are registered intervenors in this process and have previously contributed findings, data, and interpretations to FERC. A significant amount of this information has been reviewed and compiled in this report. Those sources are acknowledged in the text.

The Tables and Figures cited in this report are located in Appendix B. This is because some of them are referred to often and in different places in the report.

Interactive Maps

It may be very useful for the reader to access and use two interactive map sites that have been created online for those involved with the Mountain Valley Pipeline issue. In both cases one is able to select among types of base maps and layers of data and zoom in or out in order to view levels of detail.

The Mountain Valley Pipeline Exploratory GIS Map is focused on geological hazards in the counties along the entire MVP route, with a focus on Virginia. This tool was created by Drs. Stockton Maxwell and Andrew Foy of the GIS Center, Department of Geospatial Science at Radford University. This map is located online at:

http://www.arcgis.com/apps/MapTools/index.html?appid=bcc1646d43ad4f7fbfd4953b5d722cc7

Another interactive map, primarily focusing on the affected counties of West Virginia, was created by the **Indian Creek Watershed Association** (ICWA). It is located online at:

http://indiancreekwatershedassociation.org/icwa-interactive-environmental-map

Both sites are being revised and updated as necessary by their compilers. It is recommended that the interested reader access these maps while reviewing this report or in future assessments and deliberations regarding potential environmental issues related to the pipeline.

The Author

Ernst H. Kastning, PhD, PG, has studied caves and karst for over 50 years throughout this country and abroad. His primary expertise is karst along the entire Appalachian region extending from Alabama to New England. Over the 31 years when he has lived and worked in Radford, Virginia, he has studied karst processes and environmental problems in counties of the greater New River Valley region and adjacent counties throughout Virginia and West Virginia. His publications on karst number over 100 and many directly address karst processes and environmental impacts in the area affected by the proposed Mountain Valley Pipeline. The author's brief résumé is appended to this report. His most pertinent publications relating to the karst region of this study are cited where appropriate and listed in the References Cited at the end of this report.

Section 1

Overview of Karst

A Working Definition of Karst

Once an obscure term, the word 'karst' is being used more and more by the public and the press, particularly in regions where it is prevalent or in situations where issues involving karst come to the fore, such as in the case of the Mountain Valley Pipeline. The concept of karst is not always an easy one to convey. A number of geological dictionaries and lexicons have defined the term. Moreover, there have been several specialized glossaries of karst that provide definitions of the myriad of features and the terminology that collectively define karst (*e.g.,* Monroe, 1970; Lowe and Waltham, 1995; Field, 2002; Poucher and Copeland, 2006; Palmer, 2007). An essential first step in discussing karst is to agree on its meaning.

A very simple, concise, one-sentence definition that generally suffices is:

Karst is a landscape that is principally formed by the dissolving of bedrock.

For clarity, it is useful to add that karst is characterized by sinkholes, caves, dry valleys (with little or no surficial drainage), sinking streams, springs and seeps, solution valleys, and various forms that are sculpted on the bedrock surface (collectively known as *karren*). Hydrologically, groundwater in karst terrains flows efficiently through openings in the bedrock that have been enlarged by the dissolution process. Surface water is rapidly conveyed underground at zones of *recharge* (typically where water enters sinkholes, soil, and vertical fractures in the bedrock) and then passes through a network of conduits (fractures, partings between beds of rock, and caves). The water eventually emerges at the surface in zones of *discharge* (springs, seeps, and wells). Karst forms in rocks that are soluble to various degrees when in contact with slightly acidic natural water. Commonly, the rocks that are most easily dissolved – to form karst terrain - are carbonate units, such as limestone and dolostone (sedimentary), marble (metamorphic), and sulfate units such as gypsum (sedimentary). Nearly all rocks may be dissolved to some degree. Only minor dissolutional features develop in materials with very low solubility in water, for example, granite, gneiss, sandstone and other silicate rocks. In most cases, these features are insignificant in terms of hydrologic and environmental impact. Most significant areas of karst in the United States are found within outcrops of limestone, dolostone, marble, and gypsum. Limestone and dolostone are the principal karst formers in the area under consideration in this report.

With respect to the history of geology, the study of karst (speleology) is a relatively new and blossoming science that draws largely on the principles of geology, hydrology, and physical geography. A thorough professional understanding of the processes that occur both at the surface and in the underground, and an appreciation for the integrated hydrologic system, necessitates a familiarity with the technical aspects of karst. Today the study of karst is multidisciplinary and quantitative, involving the principles of physics, chemistry, and mathematics. The importance of karst overlaps the biological and anthropological sciences as well. The level and scope of modern karst studies are demonstrated by a proliferation of comprehensive monographs on the subject (notably those of Sweeting, 1973; Ford and Cullingford, 1976; Bögli, 1978; Jennings, 1985; Dreybrodt, 1988; White, 1988; Drew, 1995; Gillieson, 1996; Klimchouk and others, 2000; Gunn, 2004; Palmer, 2007; Ford and Williams, 2007; and White and Culver, 2011). Because the nature and processes of karst are complex, it is highly suggested that persons working with karst consult one or more of these specialized volumes. Additionally, the number of articles in scientific journals and proceedings volumes, and graduate theses on karst has expanded at a phenomenal rate in recent decades.

Requisites for the Development of Karst

Karst describes a three-dimensional landscape with characteristics that are the result of several contributing factors: (a) soluble rock (*e.g.,* most commonly limestone or dolostone), (b) structural controls that have modified the rock (*e.g.,* regional uplift or subsidence, folds, faults, and fractures), (c) chemically aggressive (acidic) circulating water that dissolves the bedrock, (d) porosity and permeability (hydraulic conductivity) that provide openings that allow groundwater to flow and dissolved material to be flushed through the system, (e) places of recharge where water can enter a karstic aquifer (*e.g.,* sinkholes, swallets, sinking streams) and places of discharge where water re-emerges at the surface (springs, seeps), (f) hydraulic gradients that create the potential for water to flow from high elevations through karst features to low elevations, and (g) sufficient time for karst to develop (typically thousands of years). Usually, but not always, there are both visual (surficial) features (*e.g.,* sinkholes, sinking streams, springs) and hidden (subsurficial) features (*e.g.,* caves and other enlarged conduits) in an area of karst. Depending upon local conditions and the size of drainage areas, the scale of karst landforms can range from quite small (*e.g.,* grooves in exposed rock outcrops and other karren) to quite large (*e.g.,* extensive cave systems, sizable sinkholes and clusters of compound sinkholes, and valleys formed by dissolution).

The composition of the rock, along with its porosity, permeability, and thickness of bedding will all affect the rock's susceptibility to be modified by contact with mildly acidic surface or groundwater. These effects will be more pronounced in areas that have significant humidity and precipitation, where topographic relief is high, and where rocks are at or near the Earth's surface. These conditions are prevalent in the Appalachian region and have contributed to the well-developed karst found there.

Recognizing Karst Features on the Surface

Karstic features on the surface can range from the extremely obvious (*e.g.,* large sinkholes, sinking streams, and/or springs), often overlooked features (*e.g.,* small sinkholes or dry valleys), subtle features (*e.g.,* swales), and very small features (*e.g.,* solutional sculpting of rock surfaces such as karren features).

Karst landforms of any size on the surface can sometimes be hidden from the casual observer. Large, dry valleys and solution valleys can inadvertently go unrecognized as karst – proverbially a "one can't see the forest for the trees" symptom. Although they may be obvious on a topographic map or from aerial photographs, especially for those persons familiar with karst, the normal valley shape sometimes disguises the true nature of a solution valley.

In tall, thick forests, tree-coverage may hide even large sinkholes (closed depressions) from being detected with aerial photography or at times while travelling on the surface. Other karstic features are too small to be discovered by aerial photography or illustrated on a topographic map, especially on standard 7.5-minute quadrangles constructed with typical contour intervals of twenty or more feet. In some cases, even smaller contour intervals may not indicate closed depressions. Site visits are mandatory to research a potentially karstic area; one cannot rely solely on sinkholes depicted on a topographic map or mapped with aerial photograph. This is an especially important point for environmental assessments where karst is a factor of risk (Hubbard, 1991). Performing ground truth is the only proven way to detect the presence and abundance of small sinkholes. In the area of concern along the MVP, the proposed corridor crosses numerous places in karst terrain where subtle sinkholes may be the only ones present. Even very small sinkholes are important indicators of karst development, especially where subsurface features (such as caves and other openings) occur. In general, the presence of sinkholes of any size in a soluble rock terrain is an indicator of a subsurface hydrologic karst environment (a network of enlarged openings that have or still do conduct groundwater).

Karstic terrains often have very thin layers of soil overlying them because the soil may be piped away almost as fast as it develops. But this is not always what occurs. For example, where nearby steeply sloping hills drain onto karstic terrain, thick deposits of clay (or other alluvium and/or colluvium) may mantle the karstic landforms, especially in areas with relatively few small fractures in the bedrock. The only discernable evidence of karst may be wet-weather springs or swales (slightly sagging areas, too shallow for most people to refer to them as sinkholes). These slight depressions are sometimes detectable after a heavy rain when water ponds in them briefly or in early spring when the vegetation starts to grow in the swales earlier than on the surrounding area. As the soil is removed from below the vegetative root mat, these areas sag and may eventually collapse into the piping cavities below. Sometimes these collapses occur when farm animals suddenly drop from view while grazing on the greener pastures! Even farm vehicles have been known to suddenly break through a thin soil mat and fall into the cavity beneath.

Sinkholes formed by the physical process of piping (an engineering term; geologists generally name the process ‘suffosion’) are associated with the soil and regolith zone that overlies bedrock. Even though sinkholes may have formed in soft, loose, insoluble materials, they are still considered features of karst. The reason for this is that during the slow process of piping, tiny particles in these horizons tend to move downward into true karstic openings in the underlying bedrock (namely fractures) and be carried away as part of the groundwater flow. Over time cavities grow in the regolith and soil, including upward growth (termed *stoping*), until their thin roofs collapse, forming the sinkholes.

Suffosion (piping) collapses are very common in the karst regions of the Appalachians. It is usually wrong to consider this kind of subsidence to be an insignificant indicator of karst. On the contrary, most of these sinkholes would not have formed if there were no openings in the bedrock beneath to carry off particles.

Wet-weather springs may flow when wetter-than-usual conditions cause a temporarily high water table. A wet-weather spring may represent a former spring that flowed when local base level was at a higher elevation.

Seeps and small gravity springs exist where groundwater flow, generally just below the water table, intersects the natural ground surface. These areas of discharge also occur in outcropping rocks, where water that has been perched on an impermeable bed discharges at the surface where the beds are exposed. Seeps will sometimes develop where quarries, roads, railroad cuts, and other excavations (*e.g.,* for pipelines) cut through a hillside and into the bedrock. Discharge may be significant and result in major springs in some cases where major flow paths are intersected (such as caves having large streams).

All of the above characteristics are found in abundance in the karst landscapes of the Appalachian Valley and Ridge region. It would be very difficult to find a path or corridor for any use (roads, power lines, gas transmission lines) through this fold belt that would totally avoid karst. However, some areas within this region have more intensive karst than others.

Sinkholes as a Measure of Karst

The strongest surficial evidence for the presence of an efficient and well-integrated subsurficial drainage network is where sinkholes have formed at discrete points of recharge. Sinkholes form in response to surficial waters draining through the ground via the easiest pathway toward the local base level. Water does not travel into and through a sinkhole because the sinkhole has pre-existed – rather, as water travels through established zones of weakness (*e.g.,* fractures, faults, or bedding-plane partings), it gradually dissolves the bedrock and carries the solute away to points of discharge on the surface. Thus, sinkholes are formed contemporaneously with active recharge (Kastning and Kastning, 2001). Tiny soil and rock fragments are also piped away, augmenting the development of sinkholes in the process. Thus, dissolutionally enlarged openings (owing to chemical weathering) and mass wasting of soil cover and break up of bedrock (owing to physical weathering) both contribute to form hollowed-out closed topographic depressions that we call sinkholes (and are internationally known as dolines). Sinkholes can be of any size, as large or small as local geologic or other natural conditions and time permit. The shapes of sinkholes or clusters of sinkholes may provide clues to their origins, if they are mapped thoroughly and analyzed carefully (Kastning, 1989b; Kastning and Kastning, 2003). Sinkholes and other surficial karst features are often highly useful in interpreting geologic structure in the subsurface (Kastning and Kastning, 1981). Structural control is crucial in the establishment of hydrologic continuity among surficial features, such as sinkholes and other recharge zones, subsurficial drainage such as caves and other conduits, and discharge zones such as springs or seeps (Kastning, 1999).

Sinkholes are used as measures of karst in many site evaluations. The observed presence of closed depressions in soluble-rock terrain is correctly interpreted as evidence for karstic groundwater flow in the subsurface. These represent places of discrete recharge where water enters the ground at specific points. Conversely, the absence of closed depressions on the surface is too often interpreted as an indicator of poor or no development of karst in the subsurface. The latter view is an erroneous assumption in many karst regions, especially in areas of diffuse recharge where water derived from precipitation percolates uniformly into the ground over an area, perhaps through an overlying insoluble bed (*e.g.,* sandstone) or through a thick mantle of soil and regolith. This can result in a surficial landscape with few if any noticeable sinkholes. Because of that erroneous assumption, small, shallow, and otherwise subtle sinkholes are often omitted from environmental studies and assessment. Even if subtle sinkholes are very numerous (and therefore important indicators of karst), not recognizing them or overlooking them can greatly alter conclusions about the presence and extent of karst in an area or at proposed construction sites.

There are many documented regions of karst where extensively explored and mapped caves lie beneath a surface devoid of sinkholes. **In areas underlain by soluble rock, the absence of sinkholes on the surface cannot be categorically interpreted as the absence of karst.**

Section 2

Karst in the Central Appalachian Region

Introduction

Large, complex karst systems are found extensively in the Valley and Ridge provinces of the Appalachian Plateau and throughout the boundary area straddling Virginia and West Virginia (Davies, 1970; Herak and Stringfield, 1972; Kastning, 1986). The primary belt of karst (*i.e.* the widest outcrops of soluble rock) extends from Mineral, Hampshire, Morgan, Berkeley, and Jefferson counties in northeastern West Virginia, southwestwardly through a double tier of counties along the western margin of Virginia, along its boundaries with West Virginia and Kentucky, to Lee County at the southwestern tip of Virginia at the Tennessee state line. Several narrow strips of karstic rocks in West Virginia parallel the primary belt. These extend from Monongalia and Preston counties in the northern part of the state to the widest of these belts in Pocahontas, Greenbrier, and Monroe counties in the southeast. Altogether, this expansive karst region lies within twenty-five counties in Virginia and eighteen counties in West Virginia, for a total of forty-three counties (Kastning, 1995b; Kastning and Kastning, 1995).

Caves are the best known karst features of this region. Tabulations of the Virginia and West Virginia Speleological surveys (VSS and WVSS, respectively) show that each state has over 4000 documented caves, nearly all of which lie within the area described above. This results in one of the highest densities of cave distribution in the United States. Most of the caves have been described in published compilations (Davies, 1958; Douglas, 1964; Holsinger, 1975). Additional descriptive accounts have appeared in various issues of the *West Virginia Speleological Survey Bulletin*, in guidebooks to previous NSS Conventions and the Eighth International Congress of Speleology (Schleicher, 1970; Virginia Region of the National Speleological Society, 1971; Hempel, 1975; Garton, 1976; Werner, 1981; and Medville and others, 1983), and in newsletters (most notably, *Virginia Cellars* of the VSS and the *West Virginia Caver*). Caves in Virginia that are important geologically, are fragile, contain unique organisms, or are environmentally sensitive have been officially designated as ‘significant’ by the VSS and the Virginia Cave Board, a collegial body of the Department of Conservation and Recreation (Holsinger, (1985). The George Washington and Jefferson National Forest includes a number of significant caves (Kastning and Kastning, 1992b). Thus the cave regions of the Virginias are well known and continue to challenge explorers, geologists, and hydrologists who are probing the physical and chemical processes of cave development and the hydrogeologic aspects of karst aquifers.

The geomorphic process of cave development is inherently complex, but essential for understanding the threat caves pose to the integrity of large high-pressure pipelines, and assessing the safety hazards of the pipeline with respect to communities along the route. This is especially true in the Appalachian fold belt (White and White, 1983; Orndorff, 1995). A comprehensive understanding of the origin of single caves, cave systems, or caves distributed over a large region, requires that all responsible factors are considered. Most important are (1) the lithology, solubility, porosity, and permeability of the host rock, (2) the chemistry of the groundwater and rates of dissolution, (3) the structural setting, (4) the existing topography and evolutionary history of the regional landscape, (5) paleoclimates, and (6) the hydrodynamics of groundwater during speleogenesis (cave and karst formation). Factors and processes important to development of caves and karst in Virginia and West Virginia are outlined in the following sections, with an emphasis on the central Appalachian region.

Karst within the region of this report is discussed in detail in Sections 3 and 4. Maps showing the distribution of soluble rock in this region (likely to have karst) can be found in Appendix B (Figures 1, 2, and 3).

Lithologic Factors

Karsted carbonate rocks that host caves in the central Appalachian region are principally dense, crystalline limestone and dolostone, that occur within three zones that parallel the Appalachian structural trend (Hubbard, 1988; McCue and others, 1939). All of these rocks were deposited during the Paleozoic Era (570 to 245 million years ago). For lithologic descriptions of formations in Virginia and geologic maps of their distribution *see* Butts (1933, 1940), Rader and Evans (1993) and Virginia Division of Mineral Resources (1993). Stratigraphic correlations in Virginia are given in Rader (1982). Detailed descriptions of carbonate rocks in West Virginia and maps showing their distribution are found in McCue and others (1939) and various county reports published by the West Virginia Geological Survey from 1910 to 1940.

Karsted carbonate rocks in the two states occur in three zones as described here. First, the oldest beds, Cambrian and Cambrian-Ordovician in age (570 to 438 million years ago), occur along broad lowlands within the Great Valley, including the Shenandoah Valley of northern Virginia and the eastern panhandle of West Virginia and the southwestern extension of the valley through Virginia. Within the Mountain Valley Pipeline region, these rocks crop out in 46 counties (28 in Virginia and 18 in West Virginia; Kastning and Kastning, 1995). Karst in these rocks is generally mature in its development and the surficial terrain is characterized by sinkholes and lack of perennial drainage in small stream channels. Sinkholes are typically clustered where bedrock of high solubility is exposed or near the surface. In some of the broad valleys, beds of limestone have relatively low dip (0-15 degrees) and sinkholes are thus distributed over wide areas. In northern Virginia, caves of the Shenandoah Valley are small to moderate in length (only a few exceed one mile in length) and typically occupy particular beds of favorable solubility, commonly a single bed. However, **in the southwestern Virginia part of this zone, long caves are more common, with over thirty exceeding one mile in length. Additionally, the number of known caves per county is higher in southwestern Virginia than in the northern part of this zone.**

The second zone of carbonate rocks lies to the west, in the westernmost counties in Virginia and in several counties in West Virginia. These units are middle to late Paleozoic in age, specifically from the Silurian to Devonian periods (438 to 360 million years ago). This zone, which is generally narrower than that of the older carbonates to the east, is comprised of several narrow exposures of limestone and dolostone (Kastning and Kastning, 1995). **These bands run through many counties in West Virginia, including Monroe County. They also traverse parts of Giles and Craig counties in Virginia.** Rocks of this zone have been intensely folded and faulted and steeply dipping beds are common. As in the zone of older rocks to the east, caves in the Silurian-Devonian units are generally confined within particular strata. Caves in these rocks are generally small to moderate in extent when compared with those in the karstic rocks to the east.

In the third zone, further to the west in the Appalachian Plateau of West Virginia, carbonate rocks are younger and are generally Mississippian in age (360 to 320 million years ago). The bedrock in the southern part of this zone is typically subhorizontal, with dips of a few degrees up to 15 degrees. **This explains the relatively broad exposures of carbonates of the Greenbrier Group in Pocahontas, Greenbrier, and Monroe counties of West Virginia. Rocks of this zone are host to the longest caves in the region and some of the longest in the United States. Moreover, the number of long caves per county is considerably higher in these rocks than in units of the other two zones** (Kastning and Kastning, 1995). This is particularly true for Monroe and Greenbrier counties in the central Appalachians.

Structural Control of Caves and Karst

The geologic structure of the cave regions of Virginia and West Virginia is complex. The entire area was subjected to large-scale tectonic stresses accompanying continental collision between the North American and African plates during the middle and late periods of the Paleozoic Era. Compressive forces acting in a northwestern-southeastern direction significantly shortened the crust in the Appalachian region, creating fold belts, extensive thrust faults, and fracture systems that characterize the structure. As a result, the regional strike of sedimentary beds is north-northeast, parallel to the trends of ridges and valleys. Dips are typically steep and at some localities beds may be vertical or overturned.

The Valley and Ridge Province is underlain by numerous parallel folds, many of which terminate to the northeast or southeast as plunging anticlines and synclines. Differential erosion during the late Tertiary and Quaternary periods (last 20 to 30 million years) has produced low valleys bounded by parallel mountain ridges. Under the humid-temperate and periglacial climates prevailing in this region during the late Cenozoic Era, dense, crystalline **limestone and dolostone beds have been significantly lowered through both dissolution and physical erosion, forming the floors of many of the broad valleys.** In contrast, dense, massive, well indurated (particles cemented with silica) sandstone units have resisted erosion and most ridge crests are underlain by these siliceous, relatively insoluble units. Beds of shale are typically exposed along the middle and lower walls of valleys. It is not uncommon for the topography to be inverted with respect to the structure, such as ridges being cored by synclines and valleys developed on anticlines. The valley of Sinking Creek, extending northeast through Giles County from Newport is a noteworthy example of the latter. **The relationship of karst features, such as sinkholes and caves, to exposures of soluble rock and regional bedrock structure (folds and strike-and-dip of bedrock) is easily seen by comparing maps.** For example, these correlations are very evident in Giles County when comparing the maps of Miller and Hubbard (1986) and Schultz and others (1986).

Caves are strongly positioned in conjunction with local structure. Most are located along the lower flanks of folds and beneath the lower slopes of valley sides. Caves are also prevalent

beneath the valley lowlands. Again, this is exemplified in Monroe County, West Virginia, and in Giles and Montgomery counties, Virginia. A fine example is the extensive sinkhole karst of the Mt. Tabor area, northeast of Blacksburg (*see* Sections 3 and 4 of this report)**. Also, a comparison of the locations and distributions of caves and sinkholes** (Miller and Hubbard, 1986) **with the lithology and structure of bedrock within in Giles County** (Schultz and others, 1986**) shows that karst features are strongly clustered and aligned in concordance with the geologic setting.**

Most long passages in caves of the Valley and Ridge Province are oriented along strike and are generally close to horizontal along their lengths. This is characteristic of conduits formed within the shallow-phreatic groundwater zone (Davies, 1960; Ford and Williams, 2007; Palmer, 1975, 1987, 1991; White, 1988). Many of these caves also have dip-oriented conduits and side passages of canyon-like cross sections that serve as tributaries to the strike-oriented master conduits. In most cases, dip-oriented passages convey infiltration from the surface, primarily through sinkholes and fractures, down steep gradients, to master conduits that ultimately carry water along strike to springs.

