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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

GEOLOGY AND SINKHOLE DEVELOPMENT IN THE HAGERSTOWN VALLEY, MARYLAND: PHASE I

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MARYLAND DEPARTMENT OF NATURAL RESOURCES
RESOURCE ASSESSMENT SERVICE
MARYLAND GEOLOGICAL SURVEY

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16. Abstract

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 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. The application of modern detailed geologic and karst mapping and data analysis allows characterization of various areas within a karst terrane by utilizing a karst susceptibility index (KSI). The KSI was developed and used in a previous study of the Frederick Valley karst terrane by the Maryland Geological Study, in cooperation with the Maryland State Highway Administration. When area data obtained from detailed GIS-based geologic maps were merged with karst feature data, the empirical KSI gave a primary picture of sinkhole potential allowing engineers, developers, and planners to gain a better understanding of sinkhole susceptibility in the area.

The methods used in the Frederick Valley study were used in this study which evaluates Maryland's largest karst terrane, the Hagerstown Valley. This phase evaluated five of the ten 7.5 minute quadrangles that make up the eastern half of the Valley. The area was mapped in detail to determine the distribution of geologic units. During bedrock geologic mapping, more than 1,500 karst features were identified and located utilizing a global positioning system.

Findings: Preliminary findings suggest an empirical relationship between types of karst features and the bedrock unit composition. In addition to bedrock composition, joints and faults appear to play important roles in the development of karst systems in the eastern half of the Valley. The findings also suggest that the impact of humans on the formation of the Hagerstown Valley karst systems is significantly less than that observed in the Frederick Valley. While it is premature make a conclusion why this is the case, it may be related to the fact that the Frederick Valley has experienced a greater level of development. The remaining five quadrangles of the Hagerstown Valley will be evaluated in the next phase of this project.

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GEOLOGY AND SINKHOLE DEVELOPMENT IN THE HAGERSTOWN VALLEY, MARYLAND: PHASE I REPORT

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Resoursce Assessment Service
Maryland Geological Survey

2009

GEOLOGY AND SINKHOLE DEVELOPMENT OF THE HAGERSTOWN VALLEY: PHASE I REPORT

EXECUTIVE SUMMARY

- Five of the ten 7.5-minute quadrangles that make up the eastern half of the Hagerstown Valley of Maryland were mapped in detail to determine the distribution of geologic units.
- During bedrock geologic mapping, karst features were identified and located utilizing a global positioning system.
- More than 1,500 karst features were identified and located in the five quadrangles studied.
- Preliminary findings suggest an empirical relationship between types of karst features and the bedrock unit composition.
- In addition to bedrock composition, joints and faults appear to play important roles in the development of karst systems in the eastern half of the Hagerstown Valley.
- Preliminary findings suggest that the impact of humans on the formation of the Hagerstown Valley karst systems is significantly less than that observed in the Frederick Valley.

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 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 *a priori* 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.

The application of modern detailed geologic and karst mapping and data analysis allows characterization of various areas within a karst terrane by utilizing a *karst susceptibility index* (KSI). The KSI was developed and employed in a study of the Frederick Valley karst terrane by the Maryland Geological Survey, in a cooperative study with the State Highway Administration (Brezinski, 2004, 2007). The findings of the Frederick Valley study demonstrated that differing compositions of limestone layers produce different karst susceptibilities. When area data obtained from detailed GIS-based geologic maps were merged with karst feature data, the empirical KSI gave a primary picture of sinkhole potential. Engineers, developers, and planners can apply this index as a first approximation in investigatory evaluation. The methods utilized in the Frederick Valley study were employed in this study which evaluates Maryland's largest karst terrane, the Hagerstown Valley. Phase I of this study, the subject of this report, deals with the eastern half of the valley and encompasses the Keedysville, Funkstown, Shepherdstown, Myersville, and Smithsburg 7.5´quadrangles (Figure 1).

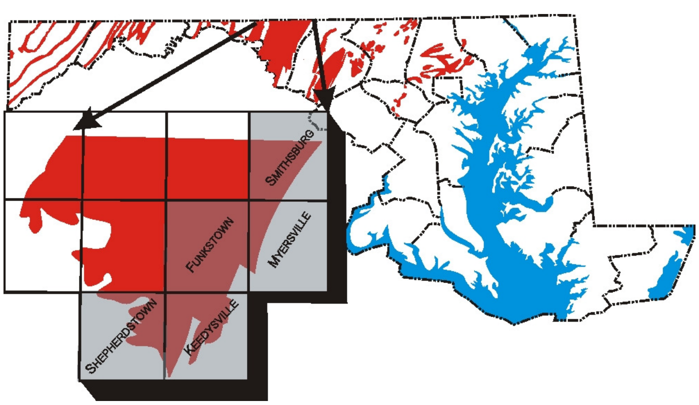

Figure 1. Areas underlain by carbonate rocks in Maryland (red) and location of Phase I quadrangles (gray).

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 (540 to 450 My 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 part of the Blue Ridge physiographic province, while the Massanutten synclinorium is the eastern section of the Ridge and Valley Physiographic Province.

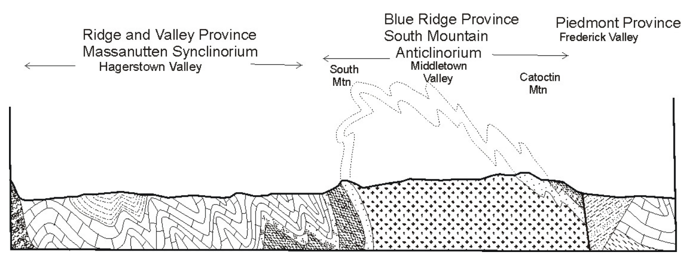

Figure 2. Idealized geologic cross section from the Frederick Valley to the western edge of the Hagerstown Valley in Maryland (redrawn and modified from Cloos, 1971).

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).

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.

LITHOSTRATIGRAPHY

Older Blue Ridge Cover Succession

Strata older than and originally lying beneath the carbonate rocks of the Hagerstown Valley succession are assigned to the Late Proterozoic to Early Cambrian Chilhowee Group. These strata originally covered the basement rocks of the Blue Ridge and are commonly termed the Blue Ridge cover sequence (Brezinski, 1992). These units in ascending order are: the Loudoun, Weverton, Harpers, and Antietam formations. In the northern Blue Ridge only the Antietam Formation has been unequivocally confirmed as Early Cambrian in age. The underlying units have questionable ages of either Late Proterozoic or Early Cambrian.

Loudoun Formation

The basal unit of the Chilhowee Group is the Loudoun Formation. Keith (1893) applied the name Loudoun Formation to an interval composed mainly of "black slate" that locally overlies the volcanogenic rocks of the Catoctin Formation. This formation exhibits considerable heterogeneity and variations in thickness. The Loudoun consists primarily of grayish-black to brownish-black phyllite and medium- to dark-gray, tuffaceous, phyllitic conglomerate. While phyllite makes up most of the formation, the dark-gray, quartz-pebble conglomerate is its most prominent lithologic characteristic. Such conglomerate intervals are very useful in marking the base of the Chilhowee Group throughout the Blue Ridge Physiographic Province of Maryland.

