Geologic and anthropogenic factors influencing karst development in the Frederick region of Maryland

David K. Brezinski

ABSTRACT

Karst features pervade the outcrop belts of Triassic, Ordovician, and Cambrian rocks in the Frederick Valley region of Maryland's western Piedmont. Detailed stratigraphic analysis and geologic and karst mapping demonstrate that individual stratigraphic units have differing susceptibilities of karst feature creation. Although the Triassic Leesburg Member of the Bull Run Formation and Rocky Springs Station Member of the Cambrian Frederick Formation have many surface depressions within their outcrop belts, the Lime Kiln Member of the Frederick Formation and the Ceresville, Fountain Rock, and Woodsboro members of the Ordovician Grove Formation have the greatest potential for development of catastrophic collapse sinkholes. Although these four members have the highest relative susceptibility, human activity can increase the potential for sinkhole activation in all units. Rerouting of surface drainage patterns, unlined drainage, and storm-water management areas and removal of significant overburden deposits significantly increase sinkhole development, but mainly, these units are inherently more susceptible to begin with.

INTRODUCTION

Geologic studies of karst areas commonly concentrate on hydrologic factors responsible for the distribution of karst features, especially in areas with flat-lying to gently dipping strata and where the bedrock composition of the region is relatively homogenous. However, areas of highly folded and faulted strata necessitate the identification of compositional variations that can have significant impact on the distribution, number, and type of karst features. One such area is the Frederick Valley of Maryland's western Piedmont (Figure 1). This area of highly folded Cambrian and Ordovician carbonates has experienced significant increases in sinkhole activity in recent decades.

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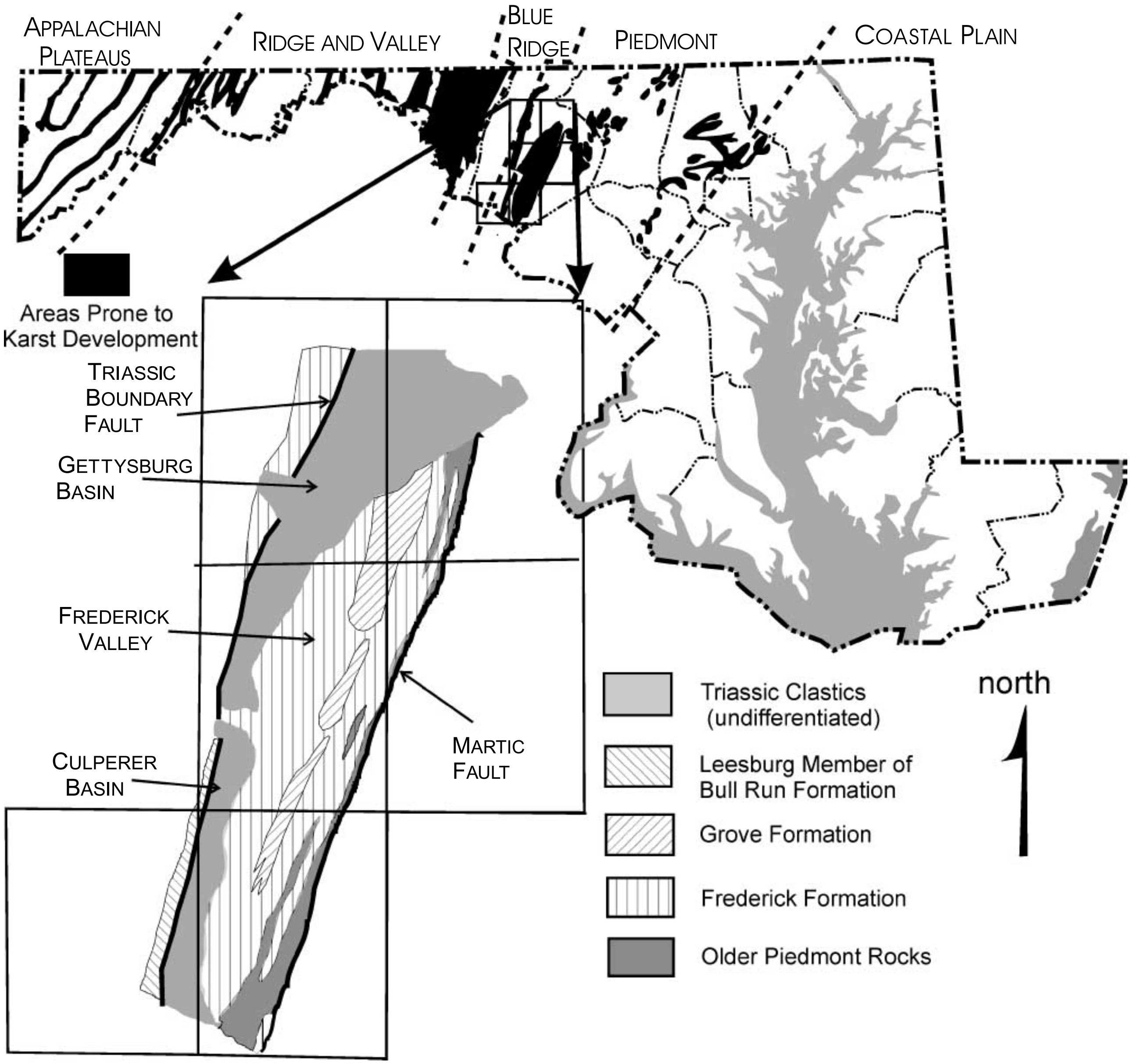


Figure 1. Map showing karst regions of Maryland with an inset map of the Frederick Valley. Modified from Brezinski and Reger (2002).

This has led planners and engineers to question whether increased incidence of sinkhole activity is the result of geological factors, human activity, or a combination of both.

The Frederick Valley is an elongate, northeast-trending lowland that stretches from the Potomac River northward for 36 km (22 mi). It is 9 km (5.6 mi) at its widest dimension and covers an area of approximately 400 km^2 (154 mi^2) in Maryland's western Piedmont. Comprehensive stratigraphic analysis, geologic mapping, and karst mapping by the Maryland Geological Survey, in conjunction with the Maryland State Highway Administration, conducted throughout a 4-yr period, have resulted in the production of detailed geologic and karst maps that demonstrate that both geologic factors and human activity are responsible for the increased proclivity of sinkhole development in recent years.

Methods

Geologic mapping of six 7.5-min U.S. Geological Survey topographic quadrangles is the basis of this study. In addition to geology, karst features such as sinkholes, depressions, and springs were noted and located using a global positioning system (GPS) receiver. Along with the geographic coordinates, data acquired at each location were karst feature identification, bedrock unit identification, presence or absence of Quaternary deposits, bedrock orientation (strike dip), and any joint or fracture orientation. During the course of the study, more than 1800 karst features were identified and located.

Regional Setting

The Frederick Valley lies near the western edge of the Piedmont physiographic province of Maryland and encompasses several physiographic subdivisions, including the Frederick Valley, the Triassic basins, and the low-grade metamorphosed phyllites of the Piedmont proper. The Frederick Valley is a broad synclinorium composed of Cambrian and Ordovician carbonate rocks. The eastern boundary of the Frederick Valley is marked by the regional Martic fault that juxtaposes low-grade metamorphic phyllites against these early Paleozoic carbonates (Southworth, 1996; Southworth and Brezinski, 2003). To the west, Triassic rocks of the Culpeper and Gettysburg basins overlap the Frederick Valley carbonates. Little difference in topographic relief exists between the early Paleozoic carbonates of the Frederick Valley and the rocks of the Triassic basins because much of the Triassic bedrock is composed of detrital limestone and dolomite whose clasts are early Paleozoic in age. Thus, the two areas have identical physiography and solubility characteristics. In this article, the Frederick Valley is considered to encompass the lowlands of early Paleozoic rocks and the Triassic carbonate rocks.

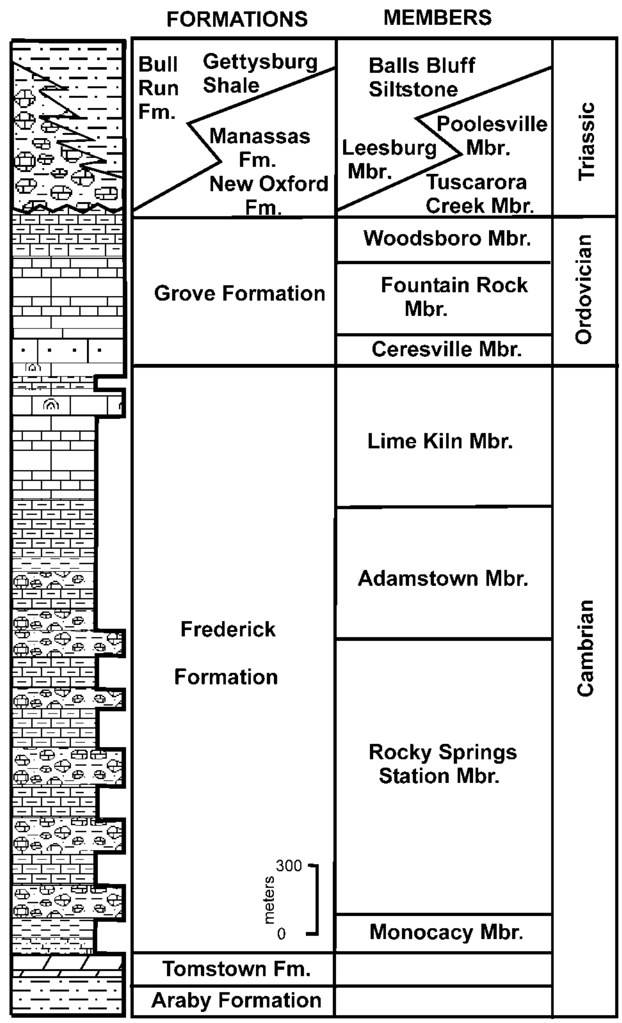


Figure 2. Stratigraphic relationships and nomenclature of the Frederick Valley and onlapping Triassic sediments.