Faults also are a relevant component of geologic structure. The role of faults in controlling karst development is complex and defies generalization (Kastning, 1977, 1984). In some cases, faults provide zones of high permeability for groundwater flow and dissolutional enlargements of conduits. Under other circumstances, rocks of different lithologies and solubilities are in contact across the fault planes, hindering karstification on the side of the fault where the rocks are less soluble. However, in yet other cases faults have exerted very little influence on caves or surficial karst features. Thrust faults tend to have the greatest effect on karst processes, in many cases simply because they are laterally extensive and the displacements are large, juxtaposing rock units of differing lithologies. Caves may develop adjacent to a thrust surface or along fractures and brecciated material within the fault zone. New River Cave in Giles County, Virginia is a well-known and documented example of control by thrust faulting (Krinitzsky, 1947; Kastning, 1977). **Thrust faults have locally influenced development of passages in caves of the Appalachian Plateau, particularly in the Greenbrier limestones in West Virginia. It is imperative in hydrogeologic assessments that the exact role of faulting during speleogenesis be determined through detailed study at each specific site where faults exist.**

As in all karst regions, joints exert considerable structural control on development of caves and surficial karst features, such as sinkholes. Joints are avenues for the circulation of chemically aggressive groundwater. It follows that joint openings are enlarged as the bedrock on the sides of joints are dissolved. Some joints are initially more open than others and may in a self-ramifying manner enlarge at greater rates than other, less-open fractures nearby.

The degree of openness of fractures and differences in hydraulic gradients along particular conduits typically leads to a dendritic, subsurficial drainage network (Palmer, 1991, 2007). Most of the larger caves in the Appalachian region consist of a contributory network wherein water infiltrating from the surface is concentrated within the karst aquifer through tributary passages that carry discharge to master conduits of flow that in turn convey water to discharge points namely springs.

All of the bedrock in the fold belt is heavily jointed, providing considerable avenues for the circulation of groundwater. Joints commonly occur as sets in the Appalachian region, whereby the strikes of joints cluster within directional intervals. The dominant sets of joints are consistent with the structural fabric of the Appalachians. Most joints are generally parallel to the strike of the bedrock and thereby are also parallel to fold axes and the strike of thrust faults. Usually there are other joints sets that are perpendicular to the primary ones or formed as conjugate pairs, but the extents and densities of these joints are generally less than those of the primary set. Joint sets are most apparent in caves that are maze-like, wherein parallel passages of two or more orientations intersect one another (Palmer, 1975).

Structure has played a significant role in the origin of long caves in Monroe County of West Virginia. Several caves exceed five miles in length. The exposure of carbonate units of the Greenbrier Limestone at the surface is broad owing to relatively little deformation of rocks in comparison to the Valley and Ridge Province to the east. Folds are broad and their limbs have shallow dips. Faulting is relatively minor and thrust sheets, although numerous in some caves, are short and of small displacement.

As mentioned previously, sinkholes and other surficial karst forms are commonly positioned along structural trends, such as along strike within bands of exposed carbonate units and along faults and joints. **Sinkholes are often aligned along narrow outcrops of steeply dipping beds.** Excellent examples of sinkholes aligned along joints in shallow dipping rocks occur in the Elbrook and Conococheague formations in Pulaski County, Virginia, just west of the New River (Kastning, 1988, 1989a). **The Monitor Lineament in Monroe County is easily spotted as a remarkable straight line in aerial imagery. It is a six-mile-long string of sinkholes, likely caused by water flowing along an ancient fracture and slowly dissolving the limestone, resulting in subsidence and collapse** (Lessing and others, 1979; Lessing, 1981; Indian Creek Watershed Association, 2012). **Many sinkholes in the Mt. Tabor Karst Sinkhole Plain of Montgomery County, Virginia are clearly aligned, attesting to the likelihood of extensive groundwater flow paths along conduits in the underlying bedrock.** The latter two examples characterize conditions of concern regarding karst and the proposed pipe line (*see* Section 4 for further clarification).

Hydrogeologic Conditions

Many caves in the Appalachian region of the Virginias formed as part of a mature, well-integrated karstic drainage system. The longer caves consist of tributary passages converging on master conduits and draining to one or just a few outlets (springs). Many caves, originally formed under shallow phreatic conditions, contain active streams today. In some caves water courses follow the pre-existing paleo-drainage; however, in other situations, the present direction of flow may be contrary to former directions. Changes in flow following speleogenesis can be largely explained by subterranean stream piracy, whereby surficial streams suddenly find routes underground (Palmer, 1972). **Sinking creeks are common in the Appalachian karst regions of West Virginia and Virginia. A classic example is Sinking Creek in Giles County. (This would be crossed by the proposed Mountain Valley Pipeline near mile post 210 and is discussed in detail in Sections 3 and 4 of this report.) Saunders and others (1981) studied the**

hydrogeology of Sinking Creek, performing dye-tracing studies (including some of the longest in the state).

In the Appalachian fold belt, surface waters flow from mountain slopes toward base-level streams in valleys, forming regionally extensive, trellis drainage networks. Meteoric (storm) water flows steeply downhill from uplands underlain by relatively impermeable sandstone and shale. Water, that encounters carbonate rock exposed low on the slopes or in the broad lowlands in the valleys, commonly sinks and enters a karstic aquifer. Infiltration is often into a sinkhole where the entire flow of a stream is captured. (Such a discrete point of recharge is often termed a 'swallet.') Excellent examples of this process are found along the lower parts of the northwestern flank of Walker Mountain in Bland County. This site, one of the designated significant karst areas in Virginia, is known as the Skydusky Hollow Karst and contains several of the longest and deepest caves in the state, including the Newberry-Banes Cave System, and Paul Penleys, Spring Hollow, Banes Spring, and Buddy Penleys caves (Holsinger, 1985). A similar situation exists below the southeastern flank of Pearis Mountain in Giles County (*see* map of Miller and Hubbard, 1986). This is known as the Wilburn Valley Karst and includes Starnes, Wilburn Valley, Yer, and other notable caves. This system consists of multiple levels, passages of small cross-section, and numerous pits. This karst area continues to be actively explored and mapped.

There have been some significantly long dye traces in Giles County in addition to those of Saunders and other (1981) mentioned above. One of the longest dye traces within the karst region of Virginia (several miles in length) was performed within the Sugar Run drainage area southwest of Wilburn Valley (Savko, 2001, under the direction of this writer). In this case, flow through one of Virginia's longest caves travels from the headwaters of Sugar Run, following strike around the nose of a plunging anticline (as mapped by Schultz and others, 1986) to emerge at Wabash Springs, one of the highest-discharge springs in the state. **Researchers with the Virginia Karst Project of the Department of Conservation and Recreation placed dyes into some large caves in the headwaters of Clover Hollow. Some of the dye emerged over four miles distant, in the cave streams of Tawneys and Smoke Hole caves. These two caves are adjacent to Sinking Creek (in close proximately to mile post 210 of the proposed Mountain Valley Pipeline).**

The area where the MVP route crosses Sinking Creek (mileposts 210) is one the most significant examples of potential hazards associated with the project. Details of these problems are presented in Sections 3 and 4.

Groundwater of the Mt. Tabor Karst Sinkhole Plain has also been extensively traced with dyes in recent years, including studies by Hayman (1972) and more recently the Virginia Karst Project of the Virginia Department of Conservation and Recreation (Fagan and Orndorff, 2008). These studies reveal a relatively broad and low-lying karst plain exhibiting a well-developed and mature karstic groundwater network. For maps and descriptions, please refer to submissions to FERC by Registered Intervenors Tim Ligon (6 May 2016, submittal 20160506-5059), Louisa Gay (6 Jan 2016, submittal 20160201-5201 FERC) and S. René Hypes of the Virginia Department of Conservation and Recreation (17 March 2016, submittal 20160317-5126).

The area where the Mountain Valley Pipeline route crosses the Mt. Tabor Karst Sinkhole Plain (mileposts* 220 to 226*) is another significant example of potential hazards associated with the

project. Details of the problems associated with the Mt. Tabor Karst Sinkhole Plain are presented in Section 4.

Numerous dye-tracing studies to date, including some of phenomenal length, attest to the development of mature and well-integrated karstic aquifers in the counties of interest in this report, especially Giles, Montgomery, and Monroe counties. If additional dye-trace studies were to be performed in the karst of these counties, the findings would certainly further strengthen the known extent of aquifers.

Considering the extent of the soluble rock exposed at the surface in this region, a major conclusion is that much of the surficial karst (sinkholes, etc.) is tied to underlying extensive networks of groundwater flow (**see** ***maps of soluble rock in Appendix B of this report, Figures 1, 2, and 3) and map of Kastning and Kastning, 1995). Much of the karst of these counties includes large integrated systems and must be treated as such with respect to potential impact of construction and surface modification by the pipeline project.***

Chronology and Sequence of Cave and Karst Development

Groundwater flow that is responsible for the dissolutional excavation of caves in carbonate rocks is guided by the lithostratigraphy (attributes of the host rock such as mineralogic composition, layering, and thickness of beds) and structure of the bedrock as described above. Hydrodynamic factors that force water through fractures and along bedding planes include the degree of porosity and permeability initially inherent in the rock and the secondary changes in these produced during the speleogenetic process. One very important factor is the hydraulic gradient, a measure that drives water through openings and which is derived from a difference in elevation. In general, steep gradients increase the rate of water flow and of dissolution. However, hydraulic gradients are intimately tied to the local relief in topography. The greater the differences in elevations on the surface between zones of recharge of water into an aquifer and zones of discharge of water from the aquifer, the greater the hydraulic gradients in developing conduits. The greatest development of caves occurs just below the potentiometric surface (water table). However, as the ground surface of the Earth is worn down through erosion, the water table drops and, hence, so does the zone of cave development (Palmer, 1987, 1991; White, 1988; Ford and Williams, 2007). As a result, the oldest caves are generally those well above local base level and the youngest are lower and closer to base level.

It is difficult to assess the age of caves, when they began to form, or the rates at which they are excavated by the circulation of water. However, some recent techniques have provided reasonable estimates. Various studies suggest that caves take nearly a million years to form in the greater Appalachian fold belt. Once those results are estimated it is also possible to calculate the rate that the surficial landscape is lowered by erosion.

When water tables drop in response to the lowering of the landscape, caves become air filled. However, most long caves in the Appalachian region have streams in them. This water is making its way from the surface to the present water table or to springs.

Both existing steep hydraulic gradients and active streams within caves are important aspects in assessing potential problems associated with siting a pipeline corridor through the karst of this region. Only sufficient dye-trace studies can properly delineate flow paths of groundwater within or near the proposed pipeline corridor where it crosses carbonate rock.

Section 3

Mountain Valley Pipeline Environmental Concerns

Introduction

To begin, there are three basic tenets when reviewing environmental concerns related to the Mountain Valley Pipeline:

(1) As previously stated, ***karst landscapes are among the most sensitive to environmental degradation. Moreover, these terrains can pose some of the most severe constraints on construction and development.*** This is well demonstrated in the vast literature on applied problems in karst. Often karst is considered a **'no-build'** zone for major construction projects.

(2) Also as previously stated, **the presence of karst features within mountainous landscapes, such as that proposed for MVP, poses challenges and creates hazards that are not present where karst features occur in non-mountainous terrain.** Topography of high relief adds considerably to environmental problems in karst.

(3) ***Areas of karst along the proposed route of the Mountain Valley Pipeline pose some of the most severe challenges and concerns for the MVP project.*** The intensity of karst as a hazard has been largely understated in the Resource Reports of the MVP application and in the Hazards Assessment by Draper Aden Associates, February 16, 2016, submittal 20160226-5404 (31274307).

Potential hazards related to karst are exacerbated when they combine with other hazards, especially soils with low physical integrity, slope stability, and potential for seismic events. MVP documents do not address the sequential or cumulative effects of these hazards. Because this is a highly important aspect of the siting process, these synergetic effects are discussed in detail in Section 4 of this report.

No gas pipeline as large as 42 inches in diameter has been constructed across the Appalachian fold belt. Existing large pipelines run over land to the west and east of these mountains, but not across them. The geologic hazards that are summarized in this report are likely partially responsible for the lack of existing large pipelines across the Appalachian ridges.

Environmental Hazards in the Appalachian Karst

It is important to delineate various environmental problems associated with karst in the Appalachian region. Karst poses environmental concern regardless of where it occurs, whether in this mountainous region or areas of lower topographic relief (Dougherty, 1983). These are discussed below.

The proposed route of the MVP passes through karst in several places. Karst terrain is a significant environmental feature throughout a segment of the project extending from milepost 172 through 234, in Monroe, Giles, Craig, Montgomery and Roanoke counties (*see* for example, Submittal 20151125-5156 to FERC Docket CP16-10, C.E. Zipper and others, "Motion to Intervene and Protest," November 2015). By example, four specific areas in West Virginia and Virginia are of particular concern and are addressed in this section. They are, from northwest to southeast: (1) exposed karst from Little Mountain to Peters Mountain in Monroe County, (2) Sinking Creek at the intersection of Routes 604 (Zells Mill Road) and 700 (Mountain Lake Road) in Giles County, (3) the area of karst at Canoe Cave on Sinking Creek Mountain in Giles County, and (4) the Mt. Tabor Karst Sinkhole Plain, northeast of Blacksburg in Montgomery County. Significant geologic, hydrologic, and environmental problems associated with these are summarized in this section.

Carbonate-rock terrains pose environmental hazards that are unique with respect to the wide spectrum of bedrock types, and karstic landscapes are particularly sensitive to environmental degradation (LeGrand, 1973; White, 1988). Stresses induced by human activity in karstic terrain result in environmental problems that are much more acute than those that would occur in terrains underlain by either crystalline (metamorphic or igneous) or clastic (other sedimentary) rock. Problems such as groundwater supply and quality and land instability abound in the Appalachian region, as they do in most populated karst regions worldwide, especially those in areas of high topographic relief. **The New River Valley Region, which is largely coincident with the area addressed in this report, has historically been one of the most sensitive karst regions within the Valley and Ridge Region (Kastning, 1989a, 1990; Kastning and Kastning, 1998).**

Groundwater Contamination

Sinkholes, abundant features in the karst of the Virginias (Hubbard, 1984), serve as funnels through which surface water readily enters ground and the aquifer. These are viewed as points of discrete recharge. However, even where sinkholes are less evident or non-existent, water can readily drain into subsurface aquifers. In these circumstance it uniformly infiltrates into surficial materials (soil and underlying regolith) and then comes in contact with the underlying soluble rock. This is termed diffuse recharge. Upon contact with the bedrock, water continues to move downward along fractures. Once underground, water freely courses through enlarged conduits, including caves, and eventually emerges at springs and seeps or is pumped to the surface by domestic or other wells. **A karstic groundwater system is a well-connected 'geologic plumbing' network, and groundwater travels through it at rates similar to water traveling in constructed pipes. There is little or no filtration of this water and contaminants may quickly enter existing water supplies.**

The zone between the surface and the bedrock is known as the **epikarst.** This includes the soil, regolith, and the sculpted upper surface of the bedrock. Epikarst is a highly important zone with respect to environmental problems. Pipelines traversing areas underlain by soluble rock (karst terrain) will be largely constructed within the epikarst. In some cases, where the soil and regolith are thin, trenching during construction may also include excavation of the bedrock. **Excavation of bedrock in karst, for example during trenching or quarrying, can be disruptive to groundwater flow and affect both quantity and quality of water** (Kastning, 2008). Soil and regolith above the bedrock is very thin in most places where the proposed MVP corridor crosses karst (*see* submittal 20151130-5432, November 30, 2015, Preserve Giles County, Section 6, especially p, 95, 97-98 via document pagination).

If there is one single environmental issue that stands out in the karst of the Appalachians, it would have to be the sensitivity of the karstic aquifers to groundwater contamination (Kastning, 1988, 1989a, 1990; Kastning and Kastning, 1991; White, 1988). This problem is universal among all karst regions in the United States that underlie areas of economic growth (Aley, 1972; Aley and others, 1972; LeGrand, 1973). Much of the karstic terrain of the Virginias lies in rural regions where environmental impacts are generally limited to those imposed by agricultural practices and highways (Davies, 1970). In some cases, karst lies within the confines of public land (parks, forests, and the like). On the negative side, the region's karstic groundwater problems are increasing with the advent of (1) expanding urbanization, (2) increased usage of environmentally damaging artificial chemicals, (3) shortage of repositories for hazardous wastes (both household and industrial), and (4) ineffective public education concerning waste disposal and the sensitivity of the karstic groundwater system. Urbanization is rapidly encroaching in the region and economic development is resulting in potentially severe karst-related environmental problems. For example, corridors for highways, high-voltage power transmission lines, and gas pipelines have emerged as threats to karst (Werner, 1983; Kastning, 1995a, 1996).

For some time, sinkholes in rural areas were highly susceptible to illegal dumping by landowners or by passersby (Hubbard, 1989; Slipher and Erchul, 1989; Kastning and Kastning, 1992a, 1993). Fortunately, this source of contamination has largely abated as the result of legislation and education. However, sinkholes continue to be infilled with brush and construction debris (generally excavated materials from elsewhere). Some of this has come from construction of corridors such as highways and transmission lines.

Efforts to bring attention to the **sinkhole contamination problem** have been moderately successful (Kastning and Kastning, 1991, 1993, 1994, 2001). Articles in local newspapers, educational materials published by the Virginia Cave Board (a collegial body of the Division of Natural Heritage, Virginia Department of Conservation and Recreation) and other publications have addressed this problem in the Virginias (Hubbard, 1989; Kastning and Kastning, 1990, 1992a, 1995; Zokaites, 1997, Veni and others, 2001).

Sinkholes have been filled with earth materials for the purpose of leveling the land for development. It is important to note that filling a sinkhole with anything is highly undesirable. Sinkholes are natural drains and points of recharge. Filling of sinkholes often leads to undesirable consequences such as groundwater contamination, clogging of natural conduits in the underlying bedrock, flooding on the surface after storms, and suffosion (piping) of the fill which may lead to subsidence or collapse. Emplacement of excavated material onto a karst terrain during the construction of a gas pipeline can lead to blockage of recharge, whether through discrete infiltration into sinkholes or through diffuse infiltration through the overburden.

Fortunately steps have been taken to legally protect the karstic environment in the Appalachian region. For example, both Virginia and West Virginia have enacted state laws that protect caves and their natural contents from vandalism and contamination. The Commonwealth of Virginia has established the Virginia Cave Board as part of the Department of Conservation and Recreation to take up matters relating to caves and karst in the Commonwealth, to advise other agencies, and to participate in education related to caves, cave science, and cave conservation.

An issue of environmental concern is the likelihood that sinkholes would be filled and drainage blocked as a result of installation of the Mountain Valley Pipeline. This can occur during construction wherein excavated material from the pipeline trench or from roads used to install the line will be displaced into nearby sinkholes. Additionally, erosion produced within the corridor may convey debris downslope into sinkholes. Blockage of natural drainage avenue through sinkholes is detrimental to recharge to an underlying aquifer as well as causing contamination of groundwater with sediment and chemicals associated with pipeline construction and maintenance.

The above paragraph expresses concern that sinkholes would be filled. I will note that the "Karst Mitigation Plan" submitted by the Applicant (Resource Report 6, Appendix D, p. 266-284 via document pagination) calls for **"stabilization"** of sinkholes. Although this term is not defined in the document, it may suggest filling.

The risk of **groundwater contamination by natural gas pipelines** is significant and real, despite the fact that methane, a primary constituent of natural gas, is volatile in the ambient environment. Natural gas transported by commercial pipelines includes many other constituents that could be non-volatile, especially in a groundwater environment. These include high-molecular-weight organic compounds that either originate in the geologic reservoirs or form via hydrocarbon synthesis under the high-pressure conditions that occur within the pipeline. As stated by Resource Report 1 in the application, "typical filtration and separation equipment" is planned for each of the proposed compressor stations, indicating that non-gaseous constituents are expected to be present. Commercial pipelines typically specify contractual limits on non-methane content for transportable fluids (*see for example,* FERC Gas Tariffs that are available on the internet for commercial gas-pipeline companies). Such tariffs typically state the expectation that some liquid contents will be included within the transported fluids. They also state non-zero limits for contaminants such as sulfur, oxygen, and water, the presence of which can stimulate hydrocarbon synthesis under high-pressure such as those that occur in pipelines.) Furthermore, solid particles known as **"black powder"** can accumulate in natural gas pipelines, and may contain toxic metals including lead, mercury, and arsenic (*see* submittal 20160512-5183 to FERC Docket CP16-10 by Sierra Club of Virginia, especially the section entitled "Soil and Groundwater Contamination" on pages 10 and 11 via document pagination). **Such particles, if present in a pipeline experiencing rupture, would likely be released along with gaseous and liquid hydrocarbons, and other contaminants, at the point of rupture.**

Collapse and Formation of Sinkholes

The potential for spontaneous or catastrophic subsidence or collapse in the karst regions of the Virginias is low. Nonetheless, **collapses occasionally occur throughout the karst.** Massive collapses in which homes or businesses are swallowed by newly formed sinkholes are rare. The most common causes for catastrophic sinkhole collapse are (1) over pumping of groundwater from karstic aquifers, resulting in a relatively sudden loss of buoyancy that uphold roofs of cavernous openings, (2) sudden or oscillatory changes in the position of the water table due to modifications to surficial runoff and infiltration to the karstic groundwater system, and (3) leaky pipelines, such as water mains or sewer lines. Most collapses occur within the overburden (soil or regolith) and seldom does bedrock fall into underlying voids.

Suffosion (Piping)

Collapse of surficial material in karst is very common in areas of construction, especially where fill is used to level land. There have been countless examples of sinkholes developing in these artificial fills. (This author has personally visited, studied, inventoried, documented, and advised landowners in at least 20 such cases from 1985 to the present.) This includes construction sites for road beds, parking lots, and buildings. It is not uncommon for sinkholes to form after construction and to damage structures built on the fill. The process responsible **(suffosion/piping)** may take years to manifest itself in collapse, but this is always a concern where fill is emplaced upon bedrock that may have openings allowing infiltration (*i.e.* karst).

In areas undergoing development, sinkholes are often viewed as unwanted holes in the ground. If they are filled in to produce level land, the potential for ensuing environmental problems is twofold: First, as stated above, naturally developed paths of infiltration are often blocked, leading to ponding or flooding on the fill. Secondly, over the long run, fill materials drain into the subsurface and settling may occur. These disturbances easily impact any structures built on the fill. Additionally, the increased weight of water, fill, and structures upon the cavernous bedrock could cause catastrophic collapse in the future.

