SPR-Part B
MD-20-P01837 G-1

MARYLAND DEPARTMENT OF TRANSPORTATION
STATE HIGHWAY ADMINISTRATION

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RESEARCH REPORT

Highway Rock Cut Inventory and Failure Potential, Allegany County, Maryland

David K. Brezinski
Rebecca Kavage Adams
Elizabeth R. Sylvia

Maryland Geological Survey
Maryland Department of Natural Resources

FINAL REPORT

May 2020

This material is based upon work supported by the Federal Highway Administration under the State Planning and Research program. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration or the Maryland Department of Transportation. This report does not constitute a standard, specification, or regulation.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. MD-20-P01873G-1	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Highway Rock Cut Inventory and Failure Potential, Allegany County, Maryland		**5. Report Date** May 11, 2020 **6. Performing Organization Code**
7. Author(s) David K. Brezinski, Ph.D., Rebecca Kavage Adams, Elizabeth Sylvia		**8. Performing Organization Report No.** DNR 12-041720-227
9. Performing Organization Name and Address Maryland Geological Survey 2300 St. Paul Street Baltimore, Maryland 21218		**10. Work Unit No.** **11. Contract or Grant No.** SP809B4F
12. Sponsoring Agency Name and Address Maryland Department of Transportation (SPR) State Highway Administration Office of Policy & Research 707 North Calvert Street Baltimore MD 21202		**13. Type of Report and Period Covered** SPR-B Final Report (May 14, 2018-May 11, 2020) **14. Sponsoring Agency Code** (7120) STMD - MDOT/SHA
15. Supplementary Notes		

16. Abstract

One hundred ninety-five, MDOT SHA-maintained, roadway embankments in Allegany County, Maryland, were cataloged as to the effects of climate, vegetation, and geology factors on slope stability. Observations included dimensions, weathering condition, and geologic structure. Recorded data was employed to evaluated the potential for slope failure such as rockfall, rock roll, rockslide, or slumping. Rockfalls were determined to be likely on slopes of greater than 60 degrees, and in massive lithologies on embankments displaying major levels of differential erosion. Rock roll was the most common potential slope failure on slopes that exceed 30 degrees of inclination. Rockslides were considered to be the dominant potential slope failure in outcrops where rock layering is inclined towards the highway. Roadside slumping or rotational dislocations were a prominent type of slope failure in highly weathered, relatively unconsolidated, rock outcrops.

17. Key Words Rockfalls, Translational landslides, Rockslides, Rotational landslides, Roadway embankments.	**18. Distribution Statement** This document is available from the Research Division upon request.		
19. Security Classif. (of this report) None	**20. Security Classif. (of this page)** None	**21. No. of Pages** 36 pages	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Department of Natural Resources
Resource Assessment Service
MARYLAND GEOLOGICAL SURVEY
Richard A. Ortt, Jr., Director

HIGHWAY ROCKCUT INVENTORY AND SLOPE FAILURE POTENTIAL, ALLEGANY COUNTY, MARYLAND

by

David K. Brezinski
Rebecca Kavage Adams
Elizabeth R. Sylvia

DNR Publication No. DNR 12-041720-227

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ACKNOWLEDGEMENTS

We would like to thank Eric Dougherty (Maryland Environmental Service (MES), formerly of the Maryland Department of Transportation State Highway Administration (MDOT SHA)) for suggesting this project. Nathan Moore, Nick Caviglia, and Ross Cutts (MDOT SHA, Office of Materials Technology (OMT)) provided helpful suggestions that facilitated this study's completion. We would also like to thank George Walker, Ryan Frankenberry, and their crew (MDOT SHA) for traffic control along MD Route 135. Helpful review suggestions were supplied by C.A. Kertis of the U.S. Geological Survey.

EXECUTIVE SUMMARY

- One hundred ninety-five, MDOT SHA-maintained, highway embankments in Allegany County, Maryland, were cataloged in an effort to gain insight into the effects of climatic, vegetative, and geology factors on embankment slope stability.
- Information was collected in real-time in ArcGIS Survey123.
- In total, more than 7,000 data observations were made.
- Each exposure was categorized as to location, dimensions, weathering condition, and geologic structure.
- Based on these data, summary evaluations were made as to the potential for rockfall, rock roll, rock slide, or slumping and rotational failures.
- Rockfalls were considered to be most prone to occur in slopes of >60º, and composed of massive sandstone or limestone lithologies, and exhibiting major levels of differential erosion
- The rockfall failure type was identified for twenty-four percent of the slopes studied.
- The most common type of potential slope failure was rock roll, a type of potential failure that was assessed to be present for fifty-one percent of the studied exposures.
- Rock roll potential was typical of exposures comprised of interbedded lithologies, and for slopes of between 30º to 60º.
- Rock slide potential was identified for fourteen percent of the exposures studied, and this failure type was largely confined to strata that were inclined into the roadway.
- Slump or rotational dislocations were identified in eleven percent of the outcrops studied, and their potential tended to be present on highly weathered outcrops that were covered by vegetation.

INTRODUCTION

Slope failure represents an important form of geologic hazard. Identification of such features on a regional scale has been accelerated, in recent years, by the study of aerial LiDAR (Light detections and ranging) imagery (Schulz, 2004, 2007; Burns and Madin, 2009). However, small-scale slope and bedrock failures, too small for aerial LiDAR identification, present a different level for hazard study. Slopes present along roadways present a substantial hazard to drivers and expense and liability to roadway agencies. Such failures are dictated by a combination of factors such as bedrock character, steepness of slope, and climatic conditions. Because the State of Maryland transects parts of five physiographic provinces, there is no single set of stratigraphic, structural, or topographic conditions that can be applied State-wide to coherently summarize potential slope failure regimes. Thus, it is necessary to evaluate roadway exposures in each physiographic province under a different set of observed and measured characteristics and constraints. In Allegany County, the bedrock consists of layered sedimentary rocks of differing erodibility. The shale, siltstone, limestone, and sandstone vary in thickness and geographic distribution. These changes in competency, along with the presence of pervasive planes of discontinuity, weather at different rates, and coupled with water infiltration and frost action, produce unstable masses of rock that, through the force of gravity, can result in slope failure. Furthermore, the compression and tension experienced by the bending of these rocks during the formation of the Appalachian Mountains produced fractures of varying orientation and attitude that can expedite weathering, frost heaving, and water transmission. These processes serve to hasten detachment and release of clasts, boulders, and blocks that can fall, roll, or slide into the roadway.

Purpose

The initial objective of this project was to catalogue the surficial character, current conditions and rockfall potential for rock exposures along State-maintained roadways within Allegany County, Maryland. This effort was initiated to record a snapshot in time for each outcrop risk for rockfalls into roadways maintained by the Maryland Department of Transportation State Highway Administration (MDOT SHA). Additionally, it was envisioned that the diverse data acquired from this effort might delineate certain rock types, structural features, or outcrop profiles that, when observed in certain combinations, produce a recognizable recurrence of slope failure types and their potential for failing. The compilation of such a recognizable suite of controlling factors may be used in production of a State-wide categorization of existing and potential slope failure characters.

Location and Physiography

Maryland presents a broad range of bedrock types and characters across five physiographic provinces. Understanding slope failure within each physiographic region of the State requires detailed knowledge of each province's bedrock, climatic, and erosional histories. The current study area lies within Maryland's portion of the eastern Appalachian Plateaus and western Ridge and Valley physiographic provinces of Allegany County, Maryland (Reger and Cleaves, 2008) (Figure 1). In general, the Ridge and Valley Physiographic Province consist of highly folded and eroded sedimentary rocks of early to middle Paleozoic age. To the east of the study area, these strata consist of early Paleozoic carbonate rocks that underlie the Great Valley Section (Hagerstown Valley, eastern Washington County) as well as middle Paleozoic limestones that underlie some narrow linear valleys a little farther to the west. In Allegany County the greatest preponderance of the Ridge and Valley Province is underlain by middle Paleozoic sandstone,

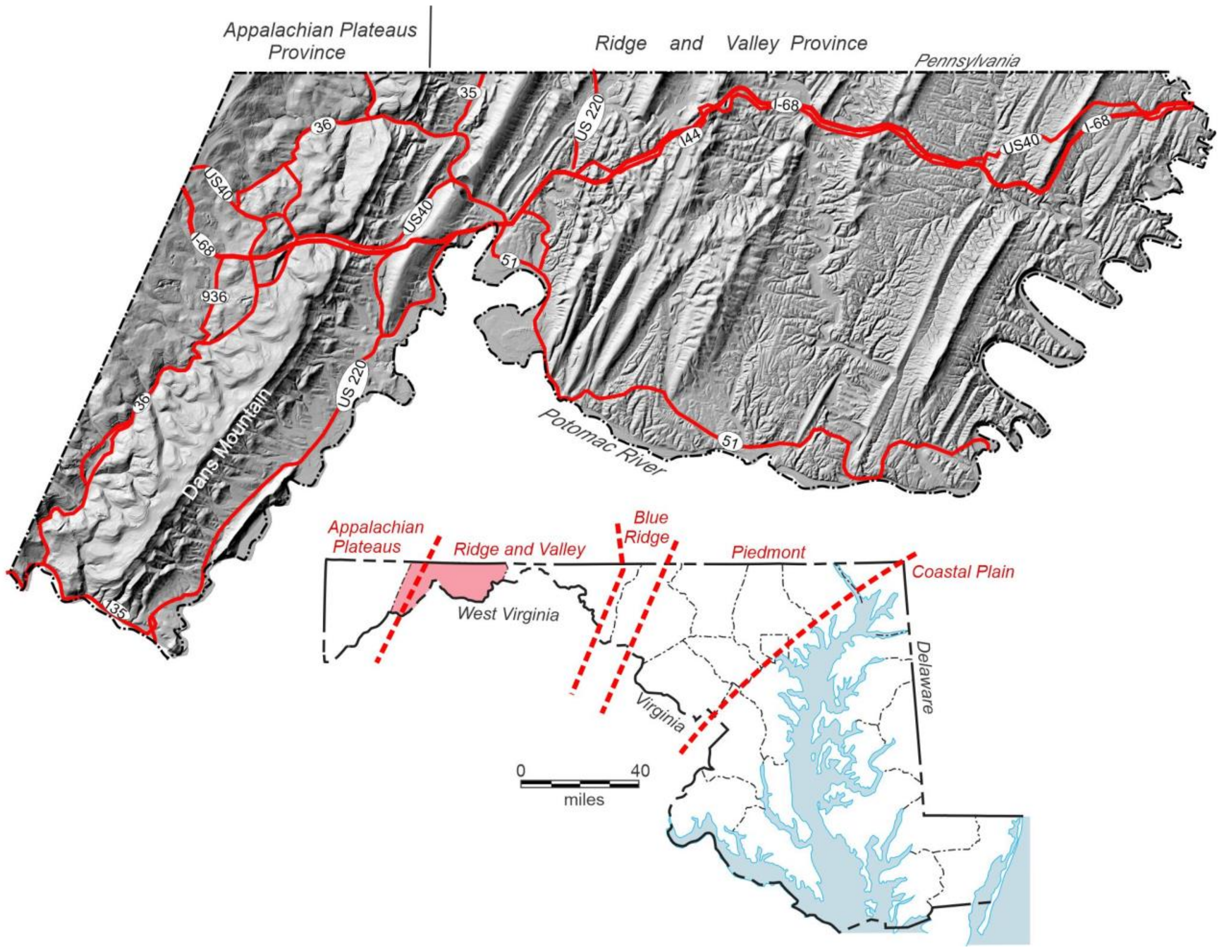


Figure 1. Light detecting and ranging (LiDAR) image of Allegany County, Maryland, illustrating Maryland State maintained highways along which rock slope failure data were collected for this study. Image from https://geodata.md.gov/topoviewer. Inset map of location of Allegany County (pink).

