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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

GEOLOGY AND SINKHOLE DEVELOPMENT OF THE HAGERSTOWN VALLEY: PHASE II SUMMARY REPORT

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MARYLAND DEPARTMENT OF NATURAL RESOURCES
RESOURCE ASSESSMENT SERVICE
MARYLAND GEOLOGICAL SURVEY

FINAL REPORT

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16. Abstract

As a part of this study, karst areas of the Hagerstown, Mason Dixon, Williamsport, Clear Spring, and Hedgesville quadrangles (western half of the Hagerstown Valley) were mapped in detail to determine the distribution of karst features relative to bedrock geologic units using a global positioning system. More than 2,100 karst features were identified and located and the following observations were made:

- There was a generally identifiable relationship between the type of karst features and the bedrock units.
- In addition to bedrock composition, joints, and faults appear to have played important roles in the development of the karst systems in the study area.
- Preliminary findings suggest the impact of human activities on karst development is less pronounced than in the Frederick Valley.
- Unlined drainageways appear to just as frequent culprits in sinkhole activity as they are in the Frederick Valley. Likewise, areas surrounding quarries and stormwater runoff ponds are common sites of sinkhole development.

This study illustrates that future development will benefit from the current studies of karst development in the Hagerstown Valley. Planners can now employ the relative karst susceptibility on the different rock units as a basis for preliminary examination of areas of the Valley that are underlain by these soluble rocks.

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PHASE II EXECUTIVE SUMMARY

- This report discusses findings of the second phase of a study by the Maryland Geological Survey and sponsored by the Maryland State Highway Administration Office of Materials Technology on the relationship between geology and sinkhole development in the Hagerstown Valley.
- Along with the bedrock geology, karst features were identified and located utilizing a global positioning system.
- More than 2,100 karst features were identified and located.
- There was a generally identifiable relationship between types of karst features and the bedrock units.
- In addition to bedrock composition, joints and faults appear to have played important roles in the development of the karst systems of the western half of the Hagerstown Valley.
- Preliminary findings suggest that human impact on karst development is less substantial than hypothesized prior to the study.
- The geology and karst maps produced by this study, can be utilized by homeowners, developers, planner, and engineers when questions arise about the karst development in the Hagerstown region.
- The study's results provide highway officials an *a priori* knowledge about locations that pose a high risk for sinkhole potential.
- With this understanding of the geologic variables that impact karst development, detailed and localized site studies have a foundation on which to build.

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INTRODUCTION

Areas underlain by carbonate rocks such as limestone, marble, and dolomite are prone to dissolution by ground-water. Such solution of bedrock produces distinctive topographic features that characterize what is known as *karst terrane*. While karst terranes are present to some degree in all areas underlain by all carbonate rocks, they develop at varying levels based on changes in the chemical makeup and geologic structure of the bedrock. Thus, there is no such thing as a *typical karst* terrane. It is therefore impossible to characterize or predict the distribution, type, abundance, or size of karst features in any particular terrane without first assembling data and evaluating the distribution of the features with respect to the distribution of mapped bedrock units, their intrinsic geologic structure, and proximity to major hydrologic features such as streams or rivers.

Phase II of this study, the subject of this report, deals with the western half of the valley and encompasses the Maryland portions of the Hagerstown, Mason-Dixon, Shepherdstown, Williamsport, Hedgesville, and Clear Spring 7.5´quadrangles (Figure 1).

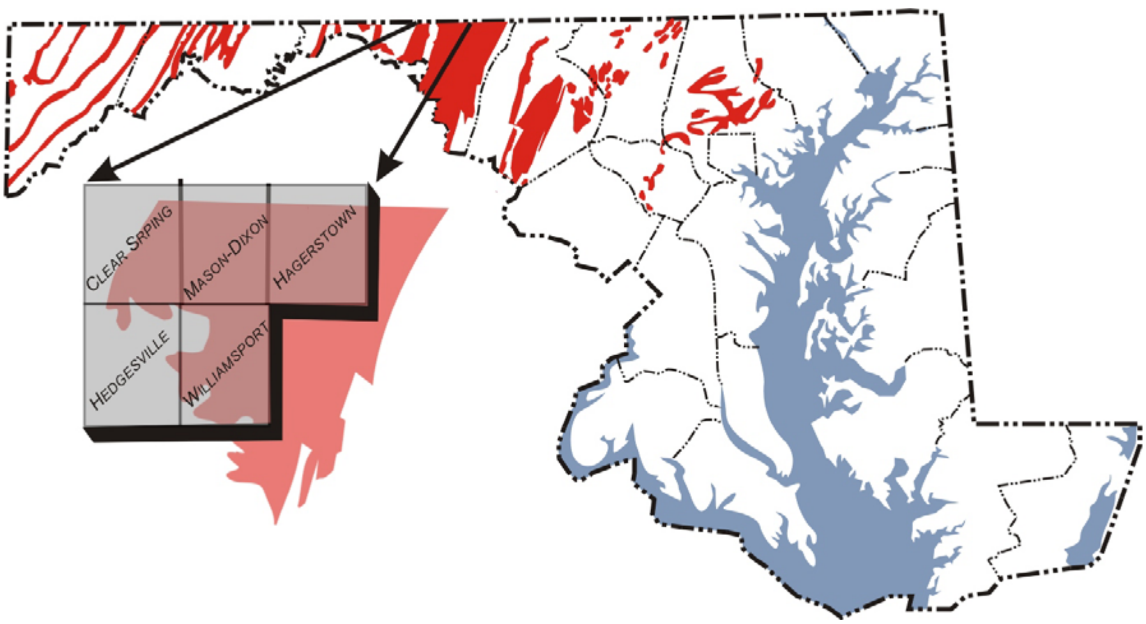

Figure 1. Areas underlain by carbonate rocks in Maryland (red) and location of Phase II quadrangles (gray).

SETTING

The Hagerstown Valley, also known as the Great Valley (Cumberland or Lehigh Valley in Pennsylvania and Shenandoah Valley in Virginia), is a continuous geologic structure that stretches from New Jersey to Georgia. This nearly 800-mile long valley is underlain by easily erodible shale and dissolvable carbonate rocks (limestone and dolomite). These rocks were formed during the Cambrian and Ordovician Periods between 540 to 445 million years ago. Mountain building episodes during the late Paleozoic (350-250 million years ago) configured these rock layers into tight folds that have been partially eroded into the landforms we see today. The Great Valley is a broad down warp or fold in the Earth's crust known as the Massanutten synclinorium. It is bordered to the east by a large up fold known as the South Mountain anticlinorium (Cloos, 1971) (Figure 2). The South Mountain anticlinorium comprises the Maryland part of the Blue Ridge Physiographic Province, while the Massanutten synclinorium, to the west, is the eastern section of the Ridge and Valley Physiographic Province.

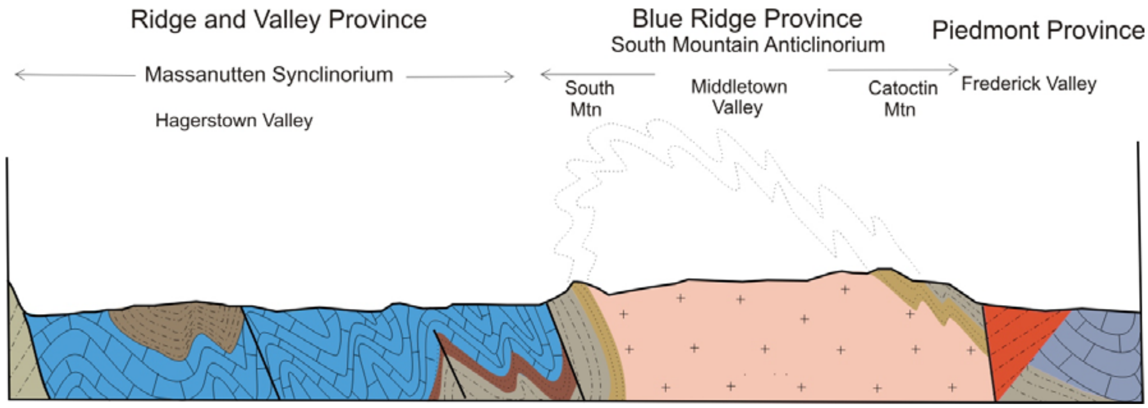

Figure 2. Idealized geologic cross section from the Frederick Valley in the Piedmont Physiographic Province to the western edge of the Hagerstown Valley in Maryland (redrawn and modified from Cloos, 1971).

HISTORY OF INVESTIGATION

Keith (1893, 1894) presented the first description of the rocks of the western Blue Ridge and eastern Great Valley. Much of his work was summarized and repeated by Bassler (1919). The stratigraphy of the Upper Cambrian through early Ordovician carbonate rocks of the Hagerstown Valley was thoroughly discussed and summarized by Sando (1956, 1957, 1958). Demicco and Mitchell (1982), Demicco (1985), and Brezinski, (1996b) presented a discussion about the genesis and depositional environments of the Conococheague Formation (Upper Cambrian) and St. Paul Group (Middle Ordovician). The first detailed descriptions of the stratigraphy of the Tomstown and Waynesboro formations of the Great Valley of Maryland and Pennsylvania were published by Brezinski (1992). Brezinski (1996a) later described the character and origin of the overlying Elbrook Formation. The stratigraphy and depositional history of the Stonehenge Limestone were delineated by Taylor et al. (1992). The overlying Rockdale Run Formation was discussed by Sando (1957) and Brezinski et al. (1999). A depositional synthesis of the Great Valley carbonate rocks was recently presented by Brezinski et al. (2012).