The reason that collapses are more common (and more frequent) in artificial fill than in natural undisturbed settings is easy to understand. When fill is put down it is rarely compacted sufficiently to attain the structural strength and density of nearby natural overburden. Porosity in fill is typically much higher than that of the surrounding undisturbed materials. (*see* Figure 5 in Appendix B). This promotes a higher migration of groundwater through the fill, leading to suffosion and eventual collapse.

Intrinsic to construction of gas pipelines is the process of burying the pipes under fill material that came out of the trench, was cut from the slope, or was brought in with trucks. **Despite the effort to compact fill, the former trench will nonetheless become a zone of enhanced percolation and flow of groundwater.** This can be envisioned as two concentric tubes. The central tube is the gas pipe that carries the product. The outer 'tube' is the surrounding fill. Its outer boundary would be the former walls and floor of the trench. **Therefore, the result would be an outer, annular, artificial pipe that carries groundwater parallel to the gas pipeline.**

As within any aquifer, **discharge is proportional to the hydraulic gradient.** In basic terms this is the slope of the path of flow from high points of recharge down to low points of discharge. The steeper the gradient, the more gravity-induced potential is applied to the flow system. It follows then that the **infilled trench surrounding a pipe on steeper slopes will have a greater discharge than it would on gentler slopes.** By design, the MVP pipeline would in many places be constructed directly up or down steep slopes of the mountains in the region. Therefore, in this case, groundwater flowing in the fill alongside the pipe would likely have a relatively high discharge and velocity of flow. By extension, suffosion and collapse in the fill could ensue, even though this process may take years and go undetected until the surface finally collapses into the growing cavity. **Sudden and unexpected collapse of the material around the pipeline could have profound consequences such as breaks in the line and ensuing cascading calamities (*e.g.*, fire, explosion, and release of toxic gases into the atmosphere and uncontrolled release of pipeline liquids into the groundwater flow system).**

Although large-scale collapse of surficial materials within the study area occurs rarely, the likelihood for karst collapse will increase within the pipeline corridor if the pipeline is constructed. Such increased risk of collapse will occur as a direct result of the construction process. Collapse is a characteristic phenomenon in karst regions where piping (suffosion) is induced by emplacement of artificial fills. Excavation of a trench for a pipeline and subsequent refilling would create subsurface zones with enhanced groundwater flows, with potential to increase rates of underground dissolution at subsurface locations receiving those flows. Underground rock dissolution caused by surface water infiltration is usually undetected until the final roof of an enlarging cavity falls in; such processes could easily and suddenly impact the integrity of the pipe.

Erosion

Erosion of surficial materials may readily ensue when an area is denuded of vegetation. Construction of gas pipelines entails excavation of a trench and subsequent placement of fill once the pipe is laid. It is necessary to construct roads along the line to allow vehicles to service the process and, on very steep slopes, along the tops of ridges to tether heavy equipment used to lay pipe. That too results in significant removal of vegetation and cutting and filling. **In effect there are two adjacent corridors: one for the pipe and one for the road. Erosion becomes a large problem along this rearranged earth material, even if moderate revegetation is carried out.** Unlike other corridors (*e.g.*, highways and some power lines), a gas pipeline would in many places go directly up and down steep mountain sides. The steeper the slope, the greater the tendency is for erosion and the more severe it may become.

To see firsthand the effect of erosion along corridors one need only walk under existing high-voltage power lines in the Appalachia region. Access roads along these lines often exhibit erosion and gouging and typically need to be repaired to be useful.

Sediment from erosion moves downslope and eventually becomes deposited where land levels off at the base of steep slopes. A problem in karst terrains of this region is that they principally exist in relatively low-lying topography, including locations at the bases of slopes.

Sediment contributed from erosion in the uplands can notably impact the karst below by (1) infilling sinkholes and blocking points of discrete recharge, and (2) blanketing an area and hindering diffuse recharge to the underlying karstic aquifer.

There are many areas where the MVP corridor moves off steep mountain slopes and onto lowlands. In many cases the lowlands are soluble rocks that have karst. Hence there is a pronounced concern that erosional debris from the corridors may impact the karst environment, including local aquifers that supply water for consumption or agriculture.

Slope Stability and Potential Seismicity

The potential for downslope movement of surficial material adjacent to the installed pipeline is an important consideration in these counties. **Movement, whether gradual (surficial creep) or catastrophic (landslide, mudslide, rockslide, or debris slide), may place segments of the pipe under lateral pressure and cause displacement.** This is likely if the material in which the line is entrenched is differentially displaced rather than uniformly along the line. Sudden slope failures would cause displacement at specific locations along the pipe, perhaps breaking welds or bending pipe to the point of failure.

It has been suggested that damage from slope failure is less likely where the line is trending directly up or down a slope (in the direction of the maximum component of gravitational force) than where the line runs parallel along a slope and has little change in elevation over that distance. In the latter situation a slide or zone of enhanced creep may put a severe bend in the line, perhaps compromising the seams where pipe segments join. However, in situations where the line is running directly up or down a slope, severe problems with potential failure may still occur, especially if suffosion is occurring. Additionally, steep segments along the line will create other issues related to movement of groundwater alongside the pipe. Determination of slope steepness and properties of soils in the vicinity of the line are crucial in identifying where this may occur. A detailed discussion of this hazard, wherein slope instability, soil character, and possible seismic disturbances can interact in a compound manner, is presented in Section 4.

Maps of slope intensity were produced in April 2016 by Drs. Stockton Maxwell and Andrew Foy of the GIS Center of the Department of Geospatial Science at Radford University. Percent slope (with 100 percent slope being 45 degrees) was calculated for 100 meter by 100 meter quadrats. The map was produced as an ArcGIS product and is available from the Center (http://www.arcgis.com/apps/MapTools/index.html?appid=bcc1646d43ad4f7fbfd4953b5d722cc7).

The New River Valley (NRV) Regional Commission provides area-wide planning for the physical, social, and economic elements of the NRV district (Montgomery, Giles, Pulaski, and Floyd counties and the City of Radford). The Commission produced a Hazard Mitigation Plan for the area that was adopted in 2005 and approved by the Federal Emergency Management Agency (FEMA). It was updated in 2011 (http://nrvrc.org/what-we-do/community-development/2011-hazard-mitigation-plan; *specifically see* Section 4.4, *Geologic Hazards: Landslide, Rockfall, Karst, and Earthquakes*). The purpose of the plan is to recognize potential natural or artificial hazards and provide guidance for implementing responses to disasters. The plan included a **Landslide Rating Map** (*see* Appendix B, Figure 4,). Dr. Chester F. Watts of the Department of

Geology, Radford University, developed that map. This small-scale map shows Giles and Montgomery counties. Factors of safety were calculated over the area and are shown as color coding on the map. The proposed MVP route traverses areas represented by fairly high risk, particularly in Giles and Montgomery counties. This is expected as the highest ridges and greatest relief are in this area. The assumption for this map is that these slides would be induced by severe storms. But, as discussed later in this report, seismic events may also trigger slides. Parameters in the factor of safety equation included slope of the ground surface, total soil thickness, saturated soil thickness, tree root strength, tree surcharge, soil cohesion, effective internal angle of friction, dry-soil unit weight, moist-soil unit weight, saturated-soil unit weight, and water unit weight. ***This hazard plan is very relevant to the pipeline siting process and apparently has not been introduced or referenced by MVP nor by its consultants.***

Soils along the route of the proposed pipeline have been studied by Nan Gray (LPSS), Dr. Steven Hodges, and Meghan Betcher, who have assessed their strength characteristics (*see* Section 4 for this data). Drs. Carl Zipper and Robert Tracy have commented on the seismic (earthquake) potential of the area through information submitted to the Federal Energy Regulatory Commission (FERC). These are submittals 20150223-5031 and 20150401-5083 to Docket PF15-3. Furthermore, the U.S. Forest Service has expressed concerns with seismic risk faced by the proposed routing of the pipeline through the Jefferson National Forest (*see* Submittal 20160311-5013 to Docket CP16-10).

Dr. Richard D. Shingles of Virginia Tech (retired-emeritus), Meghan Betcher, Project Scientist at Downstream Strategies, and Darren Jones, GIS Technician for Roanoke County have compiled tables identifying the most severe slopes and associated soils along the pipeline corridor (Tables 1-A, 1-B, and 2 in Appendix B). The tables were compiled using data from MVP Resource Reports, Appendix 1-J, “Vertical and Lateral Slope Tables,” soil data from the GIS Center of the Department of Geospatial Science at Radford University, and input from regional soil experts Nan Gray and Dr. Steve Hodges. The tables list affected soils and slope angles that are keyed to MVP designated mile indicators. These important data are presented in Section 4.

One of the most active earthquake zones in the mid-Atlantic region is the Giles County Seismic Zone (GCSZ). Bollinger (1981) and Bollinger and Wheeler (1983, 1988) present a detailed analysis of the zone with maps, geologic analysis, and seismic history that includes dates and magnitudes of recorded earthquakes in the area dating back into the late 1800s. The largest earthquake of record in the GCSZ occurred on May 31, 1897 and had an estimated Richter magnitude of 5.8 to 5.9 (Mercalli intensity VIII). It caused considerable damage in Pearisburg and surrounding areas, and it remains the largest documented earthquake in Virginia history (https://www.dmme.virginia.gov/dgmr/majorearthquakes.shtml). A recent peer-reviewed publication in a scientific journal (Biryol and others. 2016) confirms that the term “Giles County Seismic Zone” remains in scientific use, and that the GCSZ continues to be an area with enhanced seismic risk (see Figure 6, Appendix B)

Biryol and others (2016) describe the GCSZ as a “prominent, densely clustered seismic zone” that “is associated with the reactivation of normal faults in the old crystalline basement”. The GCSZ is represented by these investigators as seismically active in their Figures 9 and 10 (not shown here). The activity is being driven by underlying asthenospheric movement. (The asthenosphere is the upper layer of the earth's mantle, which lies below the lithosphere). Statements in the MVP application assert that the GCSZ is not a "significant seismic source zone."

MVP Resource Report 6, section 6.6.1.3, should be considered as non-credible by FERC based on the fact that the 1897 earthquake did occur. If the GCSZ is not a "significant seismic source", how would the applicant explain the origin of the 1897 earthquake? FERC should consider the GCSZ as a zone of enhanced seismic risk, which is consistent with an extensive record of peer-reviewed and published work (Bollinger, 1981; Bollinger and Wheeler, 1983, 1988; Bollinger; Biryol and others, 2016).

The preferred route of MVP passes through the center of the Giles County Seismic Zone as discussed in Section 4 and shown in Figure 6 (Appendix B). **Should a potential magnitude 4 to 6 earthquake occur once the pipeline is operational, there may well be a triggering of landslides on unstable or metastable slopes that could potentially disrupt the pipeline and cause significant collateral damage. Perhaps the pipeline itself may be directly broken by ground motion during an earthquake.**

It is clear that steep mountain slopes in the area of Monroe, Giles, Montgomery, Craig, and Roanoke counties are subject to mass movement including large landslides. Seismicity and severe runoff from storms have triggered these events in the past and can easily do so in the future. Earthquakes do not necessarily have to be large to do damage to the pipeline. Small events can easily trigger mass movement on metastable slopes. The Mountain Valley Pipeline would be most subject to these hazards in the many areas having steep slopes.

Ancillary Environmental Concerns Along the Pipeline Corridor

There are some other considerations relative to karst in the area under consideration. They concern the natural processes and relate to environmental hazards that are germane to siting a gas pipeline.

Valley-Train Aquifers and Allogenic Recharge to Karst

The term ***'allogenic recharge'*** describes the influx of surface water derived from a mountainside into an aquifer at a lower elevation. Allogenic recharge of karst aquifers is common in Monroe, Giles, Craig, Montgomery, and Roanoke counties as a direct result of the geologic structure of the area, where dense and weather-resistant sandstone tends to form ridgetops. Water originating here, and in other upland slopes, drains into lower-lying terrains that are often underlain by carbonate rock (limestone and dolostone) where karst is typically developed.

In conjunction with the previous comments on surficial processes, erosion, and groundwater contamination, there is another aquifer-related aspect found along mountain fronts, upslope from the valley lowlands. Unconsolidated material on the mountain slopes is extensive and much of this material occupies streambeds in smaller valleys that are cut into the slopes and flow directly downhill into the broader valleys where they become tributaries to the major streams in the lowlands. **These smaller tributary streams flowing off higher elevations, and the larger**

streams in the valleys, collectively form the rectilinear (lattice) drainage patterns that are characteristic of the Valley and Ridge Province.

Sedimentary material, such as alluvium and colluvium, found in the beds of the valley-side streams, are collectively known as **valley-train deposits**. Water flowing within these deposits is typically perched on underlying impermeable bedrock such as dense, crystalline sandstone in the highest elevations or shale further down the mountainsides. Therefore, water is unable to percolate further into the subsurface.

The importance of groundwater within valley-train deposits is often overlooked or not recognized at all. This is because most people in this region live in the low-lying valleys where the topography is gentle, and fewer homes exist in the steeper, higher elevations. Yet there are places where potable water is obtained from springs issuing from alluvium and colluvium in the streambeds. Contamination and disruption of these smaller, linearly confined aquifers can severely impact vital water supplies (Kastning and Watts, 1997).

Valleys with tributary streams flowing straight downhill to base level are visible all along the mountain fronts. Water flowing in valley-train deposits is often pirated directly into the bedrock where these small streams meet the soluble rock on the lower flanks of the mountains or in the valley bottoms. The point of recharge is often a well-defined sinkhole, pit, or other opening very near the contact of the carbonate rock with the insoluble rock upslope. Therefore, in the Valley and Ridge Province, **allogenic water from the uplands significantly recharges karst in the lowlands.**

Allogenic water derived from upland slopes should be viewed as an integral part of the overall drainage basin that contributes to a karst aquifer. Flow of storm water is very intense and rapid in steep allogenic streams. Thus, any events that alter the quantity and/or quality of water in the valley-train deposits will also rapidly impact that of the water entering a karst aquifer.

Herein lies another important concern about pipeline corridors that may be constructed through the Appalachian fold belt. What happens upstream may have significant consequences downstream. Any activity associated with construction and maintenance of a corridor in the uplands may cause ancillary problems in the lowlands. For example, **if the proposed pipeline were to significantly disturb valley-train deposits and their included water, this would impact the receiving aquifers downstream, including those developed in karst. Such occurrence may also impact users who obtain water directly from springs in the alluvium and colluvium in the upland streams. Negative effects would include reduced flow to springs, siltation, and contamination of the water supply.**

To reiterate, allogenic water, flowing from insoluble rock in the uplands, enters karst aquifers upon making contact with an outcrop of soluble rock. Upstream allogenic zones are important components of recharge for nearly all karst aquifers in this region. Documents submitted to FERC by Mountain Valley Pipeline and Draper Aden Associates do not address allogenic recharge. This is a major omission because allogenic recharge supplies drinking water for homes in karst areas. If constructed, the pipeline would not only directly impact water resources on and within karst terrains, it would also disturb the sources of allogenic water. Much of the

proposed pipeline corridor is sited in zones where allogenic recharge to karst aquifers is prevalent.

Importance of Establishing Protective Buffer Zones in Karst

A major consideration in protecting natural water supplies is the protection of contributing sources - the "upstream" areas of the flow system (Kastning and Kastning, 1997; Kastning, 2000). For surficial streams such protection entails environmental management of all tributaries within the catchment area (drainage basin). In groundwater-protection strategies, attention is usually focused on all zones that contribute recharge.

Recharge zones in karst vary considerably within a continuum. On one end of the spectrum is *diffuse recharge,* whereby water infiltrates through the soil zone or other overburden to the interface with the bedrock. Under these conditions, recharge occurs over a wide geographic area. At the other end of the spectrum is *discrete discharge,* a process whereby water enters the bedrock in distinct places. Sinkholes are excellent examples of discrete recharge. Some sinkholes take the full discharge of one or more surface streams; these locations are termed *swallets*.

As mentioned in the previous section, allogenic water is often derived from large contributing drainage areas or watersheds on upland slopes. In effect, if upstream areas contribute significant recharge to karst aquifers, they are inherently part of the greater aquifer system. If the contributing areas are subjected to construction impacts, buffer zones should be required to prevent contamination of groundwater through natural filtration. A buffer zone is an area that is identified as having significant impact on the main resource. **In general, buffer zones incorporate most of the drainage area that contributes recharge and that can be environmentally degraded through poor land-use practices.**

It is evident from the foregoing that in the case of sinkholes or sinkhole clusters, buffer zones may have to be one or more orders of magnitude larger than the size of sinkholes as indicated on a map or by other means (Kastning and Kastning, 1997; Kastning, 2000). The determination of the size of a buffer zone is based on any of several criteria: (1) the boundary of the drainage basin that contributes recharge to a sinkhole or a cluster of sinkholes, (2) the area within the contributing basin that is under potential development, (3) the natural settings, including topography, geologic parameters such as bedrock and structure, and vegetative cover, (4) inherent storm-water hydrological responses, and (5) proximity of land-use activities within the basin that may impact recharge at sinkholes and discharge at springs.

Virginia requires that resource protection areas (RPAs) be designated for land development around streams. This is required in the eastern part of the Commonwealth, and stream-buffer ordinances are in effect in various counties. Engineering criteria are available for stream buffers. Implicitly, buffers around recharge zones in karst serve a similar purpose in protecting recharge areas.

If it is known that a karst system is very extensive (often based on dye-trace studies) and that it is sensitive (*e.g.,* having rare or endangered species), it should be required that the entire area be protected with a buffer zone.

Karst terrains require special consideration for environmental protection. Environmentally sound engineering often requires that areas of karst be sufficiently delineated. This is especially true where recharge zones must be protected from contaminants introduced at the surface that may be readily conveyed into underlying aquifers discretely through infiltration at sinkholes or diffusely along dissolutionally widened fractures.

In the case of the Mountain Valley Pipeline, it is imperative to delineate buffer zones in areas of karst where it is known that there are a high densities of sinkholes, extensive mapped caves, long groundwater flow paths documented by dye-tracing, and significant allogenic recharge. Those areas include (but are not limited to): the Indian Creek to Peters Mountain area of Monroe County, the Canoe Cave area in Giles County, and the Mt. Tabor Karst Sinkhole Plain of Montgomery County, and the Elliston Karst Plain in eastern Montgomery and western Roanoke counties (discussed further in Section 4). Buffer zones would be intended to define areas that should be protected from pipeline development, especially where there are potential impacts to sensitive features within karst. Unfortunately, the MVP application routes the proposed pipeline through areas where potential impact to sensitive karst is likely. Documents submitted by Mountain Valley Pipeline and its consultants have not adequately considered buffer zones.

Water Originating Along the Eastern Continental Divide

Because water on the land surface sheds from the highest places downhill to the lowest places, the first and cleanest water comes from the uplands. Meteoric water (derived from precipitation – for example rain or snowmelt) will flow down each side of the dividing ridge. **The Eastern Continental Watershed Divide** represents an upland in the eastern United States and would be crossed by the proposed pipeline route. The Divide and adjacent ridges are sources for much of the water that flows eastward on the surface and through the subsurface from the mountain crests to the Chesapeake Bay and Atlantic Ocean. The divide also contributes water to streams that flow westward via the Ohio and Mississippi rivers to the Gulf of Mexico. Clean water in the uplands of the Appalachian Mountains is of prime concern owing to its importance as a water source, and it must remain clean. As this water subsequently enters allogenic zones, epikarst, and karst aquifers as recharge, its quality must be maintained. Both the contributing upland watersheds and the highly sensitive karst aquifers in the lowlands must be avoided by large-scale construction projects such as the Mountain Valley Pipeline.

The purity of upland water needs to be maintained. The Mountain Valley Pipeline and its consultants have not addressed this issue.

Impact of Corridors in Karst

Consideration of corridors is one of the most important aspects in addressing potential hazards posed by the MVP project. Pipelines, by their very nature, occupy corridors that cut across the landscape. In general corridors disrupt the natural environment by dissecting (partitioning) the landscape. This is important in karst as well as in all other types of terrain.

The United States is laced with several types of corridors, including those constructed for transportation (highways and railroad lines), those that transmit electrical energy (high-voltage power lines), and those constructed to transmit fluids (water, oil, natural gas). **Because about 20 percent of the land area in the United States is underlain by soluble rock, many corridors cross karst terrain** (Kastning, 1995a, 1996). **However, to date, nearly all existing natural-gas pipelines that cross karst do so in areas of low relief (low to moderate slopes).**

Corridors differ from other types of construction in one major way - they are narrow and linear. They transect the landscape, whereas buildings and similar constructs are site-specific, occupying sites that are compact in area and do not extend disproportionately far in a linear or curvilinear fashion. Corridors that pass through karst regions cut swaths across the landscape that are hundreds of feet wide. The MVP corridor would be a 50-foot-wide right of way and a construction corridor of 125 feet across. This could be wider on steep slopes.

In the case of highways and railroads, corridors are constructed with relatively gentle grades, generally less than a few percent or a few degrees in slope angle (maximum of 10 percent grade in most cases). This is necessary for efficient and safe movement of vehicles. **Corridors for power lines and pipelines are not so constrained and are often constructed over steep slopes, especially in order to shorten the route.** The movement of fluids in pipelines consumes considerable energy and requires compressor stations along the way. To minimize the expenditure of energy for transmission and also to minimize the costs of construction, design plans often call for the shortest route. However, costs of compressor stations or added costs for constructing on steep slopes are factors in the selection of routes. If the shortest routes are desired in the Appalachian Mountains, then steep ascents and descents would prevail over routes in lowlands and river valleys.

Areas of high relief and steeply sloping topography are not conducive for residential, commercial, industrial, or agricultural use and remain largely undeveloped. For this reason alone, **natural surroundings happen to be best preserved where slopes are steep. It follows that large areas of land may remain contiguous and natural landscapes and ecosystems within these tracts are preserved intact and safe from development.** However, transmission corridors cut across these areas, resulting in partitioning and fragmentation of natural areas.

Caves and other karst features occur in areas of steep slopes as well as in areas of lesser slopes. For this reason, karst landscapes are affected by corridors of all types and configurations. One of the principal environmental concerns in the selection of routes for the Mountain Valley Pipeline is the impact of karst. As previously discussed, the direction of groundwater flow in karstic aquifers is strongly governed by the structure of the bedrock. In most cases, flow is along the strike of the bedrock. This is particularly true in folded rocks such as those in the Appalachian

Mountain region. Fractures, caves, and sinkholes, as well as the axes of mountain ranges and intervening valleys, are commonly oriented parallel to the structural axes (*i.e.* along strike). This gives both the topography and the karst a hydrologic "grain," so to speak. **Hence, surface water and groundwater generally flows with the grain and less commonly across it. Transverse corridors, cutting across the grain, may lead to partitioning of flow systems** (*see* later discussion). **Additionally, longitudinal corridors that align along the grain may be positioned over karst for long distances, increasing the potential for harm of the underlying aquifers.** Other factors, such as slope stability and erosion of surficial materials, also become considerations. ***For these reasons, there is not a preferred direction for a pipeline corridor across mountainous karst.*** The compound effects of hazards in mountainous karst terrains is discussed more detail in Section 4.