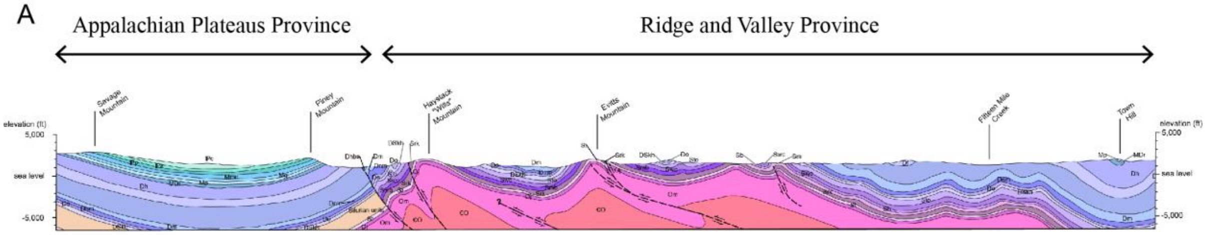
siltstone, and shale. It is the combination of several factors such as lithologic variations in steeply dipping strata along with the ease of decoupling within and between individual units of differing competence that provides the greatest concern for slope instability within this physiographic province. Elevations within the Ridge and Valley Province of Maryland range from 600 to 1,800 feet above sea level.

The dividing line between the Ridge and Valley and Appalachian Plateaus physiographic provinces has been considered historically to coincide with Dans Mountain (Figure 1). This ridge demarcates what is known as the Allegheny Structural Front, and the change from highly folded rocks (Ridge and Valley Province) to more gently folded rocks (Appalachian Plateaus Province) (Figure 2). The Appalachian Plateaus Province of western Allegany County presents a completely different suite of rocks, climate, and hazard factors. Within this area, gently inclined, thick-bedded intervals of erosion-resistant sandstone alternate with more easily weathered and eroded shales and coals. These substantial differences in bedrock erodibility create large topographic relief and steep, unstable slopes that are prone to failure. The Appalachian Plateaus Province of Allegany and Garrett counties, ranges in elevation from 1,200 to 3,000 feet above sea level.

Bedrock Geology

The physiographic provinces transecting the State of Maryland are distinguished by their topography, bedrock composition, and structure. These variables are the result of a complex history of sedimentation and mountain-building that is recorded in the geologic framework

A



B

	Formation	Abbrev.	Lithology
Penn.	Conemaugh	₱c	Interbedded sandstone, gray shale, coal, and limestone
	Allegheny	₱a	Interbedded, gray shale, tan sandstone, and coal
	Pottsville	₱p	Tan and white sandstone and gray shale
Miss.	Mauch Chunk	Mmc	Red and green sandstone and red shale
	Greenbrier	Mg	Interbedded, gray limestone and red shale
	Purslane	Mp	Tan, green-gray and pink, cross-bedded sandstone
Devonian	Rockwell	MDr	Tan sandstone and gray shale
	Hampshire	Dh	Red sandstone, siltstone, and shale
	Foreknobs	Df	Conglomerate, tan sandstone, and green gray shale
	Harrell/Brallier/Scherr	Dhbs	Black and gray shale, and thin bedded sandstone
	Mahantango	Dm	Gray silty, shale and massive, fine-grained sandstone
	Marcellus/Needmore	Dnm	Gray to black shale with thin black limestone interbeds
	Oriskany	Do	White, thick-bedded to massive sandstone
	Keyser/Helderberg	DSkh	Gray limestone, chert, and dark gray shale
Silurian	Tonoloway	Sto	Thinly laminated, shaly limestone
	Wills Creek	Swc	Gray and tan shale and dolomite
	Bloomsburg	Sb	Reddish brown siltstone and shale
	McKenzie	Sm	Gray thin-bedded limestone and shale
	Rose Hill/Keefer	Srk	Reddish gray shale and tan sandstone
	Tuscarora	St	Light gray, dense sandstone
Camb./Ord.	Juniata	Oj	Red sandstone, siltstone and shale
	Older Cambrian and Ordovician Rocks	€O	Gray sandstone and shale, and limestone and dolomite. Not exposed at surface in Allegany County.

Figure 2. Bedrock stratigraphy and structure of Allegany County, Maryland. A, Idealized interpretive geologic cross section of bedrock units and structures for Allegany County. Taken from Brezinski and Conkwright (2013). B, Stratigraphic units exposed at the surface in Allegany County. Abbreviated symbols correspond to those units identified in cross-section A.

of the State. In western Maryland the stratigraphic history is preserved in an exposed rock succession composed of highly variable lithologies. While it is beyond the scope of this report to discuss the detailed origin, character, and variable relationship of these rocks, knowledge of their general character and propensity to slope failure is relevant.

The oldest rocks exposed in Allegany County are assignable to the Juniata Formation. These Ordovician rocks are exposed in the Cumberland Narrows, but do not reach the surface anywhere else in the County. Above the Juniata Formation is the Silurian Tuscarora Formation.

This light gray, dense sandstone is resistant to both weathering and erosion and is the most prominent ridge-forming rock unit in the County. This formation creates the cliffs along the Narrows, also can be observed at the crest of Haystack Mountain on I-68 as well as the crest of Evitts Mountain at Rocky Gap State Park.

Above the Tuscarora Formation is an interval of Silurian strata that are generally less resistant to weathering and erosion than is the Tuscarora Formation. The basal unit, the Rose Hill Formation, consists of reddish to gray-green shale containing thin, fine-grained sandstone beds and scattered ironstone zones. This unit was noted during this study for its proclivity to form slides, especially along bedding planes and where it is steeply inclined. The top of the Rose Hill Formation is marked by an interval of interbedded sandstone and shale that is termed the Keefer Sandstone.

Above the Keefer Sandstone is an interval of thinly interbedded limestone and shale known as the McKenzie Formation. The McKenzie Formation is overlain by a package of red, fine-grained sandstone, siltstone, and shale assigned to the Bloomsburg Formation. These red strata are in turn overlain by the Wills Creek Formation. The calcareous shale and dolomite that characterize the Wills Creek Formation grade up-section into a thick interval of thinly laminated to thin-bedded limestone of the Tonoloway Formation. The Tonoloway Formation grades upward into a more massive limestone unit termed the Keyser Formation which is in turn overlain by interbedded limestone, chert, and shale of the New Creek, Corriganville, and Mandata members of the Helderberg Formation. These units, along with the Keyser Formation, are collectively termed the Keyser-Helderberg formations on Maryland Geologic Survey geologic maps (e.g., Brezinski and Conkwright, 2013) (Figure 2B).

The cherty rocks of the upper part of the Keyser-Helderberg interval grade upward into a massive, white sandstone known as the Oriskany Formation. The sandstones of the Oriskany Formation form ridges such as Martin and Warrior mountains. Sharply overlying the Oriskany Formation is a succession of Devonian dark gray to black shale, and gray, fine-grained, silty sandstone. This succession of units consists of the Needmore, Marcellus, Mahantango, Harrell, Brallier, and Scherr formations. These units occur throughout central and eastern Allegany County and typically form highly weathered slopes or flat-bottomed valleys. Overlying the Devonian shaly rocks is the Foreknobs Formation, an interval of greenish gray shale, and conglomeratic sandstone. Conglomeratic sandstones of this formation underlie Green Ridge and Polish Mountain. The Foreknobs Formation grades upward into reddish brown sandstone, siltstone, and shale of the Upper Devonian Hampshire Formation.

The Hampshire Formation grades up-section into tan, marine sandstone and gray shale of the Devonian-Mississippian Rockwell Formation. This unit in turn progresses upward into thick-bedded, greenish gray, and reddish-brown sandstone of the Purslane Formation which forms Town Hill. Overlying the Purslane Formation is an interval of interbedded limestone and reddish shale called the Greenbrier Formation. These strata are easily eroded and consequently, rarely exposed. Overlying the Greenbrier Formation is a succession of interbedded reddish brown and greenish gray sandstone and red-brown shale and siltstone assignable to the Mauch Chunk Formation. Sharply covering the Mauch Chunk Formation is an interval of thick-bedded to massive sandstone termed the Pottsville Formation. This unit is a major ridge-forming interval of the Appalachian Plateaus Province owing to its resistance to weathering and erosion. It forms the highest elevations in Allegany County, such as Dans, Piney, and Big Savage mountains. Above the Pottsville Formation is the Allegheny Formation. This unit is characterized by interbedded layers of tan, thick-bedded to massive sandstone, gray shale, and coal. Above the

Allegheny Formation is the Conemaugh Formation. This stratigraphic unit, like the Allegheny Formation, consists of interbedded sandstone, shale and coal; however, many of the coal beds in this formation are typically thin, discontinuous, and impure. The youngest stratigraphic unit encountered during this study is the Monongahela Formation. The Monongahela Formation is characterized by mineable coal, thick intervals of gray shale, and thin layers of non-marine limestone.

Previous Study

Study of the bedrock geology of Allegany County, Maryland has concentrated mainly on detailed geologic mapping of bedrock units (Berryhill et al., 1956; Dennison, 1963; De Witt and Colton, 1964; Glaser, 1994a-e; Glaser and Brezinski, 1994, 1996; Brezinski and Conkwright, 2013). In contrast, studies attempting to understand aspects of slope failure or rockfall hazard systems within Allegany County are extremely sparse (Southworth and Schultz, 1986; Pomeroy, 1988). Previous rock failure studies in Maryland have focused on the poorly indurated strata and high-relief areas adjacent to the Chesapeake Bay (Leatherman 1986; Pomeroy, 1988).