PALEOZOIC STRATIGRAPHY

Tomstown Formation

The western edge of the Frederick Valley and eastern edge of the Blue Ridge is marked by a thin interval (<50 m; <1640 ft) of sheared dolomite. Because of its similar stratigraphic position, this dolomite has been correlated with the Lower Cambrian Tomstown Formation of the Great Valley (Brezinski, 2004a). The Tomstown Formation east of the Blue Ridge in Maryland consists of light gray to light-medium-gray, highly foliated, micaceous, saccharoidal dolomite.

Frederick Formation

The main Cambrian unit in the Frederick Valley is the Frederick Formation (Figure 2). This unit comprises four members that are in ascending order: the Monocacy, Rocky Springs Station, Adamstown, and Lime Kiln members.

Monocacy Member

Along the eastern margin of the Frederick outcrop belt, an interval of interbedded black shale and limestone breccia makes up the lowest strata of the Frederick Formation (Brezinski, 2004a). The Monocacy Member consists of several thin intervals (<10 m [<33 ft] thick) of black organic shale that are interbedded with tan to dark-gray, bioturbated dolomite. The knotty-appearing lithology is diagnostic of this member and makes it easily recognizable in the field.

Rocky Springs Station Member

Above the shaly Monocacy Member, the Frederick Formation consists of a thick (>300-m; >1000-ft) interval of dark-gray limestone known as the Rocky

Springs Station Member (Reinhardt, 1974). It consists of interbedded, very thinly bedded, dark-gray, shaly limestone; medium-bedded, sandy, gray limestone; and thick-bedded, medium-gray, polymictic limestone breccia. The polymictic breccia beds are diagnostic of this member and are key characteristics to its origin and recognition.

Adamstown Member

Overlying the Rocky Springs Station Member is an interval approximately 300 m (1000 ft) thick that is characterized mainly by dark-gray, very thinly bedded, lime-mudstone with shaly partings. Reinhardt (1974) named this interval the Adamstown Member. Superficially, the Adamstown Member is similar to the underlying Rocky Springs Station Member, except that it lacks thick polymictic breccia beds.

Lime Kiln Member

The youngest member of the Frederick Formation is the Lime Kiln Member (Reinhardt, 1974), consisting of thinly interbedded dark-gray, lime-mudstone and black, calcareous shale with a few thicker layers up to 30 cm (12 in.) in thickness in the lower part. The scattered thicker layers become more prominent and abundant upsection. Also common near the middle and top of the member are lenticular, medium-gray, sandy, lime-grainstone and packstone and algal thrombolites and stromatolites.

Grove Formation

The youngest formation in the Frederick Valley proper and forming the core of the synclinorium is the Grove Formation (Reinhardt, 1974). Although some strata in the lower Grove may be Cambrian in age, most of the formation is Lower Ordovician. The Grove consists of three members that are in ascending order: the Ceresville, Fountain Rock, and Woodsboro members (Figure 2).

Ceresville Member

The lowest Grove Member, the Ceresville, consists of 50–70 m (164–230 ft) of light-gray, fractured, sandy dolomite that is interbedded with intervals of very light-gray, fractured, fine-grained dolomite. The sandy layers exhibit abundant cross-bedding, some of which is herringbone.

Fountain Rock Member

Overlying the distinctive lower sandy member and making up the bulk of the formation's thickness, is an interval composed of thickly bedded, algal thrombolitic lime-mudstone; tan, laminated, dolomitic lime-mudstone to dolostone; and light-gray, sandy, intraclastic lime-packstone to grainstone named the Fountain Rock Member (Brezinski, 2004a). This member attains an estimated thickness of more than 700 m (2300 ft).

Woodsboro Member

The Woodsboro Member is the stratigraphically youngest member of the Grove Formation and consists of thinly interbedded, dark-gray, thin-bedded, highly bioturbated, lime-mudstone and thin-bedded, medium-gray, lime-mudstone. The bioturbated strata consist of knotty-weathering, gray lime-mudstone, interstratified with tan-weathering, argillaceous dolomite. Because the top of the Woodsboro Member has been eroded by pre-Triassic erosion, only about 500 m (1640 ft) of the member are preserved.

TRIASSIC STRATIGRAPHY

Overlapping the western margin of the Frederick Valley are Triassic strata that were deposited within fault-bound basins (Figure 1). These rocks are assignable to the Culpeper and Gettysburg basins and contain several intervals of detrital limestone breccias that are karstic in character.

Bull Run Formation and Gettysburg Shale

Although different stratigraphic terminology separates the rocks of the Culpeper and Gettysburg basins, the strata are essentially identical. In the Culpeper Basin, strata that crop out along the western margin are termed the Bull Run Formation, whereas the Gettysburg Basin's equivalent is termed the Gettysburg shale. The Bull Run Formation is characterized by the intertonguing of the Leesburg Member and the Balls Bluff Siltstone Member. The Leesburg Member is a light reddish-gray carbonate breccia that is a significant karst unit of the western Piedmont. Most of the clasts of the Leesburg Member are rounded to subangular, are poorly sorted, and are cemented by reddish calcareous clay. An unnamed conglomerate equivalent to the Leesburg occupies a similar stratigraphic position in the Gettysburg Basin

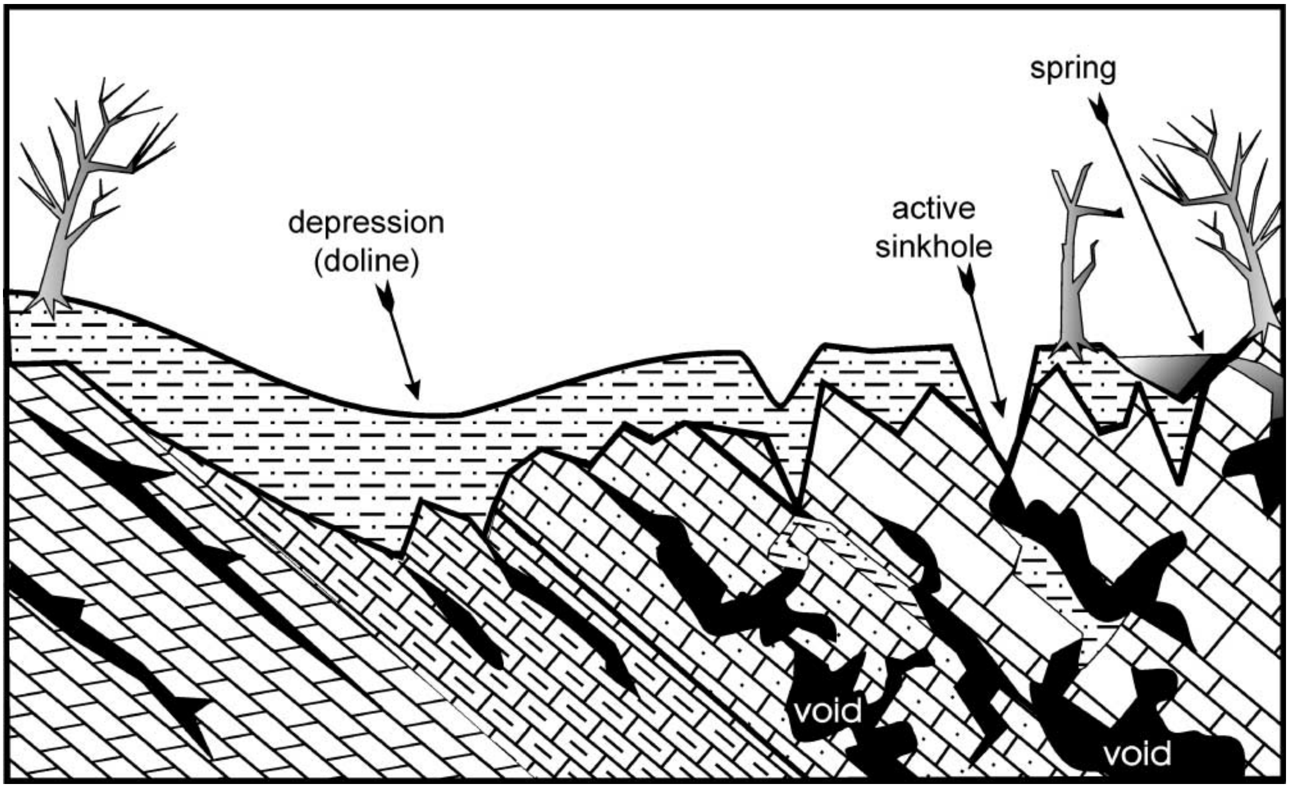


Figure 3. Idealized diagram illustrating karst features identified in this study and their interpreted relationship to underlying bedrock.

within the Gettysburg shale. The Balls Bluff Siltstone is a fine-grained lateral equivalent to the conglomerates of the Leesburg Member. The Balls Bluff Siltstone consists of reddish-brown to brownish-red, thin- to medium-bedded, argillaceous, sandy siltstone to silty mudstone, identical to the Gettysburg shale. The Leesburg is estimated to be as much as 1000 m (3300 ft) thick, whereas the Balls Bluff is estimated to be as much as 1500 m (4900 ft). No measured thickness is known for the equivalent lithologies in the Gettysburg Basin.