There are five general types of environmental and construction problems associated with karst terrain and each is an important consideration in siting corridors (Kastning, 1995a, 1996): (1) land instability and collapse, (2) flooding and siltation, (3) groundwater contamination, (4) destruction of caves or their contents, and (5) disruption of hydrologic flow paths. They are addressed further here with respect to corridors, such as those of the proposed Mountain Valley Pipeline.

Instability and collapse.

In some localities, karst terrains may be inherently unstable and prone to unexpected collapse of bedrock. Sinkholes (dolines) forming upon catastrophic **collapse of a dissolution void (*e.g.,* cave)** in the natural environment of this region are relatively rare. However, if trenching for a pipeline were to remove enough bedrock above such a cavity, collapse of a thinned bedrock roof may be triggered during construction, or it may spontaneously occur at a later time, perhaps severely damaging the pipeline. Moreover, the weight of a pipe and its contents may be enough to collapse a thin roof span that has marginal stability.

As mentioned elsewhere, **suffosion of fill material around a pipeline** (*i.e.* development of cavities in the fill as particles are sapped downward into karstic openings by groundwater) is also likely cause stability problems and collapse. This may occur years after installation of a pipeline, as the sapping of particles and enlargement of a cavity in the fill material is a slow, but steady process.

Often the surface of soluble rock beneath the soil and regolith is pitted, with cutters (typically well etched and dissolutionally widened fractures) and grikes (intervening blades of bedrock separating cutters). Pinnacles (grikes) of bedrock under a pipe may lead to bending of the pipe as it sags into the space between pinnacles (cutters). Therefore, an uneven bedrock surface beneath an entrenched pipe may lead to differential subsidence, and thereby to deformation and failure of the pipe.

Flooding and siltation

Closed depressions, such as sinkholes, have no natural surficial outlets for excess meteoric water (derived from precipitation). Under normal conditions, sinkholes drain to the subsurface at rates sufficient to allow the recharge water to efficiently percolate into the underlying aquifer. However, at times the bottoms of sinkholes become silted and wholly or partially plugged. This may cause sinkholes to periodically flood under storm conditions. Siltation is often caused by erosion brought on by improper land use adjacent to sinkholes. **Disruption of the surficial topography, clear-cutting, and removal of vegetation along corridors often lead to flooding and siltation in sinkholes** unless proper mitigating measures are implemented.

Pipeline corridors are kept relatively clear of vegetation. Access roads leading to the corridors and also running parallel to the pipelines for maintenance are also devegetated. Both of these components augment erosion and, when corridors are located within or topographically above karst in mountainous terrain, it is likely that the sediment thus derived may be washed into sinkholes, causing siltation and flooding.

Contamination of groundwater.

Accidental spills along a pipeline may occur during construction or maintenance. Of course, if an active line ruptures, the products may easily enter groundwater, including that in karst. **Hydrocarbon compounds** released from gas pipeline ruptures may be carcinogenic.

Destruction of caves or their contents.

Corridors may intersect caves, especially during the excavation of a trench. Occasionally, small caves are totally obliterated. In other situations, new artificial entrances may be added to caves during excavation. Aside from the degradation or elimination of the aesthetic character of a cave (*e.g.,* broken speleothems), there may also be subtle, yet significant, damage to delicate cave ecosystems. In some cases, the effects may be catastrophic. Globally rare or endangered fauna may be threatened or killed. For example**, in the Mt. Tabor Karst Sinkhole Plain, cave conservation areas have been delimited in order to protect rare troglobitic species known to inhabit some of the caves. In some cases, archeological sites in caves may be disturbed.**

Disruption of hydrologic flow paths.

Corridors, once in place and during the construction phase, have the potential to significantly alter the direction of water flow and to disrupt zones of recharge and discharge, particularly in karstic aquifers (Figures 5A and 5B). **Transverse corridors,** cutting across the hydrologic and structural grain, may not only partition the surface environment when such previously contiguous and undeveloped areas are segmented, but may do likewise to flow networks for surface water and groundwater. Partitioning of aquifers occurs (1) where flow paths are interrupted by excavation or (2) where infilling occurs during construction of corridors or after subsequent erosion and siltation. This may be an issue in the **Mt. Tabor Karst Sinkhole Plain** where dye traces have shown multiple flow paths. Another highly significant example of disruption of groundwater flow occurs where the line is routed across **Sinking Creek in Giles County** (MVP milepost 210). Both of these locations are discussed in detail in Section 4. The region between Fort Lewis Mountain and Poor Mountain in Roanoke County is underlain by karst *(see* Appendix B, Figure 9). Entrenchment of a pipeline may affect the **Elliston-Lafayette Karst Plain** and water provided by the Spring Hollow Reservoir.

Derangement of drainage networks brought on by corridors can result in severe imbalances in the water budget, and thereby critical lowering of water levels in wells or reduction of discharge through flow systems, including caves. Blockage of natural flow paths could cause back flooding upstream of the blockage. Alteration and derangement of flow paths can readily impact existing water supplies and can change the hydrologic character of caves, severely affecting the growth of speleothems or disrupting delicate biological ecosystems. Unfortunately, once corridors are in place, these effects may not be easily detected from the surface and it may be too late to correct any harm that may have been done. Canoe Cave in Giles County (Appendix B, Figure 7), Slussers Chapel Cave, and others in the Mt. Tabor Karst Sinkhole Plain (Appendix B, Figure 8) are among those of particular concern (*see* discussion in Section 4). Caves and springs along the corridor in Monroe County, between mileposts 181-187 and 194-195, as well as caves in the Ripplemead area in Giles County may also be impacted in this way.

Partitioning of the natural environment

Broad corridors result in dividing natural areas into smaller tracts (Figure 5C). This can severely impact the biological realm. Some land animals may not travel or migrate across a cleared zone and their normal movement may become curtailed or altered, decreasing the diversity of species within smaller tracks. Conversely, newly created open space may provide avenues for undesirable invasive species (animals or plants) to invade an area. Further discussion on partitioning (fragmenting) topic is found in Appendix A.

Partitioning may also disrupt aquatic and terrestrial species that inhabit caves. Some species are globally rare or threatened (including examples in the Mt. Tabor Karst Sinkhole Plain). These species have been identified and listed by the Natural Heritage Program of the Virginia Department of Conservation and Recreation (DCR) which maintains an extensive database of such organisms. S. René Hypes of DCR, in her letter of May 17, 2016 to FERC (20160317-5126(31318143)), identifies some of the species of crucial concern. Avenues of natural migration of animals through caves in a karst aquifer may be severely altered through partitioning by a pipeline corridor. To ensure that this would not occur would require intensive additional study in specific caves and karst areas, including biological inventories.

A Recent Bellwether of Potential Gas Pipeline Problems in the Region

It is instructive here to refer to a recent gas-pipeline incident in the region of interest regarding the threat of groundwater contamination:

In 2014, **Columbia Gas of Virginia (CGV)** installed a 16-mile long, 8-to-10-inch-diameter pipeline from Peterstown, West Virginia, over Peters Mountain to the Celanese Acetate Plant in Narrows, in western Giles County, Virginia. This line was installed to bring natural gas to the Celanese plant. It was buried in a trench excavated through karst over a recharge area that supplies water to a spring that is used as a water supply by the **Red Sulphur Public Service District** (RSPSD) in Peterstown, West Virginia. In 2015 the Dominion Pipeline Monitoring Coalition (DPMC) registered a formal complaint to the Virginia Department of Environmental Quality (DEQ) regarding several serious issues arising from the new pipeline. These included erosion and sedimentation issues and contamination of groundwater of the RSPSD water supply by diesel fuel from heavy machinery involved in the construction process (*see* Complaint and Request for Compliance Enforcement letter from DPMC to DEQ, dated November 11, 2015). DEQ had inspected the sites in April and May of 2015 and listed several non-compliance citations on the part of CGV with respect to the Celanese pipeline (*see* letter from Robert J. Weld to Rick Webb, dated December 22, 2015). The citations include (1) failure to properly install and maintain sediment control structures, (2) failure to identify and protect sensitive environmental features, and (3) failure to preserve watershed hydrologic function through the development and implementation of a storm-water management plan. Slope stability was also found to be a contributing factor. More recently, additional comments on the CGV Celanese pipeline were submitted by Louisa Gay to FERC, in a letter dated June 20, 2016, addressing how these problems can be extended to other sensitive areas along the route, including the Mt. Tabor Karst Sinkhole Plain.

The CGV Celanese pipeline is a 10-inch-diameter pipe. (CGV is interested in upgrading this to a 12-nch pipe). The problems associated with the pipe installed in 2014 were manifested within a year, and caused a lengthy shutdown of the RSPSD water treatment plant, considerable public outcry, and attention in the media. **The hazardous situations that ensued with this relatively small gas line, as bad as they were, would pale in comparison in magnitude with similar hazards associated with a 42-inch pipeline.** The diameter of a 42-inch pipe is 4.2 times that of a 10-inch pipe, and the cross-sectional area of a 42-inch pipe is 17.6 times that of a 10-inch pipe. It follows that **environmental problems or catastrophic failure of a 42-inch pipe would be at least an order of magnitude larger those corresponding to a failure of a 10-inch pipe. All of this is exacerbated by the long distance that these lines extend over the mountainous and high relief of the Appalachian fold belt in this region.**

Summary

The potential problems discussed in this section regarding pipelines and their corridors as they cross karst landscapes are paramount considerations that must be addressed. Much of the foregoing topics has not been adequately addressed (or in some cases not at all) in the documents submitted by Mountain Valley Pipeline or its consultants in the application process.

Section 4

Compound Effects of Geologic Hazards:
With Significant Examples Along the Pipeline Corridor

Introduction

Any one of the individual hazards discussed to this point is of high concern in ascertaining the viability of an environmentally safe natural-gas pipeline in the Appalachian Valley and Ridge Province. However, karst processes (both on or below the surface), slope stability, soils, surface hydrology, severe weather, seismicity, and natural habitats are interrelated into a natural system. Similarly, the hazards discussed in Section 3 rarely operate alone in this region. Two or more can act simultaneously or they may occur sequentially as a cascading series of events. In fact, one hazard may induce another. (For example, an earthquake may trigger a landslide that, in turn, may block and disrupt a stream.) This section explores potential compounded effects along the pipeline corridor in detail.

Karst is an important environmental consideration in its own right over much of the proposed pipeline route through these counties. However, in most cases, the karst environment can be impacted by changes in its upstream recharge zone, movement of eroded or landslide induced material onto the karst from above, contamination of surface streams that provide recharge to underlying aquifers, and other events. The specific sites discussed in detail below illustrate compound hazards.

The documents submitted by MVP and its consultants in general do not address the aggregate effects of multiple hazards. By addressing hazards individually, combined effects of interrelated simultaneous or cascading events are overlooked. In most cases a hazardous condition or event will be complex, with multiple components. It is imperative that a potentially threatening project such as this maximum-size, highly pressured natural gas pipeline be analyzed systematically based upon compounded potential hazards. The four selected sites discussed later in this section illustrate the need for this approach.

Potential Slope Failure Along the Proposed MVP Corridor, Compounded by Soil Character and Seismicity

> The following discussion has been adapted from material compiled by Richard D. Shingles, Ph.D. with major contributions from Meghan Betcher (Project Scientist at Downstream Strategies), Nan Gray (Licensed Professional Soil Scientist), Darren Jones (GIS Technician for Roanoke County), Carl E. Zipper, Ph.D. and Steven C. Hodges, Ph.D. (Professors, Crop and Soil Environmental Science, Virginia Tech), Robert J. Tracy, Ph.D. (Professor of Geosciences, Virginia Tech), and Alfred M. Ziegler, Ph.D. (Professor Emeritus of Geology, University of Chicago)

An important aspect of geologic hazards along the proposed corridor of the Mountain Valley Pipeline (MVP) is the compound effect of slopes, soils, and potential earthquakes (seismicity). The following is a summary of parameters that impose these hazards along the corridor in Monroe County, West Virginia, and Giles, Craig, Montgomery, and Roanoke counties in Virginia.

Steep slopes are presented first, in relation to soil characteristics that could exacerbate slope failure. Tables of slopes and soil conditions (Appendix B) list these relationships and are keyed to MVP designated mileposts. The seismicity of the area is then summarized. A seismic event could trigger slope failure, especially after soils and vegetation have been disturbed or removed during construction. However, slopes may be unstable or metastable and failure could be triggered by other contributing factors such as severe storms and precipitation or erosion that lessens slope stability. Soils on unstable slopes can also exhibit a form of slow and persistent movement known as ‘soil creep’ that can exert significant effects over time.

The dictionary definition of **“soil creep”** describes a well-documented phenomenon, *i.e.* “slow down-slope movement of earth materials under the influence of gravitation.” Soil creep has been documented to occur in steep-slope terrain by numerous studies and is endemic to Giles County owing to the abundance of shrink-swell soils (*e.g.,* Young, 1960; Yamada, 1999; Oehm and Hallet, 2005).

Steep Slopes

The path of the MVP corridor through Monroe County crosses successive valleys and ridges - characterized by steep slopes (Table 1A, Appendix B, compiled by Meghan Betcher) and karst terrain. Streams, springs, and groundwater in this region provide drinking water to the population of the county, both through private springs and wells and by public drinking-water providers. The construction of the MVP would pose a significant threat to water supplies for a large number of the residents of this and neighboring counties.

The MVP is projected to cross several **“zones of critical concern” (ZCC)** - defined as “a section of corridor along streams within a watershed that warrants detailed scrutiny owing to its proximity to a zone of recharge and susceptibility to potential contaminants." Among the most susceptible in Monroe County are the Big Bend Public Service District (PSD) and Red Sulphur PSD.

The preferred route crosses the ZCC for the **Big Bend PSD** in at least two locations within the county, at Mileposts 175.71-176.06, where slopes are greater than 30 percent with an average maximum vertical slope of 62 percent for approximately one mile.

A significant part of the ZCC for the **Red Sulphur PSD** lies within an area of karst. The proposed route crosses through this ZCC at least three times and runs along a ridge of Little Mountain where slopes average over 40 percent for more than a mile. The extent of the projected MVP that descends on the west slope of Peters Mountain, in the headwaters of the Red Sulphur PSD, traverses slopes greater than 40 percent for nearly a mile. Construction in this area in 2014 for the Celanese 10-inch Natural Gas pipeline in Giles County resulted in significant turbidity in the Red Sulphur PSD, that has since adversely impacted the drinking-water quality. This PSD serves 4,000 households and is supplied by a groundwater well and spring located in karst terrain. A diesel-fuel spill in this right-of-way resulted in a two-week shutdown of the PSD in July, 2015. (See "Watch group files complaint over Columbia gas pipeline project", http://www.newsleader.com/story/news/local/2015/11/12/pipeline-watch-group-files-complaint/75647890/). These problems resulted in considerable controversy and press coverage, leading to investigation and suggested corrective measures that were imposed by the Virginia Department of Environmental Quality. Additional concerns about this situation are presented Section 3.

In addition to impacts to public drinking water systems, many **private drinking water sources** may be impacted by the MVP in this area. A large part of the rural population obtains drinking water from private springs and wells, many of which are located on the steep slopes of Monroe County and fed by waters from within the karst aquifer. These private water sources are at risk from adverse changes in water quality and quantity owing to disruption of flow patterns.

Table 1-B (Appendix B, compiled by Richard D. Shingles and Darren Jones) shows the most severe slopes along the proposed route from Giles County through Roanoke County. The proposed MVP descends from Peters Mountain into Giles County and runs southeastward for about 15 miles across ridges and valleys to Newport, at the eastern end of the county. There it turns northeast, running along the northwestern flank of Sinking Creek Mountain into Craig County and then crosses Sinking Creek Mountain and runs southeast again, over Brush Mountain, and into the Mt. Tabor Karst Sinkhole Plain in Montgomery County. Table 1B (Appendix B) includes twelve areas along the MVP route along the west-east route where the maximum slope averages over 40 percent. Seven of these most severe slopes extend for approximately one mile each. One of the steep zones is at the three-way intersection of Mountain Lake Road, Zells Mill Road, and Sinking Creek (within 300 feet of the Link Covered Bridge, near MVP milepost 210). Another steep zone is above Canoe Cave and related karst features there.

In summary, over half (53.5 percent) of the preferred route from Monroe to Roanoke counties has slopes that are 20 percent grade or greater. Over one-third (36 percent) of the slopes that exceed 20 percent grade are 35 percent grade or greater, requiring "special engineering techniques" according to MVP. Thus 19 percent of the slopes along this route are over 35 percent in grade, creating very serious construction problems that in turn would

enhance the likelihood of both erosion and slides on slopes.

Soils

The possibility of significant erosion problems, and ensuing slides following construction, is greatly enhanced by a preponderance of the **active shrink-swell soils with significant plasticity**: Carbo, Faywood, Frederick, Nolochucky, Poplimento and Sequoia. Additionally, these soils have **poor drainage** and hence, **low bearing strength** that would enhance sliding on steep slopes. Table 2 (Appendix B, created by Dr. Steven Hodges) lists soils that contribute to slope stability and their key attributes. These pose severe engineering challenges. The construction of the MVP on slopes of 35 percent or higher will require extraordinary techniques, where machines for excavating trenches and laying pipe are attached by cable to heavier equipment atop ridges. This would result in considerable additional clearing of ridge tops and slopes. Soils of poor bearing strength would become loaded with the force of heavy machinery. Indeed, the weight and vibrations of heavy machinery atop ridges covered with these soils, and supporting other heavy machinery, can push saturated cohesive soils over and down ridges (*see* drainage and hydrology ratings in the tables). Thus, ironically, **the extraordinary solution that MVP plans to use for laying pipe on very steep slopes would compound the engineering problems and threaten the integrity of the pipeline.**

It is interesting to note that Giles County is blanketed with slip-swell soils, far more than any of the other counties along the route (compare Tables 2 and 3, Appendix B). It also has more areas of karst (approximately 80 percent of its land area) and is very close to the center of the Giles County Seismic Zone. **Giles County alone would severely impede construction and maintenance of a safe and viable gas pipeline.**

Bedrock

Data in Tables 1 and 2 (Appendix B) underestimate a likely potential cumulative threat. Further hazards occur in sites with relatively undisturbed thin surface soils and regolith. **The extraordinary engineering techniques of MVP would disturb the subsoil, break its structure, expose the subsoil to rainfall and erosion, and compact soils during reclamation.** If the native surface soils are unsuitable, the disturbed soil will very likely be much more so. Depth-to-rock ratings are included in Table 2 because some of the severe ratings result from shallow soil depth. One reason why Giles County has not become highly developed is that steep slopes covered in fragile soils are highly prone to slope slides. The unstable character of these mountain slopes is evidenced by well-documented, extensive and large, historic landslides along the southeastern flank of Sinking Creek Mountain (Schultz, 1986,1993; Schultz and Southworth, 1989; United States Forest Service, 2000; Whisonant and others, 1991). Such slopes will not be able to bear the load that MVP is planning to impose.

Based on depth-to-rock associated with predominant soils along the MVP route, extensive blasting will likely be necessary. Blasting will occur in areas of sink holes, springs, and wells. The extent of karst underlying these soils, especially in the vicinity of the karst systems associated with Pig Hole, Echols, Smokehole, Tawney's and Canoe caves and the extensive Clover Hollow karst system along Zells Mill Road, presents significant threats to both residential water sources and to the structural integrity of a large, high-pressure pipeline.

Based on their soil studies, Nan Gray and Steven Hodges judge this region as a **no-build zone for the pipeline**. Upon a close reading and scrutiny of MVP Resource Report 7-Soils (Appendices 7-A1, 7-A2, 7B, 7C, 7D and Table 7.2-4), Gray observes that the contractors for assessing soils along the route "report the dangers of the route in significant detail." The details indicate **approximately 60 percent of the route through West Virginia and Virginia is in karst and/or shrink-swell soils, making it unsafe and unsuitable for the type of construction** proposed in the application. (*see* Review of Resource Report 7 in the Motion to Intervene and Protest (Docket CP16-10-000) submitted by Preserve Giles County (20151201-5127).

Giles County Seismic Zone

The Giles County Seismic Zone (GCSZ) further complicates hazards along the proposed MVP corridor. At Pearisburg, the county seat of Giles County, the planned MVP route passes a very short distance from the center of the active Giles County Seismic Zone (GCSZ; *see* map of Figures 6A and 6B in Appendix B). The Virginia Department of Mines, Minerals and Energy (DMME) has designated the GCSZ as a "Seismic Hazard" (DMME. Mapping Seismic Hazards in Virginia. http://dmme.virginia.gov/ DGMR/EQHazardMapping.shtml). The agency web site reports, "Most earthquakes in Virginia are not associated with a known fault, but occur within three distinct seismic zones…," one of which is the otherwise well-documented Giles County Seismic Zone. This zone was not recognized in the MVP resource reports depicting seismic zones in relation to the proposed pipeline. The GCSZ does not appear in Figure 6.1 of Appendix 6-D of their report on geologic hazards. The source of this map was likely a smaller-scale map of seismicity in the entire United States on which the GCSZ did not appear owing to resolution considerations of the map. Nonetheless, omission of the GCSZ is serious because seismicity provides a significant threat along the pipeline route.

Bollinger (1981) and Bollinger and Wheeler (1983, 1988) have described the GCSZ in considerable technical detail. In their recent peer-reviewed paper, Biryol and others (2016) provide a new and major understanding of seismicity in the southeastern United States, including the GCSZ. They confirm that the term "Giles County Seismic Zone" remains in scientific use, and the GCSZ is considered to be an area with enhanced seismic risk. Dr. A.M. Ziegler, Professor Emeritus of Geology from the University of Chicago, in his letter of November 25, 2015, provides further comment on the GCZS, including reference to mapping of the zone by DMME (Figure 6).

MVP Resource Report 6 (Geology) acknowledges that the GCSZ is "primarily known for being the epicenter of a strong May 31,1897 earthquake that was subsequently characterized under modern standards of MM-VIII, magnitude 5.8." MVP dismisses a recurrence of such an event during the life of the pipeline as being exceedingly small. However, the March 9, 2016 letter from U.S. Forest Service to the FERC challenges this conclusion, requesting a more rigorous study of the GCSZ. This letter references pertinent publications, including findings indicating that ridgetop amplification of ground shaking of approximately 0.12 G from seismic activity may have been responsible for massive slope slides along Sinking Creek Mountain, reported by Whisonant and others (1991). **These findings forecast the potential for future seismically induced slides on steep slopes in the area.**

The U.S. Forest Service letter cites research by Schultz (1993) that "shows that the rock block slides (along Seeking Creek Mountain) may have been emplaced as a single catastrophic event of short duration." Schultz and Southworth (1989) state: '**The apparent clustering of large landslides near the Giles County, Virginia seismic zone suggests that seismic shaking may have been an important triggering mechanism**."