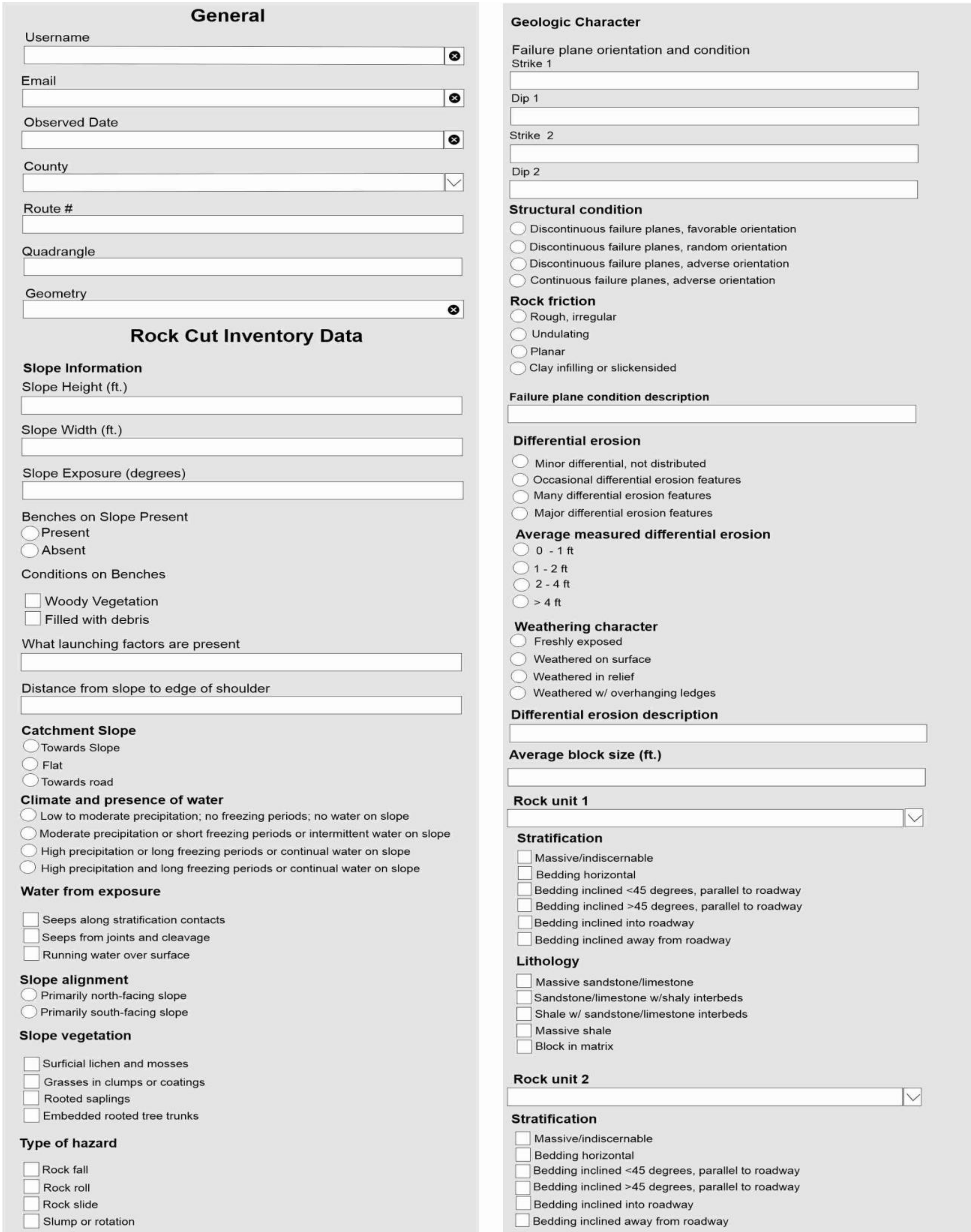
In the Ridge and Valley Province area of slope failure studies are well-known (Schultz and Southworth, 1989). In Maryland three previous slope failure sites have been documented. Ancient rockslides on the west slope of Wills Mountain were thought to be caused by undercutting of the Juniata and Tuscarora formations by Wills Creek (Southworth and Schultz, 1986). Slope failures on MD Route 48 in the Rose Hill Formation west of Cumberland, and on MD Route 51 in the Oriskany Formation south of Cumberland were attributed to a combination of dip slope, shale beds, and presence of water (Pomeroy, 1988). In the Appalachian Plateaus Province portion of the study area, Pomeroy (1988) identified the potential for rockfalls near Westernport from thick Pottsville and Allegheny sandstone overhangs, and postulated that slope movements along MD Route 36 were due in part to water from abandoned strip mines in the Conemaugh and Monongahela formations. Pomeroy's work represents early attempts to display mapped landslides and areas vulnerable to slope failure in Maryland. His generalized effort was presented at a scale of 1:500,000, and thus provided limited site-specific insight for understanding and predicting rock slope failures. Beyond Pomeroy's work to identify isolated landslide areas, there have been few geologic maps (Brezinski, 2019; Brezinski and Glaser, 2014) that have attempted to display areas of potential slope failure or interpreted landslides within Maryland.

ROADWAY ROCKCUT INVENTORY SURVEY

Methods

This field investigation was tasked to characterize rock cuts along roadways maintained by the Maryland Department of Transportation's State Highway Administration (MDOT SHA) throughout Allegany County, Maryland. A digital catalogue was created for these exposures, to detail their character. These data were collected using ESRI's Survey123 application on an electronic tablet (Figure 3). Because Survey123 was already utilized by MDOT SHA for slope inventories, that data collection format was appropriately modified to meet the focus of the current study.

It was initially estimated that this study would collect data for approximately 155 rock cuts. However, during the course of the study additional exposures were identified on which data were collected. The final number of exposures examined was 195 (Figure 20). Additionally, several exposures that had long been recognized for their rockfall and slope failure potential were examined, characterized, and three-dimensionally imaged utilizing drone photography. The drone photography was meant to augment Survey123 examination and



General

Username

Email

Observed Date

County

Route #

Quadrangle

Geometry

Rock Cut Inventory Data

Slope Information

Slope Height (ft.)

Slope Width (ft.)

Slope Exposure (degrees)

Benches on Slope Present
- Present
- Absent

Conditions on Benches
- Woody Vegetation
- Filled with debris

What launching factors are present

Distance from slope to edge of shoulder

Catchment Slope
- Towards Slope
- Flat
- Towards road

Climate and presence of water
- Low to moderate precipitation; no freezing periods; no water on slope
- Moderate precipitation or short freezing periods or intermittent water on slope
- High precipitation or long freezing periods or continual water on slope
- High precipitation and long freezing periods or continual water on slope

Water from exposure
- Seeps along stratification contacts
- Seeps from joints and cleavage
- Running water over surface

Slope alignment
- Primarily north-facing slope
- Primarily south-facing slope

Slope vegetation
- Surficial lichen and mosses
- Grasses in clumps or coatings
- Rooted saplings
- Embedded rooted tree trunks

Type of hazard
- Rock fall
- Rock roll
- Rock slide
- Slump or rotation

Geologic Character

Failure plane orientation and condition

Strike 1

Dip 1

Strike 2

Dip 2

Structural condition
- Discontinuous failure planes, favorable orientation
- Discontinuous failure planes, random orientation
- Discontinuous failure planes, adverse orientation
- Continuous failure planes, adverse orientation

Rock friction
- Rough, irregular
- Undulating
- Planar
- Clay infilling or slickensided

Failure plane condition description

Differential erosion
- Minor differential, not distributed
- Occasional differential erosion features
- Many differential erosion features
- Major differential erosion features

Average measured differential erosion
- 0 - 1 ft
- 1 - 2 ft
- 2 - 4 ft
- > 4 ft

Weathering character
- Freshly exposed
- Weathered on surface
- Weathered in relief
- Weathered w/ overhanging ledges

Differential erosion description

Average block size (ft.)

Rock unit 1

Stratification
- Massive/indiscernable
- Bedding horizontal
- Bedding inclined <45 degrees, parallel to roadway
- Bedding inclined >45 degrees, parallel to roadway
- Bedding inclined into roadway
- Bedding inclined away from roadway

Lithology
- Massive sandstone/limestone
- Sandstone/limestone w/shaly interbeds
- Shale w/ sandstone/limestone interbeds
- Massive shale
- Block in matrix

Rock unit 2

Stratification
- Massive/indiscernable
- Bedding horizontal
- Bedding inclined <45 degrees, parallel to roadway
- Bedding inclined >45 degrees, parallel to roadway
- Bedding inclined into roadway
- Bedding inclined away from roadway

Figure 3. ESRI Survey123 form constructed for the study of roadside slope characterization of Allegany County, Maryland.

create a representational mosaic of these exposures to help in understanding these troublesome outcrops.

Survey123 Data Collection

The Survey123 data collection form constructed for this study (Figure 3) contains two broad categories of data: general and geologic. General data characteristics were so termed because they represent extrinsic factors affecting rock slope quality. General data include route number, topographic quadrangle, coordinates, slope dimensions (width, height, angle of inclination), orientation, presence of elevated benches, character of roadside catchment, and presence of potential launching factors. Lastly, climate was described by the amount of regional precipitation and freezing, presence and character of water on the outcrop, and vegetation type.

Geologic factors, largely intrinsic in nature, also control slope, shape, and failure potential. Geologic data include lithology, differential erosion, and typical block size, as well as failure plane (s). Failure planes were assessed for their orientation, continuity, and surface roughness (rock friction). Differential erosion was characterized by its abundance, distribution, and magnitude. Representative digital images of each exposure were taken to record its condition at that point in time.

General Survey Elements

As mentioned previously the first type of data collected for this study was general information. Besides location data, this includes information about the physical appearance of the roadside, such as slope and climate and vegetation characteristics.

Slope Information

Each roadway exposure was initially characterized by its size and shape. Height was measured by laser rangefinder, from the bottom of the rock cut to the top of the slope (Figure 4A). At some outcrops the top of the slope was marked at the base of the first or second bench if the portion of the cut above this point did not appear to be contributing material to the slope below. Slope width also was measured by laser rangefinder from one end of the cut to the other, parallel to the road. Slope exposure was measured with a compass clinometer as the average angle in degrees of the slope face. Beds of rock protruding from the slope were noted as potential launching factors, since they present the possibility of loose material being rolling down the slope and being discharged on to the roadway (Figure 4B).

Benches and Catchment Character

The presence of a catchment area adjacent to the roadway provides space where fallen debris can come to a rest rather than enter the roadway. Benches represent catchment areas that are elevated above the roadway. When empty, these features can be horizontal or inclined away from the roadway: however, they can become inclined toward the roadway when filled (Figures 5A-C). Measurements were taken to determine the distance from the slope to the edge of the shoulder. The interval measured was from the edge of the hard road surface to the base of the slope.

The presence or absence of benches is generally dictated by the height of the exposure. Those exposures less than twenty feet in height rarely have benches. Those greater than forty feet in height typically possessed at least one level of elevated bench (Figure 5D). Although benches

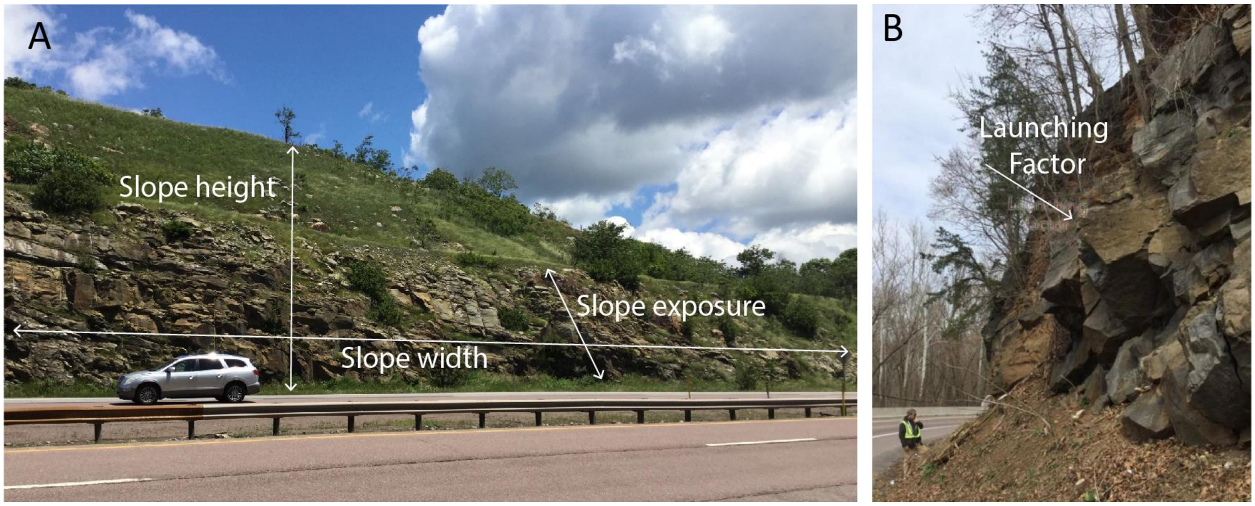


Figure 4. Embankment characterization. A, Slope dimensions. B, Launching factors.

represent elevated catchment areas, when they become filled with debris they can themselves become a launching factor, propelling rolling debris on to the roadway, and beyond roadside catchment (Figure 5E). Thus, filled benches switch from a safety factor to a hazard. When benches become filled, they also tend to spawn vegetation growth (Figure 5F).