The high variability in thickness of the Loudoun Formation has been postulated to be the result of abrupt irregularities in the depositional surface up on which the Loudoun was deposited. Presumably, topographic lows in the underlying Catoctin Formation accumulated sediments that were subsequently preserved as thick layers of phyllite and conglomerate. The highly variable composition of the conglomerate member may be related to differences in very localized source areas.

Weverton Formation

Keith (1893, 1894) named the main ridge-forming unit of the Blue Ridge of Maryland the Weverton Formation. Brezinski (1992) subdivided the Weverton Formation into three members. In ascending order these members are the Buzzard Knob, Maryland Heights, and Owens Creek.

Buzzard Knob Member: The lowest member of the Weverton Formation is the Buzzard Knob Member, which is the main ridge-forming unit in the Maryland Blue Ridge. This member is underlain by the Loudoun Formation, and by the Catoctin Formation where the Loudoun is absent. Typically, the member can be subdivided into lower and upper quartzite units. The lower unit is approximately 45 feet thick and consists of very light-gray to yellowish-gray, medium-bedded, medium- to coarse-grained, well-sorted quartzite. The basal beds of this unit are very coarse-grained quartzite. The upper resistant unit is light-gray to medium-gray, coarse-grained quartzite with dusky-blue, grayish-olive, and grayish-yellow bands, and is approximately 50 feet thick.

Maryland Heights Member: The middle member of the Weverton Formation is composed of alternating layers of medium-gray quartzite, medium-dark-gray, conglomeratic graywacke, dark-gray phyllite, and metasiltstone. Named the Maryland Heights Member by Brezinski (1992) for exposures at the southern end of Elk Ridge, this member is approximately 300 feet thick. The upper contact of the member is defined as the level where the thin-bedded siltstones of the Maryland Heights Member are replaced by the thick-bedded graywacke of the overlying Owens Creek Member.

Owens Creek Member: The upper member of the Weverton consists of a ledge-forming quartzite that Brezinski (1992) named the Owens Creek Member. The type section for this member is along Owens Creek and Maryland Route 550 on Catoctin Mountain. This member consists of interbedded, dark-gray phyllite, thin-bedded, coarse-grained, dark-gray metagraywacke, and interbedded, medium- to dark-gray, thin-bedded, coarse-grained greywacke, dark-gray, quartz-pebble conglomerate; and a few intervals of greenish-gray, quartzose, ferruginous siltstone.

Harpers Formation

Overlying the coarse-grained ridge-forming quartzites of the Weverton Formation is an interval of metamorphosed shale, siltstone, and sandstone named the Harpers Formation. The type section for this formation is at Harpers Ferry, West Virginia, where it is characterized by several hundred feet of dark-gray to olive-black, medium-grained sandstone and siltstone with thin beds (1 to 4 inches) of medium-gray, fine-grained sandstone. The middle of the formation consists of 700 to 1,000 feet of greenish-black to brownish-black, highly cleaved siltstone, fine-grained sandstone, and some silty shale (Brezinski, 1992). Locally, fine- to medium-grained, brownish-black, olive-gray to greenish-black sandstone units, up to 40 feet in thickness, can be traced within the formation (Southworth and Brezinski, 1996). From the Maryland-Pennsylvania boundary line north, thick tongues of ferruginous sandstone, containing *Skolithos* burrows occur in the unit. These sandstones are extensions of the Montalto Member of the Harpers Formation of Pennsylvania (Jonas and Stose, 1938). The uppermost Harpers Formation consists of interbedded dark-greenish-gray to olive-black, sandy siltstone and shales and light-gray to medium-light-gray, fine-grained sandstone, with beds 2 to 6 inches thick. These beds contain very abundant *Skolithos* burrows.

Antietam Formation

The uppermost formation of the Chilhowee Group is the Antietam Sandstone (Keith, 1893, 1894). Although the unit tends to form prominent ridge on the eastern edge of the Great Valley, rarely does it crop out. The Antietam Formation consists of light-gray to light-brown, medium-bedded, medium- to fine-grained sandstone. These strata typically weather to angular cobbles of cross-bedded, *Skolithus*-bearing sandstone.

The Antietam Formation has been shown to be Lower Cambrian in age through the presence of the trilobite *Olenellus* (Nickelson, 1956; Brezinski, 1992).

Great Valley Succession

The Late Proterozoic to Lower Cambrian Blue Ridge cover rocks of the Chilhowee Group are overlain by a thick succession of carbonate rocks known as the Great Valley succession. This episode of deposition of carbonate strata began during the Lower Cambrian with the Tomstown Formation and persisted nearly continuously for 90 million years until the Late Ordovician. This prolonged period of carbonate deposition resulted in the accumulation of more than 12,000 feet (3,600 m) of largely shallow water carbonate rocks (figure 3). This carbonate episode ended with the formation of the Taconic Mountains near the end of the Ordovician Period.

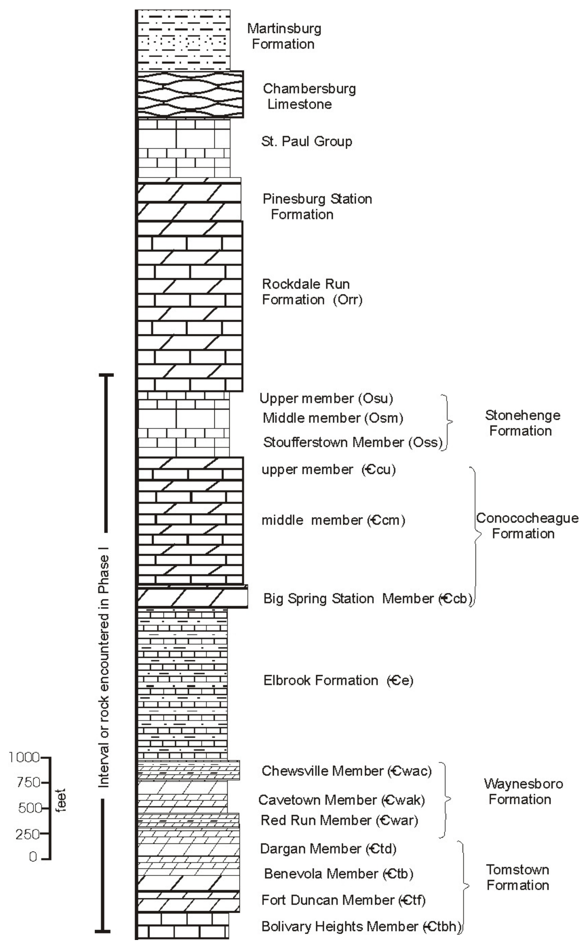

Figure 3. Stratigraphic column of the carbonate rocks of the Great Valley succession in the Hagerstown Valley in Maryland.