An important understanding of the effects of earthquakes in the vicinity of the proposed pipeline needs to be emphasized. **Even though a very-high-magnitude earthquake (Richter magnitude 5.0 or greater) has not occurred in the GCSZ since 1897, the more time that elapses, the more likely it is that such event may occur.** This is simply a basic tenet of magnitude-frequency analysis of natural events (such as earthquakes, volcanic eruptions, floods, storms). The recurrence interval for a 5.0 earthquake in the GCSZ is not well determined, yet the possibility exists that one can occur at any time.

The probability of the catastrophic 1897 re-occurring is unknown and *that* is a problem. However, catastrophic seismic activity - like the 5.8 magnitude quake of 1897 in Giles and 2011 in Mineral, Virginia (less than 200 miles from Giles County) are not the only or primary concern. Of equal importance for a 42-inch high-pressure gas pipeline in this area are frequent moderate earthquakes. Bollinger and Wheeler (1983) report nine earthquakes in or near Giles County over a 22-year period (1959-1981), the largest of which was mb = 4.6. MVP Resource Report 6, (Table 6.4-1) indicates a 4.3 GCSZ quake in 1974 and five additional earthquakes of a magnitude of 4.0 or greater within 100 miles of the MVP pipeline for the period 1976-2006. On the basis of these reports, ground shaking of the magnitude 4.0 or higher is highly likely during the planned life time of the pipeline. Given the history of slope slides in Giles County, there should be genuine concern that the combination of steep slopes, poor soils and moderate ground shaking could contribute to an *immitigable* failure with catastrophic consequences. Emergency response time, let alone mitigation, would be moot. This is a major concern that has not been adequately addressed in the MVP resource reports.

Therefore, continuing seismic activity in the GCSZ (a high frequency of magnitude 2.5 or larger earthquakes), produces a major risk when compounded with the already co-existing problems of karst, slope, and soil hazards at sensitive locations along the proposed pipeline route. This poses severe engineering challenges in constructing the pipeline, and calls into question whether the pipeline should be built at all.

Compounding of hazards along the preferred route alone suggests that avoidance of the region altogether is in the best interest of MVP and FERC, and certainly to the overwhelming majority of residents of Giles and adjacent counties. Many of the residents submitted comments to FERC, demonstrating their anguish over the very real threat to water supplies in karst and the possibility of a catastrophic pipeline failure.

With or without a significant seismic event, slope failure is in itself a significant continuing concern. In commenting to FERC on March 30, 2015, Dr. Robert Tracy (Professor of Geosciences at Virginia Tech) states: “Even holding constant the seismic hazards, along the MVP route most subject to seismic activity, there is a very high probably of differential slope failure, with slide masses moving at differential rates with abrupt boundaries (effectively soil faults) separating masses.”

Four Examples of Compounded Geologic Hazards Along the Corridor

The foregoing discussions illustrates the most important concerns related to the proposed pipeline. Four sites along the route have been selected for elaboration in order to describe how hazards indeed do interact in this region. This by no means implies that these are the only areas of potential problems along the route as there are many more along the preferred route, such as in the vicinity of Ripplemead and Pembroke in Giles County (MVP mileposts 200-205), Pig Hole Cave area on the southwestern flank of Salt Pond Mountain in Giles County (MVP mileposts 207-209), and the karst plain near Elliston and Lafayette in eastern Montgomery County and western Roanoke County (MVP mileposts 230-240; *see* Appendix B, Figure 9). Compounded hazards also exist along the various alternative MVP routes. In some specific places perhaps only one or two of the hazards may be dominant. In all of the following cases, the severity of the hazards is significant and should not be ignored. It is important that all contributing potential hazards along every mile of the pipeline route, and their cumulative impact be taken into account during FERC deliberation process. Interacting, compound hazards are particularly troublesome and must be considered together as this may cause greater damage and dangers than would occur if they occurred individually.

Karst from Indian Creek to Peters Mountain, Monroe County

Monroe County, West Virginia is well-known for a large number of caves, some of which are extensive (Hempel, 1975). Indeed, it is home to extensive areas of karst (*see* Appendix B, Maps 1 and 3). The proposed Mountain Valley Pipeline poses some significant concerns where it passes through the county.

The significant areas of potential problems associated with karst have been identified in letters and depositions by citizens and experts in Monroe County. Among those who submitted comments to FERC include, Dr. Alfred F. Ziegler (Professor Emeritus of Geology, University of Chicago, and resident of the county), Dr. Paula C. Dodds (Licensed Professional Geologist, Laurel Mountain Preservation Association), Harold ‘Rocky’ Parsons (geologist, expert on karst, member of the Monroe County Planning Commission), and Judy Azulay and Nancy Bouldin (members of the Indian Creek Watershed Association (ICWA). It is highly recommended that their input be considered. It is also instructive to consult the Karst Hydrology Atlas of West Virginia (Jones, 1997) for an overview of extensive dye traces performed in that state over the years.

There are several areas of karst where the pipeline could inflict significant potential environmental impact. Some of those are outlined here – the details are in the reports listed by the people above. Of particular interest are the letters from the Indian Creek Watershed Association of October 14, 2015 and November 13, 2015. The letters from Parsons, dated June 6 and November 26, 2015, provide additional information.

Of particular concern are karst features close to where the proposed corridor crosses Indian Creek near Greenville (MVP mileposts 181-182). Indian Creek, which drains significant karst to the east, flows directly into the New River to the west. Surface water and water in the underlying karstic aquifer would be at risk from the pipeline.

Another area of concern lies along Ellison Ridge and in the Hans Creek Valley (MVP mileposts 182-187). Numerous springs are located in this vicinity. Hans Creek is a sinking stream. Considerable recharge enters the underlying aquifer at its insurgence and emerges 0.3 mile downstream. There are numerous subtle karst features, mostly sinkholes, that indicate that this is an important recharge zone.

Numerous karst features occur between Little Mountain and Peters Mountain (MVP mileposts 194-195). As reported in the above cited letters to FERC from the Indian Creek Watershed Association, there are several caves, sinkholes, and a sinking stream in the karst that would be crossed by the pipeline at this locality. There are many springs along Peters Creek Mountain that provide water for all three of the water districts in the county, serving up to 70 percent of the households, public schools, and other users. One of the most at risk is the Red Sulphur Public Service District. Sweet Springs Valley Water Bottling Company, an award-winning water bottling company, derives water from these springs.

As with other mountain ridges along the pipeline corridor, there is significant allogenic recharge to karst aquifers from upland, non-carbonate terrains in this part of West Virginia. The karst aquifers identified above receive considerable recharge from allogenic sources. Hence, watershed delineation and establishment of buffer zones are critical in addressing impacts.

Slope stability and seismicity are ‘red flags’ in the Indian Creek to Peters Mountain section of the corridor. As seen in the data in Table 1-A (Appendix B), average maximum slopes are in excess of 40 percent. The likelihood of mass movement, including slides, is present along this segment of the corridor, leading to potential problems of slope stability as outlined in this Section of the report.

This part of Monroe County also lies within the Giles County Seismic Zone (*see* Appendix B, Figure 6A). Dr. Alfred M. Zeigler comments:

> “The U.S. Geological Survey (Bulletin. 1839-E) reports that there was a ‘landslide of considerable proportions’ also reported at the time, on the face of Wolf Creek Mountain in Giles Co. The authors of this bulletin, published in 1990, searched for surface expression of ‘neotectonic’ features, such as recently active faults, without success, but did report ‘a giant rock-slide complex on Sinking Creek Mountain,’ also in Giles County, and [hypothesized] that it had been caused by seismic shaking, as had the ‘numerous other rock

> falls and slides in the area.' They also implied that crustal warping might be indicated by variations in the elevation of terraces along the New River. Of course, a major rock-slide would completely disrupt a pipeline and this prospect would be worse than crossing a fault. This is because a fault is a known quantity with a known location and sense of movement, and could probably be allowed for by the pipeline engineers. The location of rock-slides, however, would differ each time and the effects could not be allowed for, even if they could be predicted.

In summary, the karst areas in Monroe County, where the proposed pipeline is routed, are subject to the compound hazard conditions that are described earlier in the section. This includes all of the concerns about karst as well as hydrogeology, slope stability, soil strength, and seismicity.

Sinking Creek Along Zells Mill Road, Giles County

Perhaps the most perplexing juxtaposition of the Mountain Valley Pipeline with the geologic and hydrologic settings is at MVP mileposts 208 to 210, where the proposed corridor would come down Salt Pond Mountain and cross Sinking Creek in Giles County (*see* Appendix B, Maps 1 and 2). This results in a situation in which the complexities result in a proverbial 'weak link' along the route of the pipeline.

First, the area comprised of the flanks of Salt Pond Mountain and Sinking Creek at its base include one of the most significant areas of karst in the county. The caves at the upstream reaches of Clover Hollow (including Clover Hollow and Stay High caves) have water that has been dye-traced to flow to two other significant caves along Sinking Creek, Smokehole and Tawneys caves (Fagan and Orndorff, 2008). The latter caves are less than 0.2 mile from MVP milepost 210, where the pipeline would cross Sinking Creek. This is one of the longest dye-traces performed in Virginia to date (on the order of four miles in straight-line distance). Another one of the longest traces in this vicinity, from where Sinking Creek crosses U.S. Route 460 to the New River, was performed by Saunders and others (1981). Dye placed in Sinking Creek near Smokehole and Tawneys caves emerged at a spring along the New River, over seven miles distant. This information leads to a clear conclusion that **this is an area of extensive and well-integrated flow networks in the subsurface. Hence constructing a pipeline across this area would risk contamination of sizable karst aquifers.**

Even though Sinking Creek at this intersection with Mountain Lake and Zells Mill roads has perennial flow, it is in this reach that a substantial part of the streamflow sinks into its bed and into the soluble bedrock beneath. From here to its confluence with the New River, Sinking Creek continues to lose flow and late in some years the surficial streambed is entirely dry and all of the water is in its subsurficial route.

It is likely that where the MVP would cross Sinking Creek (milepost 210), some of the sinking water is running beneath the stream bed and that it would not be flowing deeply in the karst. Should MVP select to drill a horizontal hole beneath Sinking Creek for the pipe at this intersection, there would be an immitigable problem with groundwater. Such a horizontally drilled hole would undoubtedly intersect the path of water flow in the bedrock beneath the creek. This would interrupt the natural subsurface flow, influencing groundwater resources supplying numerous homes. This placement, within a zone of active and sustained groundwater flow, would also cause unwanted future problems with the pipe, in an aqueous groundwater environment.

Any other choice for a pipe of this size crossing Sinking Creek is also untenable. It would then have to be placed above the stream in some fashion, perhaps suspended on a bridge-like structure. Diverting the flow of Sinking Creek in some way would also not be possible, given the perennial subsurface component of the stream and well-documented frequent flooding of the streambed in response to significant storm and snowmelt runoff.

Groundwater problems constitute only one of the severe challenges at this site. From the data on slopes (*see* above) and slope maps, it can readily be seen that the corridor would descend very steeply from the flanks of Salt Pond Mountain to where it would meet Sinking Creek. The slope here is nearly 55 percent (Table 1-B) and the soils (namely a very rocky Carbo, the most active and problematic of the shrink-swell clays) have poor strength (Table 2). Thus slope stability, owing to the combination of a severe slope and the worst slip soil, is a critical issue at this location. This, in addition to close proximity to the center of the Giles County Seismic Zone (Appendix B, Figure 6A) could induce landslides on metastable slopes. Thus, the Route 700 – Route 604 intersection is one of the worst locations for a large high-pressure pipeline.

So, as with the previous case in Monroe County, **the Sinking Creek site is not suitable for the pipeline.** Crossing Sinking Creek over a reach where it is losing water to the subsurface is a very poor choice. Hydrologic conditions, whether on the surface or in the subsurface would severely impact construction and contribute to degradation of the pipe once it is in place. Also, should a failure in the pipeline occur at Sinking Creek, contaminants would follow the established routes of infiltration and be introduced into the extensive groundwater system of Sinking Creek extending all of the way to the New River (as determined by the dye traces by Saunders and others (1981). Moreover, a pipeline failure would severely impact residents drawing water from wells. Apparently MVP was not aware of these highly important constraints imposed by Sinking Creek. **This location is obviously a 'no-build' option.**

Canoe Cave and Karst, Giles County

The proposed route of the Mountain Valley Pipeline appears to go right over Canoe Cave, located along the northwestern flank of Sinking Creek Mountain in Giles County (*see* Appendix B, map of Figure 7). The cave lies beneath the centerline of the proposed MVP corridor between mile posts 213 and 214. At approximately 3000 feet in length, the cave has water and significant biota (letter from S. René Hypes of the Virginia Department of Conservation to FERC dated March 17, 2016).

Although Canoe Cave is still being explored and surveyed, it and its environs have been designated as a cave conservation site by the Virginia Cave Board and the Virginia Speleological Survey. These organizations maintain a list of significant caves and karst areas (Holsinger, 1985). The list is periodically brought up to date to include discoveries of new caves, new passages in caves, or new significant and sensitive findings within caves.

The entrance to the cave is located about 3500 feet downslope from the crest of Sinking Creek Mountain. This is a fine example of a major cave located below a zone of allogenic recharge from which it derives its water (see previous discussion above). In fact, springs in the colluvium above the cave are reportedly being used as water supplies. Water from this zone enters the soluble rock in the vicinity of Canoe Cave and it is likely that the water encountered in the cave is from a swallet just east of the cave entrance that takes allogenic water from above. Both this swallet and the cave entrance are within a few feet of the center line of the proposed pipeline. In places Canoe Cave is very near the surface, with little overlying bedrock. There is a spring further downslope that may be the exit from water in the cave. This is well illustrated in Figure 7 (Appendix B) and discussion of the Hypes letter referred to above.

Canoe Cave, the colluvial material, swallet, and spring together constitute a hydrologic groundwater system. Steep slopes Frederick soil series at this location indicate that the material above and over the cave is prone to significant mass movement (*see* Table 2, Appendix B and discussion above in this section). If the pipeline is constructed, this location could be highly problematic (1) should a severe rainfall event occur and enable downslope soil movement, (2) should a sizable earthquake occur (the area is in close proximity to the Giles County Seismic Zone), or (3) should slow and persistent downslope soil movement (soil creep) deform the pipe. Any of these may be sufficient to cause rupture.

Mt. Tabor Karst Sinkhole Plain and Associated Areas, Montgomery County

Arguably the most significant area of karst in the path of the proposed MVP pipeline is the broad lowland area of exposed carbonate rock that constitutes the Mt. Tabor Karst Sinkhole Plain. It is located northeast of Blacksburg in a residential area along Mt. Tabor Road. The proposed MVP pipeline traverses the karst plain for four miles, from mile post 220 to mile post 226 (*see* Appendix B, Figures 1, 2, and 8). The area is well documented in maps that have been submitted by various individuals and groups. Letters submitted to FERC by S. René Hypes (April 6, 2015; March 17, 2016; May 20, 2016), Louisa Gay (January 6, 2016), and Tim Ligon (December 7, 2015) are among those especially informative and provide detailed information showing sinkholes, dye traces, and the proposed route of the pipeline. It is important to note that the Virginia Department of Conservation and Recreation, the Virginia Cave Board, and the Virginia Speleological Survey have delimited two cave conservation sites that are traversed by the proposed corridor: Slussers Chapel Cave Conservation Site and Old Mill Conservation Site. The proposed routes of the pipeline, shown on the aforementioned maps, traverse these sites. The proposed corridor also passes through a segment of the Mill Creek Springs Natural Area Preserve, as shown in the Hypes letter of May 20, 2016.

Recently (April 21, 2016) MVP proposed an alternative route in the Mt. Tabor Karst Sinkhole Plain in order to address issues raised by the Virginia Department of Conservation and Recreation (Hypes letter of March 17, 2016). The alternate corridor is designed to avoid some of the more imposing sinkhole complexes traversed by the proposed corridor. The new route is shown in the Hypes letter of May 20, 2016. However, the alternate path would traverse the two cave conservation sites. In fact, the length of the proposed alternate corridor within these conservation sites exceeds that of the original proposed corridor. Furthermore, the proposed alternate corridor would still be positioned on soluble rock and for an extended length along the lower flank of Brush Mountain where slopes are undesirably steep (*see* data on slopes and soil for this stretch of the pipeline a presented in Table 1B, Appendix B). This leads to very similar slope stability problems that are identified and discussed above for the Monroe County sites and Canoe Cave.

Further along this alternate path, the route passes over another part of the Mt. Tabor Karst Sinkhole Plain. The density of sinkholes appears to be less along this path based on those identified on topographical maps and aerial photography. (It is very likely that a high number of small sinkholes are present that do not show at that scale). Nonetheless, based on extensive dye-traces performed in the area, there is considerable reason to assume that the plain of karst is contiguous in the subsurface. A well-integrated aquifer underlies the entire Mt. Tabor Karst Sinkhole Plain wherein groundwater is efficiently conveyed from places of recharge (sinkholes as well as the interfluves among them) to places of discharge, including the identified springs in the area – such as the primary spring that discharges to Mill Creek Springs Natural Area Preserve (as documented by the 20 May 2016 letter by Hypes). Moreover, there are many wells in the plain that draw water from the aquifer. This water is used for domestic and agricultural needs in an area that is not served by public water supply.

As with the other three case examples discussed above, the Mt. Tabor Karst Sinkhole Plain is also subject to material being derived from uplands such as Brush Mountain and washed onto the karst plain. Slope and soil conditions on Brush Mountain, while not as severe as on Sinking Creek Mountain (Table 1-B, Appendix B), nonetheless contribute material washed onto the sinkhole plain. This area is also within the Giles County Seismic Zone (Appendix B, Figure 6A). Therefore, siting the MVP through the Mt. Tabor Karst Sinkhole Plain is another situation where environmental impacts and hazards are compounded.

There is every reason to believe that the entire Mt. Tabor Karst Sinkhole Plain is a single, extensive, and well-integrated karst aquifer. The only solution that would ensure that a pipeline would not negatively impact this karst and the underlying aquifer would be to entirely avoid the Mt. Tabor Karst Sinkhole Plain and its contributing watershed.

Additional Sites

The four sites evaluated in detail above were selected to illustrate the scope of environmental problems associated with the proposed Mountain Valley Pipeline. They inherently exhibit compound hazards. There are several other places along the proposed corridor that should not be ignored in the deliberation process. For example, Milepost 215.7-215.8 in Craig County, a steeply sloping site declared “unconstructable” by MVP’s routing engineer, passes immediately above two sinkholes and through a third. A second example is near Elliston and Lafayette in eastern Montgomery and western Roanoke counties (*see* Appendix B, Figure 9). There are several caves in this area (Wickersham, 1988), including Dixie Caverns (a popular show cave that offers tours to the public) and Goodwins Cave (the longest known cave in the county). Both of these are listed as ‘cave conservation sites’ by the Virginia Cave Board (within the Department of Conservation and Recreation) and the Virginia Speleological Survey (Holsinger, 1985). Additionally, the Spring Hollow Reservoir, a major water source in the greater Roanoke area, has been constructed on karst terrain. The route of the proposed pipeline passes within a mile or so from these features; and the mile-wide corridor includes an extended recharge zone on the karst plain in the lowlands between Paris Mountain and Poor Mountain (Appendix B, Figure 9).

Summary

Four of the most compelling sites where compound hazards are pronounced have been discussed above. It bears restating that there are other areas of karst along the proposed corridor between and among these sites and in Roanoke County to the east and within the larger region. There is no doubt that the extensive karst of the Appalachian Mountains poses an unacceptable risk in constructing a durable pipeline within this very dynamic regional setting.

There are two likely consequences when compound hazards act in unison. First the combination of severe slopes, poor soils, and disturbances and loading during construction of the pipeline can lead to severe erosion and sedimentation and damage to surface water and aquifers that are vital to residents and to the ecosystem. Second, construction in areas of severe slopes, slip soils, and likely ground shaking from earthquakes raises the real possibility of an immitigable failure of the pipeline and ensuing catastrophic events. These issues support the conclusion that this region is a no-build zone for a gas pipeline of this size.

Conclusions:

Karst Terrain in Appalachians as a 'No-Build' Zone

Construction of a large, 42-inch-diameter gas pipeline across the central Appalachian fold belt is without precedent. The magnitude of this undertaking is daunting. The size of the high-pressure pipe and a terrain that is high in relief and complex in its geology poses considerable risks for planning, avoiding known risks, engineering design, and construction challenges. The Mountain Valley Pipeline proposal creates concern for significant risk of adverse impacts due to the nature of the terrain that the line would cross.

There are serious problems imposed by geologic and hydrogeologic constraints. They fall into two basic categories: (1) the impact of the geologic setting on constructing and safely maintaining the pipeline and (2) the environmental impacts of the pipeline on the land that it would pass through and to the population that is concerned about safety and relies on clean available groundwater.

As discussed in this report, the predominant geologic factors are:

Karst **Hydrogeology** **Slope Stability** **Soil** **Seismicity**

Although each of these five topics has serious specific considerations that have not been adequately addressed by the applicant, the greatest concern arises when it is realized that all five types of hazards are prominent in the region and often compounded. Where and when they occur together, geologic attributes operate as a system and not individually. A problematic condition in one may cause consequences in one or more of the others. Severe slopes and high-slip soils would challenge engineering design of the pipeline and its operation and maintenance. Such challenges are enhanced by the potential for significant seismic events owing to the proposed location of the pipeline.

The region addressed in this report (Monroe County and a segment of Summers County in West Virginia and Giles, Craig, Montgomery, and Roanoke counties in Virginia) is the most environmentally sensitive along the entire proposed pipeline route. Crossing the Valley and Ridge Province in general raises profound questions and concerns.

I have reviewed materials to date submitted by Mountain Valley Pipeline (MVP), including contributions from their consultants, in its application to the Federal Energy Regulatory Commission. Additionally, I have studied numerous submissions by agencies (U.S. National Forest Service, Virginia Department of Conservation and Recreation, Virginia Department of Environmental Quality), by county governments, and by groups and individuals who live, work, and own property in the affected counties. My evaluations, analysis, and conclusions are based upon careful review of these documents in light of my experience as a professional geologist with over 50 years of applied experience in karst and environmental geology, especially pertaining to the Appalachian region of the eastern United States.

Mountain Valley Pipeline has not adequately addressed many of the environmental concerns germane to this region, contrary to FERC policy to "avoid and minimize" adverse effects. Moreover, MVP has totally ignored compound effects of hazards. Numerous findings that have been generated and submitted by registered intervenors, professionally done with due diligence, have brought to light considerable details, many of which bring aspects of the MVP application into question.

The geologic environment, including active processes in karst, slopes, soils, and earthquakes, are a physical part of an overall natural system. However, the findings discussed in this report extend into the biological ecosystem as well. Lifeforms, whether in the forests, grasslands, soil, streams, or in caves and groundwater are an integral part of the system (discussed in Appendix A). Erosion and sedimentation, contamination of surface streams, wells, and aquifers, and partitioning (as mentioned earlier and discussed in Section 3) are destructive to the entire ecosystem, biological as well as physical. The concerns advanced in this report extend well beyond the geological setting.