Manassas Formation–New Oxford Formation

Overlying the Bull Run Formation in the Culpeper Basin is the Manassas Formation. Its Gettysburg Basin equivalent is known as the New Oxford Formation. The Manassas consists of two members in Maryland: the Poolesville and the Tuscarora Creek members (Lee, 1977; Lee and Froelich, 1989). The Poolesville Member consists of a thick interval of reddish-brown, coarse-grained sandstone interbedded with red and reddish-brown, silty mudstone and laminated, micaceous siltstone. This unit is identical in character to the New Oxford Formation of the Gettysburg Basin. The Tuscarora Creek Member is a thickly bedded, light gray-weathering, carbonate conglomerate to breccia that crops out along the eastern margin of the Triassic belt at the base of the Manassas Formation. The same stratigraphic position is occupied by an unnamed quartz conglomerate in the Gettysburg Basin. The estimated thicknesses of the Manassas and Tuscarora Creek members are 1000 and 60 m (3300 and 196 ft), respectively. The thickness of the New Oxford Formation is unknown, but is assumed to be similar to that of the Manassas Formation.

KARST FEATURES AND THEIR DISTRIBUTION

The second part of this study was concerned with the identification and precise location of karst features and the evaluation of whether their distribution, density, and dimensions are related to bedrock geology or some other factor.

The three types of karst features identified are depressions (dolines), active sinkholes, and karst springs (Figure 3). Because caves are so rare in the Frederick Valley, they were not included in the karst features identified.

Geologic Factors Influencing Karst Development

Although a variety of natural and anthropogenic factors contribute to the distribution, density, and type of karst features in any given area, this study concentrates on geologic factors that control their occurrence.

Fractures

Fractures are an important geologic structure governing the relative susceptibility of rock units to karstification. They include cleavage, joints, and faults as well as minor partings in stratification. To assess the function of fractures in the development of karst features and to evaluate variations in fracture trends within the different lithologic units, the azimuths of more than 1000 fractures were measured from three locations in the Grove Formation and two locations in the Leesburg Member of the Bull Run Formation. A graphic summary of these data shows that there is a single main fracture pattern in the Grove Formation (Figure 4). This pervasive joint system has a mean azimuth of 288° (Figure 4A). An ancillary fracture system has an azimuth of 20°. This secondary system coincides with the axial planar cleavage of the Frederick Valley synclinorium (Figure 5A, B). Fractures in the Triassic Leesburg Member exhibit a completely different trend (Figure 4E–G). The main fracture trend has a mean azimuth of 87°, with a conjugate set having an azimuth of 315° (Figure 5C, D). The considerable difference in the orientation of the joint directions between the Ordovician Grove Formation and the Triassic Leesburg Member of the Bull Run Formation is caused by varying tectonic stresses that acted on these units during different geologic episodes.

Faults, based on stratigraphic offset or missing units, are difficult to recognize within the Frederick Valley sequence because of the poorness of exposure. However, several small faults have been mapped in the main quarries of the valley. A series of en echelon normal faults can be recognized in the Woodsboro Quadrangle (Brezinski and Edwards, 2004). Geographic information system maps of the geology and GPS locations of the sinkhole distributions suggest that numerous sinkholes are located along these normal faults (Figure 6).

Surface Drainage Patterns

Boyer (1997, his figure 8) demonstrated a positive relationship between natural surface drainage patterns and sinkhole development south of Frederick City along Interstate 270. He showed that large numbers of recently active sinkholes were found within the drainage lowlands that had flowing surface waters during high rainfall periods.

The relationship between natural drainageways and sinkhole development was verified at numerous locations during this study. This relationship is illustrated in Figure 7, where surface drainage follows the joint patterns of the underlying bedrock in the outcrop area of the Triassic Leesburg Member of the Bull Run Formation. Active sinkholes commonly appear in these stream channels. A similar relationship can be documented in areas underlain by the upper Frederick and Grove formations (Figure 8). An excellent example illustrating the connection between drainage and sinkholes is within the southern reaches of the City of Frederick (Figure 9). This area has long been prone to active sinkhole formation. A significant issue for this area is determining whether the sinkholes are the consequence of some geologic factor, or whether they are influenced by local manmade features such as the highway or the quarry. The geology for the area was mapped in detail, using an enlarged version of the U.S. Geological Survey 7.5-min Frederick quadrangle. The Frederick and Grove formations were divided following the nomenclature followed herein. The Grove Formation in this area consists of the Ceresville and Fountain Rock members.

Based on the geologic mapping, there is a modest correlation between rock unit and prominence of sinkhole development. Most sinkholes lie within the outcrop belts of the Lime Kiln Member of the Frederick Formation and the two lower members of the Grove Formation. Overlaying the surface drainage patterns on the geologic map enhances our understanding of sinkhole development in this area. These drainage channels are located by making transits with a global positioning system and walking the topographic lows of the inferred lowlands. Most active or filled sinkholes in this area fall near or within these drainage channels. If the entire low area of the former flood-plain deposits is included (shaded areas of Figure 9), an even greater correlation is obvious.

Sinkhole data demonstrate that there is a strong correlation between natural drainage patterns and sinkhole activity. This is especially true when we overlie drainage systems on the Lime Kiln Member of the Frederick Formation or one of the members of the Grove Formation. An awareness of this relationship might be especially useful in monitoring developing areas where the surface drainage pattern has been changed or obliterated.

Paleokarst

At least one episode of karstification predates the deposition of the onlapping Triassic rocks, about 220 m.y. Evidence of this earlier episode of karstification includes

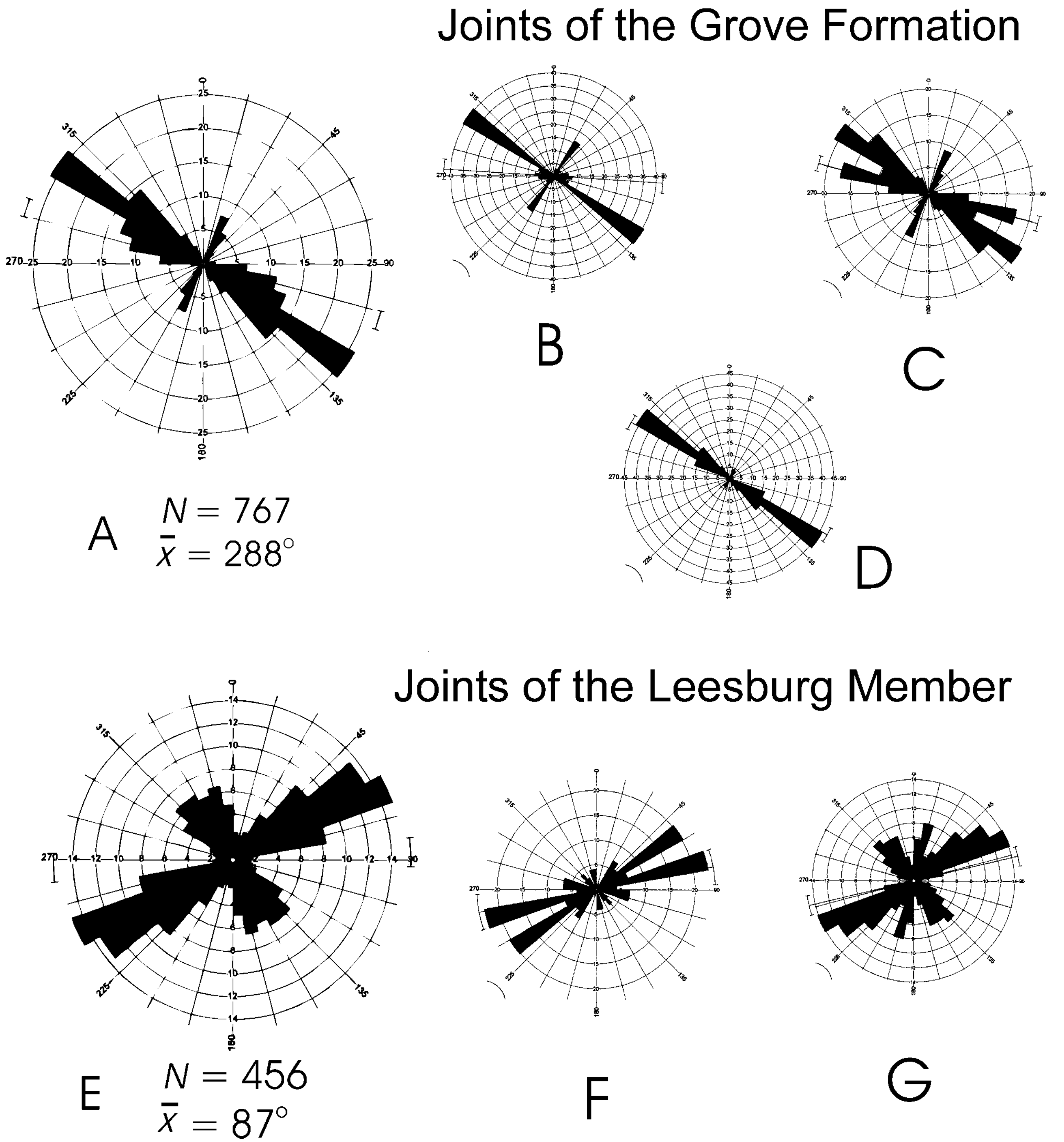


Figure 4. Rose diagrams of 1061 fracture surfaces. (A) Composite azimuths of joints measured from the Grove Formation from three separate locations (B–D). (E) Composite azimuths of joints measured from the Leesburg Member of the Bull Run Formation at two locations (F, G).

red siltstone infillings of joint planes within the Frederick and Grove formations. These joints can range from hairline fractures to 6 in. (15 cm) in width. Some of the joints appear to be widened by solution prior to their filling (Figure 10A, B). Locally, the red muds have so thoroughly penetrated the fractures of the bedrock that the Frederick and Grove formations have taken on the red coloration of the Triassic sediments.