Hydrologic study of the carbonate rocks of the Great Valley of Maryland was first conducted by Nutter (1973). Duigon (2001) investigated the karst hydrogeology of the Hagerstown Valley through examination of a water well inventory.

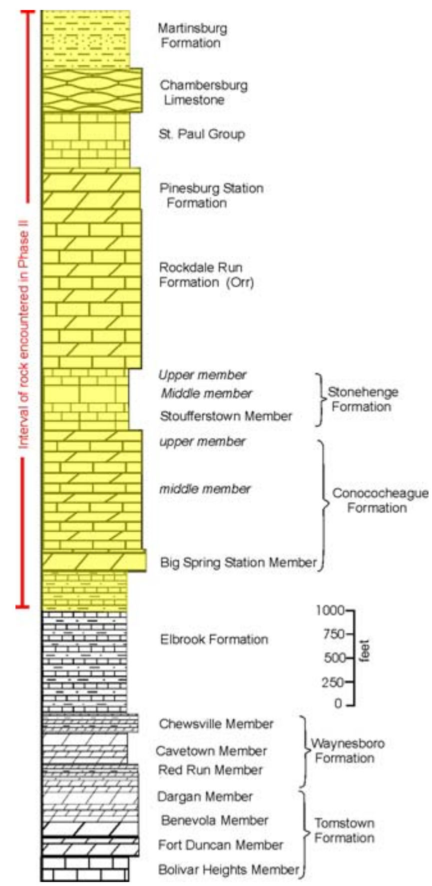

Figure 3. Stratigraphic column of rock units exposed in the Great Valley of Maryland (i.e., Hagerstown Valley). Highlighted interval is stratigraphic succession that was encountered during Phase II of this study.

LITHOSTRATIGRAPHY

Elbrook Formation

The oldest strata exposed in the area mapped during the Phase II part of the study belong to the Elbrook Formation. Brezinski (1996a) identified three informal members within the Elbrook Formation in Maryland. These three members were informally termed the lower, middle, and upper members. This unit gets its name from the type section near Elbrook, Franklin County, Pennsylvania.

The contact between the Chewsville Member of the Waynesboro and the overlying Elbrook Formation is not present in the Phase II map area and only part of the lower member is preserved.

Lower Member: The lowest 700 feet of the Elbrook Formation consists of cyclic light-gray limestone, tan shale, and tan, shaly dolomite. The overwhelming characteristic lithologies of this interval are yellowish-weathering shale and dolomitic shale that commonly contain mudcracks. Interbedded with these yellowish dolomitic shales are white to very light-gray, thinly bedded limestone strata. Exposures of this member typically produce abundant chips of tan, shaly, and laminated dolomites, dolomitic silty shale, and green gray to tan, calcareous shale.

Locally, distributed within the cyclic strata are several intervals of medium- to dark-gray, bioturbated limestone. These dark-gray limestone units range in thickness from 20 to 40 feet. The dark-gray limestones can be traced locally, but cannot be correlated between the eastern and western sides of the Great Valley.

Middle Member: Unlike the shaly dolomitic lower member, the middle member is composed predominately of limestone. This member is best exposed along the western limb of the Great Valley, but has locally been recognized on the eastern flank as well. This limestone interval is comprised predominately of argillaceous, medium-gray, medium-bedded, locally lumpy- to nodular-bedded, ioturbated limestone with thin interbeds of dark-gray, tan-weathering, laminated and fractured dolomite. The dolomite beds are rarely thicker than 3 feet, but the limestone intervals typically range from 15 to 30 feet in thickness. Burrow-mottling is exhibited as tan-weathering, silty, dolomitic infilling within the gray limestone. Bedding is generally indicated by thin (< 0.25 in), shaly partings, and fossil fragments are present in many layers.

Although the middle member is rarely completely exposed its thickness can be estimated at approximately 200 feet.

Upper Member: Above the middle limestone member the Elbrook Formation is comprised of a thick interval of cyclic, medium gray, medium-bedded limestone, dolomite, and dolomitic shale. This part of the formation was informally termed the upper member by Brezinski (1996a). The upper member consists of medium-gray, thrombolitic limestone intervals, 1 to 6 feet thick, interbedded with light gray to tan weathering laminated dolomite 1 to 3 feet thick. The thrombolitic intervals exhibit a pinching and swelling appearance in outcrop. The tops of many of the thrombolitic intervals display digitate and laterally-linked hemispherical stromatolites. Such stromatolitic intervals are typically overlain by fractured, tan-weathering, silty dolomite, and thick-bedded, tan dolomite bearing mudcracks.

The upper member can be distinguished from the lower by the well-developed stromatolitic and thrombolitic limestone in the former and the well-developed shaly intervals in the latter.

Conococheague Formation

The youngest Cambrian rock unit in the Hagerstown Valley carbonate succession consists of interbedded limestone and dolomite that Stose (1908) named the Conococheague Formation. The type area for the Conococheague Formation is along Conococheague Creek in Franklin County, Pennsylvania. Because this unit is so thick, previous workers attempted to subdivide and map the Conococheague Formation as separate members. However, because there is considerable variation in the lithologic character of the formation between the eastern and western outcrop belts, nomenclatural overlap and confusion have arisen (Wilson, 1952; Root, 1968; Bell, 1993; Duigon, 2001).

Big Spring Station Member: Wilson (1952) named the predominately dolomitic lower strata of the Conococheague Formation the Big Spring Station Member for exposures along the CSXT railroad tracks near the town of Big Springs. Near the type area the Big Spring Station Member is approximately 250 feet thick and consists of tan and buff-weathering dolomites containing cross-bedded calcareous sandstones up to 3 feet thick. Root (1968) lumped the dolomitic strata near the base of the Conococheague within his newly named Zullinger Member. Duigon (2001) did not recognized the Zullinger Member in Maryland, but included much of this lithologic sequence within an informal "middle member" and segregated out dolomitic strata near the base of the formation, which they assigned to the Big Spring Station Member.

Middle member: Root (1968) elevated the Conocheague from formation to group status. Futhermore, he named the lower member of the Conococheague Group, the Zullinger Formation. This unit gets its name for exposures near Zullinger in southern Franklin County, Pennsylvania. Root (1968) proposed that this formation made up most of the Conococheague Group in southern Pennsylvania. These dolomite strata appears equivalent to the Big Spring Station Member of the Conococheague Formation of Maryland. Thus, within current study, the Conococheague is considered a formation and the Big Spring Station Member that formations basal subdivision.

The middle member, as recognized for this study, consists of a thick succession of interbedded, thick-bedded, medium- to dark-gray, thrombolitic limestone and medium to dark-gray, ribbony, and tan, laminated, dolomitic limestone. The alternations between thrombolitic to ribbony limestone varies from 200 feet to 300 feet (Brezinski et al., 2012). Within these alternations are thinner lithologic repetitions, ranging from 3 to 15 feet thick, that appear to represent individual shallowing cycles recognized by Demicco (1985). Within the thrombolitic intervals these smaller cycles consist of thick, massive, thrombolitic stata, up to 20 feet thick, alternating with thin ribbony limestone intervals. Within the predominately ribbony intervals the alternations consist of thick, ribbony intervals containing thin (> 2 feet) thrombolitic layers alternating with tan, laminated, mudcracked dolomite and dolomitic limestone.

Measured stratigraphic sections along the C&O Canal National Historical Park suggest that the middle member is approximately 1,500 feet thick on the western side of the Valley and well over 2,000 feet thick on the eastern side.

Upper member: Near the top of the Conococheague Formation the thick interval of large- and small-scale cycles that characterizes the middle member is replaced by a succession of limestone in which little cyclicity is evident. Root (1968) termed this part of the Conococheague Formation the Shady Grove Member, but it is herein termed an informal "upper member." The upper member consists of interbedded light- to medium-gray, sandy, intraclastic, cherty, lime grainstone, and ribbony, lime mudstone. There are a few thin thrombolitic intervals present but these rarely exceed 1 foot (30 cm) in thickness. Near the top of the member the ribbony interval, become thicker and more prominent and are gradually replaced by the thick, ribbony layers of the overlying Stonehenge Formation.

The upper member is between 350 and 500 feet thick, but no complete sections of this member were measured in Maryland.