Karst is one of the most environmentally sensitive geologic landscapes on Earth. It is a major underlying component in the region of this report. Mountain Valley Pipeline and its consultants have barely 'scratched the surface' in adequately assessing the three-dimensional attributes of karst and identifying the hazards that it imposes on construction and safe maintenance of the pipeline. Merely mapping sinkholes that appear on topographic maps and aerial imagery not only misses subtle karst features on the surface, but totally ignores the complex, well-integrated, efficient networks of groundwater flow through extensive karst aquifers. Detailed inventories of all sinkholes, caves, recharge areas, and springs, along with systematic dye-tracing, are necessary in order to identify a route through a veritable gauntlet of such features. Based on lengthy experience in studying this region and professional familiarity with karst processes in general, I am confident that a safe and environmentally sound route for a pipeline of this magnitude <u>cannot</u> be identified, engineered, constructed, nor maintained through the karst of the rugged Valley and Ridge Province.

I strongly suggest that the reader, as part of due diligence, closely examine the environmental problems that have occurred shortly after the recent construction of the Columbia Gas of Virginia (CGV) pipeline on Peters Mountain servicing the Celanese plant near Narrows, Virginia. This example, existing in the very setting of the proposed MVP route, serves as an omen. The CGV pipeline is a 10-inch-in-diameter pipe. The proposed MVP 42-inch pipe is 4.2 times larger in diameter and 17.6 times the cross-sectional area than a 10-inch pipe. In turn, the amount of construction and movement of material during trenching would be much greater, adding to the enormity of erosion, groundwater disruption, and failure of slopes. More ominously, if the integrity of this large pipe were to be compromised, the resulting catastrophic events would be at least on order of magnitude greater than with a 10-inch pipe. These are reasons enough to seriously weigh the potential consequences of constructing the MVP pipeline through the hazardous terrain of the Valley and Ridge Province.

As stated in Section 4 of this report, "there are two likely consequences when compound hazards act in unison. First the combination of severe slopes, poor soils, and disturbances and loading during construction of the pipeline can lead to severe erosion and sedimentation and damage to surface water and aquifers that are vital to residents and to the ecosystem. Second, construction in areas of severe slopes, slip soils, and likely ground shaking from earthquakes raises the real possibility of an immitigable failure of the pipeline and ensuing catastrophic events. These issues support the conclusion that this region is a no-build zone for a gas pipeline of this size."

The identified problems associated with the pipeline, potentially a major intrusion into the Valley and Ridge region, impact the entire natural environment. Deliberation related to the MVP application must approach the natural system as a whole. In turn, human quality of life is intimately tied to the natural ecosystem. Degradation of the natural environment has direct consequences on individuals and communities living on or near path of the pipeline, including local economies dependent on nature-based tourism.

Mountain Valley Pipeline has routed its proposed pipeline through one of the most environmentally sensitive areas of our nation. As a direct result of the routing, the pipeline (if constructed) would be subjected to serious geologic impact. Many of the potential hazards discussed in this report have not been adequately identified in the MVP application, nor have suitable mitigation measures been advanced. This report, along with the meticulous scrutiny by the U.S. Forest Service (*see* Submittal 20160311-5013 to Docket CP16-10 (31305006)) and reviews by the Virginia Department of Conservation and Recreation (letters from S. René Hypes, March 17 and May 20, 2016) provide a detailed accounting of severe potential hazards along the proposed MVP corridor.

My recommendation, based on the multiple environmental issues and potential hazards, is for FERC to reject the application. The stakes are very high and the risks are far too great.

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Appendix A

Ecological Implications of Partitioning the Landscape by the Proposed Mountain Valley Pipeline

The following discussion has been adapted from material compiled and submitted to FERC by Brian Murphy, Ph.D., Professor, Department of Fish and Wildlife Conservation, Virginia Tech, Blacksburg, Virginia)

Threats posed by the construction of a large high-pressure pipeline through a region characterized by geologic hazards discussed in this report apply to all native species, not just humans. Additionally, the proposed Mountain Valley Pipeline would partition the lands that it traverses. The following discussions address ecological issues as they affect wildlife in or near the path of the proposed pipeline corridor. The ecosystem is intimately linked with the geologic environment that has been addressed earlier in the body of this report.

Any map of gas pipelines in the eastern United States clearly shows that past construction has paralleled the mountains on either side of the Eastern Continental Divide, rather than trying to cross this hazard-prone and ecologically sensitive zone (*e.g.,* http://naturalgas.org/naturalgas/transport/). Trying to cross the heart of the Appalachian Mountains continues to be a very bad idea, for all the reasons discussed above and summarized below.

Native Aquatic Fauna

Native aquatic fauna (many of them threatened or endangered) rely on clear mountain streams for survival. Erosion and sedimentation caused by the construction and operation of the MVP would have severe impacts on water quality, and thus on these sensitive species. Erosion from the mountain slopes crossed by the MVP is inevitable. The steepness of slopes to be crossed far exceeds those recommended by the Bureau of Land Management (BLM) for road construction related to oil- and gas-related energy development in their "Gold Book" (http://www.blm.gov/wo/st/en/prog/energy/oil_and_gas/best_management_practices/gold_book.html). Roads to be constructed on slopes between 8 and 16 percent require special permission from the BLM, and construction beyond 16 percent is prohibited owing to the potential for severe environmental damage. The FERC "normal" guidelines for erosion and sedimentation control (ESC) on pipeline projects contain no special recommendations for severe slopes (which can exceed 80 percent on the MVP as currently routed), and sedimentation problems on numerous previous FERC approved projects show the inevitable result. The TRANSCO pipeline in central Virginia, the very pipeline that MVP will connect to, is still causing stream sedimentation problems some 30 years after its construction, and that pipeline is in "flat" terrain compared to the mountainous terrain of the MVP plan. Another FERC approved project (the Tennessee Pipeline) was expected to have extreme erosion potential in Tennessee owing to severe terrain. Those problems indeed materialized despite special precautions designed for mitigation, and threatened freshwater mussels were negatively impacted as a result. While not a FERC approved project, the recent erosion, stream sedimentation, and groundwater contamination problems on the Williams Pipeline connector to the Celanese plant in Narrows, Virginia clearly demonstrate the dangers of building in this terrain. Not only will severe slopes lead to inevitable erosion, but the planned “reclamation” of these areas is completely inadequate. The MVP plan to “reclaim” the construction zone by planting grasses is untenable. The soils are shallow and poorly developed and will not support such vegetation. Furthermore, mass movements would accelerate problems of erosion and sedimentation. When reclamation fails, the pipeline corridor would be invaded by a host of nonnative invasive plant species that can thrive in this poor-quality soil. Those invasive plants would spread quickly throughout the corridor and would cause expensive control problems for the U.S. Forest Service and adjacent landowners.

Interior Forest Species

Interior forest species will be negatively impacted by fragmentation of the forest caused by the linear pipeline corridor. The corridor will divide what are now large unbroken tracts of forest. Birds of the interior forest and many other animals (*e.g.* bears, salamanders, etc.) cannot effectively use the resultant smaller tracts, and many cannot or will not cross the corridor during daily or migratory movements. Many of these animal species and many species of interior-forest plants, cannot function properly within as much as several hundred feet of the forest edge. The pipeline corridor would not just permanently modify the forest within the 125-foot construction corridor, but impacts of the clearing would allow sun and severe weather to penetrate what once was interior forest. This would change the moisture regime and consequently the plant species found in this extended zone. Invasive plants would penetrate what once was interior forest, and invasive animals would readily utilize the corridor and thus negatively impact interior-forest animals that they once never encountered. The zone of major impact on the forest would not be confined to the 125-foot construction corridor. An effective corridor of degraded ecosystems may result that would be five to ten times that wide.

Appalachian Karst and Biodiversity

Dissolution and erosion of limestone and dolostone in this region have created an extensive karst landscape, creating a network of sinkholes, underground streams, caves, and the like. This has also resulted in unusual communities on these carbonate rocks. During glaciations of the Pleistocene Epoch, the Appalachians acted as a mesic and thermal refuge for a number of species and communities. In a similar manner, after the retreat of the glaciers, cold-adapted communities, such as cranberry bogs, remained in refugia in cooler parts of the Appalachians, well south of their usual range. The prevalent carbonate rocks and karst in this ecoregion are associated with unique fauna within caves, including bats, salamanders, and a wide variety of invertebrates. The diversity and distribution of these species are not yet adequately known, but they likely rival cave faunas around the world in richness and endemism. Cave habitats in the Appalachian region include several federally listed rare and/or endangered species including the Madison cave isopod, Townsend’s big-eared bat and Indiana bat. (From: https://lccnetwork.org/lcc/appalachian)

Partitioning (fragmentation) of ecosystems by construction has been studied in many places on the Earth. There is an extensive literature addressing the effect of swaths of denuded land (*e.g.* corridors) on distribution of animals and plants distribution and movement and migration of animals. How construction allows the introduction of invasive species is also a topic of major concern among ecologists. The recent bestselling book, *The Sixth Extinction* (Kolberg, 2014) is a valuable resource in understanding these global problems. Chapter 9 discusses fragmentation of forests and Chapter 10 addresses invasive species.

Additional supportive information on the ecosystems of the Appalachian Mountains and biodiversity on land, in streams, and in the subsurface can be found on the following web sites:

http://applcc.org/cooperative/our-plan/section-1/biodiversity-hotspot
https://lccnetwork.org/lcc/appalachian

Appendix B

Tables, Figures, and Maps

The tables, figures, and maps in this appendix have been cited in the text of the report. They are included here in one place in order to facilitate referring to them because most are referenced several time and in different sections of the report.

The three tables, 1-A, 1-B, and 2, show data related to slopes and soils along the route of the proposed Mountain Valley Pipeline. They were compiled by Dr. Richard D. Shingles from sources identified in Section 4 of this report and stated on the tables themselves. The primary references to these tables is in Section 4 of this report, beginning on page 44 with the discussion on slope failure.

The first three figures (regional maps) are described in detail below. The remaining figures (4 through 9) have self-explanatory captions. The significance and content of each figure are given in the appropriate places in the text.

Notes on the Regional Maps

> *The first three Figures are maps that been adapted and compiled by Dr. Richard D. Shingles from ArcGIS mapping by Drs. Stockton Maxwell and Andrew Roy of the GIS Center, Radford University. Data used in the mapping originates from various published sources and base maps available from online databases.*

Figures 1, 2, and 3 show the general configuration of selected stratigraphic units with respect to the path of the proposed Mountain Valley Pipeline. They illustrate areas of outcrop of carbonate rock units that are considered soluble, in this case limestone and dolostone.

Soluble rocks are typically prone to the development of karst on the surface (sinkholes, swallets, sinking streams, dry valleys, springs, etc.) and/or in the subsurface (enlarged fractures, cavities, enterable caves, etc.). Sinkholes that are large enough to be indicated on the maps have been incorporated from mapping by Hubbard (1984, 1988) and Miller and Hubbard (1986).

It needs to be pointed out that soluble rocks may or may not always exhibit developed karst on the surface. However, in this region it is highly likely that karst landforms can be found throughout the delineated areas, especially where karst is present in the subsurface (caves and other openings).

One of the most striking observations is the amount of soluble rock within the counties. Giles County has the greatest area of exposed soluble rock (approximately 80 percent coverage) and Montgomery is also high (approximately 60 percent coverage). In terms of potential environmental problems, these two counties are the most significant of those along the MVP pipeline corridor. However, Monroe County in West Virginia and Craig and Roanoke counties in Virginia also have extensive areas of karst.

It should be understood that karst features (sinkholes, caves) as shown on these maps are incomplete. Those shown are sinkholes identifiable on topographic maps and aerial imagery. Many of those have been verified during field reconnaissance. These surveys of karst were completed prior to the year 2000 (Hubbard, 1984, 1988; Miller and Hubbard, 1986). This data has subsequently been incorporated into the karst maps of Tobin and Weary (2004) and Weary (2008). Countless smaller sinkholes remain unrecorded owing to the resolution and techniques used in the mapping process (Kastning, 1989b; Kastning and Kastning, 1993, 2003). As discussed in Section 3, the identification of small sinkholes is an important step in designating buffer zones during development and construction in karst terrains (Kastning, 2000; Kastning and Kastning, 1997).

Exploration and mapping of karst features within areas traversed by the proposed pipeline corridor continues. For example, a new cave entrance was discovered in early 2016 at a distance of approximately 1000 feet from milepost 223 along the proposed corridor in the Mt. Tabor Karst Sinkhole Plain. This is a potentially significant karst feature that has not yet been fully explored or mapped. Initial explorations have found cavities large enough for human entry and extend approximately 100 feet vertically and 300 feet horizontally. Additional cavities are very likely awaiting exploration. Air flows within the new cave indicate a connection to one or more other openings on the surface at unknown locations. (These details are via personal communication from Dr. Carl E. Zipper, and indirectly from personnel who have explored the new cave on behalf of the Virginia Speleological Survey,)

Figure 1: Valley and Ridge Province: Karst-Bedrock and Sinkholes

This map shows the entire length of the Mountain Valley Pipeline as it extends across Monroe County in West Virginia, and Giles, Craig, Montgomery, and Roanoke counties in Virginia. It is a small-scale map providing an overview of the extent of karst in the region. The topography is shown in shaded relief and the carbonate rocks prone to development of karst are superimposed. Major sinkholes in Giles and Montgomery counties, Virginia, are shown.

Figure 2: Giles to Mount Tabor Plain in Montgomery County, Ridges & Valleys, Soluble Rock and Prominent Karst Features

This is an expanded map (larger scale) of part of the area shown in Figure 1, specifically for Giles and Montgomery counties in Virginia. It includes details of sinkhole distribution. The red-circled areas (in Virginia) from left to right are (1) Sinking Creek, along Zells Mill Road, Giles County, (2) Canoe Cave and Karst, Giles County, and (3) Mt. Tabor Karst Sinkhole Plain, Montgomery County.

Figure 3: Monroe County from Little Mountain to Peters Mountain: Steep Slopes & Soluble Rock

This is an expanded map (larger scale) of part of the area shown in Figure 1, specifically for Monroe County in West Virginia. As in Figures 1 and 2, areas of soluble rock are indicated. The proposed Mountain Valley Pipeline is outlined as a 1.5-mile wide corridor. Steep slopes are indicated within that corridor.

Table 1-A. Ridge and Valley Severe Slopes and Soils on MVP route: Monroe County

Mile Posts	Distance miles	Mountain	Ave. Max Vertical Slope %	Predominant Soil Types
175.71-176.06	0.97	Wind Creek crossing, within Zone of Critical Concern for Big Bend Public Water Supply	61.81	Ceteache Litz complex
176.57-176.68	0.11	Crossing of tributary to Stony Creek	57.02	Ceteache Litz complex
180.33-180.66	0.33	High Top	40.46	Ceteache Litz complex, Dekalb channery loam
181.82-183.9	2.08	Crossing of Indian Creek; ridge above Hans Creek, crosses tributaries to Hans Creek	42.76	Litz silt loam, Dekalb channery loam
184.81-186.84	2.03	Ellison Ridge and Hans Creek crossing	51.60	Lily sandy loam, Dekalb channery loam, Laidig channery loam
187.90-187.95	0.05	2,393 ft. Mountain	61.49	Ceteache-Litz complex
190.59-191.48	0.89	Little Mountain	46.38	Frederick and Dunmore, Dekalb channery loam
192.55-192.84	0.29	Little Mountain	41.01	Dekalb channery loam and Weikert channery silt loam
193.62-193.71	0.09	Slope leading to Painter Creek crossing and Red Sulphur PWSD	55.14	Weikert channery silt loam
194.75-195.69	0.73	Peter’s Mountain western slope and RS PWSD	48.64	Laidig channery loam

Table derived from MVP 1-J Slope Tables, MVP 7.5 Minutes Topo Maps, and Mountain Valley Pipeline Exploratory GIS Ma

Table 1-B. Ridge and Valley Severe Slopes and Soils on MVP route: Giles Co. - Roanoke Co.

Mile Posts	Distance miles	Mountain	Ave. Max Vertical Slope %	Predominant Soil Types
196.94 - 198.03	1.09	Peters Mountain east slope	59.4	Nolichucky very stony loam
198.87 - 199.92	1.05	Down slope west of Kimbalton	45.7	Frederick very stony silt loam
200.12 - 201.04	0.92	2317 ft Mountain	36.1	Braddock sandy loam
201.43 - 202.42	0.99	2330 ft Mountain	46.7	Carbo silty clay loam very rocky
203.1 - 204.23	1.13	2500 ft Mountain	47.5	Nolichucky very stony sandy loam
204.26 - 204.76	0.5	2493 ft Mountain	39.5	Frederick very gravelly silt loam
204.77 - 205.58	0.81	2500 ft Mountain	46.0	Frederick very gravelly silt loam
206.79 - 207.27	0.48	2683 ft Mountain	55.1	Carbo, Frederick
207.82 - 208.24	0.42	Down and cross slopes	50.0	Frederick gravely silt loam
209.71 - 209.88	0.23	Down slope to Rt 700 & Rt 604	54.9	Carbo silky clay loam very rocky
209.93 - 210.51	0.58	Rt 700 to Winding Way Dr	40.5	Braddock, Gilpin, Sequoia
211.4 - 212.35	0.95	Newport: Rt 700 to Rt 42	54.0	Frederick gravel-outcrop complex
213.65 - 213.76	0.11	Canoe Cave	56.4	Frederick: Newport to Canoe Cave
214.5 - 214.92	0.42	Rock outcrop complex	44.5	Carbo
220.05 - 220.83	0.78	Slope to Mt Tabor Sinkhole Plain	50.0	Berks-Clymer
225.96 - 226.26	0.3	Paris Mountain western slope	73.3	Carbo - Chilhowie
229.54 -229.82	0.28	Slope : Mont-Roanoke Co. Line	73.3	unclassified
234.66 -235.17	0.51	Slope: Mont-Roanoke Co. Line	60.8	unclassified
236.12- 236.84	0.72	Poor Mountain	64.51	Sylvatus Very Channery Silt Loam
237.67 - 238.94	1.27	Poor Mountain	52.2	Sylvatus Very Channery Silt Loam

Table derived from MVP 1-J Slope Tables, MVP 7.5 Minutes Topo Maps, and Mountain Valley Pipeline Exploratory GIS Map

Table 2. Soils that Contribute to Slope Stability and Their Key Attributes

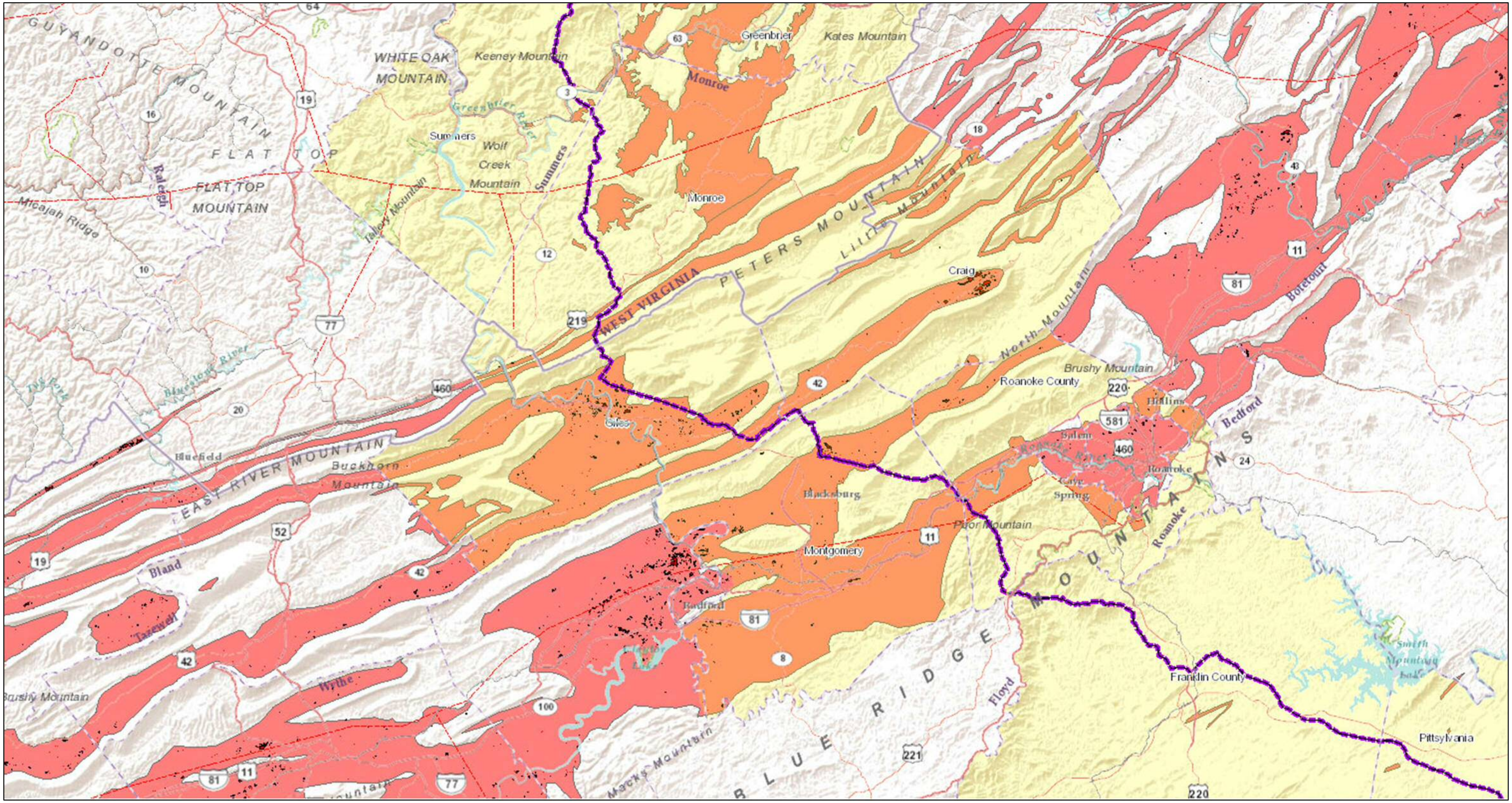
Soil Series	**(1) Plasticity Index**	**(2) Shrink-swell Potential**	**(3) Bearing Strength (for Roadfill)**	**(4) Drainfield/ Suitability**	**(5) Depth to Rock**	**(6) Hydrology**	**(7) Mineralogy**
Allegheny	15	L	Good	Mod (Flooding)	>60”	Flooding	Mixed
Bailegap	20	L	Poor (Stony)	Sev	40-60”		Siliceous
Berks	10	L	Poor	Sev (Depth)	20-30”		Mixed
Braddock	33	M	Fair	Mod (Perc)	>60”		Mixed
Carbo	55	H	Poor (LS, SS)	Sev (Perc)	20-40”		Mixed
Chagrin	NP, Sandy	L	Good	Sev (Flooding)	>60”	Flooding	Mixed
Chavies	10	L	Good	Mod (Flooding)	>60”	Flooding	Mixed
Cotaco	15	L	Fair (Wetness)	Sev (Wetness)	>60”	Wetness	Mixed
Drall	10	L	Poor	Sev (Sandy)	40-60”		Siliceous
Faywood	45	M	Poor (LS)	Sev (Perc)	20-40”		Mixed
Fluvaquents	No Data	No Data		Sev (Flooding)		Flood plain	No data
Frederick	55	H-M	Poor (LS)	Sev (Perc)	>60”		Mixed
Gilpin	15	L	Poor (Thinness)	Sev (Depth)	20-40”		Mixed
Jefferson	15	L	Good	Slight	>60”		Siliceous
Lehew	7	L	Poor	Sev (Depth)	20-40”		Mixed
Lily	15	L	Poor	Sev (Depth)	20-40”		Siliceous
Nolichucky	25	M	Poor (LS, SS)	Mod (Sev Perc)	>60”		Siliceous
Poplimento	60 Clayey 30 silty	H-M	Poor (LS, SS)	Sev (Perc)	>60”		Mixed
Sequoia	40	M	Poor (LS)	Sev (Perc)	20-40”		Mixed
Timberville	30	M	Fair (LS, SS)	Sev (Wetness)	>60”	Flooding	Mixed
Wallen	10	L	Poor (Stony)	Sev (Depth)	20-40”		Siliceous

Compiled by Dr. Steven Hodges, Soil Scientist, from USDA NRCS 1985 Soils Survey of Giles County, Virginia: Tables 10 – 16.