Locations where Triassic–age breccias exist were mapped within the outcrop belts of the Frederick and Grove formations. These breccia intervals contain angular limestone pieces measuring 6–24 in. (15–60 cm)

Figure 5. (A) Fracture pattern exhibited by the Ceresville Member of the Grove Formation. The azimuth of the main joint set marked by the strike arrow is 65°. (B) Intersection of joint and cleavage planes as manifested by intersecting and coalescing sinkholes in the Lime Kiln Member of the Frederick Formation. (C) Solution-widened joints characteristic of the Triassic Leesburg Member. (D) Buried and filled joint surfaces in the Leesburg Member showing the solution-widened fractures.

long in a red mudstone to siltstone matrix (Figure 10C). These occurrences are interpreted to be breccias formed by the collapse of ancient sinkholes or caverns. Because the lithologies in these ancient sinkhole fillings have a high percentage of clastic material that does not weather or dissolve as readily as the surrounding carbonates, they tend to form topographic highs.

Stratigraphic Controls

Comparison of different generations of geologic mapping (Brezinski, 2004a, figure 40) demonstrates that precise geologic mapping and sinkhole location can delineate certain stratigraphic intervals that have a greater sinkhole propensity (Table 1).

The *a priori* assumption that karst features occur in varying densities within the different stratigraphic units appears valid. However, some units such as the Tomstown Formation and Monocacy Member of the Frederick Formation had too few numbers to be statistically usable. As might be expected, not all carbonate units in the Frederick Valley exhibit an equal susceptibility to karst development (Figure 11). From this illustration, it can be shown that some units such as the Triassic Leesburg Member of the Bull Run Formation have greater tendencies for depression formation (32.3% of all depressions), while not being particularly susceptible to the formation of active sinkholes (6.4% of all active sinkholes). This is a similar relationship to that shown by the Rocky Springs Station Member of the Frederick Formation. The Adamstown Member of the Frederick Formation and Woodsboro Member of the Grove Formation displayed low totals in both categories, although the Grove had a very high ratio of active sinkholes to depressions (1.29). This ratio of

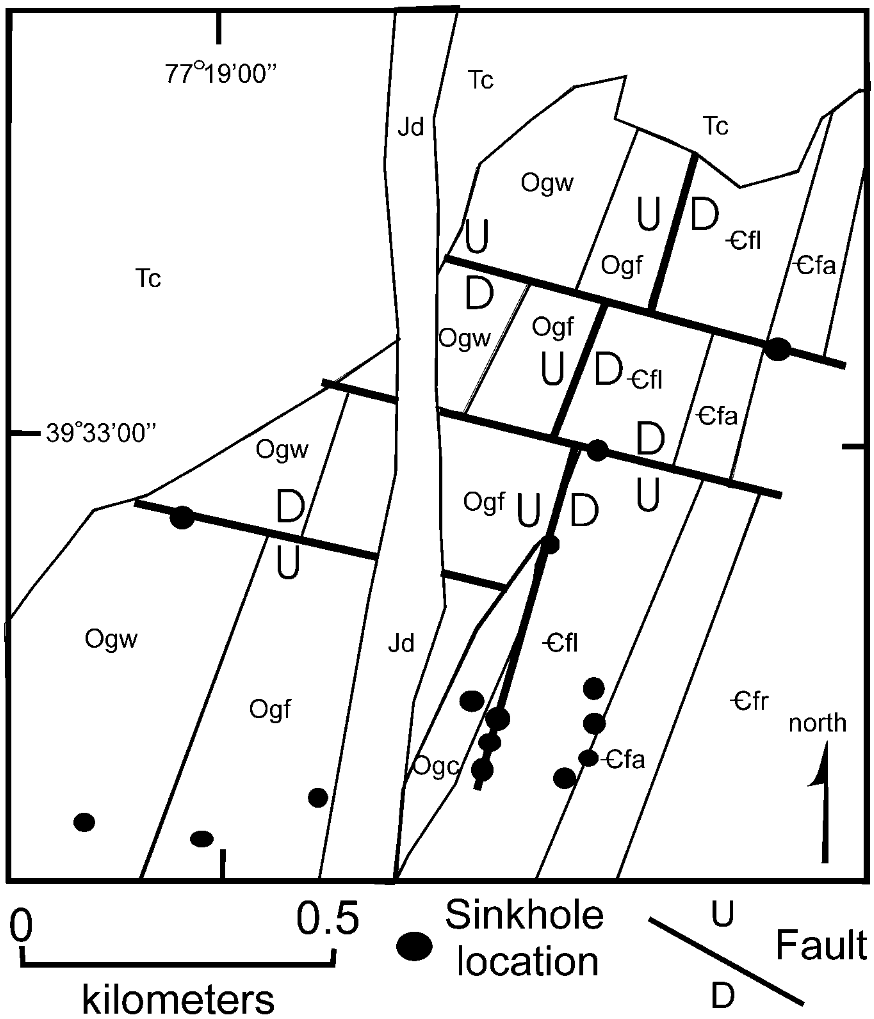


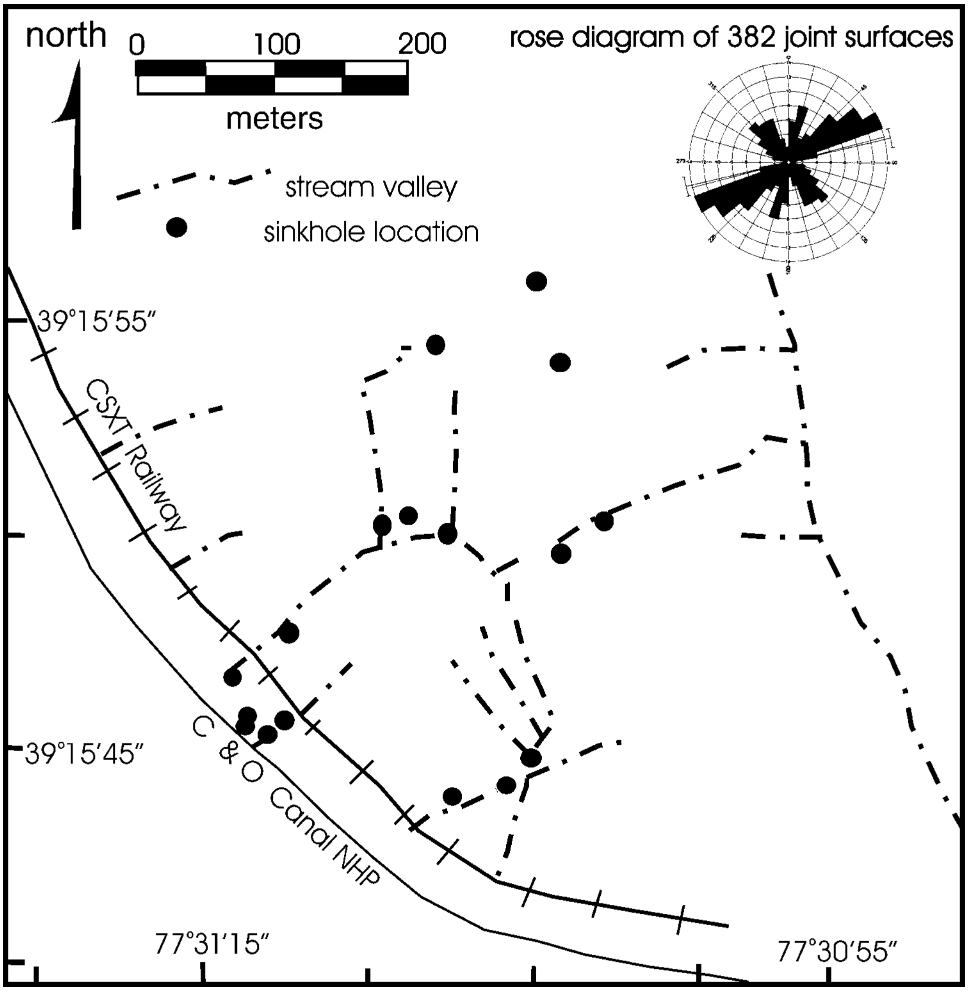
Figure 6. Detailed geologic map of an area exposed at the LeGore and Barrick quarries north of Woodsboro, where sinkhole distribution appears to be controlled by faults. Mapping is taken from Brezinski and Edwards (2004). Unit keys: Cfr = Rocky Springs Station Member; Cfa = Adamstown Member; Cfl = Lime Kiln Member; Ogc = Ceresville Member; Ogf = Fountain Rock Member; Ogw = Woodsboro Member; Tc = undifferentiated Triassic clastic rocks; Jd = Jurassic diabase dike rock.

active sinkholes was, by far, the highest seen for any unit. The low total number of karst features in the Woodsboro Member may be misleading because this unit underlies a very small surface area. In the case of the Adamstown Member, the low number of depressions (73) and active sinkholes (13) and a low ratio of active sinkholes to depressions (0.18) are offset by the second highest number of springs (7).