Stonehenge Limestone

Overlying the Conococheague Formation is an interval of Lower Ordovician limestone that Stose (1908) named the Stonehenge Limestone. The type section of the Stonehenge Limestone is in Franklin County, Pennsylvania, where the formation is more than 900 feet thick. Sando (1957) subdivided the formation into two members, a basal algal member and an upper mechanical limestone member. Later, Sando (1958) included the upper ribbony strata of the Concocheague Formation within his newly named basal member, the Stoufferstown Member. He then lumped the algal and mechanical limestone members together into an upper member. Bell (1993) subdivided and mapped the Stonehenge Formation into four units, including the basal Stoufferstown Member. Measuring of numerous stratigraphic sections for the current study suggests that a combination of Sando's work yields a utilitarian three-fold subdivision that could be employed for mapping purposes. Thus, a tripartite subdivision for the Stonehenge Formation is employed in the current study. This includes the basal Stoufferstown Member, a middle member corresponding to Sando's (1957) algal limestone, and an upper member equivalent to Sando's (1957) mechanical limestone.

Stoufferstown Member: The thick, ribbony limestone interval that was recognized as the top of the Conococheague Formation by Sando (1957) was reassigned to the basal Stonehenge Formation by Sando (1958). Named the Stoufferstown Member, this unit consists of dark-gray, thin-bedded to ribbon-bedded, siliceous lime mudstone. Individual limestone layers are 0.25 to 1.0 inches thick and are typically separated by thin, wispy, black to dark-gray argillaceous to silty layers that weather out on solution faces. The Stoufferstown Member ranges from 175 to 275 feet in thickness.

Middle member: Overlying the thinly bedded Stoufferstown Member is an interval composed of medium-gray, massive to thick-bedded, algal lime mudstone to boundstone. Sando (1957) originally termed this lithology the lower member of the Stonehenge, but Sando (1958) later lumped this lithology with the overlying mechanical limestone into his upper member. In the current study, this member is considered the informal middle member of the Stonehenge and the equivalent to the entire lower biohermal facies and much of the middle ribbony carbonate facies as mapped by Bell (1993).

In outcrop, the middle member is readily identifiable by the massive outcrop pinnacles of unbedded lime mudstone formed by dissolution. Individual algal colonies can be as much as 12 feet thick. However, near the top of the member thinner layers of thrombolites are interbedded with ribbony lime mudstone and rippled lime packstone. This member ranges from 450 up to 500 feet in thickness.

Upper member: The absence of thick thrombolites marks the transition from the middle to upper members of the Stonehenge Formation within the current study. Sando (1957) considered this portion of the section part of the upper member of the Stonehenge Formation, and Sando (1958) termed it the upper mechanical limestone. These strata also would be equivalent to parts of Bell's (1993) middle ribbony carbonate facies and upper limestone facies.

The upper member of the Stonehenge Formation consists of medium to dark-gray, thin- to medium-bedded, locally ribbon-bedded, intraclastic lime mudstone, and intraclastic and oolitic lime packstone. This member ranges from 325 to 400 in thickness.

Rockdale Run Formation

Overlying the limestone of the Stonehenge Formation is a thick interval of cyclically bedded carbonate strata that Sando (1956) termed the Rockdale Run Formation. The type section of this formation is along Rockdale Run in Washington County, Maryland. The contact between the Stonehenge and overlying Rockdale Run Formation is readily identifiable in the field by the first appearance of tan, laminated dolomite or dolomitic limestone. This first dolomitic bed signals the return to cyclic deposition. The Rockdale Run Formation is more than 2,700 feet thick in the Hagerstown Valley. Sando (1957) identified three informal members within the Rockdale Run Formation that he believed were lithologically distinct intervals. Within the lower 200 feet the Rockdale Run Formation consists of cycles of interbedded thrombolitic and stromatolitic lime boundstone and light gray to tan, laminated dolomite. Many of the algal heads in this stratigraphic interval have been replaced by silica. Where this part of the formation crops out, large blocks of chert typically are preserved in the soil. This basal interval is overlain by approximately 200 feet of medium gray limestone containing abundant oolitic packstone intervals. The oolitic interval in turn is overlain by the upper part of the formation composed primarily of cyclic bioturbated and ribbony limestone and tan to gray dolomite, commonly laminated. Near the top of the formation the limestone part of these cycles is lost and the formation is almost totally dolomitic.

Pinesburg Station Dolomite

The dolomitic strata of the upper Rockdale Run Formation grade upsection into thick-bedded, light gray fractured dolomite of the Pinesburg Station Dolomite. The contact is placed where the cycles of alternating gray limestone and tan fractured and laminated dolomite of the Rockdale Run Formation are replaced by buff weathering fractured dolomite of the Pinesburg Station. This unit was named by Sando (1956) for exposures in fields northwest of the village of Pinesburg, Washington County, Maryland. The formation is well-exposed along the C&O National Historic Park south of Pinesburg where 337 feet of stratigraphic section were measured. The Pinesburg Station Formation consist of light to medium gray, buff-weathering, fine-grained, medium- to thick-bedded dolomite alternating with medium beds of light gray, laminated dolomited.

Alternations of thick-bedded dolomite with dololaminites attest to the cyclic nature of the original sediment. Commonly this massive to thickly-bedded dolomite is highly fractured to brecciated. Much of the characteristic fracturing of this unit is attributable to tectonic deformation, but some of the brecciated of the thinner dolomite layers has been interpreted as having formed during periods of subaerial exposure and dissolution by fresh waters (Mussman and Read, 1986).

The regional development of dolomite and dolomitic cycles during this period of deposition is widespread in not only the central Appalachians, but throughout the eastern United States is attributable to a global drop in sea level and restriction of the carbonate platform during the later parts of the Early Ordovician (Morgan, 2012). This led to exposure of much of the platform and creation of a widespread lacuna manifested in the Knox Unconformity (Ryder et al., 1992, Morgan, 2012, Brezinski et al., 2012). In the Great Valley the precise stratigraphic position and magnitude of lacuna for the Knox unconformity are not well constrained. It does not, however, appear to coincide with any formational boundary, but is confined within the upper Rockdale Run Formation.

St. Paul Group

Overlying the fractured buff dolomites of the Pinesburg Station is an interval of interbedded limestone and dolomite that Neuman (1951) termed the St. Paul Group. The St. Paul Group can be subdivided into a lower formation, the Row Park Limestone, and an upper, the New Market Limestone. The Row Park Limestone consists of several intervals of massive, light gray, dense, fine-grained limestone. These massive limestone intervals, are up to 30 feet thick and exhibit irregularly shape calcite filled voids termed "birds eye." These filled voids are believed to represent gas bubbles that filled the fine-grained lime mud during deposition. The void were subsequently filled with crystalline carbonate.

Overlying the Row Park Limestone is an interval of interbedded, gray, to grayish brown limestone and thinly laminated, dolomitic limestone, and tan laminated dolomite. The interbedded limestone and dolomite interval is termed the New Market Limestone. The combined thickness of the St. Paul Group is between 230 to 330 feet thick. Because both formations contain similar lithologies the were not separated during mapping during the current study.

Chambersburg Formation

Overlying the cyclically bedded, light gray limestone and tan dolomite of the New Market Limestone is an interval of dark gray, argillaceous, thin- to medium-bedded, locally nodular-bedded, fossiliferous limestone termed the Chambersburg Limestone. Named by Stose (1906) for exposures near Chambersburg, Pennsylvania, this unit is the stratigraphically youngest carbonate unit of the Great Valley. In northern Virginia, the light-colored upper limestone strata of the New Market Limestone interfinger with, and are replaced by, a dark gray, thin- to medium-bedded, siliceous, argillaceous lime wackestone termed the Lincolnshire Formation (Read, 1986; Radar and Read, 1989). However, in Maryland the thinly bedded cherty Lincolnshire lithologies are absent, and the medium-bedded limestone of the New Market are sharply replaced by the deeper-water argillaceous and nodular-bedded lithologies of the Chambersburg Foramtion.

The Chambersburg Limestone varies between 250 to 400 feet thick, but averages approximately 300 feet in thickness in Maryland. The thin-bedded, dark gray, argillaceous basal strata grade upsection into 15 to 20 m of dark gray, shaly, nodular limestone that are locally termed the "*Echinosphaerites* beds" (Neuman, 1951, Brezinski, 1996b). These nodular beds in turn grade upwards into thin-bedded argillaceous limestone and then into a thickly-bedded, bioturbated lime wackestone that is up to 10 m thick. These thick-bedded limestone occur near the middle of the formation, and then are inturned replaced by thinly bedded lithologies and then the wavy to nodular-bedded lime mudstones at the top of the formation.

Brezinski et al. (2102) interpreted the vertical arrangement of lithologies in the Chambersburg Limestone as a record of two separate transgressive episodes. The earlier deepening episode was initiated within the upper New Market Formation. The upsection transition from medium-bedded, bioturbated limestone into thinly bedded and then nodular-bedded lithologies was interpreted as representing the deepening from intertidal (New Market) lithofacies into deeper ramp environments (*Echinosphaerites* interval). Shoaling shallow subtidal environments is recorded upsection in the thickly-bedded middle part of the Chambersburg Limestone, followed back to deeper water environments at the top of the formation.