Climate

The climate of a region dictates the amount and type of weathering that affects the rock outcrops in the area. Four categories were created to encompass climate variations, but only two effectively summarize these factors in Allegany County. The first was moderate precipitation with short freezing periods. This category was used for most outcrops within the Ridge and Valley Province of central and eastern Allegany County. The second category used was high precipitation and long freezing periods or continual water on slope. This entry was used for outcrops along highways within the Appalachian Plateaus Province of western Allegany County.

These climate zones were directly correlated to the physiography of the region. Dans Mountain serves to divide the Appalachian Plateaus Province from the Ridge and Valley Province (Figure 1). Westward from Dans Mountain areas of higher elevation, some greater than 3,000 feet, are subject to increased levels of precipitation and longer periods of frost and/or freezing (Figure 6). Some areas of Allegany County have diurnal freezing and thawing for more than 220 days out of the year (Figure 6B). Lienhart (1988) considered the freeze-thaw intervals and the demonstrable durability of rock as important factors in the evaluation and understanding of engineering materials.

At the higher elevations, the increased precipitation and prolonged freezing and thawing periods tend to produce higher rates of physical weathering resulting in greater levels of differential erosion. To the east, the lower elevations of the Ridge and Valley Province experience a less intense and shorter frost and freeze period. Furthermore, the elevation of Allegheny Structural Front (e.g., Dans Mountain), which exceeds 2,800 feet in elevation, creates an orographic effect, resulting in a rain shadow within the Valley and Ridge immediately to the east of this ridge. The drier climate and shorter freezing periods in eastern Allegany County produce a lower potential for physical weathering of the rock that translates into reduced propensity for differential erosion. Moreover, these drier areas are known to promote a semiarid flora referred to as “shale barrens” (Platt, 1951). Areas with shale barren development have greatly reduced rooting and mechanical weathering from root penetration.

Figure 5. Benches and catchments styles and character. A, Catchment shoulder sloping away from roadway. B, Flat catchment shoulder. C, Shoulder inclined towards roadway. D, Elevated catchment bench clear of debris. E, Elevated bench nearly filled with debris. F, Elevated bench with woody vegetation.

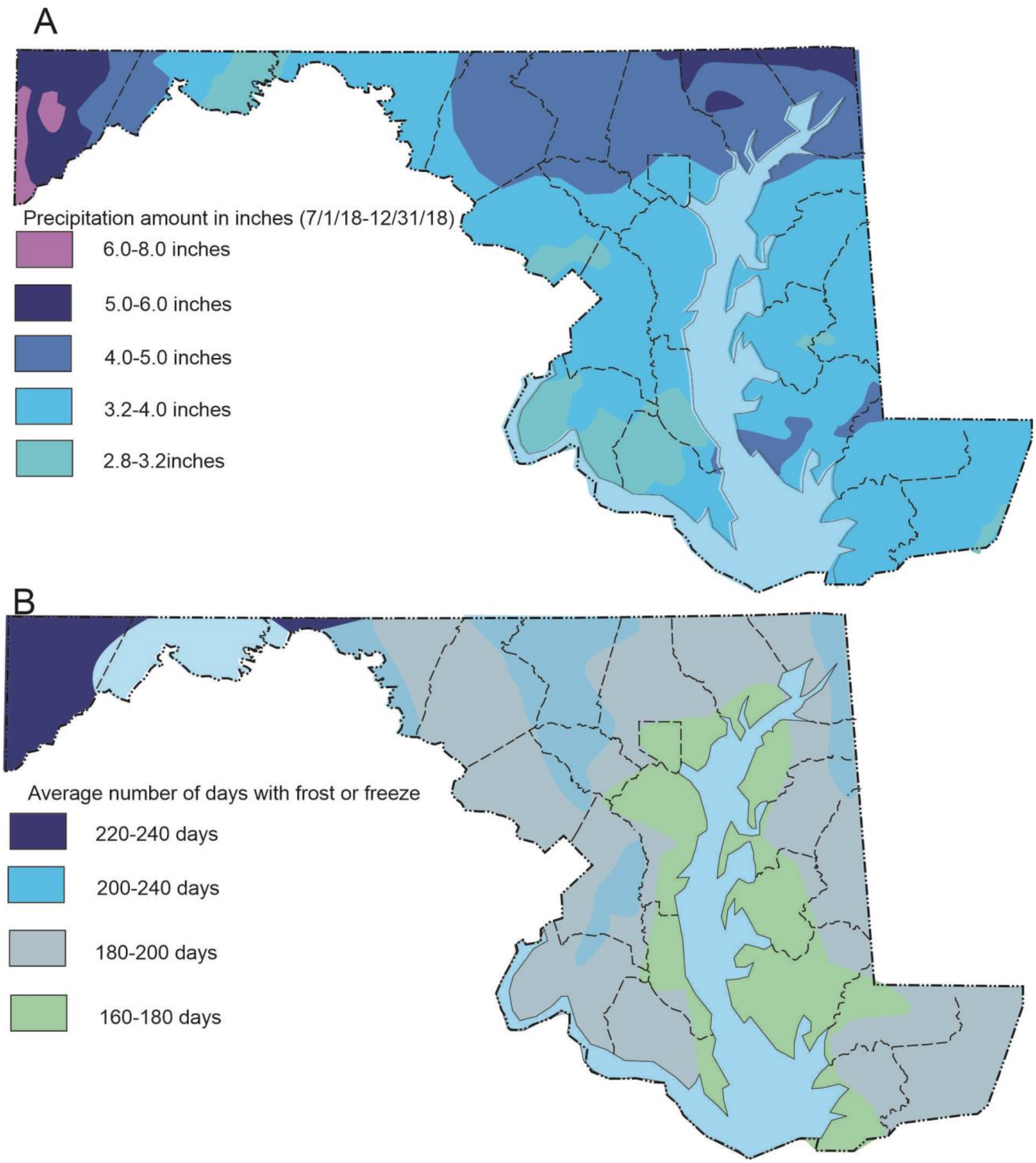


Figure 6. Variations in climate characteristics that are important in slope failure. A, Precipitation levels within the State of Maryland for the second 6 months in 2019 (data from http://prism.oregonstate.edu/). B, Generalized map of the number of days per year with potential frost or freeze. Data extracted from [extension.umd.edu/hgic/topics/fall-frostfreeze-dates-maryland].

Water on/from Exposure

Water seeping from or running on rock slopes constitutes a significant secondary contributing factor to roadside slope failure potential for several reasons (Figure 7). Most importantly, water can serve as a lubricant that reduces friction between rock layers and along fractures and parting surfaces. This reduced friction, especially where failure planes are steeply inclined, can contribute to the triggering of slope failure events. Where subvertical, fractures can increase the conductivity of the water downward into subsurface stratification planes and reduce friction along those surfaces.

In areas where frost and freezing are prevalent, fractures containing water can freeze at night and thaw during the day, thus producing a mechanical process known as frost wedging. North-facing slopes preferentially preserve water at the surface that can remain frozen for extended periods of time. Where episodes of repeated freezing and thawing are a factor, frost wedging can force apart and widen openings in the rock. Frost-wedging is a highly effective way to break apart large rock masses (Oilier, 1969).

Figure 7. Degrees of variation in the amount and distribution of water on roadside slopes. A, Water seeps along stratification. B, Water seeping along joints and fractures. C, D, Water covering the surface of outcrops.

Slope Vegetation

The prominence and type of vegetation can play a significant role in roadway slope failure. Rooting by grassy and woody vegetation is an important component of the physical and chemical weathering of outcrops in temperate biomes. In these climate zones ice fragments the bedrock by repeatedly freezing and thawing. Consequently, biotic element are not only attracted to these locations. Their rooting can further fragment rocks and their rootlets can propagate along fractures to loosen blocks and boulders.

Figure 8. Differences in vegetation between north-facing and south-facing slopes. A, Rooted tree saplings and grasses developed on a north-facing slope of sandstones of the Oriskany Formation. B, South-facing slope from the same road cut as A. This face contains grasses and few shrubs. C, Highly vegetated north-facing slope on shales of the Brallier Formation. Vegetation includes rooted trees, saplings, shrubs, and grasses. D, South-facing slope corresponding to the location shown in C. This slope exhibits only sparse grasses.

As a general observation, vegetation of all types tends to be better developed both where water is present on the outcrop. North-facing slopes maintain moisture that allows increased vegetation development. Branson and Shown (1989) proposed that north-facing highway slopes tended to contained shrubby vegetation, while south-facing slopes more often displayed grassy and herbaceous flora (Figure 8). These authors opined that the cause for these vegetation differences was related to the differing levels of solar radiation. They maintained that south-facing slopes were associated with increased levels of sunlight that resulted in elevated temperatures, reduced moisture, and a reduced potential for plant colonization and growth. Furthermore, these authors suggested that increased duration of freeze-thaw potential on north-facing slopes led to greater moisture availability in those locations. It is in this position that most lichens and mosses were observed during the current study (Figure 9A). In contrast, the presence of grassy vegetation on south-facing slopes tended to be present where water was preserved in fractures and partings of the bedrock units (Figure 9B). Saplings and rooted trees were generally found to verify Branson and Shown's (1989) findings in that they tended to be better established on the north-facing exposures at road cuts (Figures 8 C, D).

Figure 9. Types of vegetation on roadside slopes. A, Lichens and mosses. B, Grasses in clumps or coatings. C, Rooted saplings. D, Embedded and rooted tree trunks.