Notation: L = Low, M = Medium, H = High, Mod = Moderate, Sev = Severe, Perc = slow percolation; Depth = shallow, LS = low strength, SS = shrink-swell.

Special construction techniques are required for plasticity scores over 30, M, H, Poor, Mod, Sev and mixed. Blasting required for depth < 60”.

Figure1. Valley and Ridge Province: Karst-Bedrock and Sinkholes



June 27, 2016

1:577,791

0 5 10 20 mi

0 10 20 40 km

MVP_125ft_buffer

MVP_Route_Most_Recent

Natural_Gas_Market_Hubs

Natural_Gas_Liquid_Pipelines

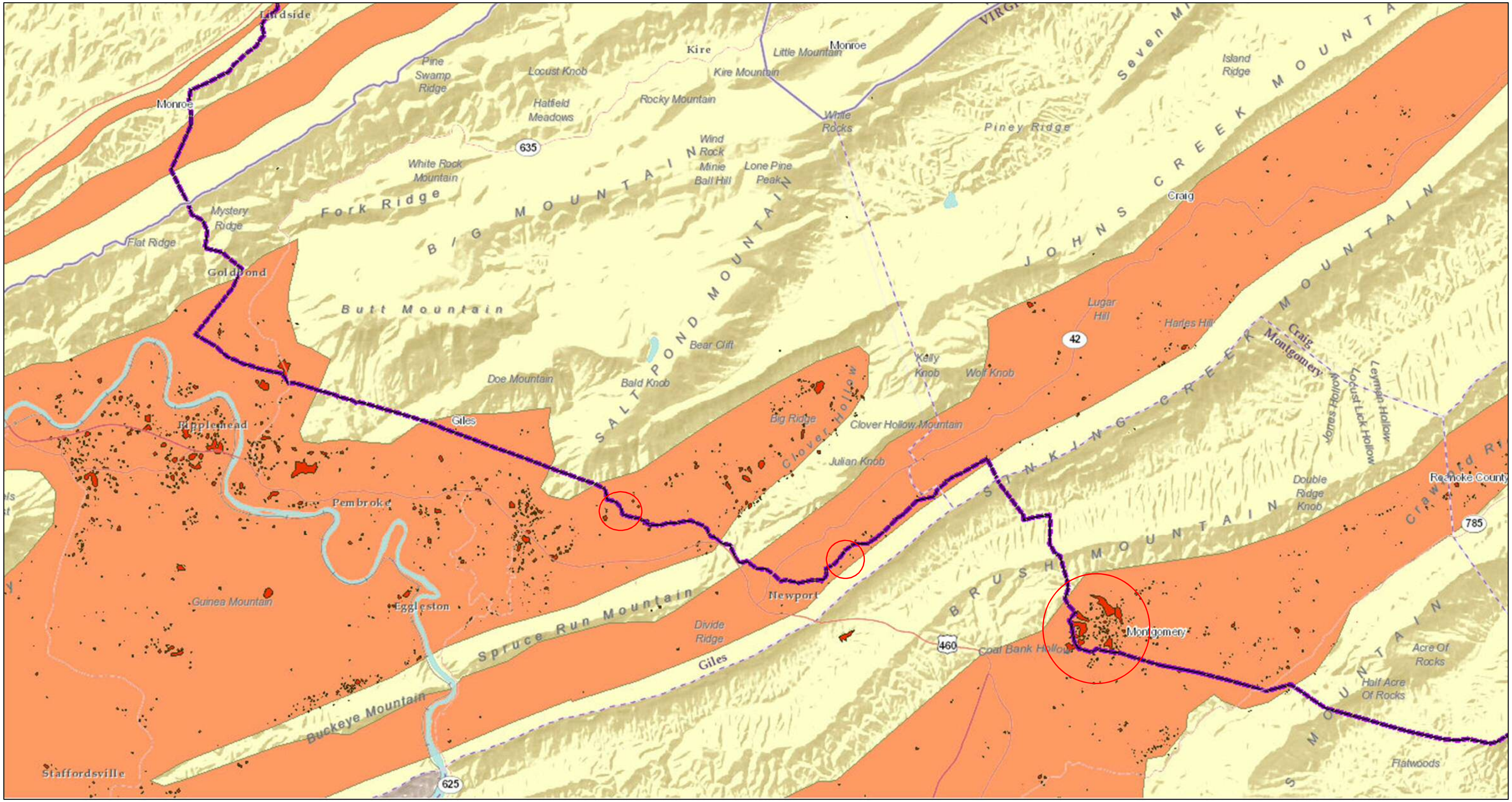
🟨 Affected Counties

Sinkholes from VDMR

🟥 Karst Bedrock

Sources: Esri, DeLorme, USGS, NPS
Sources: Esri, USGS, NOAA

Figure 2. Giles to Mount Tabor Plain: Ridges & Valleys, Soluble Rock and Prominent Karst Features



June 27, 2016

1:144,448

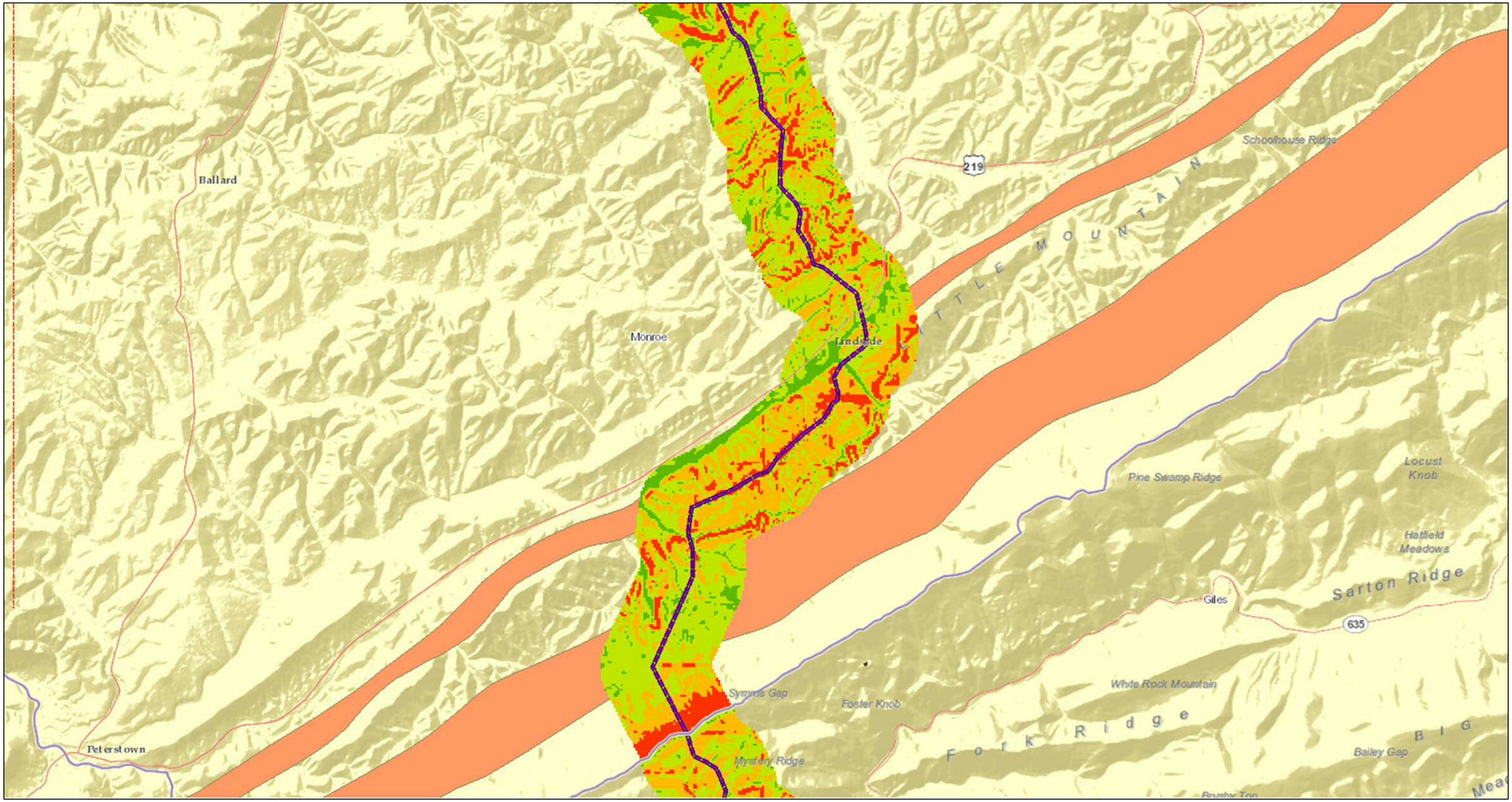
0 1.75 3.5 7 mi

0 2.75 5.5 11 km

- MVP_125ft_buffer
- MVP_Route_Most_Recent
- Natural_Gas_Market_Hubs
- Natural_Gas_Liquid_Pipelines
- 🟨 Affected Counties
- Sinkholes from VDMR
- 🟥 Karst Bedrock

Sources: Esri, DeLorme, USGS, NPS
Sources: Esri, USGS, NOAA

Figure 3. Monroe County from Little Mountain to Peters Mountain: Steep Slopes & Soluble Rock



June 27, 2016

1:72,224

0 0.75 1.5 3 mi

0 1.25 2.5 5 km

□ MVP_125ft_buffer

▬ MVP_Route_Most_Recent

✷ Natural_Gas_Market_Hubs

--- Natural_Gas_Liquid_Pipelines

🟨 Affected Counties

≡ 0 – 7

🟧 8 - 25

🟩 26 - 40

🟥 > 40

🟥 Sinkholes from VDMR

🟥 Karst Bedrock

Sources: Esri, DeLorme, USGS, NPS
Sources: Esri, USGS, NOAA

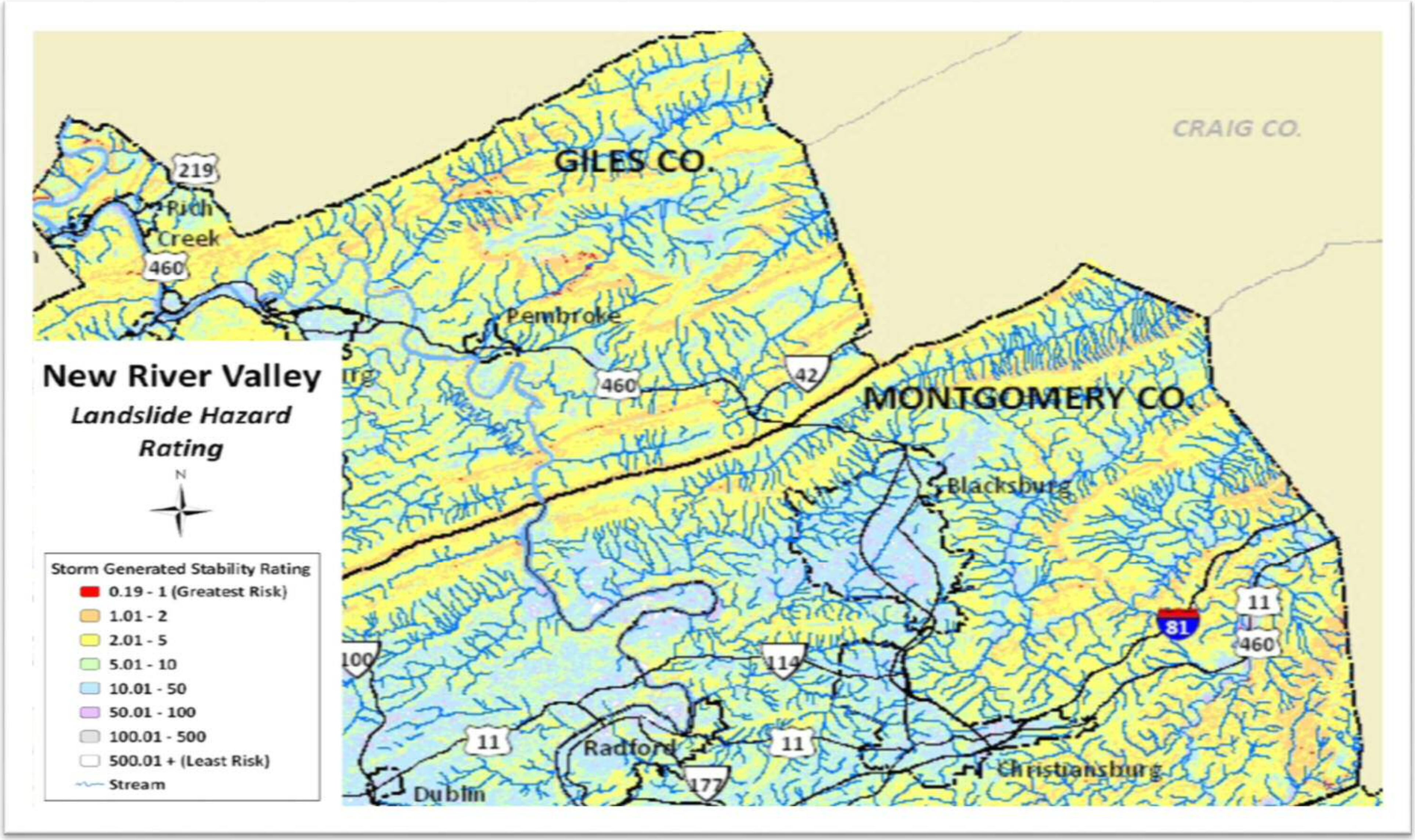


Figure 4. *A part of the New River Valley Landslide Hazard Rating map excerpted from the* 2011 New River Valley Regional Commission's Hazard Mitigation Plan, *as described and referenced in Section 3 of the text. In essence, this is a map of slopes that are prone to failure in response to large storms. Seismic shocks in the Giles County Seismic Zone may also cause failure as well in the areas of risk. The values in the explanation are factors of safety derived using a Level I Stability Analysis Model.*

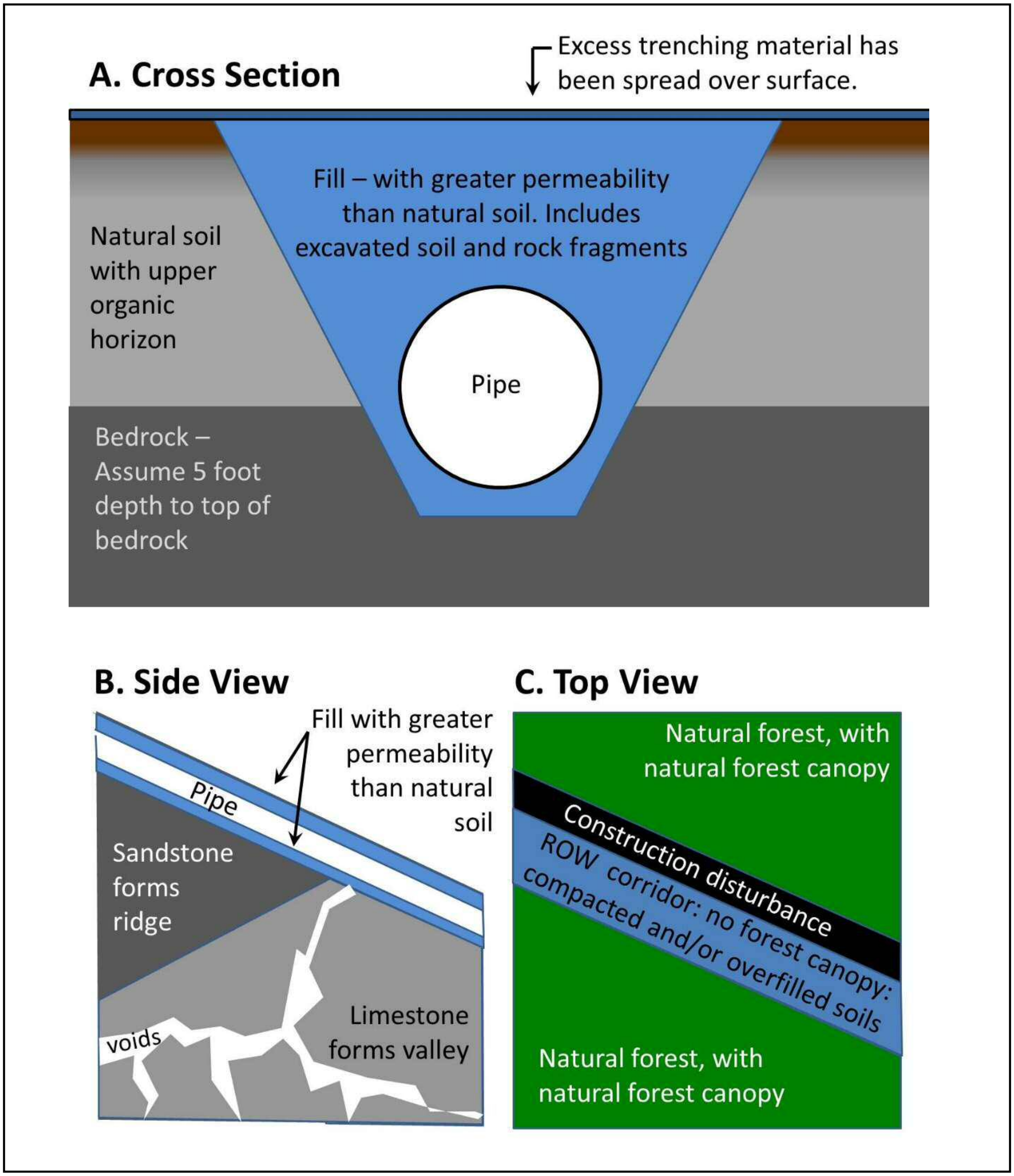


Figure 5. *Sketch of pipeline configuration. (A) Cross section of pipeline showing typical dimensions, bedrock, natural regolith (and soil) zone, and fill materials after construction. (B) Longitudinal section showing typical surface slope with pipeline in filled trench. Variations in substrate include insoluble bedrock upstream in allogenic recharge zone (here depicted as sandstone) and soluble bedrock with developed voids (here depicted as limestone). (C) Plan view indicating that the pipeline right-of-way corridor (including disturbed adjacent zone) has transected a forested area (for discussion, see Appendix A).* Drawing by Dr. Carl Zipper.