Martinsburg Formation

The contact between the Chambersburg Limestone and the overlying Martinsburg Formation is gradational over several hundred feet of stratigraphic section. The basal Martinsburg Formation consists of thinly interbedded calcareous shale and argillaceous limestone. In Virginia, this interval was named the Stickley Run Member (Epstein et al., 1995). Above the Stickley Run Member the Martinsburg Formation consists of dark gray to black, brittle shale with thin (0.5 inch) interbeds of dark gray siltstone. This dark gray to black shale interval is equivalent to the Utica Shale, a carbonaceous shale present in New York and western Pennsylvania. The Stickley Run lithologies and the black shale at the base of the Martinsburg were mapped together during the current study and labeled the "lower member. Base on outcrop width the lower member of the Martinsburg is approximately 2,000 feet thick.

Within the upper part of the Martinsburg's lower member, thin sandstone beds between 2 to 6 inches in thickness are present within the dark gray shale. These thin sandstone beds exhibit a fine graded bedding and sole markings. Progressing upsection the thickness and number of these sandstone interbeds increases. These sandstone interbeds become so prominent upsection that in some intervals they make up more than 50% of the stratigraphic section. Some sandstone intervals are up to 30 feet thick.

KARST FEATURE DISTRIBUTION

The stratigraphy discussed above provides a generalized lithologic foundation that can be roughly equated with broad changes in rock composition. Thus, the distribution of the number and types of karst features can be compared with these broad differences in rock makeup. Lacking such a well-defined basis for comparison, it would not be possible to evaluate whether the distribution of karst features is related to geologic factors such as bedrock composition. The remainder of this report will discuss the identification and distribution of karst features, and the evaluation of whether their distribution, frequency, and dimensions are related to bedrock geology or some other factor.

Four types of karst features were identified during the current study. These are: depressions, active sinkholes, karst springs, and caves (Figure 4). Closed depressions were by far the most common type of karst feature encountered. Depressions are low areas towards which the surrounding topography is inclined (Figure 5A). These depressions are typically bowl-shaped, but can be elongate. Depressions vary greatly, not only in their outline, but also in size. They can occur as small shallow depressions as little as several yards across to broad indentations, more than 100 yards across. Such large, shallow depressions tend to form in areas along the western margin of the Hagerstown Valley in areas covered by thick accumulations of colluvium or along the river systems where terrace gravels are present. These large features appear to represent slow dissolution of the underlying bedrock. The soil surface slowly subsides as the bedrock dissolves. Through time smaller depressions can coalesce to form large depression.

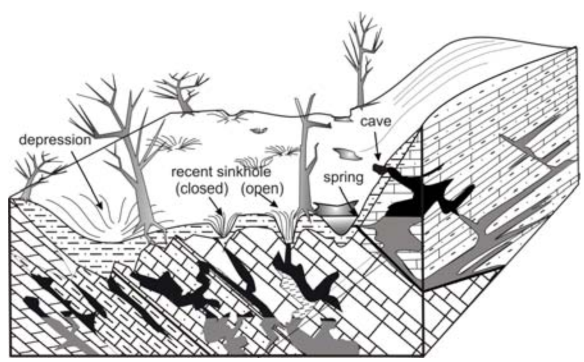

Figure 4. Idealized karst and the types of features identified for this study.

The second category of karst features recognized in this study is active collapse sinkholes. Just as with depressions, active sinkholes can display a wide range of variation in shape. The most common, and widely recognized, type of active sinkhole in the Hagerstown Valley exposes an open throat and occurs as clearly open holes (Figure 5B). The active category also includes narrow, steep-sided depressions that lack an open throat, but are unvegetated suggesting some recent activity. Soil cover-collapses occur when soil bridges that covered an open or partially open subterranean void fail. Collapses that are known to have occurred in recent years and have been repaired are also included in this category. Lastly, swallowholes in streambeds wherein the stream starts subterranean flow are considered as a specific type of active sinkhole.

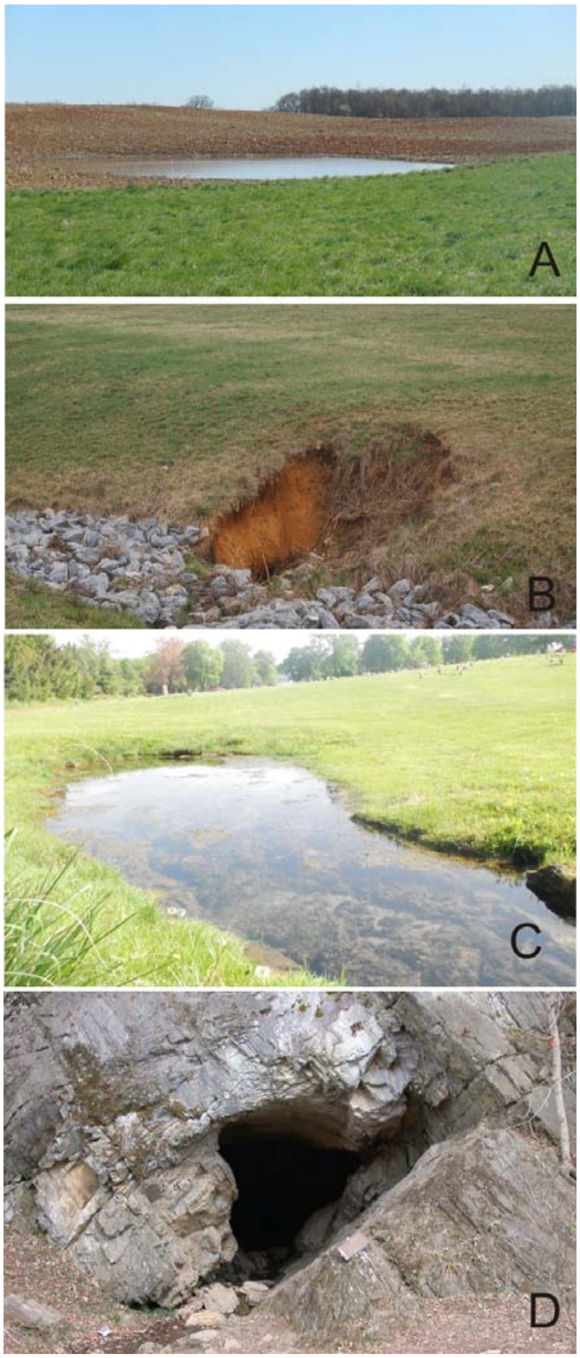

Figure 5. Categories of karst features identified and located for this study. A, Depression. B, Active collapse. C, Karst spring. D, Cave.

The third category of karst features is karst springs (Figure 5C). While these are not one of the more common types of karst feature, they represent an important character that helps shed light on movements of subterranean water.

Caves are the most uncommon, but one of the most important types of karst features identified during the current study (Figure 5D). Caves are open voids of varying size that are produced by subterranean groundwater flow and subsequent dissolution.

Karst features were identified and located in conjunction with field efforts to acquire data during geologic mapping of the Hagerstown, Mason-Dixon, Shepherdstown, Clear Spring, and Hedgesville 7.5-minute quadrangles. These geographic areas were canvassed during geologic field mapping, and definable karst features were precisely located and identified utilizing a Trimble GeoExplorer III® Global Positioning System (GPS) receiver. Most features were located by placing the GPS unit within the feature while a satisfactory number of satellites were in the constellation. The minimum number was usually five satellites, with an optimal number of seven satellites. In some circumstances, features that could not be entered because of property permission constraints were located by offsetting to another location where the azimuth back to the feature could be determined, and the distance could be delineated by utilizing a laser range finder. While this level of precision is insufficient for most surveying purposes, even the unprocessed files are considered of sufficient resolution for the current study, especially when one considers that some of the larger depressions can be up to 200 feet in diameter. The karst feature locations were stored in the State Plane Coordinate System with a North American Datum (NAD) of 1983.

In addition to the geographic coordinates, data acquired at each location included the karst feature type, bedrock unit identification, presence or absence of Quaternary deposits that might cover the feature, and other possibly significant characteristics, such as location in a drainage lowland, drainage ditch, or storm-water management reservoir.

Karst Feature Summary

More than 2,100 karst features were identified and located in the six quadrangles studied. Figure 6 gives a representation of the relative percentages of the four types of features identified in Phase II. Depressions are by far the most common feature recorded, making up approximately sixty-three percent of all the readings. Active sinkholes comprised nearly twenty-eight percent of the features. Springs and caves constituted 9.6 percent and 0.1 percent of all karst features, respectively.

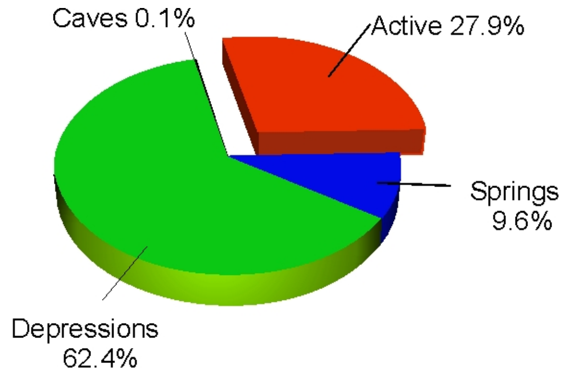

Figure 6. Pie diagram of relative percentages of karst features identified during Phase II of the Hagerstown Valley Karst Project.