Type of Hazard

Four generalized categories of slope failure were utilized for this study. The first of these hazards is rockfalls, which encompasses rock topples of other authors (Hungr et al., 2013). This type of failure requires a precipitously steep slope at the outcrop, often in excess of 70 degrees. Moreover, adverse failure planes frequently create greater potential for this type of failure (Figure 10A). The second category of slope failure is termed rock roll (Figure 10B). This most common type of failure varies in prominence based upon the inclination of the slope. Commonly, slope angles between 50 and 70 degrees yield rock rolls. Lithologies that typically are associated with rock rolls are interbedded sandstone/limestone and shale where differential weathering is prominently identified. Rock slides are a failure type that tends to occur where stratification is inclined towards the highway (Russell et al., 2008) (Figure 10C). This category includes detachments that are parallel to subparallel to bedding surfaces. Slide type failures tend to be intricately associated with the presence of intersecting groups of joints that can be oriented sub-perpendicular to the direction of the slide. The jointing, whether discontinuous or continuous, provides areas that allow detachment of rock slabs near the head of the slide. These types of slope failures are much more common in the highly folded strata of the Ridge and Valley Province. The last category of hazard considered was slump or rotational slides (Figure 10D). This type of hazard tended to be observed in outcrops that were highly weathered and vegetated, or where thick soil intervals had developed on steep slopes.

Geology Survey Elements

The second type of data collected for this study is geologic factors. These data include information on lithology, stratification, differential erosion, and the character of failure planes in the rock. Vanderwater et al. (2005) attempted to classify and correlate dependence of slope failure mode on geologic variables. Their study indicates that lithologic variations and the number of discontinuities (i.e. failure planes) are significant predictors of rockfall type in the Tennessee Rockfall Hazard Rating System.

Failure Plane Character

It was an *a priori* assumption of this study that the type, orientation, and character of the dominant fracture system in the bedrock, whether joints, faults, or stratification, represented a prevailing factor in roadside slope failures. These fracture systems were noted during observations made during the course of this study and are recognized as potential failure planes. This assumption is based on previous studies of roadside rock slope failures (Russell et al., 2008).

Joints are planar to subplanar brittle fractures of the bedrock along which no perceptible movement has taken place. They tend to form by shear or extensional stresses. Joints generally occur as semi-rectilinear patterns that are genetically related (Hobbs et al., 1976). These fractures are generally discontinuous where they are displayed within interbedded lithologies, but are more continuous where they pass through massive interbedded lithologies (Figure 11). The number, spacing, and orientations of joint sets vary with respect to the bedrock composition and their position on fold limbs. Road excavation through massive rock types can lead to the formation of extensional joints that form parallel to the roadway. In such cases extensional joints form from the release of confining pressure. These extensional joints are especially common within sandstone units of the Ridge and Valley Province. Another type of fracture forms subparallel to fold axes. These closely spaced fractures are termed cleavage.

Figure 10. Type of slope failures and resulting hazards identified during this study. A, Rockfall. B, Rock roll. C, Rock slide. D, Slump (rotation) scar.

The orientation of joints or other fracture systems with respect to the roadway is important to note because such failure planes dictate a propensity and direction of slope failure. For the current study, joints and fractures that dipped away from the roadway were considered adverse while those dipping towards the highway were recognized as favorable (Figure 11). Although this may seem contrary to general reasoning, it was theorized that the adverse orientations were more likely to produce rockfalls and favorable more likely to yield rock slides and rock rolls. Vanderwater et al. (2005) noted that using the terms *favorable* and *adverse* for rockfall hazard was "ambiguous." This is because the term *favorable* when used for fracture plane characterization implies favorable as stable, and did not necessarily represent favorability for failure.

Rock Friction

While the orientation of the fracture planes is important in regards to the type of failure, the intrinsic character of the fracture provides insight into its origin and potential for movement. This character is herein termed *rock friction*. Rock friction, where observable, was cataloged only for the primary fracture system (Figure 12). At some exposures this was the dominant joint set, while at others it is represented by partings along stratification or faults. Identifying this

Figure 11. Failure plane character. A, Discontinuous and favorable orientation. B, Discontinuous and random orientation. C, Discontinuous and adverse orientation. D, Continuous and adverse orientation.

character is considered important because it provides insight as to the potential for further movement along the observed discontinuity. Rough surfaces have a rough and irregular texture to the touch (Figure 12A). Undulating surfaces suggest a level of shearing and movement along the surface (Figure 12B). These surfaces tend to be rounded rather than smooth and planar. Planar surfaces typically display smooth surfaces that may be parallel to one another (Figure 12C). Lastly, slickenside surfaces are tectonically smoothed fractures and suggest that movement parallel to the fracture surface has taken place (Figure 12D).

Differential Erosion

There are considerable differences in the rates of weathering and erosion, when one considers lithology, slope angle, outcrop compass orientation, and physiographic province. These variations in erosional susceptibility can produce a range of rock overhang characteristics that can result in increased likelihood of rock failure (Figure 13). The rock types least affected by such erosion are massive lithologies such as sandstone, limestone, siltstone, and to a lesser degree, shale (Figure 13A). Because of their homogeneity these lithologies typically have fewer bedding discontinuities along which weathering and erosion can occur. These lithologies tend to form a

Figure 12. Rock friction. A, Rough and irregular. B, Undulating. C, Planar. D, Slickensides.

subvertical wall with little overhang. In contrast, interbedded lithologies provide varying levels of both weathering and erosion. This variation is known as differential erosion (differential weathering of Vanderwater et al., 2005). The pervasiveness of interbedding is also a key component in the potential for the number and prominence of differential erosion features (Figures 13B, C). With greater differential erosion there is an increased likelihood for the formation of overhanging ledges (Figure 13D), which therefore present greater potential for both rockfall and rock roll events.

Weathering Character

Weathering character is closely related to differential erosion (Figure 14). While Vanderwater et al. (2005) considered these to be the same factor, they will be treated separately herein. Newly created exposures generally present no substantial weathering characteristics. However, with age, rock exposures develop features as a result of weathering. No study outcrop in Allegany County was considered freshly exposed. Massive rock exposures that are susceptible to chemical and physical weathering, have been exposed for a considerable time, or are oriented so that weathering is more effective, tend to display irregular surfaces (Figure 14B). Many more outcrops were categorized as being weathered in relief. These are especially common within limestone strata where solution has removed shaly or more soluble layers along stratification (Figure 14C). The final category, weathered with overhanging ledges, is considered typical of thick

Figure 13. Differential erosion. A, Minor differential erosion within massive siltstone. B, Occasional differential erosion along sandstone interbeds. C, Many differential erosion surfaces within interbedded sandstone and shale. D, Major differential erosion at the contact between the Pottsville and Mauch Chunk formations.

interbedded lithologies, where more massive intervals of rock are interbedded or underlain by more easily removed lithologies (Figure 14D). In this case, weathering produces overhanging ledges created by major differential weathering and erosion. Overhanging ledges appear to be more prevalent where higher levels of freeze-thaw cycles and precipitation are present. Thus, rock exposures of the Appalachian Plateaus Province show greater levels of differential weathering.

Stratification

Because all of the rocks in Allegany County are sedimentary in origin, all bear some level of layering, otherwise known as stratification, or more commonly, bedding (Figure 15). The type, character and orientation of stratification are critical to the understanding of the type of potential slope failure. Massive strata, because of their internal structure, tend to have fewer numbers of failure planes and differential erosion surfaces (Figure 15A). This character, especially common when the rocks are nearly horizontal, tends to present steep roadside slopes and often an elevated launching potential. Strata whose dips are oriented parallel to the roadway present greater thickness of strata available for weathering and exposure, although there is a reduced potential for

Figure 14. Weathering of outcrop. A, B, Weathered on surface. C, Weathered in relief. D, Weathered with overhanging ledges.

strata decoupling and sliding into the roadway (Figure 15C-D). Strata dipping into the roadway tend to present greater potential for slides, glides, or detached rock masses where rock can be displaced into the highway right-of-way (Figure 15E). Likewise, this orientation of stratification provides abundant potential for rock roll events where weathered and decoupled blocks can roll down the inclined slope and into the roadway. By contrast, strata dipping away from the roadway can present steep slopes, but a reduced potential for either slides, falls, and rolls (Figure 15F).

Lithology

The composition, or lithology, of the rocks through which a road cut passes is a fundamental geologic aspect that affects potential for slope failures (Figure 16). Massive sandstone and limestone tend to create steep slopes adjacent to the roadway, and based upon the type and prominence of failure plane within these rock types, may create the potential for rockfalls and rock rolls (Figure 16A). Lithologies that are pervasively interbedded present the greatest potential for differential weathering (Figure 16B, C). Within these lithologies, failure planes may create an increased potential for rockfall and rock roll. If such interbedded lithologies are oriented with dips into the roadway, especially when water is concentrated along bedding planes, they present the

Figure 15. Stratification. A, Massive with stratification poorly discernible. B, Stratification horizontal. C, Stratification inclined parallel to road at <45 degrees. D, Stratification inclined parallel to road, > 45 degree angle. E, Stratification inclined into roadway. F, Stratification inclined away from roadway.

Figure 16. Lithology. A, Massive sandstone/limestone. B, Sandstone/limestone with shaly interbeds. C, Shale with sandstone/limestone interbeds. D, Massive shale. E, Block in matrix.

greatest potential for massive rock slides. Subhorizontal intervals of massive shale rarely are capable of creating steep slopes. These units tend to weather to slopes of small chips and thick soil. These slopes are readily vegetated, and where abundant water is available, can produce slumps and rotations into the roadway. Lastly, irregular sandstone blocks in existing or preexisting landslides can form incoherent masses of loose blocks (Figure 16E). These blocks can roll or slide into the roadway under the influence of frost action or gravity.

Site-Specific Outcrop Survey Utilizing Areal Drone Imagery

Methodology

Unmanned Aerial Vehicle (UAV) flights were used to capture images and videos in order to assess rockfall sites along MD 135 near Luke and Westernport in Allegany County. Both visible light and infrared imagery were collected with the UAV. MDOT SHA performed traffic control during the surveys; they closed one lane to ensure safety of the researcher and UAV pilot. The UAV was flown no more than 100 feet in the air, and was flown within the closed lane. A DJI Mavic 2Enterprise Dual drone with iPad running the DJI Pilot application was used.

UAV video was collected by manual flight and collected in segments for longer outcrops. To collect video, the UAV lifted off the ground to about the height of the top of the outcrop, or to a nearby area of interest (i.e., potential area of groundwater seepage above the outcrop), and maneuvered horizontally at roughly the same elevation across the outcrop. Each segment was approximately 250 feet long. Once the UAV reached the end of the segment, the pilot lowered the elevation of the UAV and continuously captured video as it flew back towards the crew. While the UAV pilot monitored the UAV in air, a geologist monitored the iPad to ensure overlapping data collection. The UAV flight continued in a back-and-forth pattern until ground-level video was captured.

Pix4D Mapper software was used to take the video from each section, break it into frames, and utilize the images to create a point cloud and a singular stitched image by utilizing structure from motion technology. The UAV is equipped with a global positioning system (GPS), stored location coordinates in WGS 1984 UTM Zone 17N.

Advantages

Drone imagery had a few advantages for characterizing rockfall sites. First, it captured in-depth video, in both visible and infrared light, at heights and angles not visible from the road. This allowed the researchers to see failure planes, water sources, and loose blocks not captured in traditional data collection (Figure 17A). This video could be used to monitor sites over time. Second, viewing the infrared video side-by-side with visible light video was helpful in correlating temperature variations for potential areas of groundwater seepage (Figures 17B, C). Third, drone data collection was relatively quick. Three road cut sections 200-300 feet long, west of Westernport, took approximately 2 hours to collect, including MDOT SHA traffic control set-up.

