PHASE 1 GEOLOGIC MAP DATABASE OF KARST GEOLOGY IN THE I-81 CORRIDOR

Supplemental Text and Figures for Open-file Report 2022-10

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VIRGINIA Energy

November 4, 2022

INTRODUCTION

This report accompanies a derivative geologic map and geodatabase developed by the Virginia Department of Energy, Geology and Mineral Resources Program (GMR). The intent of these products is to help landowners, businesses, industries, consultants, and government agencies make wise decisions in karst areas. Karst is a type of landscape that develops when the underlying bedrock is partially dissolved by groundwater. Karst areas contain environmentally sensitive features such as caves, springs, sinking streams, and sinkholes (Figure 1). This geodatabase is a product of a first phase of work that will eventually provide similar information for all areas along Interstate 81 and U.S. Route 11 in Virginia (Figure 2).

Geologic layers in the geodatabase include polygons that show the distribution of soluble carbonate bedrock and surficial deposits that lie on top of the bedrock, lines that show the locations of known faults, folds, and dikes within carbonate bedrock, and points that identify relevant structural measurements, Virginia Department of Transportation (VDOT) geotechnical borings with external links to available logs, VDOT sinkhole mitigation locations, and GMR carbonate rock sample locations with available specimens, thin sections, and/or geochemical analyses. Springs and sinkholes are provided as separate layers. In addition, a model of the density of karst features is provided, derived using sinkhole data developed during this project and from the Virginia Cave Board.

LOCATION AND GEOLOGIC SETTING

Interstate 81 extends for 325 miles in western Virginia and generally parallels U.S. Route 11 (Figure 2). Corridors along these two transportation routes contain farms, residential developments, diverse industries and businesses, and 25 colleges and universities. The first phase of the karst derivative mapping for this project includes approximately 107 miles of interstate, from approximately mile marker 295 at Strasburg to approximately mile marker 188 at Lexington. It encompasses 18 7.5-minute topographic quadrangles (Figure 2) extending from the Toms Brook quadrangle in the northeast to the Lexington quadrangle in the southwest and includes all or a portion of the towns and cities of Strasburg, Woodstock, Edinburg, Mount Jackson, New Market, Broadway, Harrisonburg, Bridgewater, Staunton, Stuarts Draft, Buena Vista, and Lexington. The study area contains headwater portions of the Shenandoah-Potomac River and James River watersheds.

Much of the map area is located within the Valley and Ridge Geologic Province. The sedimentary bedrock of this province has been folded and broken in many places by faults (Figure 3). Bedrock layers include resistant sandstone and chert, and less resistant shale, limestone, and dolostone. The weathering and erosion of these variable earth materials has resulted in a distinctive topography consisting of northeast-trending ridges and valleys, and conical hills (Figure 3). Portions of Cornwall and Vesuvius quadrangles in the southern portion of the map area contain areas underlain by metamorphic bedrock of the Blue Ridge Geologic Province, which are generally more resistant to weathering and not prone to karst development. Bedrock throughout the map area is overlain in places by loose sediment that was deposited by flowing water or gravity. In other areas, the regional climate over time has produced a variably thick mantle of residual soil through the process of chemical weathering.

Figure 1. Photos of karst-related features in and near the project area. (a) sinkhole in a wooded area near Lexington, (b) water-filled sinkhole west of Harrisonburg, (c) cave opening in northern Rockingham County, (d) spring west of Broadway, (e) channels called runnels that form when water flowing along limestone dissolves bedrock, near Lexington, (f) tufa or travertine (calcium carbonate) that precipitates when a spring brings up groundwater quickly from depth along a fault, west of Broadway.