Geologic Factors Affecting Karst Feature Distribution

Lithology

A major working hypothesis of this study is that lithology, or rock composition, plays a significant role in controlling karst feature distribution. To test this postulate it was necessary to precisely map the rock units and then compare their outcrop pattern with karst feature distribution. Of paramount importance to the geologic mapping aspect of this study was the use of reliable stratigraphic units that are lithologically consistent and extensive enough that future workers could repeat the mapping without substantial differences. However, a point of diminishing returns had to be considered when subdividing the individual formations. Subdivisions that are this fine might not yield sufficient numbers of karst features from each category to be statistically valid.

Unit	*Depressions*	*Active*	*Springs*	*Cave*	*Total*
Chambersburg	***56***	***8***	***5***	***0***	***69***
St. Paul Gp.	***22***	***68***	***12***	***0***	***102***
Pinesburg Station	***25***	***12***	***6***	***0***	***43***
Rockdale Run	***214***	***151***	***63***	***0***	***428***
Stonehenge	***234***	***165***	***53***	***0***	***452***
Conococheague	***544***	***164***	***53***	***1***	***762***
Elbrook	***225***	***22***	***11***	***1***	***259***
Total	***1,320***	***590***	***203***	***2***	***2,115***

Table 1. Compilation of numbers of karst features identified within each formation in the Hagerstown Valley.

The Hagerstown Valley succession shows that not all carbonate units exhibit an equal susceptibility to karst development (Figure 7, 8, Table 1). The individual carbonate units contained varying numbers of karst feature. Table 1 summarizes the types and numbers of karst features with respect to the individual geologic units. Significant areas underlain by the Elbrook, Conococheague, Stonehenge and Rockdale Run formations are present in the quadrangles selected for Phase II of this study. Figure 7 is a stacked bar chart that summarizes the relative number of karst features in the carbonate rock units as shown in Table 1. Some units are more susceptible to depression formation (e.g.,Elbrook Formation), while others are more prone to active sinkhole

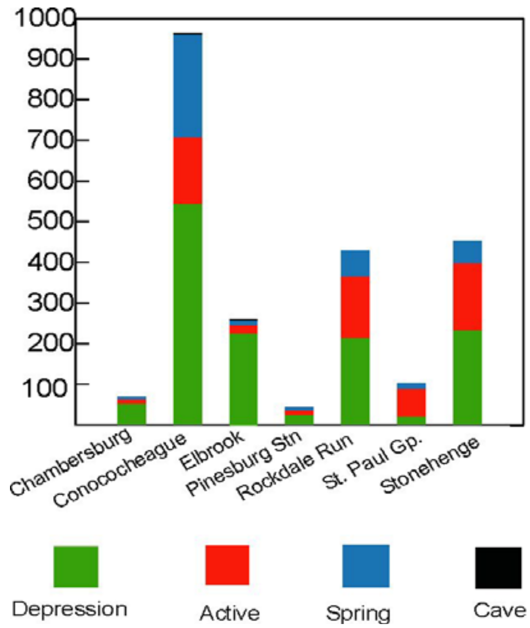

Figure 7. Stacked bar chart of numbers of karst feature types in Phase II of the Hagerstown Valley Karst Study.

development (Stonehenge Formation), or appearance of springs (Rockdale Run Formation). These data on the relationship of karst features to lithologic units are also summarized as pie diagrams (Figure 8). These numbers and relative percentages within these units differ from Phase I of this study.

Examination of Table 1 and Figures 7 and 8 verifies the working hypothesis of this study that not all geologic units exhibit a consistent and predictable distribution or ratio of karst features. However, assigning possible reasons for these differences may be more than simply compositional changes. Other geologic factors could possibly further impact karst proclivity. For example, Figure 9 illustrates how certain strata within the Conococheague Formation tend to be more soluble than others. Additonally, other geologic factores appear to play important roles karst feature development.

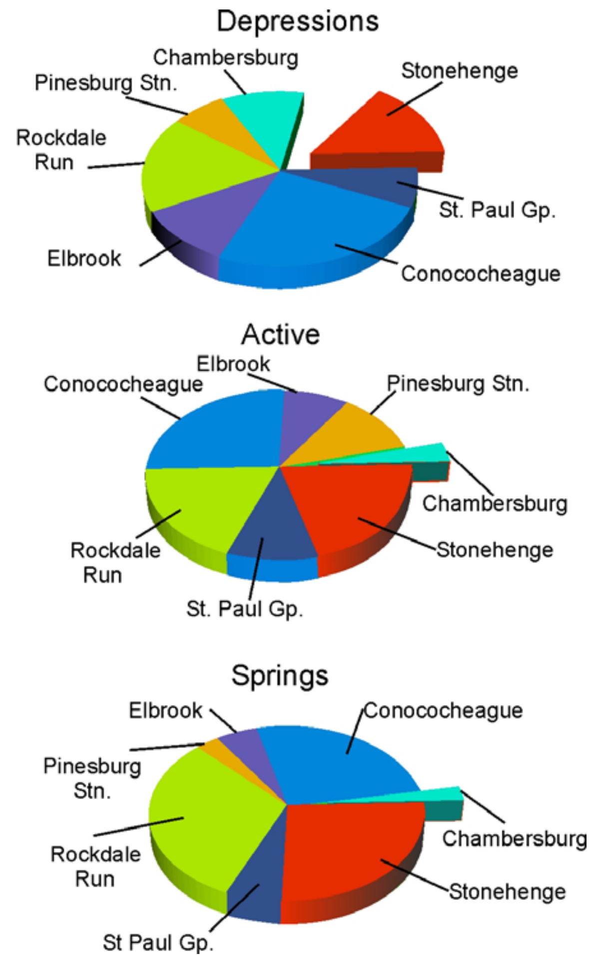

Figure 8. Pie diagrams of relative percentages of depressions, active sinkholes, and springs identified in Phase II of the Hagerstown Valley Karst Study.

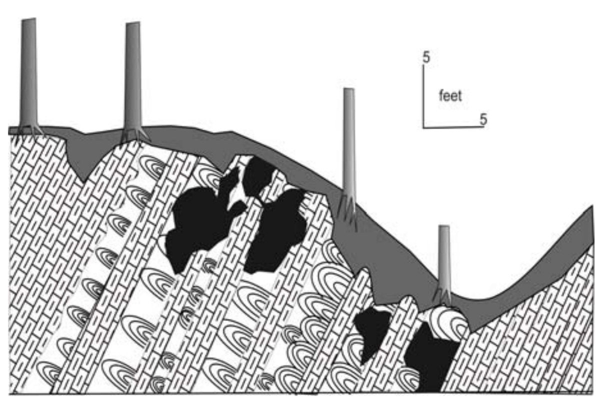

Figure 9. A, Sketch of solution cavity preferentially forming along purer carbonate intervals bearing algal thrombolites of the middle part of the Conococheague Formation

Fractures

Beyond lithology one of the most pervasive and important factors governing the distribution of karst features is geological structure (Jennings, 1985). This broad term encompasses all forms of depositional and deformational features such as bedding, joints, folds, and faults. During the course of Phase II several of these types of structural features were correlated with the distribution and density of karst features. In poorly consolidated carbonate rocks, bedding and internal porosity are perhaps the most important conduits for solution waters. However, in well-lithified carbonates like those seen in the Hagerstown Valley, other types of fractures tend to be the main avenues for dissolution (Beck, 1986).

Figure 10. Reticulate pattern of joints within the Stonehenge Limestone exhibiting minor solution.

One of the most underemphasized types of fractures that play an important role in karst development is created during deposition of layered sedimentary rocks. This system of fractures is termed bedding, stratification, or parting. Minute openings created by changes in depositional processes, such as energy level, temperature, or sea level height, produce differences in grain size or composition. The resulting change in grain size, shape, or composition produces compositional or structural changes in the layers and in some places planes of weakness known as parting. During deformation such incompetent layers create amplified deformation and fracturing, and allow movement and dissolution by interstitial and intrastratal waters. Such narrow voids are especially important in horizontal sedimentary successions, but they are also evident in folded strata where they may be widened or even closed.

Breaks or cracks in the rocks, known as joints, pervade nearly all ancient deformed rock types (Figure 10). In the Hagerstown Valley several prominent sets of joints are documented pervading nearly every rock unit. These fracture systems are parallel to subparallel planar cracks that appear to have been formed by compressional and tensional stresses during the creation of the Blue Ridge Anticlinorium and Hagerstown Valley. Most of these stresses were formed during the Alleghanian mountain building episode approximately 250 million years ago. By measuring the orientation of hundreds of these fractures, a recurrent pattern in their occurrence can be obtained. The most pervasive set of fracture azimuths range from 290º to 315º (Fig. 11 A-F). A secondary, less prominent set of joints has an orientation that is nearly east-west with an azimuth that ranges from 15º to 30º (Fig. 11 C-E).