Other units, such as the Lime Kiln Member of the Frederick Formation (16.8% of all depressions, 33.6% of all active sinkholes) and the Fountain Rock Member of the Grove Formation (14.9% of all depressions, 26.9% of all active sinkholes), have comparatively high numbers of both active sinkholes and depressions. Consequently, these two units appear to be the most highly prone to karst development in this study.

The reasons for differences in the overall numbers of karst features within each unit may be the result of lithologic, structural and hydrologic factors. For instance, the high number of depressions and low number of active sinkholes in the Leesburg Member is interpreted to be the result of the massive, dolomitic conglomerate lithology and the regularly spaced, solution-enlarged joints (structure). Similarly, the low numbers of active sinkholes in the Rocky Springs Station and Adamstown members of the Frederick Formation also are probably the result of lithology and structure. The thin-bedded, shaly limestones that characterize the bulk of both these units exhibit few joints, as well as abundant argillaceous layers. These layers absorbed strain during the folding of the units and, thus, are less likely to have the brittle fractures seen in more massive units. These argillaceous layers also produce clay that impedes further water movement. In contrast, the Ceresville Member of the Grove Formation is predominantly thick-bedded, highly fractured dolomite with few clayey intervals. This unit has few identified depressions and has a high ratio of active sinkholes to depressions. The high karst susceptibility exhibited by both the Lime Kiln and Fountain Rock members is interpreted to be caused by

Figure 7. Detailed map illustrating stream drainages and sinkhole development in the Triassic Leesburg Member of the Bull Run Formation. Streams and sinkholes were precisely located using a global positioning system; both show a preferred trend that parallels the dominant joint directions as indicated by the rose diagram. Sinkholes are largely restricted to the drainage lows created along the inferred solution-widened joints.



composition. Because both the upper part of the Lime Kiln Member and the Fountain Rock Member are characterized by thick intervals of algal thrombolites, stromatolites, and lime grainstone, these purer carbonate intervals are more susceptible to dissolution (Brezinski, 2004a).

Karst Susceptibility

Although the raw karst feature data (Table 2) ostensibly demonstrate the relative karst susceptibility of each stratigraphic unit, other statistics show a somewhat different picture. For example, when the total number of karst features is compared to the number of features per square mile, some units that have a high number of features (e.g., Rocky Springs Station Member) have a relatively low number per square mile (Table 3). This is because some units have large outcrop areas and, therefore, have more area in which to develop karst features. This contrasts with some units that may have small outcrop areas (e.g., Woodsboro Member) and moderately low numbers of karst features, but a very high number of features per square mile. Clearly, a high number of features per unit area is a more important indication of karst susceptibility than the raw number of features contained within that unit. Thus, the Woodsboro Member is much more susceptible to karst development than the Rocky Springs Station Member, although the latter has many more karst features within its outcrop belt. Likewise, the number of active sinkholes per unit area or the ratio of active sinkholes to depressions is much more illuminating than simply totaling the number of features per stratigraphic unit. Ratios, like the number of active sinkholes to depressions for a particular stratigraphic unit, are valuable, but a statistically significant number of features must be present in order for ratios to be meaningful. Otherwise, misleadingly high or low values can give a false impression as to the susceptibility of a unit. This is demonstrated by the Monocacy Member, which has only four

Figure 8. Examples of drainage lowlands acting as sites of sinkhole activity. (A) Parking lot built in the Ceresville Member of the Grove Formation in the northeast City of Frederick collapsed along the prehistoric drainage area. (B) Coalescing sinkholes in the Lime Kiln Member of the Frederick Formation along the drainage lowland in the southeast City of Frederick.

karst features recognized within its outcrop belt. However, it has a relatively high ratio of 1.0 (active sinkholes to depressions) because two active sinkholes and two depressions were identified in the study area. By applying all of these statistics, one can obtain a fairly clear understanding of the relative susceptibility of each stratigraphic unit to the development of karst features. Based on this premise, a generalized susceptibility index was developed for the stratigraphic units in this study. The karst susceptibility index (SI) is a simple ratio of the number of active sinkholes per square mile to the total number of karst features per square kilometer of exposure for each stratigraphic unit.

$$SI = (\text{active}/\text{mile}^2)/(\text{number of features}/\text{mile}^2)$$

or more simply

$$SI = (\text{number of active sinkholes})/(\text{total number of features})$$

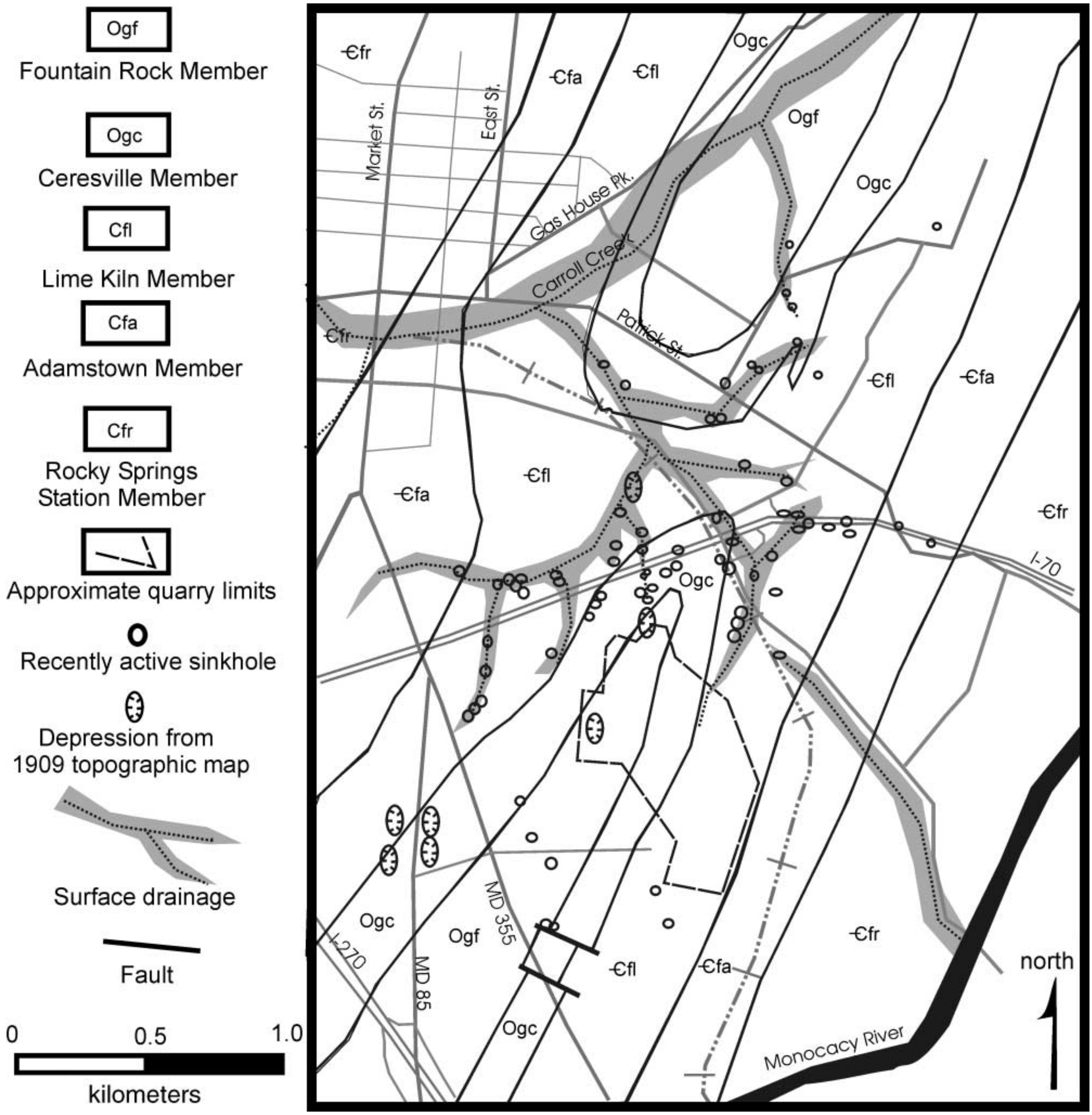


Figure 9. Geologic map of a part of the Frederick quadrangle illustrating the relationship between geology, surface drainage pattern, and sinkhole development. Drainage network and sinkhole locations were determined using a global positioning system. Mapping taken from Brezinski (2004b).

This index gives a relative value for the sensitivity of a particular rock unit to the development of karst features and is somewhat more quantitative than the raw data presented in Table 3.