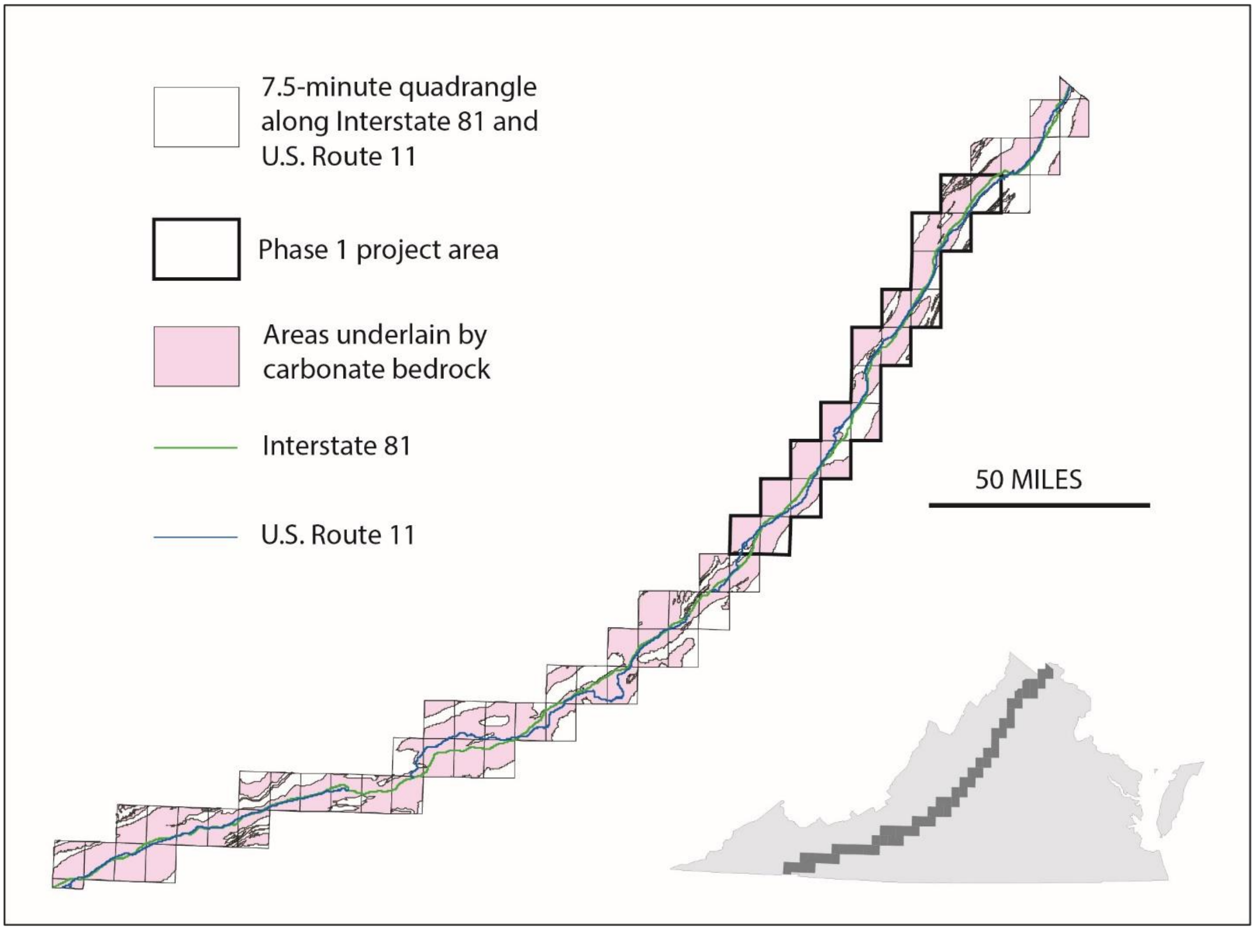

Figure 2. Map showing the location of the karst derivative mapping project area, and the portion of the project area underlain by carbonate bedrock, as portrayed by Witt and others (2021).

GEOLOGY AND KARST DEVELOPMENT

The character of bedrock layers plays an important role in karst development. Limestone and dolostone layers are composed largely of carbonate minerals that are soluble in groundwater. Sandstone, shale, and siltstone layers are composed of mostly non-carbonate minerals and are relatively insoluble. Limestone is more soluble than dolostone, and pure limestone is more soluble than impure limestone that is mixed with mud or dolomite (Figure 4). A limestone layer that is interbedded with less soluble layers may dissolve more quickly if a path of least resistance develops within the layer over time and groundwater flow is concentrated along that path. Carbonate map units within the Karst Derivative Phase 1 project area range from mostly pure limestone to dolostone or lime mudstone mixed with non-carbonate rocks (Figures 5-8; Table 1).