Tomstown Formation

The oldest carbonate unit of Maryland's Great Valley is the Tomstown Formation. Stose (1908) applied the name Tomstown Dolomite to this poorly exposed interval that occurs directly above the Antietam Formation and below the shales of the Waynesboro Formation. Brezinski (1992) identified and subdivided the formation into four laterally continuous and mappable members. These are, in ascending order, the Bolivar Heights, Fort Duncan, Benevola, and Dargan members. Stose (1910) estimated that the Tomstown Formation is approximately 1,000 feet thick in the type area, but measurements provided by Brezinski (1992) suggest that the formation is nearly 1200 feet in thickness. This is consistent with estimates of Woodward (1949) for the formation in West Virginia.

Bolivar Heights Member: The basal member of the Tomstown Formation is the Bolivar Heights Member. The Bolivar Heights Member is characterized by a tan, vuggy dolomite at its contact with the underlying Antietam Formation. This dolomite ranges from 10 to 40 feet in thickness. Overlying the basal dolomite is an interval, 40 to 50 feet thick, composed of very light-gray, sheared, laminated, dolomitic marble that Brezinski (1992) termed the Keedysville Marble Bed. Brezinski et al. (1996) proposed that the Keedysville Marble Bed was a stratotectonic unit formed either during the Late Ordovician or early in the Late Paleozoic Alleghanian orgeny. Above the Keedysville marble bed the Bolivar Heights Member consists of between 200 to 250 feet of thin- to medium-bedded, dark-gray, ribbony, burrow-mottled, lime mudstone that weathers light-gray in color. The amount and density of bioturbation generally tends to increase upsection and in many locations the burrows have been distorted during Alleghanian deformation.

Fort Duncan Member: Overlying the limestone strata of the Bolivar Heights Member is an interval, ranging in thickness from 200 to 250 feet thick, of dark-gray, medium- to thick-bedded, knotty dolomite that Brezinski (1992) named the Fort Duncan Member. The Fort Duncan Member consists of burrow-mottled to knotty dolomite that weathers to an irregular, rough surface. In polished slabs the knotty or burrowed areas appear to be represented by dark-gray, rounded clots of fine-grained dolomite with white, void-filling, sparry dolomite. Individual clots show no internal structure, but this appears to be largely the result of the destruction of the original fabric by the dolomitization process.

The contact of the Fort Duncan Member with the overlying Benevola Member is gradational over approximately 15 feet. The boundary is represented by a gradual decrease in the amount and distinction of the knotty appearance as well as a gradual lightening of color from dark-gray dolomite to very light-gray dolomite.

Benevola Member: Overlying the dark-gray, knotty dolomite of the Fort Duncan Member is an interval of light-gray to white, massive dolomite that varies from 70 to 140 feet in thickness that Brezinski (1992) named the Benevola Member. The Benevola Member is a white to very light-gray, sugary dolomite both on fresh and weathered surfaces. The Benevola Member also has a tendency to be highly fractured. Bedding is rarely evident within the Benevola Member, but polished slabs of the unit commonly display faint ghosts of cross-bedding. At the type section the Benevola Member consists of two massive, light gray dolomite units separated by an interval, 17 feet thick, comprised of laminated and bioturbated, gray dolomite. However, at most locations the unit occurs as a single, massive, white dolomite interval.

The contact between the Benevola Member and the overlying Dargan Member of the Tomstown consists of an intercalated succession of light-gray, thick-bedded to massive dolomite, alternating with thinly laminated dolomite.

Dargan Member: The uppermost member of the Tomstown Formation is the Dargan Member. This unit is the thickest member of the formation and locally exceeds 700 feet. The Dargan Member consists of interbedded dark-gray, bioturbated dolomite and gray laminated dolomite. The dark-gray, bioturbated dolomite intervals range from 3 to 9 feet in thickness and alternate with intervals of medium- to dark-gray, laminated dolomite, 1 to 6 feet thick. The upper 300 to 400 feet of the member consist of interbedded, dark-gray, bioturbated and oolitic dolomite; dark-gray, laminated limestone; and tan, laminated, silty dolomite, and mudcracked, laminated cryptalgal and domal stromatolites. Near the top of the member numerous thin laminated, algal limestone strata are interbedded with the laminated dolomite.

The contact between the Dargan Member of the Tomstown and the overlying basal Waynesboro Formation is relatively sharp. It is represented by the rapid replacement of alternating stromatolitic limestone and tan dolomite cyclic carbonates with a greenish-gray to tan calcareous shale and tan dolomite of the Waynesboro Formation.

Waynesboro Formation

Overlying the Tomstown Formation is an interval of interbedded carbonates and clastics known as the Waynesboro Formation. This formation was named by Stose (1908) for exposures surrounding the town of Waynesboro, Franklin County, Pennsylvania. Traditionally, the Waynesboro has been characterized as red shale and sandstone, but many authors (Bassler, 1919, 1975; Fauth, 1981) recognized a three-fold subdivision of the formation. This led Brezinski (1992) to subdivide the formation into three members. In ascending order they are: the Red Run, Cavetown, and Chewsville members.

Red Run Member: The base of the Waynesboro Formation marks a discrete change from the pure carbonate deposition of the Tomstown Formation. The basal Waynesboro Formation, named the Red Run Member by Brezinski (1992) consists of interbedded, gray, calcareous, bioturbated sandstones, laminated and ribbony, sandy dolomite, and olive-gray, silty, mudcracked, calcareous shale. Sandstone layers are rarely more than 3 feet thick and are separated from one another by thin (< 1 foot thick), red-brown shale and shaly stringers, and tan ribbony to laminated, silty dolomite. This member weathers to blocks of calcareous sandstone and tan sandy dolomite chips.

The thickness of the Red Run Member varies between 150 and 200 feet. It is a continuous member throughout southern Pennsylvania and extends into northern Virginia. Where exposed, the upper contact of the Red Run Member consists of interbedded shaly and sandy strata with an upward increase in laminated and bioturbated limestone and dolomite.

Cavetown Member: Overlying the shaly and sandy strata of the Red Run Member is the medial part of the Waynesboro Formation named the Cavetown Member (Brezinski (1992). The Cavetown Member is the thickest member of the formation, but also its most poorly exposed. The Cavetown Member characteristically forms a valley or topographically depressed area between the adjacent low ridges created by the upper and lower, more clastic-rich, members. Because the Cavetown Member contains lithologies common to the Dargan Member of the Tomstown and Elbrook Formation, this member is commonly mistaken for these two formations (Cloos, 1941; Edwards, 1978). Based on outcrop width and composite measured sections Brezinski (1992) estimated the thickness of this member at 400 to 600 feet.