When the SI is compared to the raw numbers of karst features (Table 2 versus Table 3), a different picture of susceptibility appears. Some units with large numbers of karst features (Rocky Springs Station Member and Leesburg Member) have comparatively low SIs, whereas others with modest totals of features (Ceresville and Woodsboro members) have high SIs. This is because the SI emphasizes active sinkholes. In this study, the active sinkholes were weighted because they pose the greatest risk for economic loss and personal injury

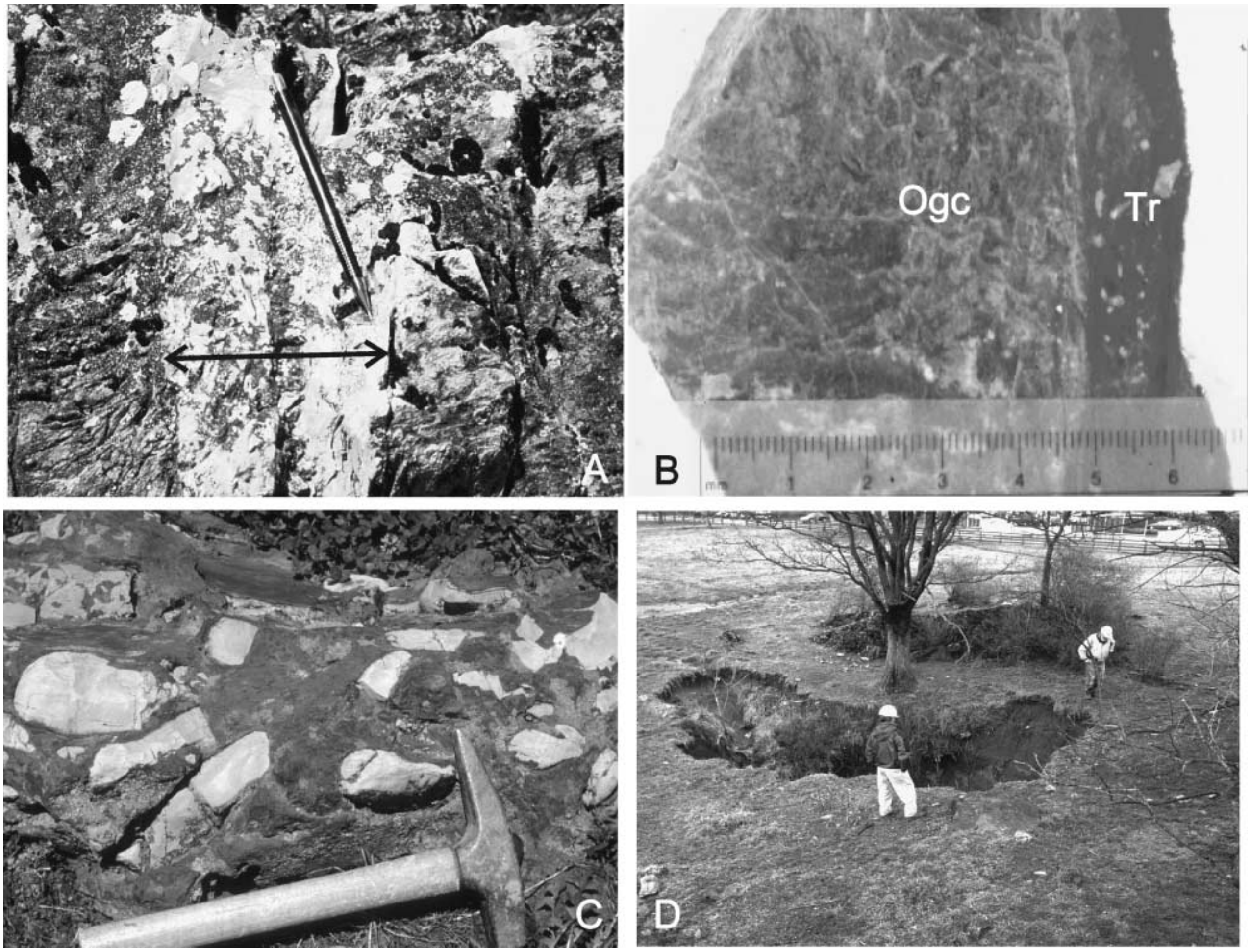


Figure 10. Examples of paleokarst. (A) Triassic clastics filling a solution-widened joint in the Ceresville Member of the Grove Formation. (B) Polished slab of the same joint surface in the Ceresville Member. (C) Collapse breccia of Ceresville Member (light) surrounded by Triassic clastics (dark) filling pre-Triassic sinkhole. (D) Interpreted pre-Triassic sinkhole exhibiting recent reactivation.

than do depressions or springs. Critical to this was the recognition that large areas, both developed and undeveloped, are underlain by either the Rocky Springs Station Member of the Frederick Formation or the Leesburg Member of the Bull Run Formation, and only rarely have catastrophic collapses been identified within these areas. Conversely, the Woodsboro Member of the Grove Formation has little development in areas underlain by it, yet relatively high numbers of catastrophic collapses were recognized where this member occurs. Of course, calculation of the SI requires statistically significant numbers of features; otherwise, spurious figures may arise. This is exemplified by the SI of 0.54 for the Monocacy Member of the Frederick Formation. Although this index value would normally indicate a strong susceptibility to the development of active sinkholes, in this case, the index is based on only four karst features.

Table 1. Comparison of Numbers of Sinkholes in Each Stratigraphic Unit*

Map Author	Unit**	Numbers of Sinkholes
Jonas and Stose (1938)	Og	27
	Cf	34
Reinhardt (1974)	Og	31
	Cfl	26
	Cfa	4
This study	Ogf	5
	Ogc	13
	Cfl	40
	Cfa	3

*From three generations of geologic mapping in the southern City of Frederick. Symbols are the same as in Figure 9.

**Abbreviations: Og = Grove Formation (undifferentiated); Cf = Frederick Formation (undifferentiated).

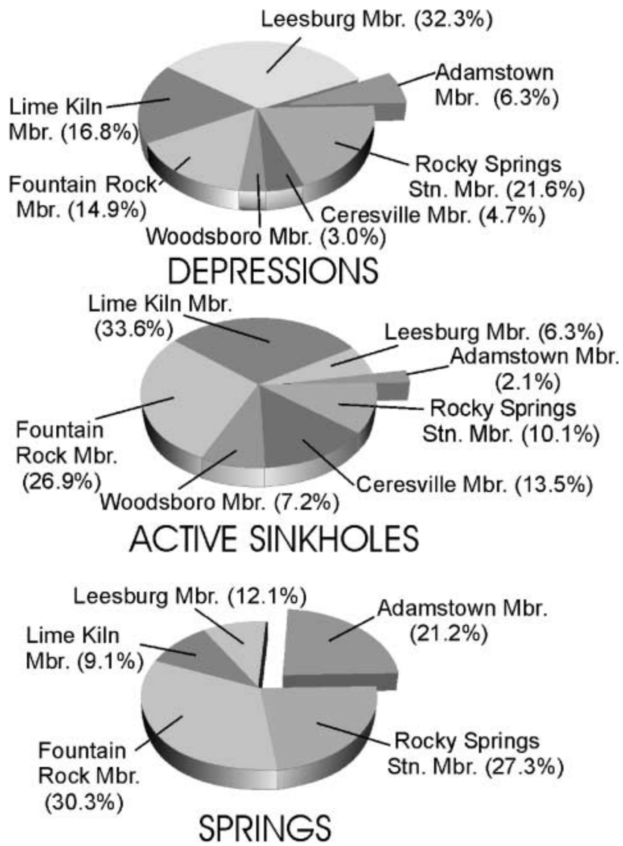


Figure 11. Pie diagrams of the relative percentages of karst features in the individual rock units used in this study.

Table 2. Summary of Karst-Feature Distribution with Respect to Stratigraphic Unit

Unit*	Depressions	Active	Springs	Total
Trl	374	39	4	417
Ogw	35	45	0	80
Ogf	172	167	10	349
Ogc	54	84	0	138
Cfl	195	209	3	407
Cfa	73	13	7	93
Cfr	251	63	9	323
Cfm	2	2	0	4
Ct	3	0	0	3
Total	1159	622	33	1814

*Abbreviations: Ct = Tomstown Formation; Cfm = Monocacy Member; Cfr = Rocky Springs Station Member; Cfa = Adamstown Member; Cfl = Lime Kiln Member; Ogc = Ceresville Member; Ogf = Fountain Rock Member; Ogw = Woodsboro Member; Trl = Leesburg Member.

Human-Induced Factors Influencing Karst Development

Although geologic factors can be demonstrated to be a significant factor in the abundance and distribution of active sinkholes in the Frederick Valley, these factors are oftentimes exacerbated by human activities. During this study, factors such as urban development, quarrying, and highway construction were observed to have contributed locally to sinkhole activity.

Storm-Water Management Areas

A common site for active sinkhole development is within storm-water basins or management ponds constructed in the vicinity of business parks or housing developments (Kochanov, 1999). During construction, the soil is stripped away, commonly exposing the underlying bedrock. When these ponds become active during periods of high rainfall, the clay plugs in any exposed solution cavity may collapse. Moreover, these basins are generally constructed along existing low-lying drainage, areas that are already susceptible to sinkhole activation (Figure 12A). A similar situation along a natural drainage channel is illustrated in Figure 13. When such storm-water management areas are constructed over bedrock with an increased susceptibility (e.g., Lime Kiln, Ceresville, and Fountain Rock members), an even greater incidence of sinkhole activity may occur.