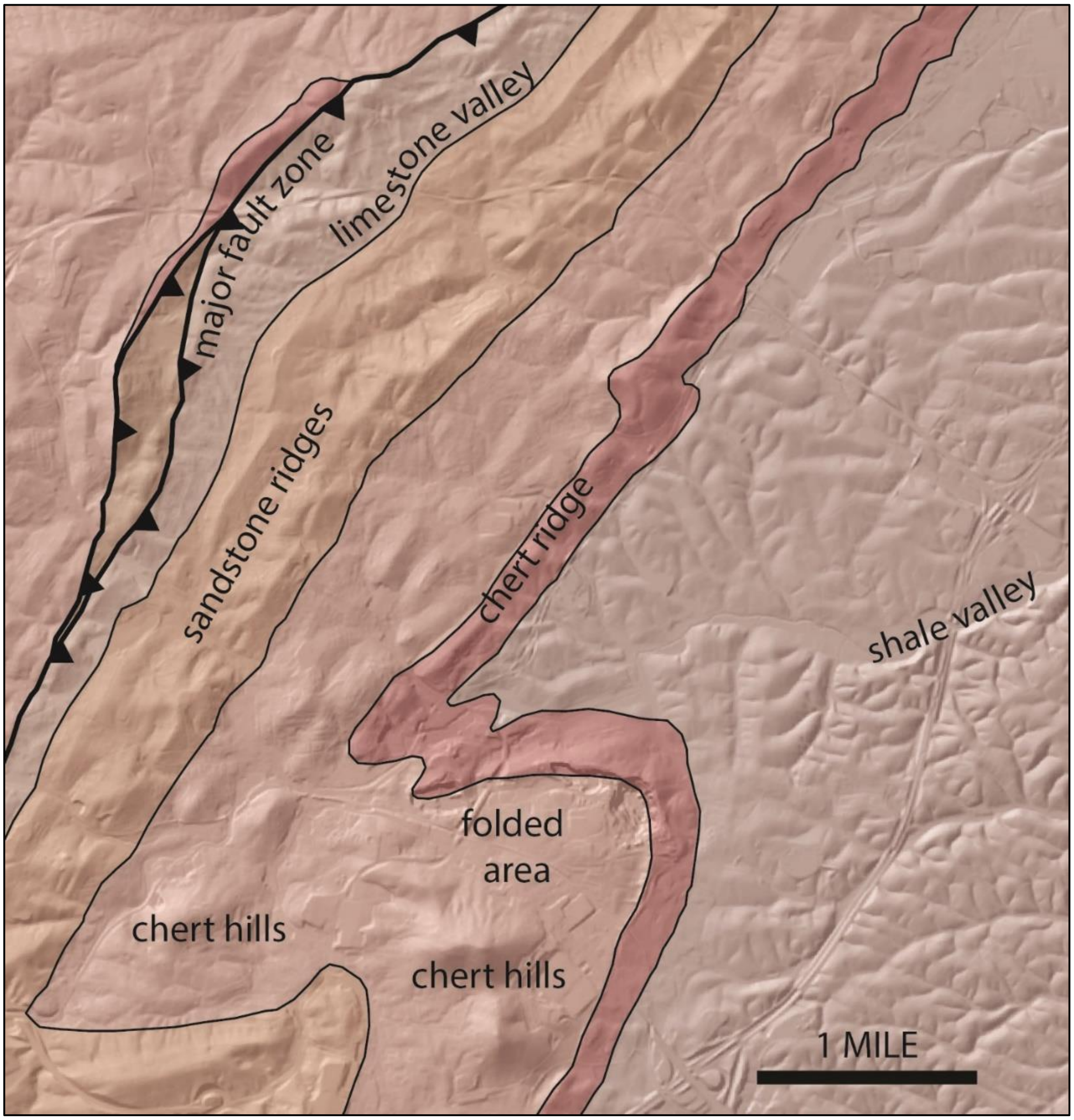

Figure 3. Map showing a portion of the project area, east of the City of Staunton. Each color represents a different bedrock formation. Typical geologic features such as folds, faults, and bedrock-controlled landforms can be observed. Geology is after Rader (1967) and Duncan and others (2004).

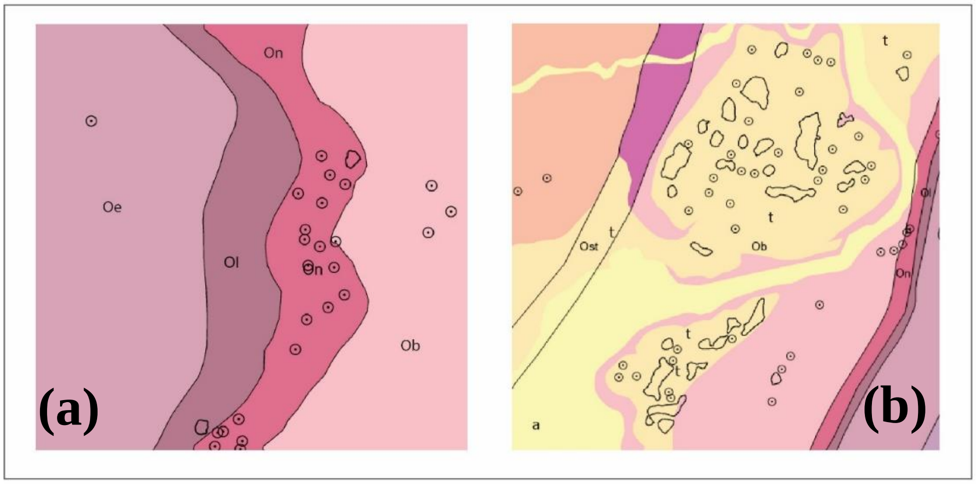

Figure 4. Sinkholes (circled dots and irregular areas with black outlines) have an increased density when associated with (a) a purer limestone formation, such as the New Market Limestone, south of Harrisonburg, and (b) terrace deposits along the north fork of the Shenandoah River near New Market.

Table 1. General characteristics of carbonate map units in the Karst Derivative Map Phase 1 project area, based on observations made during mapping in the area.

Map Unit / Lithology	Solubility	Residual soil
Mostly limestone		
Helderberg Group (Dhl)	high	thin
Lincolnshire Formation Ol)	moderate to high	thin to medium
New Market Limestone (On)	high	thin
Stonehenge Limestone Ost)	moderate to high	thin to medium
Mostly dolostone		
Shady Dolomite (Cs)	moderate	thin to thick
Mostly dolostone and limestone		
Beekmantown Formation (Ob)	moderate to high	medium to thick
Conococheague Formation (Occo)	moderate to high	medium to thick
Mixed limestone and lime mudstone		
Edinburg Formation (Oe)	low to high	thin to medium
Martinsburg formation (Ombc)	low to moderate	thin
Carbonate and non-carbonate rock		
breccia (b)	variable	variable
Devonian and Silurian Rocks (DS and Dsu)	variable	variable
Waynesboro (Cwb)	variable	thin to thick

Figure 5. Photos of relatively pure limestone map units, (a) New Market Limestone and (b) Lincolnshire Formation, both near the hamlet of Tenth Legion, (c) Helderberg Group limestone west of Broadway, and (d) Stonehenge Limestone south of the town of Broadway.

Geologic structures are also important in the development of karst. Bedrock layers that have closely spaced fractures can interact more effectively with groundwater, which increases the rate of chemical weathering. Faults can fracture the adjacent bedrock and juxtapose different types of bedrock layers. When groundwater moving through a soluble layer encounters a non-soluble layer at a fault boundary, groundwater sometimes makes a path along the fault plane to the surface and emerges as a spring (Figure 9). Folding can also place a soluble bedrock layer in a favorable position for karst development. Springs are sometimes observed where the hinge of an anticline (up fold) intersects the ground surface (Figure 9). Sinkholes are sometimes observed to be more dense in areas near the hinge of a fold where soluble beds are parallel to the ground surface over larger areas. On the limbs of folds, sinkholes exhibit a linear pattern tracing a soluble layer that is dipping more steeply into the earth.

Figure 6. Photos of mixed carbonate units. (a) Elbrook Formation, which contains dolostone, limestone, and non-carbonate rock layers at the base, near Cornwall, (b) Waynesboro Formation, which contains dolostone, lesser limestone, and approximately 50% non-carbonate rocks, near Cornwall, (c) Conococheague Formation, which contains limestone with lesser dolostone and sandstone, near Vesuvius, and (d) Beekmantown Formation, which ranges from being nearly all dolostone to interbedded dolostone and limestone, west of Harrisonburg.