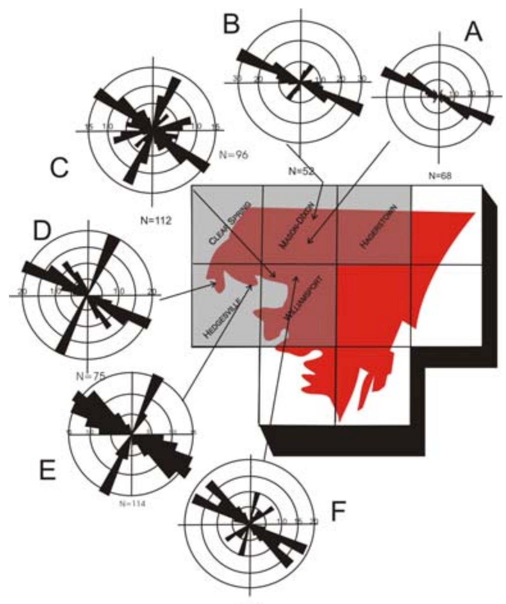

Figure 11. Variability of fracture directions within the western part of the Hagerstown Valley of Maryland. A, Rockdale Run Quarry, Rockdale Run Formation; B, Cress Road, Pinesburg Station. C, McMahons Mill, Stonehenge Formation; D, Four Locks, Conococheague Formation; E, C&O at Gift Road, Stonehenge Formation; F, C&O Potomac Sportsman Club.

The spacing of this fracture system tends to be more prominent and more closely spaced within shaly strata, such as the Elbrook Formation. This fracture system also tends to parallel the axial planes of all the major folds of the region. This system of fractures is interpreted as axial planar cleavage related to fold formation. Axial planar cleavage forms parallel to the axes of major folds (Fig. 12E). In the Hagerstown Valley the major folds include the South Mountain Anticlinorium and Massanutten (Great Valley) Synclinorium (Figure 2). Cleavage is a spaced fracture system, or cleaving of the rock, that is created perpendicular to the main stress field during the bending of competent rock strata during folding.

The least common type of fracture encountered in the eastern Hagerstown Valley is one that exhibits some sort of translational movement. These types of fractures are called faults. Some faults display movement of as little as several feet; others may have movement that is measured in miles or kilometers. With such distances, subterranean waters have prolonged opportunity for moving through these fractures and for dissolution of adjacent limestone.

Examples of Geologically Controlled Karst

During Phase II numerous cases of solution widened fractures were observed and documented. Excellent examples of this can be seen at most well-exposed outcrops, such as those along roads and highways. Dissolution of certain layers parallels the oriented bedding planes. In these cases the prominence of dissolution of a single layer is demonstrable (Figure 12).

The intersection of several types of fractures commonly allows for the creation of a network of dissolution in karst terranes. Where one joint set intersects another joint set, or where joints and cleavage intersect or joints and stratification intersect there are abundant opportunities for water to permeate and dissolve the surrounding rocks. The result is a system of interconnecting pathways for water to migrate and as a result dissolution to occur. This maze of constantly widening fractures produces what is termed "pinnacle karst" (Fig. 13). When the soil is stripped away these pinnacle exhibit a striking topography. Thus, predicting the subterranean distribution of the soil-bedrock contact is impossible.

Figure 12. Solution widened bedding plane. Preferential solution of laminated dolomitic interval within the Rockdale Run Formation.

Figure 13. Pinnacle karst in the Rockdale Run Formation. Dissolution of joint network resulting in the formation of limestone pinnacles in the areas between joints.

Faults

Various scales of faults have been recognized within the Phase II study. Faults can be shown to have a demonstrable affect on karst development. While sinkholes are not pervasively developed along identified faulting, springs are. Brezinski (2004) noted that faulting had very little recognizable influence on karst development in the Frederick Valley. However, this is not the case for the Hagerstown Valley. Within the Hagerstown and Mason-Dixon quadrangles, a line of springs can be show to coincide with the contacts between the carbonate units and the Martinsburg Formation (Figure 14). Because of the truncations of various carbonate units along the strike of this contact, it has been mapped as the Williamsport Fault, a major fracture system that can be traced from Virginia to Pennsylvania. In the Williamsport Quadrangle fracturing associated with the faulting as well as the placement of impermeable clastics of the Martinsburg Formation against the readily soluble Stonehenge and Rockdale Run formations.

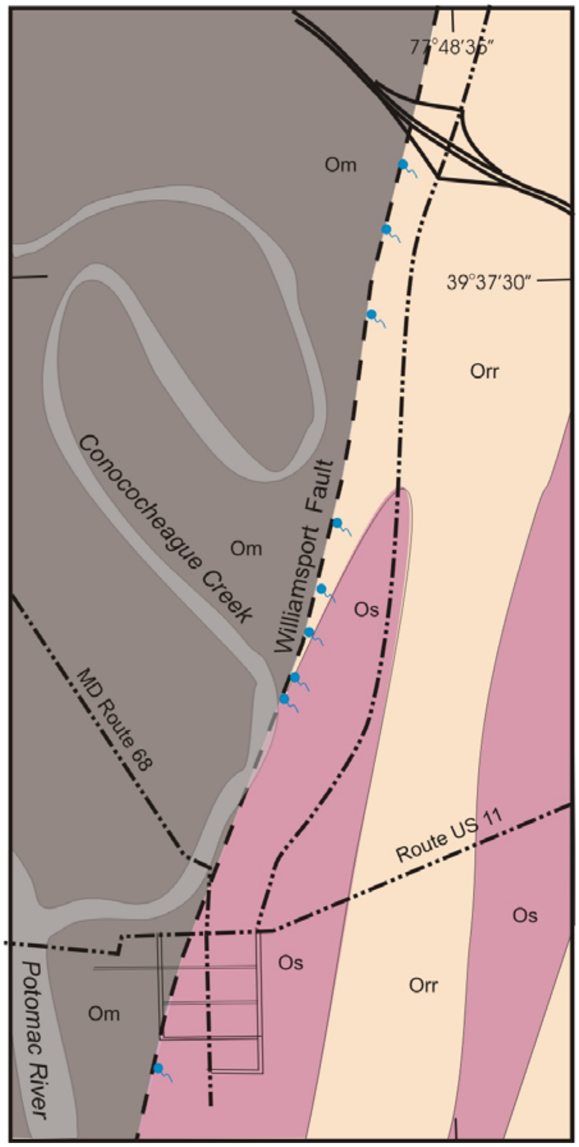

Figure 14. Distribution of springs along the Williamsport Fault at the contact between the Stonehenge and Rockdale Run formations and the Martinsburg Formation (gray) around Williamsport. Modified from Brezinski (2014)

Many small faults obliquely intersect the tectonic strike of the region. These localized faults are generally termed cross-faults because they cross regional strike. Duigon (2001, fig. 18) has shown that the fracturing along these small cross-faults may allow dissolution and permit the development of springs. During the current phase of the study the distribution of swallow holes and springs along Cress Road can be shown to be related on localized cross-faulting that parallels the road.

Surface Drainage Patterns

As is typical of most karst terranes, the surface drainage of much of the Hagerstown Valley lacks perennial streams outside of the major trunk streams such as the Antietam, Beaver, and Conococheague creeks. A dendritic drainage pattern is reflected by the topography more so than by the surface streams. In most cases, this pattern manifests itself as a series of swales, or ephemeral drainageways, that only contain running streams after heavy rain or snow melts. Under normal conditions, surface runoff quickly finds its way to subterranean courses that transfer the waters to the local base level. Notwithstanding

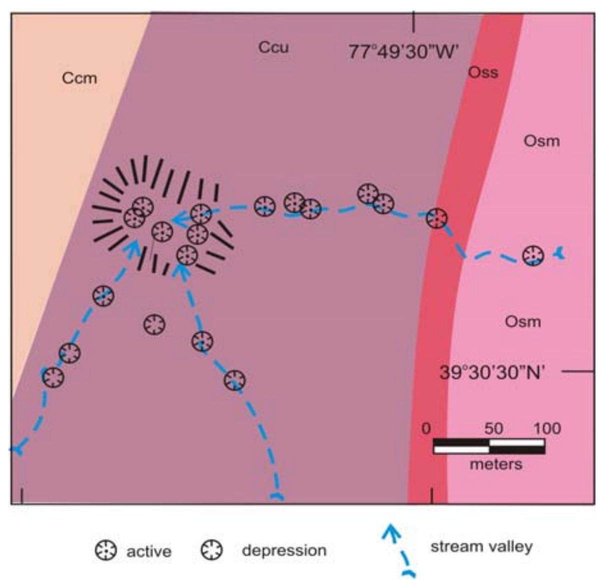

Figure 15. GPS sketch map of an area within the Williamsport Quadrangle demonstrating the relationship between sinkholes and drainage.

the lack of surface streams, these drainageways reflect areas of increased water movement. Consequently, the underlying bedrock can exhibit indications of increased dissolution. The extra dissolution that is inferred to take place in these swales makes them prime areas for sinkhole development.

Figure 16. Some human-induced karst problems. A. Unlined drain within the Rockdale Run Formation at Hagerstown Airport producing sinkhole activity. B. Opening of cave in Conococheague Formation by quarrying in eastern Hagerstown. C. Sinkhole activity in newly created storm water management pond.

An example of this was observed in the Williamsport Quadrangle where several streams converge on a series of active sinkholes (Figure 15). Furthermore, the lowlands in which these streams are located are the location of active sinkhole development.