Disadvantages

However, there were challenges to drone imagery collection. Safety of the drone survey crew and passing drivers was the first concern. Even with one lane of traffic control in place, the drone crew did not have abundant room to maneuver themselves and keep the UAV a safe distance from passing vehicles. Second, there were obstructions to the drone flight path, such as overhanging power lines and trees, and it was easy to lose sight of the drone when flying high enough (>100 feet) to capture images of the upper portion of the hillslope. Third, images produced by stitching drone photos together were somewhat distorted. Furthermore, processing was time-intensive without a super-computer or cloud processing features. For example, a stitched image of 850 photos for a 25-foot-wide slide area west of Westernport took approximately 15 hours to process (Figure 18C). Fourth, due to low resolution of infrared video capture, infrared images did not produce a coherent stitched image. Additionally, when the UAV was not flown far enough away from the outcrop, or was rotated while flying, the resulting stitched image was distorted (Figures 18B, C).

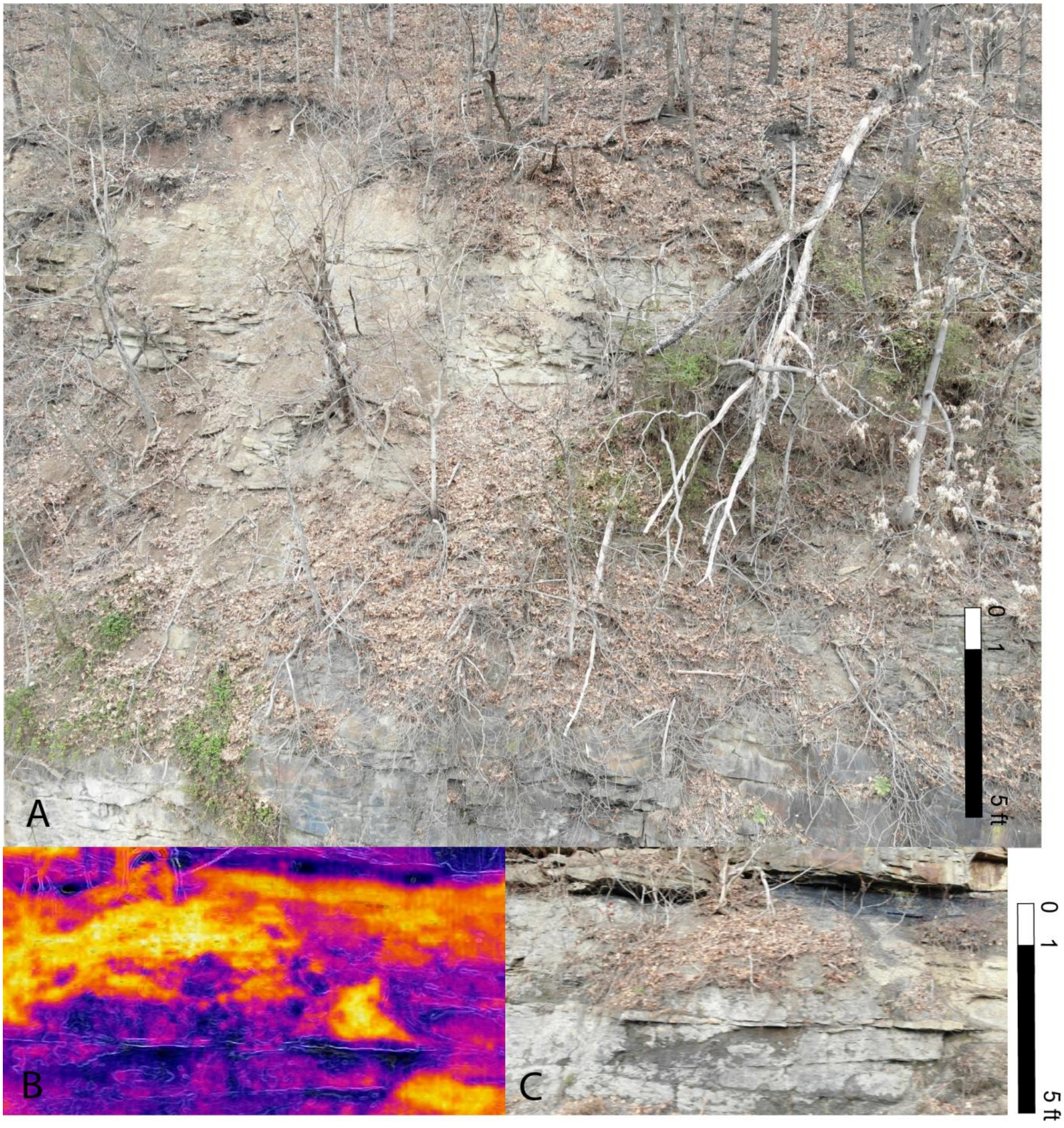


Figure 17. Drone imagery. See Figure 18A for location. A, Slide scarp approximately 50 feet above road, on hillside above two massive sandstone layers. Not visible from road level. B, Infrared drone imagery (orange/red = warm, purple/black = cold) of bedrock layers (purple) with water (black) exiting along stratification in the Allegheny Formation. C, Visible drone imagery, same area as B.

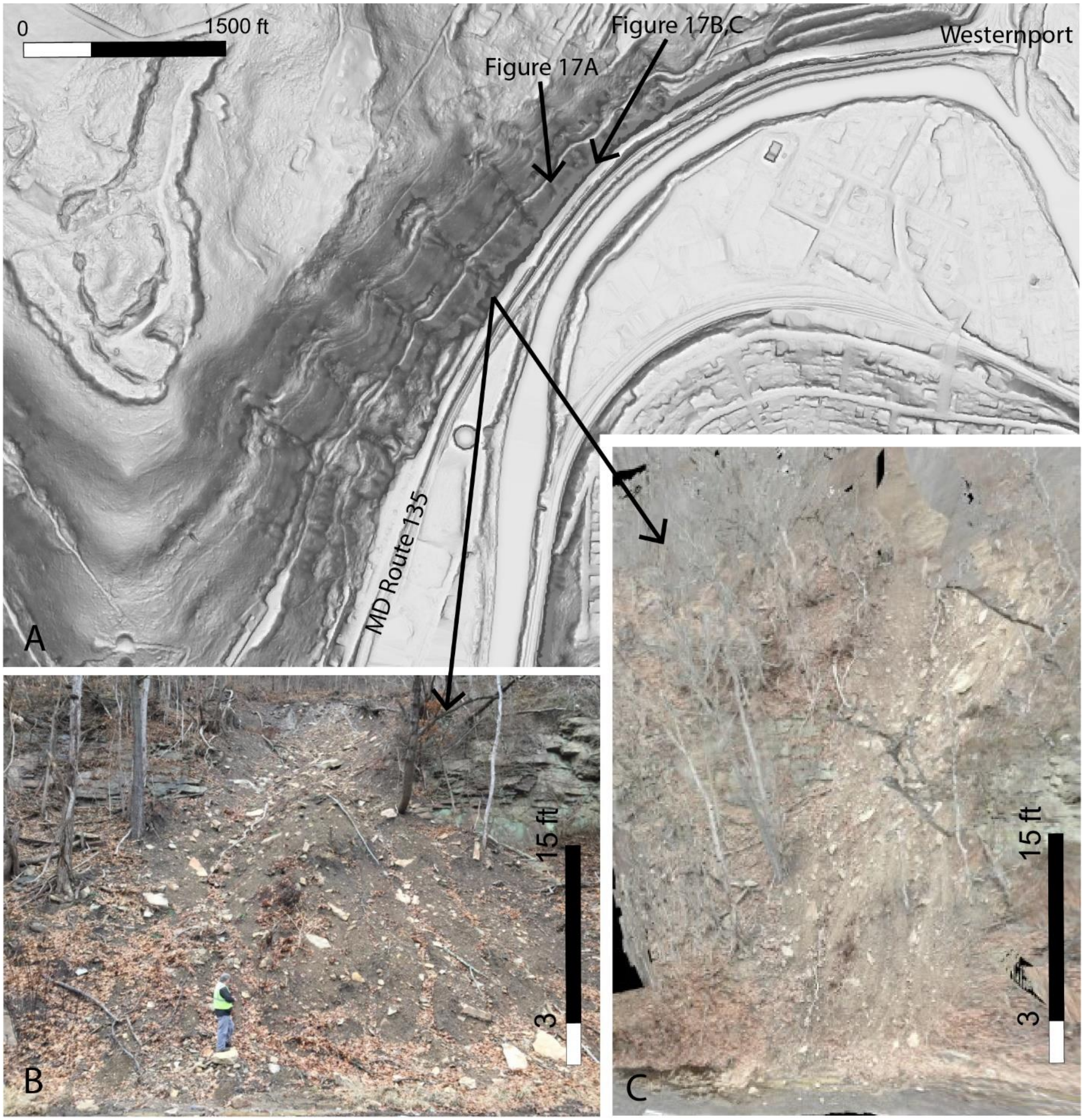


Figure 18. Slope failures. A, LiDAR image showing channel visible on hillslope above MD Route 135 that leads to slide area in photos B and C. Similar channels nearby also visible. B, Standard photo of slide area. C, Stitched image of drone photography, same location as B.

Analysis

Examination of drone video footage, in visible light and side-by-side with infrared light, emphasizes the importance of groundwater exiting along bedrock stratification, and delineates a slope failure above the height visible from the roadside on MD 135, both east and west of Westernport. The groundwater seepage and slope failure are likely related; both features may be exacerbated by drainage from mining in coal beds at and above the level at which water exits the hillside in the MD 135 road cut. Strip and deep mining in the Upper Freeport, Barton, and Pittsburgh coal beds is visible in recent Garrett County LiDAR hillshade imagery (MDiMap, 2015) and was documented in historic mine maps of Franklin Hill that forms the promontory above the study outcrops. Most of the visible channels on this hillslope initiate at the level of the Upper Freeport coal.

Evaluation of Survey Geology Elements

The rock outcrop characteristics of 195 roadside slope exposures (Figure 19) were cataloged using the above-categorized features. For each of these locations, up to 36 outcrop qualities were recorded, and images of multiple perspectives of the outcrop also were taken. When evaluating the more than 7,000 data observations, it became difficult to sort out subtle relationships. Because of the voluminous nature of this data set geologic insights gathered from both the field work and empirical data collection are summarized herein. Complete data analysis was viewed as beyond the goals of the current effort.