The lowest 200 feet of the Cavetown Member consist of thick-bedded to massive, medium-gray, extremely fine-grained limestone and bioturbated dolomite. This pure carbonate lithology has, in the past, been quarried. The middle 200 feet of this member consist of interbedded, medium- to dark-gray, bioturbated, ribbony dolomitic limestone and ribbony to laminated dolomite with intervals of interbedded, tan dolomite, light-gray, fine-grained, calcareous sandstone, and olive-gray, calcareous shale. The upper part of the Cavetown Member is a thick-bedded to massive, medium- to dark-gray, bioturbated, dolomitic limestone to dolomite containing numerous intraclastic grainstone to oolitic intervals. This part of the member, like the section at the base, contains relatively pure carbonate intervals and is highly quarried.

The gradational contact between the Cavetown and overlying Chewsville Member is exposed along the CSX tracks 0.25 mile west of the Cavetown quarry. This exposure illustrates how the interbedded dolomite and shaly limestone of the upper part of the Cavetown Member are abruptly replaced by the siliciclastic beds of the Chewsville Member.

The Cavetown Member, like its name implies, is highly susceptible to dissolution. This is suggested by the development of numerous caves within this member especially those at Mt. Aetna and Cavetown.

Chewsville Member: The most distinctive part of the Waynesboro Formation is the uppermost 150 to 200 feet of the formation. This stratigraphic package was named the Chewsville Member by Brezinski (1992) and is characterized by a succession of interbedded dark-reddish-brown siltstone, sandstone, and shale similar to that of the Red Run Member. At the type section, along the CSX railroad tracks east of Chewsville, Washington County, Maryland), the Chewsville Member consists of nearly 150 feet of cyclically interbedded, dusky-red and dark-reddish-brown, sandy siltstone and shale, grayish-red, grayish-pink, and pinkish-gray, medium- to fine-grained sandstone, and light-brown to grayish-orange, silty and sandy, laminated dolomite. Less common lithologies include light-olive-gray shale and medium-gray, stromatolitic and bioturbated dolomitic limestone. The reddish-brown siltstone units are commonly rippled and mudcracked, whereas the sandstone beds are pervasively cross-bedded and exhibit *Skolithos* burrows.

Like the basal Waynesboro Formation, the arrangement of repetitive lithologies in the Chewsville Member suggest that it was formed in a shallow subtidal deposits, shallowing into cross-bedded intertidal sandstones, and then into supratidal red, mudcracked siltstone and shale suggest cyclic conditions. This contrasts the massive carbonate strata of the Cavetown Member, which was deposited in deeper water environments. This change in character has implications for the development of karst. Both the lower and upper member were found to be relatively devoid of karst features while the middle member was determined to be highly susceptible.

Elbrook Formation

Sharply overlying the mixed clastic-carbonate strata of the Chewsville Member of the Waynesboro Formation is a thick interval of cyclic limestone and dolomite that Stose (1908) named the Elbrook Limestone. Now termed the Elbrook Formation, the type section of this unit is poorly exposed near Elbrook, Franklin County, Pennsylvania.

Although Brezinski (1992) believed that the contact between the Chewsville Member of the Waynesboro and the overlying Elbrook Formation was gradational Brezinski (1996a) demonstrated that this contact contained a significant time gap and therefore was unconformable. This is consistent with suggestions of Read (1989) that indicated that equivalent strata in southeastern Virginia contain a time gap of as much as 5 million years. Taylor et al. (1997) have shown that the contact between these two formation is a hiatus that spans much of the Middle Cambrian, an interval of time as much as 10 million years in duration.

Brezinski (1996a) identified three informal members within the Elbrook Formation that he was unable to map. These three members will be herein informally termed the lower, middle, and upper members.

Lower Member: The base of the Elbrook Formation throughout the central Appalachians is composed of 25 feet of medium-gray, medium-bedded limestone. Above this basal limestone, the lower member is composed primarily of 700 feet 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. In the eastern outcrop belt the interbedded tan shale and dolomitic shales, characteristic of the lower Elbrook, are well-exposed at numerous small outcrops (Brezinski, 1996a), where relatively thick shaly intervals are punctuated by a medium-light-gray, wavy-bedded limestone. 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. This is consistent with thickness measurements obtained along the C&O Canal and CSXT railroad tracks east of McCoys Ferry near the western border of the Hagerstown Valley.

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.

Near McCoys Ferry over 1,400 feet of this member were measured. Thus, the upper member appears to make up the greatest thickness of the Elbrook Formation. It is also the best exposed member. 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.

Elbrook-Conococheague contact

Unlike the sharp basal Elbrook contact, identifying the contact of the top of the Elbrook with the overlying Conococheague Formation is often difficult. The upper Elbrook Formation appears to exhibit a gradational contact with the overlying Conococheague Formation. This is because the carbonate cycles that characterize the upper member of the Elbrook Formation are also present within the overlying Conococheague Formation. In the western outcrop belt, the top of the Elbrook is placed at the base of the lowest occurring 3-foot thick quartzarenite bed (Demicco, 1981). Along the eastern outcrop belt, the contact is placed where the tan to yellowish dolomites, that Wilson (1952) considered the Big Spring Station Member of the Conococheague Formation, totally replace the thrombolitic limestone intervals that characterize the Elbrook Formation.

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 on the western edge of the valley. 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. These characteristic sandstones are absent within the member on the eastern side of the valley. Because of this, Root (1968) lumped the dolomitic strata near the base of the Conococheague within his newly named Zullinger Member. Bell (1993) and 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. On the eastern side of the valley, the Big Spring Station Member consists of interbedded massive fractured tan dolomite and thickly-bedded, light-gray, thrombolitic dolomite. These strata tend to from a low, gentle rise adjacent to the stratigraphically subjacent Elbrook Formation and weather to a thin soil with tan-weathing dolomite chips. On the eastern side of the valley this member may exceed 300 feet in thickness.

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. Remeasurement of the Zullinger type section during the current study determined that was an interval of dolomite strata at the base of the Zullinger Formation. These dolomite strata appears equivalent to the Big Spring Station Member of the Conocheague Formation of Maryland. Thus, within current study, the Conococheague is demoted back to formation status and the Big Spring Station Member is now recognized in both the western and eastern outcrop belts, Furthermore, Zullinger Formation of the equivalent Conococheague Group of Pennsylvania is equivalent to the Big Spring Station and Middle members of the Conococheague Formation of Maryland.

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. 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.

Root (1968) maintained that this part of the Conococheague Formation was nearly 2,000 feet thick. This thickness would also include the 250 to 300 feet of dolomite at the base of the formation, herein considered the Big Spring Station Member. 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 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, thinly-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. Approximately 30 feet above the base of the member is an interval of massive, dark-gray, thrombolitic lime mudstone. This layer is more than 9 feet thick on the eastern side of the valley and thins to less than 3 feet on the western side. 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 thickly 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.