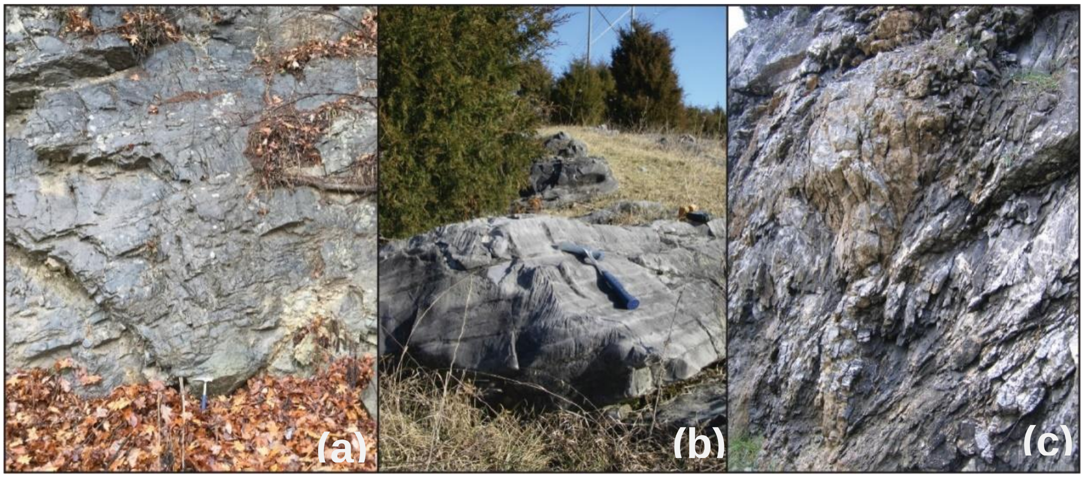

Figure 7. Photos of other selected map units. (a) Shady Dolomite, which is mostly dolostone, (b) Edinburg Formation, which contains lime mudstone, limestone, and calcareous shale, near Tenth Legion, and (c) lower Martinsburg Formation, contains calcareous shale and thin beds of lime mudstone, east of Lexington.

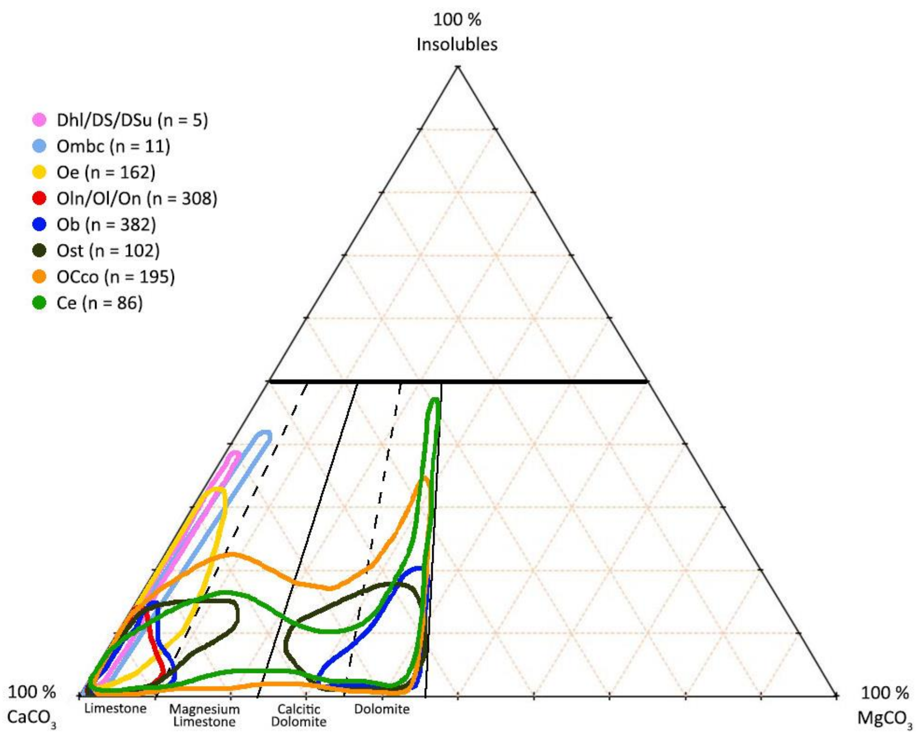

Figure 8. Ternary diagram illustrating the range of chemical compositions of carbonate rocks within map units using the classification system of Hershey and Maher (1985), based on analyses from Giannini and Hostettler (1994), and other unpublished GMR analyses. Dhl/DS/DSu = Devonian and Silurian formations, undivided, including the Helderberg Group, Ombc = lower Martinsburg Formation, Oe = Edinburg Formation, Oln = Lincolnshire Formation and New Market Limestone, Ob = Beekmantown Formation, Ost = Stonehenge limestone, OCco = Conococheague Formation, Ce = Elbrook Formation.