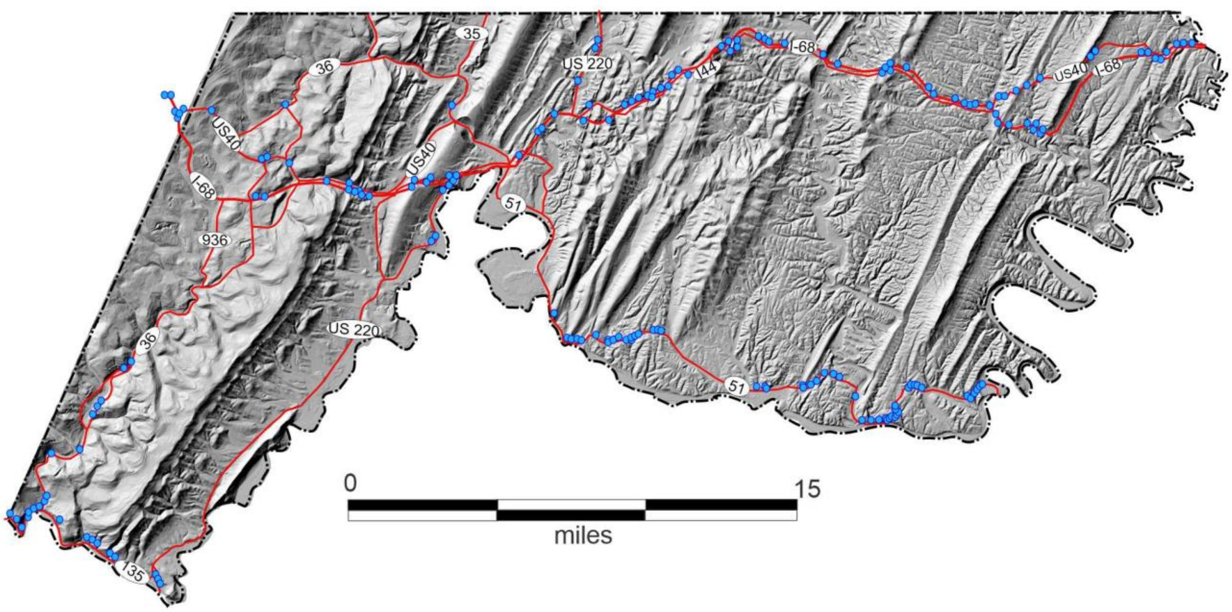


Figure 19. Summary map illustrating approximate locations of highway slopes evaluated during this study (blue dots).

The geographic distribution of studied exposures gives a representative sampling of rock units, physiography, and structural qualities for the bedrock of Allegany County (Figure 19). Figure 20 illustrates the relative potential for the individual types of slope failure as inferred from observations take from the 195 roadside sites. Rock roll was the most common type of potential slope failure and accounted for more than 51% of the locations. Nearly one-quarter of the locations had some level of rockfall potential (24%), while rock slides and slumps or rotations had a 14 % and 11% failure potential, respectively.

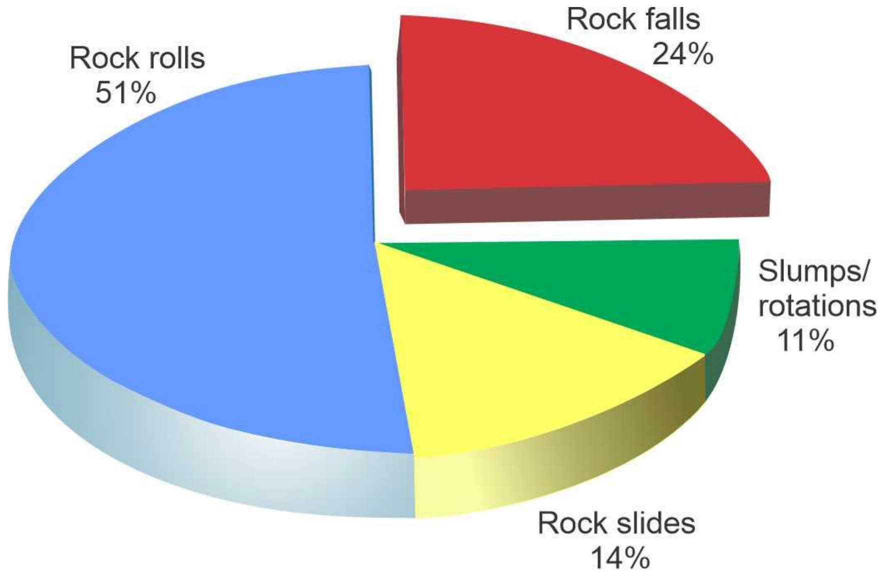


Figure 20. Pie diagram showing relative percentages of potential slope failures identified from roadside exposures in Allegany County, Maryland.

Perhaps one of the most fundamental relationships confirmed by this data set is that steeper slopes produce greater potential for slope failure incidence (Figure 21). Based upon these data, rockfall potential exists in slopes ranging from 40 to 90 degrees. Elevated prospects exist in slopes greater than 70 degrees (Figure 21A). Interpreted potential for rock roll ranged in slopes of between 20 to 70 degrees (Figure 21B). Greatest interpreted potential was for slopes of between 40 and 50 degrees. Surmised rock slide potential was found for slopes that ranged between 30 and 90 degrees (Figure 21C). Although the inferred potentials were on slopes between 50 to 60 degrees, these number are largely confined to strata that dip towards the roadway. The potential for slumps and rotations was found to be similar in slope steepness as for rock slides (Figure 21D). The range for these potential failures was from 30 to 80 degrees, with an identified peak probability at between 40 to 50 degrees.

Although slope steepness was one of many factors determined to contribute to type of slope failure, subsequent discussion will concentrate on what are considered as geologic factors. These intrinsic rock characteristics were deemed to play substantial roles in the type of slope failures (Figure 22). Based upon review of these data, information on stratification, lithology, fracture character, and differential erosion were chosen for evaluation.

The orientation of stratification was judged to be a significant contributing factor in roadway slope failures (Figure 22A). Based upon inferences derived from these data, rockfall potential appears to be highest within strata that are either horizontal or are inclined parallel to the

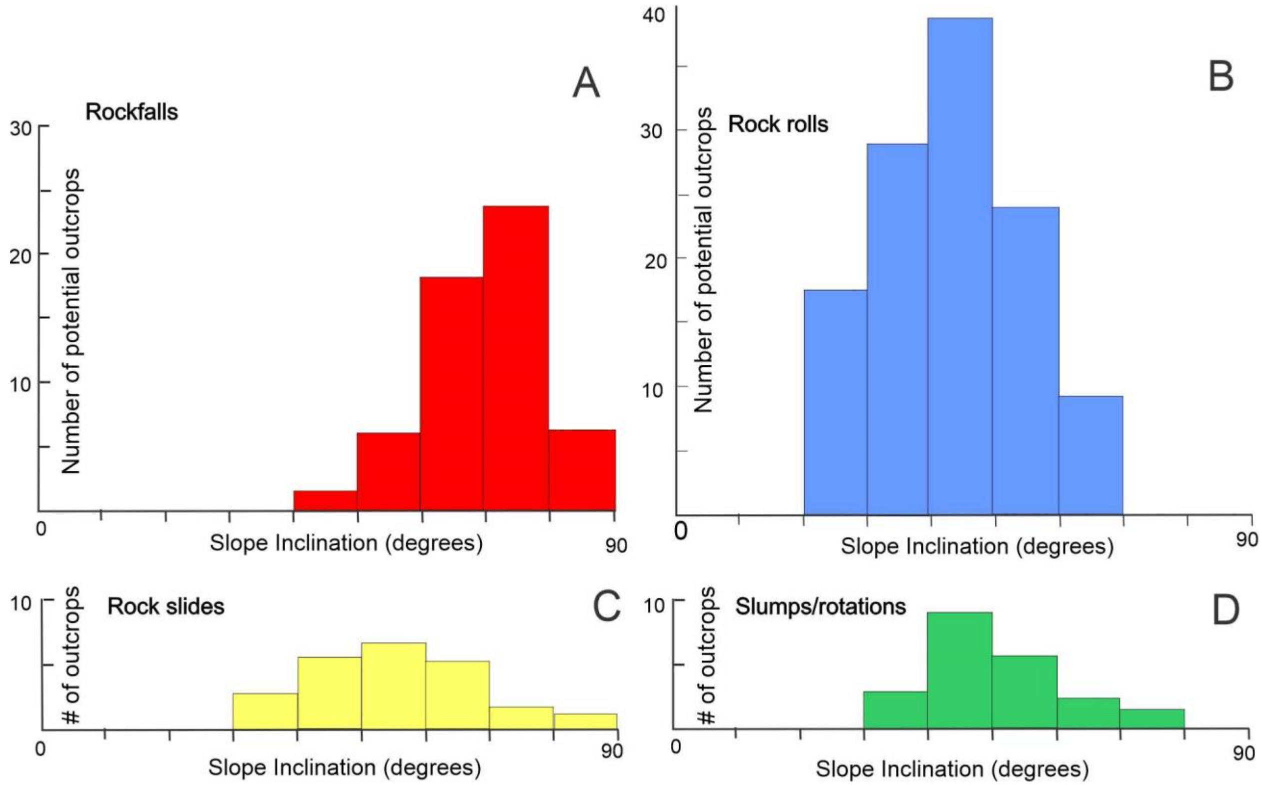


Figure 21. Embankment steepness and its relationship to slope failure type.

roadway, but at less than 45 degrees. The potential for rock roll is deduced to be relatively constant across the varying strata orientations. The only exception is a minor increase in potential for cases where bedding is parallel to the roadway and inclined at less than 45 degrees. Rock slide probability is generally low, except where strata are inclined into the roadway. Slumps or rotations do not seem to be substantially related to stratification.

Based on outcrop numbers, lithology was considered a significant geologic factor contributing to potential slope failure (Figure 22B). Allegany County data demonstrate that rockfall potential is substantially higher within massive lithologies than within other rock types. This relationship is somewhat reduced within thick-bedded sandstone and/or limestone units that have interbedded shaly layers. Rockfalls are lower in potential where shale with interbeds of sandstone, massive shale, and block in matrix form the slope. The reason for this relationship may not be directly related to lithology, but it maybe tied to road construction techniques. Outcroppings of massive sandstone, or thick intervals of sandstone with shaly interbeds are capable of forming steep-sided rock exposures. As such, excavations passing through these lithologies tend to be steeper than those that pass through rock types that are less resistant to weathering and erosion, like shale. The resulting steep road cuts, therefore, is more prone to rockfall incidence.

Rock roll was the most prevalent type of slope failure associated with divers lithologic packages. This failure type makes up between 50% and 77% of the potential failures within interbedded lithologies, but typically makes up less than 50% of the inferred failure potential within massive lithologies. Rock slides and slumps and rotations appear to be little associated with lithology.