The middle member of the Stonehenge Formation represents the most easily soluble rock units of Phase I. The largest number of active were found in this member.

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. Only the lower half of the Rockdale Run Formation is exposed in the quadrangles that make up Phase I of this study.

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 eastern 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.

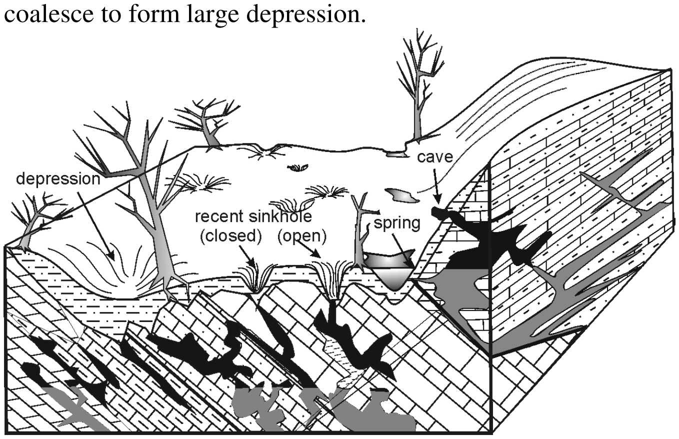

Figure 4. Idealized karst and the types of features identified for this study.

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 features. 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 have unvegetated suggesting 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.

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 characteristic 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 Keedysville, Shepherdstown, Harpers Ferry, Funkstown, Myersville, and Smithsburg 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.

Once data were collected in the field, all GPS files were post-processed. Post-processing is an office procedure whereby the locations identified by the field receiver are differentially corrected by comparing the exact position of the satellites in the constellation as recorded by the field receiver with the position of the satellites as recorded by a base station. The primary base station used in this study is the U.S. Geodetic Survey receiver at Hagerstown, Maryland. When that base station was not operating, the secondary station was Gaithersburg, Maryland or Richmond, Virginia. In some cases, poor field data quality, owing to an inadequate satellite constellation, produced files that could not be post-processed. In such cases these data points were either used without being differentially corrected, or the sites were revisited to acquire new data. The *corrected* GPS files and their locations typically gave a precision of less than 1 meter; however, those that were not corrected commonly gave accuracy of 5 to 10 meters. While both of these levels of precision are insufficient for most surveying purposes, even the unprocessed files were considered of sufficient resolution for the current study, especially when one considers that some of the larger depressions were more than 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.

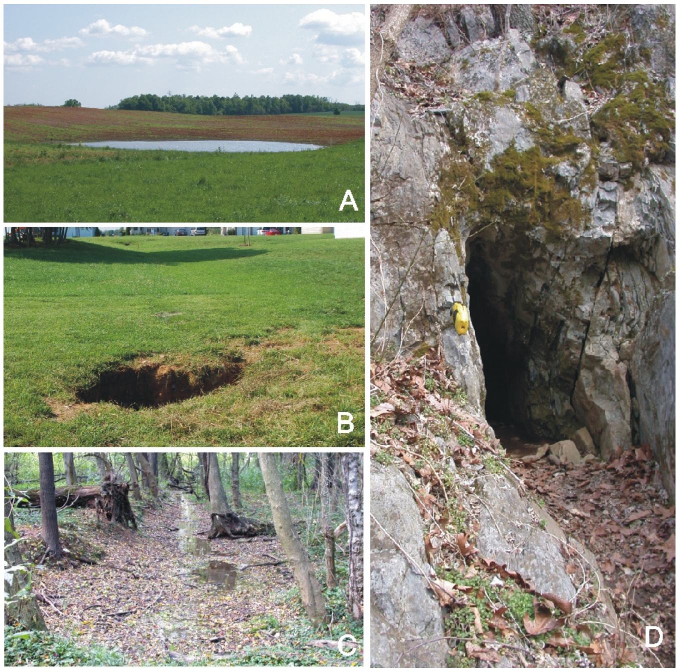

Figure 5. Categories of karst features identified and located for this study.

Karst Feature Summary

More than 1,500 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 1. Depressions are by far the most common feature recorded, making up nearly seventy percent of all the readings. Active sinkholes comprised nearly twenty-two percent of the features. Springs and caves constituted 7.4 percent and 0.9 percent of all karst features, respectively.

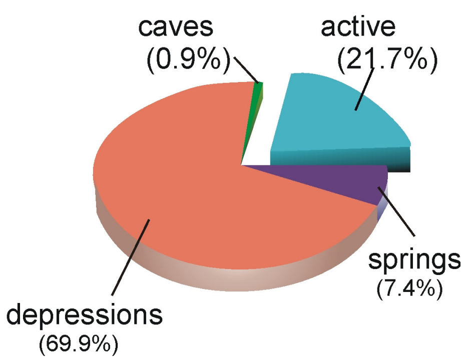

Figure 6. Pie diagram of relative percentages of karst features identified during Phase I of the Hagerstown Valley Karst Project.

These percentages differ only modestly from those observed in the final results of the Frederick Valley karst terrane study (Brezinski, 2004, fig. 26). Within the Frederick Valley depressions were only slightly less abundant, constituting sixty-four percent of all karst features. Conversely, active sinkholes were more prevalent in the Frederick Valley, and made up slightly more than thirty-four percent karst features. Springs are significantly less prominent in the Frederick Valley, makeing up only 1.8 percent of karst features. Caves were so rare in the Frederick Valley that they were not considered in that study. The reader should keep in mind that these numbers are incomplete and that more than half of the areas underlain by karst have yet to be examined in this study. Thus, it is likely that the numbers presented here will change.

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.

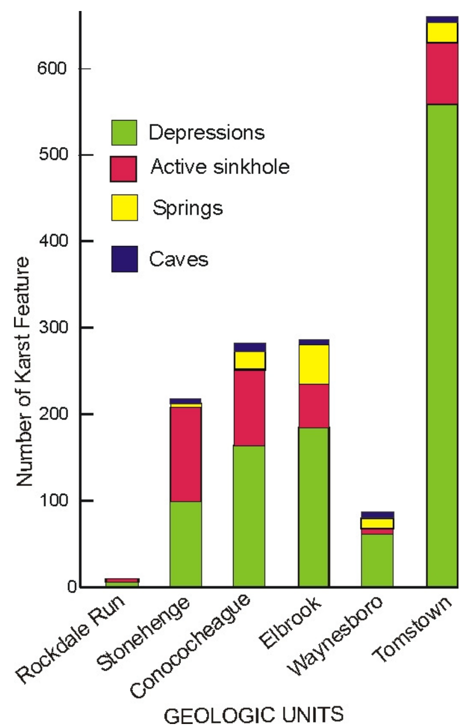

Figure 7. Stacked bar chart of numbers of karst features in Phase I of the Hagerstown Valley Karst Study.