Human Factors Affecting Karst Feature Development

In addition to geologic factors, the activities of humans, such as road construction, housing development, and quarry dewatering, can have a significant impact on the development of karst features (Brezinski, 2007). In the Hagerstown Valley the effects of man on karst development appear to be less acutely evident than it was shown to be in the Frederick Valley (Brezinski, 2004). Several cases of anthropogenic factors contributing to karst feature development can be illustrated. Some of these are shown in Figure 16. Unlined drainageways, appear to be just as frequent culprits in sinkhole activity as they are in the Frederick Valley (Figure 16A). Likewise, areas surrounding quarries and storm water runoff ponds are commonly sites of sinkhole development (Figure 16 B, C).

This study illustrates that future development will benefit from the current studies of karst development in the Hagerstown Valley. Planners can now employ the relative karst susceptibility of the different rock units as a basis for preliminary examination of areas of the Valley that are underlain by these soluble rocks.

IMPLICATIONS FOR HIGHWAY SITE EVALUATION

Brezinski (2004) enumerated several geologic factors that controlled the type, number, and distribution of karst features. Furthermore, Brezinski (2007) showed that human activity and the relative position of the ambient water table related to local topography also can have deleterious effects on sinkhole development. All of these factors to varying degrees have demonstrable implications for road and highway site planning, construction, and maintenance. Key human factors impacting sinkhole development include the creation of unlined drainage and stormwater management basins, the disturbance of overburden, and the rearrangement of surface drainage and streams. These factors all are commonly employed during highway construction and improvement. Knowledge of their relative importance in any one area may be critical in road engineering and site evaluation. The nexus of these geologic, topographic, and human factors in sinkhole development can produce a highly unstable karst regime.

One example of how the overlapping of these factors can impact highway construction was illustrated by Brezinski (2007, fig. 9) for an area of Maryland's Frederick Valley. Brezinski (2004, 2007; Brezinski et al., 2004) identified several rock formations in the Frederick Valley that were highly susceptible to sinkhole formation. Wherever these formations cropped out, sinkhole activity was higher than normal. Additionally, several areas were identified within the outcrop belts of these susceptible rock formations where catastrophic collapse sinkholes were extremely common. These highly active areas were located adjacent to active quarrying, where urban development was occurring, or where surface streams had been rerouted. One particular area was identified where the geologic, topographic, and human were impactful (Brezinski, 2007, fig. 9). This area, located along Interstate 70, was subsequently chosen as a site for a storm water management basin. During excavation and construction of this basin, the floor of the excavation became unstable with an increased incidence of collapse sinkholes. Repeated attempts were made to stabilize the floor of the basin by grouting, but collapse sinkholes continued to appear. Some sinkholes were grouted repeatedly. The results were a delay in basin completion, and increased project costs from grouting, Grout usage increased above preconstruction estimates by nearly an order of magnitude.

In the Hagerstown Valley, several formations also exhibit strong tendencies towards active sinkhole development while others show only modest affinities (Table 1). For instance, within the St. Paul Group, 67% of all karst features are active sinkholes. Conversely, only 8% of the karst features are active sinkholes in the Elbrook Formation. These numbers demonstrate great variability in sinkhole susceptibility from one unit to another. The reasons for these variations are numerous, but most often can be attributed to the purity of the calcium carbonate that makes up the particular unit (see Figure 9 of this report). That prerequisite knowledge is important in identifying areas that might experience increased sinkhole potential in the future. Also important in this identification is the presence of complicating factors, such as joint systems, and a depressed water table as was seen in the Frederick Valley.

One area of sinkhole potential in the Hagerstown Valley was identified during the course of this study. This area is located along Interstate 81 near the Potomac River at Williamsport (Figure 17). In this area, numerous active sinkholes and depressions were identified and located. These karst features are almost completely contained within the outcrop belts of the highly karst susceptible middle and upper members of the Stonehenge Limestone. Furthermore, along Interstate 81, several active and filled sinkholes are present within unlined highway drainage (Figure 18). The localized density of sinkholes in this area can be attributed to the overlapping of a number of factors. In addition to the presence of the highly susceptible Stonehenge units, and the Williamsport fault, a

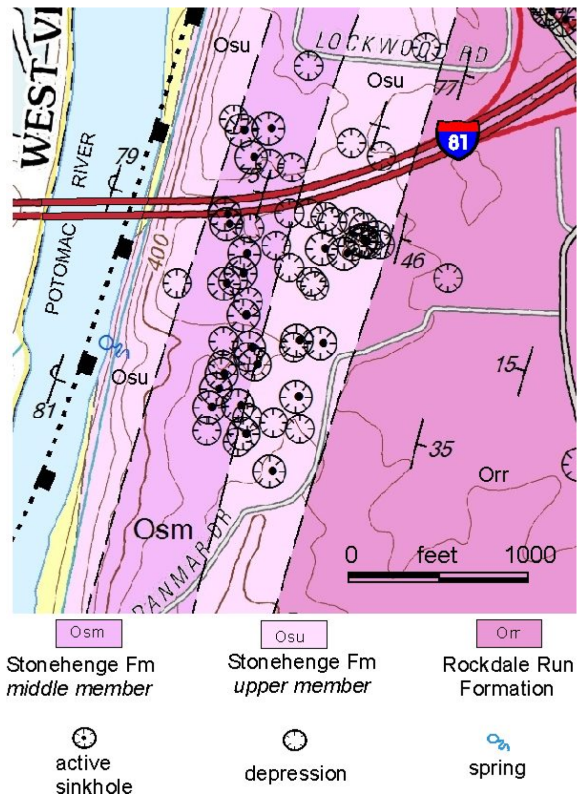

Figure 17. Geologic map of karst features along the Potomac River southwest of Williamsport, Maryland. Map illustrates high karst susceptibility within the middle and upper members of the Stonehenge Limestone. Taken from Brezinski, 2014.

depressed water table exists. The local water table is governed by the elevation of the Potomac River, which is at 340 feet above sea level. The land surface along Interstate 81 is at 400 feet, more than 60 feet higher than the water table. Thus, in this area surface and ground water must drop as much as 60 feet to reach the water table. This hydraulic differential provides a greater potential for the removal of soil water and could lead to increased sinkhole occurrence or propagation.

Figure 18. Incipient sinkhole in unlined roadside drainage in the median of Interstate 81.

In summary, the geologic, topographic, and human activity factors that contribute to sinkhole formation, and that are identified during this study, can be utilized as a set of baseline characters in any current and future highway improvement project and site study. These characters provide a foundation from which more detailed and localized site studies may be based. This information provides an underpinning that site developers can employ in identifying high sinkhole susceptibility areas.

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REFERENCES

Bassler, R.S., 1919, The Cambrian and Ordovician deposits of Maryland: Maryland Geological Survey Systematic Report, 424 p.

Beck, B. F., 1986, A generalized genetic framework for the development of sinkholes and karst in Florida, U.S.A: Environmental Geology Water Sciences, 8:5-18.

Bell, S.C., 1993, Geology of the Hagerstown Quadrangle, Washington County, Maryland: Maryland Geological Survey Geologic Map, scale 1:24,000.

Brezinski, D.K., 1992, Lithostratigraphy of the western Blue Ridge cover rocks in Maryland: Maryland Geological Survey, Report of Investigations 55, 69 p.

Brezinski, D.K., 1996a, Stratigraphy of the Elbrook Formation (Middle to Upper Cambrian) in Maryland and adjacent states: Maryland Geological Survey, Special Publication 3, p. 165-186.

Brezinski, D.K. 1996b, Carbonate Ramps and Reefs: Paleozoic Stratigraphy and Paleontology of Western Maryland: Maryland Geological Survey Geologic Guidebook 6, (for the North American Paleontological Convention VI).

Brezinski, D.K., 2004, Stratigraphy of the Frederick Valley and its relationship to karst development: Maryland Geological Survey, Report of Investigations 75, 101 p.

Brezinski, D.K., 2007. Geologic and Anthropogenic Factors Influencing Karst Development in the Frederick :Region of Maryland: Environmental Geosciences, 14:41-38.

Brezinski, D.K., 2014, Geologic and karst features map of the Williamsport quadrangle, Washington County, Maryland: Maryland Geological Survey digital geologic map WILLI2014.1, scale 1:24,000.

Brezinski, D.K., Anderson, T., and Campbell, P. 1996, Evidence for a regional detachment at the base of the Great Valley sequence in the central Appalachians: Maryland Geological Survey Special Publication 3, p. 223-230.

Brezinski, D. K., Repetski, J. E., and Taylor, J. F., 1999, Stratigraphic and paleontologic record of the Sauk III regression in the central Appalachians: *in* V. L. Santucci, and L. McClelland, eds., National Park Service Paleontological Research: 4: 32-41.

Brezinski, D.K., Reger, J.P., and Baum, GR. 2004, Sinkhole susceptibility, *in* Meeting Challenges with Geologic Maps, American Geological Institute Environmental Awareness Series, p. 36-37.

Brezinski, David K., John F. Taylor, and John E. Repetski, 2012, Sequential development of platform to off-platform facies of the great

American carbonate bank in the central Appalachians, in J. R. Derby, R. D. Fritz, S. A. Longacre, W. A. Morgan, and C. A. Sternbach, eds., The Great American Carbonate Bank: The geology and economic resources of the Cambrian – Ordovician Sauk megasequence of Laurentia: AAPG Memoir 98, p. 383 – 420.