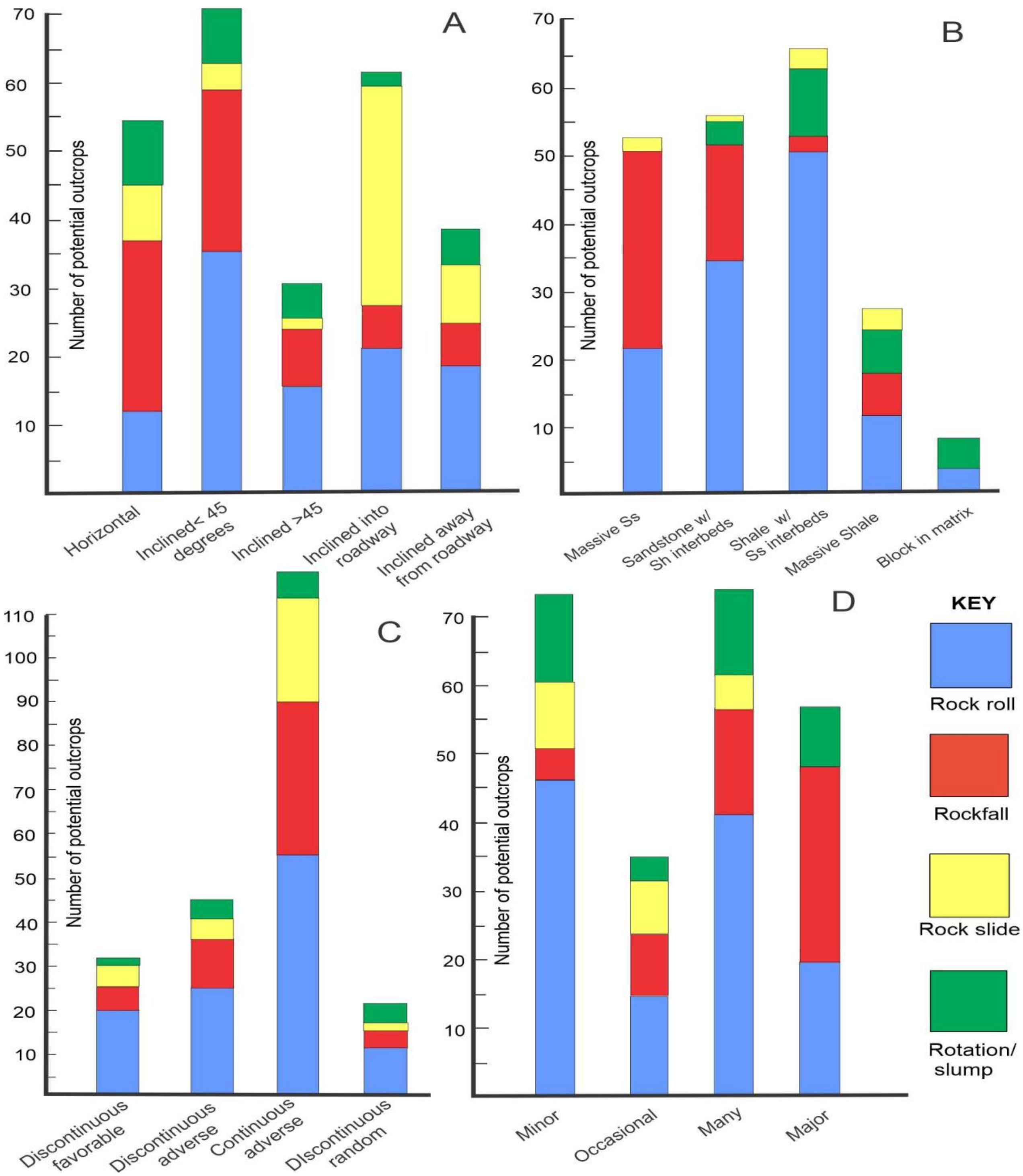


Figure 22. Geologic factors related to slope failure. A, Stratification and its frequency in potential failure. B, Lithology and its potential frequency in failures. C, Character of fracture planes and relations to slope failure type. D, Amount of differential weathering and its potential relationship to type of slope failure.

One geologic factor that appears to play a substantial role in the potential for roadway slope failure is the character of the fracture planes within the rock unit (Figure 22C). Fracture planes that are continuous and adverse to the roadway appear to be correlative to most types of failures. This type of fracture system was interpreted to be responsible for 57% of potential failures in the outcrops studied. No other joint or fracture characteristic was responsible for more than 20% of potential failures.

Another factor that impacts the likelihood, degree, and type of slope failure is the extent of differential erosion (Figure 22D). This figure illustrates the increased potential for rockfalls where major amounts of differential erosion are present. This is because signficant amounts of differential erosion create over-steepening of slopes and lead to a greater likelihood of rockfalls. Also, rock roll can be shown to have an increased potential where many differential erosion surfaces exist. Differential erosion does not appear to play a significant role in the creation of rock slides or slumps and rotations.

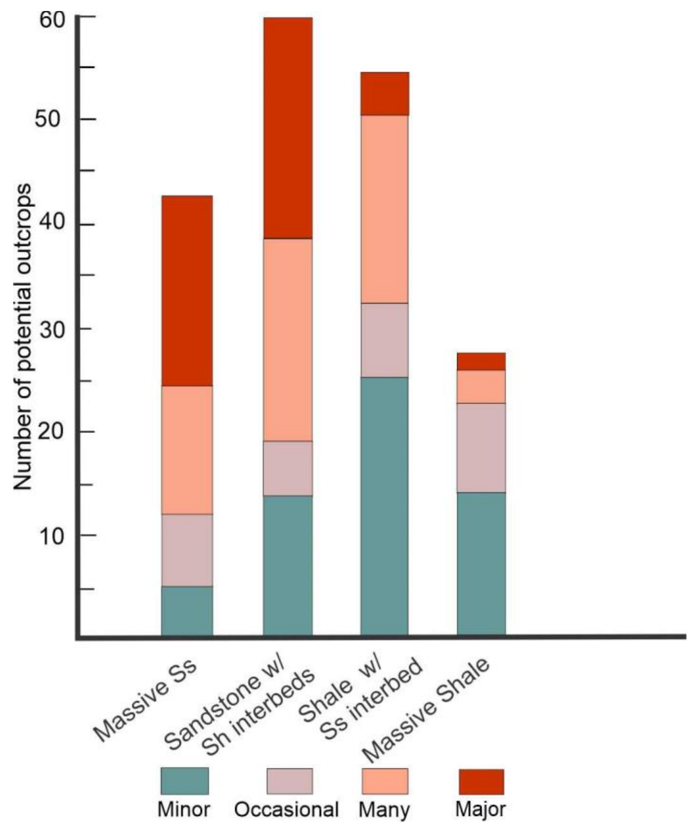


Figure 23. Lithology and its potential relationship to differential erosion.

As discussed in the earlier section on differential erosion, this feature is related to both the weathering rate and lithology. Because differential erosion or differential weathering is more pronounced in interbedded lithologies, it would appear to have a greater tendency to produce loosened rock fragments within those lithologies. Figure 23 illustrates this relationship between differential erosion and lithology. Contrary to *a priori* notions, massive lithologies that are resistant to erosion, such as sandstone and limestone, as well as those resistant lithologies with thin interbeds of shale display a definite differential erosion potential. Meanwhile, shales with lesser amounts of interbedded sandstone and/or limestone and massive shales tend to produce lower levels of differential erosion potential.

Geologic Factor Summary

In Allegany County, Maryland, climate, topography, and geology all play varying roles in highway slope stability. Variations in precipitation, elevation, and climate are extrinsic factors that act on outcrops on a regional scale. In contrast, geologic factors such as bedrock composition, orientation, and structure are local factors that may vary from one outcrop to another. These outcrops characteristics produce gradational variations that intrinsically control slope failure. Several key geologic factors are summarized in Table 1.

Failure type	Lithology	Stratification	Differential Erosion	Fracture Character	Slope Steepness
Rock fall	Major factor in massive to interbedded lithologies	Important factor when strata are horizontal to dipping @ <45°	Major factor	Major factor when fractures are continuous and adverse	Very important on slopes >60°
Rock roll	Especially important with interbedded lithologies	Greatest on beds inclined <45°	Varies from minor to many	Very Important factor when fractures are continuous and adverse	Greatest on slopes of 30 to 60°
Rock slides	Minor factor for interbedded and shaly lithologies	Major factor when strata dips into roadway	Minor factor in slide occurrences	Major factor when oriented normal to inclined bedding	Minor factor
Slump/ rotation	Not significant factor	Minor factor with inclined strata	Not significant factor	Not significant factor	Important factor

Table 1. Summary of factors contributing to potential roadway embankment failures in Allegany County, Maryland.

Regional topographic and climatic, and local geologic factors provide contributing roles in slope failure. However, geologic factors provide a metric that allows empirical evaluation of potential failures.

GLOSSARY

Anticline – A convex-upward bend in rock, the central part of which contains the oldest section of rock.

Argillaceous – Containing significant amounts of clay.

Bedding – Original or depositional layering in sedimentary rocks. Also called stratification.

Bedrock – Solid rock that underlies unconsolidated material, such as soil.

Limestone – A rock composed of calcium carbonate.

Cherty – Consisting, or being made up of high contents of microcrystalline SiO_2.

Cleavage – A dense set of subparallel stress fractures cause by the bending of strata within folded rocks.

Colluvium – A sedimentary deposit formed by the movement of unconsolidated material down steep slopes.

Cross-bedding – The arrangement of sedimentary beds tilted at different angles to each other, indicating that the beds were deposited by flowing water or wind.

Fault – A rock fracture in rock along which movement can be identified.

Fracture **-** A crack or break in rock.

Joint – A fracture along which no movement has occurred.

Interbedded – Alternations of layers of rock with beds of a different kind of rock.

Landslide – Any group of mass movements characterized by downslope passage of rock or soil.

Lithology – Referring to the composition and character of a specific rock type.

Orographic effect –Change in climatic conditions that result from sharp variations in elevation.

Physiographic – The topographic character of a regions based on it climate, bedrock, their orientation, and weathering.

Sandstone **-** A clastic sedimentary rock composed of sand-size particles. This size ranges in diameter from 1/16 millimeter to 2 millimeters.

Shale – A clastic sedimentary rock composed of clay particles.

Shale barren – Hill slope, generally south facing, where paucity of precipitation provides opportunity for colonization by arid to semiarid vegetation.

Slickensides– A polished rock surface created by frictional movement of rocks.

Slump – Downslope movement of water-saturated material such as rock and soil along a curved failure surface.

Strata – Layers of sedimentary rock.

Stratification – The layering in sedimentary rock.

Rockfall – Slope failure where loosened rock fragments fall ono the roadway. Includes rock topples.

Rock roll – Gravity induced failure created by downslope rolling of dislodged rock fragment. ***Rock slides*** **-** Downslope movement of sheets of rock along planar sliding surface such as a bedding surface or fracture plane.

Rain shadow – Areas that experience reduced precipitation as a result of their presence on the leeward side of a topographic ridge or mountain range.

Weathering – The process of chemical and physical breakdown of rock into soil by water, ice, and atmospheric, and biologic means.

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Larry Hogan
Governor

Boyd K. Rutherford
Lt. Governor

Jeannie Haddaway-Riccio
Secretary

Charles Glass
Deputy Secretary

A message to Maryland's citizens

The Maryland Department of Natural Resources (DNR) seeks to balance the preservation and enhancement of the living and physical resources of the state with prudent extraction and utilization policies that benefit the citizens of Maryland. This publication provides information that will increase your understanding of how DNR strives to reach that goal through the earth science assessments conducted by the Maryland Geological Survey.

MARYLAND DEPARTMENT OF NATURAL RESOURCES
Resource Assessment Service
Tawes State Office Building
580 Taylor Avenue
Annapolis, Maryland 21401
Toll free in Maryland: 877-620-8DNR
Out of State call: 410-260-8021
TTY users: Call via the Maryland Relay
Internet Address: dnr.Maryland.gov

MARYLAND GEOLOGICAL SURVEY
2300 St. Paul Street
Baltimore, Maryland 21218
Telephone Contact Information: 410-554-5500
Internet Address: mgs.md.gov

DNR Publication No. 12 DNR 12-041720-227
2020