Unit	Dep.	Act.	Spr.	Cave	Tot.
Rockdale Run	2	2	0	0	**4**
Stonehenge	98	109	1	0	**208**
Conococheague	165	87	15	5	**272**
Elbrook	179	52	52	3	**286**
Waynesboro	66	4	11	4	**85**
Tomstown	551	72	29	1	**653**
Total	**1,061**	**326**	**108**	**13**	**1,508**

Table 1. Compilation of numbers of karst features identified within each formation in the Hagerstown Valley. The reader should note that the Elbrook, Conococheague, and Rockdale Run Formations represent partial data. Large areas underlain by these formations will be examined in the Phase II study.

The Hagerstown Valley succession, similar to the Frederick Valley rocks, shows that not all carbonate units exhibit an equal susceptibility to karst development (Figure 7, 8, Table 1). Although all the carbonate units contained at least one type of karst feature, these features were not distributed evenly throughout the Hagerstown Valley geologic units. Table 1 summarizes the types and numbers of karst features with respect to the individual geologic units. The reader should keep in mind that for some units these data are incomplete. 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., Tomstown Formation), while others are more prone to active sinkhole development (Stonehenge Formation), or appearance of springs (Elbrook 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 will certainly change after completion of Phase II of this study. However, the total and ratios of karst features for the Tomstown and Waynesboro formations will remain the same since no areas within the Phase II quadrangles are underlain by these two formations.

Examination of Table 1and Figures 7 and 8 verifies the *a priori* 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 is premature.

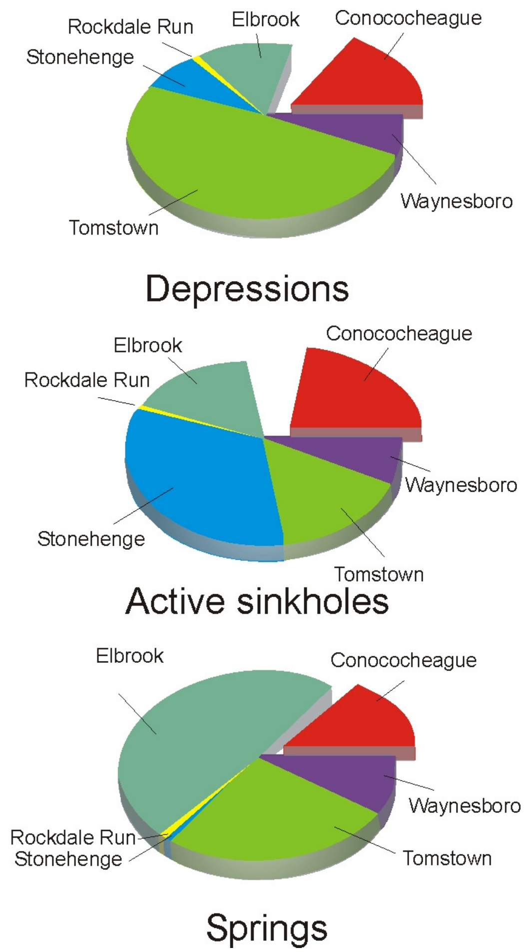

Figure 8. Pie diagrams of relative numbers of depressions, active sinkholes, and springs identified in Phase I of the Hagerstown Valley Karst Study.

Fractures

One of the most widely accepted group of factors governing the distribution of karst features is geological structure (Jennings, 1985). This broad term encompasses all forms of depositional and deformational features. During the course of

Phase I of this study 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).

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 are created by changes in depositional processes, such as energy level, temperature, or sea level height, and 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.

Figure 9. Reticulate pattern of joints within the Elbrook Limestone.

Breaks or cracks in the rocks, known as joints, pervade nearly all ancient deformed rock types (Figure 9). 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 (Figure 10). The most pervasive set of fracture azimuths range from 290º to 315º (see Figure 10, rose diagrams A, C, D, G, H, I). A secondary, less prominent set of joints has an orientation that is nearly east-west with an azimuth that ranges from 80º to 100º (see Figure 10, rose diagram G).

A third prominent system of fractures pervades the rocks of the Hagerstown Valley. Unlike the northwest and west striking sets mentioned above, this prominent northeast trending system of fractures can be attributed to a different stress field. The spacing of this fracture system tends to be more prominent and more closely spaced within shaly strata, such as the Red Run and Chewsville members of the Waynesboro Formation and the lower member of 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. In the Hagerstown Valley the major folds include the South Mountain Anticlinorium and

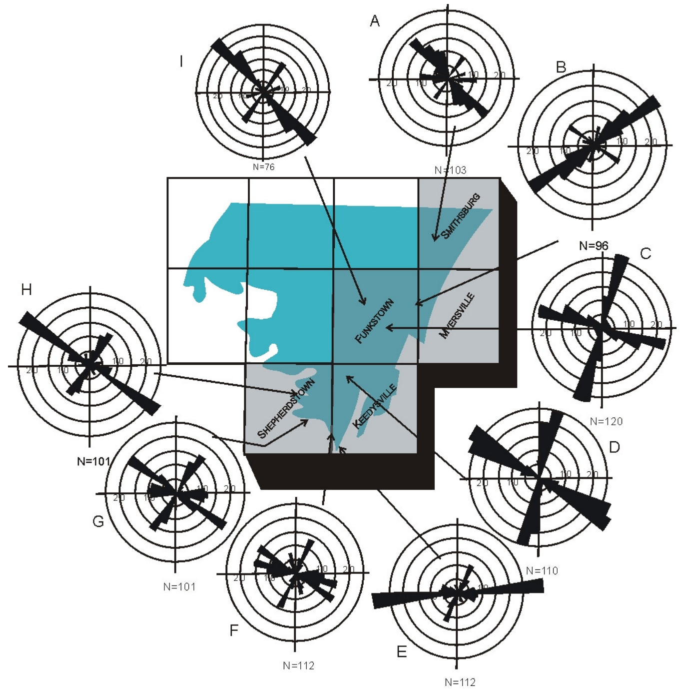

Figure 10. Dominant fracture directions within the eastern part of the Hagerstown Valley of Maryland as indicated by rose diagrams based on the measurement of fracture systems at several locations. A, Cavetown Quarry, Waynesboro Formation; B, Beaver Creek Quarry West, Elbrook Formation; C, Crystal Grottoes, Tomstown Formation; D, Keedysville, Tomstown Formation; E, Tomstown Formation, Fort Duncan Member, Maryland Bank; F, C&O Lock number 37, Tomstown Formation; G, Shepherdstown, Elbrook Formation; H, Snyders Landing, Conococheague Formation; I, Westfields, Stonehenge Formation.

Massanutten (Great Valley) Synclinorium. 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 Features

During Phase I numerous cases of solution widened fractures were observed and documented. One of the most prominent example is illustrated in a sketch made along the C&O Canal in the Keedysville Quadrangle (Figure 11).