Unlined Road Drainage

Another common location for active sinkhole occurrence is within unlined road drainageways (Figure 12B–D). Like storm-water management areas, road drainages are excavations that remove the soil cover from inactive or filled sinkholes, so that during subsequent periods of

Table 3. Summary of Area Underlain by Each Unit and Ratio of Karst Features per Unit Area

Unit*	Area (mi^2)	Features (mi^2)	Active (mi^2)	Active Sinkhole/ Depression Ratio	SI
Trl	8.72	42.89	4.47	0.09	0.10
Ogw	1.28	62.5	35.16	1.29	0.56
Ogf	9.77	35.62	17.09	0.97	0.48
Ofc	3.52	39.21	23.86	1.56	0.61
Cfl	9.98	40.78	20.94	1.07	0.51
Cfa	12.14	7.66	1.07	0.18	0.14
Cfr	31.60	10.22	1.99	0.25	0.20
Cfm	7.18	0.56	0.28	1.00	0.54
Ct	0.97	3.09	0.00	0.00	0.00

*Abbreviations: Ct = Tomstown Formation; Cfm = Monocacy Member; Cfr = Rocky Springs Station Member; Cfa = Adamstown Member; Cfl = Lime Kiln Member; Ogc = Ceresville Member; Ogf = Fountain Rock Member; Ogw = Woodsboro Member; Trl = Leesburg Member. SI = susceptibility index.

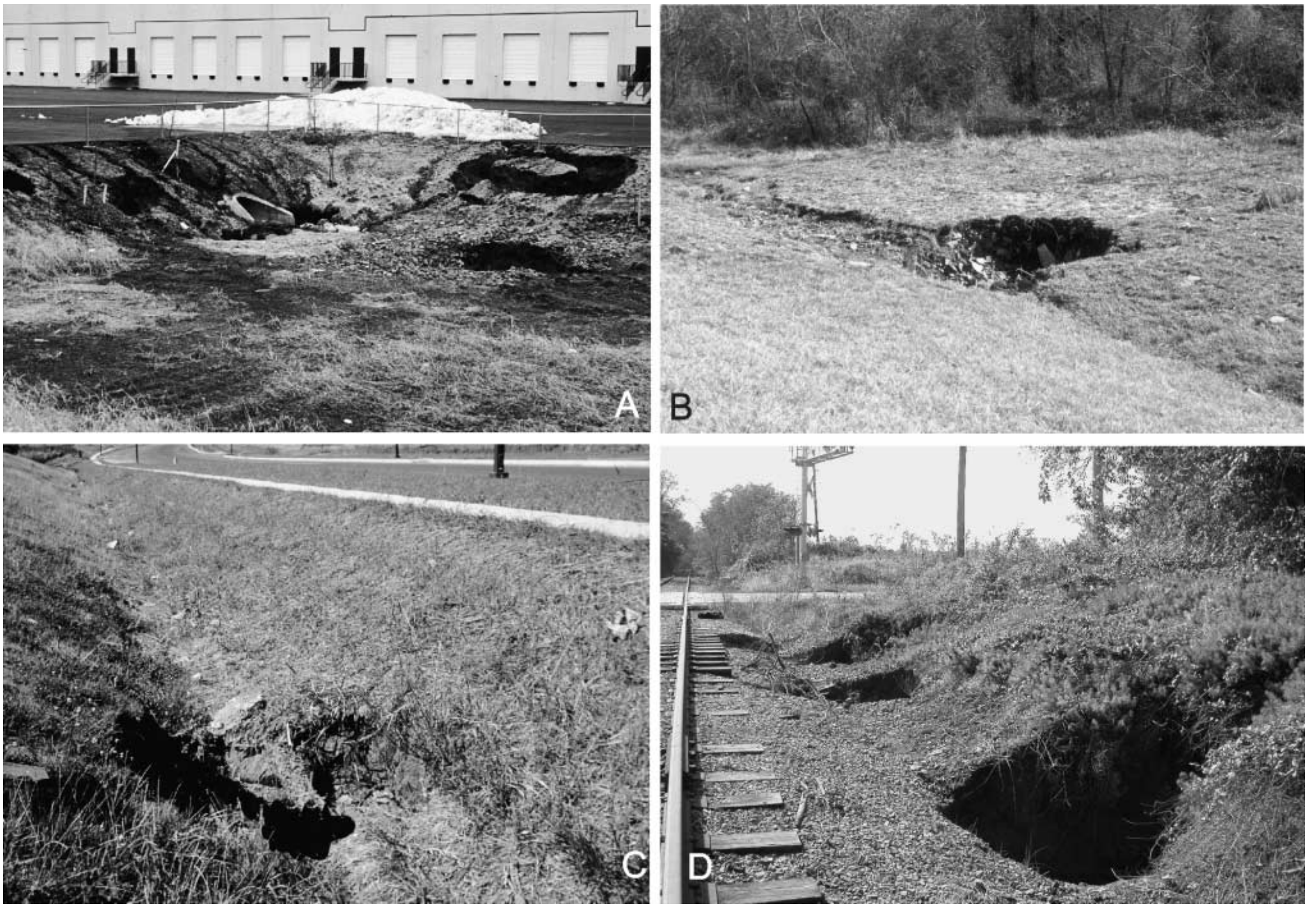


Figure 12. Sinkhole activation and unlined drainage. (A) Storm-water management area north of Buckeystown. (B, C) Unlined road drainage. (D) Unlined drainage adjacent to railroad.

rainfall, these features become activated. However, unlike storm-water management ponds, sinkholes activated along roadside drainage ditches were observed in nearly all lithologic units identified in this study. An example illustrated is in Figure 14. Although much of this area lies mainly in the outcrop belt of the relatively unsusceptible Adamstown Member of the Frederick Formation, the unlined road drainage on the south side of the highway is the site of increased sinkhole activity as compared to the lined drainage on the northern side.

Rerouted Stream Drainages

In many areas throughout the Frederick Valley, housing and business development, as well as road construction, have necessitated the rerouting of surface drainages. Rerouting was mentioned briefly in the section dealing with surface drainage patterns. However, this common practice in the Frederick area may be a significant contributor to the creation of zones of sinkhole activity. One particular example that demonstrates the results of this practice is in the northern reaches of the Frederick Valley, where industrial construction necessitated the rerouting of Israel Creek and the partial filling of a part of its natural channel (Figure 15). The exposed section of the abandoned channel has been the site of frequent sinkhole activity ever since. Compounding the problem is the fact that the rerouted section lies within the outcrop belt of the Lime Kiln Member of the Frederick Formation, one of the most troublesome stratigraphic units for karst development in the valley. In this case, the static relationship between soil cover and water content near the channel was destroyed during channel rerouting, and this resulted in a very high incidence rate of sinkhole formation.

Quarry Activity

Quarry activity has long been recognized as an activator of sinkholes (Boyer, 1997). In areas surrounding active quarries, the water table is commonly depressed by pumping during mining. This localized base level for the water table is commonly lower than it would be under normal conditions. The new hydrologic gradient

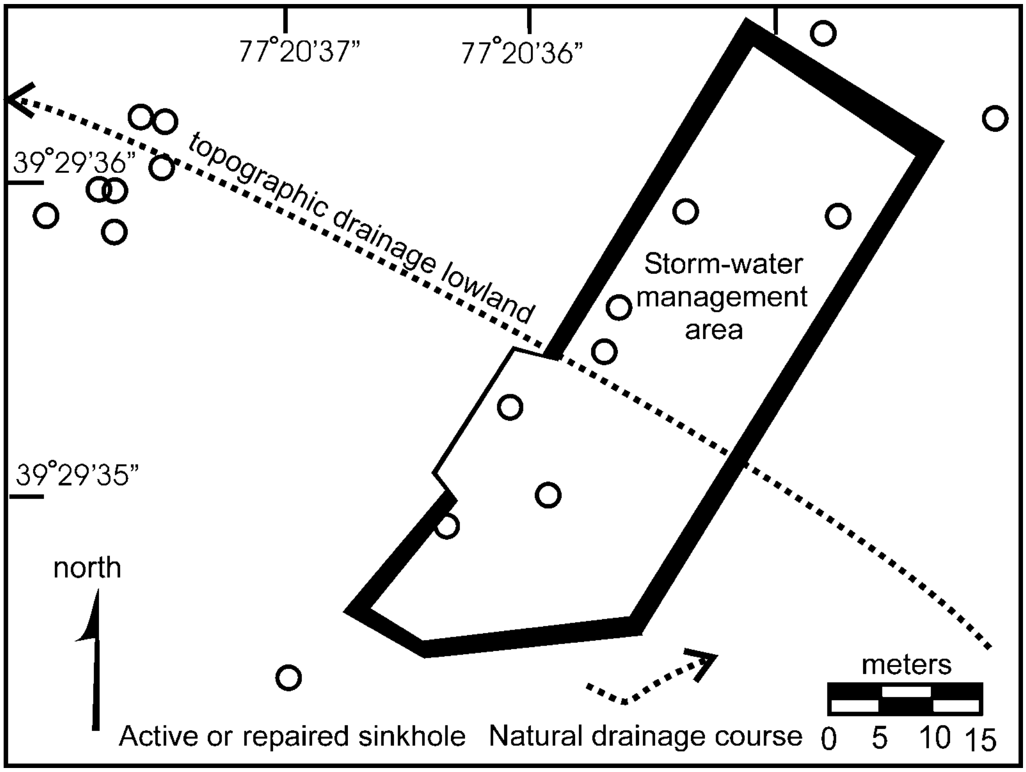


Figure 13. Distribution of active sinkholes and their relationship to a storm-water management area and predevelopment surface drainage in Walkersville. Nearly all active sinkholes occur either directly within the storm-water catch basin or the relict drainage.

allows subterranean voids that normally would be filled with sediment, to be flushed out by water moving along the steepened gradient.