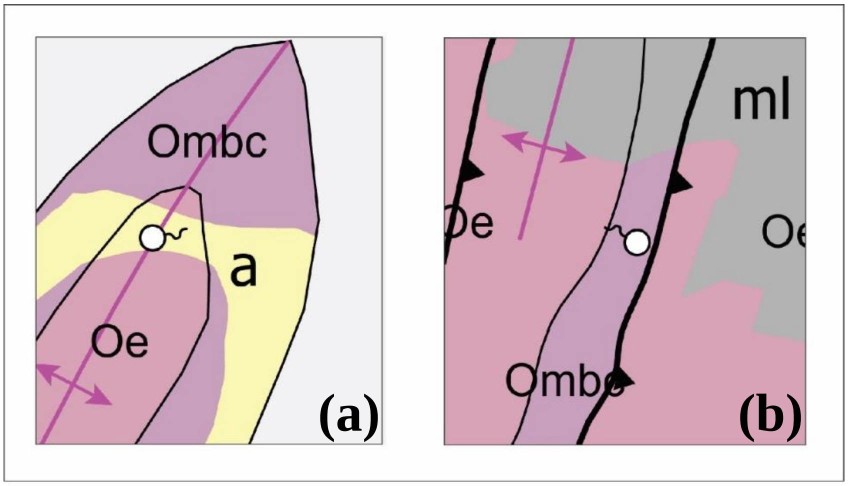

Figure 9. Examples of springs (white circle with wavy line in downstream direction) on geologic maps near (a) the hinge of a fold (magenta line with arrows) and (b) a fault (bold line with teeth). Both examples are from the Broadway quadrangle. Geology after Heller and others (2014).

Fractures that allow for groundwater movement are most likely to develop along existing bedding, cleavage, and joint planes. Statistical analyses of these measurements can provide insights to their orientations over a large area. The analysis of the 18 7.5-minute quadrangle area was split into two domains by the Staunton-Pulaski thrust fault, which is a major structural break in the geology (Figure 10). This statistical analysis reveals that most bedding planes trend NE-SW (Figure 11A-B). Due to folding, bedding planes dip into the earth at various angles, but most commonly dip moderately to steeply to the SE (Figure 11A-B). Cleavage planes are generally steeper than bedding planes and trend in a similar NE-SW direction (Figure 11C-D). Joint planes are most often oriented in a NW-SE direction, and the majority dip moderately to steeply into the earth (Figure 11E-F). Linear sets of sinkholes are commonly observed to be parallel to the regional trends of bedding and cleavage, suggesting that fractures developed along these surfaces are important to karst development. Clusters of sinkholes trending N to NW are less frequently observed, suggesting some karst development may also be related to fractures developed along pre-existing joints.

The density and characteristics of sinkholes that develop in an area are also controlled by the type of soluble bedrock that is present (Table 1). In many areas within purer limestone units where sinkholes are well exposed at the surface, it is apparent that dissolution of bedrock is the primary process involved in sinkhole formation, as these rocks do not typically develop thick overlying soils (Table 1). While breccias observed in some areas do suggest the collapse of overlying rock may play a role in the formation of some sinkholes, historical reports are rare. In contrast, impure limestones and dolostones that are interbedded with other non-carbonate rock types tend to develop thicker soils (Table 1). The sinkholes developed in this type of bedrock can sometimes involve the collapse of overlying soil above a void that has formed by dissolution of the underlying bedrock and winnowing away of soil by recharging groundwater. Cover collapse sinkholes are reported on a regular basis, and are sometimes related to a recent change in land use that impacts surface water runoff, groundwater recharge, or aquifer conditions. Most rapid sinkhole collapses reported to