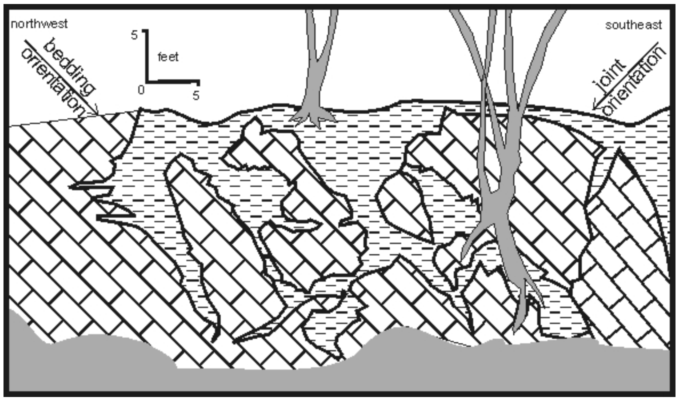

Figure 11. Sketch of filled solution cavities within the Bolivar Heights Member of the Tomstown Formation along the C&O Canal National Historic Park at milepost 65.3. Solution-filled cavities tend to parallel original limestone layering (bedding) and main jointing direction.

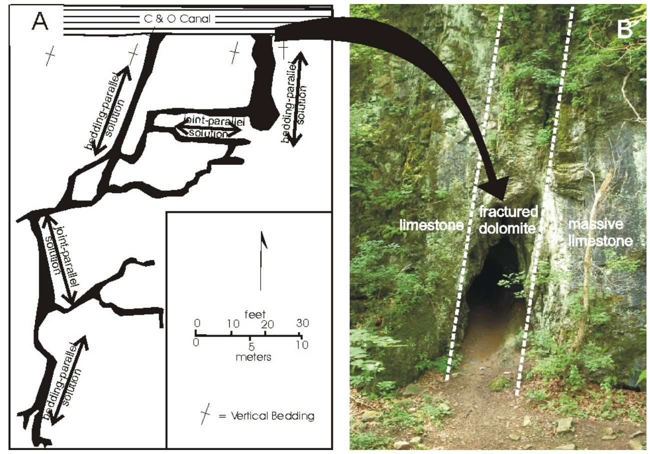

Figure 12. A, Sketch of solution cavities of Snyders Landing Cave No. 2 from Franz and Slifer (1971). At this location main passageways of the cave parallel the vertical stratification, while side passages parallel the dominant joint system. B, Cave entrance illustrates compositional differences in vertically oriented stratification of the Conococheague Formation (white lines). The cave is restricted to the highly fractured dolomite layer.

At this site, solution avenues tend to parallel the overturned bedding of the Bolivar Heights Member of the Tomstown Formation. A secondary solution system is clearly parallel to the main fracture system, which in this case is the joint network.

A second exemplary case is the Snyders Landing Cave No. 2, near Sharpsburg (Figure 12). At this location, solution along the vertical stratification provides the main passageways for the cave, while a secondary system appears to parallel a prominent joint set.

The intersection of several types of fractures commonly allows for the creation of a network of dissolution in karst terranes. Where joint and cleavage or joints and stratification intersect there are abundant opportunities for water to permeate and dissolve the surrounding rocks. An excellent example of where this type of intersecting fracture dissolution occurs in Crystal Grottoes (Figure 13). At this location the Bolivar Heights Member of the Tomstown Formation is exposed near the hinge of an overturned fold and the limestone strata are nearly horizontal. These rocks are pervaded with a network of fractures that have widened to form the cave. Dissolution along the two main fracture networks has created a rectilinear pattern of passages that tend to lie subparallel to the two main fracture systems, joints and cleavage.

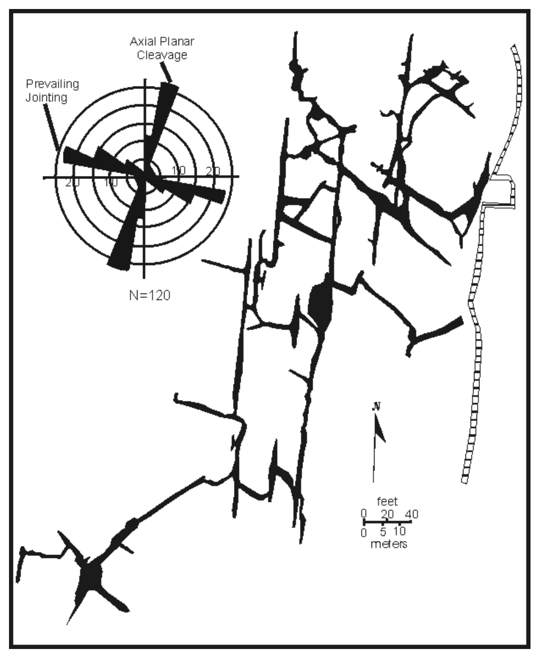

Figure 13. Map of solution cavities that make up Crystal Grottoes (from Franz and Slifer, 1971). Rectilinear arrangement of passages tends to parallel the two dominant fracture systems, a northwest-trending joint system, and a northeast-trending axial planar cleavage. Joint rose shows results of 120 fractures measured from the nearby vicinity.

Faults

Various scales of faults have been recognized within the Phase I study. Two notable faults with regard to karst are the South Mountain Fault that is present along the base of South Mountain, and the Eakles Mills Fault. 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 Smithsburg Quadrangle, a line of springs at the base of South Mountain is interpreted to coincide with the contact between the Harpers and Tomstown formations (Figure 14). This contact has been mapped as the South Mountain Fault, a major fracture system that can be traced from Loudoun County, Virginia to Adams County, Pennsylvania, a distance of 60 miles (Southworth and Brezinski, 1996). In the Smithsburg Quadrangle fracturing associated with the faulting as well as the placement of impermeable clastics of the Harpers Formation against the readily soluble Bolivar Heights Member of the Tomstown Formation are interpreted as producing this line of springs.

In addition to the line of springs identified along the South Mountain Fault, an excellent case can be made for fault-controlled springs that coincide with the trace of the Eakles Mills Fault. However, unlike the South Mountain Fault, this fault places carbonate rocks against carbonate rocks. Moreover, Brezinski (1992) showed that the Eakles Mills Fault is a vertical structure displaying a well-developed vertical fracture cleavage. The fracturing and postulated solution is interpreted to have produced a line of springs in the vicinity of Doubs Mills at US Route 40. At this location closely spaced springs appear to follow the mapped trace of the Eakles Mills Fault (Figure 15). At one location along the fault trace artesian flow can be shown to occur in a line of three closely spaced springs.

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 a cross is interpreted to have produced the spring at the Albert Powell State Trout hatchery. This high flow spring is believed to be situated along a large cross-fault that parallels Interstate 70 at Exit 35 (Figure 15).