Cloos, E., 1941, Geologic Map of Washington County: Maryland Geological Survey, Scale: 1:62,500.

Cloos, E., 1971, Microtectonics of the western edge of the Blue Ridge Maryland and Virginia: Johns Hopkins University Studies in Geology, No. 20, 234 p.

Demicco, R.V., 1981, Comparative sedimentology of an ancient carbonate platform: the Conococheague Limestone of the central Appalachians: unpublished Ph.D. dissertation, Johns Hopkins University, Baltimore, 333 p.

Demicco, R.V., 1985, Platform and off-platform carbonates of the Upper Cambrian of Western Maryland, USA: Sedimentology, 32:1-22.

Demicco, R.V., and Mitchell, R.W., 1982, Facies of the Great American Bank in the central Appalachians: *in* Little, P.T., ed., Central Appalachian Geology: Northeastern-Southeastern Sections of Geological Society of America, Fieldtrip Guidebooks, p. 171-266.

Duigon, M. T. 2001, Karst hydrogeology of the Hagerstown Valley, Maryland. Maryland Geological Survey Report of Investigations 73, 128 p.

Edwards, J., 1978, Geologic Map of Washington County: Maryland Geological Survey County Map, scale 1:62,500.

Epstein, J.B., Orndorff, R.C., and Rader, E.K., 1995, Middle Ordovician Stickley Run Member (new name) of the Martinsburg Formation, Shenandoah Valley, northern Virginia, IN Stratigraphic notes, 1994: U.S. Geological Survey Bulletin, 2135, p. 1-13.

Franz, R., and Slifer, D., 1971, Caves of Maryland. Maryland Geological Survey Educational Series No. 3, 120 p.

Jennings, J.N., 1985. Karst Geomorphology: Basil Blackwell, New York, 293 p.

Jonas, A.I., and Stose, G.W., 1938, Geologic map of Frederick County, and adjacent parts of Washington and Carroll Counties: Maryland Geological Survey, Scale 1:62,500.

Keith, A., 1892, Geologic structure of the Blue Ridge in Maryland and Virginia: American Geologist, 10: 362-368.

Keith, A., 1893, Chapter III, Geology, *in* Williams, G.H., and Clark, W.R., Maryland: It's Resources, Industries, and Institutions, Maryland Geological Survey, p. 68.

Keith, A., 1894, The Harpers Ferry Folio: U.S. Geological Survey, Atlas Folio 10, 5 p.

Morgan, W.A., 2012, Sequence stratigraphy of the great American carbonate bank, in J. R. Derby, R. D. Fritz, S. A. Longacre, W. A. Morgan, and C. A. Sternbach, eds., The great American carbonate bank: The geology and economic resources of the Cambrian — Ordovician Sauk megasequence of Laurentia: AAPG Memoir 98, p. 37 – 82.

Mussman, W. J., and J. F. Read, 1986, Sedimentology and development of a passive- to convergent-margin unconformity: Middle Ordovician Knox unconformity, Virginia Appalachians: Geological Society of America Bulletin, v. 97, p. 282–295,

Neuman, R.B., 1951. St. Paul Group: A revision of the "Stones River" Group of Maryland and adjacent states. Geological Society of America Bulletin, 62:267-324.

Nickelsen, R.P., 1956, Geology of the Blue Ridge near Harpers Ferry, West Virginia: Geological Society of America Bulletin, 67:239-270.

Nutter, L.J., 1973. Hydrogeology of the carbonate rocks, Frederick and Hagerstown Valleys, Maryland: Maryland Geological Survey Report of Investigations 19, 70 p.

Rader, E. K., and J. F. Read, 1989, Early Paleozoic continental shelf to basin transition, northern Virginia, 28th International Geological Congress, fieldtrip guidebook T221: Washington, D. C., American Geophysical Union, 9 p.

Ryder, R. T., A. G. Harris, and J. E. Repetski, 1992, Stratigraphic framework of Cambrian and Ordovician rocks in the central Appalachian Basin from Medina County, Ohio, through southwestern and south-central Pennsylvania to Hampshire County, West Virginia: U.S. Geological Survey Bulletin 1839-K, 32 p.

Read, J. F., 1989, Controls on Evolution of Cambrian-Ordovician passive margin, U.S. Appalachians, *in* P.D. Crevello, J.F. Read, J.F. Sarg, and J.L. Wilson, eds., Controls on Carbonate Platform and Basin Development: SEPM Special Paper 44, p. 147-165.

Root, S.I., 1968, Geology and Mineral Resources of Southeastern Franklin County, Pennsylvania: Pennsylvania Topographic and Geologic Survey (4th series), Atlas 119, 118p.

Sando, W.J., 1956, Nomenclature of Lower Ordovician rocks of Washington County, Maryland: Geological Society of America Bulletin, 67:935-938.

Sando, W.J., 1957, Beekmantown Group (Lower Ordovician) of Maryland: Geological Society of America Memoir 68, 161 p.

Sando, W.J., 1958, Lower Ordovician section near Chambersburg, Pennsylvania: Geological Society of America Bulletin, 69:837-854.

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

Bulletin 2123, 33 p.
Stose, G.W., 1906, Sedimentary rocks of South Mountain, Pennsylvania: Journal of Geology, v. 14, p. 201-220.
Stose, G.W., 1908, Cambro-Ordovician limestones of the Appalachian Valley in southern Pennsylvania: Journal of Geology, 16:698-714.
Stose, G.W., 1910, The Mercersburg-Chambersburg Folio: U.S. Geological Survey, Geologic Atlas Folio 170, 144 p.
Taylor, J.F., Repetski, J.E., and Orndorff, R.C., 1992, The Stonehenge Transgression: A rapid submergence of the central Appalachian platform in the early Ordovician: *in* Webby, B.D., and Laurie, J.F., (eds.), Global Perspectives on Orodovician geology. Balkema, p. 409-418.
Wilson, J.L., 1952, Upper Cambrian stratigraphy in the central Appalachians: Geological Society of America Bulletin, 63:275-322.
Woodward, H.P., 1949, The Cambrian System in West Virginia: West Virginia Geological Survey Report, v. 20, 317 p.

GLOSSARY OF GEOLOGICAL TERMS

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

Anticlinorium. A broad upward bend in the crust made up of a series of anticlines and synclines, grouped that taken together they have the general outline of an arch;

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

Bedrock. Referring to solid rock that underlies unconsolidated material, e.g.,. soil

Breccia. A clastic rock composed of particles more than 2 millimeters in diameter and marked by the angularity of its component grains and rock fragments.

Carbonate . One of several minerals containing one central carbon atom with strong covalent bonds to three oxygen atoms and typically having ionic bonds to one or more positive ions.

Cave. A naturally formed void or opening beneath the surface of the Earth, formed by dissolution of carbonate bedrock.

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

Cleavage. The tendency of certain minerals to break along distinct planes in their crystal structures where the bonds are weakest. Cleavage is tested by striking or hammering a mineral, and is classified by the number of surfaces it produces and the angles between adjacent surfaces.

Conglomerate. A clastic rock composed of particles more than 2 millimeters in diameter and marked by the roundness of its component grains and rock fragments.

Doline. A bowl or funnel shaped closed depression formed from the dissolving of underlying bedrock. Equivalent to a depression of this report.

Dolomite. A carbonate rock made up of more than 50 percent of the mineral calcium-magnesium carbonate ($CaMg(CO_3)_2$).

Fault. A fracture dividing a rock into two sections that have visibly moved relative to each other.

Fold. A bend that develops in an initially horizontal layer of rock, usually caused by plastic deformation. Folds occur most frequently in sedimentary rocks.

Fracture. A crack or break in rock.

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

Joint. A fracture in rock where no visible moved has taken place.

Karst. A topography characterized by caves, sinkholes, disappearing streams, and underground drainage. Karst forms when groundwater dissolves pockets of limestone, dolomite, or gypsum in bedrock.

Limestone. A sedimentary rock composed primarily of calcium carbonate. Some 10% to 15% of all sedimentary rocks are limestones. Limestone is usually organic, but it may also be inorganic.

Oolitic. Pertaining to a rock that consists of carbonate grains that have concentric layers of growth.

Sandstone. A clastic rock composed of particles that range in diameter from 1/16 millimeter to 2 millimeters in diameter. Sandstones make up about 25% of all sedimentary rocks.

Sinkhole. An open, circular or funnel-shaped hole of depression in the ground that forms when soluble rocks dissolve and soil collapses.

Spring. A location or zone where ground water discharges to the surface.

Strata. An individual layer of a sedimentary rock.

Stromatolite. A layered limestone deposit formed by photosynthesizing colonial algae.

Swallowhole. An opening within a stream channel that accepts stream flow to the underground

Syncline. A concave fold, or fold that bend downward, whose central part contains the youngest section of rock.

Synclinorium. A regional series of synclines and anticlines grouped together so they have the general outline of a trough.

Thrombolite. A form of stromatolite that has a clotted, rather than a laminated structure.