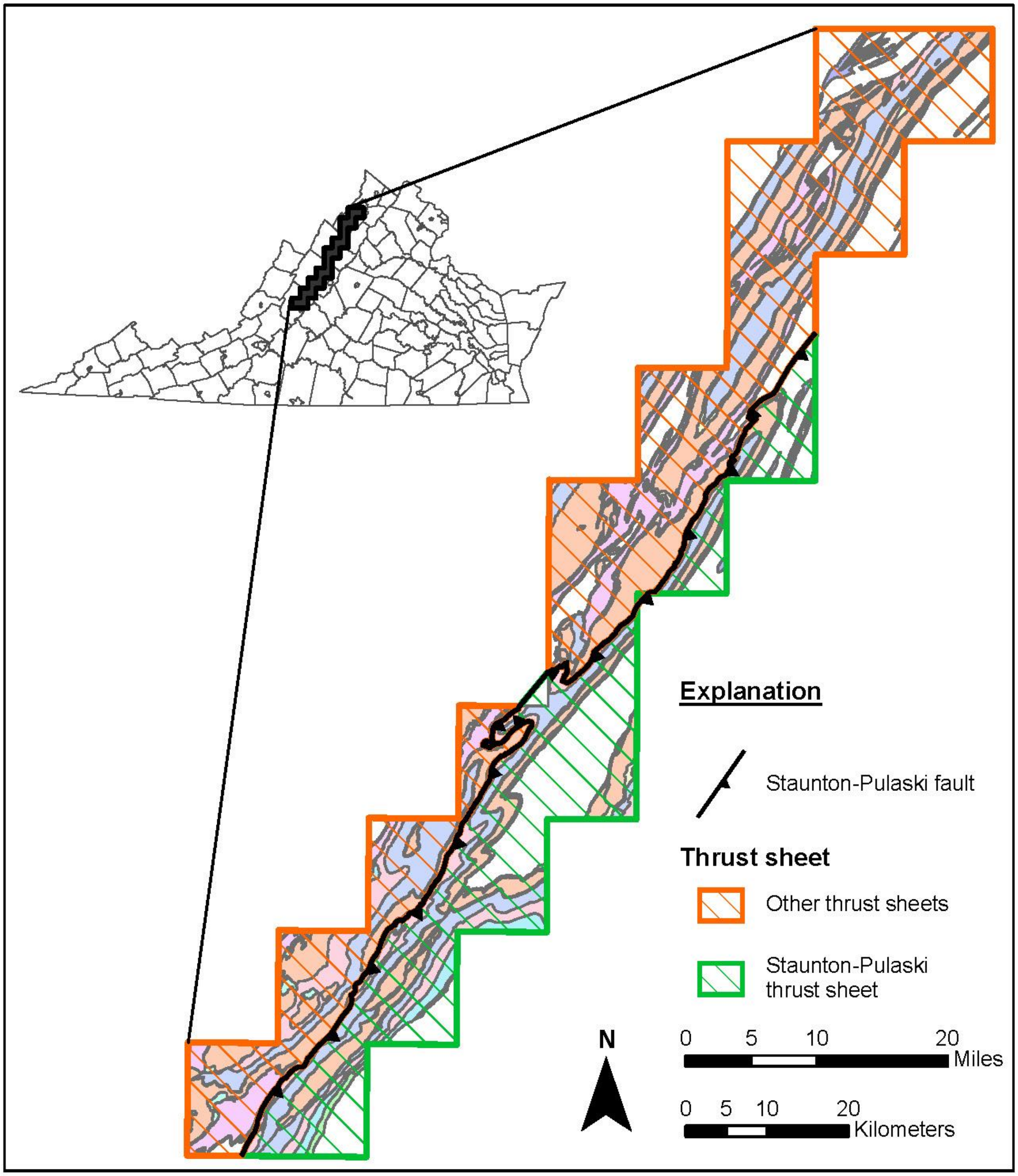

Figure 10. Map of the Phase 1 Karst Derivative Map project area showing two major structural domains bounded by the Staunton-Pulaski thrust fault. These two domains were used to group structural measurements for analysis.

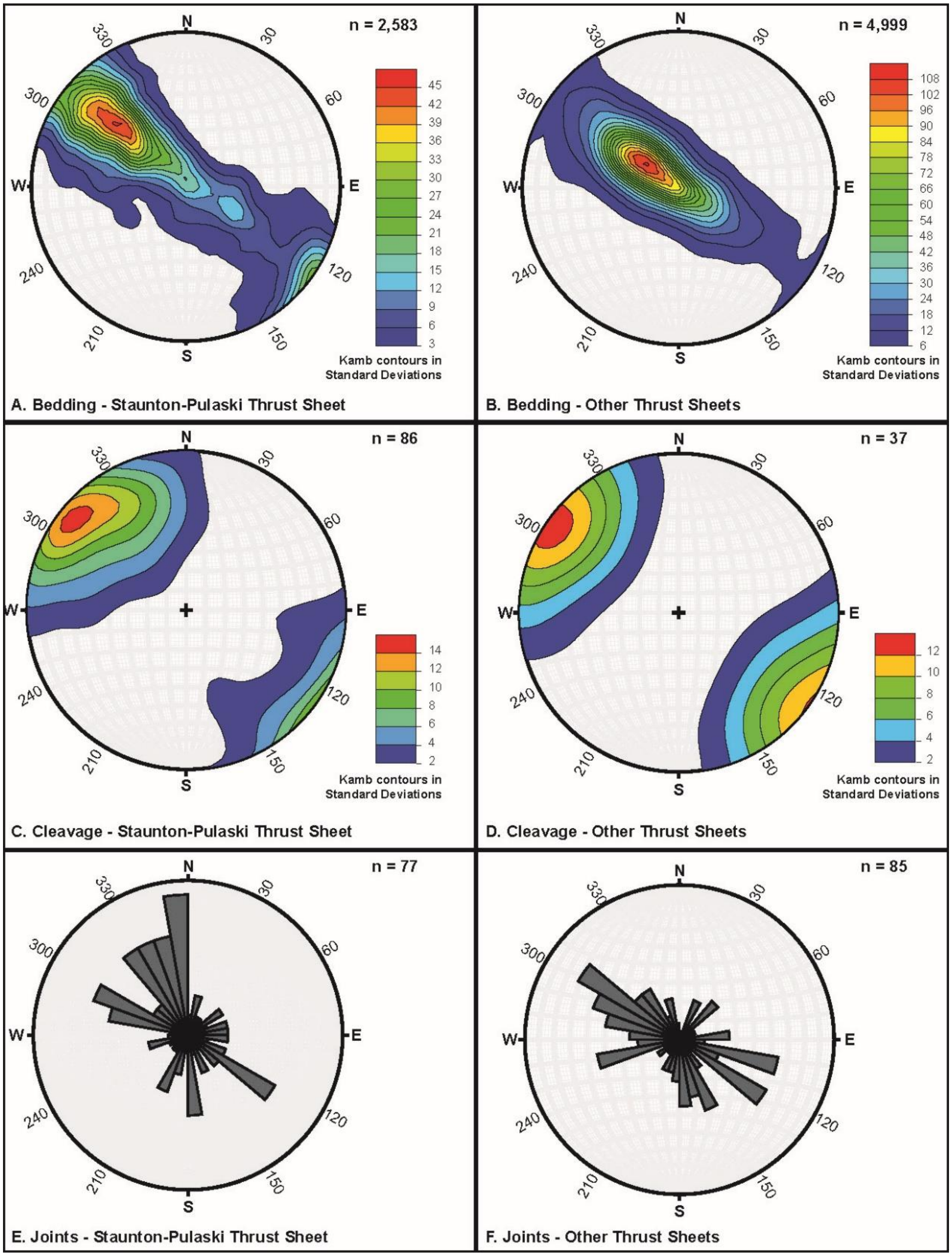

Figure 11. Stereonets showing the statistical orientations of bedding, cleavage, and joint planes in the Phase 1 Karst Derivative Map project area. A-D show contours of poles to these planes, which is a line perpendicular to the plane. E and F show statistical trends of fracture and joint planes, the majority of which are moderately to steeply dipping.