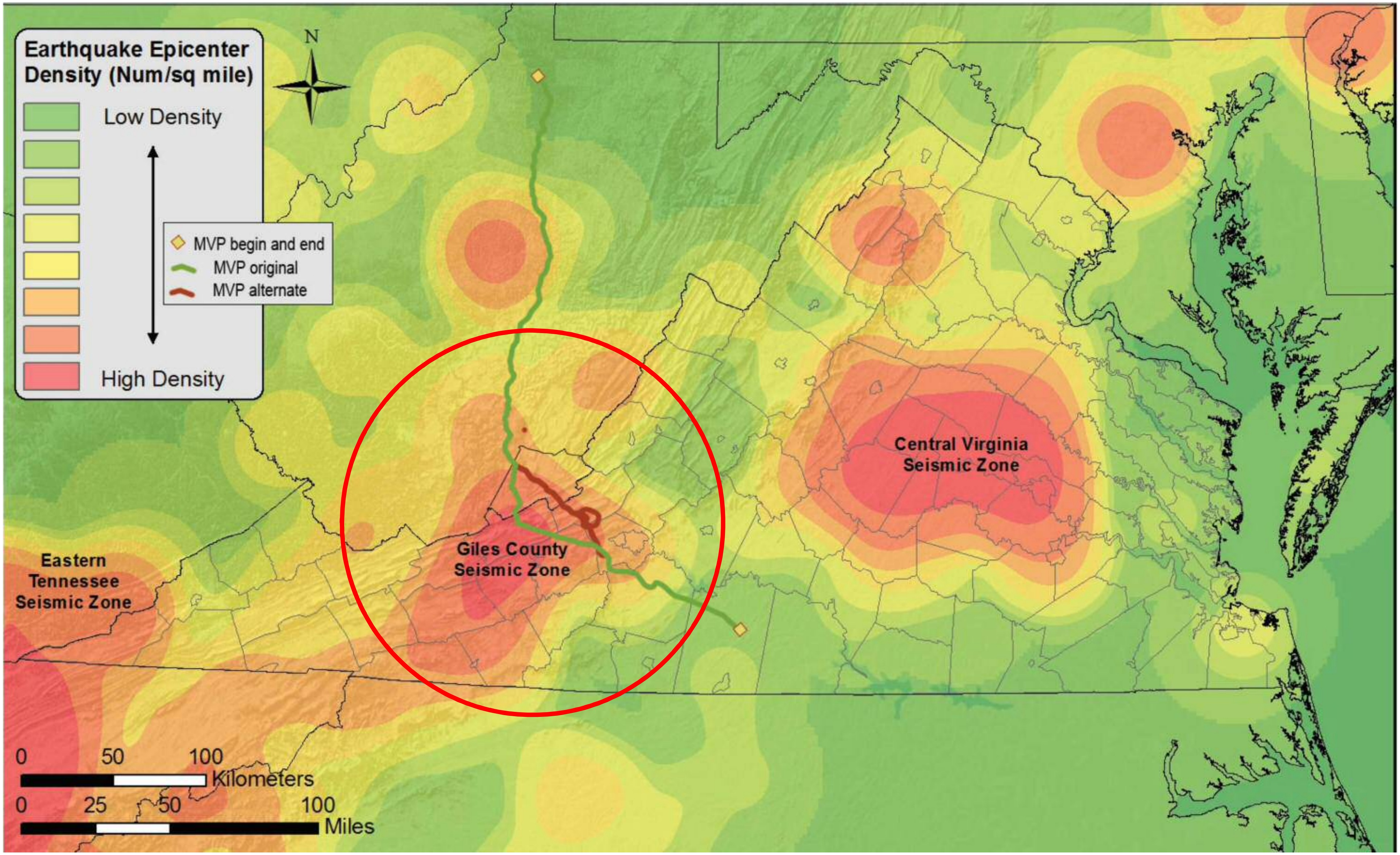


Figure 6-A: *Seismic Zones in Virginia and West Virginia. The Giles County Seismic Zone is clearly shown in relation to the routes that have been proposed by Mountain Valley Pipeline (green and brown lines, added by Dr. Alfred M. Ziegler). Note the proximity of the proposed pipeline routes to the center of the seismic zone. The source map, entitled "Earthquake Epicenter Density," is from "Mapping Geologic Hazards," on the website of the Virginia Department of Mines, Minerals: (http://dmme.virginia.gov/DGMR/EQHazardMapping.shtml).*

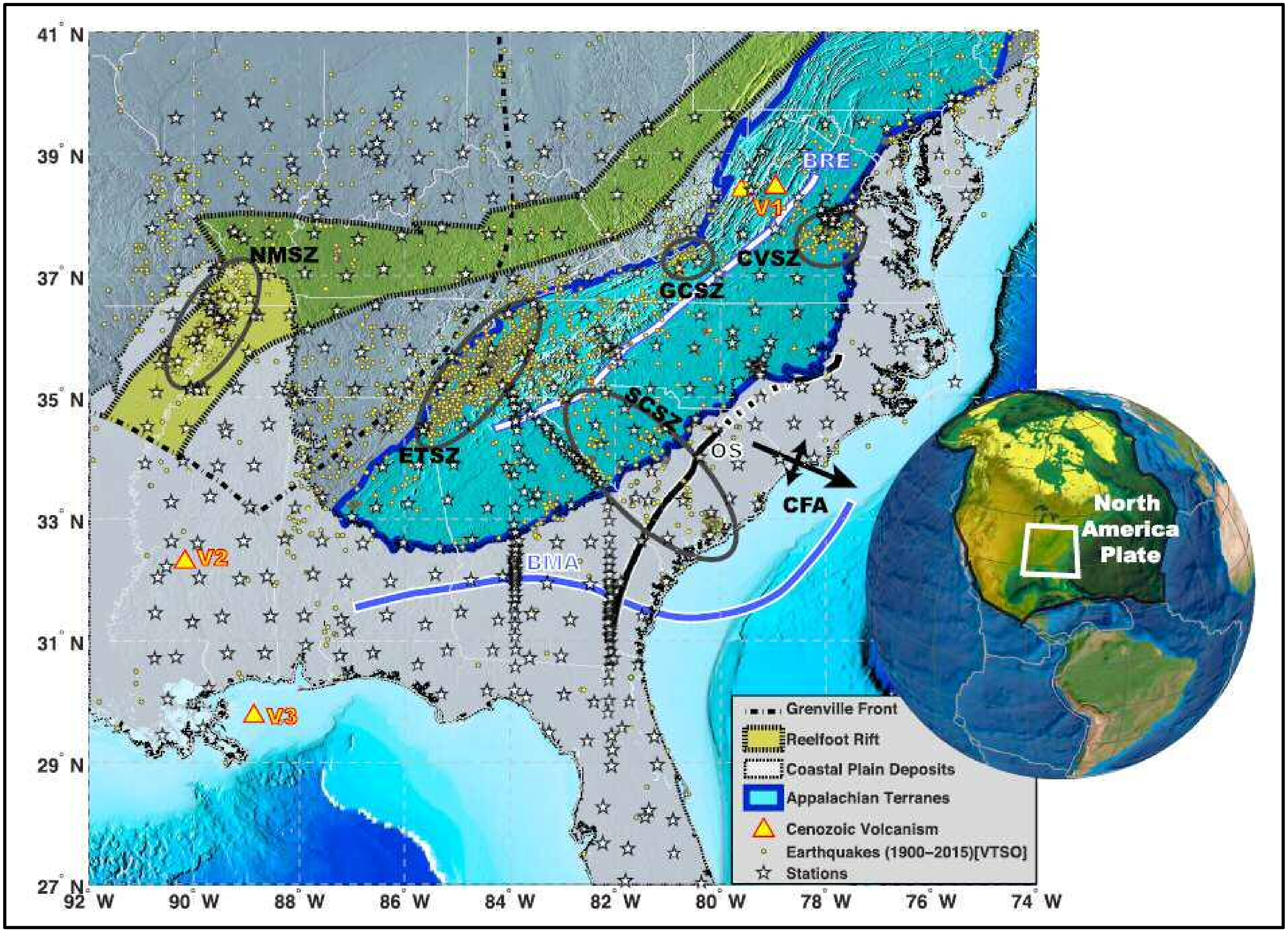


Figure 6-B. Map showing significant seismic features of southeastern USA. The Giles County Seismic Zone (GCSZ) is located in upper right. Stars represent seismographic stations. The map is excerpted from Biryol and others (2016), which is a copyrighted work, and should not be distributed. (Below) Map of Virginia seismic hazards prepared by Virginia Department of Mines, Minerals and Energy, https://dmme.virginia.gov/DGMR/EQHazardMapping.shtm

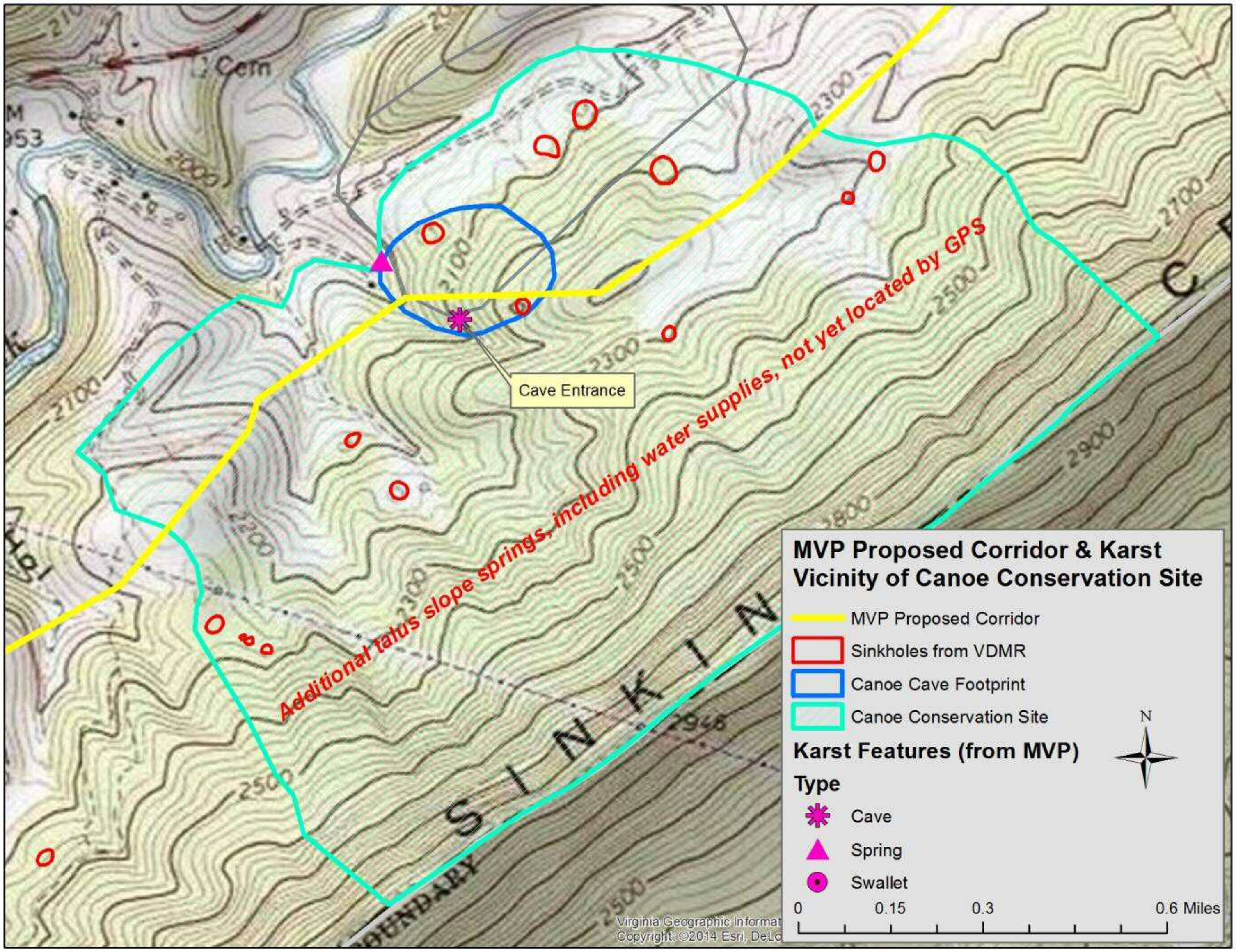


Figure 7. *Area around Canoe Cave, Sinking Creek Mountain, Giles County, Virginia. The proposed route of the Mountain Valley Pipeline passes over Canoe Cave and within a few hundred feet of its entrance. Sinkholes that take allogenic recharge (swallets) and a spring directly downhill from the cave (a likely resurgence of water from the cave) are indicated. The area outlined in light blue is a designated cave conservation site.*

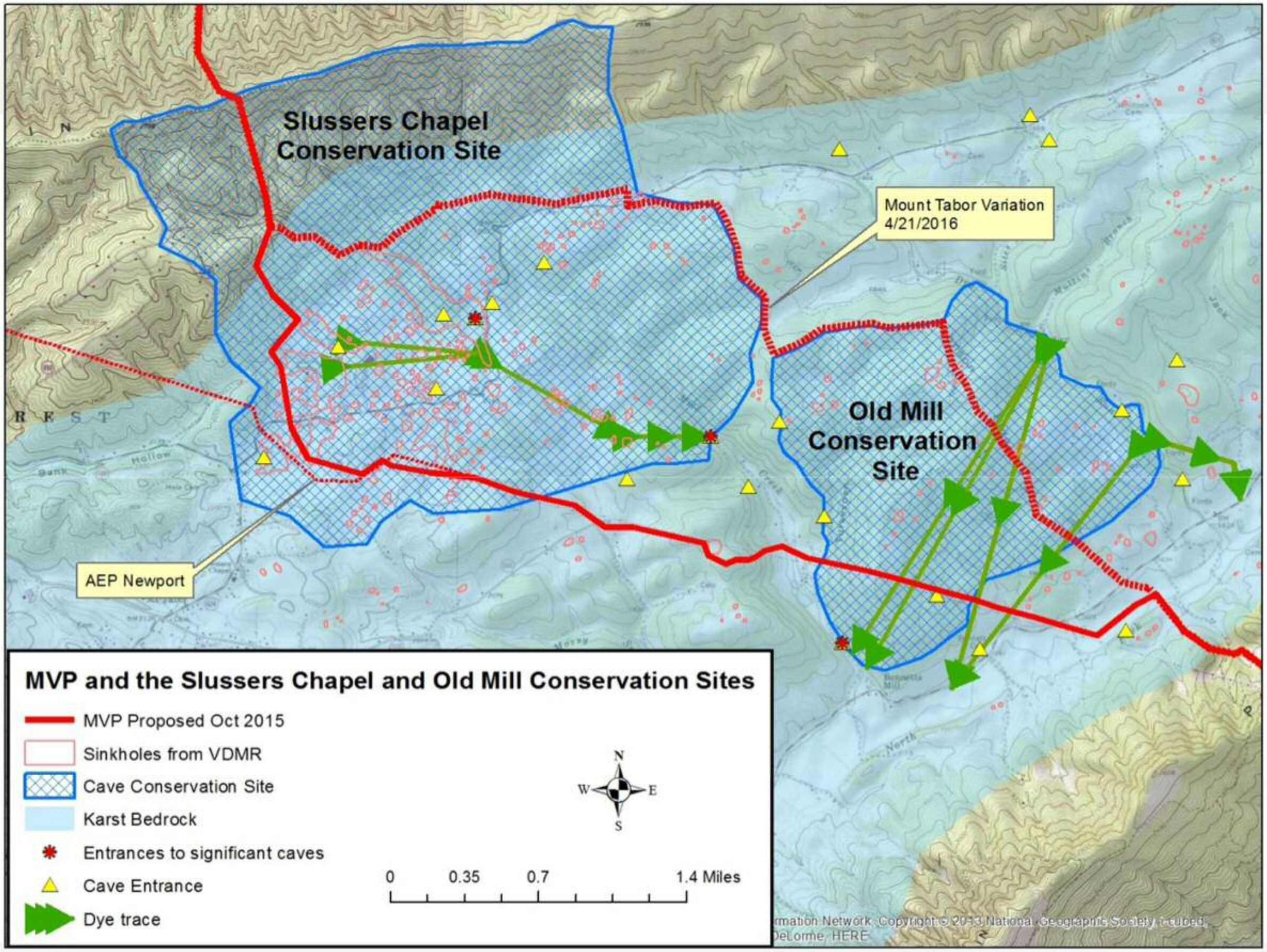


Figure 8. A part of the Mt. Tabor Karst Sinkhole Plain, Montgomery County, Virginia. The original proposed route of the Mountain Valley Pipeline (the southernmost solid red line) passes through the Slussers Chapel Cave and Old Mill Cave conservation sites (outlined in blue). The northern dashed red line is an MVP suggested alternative. Sinkholes are shown in faded red and numerous dye-trace paths are indicated in green. The entire karst plain (shaded in light blue) is underlain by karsted bedrock. This is a large contiguous area of karst with an extensive, well integrated groundwater network that both alternate routes pass over.

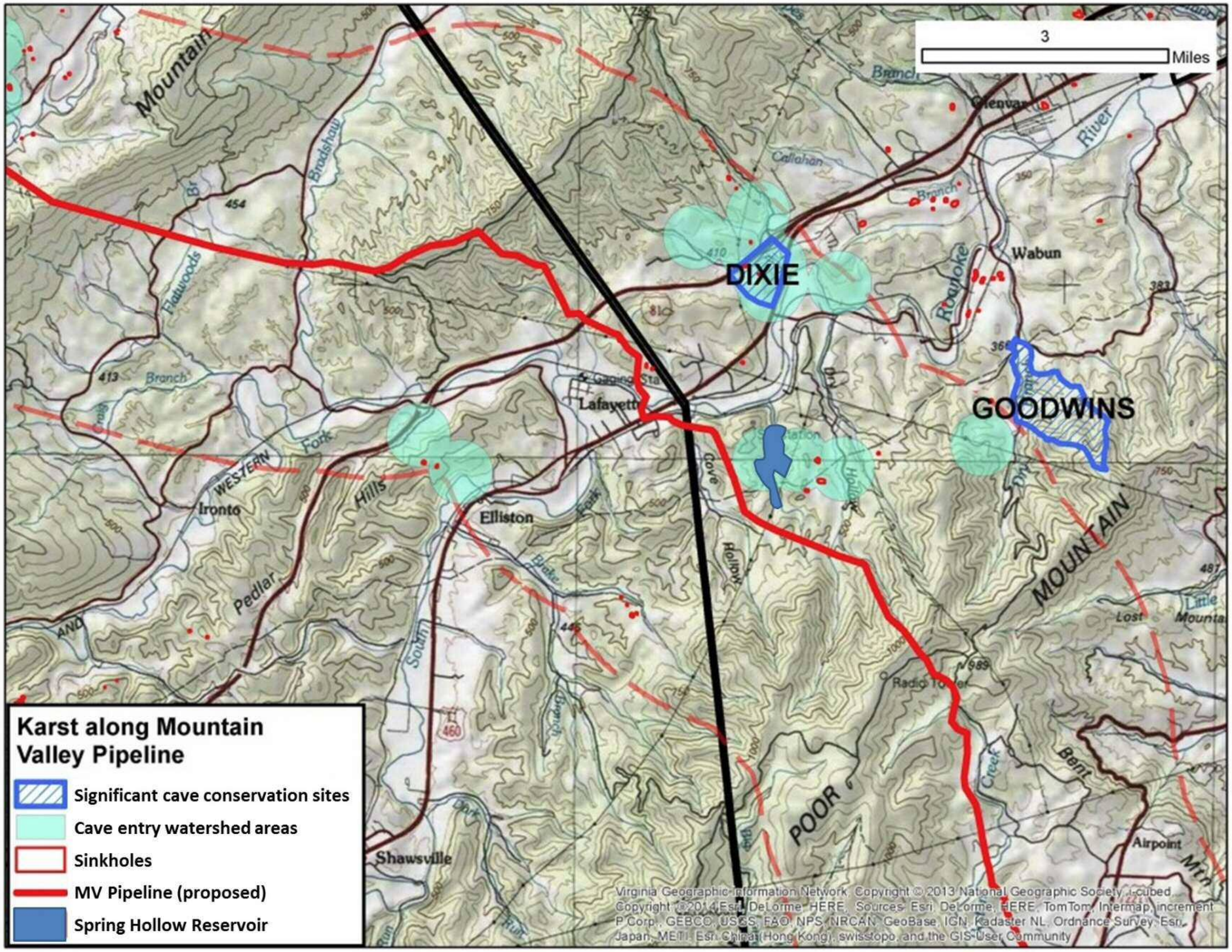


Figure 9. *Area of karst in the vicinity of Elliston and Lafayette, eastern Montgomery County (left) and western Roanoke County (right). This map shows the Dixie Caverns and Goodwins cave conservation areas, sinkholes, and watersheds contributing recharge to these karst features. The Spring Hollow Reservoir, lying within the karst, is also indicated. The dark black line is the county boundary between Montgomery and Roanoke. The proposed MVP pipeline route and a two-mile-wide corridor boundary are shown by the solid red and dashed red lines respectively.*

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GEOSCIENTIST….HYDROGEOLOGIST….ENGINEER, HISTORIAN….FREELANCE WRITER

Resource Management …. Education and Interpretation …. Natural and Human History

Summary of Qualifications

Ph. D. and M. S. Degrees in Geology with extensive professional experience as a Scientist and Educator in resource management including environmental problems associated with land use and hydrogeological problems associated with management of fragile ecosystems both above and below ground. Demonstrated ability to lead cross-functional teams, to coordinate and manage complex problems. Designed and implemented policies and procedures with respect to applied geosciences, engineering geology, and hydrogeology. Outreach education and interpretation regarding geologic, environmental, and historic resources. Includes over forty-seven years of experience with karst processes. Retired from university teaching.

Expertise and ***Knowledge***:

- *Project Leadership*
- *Administration & Planning*
- *Program Development*
- *Needs Assessment/Evaluation*
- *Alliances/Partnerships*
- *Performance Analysis*
- *Regulatory Issues/Compliance*
- *Risk Assessment/Evaluation*
- *Instructor/Facilitator*
- *Data Collection/Analysis*
- *Presentations*
- *Report Writing*
- *Community Relations*
- *Problem Solver*
- *Computer Proficient*

Selected Accomplishments

Produced high-quality geotechnical and hydrogeologic studies for a wide range of clients including engineering/environmental consulting firms, governmental organizations (local, state, and federal), and developers. Have authored over 40 technical consulting reports and cartographic products. Recognized expert in my field, providing input to governmental agencies, military bases, planning committees, civic organizations, citizen-action groups, and educational institutions. *

Managed and ***advised*** projects, including the geologic mapping program of the New Hampshire Geological Survey, projects of geotechnical consulting companies, and graduate-thesis research of a number of graduate students. These have included grant and proposal writing, budget management, and public outreach and education. *

Regularly presented and ***submitted*** results of research and geotechnical findings at professional and technical meetings, symposia, public hearings, and as an expert witness in courts of law. Have authored approximately 15 monographs, 80 articles and geologic maps, and 60 abstracts in the geologic literature. Have led over 30 field trips. Designed and scripted high-profile, museum-quality displays and exhibits. Accomplished cartographer, photographer, editor, and media spokesperson. *

* Detailed supportive information available on request.

Professional Experience

NEW HAMPSHIRE DEPARTMENT OF ENVIRONMENTAL SERVICE, Concord, NH 2007-2011

Manager of Geologic Mapping –New Hampshire Geological Survey

Water Consevationist – Drinking Water and Groundwater Bureau

- Managed bedrock and surficial geologic mapping (1:24,000-scale-quadrangles) under the National Cooperative Geologic Mapping Program (StateMap) of the U.S. Geological Survey.
- Supervised 4 to 5 contract geologists as well as personally mapping surficial geology.
- Provided for GIS compilation and assembly of maps for on-demand availability.
- Worked with various federal and state agencies as well as with local governments.
- Gave presentations at professional meetings and leading geological field trips including public outreach and education programs.
- Involved in grant proposal writing, budgeting, financial operations, and personnel allocation.

ENVIRONMENTAL ENGINEERING, INC., Blacksburg, VA 2007

Consulting Engineer.

- Conducted various geophysical investigations.
- Provided for remediation of ground-water contamination, in cooperation with the Virginia Department of Environmental Quality.

RADFORD UNIVERSITY, Radford, VA 1985-2006

Professor/Associate Professor – Department of Geology

- Taught Geomorphology, Hydrogeology, Advanced Groundwater Hydrogeology (graduate course), Environmental Geology (beginning and intermediate), Physical Geology, Historical Geology, and occasionally special topics (e.g. Karst Geology).
- Advised graduate students, 1996-2006 (Senior advisor for two completed M.S. degrees).
- Instructor, Elderhostel courses, Department of Continuing Education.
- University service: Departmental, college, and university-wide committees.
- Highly active in research, publishing, outreach, and consulting.

UNIVERSITY OF CONNECTICUT, Storrs, CT 1981-1985

Assistant Professor/Instructor – Department of Geology and Geophysics

- Taught Hydrogeology, Engineering Geology, Advanced Hydrogeology, Field Problems in Hydrogeology, Geomorphology, and introductory and seminar courses.
- Advised graduate students (Senior advisor for five completed M.S. degrees).
- Served on various departmental, college, and university-wide committees.
- Highly active in research, publishing, outreach, and consulting.

Previous positions included Assistant Professor at Murray State University (KY), Geologist, Environmental Geologist, Geophysicist, Hydrogeologist, Research Scientist, and Analytical Engineer at organizations including the University of Texas, Radian Corporation, Texaco, Inc., and Pratt and Whitney Aircraft

Education & Certification

Doctor of Philosophy in Geology, The University of Texas at Austin, Austin, Texas, 1983
Master of Science in Geology, The University of Connecticut at Storrs, Storrs, Connecticut, 1975
Bachelor of Electrical Engineering, Rensselaer Polytechnic Institute, Troy, New York, 1966

Certified Professional Geologist (Commonwealth of Virginia) – Active