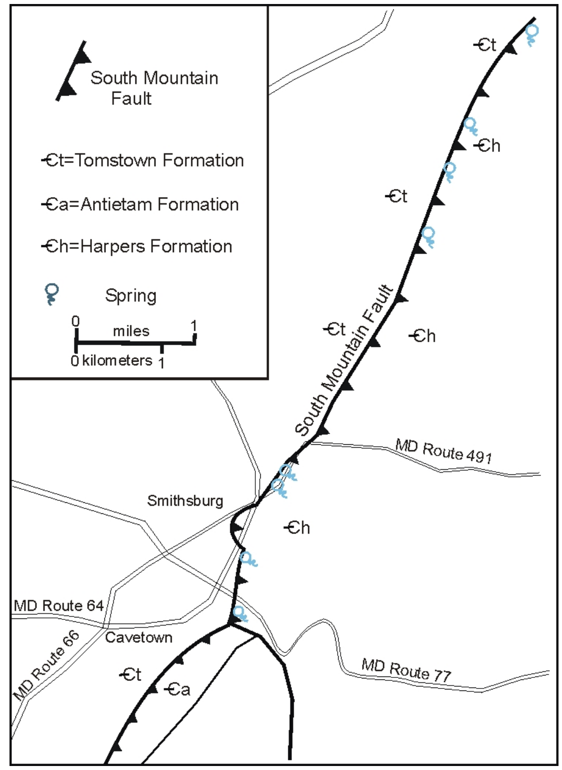

Figure 14. Distribution of springs along the South Mountain Fault in the Smithsburg Quadrangle.

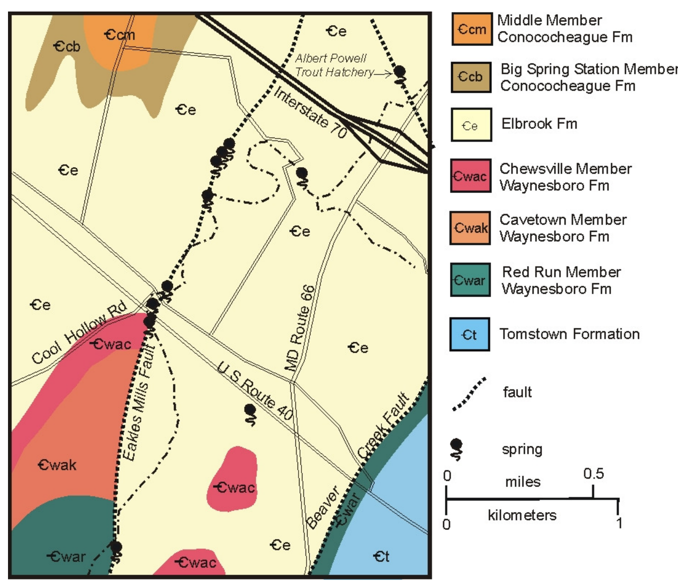

Figure 15. Distribution of springs along the Eakles Mills Fault near Doubs Mill and U.S. Route 40.

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 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 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.

An example of this was observed in the Funkstown Quadrangle where the localized streams and lowland parallel one another (Figure 16). These lowlands are locations where most of the active sinkholes in the area are present. These drainage lowlands tend to parallel the main joint system of the area.

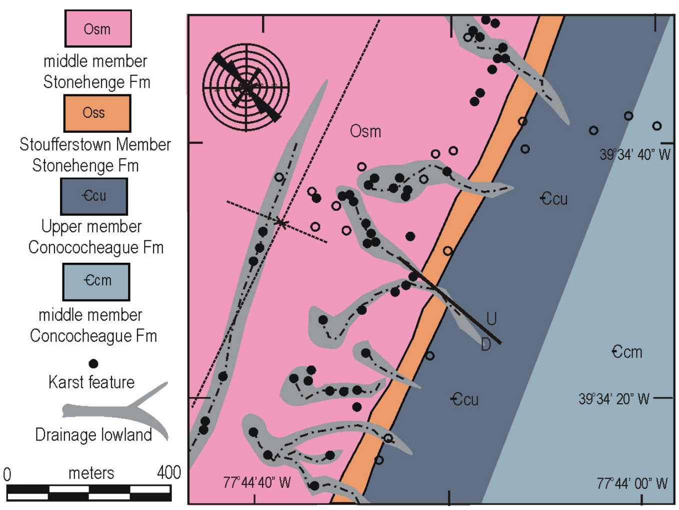

Figure 16. GPS sketch map of an area within the Funkstown Quadrangle exemplifying the relationship between sinkholes and drainage lowlands. Stream valleys are interpreted as paralleling the main joint network in the area.

Other Factors Affecting Karst Feature Genesis

Brezinski (2004, 2007) has shown that within the Frederick Valley, the activities of humans, such as road construction, housing development, and quarry dewatering, can have a significant impact on the development of karst features. In the Hagerstown Valley the effects of man on karst development appear to be less acutely evident than in the Frederick Valley. It is premature to confidently judge the reason for this; however, it may be simply that the Hagerstown Valley has yet to experience the level of development that currently characterizes the Frederick Valley.

Several cases of anthropogenic factors contributing to karst feature development can be illustrated. These are shown in Figure 17. Drainageways, appear to be just as frequent culprits in sinkhole activity as they are in the Frederick Valley. Likewise, storm water runoff ponds are commonly sites of sinkhole development. A more comprehensive evaluation as to the extent and frequency of these features will be examined during the second phase of this study.

Figure 17. Unlined road drainage and active sinkhole development within the Elbrook Formation. Sinkhole activation within a storm water management pond.

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GLOSSARY OF GEOLOGIC TERMS

alluvium
Unconsolidated sedimentary deposit left by a stream, stream channel, or floodplain.

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;

artesian
Movement of spring water that rises to the surface due to pressure.

bedding
Original or depositional layering within sedimentary rocks. Also known as stratification.

bedrock
Referring to solid rock that underlies unconsolidated surficial material such as 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
Generic term for any rock made up of the carbonate mineral group (CO^3) and composed chiefly of calcium or magnesium.

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 ($CaMg(CO^3)2$).

dolostone
A sedimentary rock composed primarily of dolomite, a mineral made up of calcium, magnesium, carbon, and oxygen. Dolostone is thought to form when magnesium ions replace some of the calcium ions in limestone, to which dolostone is similar in both appearance and chemical structure.

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.

foliation
The arrangement of a set of minerals in parallel, sheet-like layers that lie perpendicular to the flattened plane of a rock. Occurs in metamorphic rocks on which directed pressure has been exerted.

fracture
A crack or break in rock.

interbedded
Alternations of layers of differing composition or grainsize.

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.

quartzite
An extremely durable, nonfoliated metamorphic rock derived from pure sandstone and consisting primarily of quartz.

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 depression in the ground that forms when soluble rocks dissolve. In current study, such depression must show signs of recent opening.

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

strata
An individual layer in 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 crustal downwarp composed of a 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 as seen in stromatolites.