GMR in the past 20 years have been in mixed carbonate units with thicker soils, most commonly the Beekmantown, Conococheague, Elbrook, and Waynesboro Formations. Twenty of 21 VDOT sinkhole repairs in the map geodatabase are also in similar units, mostly the Beekmantown and Conococheague Formations.

The presence of surficial deposits also plays a role in the development of sinkholes. Sinkholes are more abundant in areas overlain by elevated terrace deposits (Figures 4 and 13). This is presumably because such deposits are porous and permeable and located on flat upland surfaces where groundwater recharge is expected to be high. Over time, these conditions increase rates of chemical weathering, bedrock dissolution, and soil formation. Under such conditions, even moderately soluble rock like dolostone and lime mudstone could be expected to develop abundant sinkholes.

DEVELOPMENT AND ANALYSIS OF A SINKHOLE LAYER

During the first phase of the derivative karst mapping project, an important goal was to develop a methodology to map sinkholes in a consistent and comprehensive way. This was accomplished using a semi-automated process to detect depressions in a statewide high-resolution (1-meter) LIDAR-derived digital elevation model (DEM), generally following the methods of Doctor and Young (2013). A user-friendly geoprocessing tool was developed in-house using ModelBuilder in ArcGIS Pro. The tool removes subjectivity from the analysis, automates the process of delineating karst features, and can be customized based on the resolution of input data and scale of the study area.

During a preliminary review of the model results, it was determined that features smaller than 500 ft^2 (46.45 m^2) and having a depth of less than 0.59 ft (0.18 m) were too small to verify or portray at the scale of mapping. It was also determined that the final outputs required a standardized visual inspection to remove depressions which are not likely to be karst-related, including impoundments, artificial dams created by roadways, and development and mining-related features. Every delineated feature was examined to determine if it was a probable sinkhole, possible sinkhole, or false sinkhole. "Probable" indicates that the feature is likely a sinkhole or other karst feature. "Possible" indicates there is uncertainty in whether or not the feature is related to karst processes, and it would take additional effort (such as field investigation) to determine if the feature is karst-related. Assigning a "false" value indicates that the feature is not likely a karst feature and the feature was deleted from the dataset. To ensure quality control and consistency, a decision tree was used while comparing features against basemaps that included aerial photography, LIDAR-derived DEMs (hillshade and slopeshade), topographic maps, and previous geologic mapping. After using the decision tree to remove false positives, 1,026 larger features remained as sinkholes drawn as polygons and 5,903 smaller features remained as sinkholes drawn as points.

A statistical analysis of the data largely supports empirical observations. Nearly 40% of the identified sinkholes are in areas underlain by the Beekmantown Formation, which is rated as moderate in solubility (Table 1; Figure 12). This is likely due to the extensive nature of the map unit, which encompasses nearly 38% of the carbonate bedrock portion of the map area. The density of sinkholes in areas underlain by this map unit is approximately the same as the average density of 3.5 sinkholes/km^2 for the entire map area (Figure 12). The New Market Limestone and Lincolnshire Formation, rated as having a high solubility, have the highest density of sinkholes,

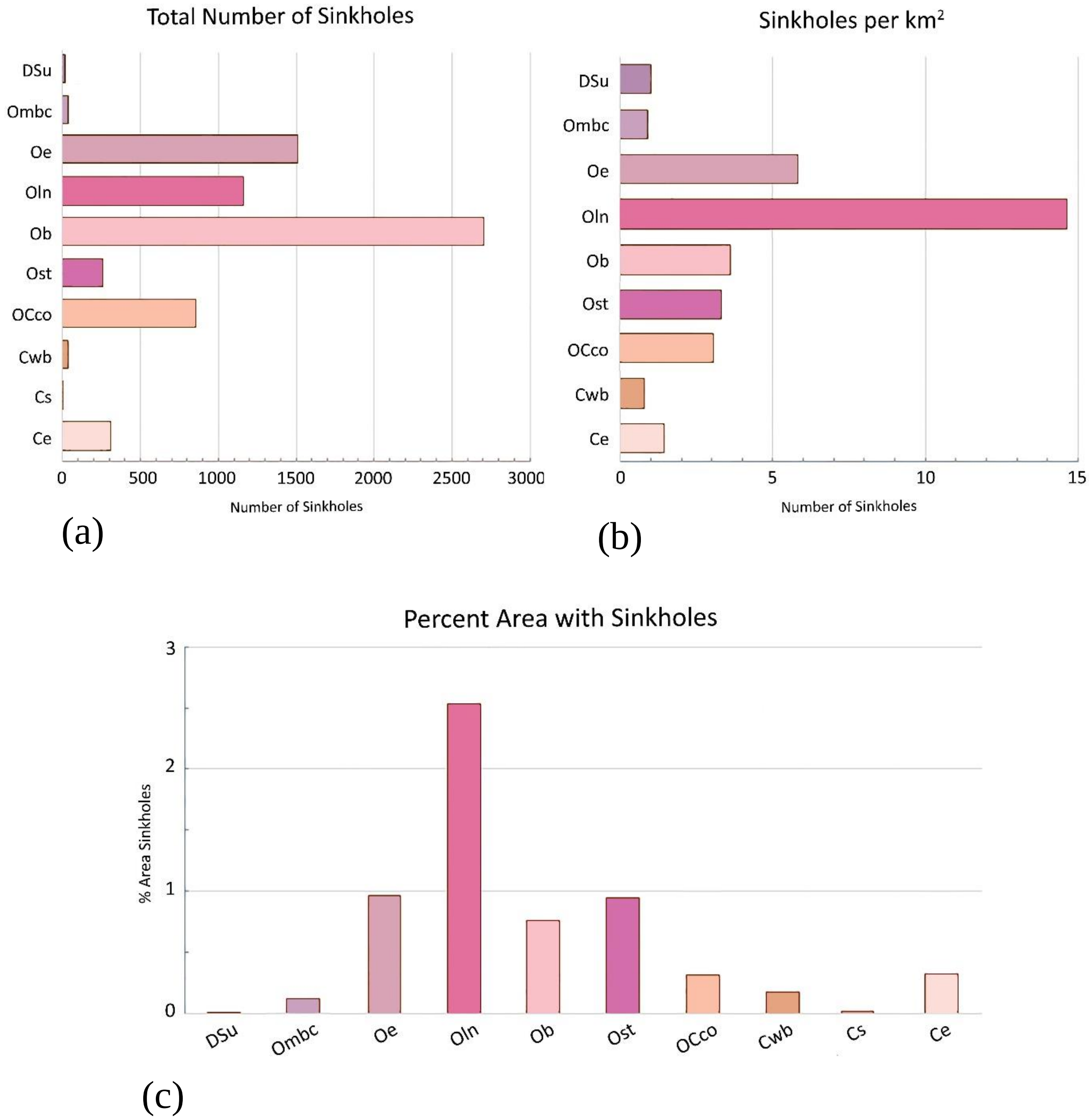

Figure 12. Plots showing the (a) total number of sinkholes identified by bedrock map unit, (b) the density of sinkholes per square km within each bedrock map unit, and (c) the total percentage of land area within each bedrock map unit that is within sinkholes. DSu = Devonian and Silurian formations, undivided, including the Helderberg Group, Ombc = lower Martinsburg Formation, Oe = Edinburg Formation, Oln = Lincolnshire Formation and New Market Limestone, Ob = Beekmantown Formation, Ost = Stonehenge limestone, OCco = Conococheague Formation, Ce = Elbrook Formation, Cwb = Waynesboro Formation, Cs = Shady Dolomite.

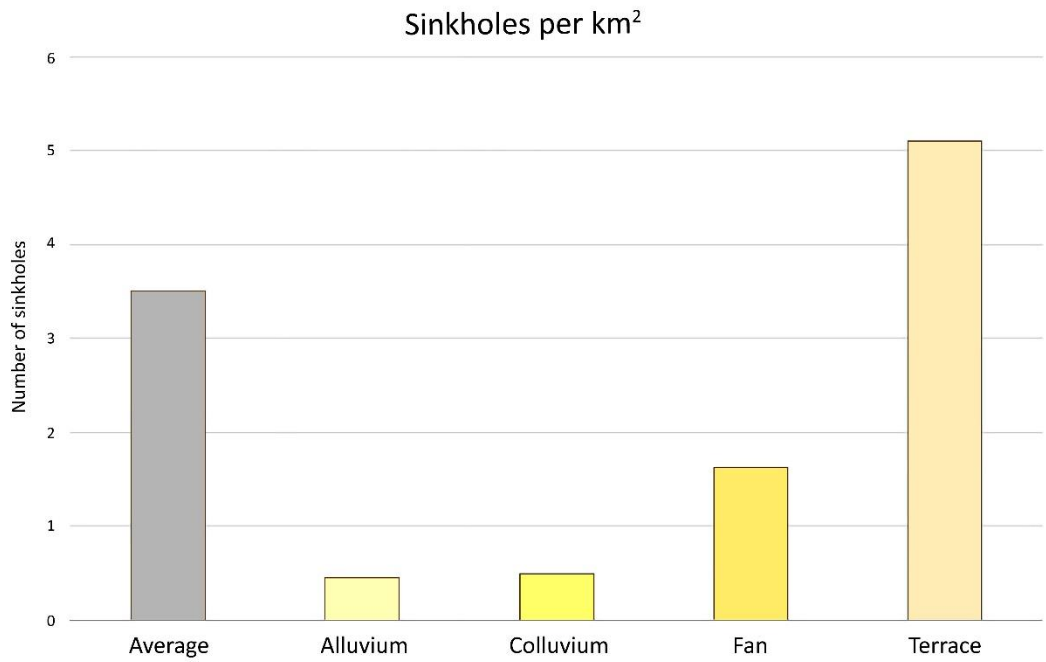

Figure 13. Density of sinkholes in areas overlain by four different types of surficial deposits, compared to the average density of sinkholes in the map area. The density of sinkholes is significantly lower in areas overlain by modern alluvial and colluvial deposits, and higher in areas overlain by terrace deposits.

with nearly 15 sinkholes/km^2, followed by areas underlain by the Edinburg Formation and Stonehenge Limestone (Figure 12). Nearly 2.5% of the total land area underlain by the New Market Limestone and Lincolnshire Formation is within identified sinkholes (Figure 12), but in all other map units it is less than 1%.

The statistical analysis makes it clear that the development of sinkholes is affected in areas where bedrock is overlain by surficial deposits. Areas overlain by alluvial and colluvial deposits have a significantly lower density of sinkholes compared to the average location, but sinkholes are significantly more dense in areas overlain by elevated terrace deposits (Figure 13). Interestingly, in some portions of the map area that do not have mapped terrace deposits, but are in similar slope positions, comparable patterns of dense sinkholes can be observed. These sinkholes may be a remnant signature of a terrace deposit that has been eroded away, or perhaps indicate an area where a terrace deposit was missed during mapping and further work may be required.

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