Increased sinkhole activity was observed around every quarry in the Frederick Valley. This has been a serious problem in the southeastern parts of Frederick City, where a long-lived quarry has been blamed for increased sinkhole activity (Figure 10D). Complicating this case is the fact that highway and business development has rerouted many of the area's streams and

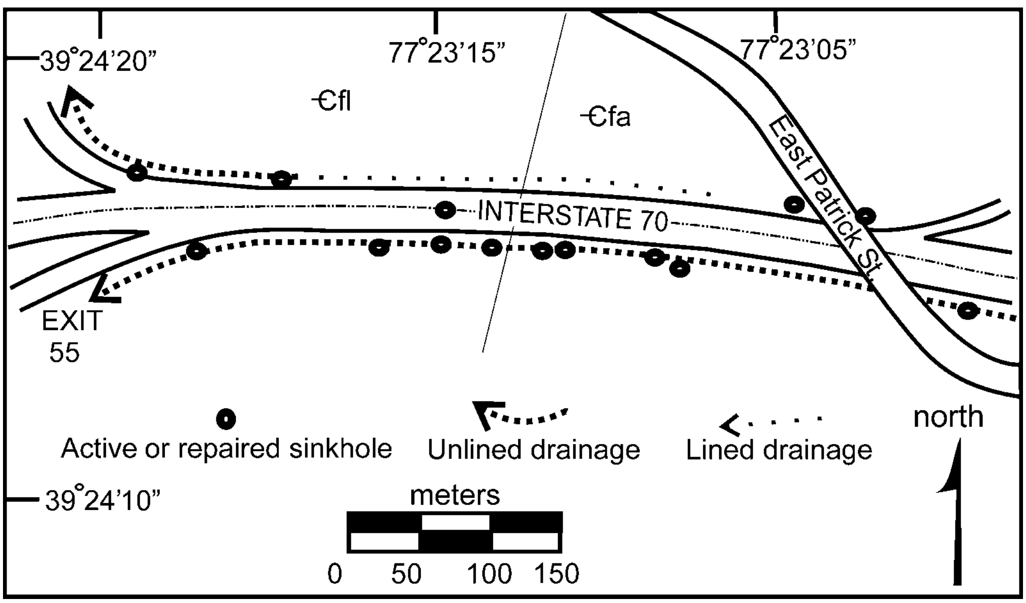


Figure 14. Geologic sketch map of the distribution of active sinkholes and their relationship to roadside drainage ways along Interstate 70 in southeastern Frederick City. Most of the active sinkholes are in the outcrop belt of the Adamstown Member of the Frederick Formation. Note that the area of lined drainage on the north side of the highway has no active sinkholes,whereas the corresponding unlined area to the south has numerous sinkholes. Geologic symbols: Frederick Formation, Cfa = Adamstown Member; Cfl = Lime Kiln Member.

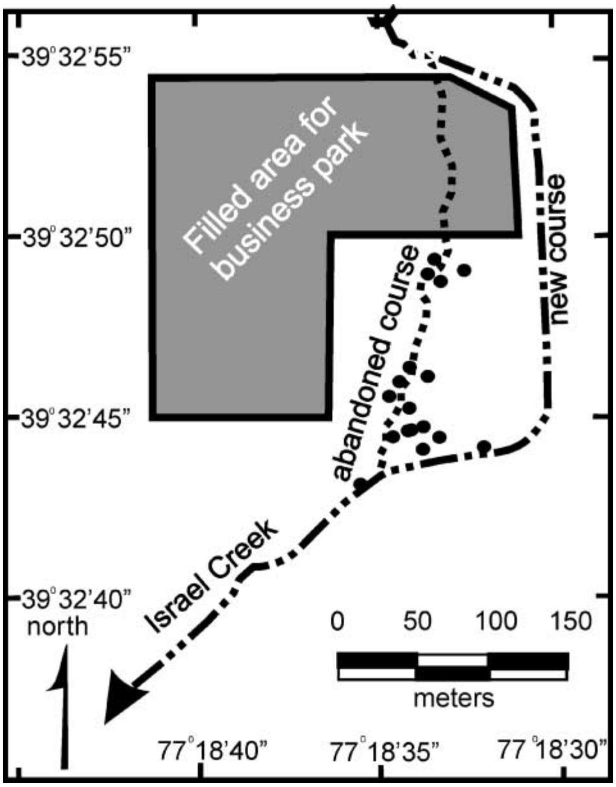


Figure 15. Sketch map of the distribution of active sinkholes and their relationship to an abandoned stream channel in an area of rerouted drainage northeast of Woodsboro.

natural drainage patterns. Furthermore, this quarry is located in the Lime Kiln Member of the Frederick Formation, a unit exhibiting one of the highest levels of karst susceptibility in the Frederick Valley. Consequently, it appears that bedrock composition, rerouted drainages, unlined drainage, and quarry activity may all be contributing factors to sinkhole development at this location.

Overburden Disturbance

Increased development in the Frederick Valley has resulted in the removal and rearrangement of large areas of soil cover. This disruption of infiltration paths, surface drainage, and subterranean flow appears to locally influence the proclivity for sinkhole development. In many cases, the disrupted area is immediately covered by either asphalt or building structures. In these instances, no recognizable increase in sinkhole activity was observed during the course of this study. However, in several locations, the removal of the overburden was followed by prolonged periods of exposure of the disrupted area. In such cases, a sharp increase in sinkhole activity was noted, especially where the rock unit that underlies the disturbed area belongs to one of the geologic units more susceptible to karst feature development.

An example of this is a business park in northeastern Frederick City (Figure 16). In this area, business

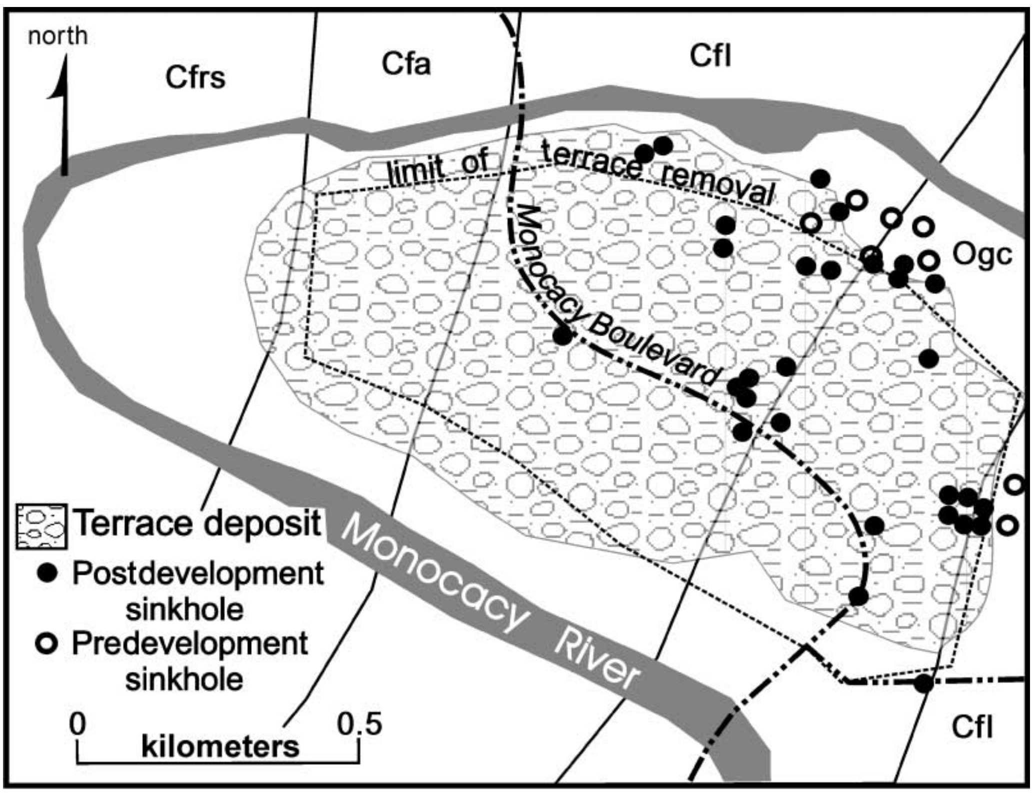


Figure 16. Geologic map of an area at the border of the Frederick and Walkersville quadrangles illustrating the relationship between the timing of sinkhole development and the removal of surficial deposits (river terrace). Note how sinkholes were confined to the banks of the Monocacy River prior to excavation, but became more abundant in the Lime Kiln and Ceresville members after terrace gravels were removed. Geologic symbols: Frederick Formation, Cfr = Rocky Springs Station Member; Cfa = Adamstown Member; Cfl = Lime Kiln Member; Grove Formation, Ogc = Ceresville Member.

park development necessitated the removal of thick accumulations of Monocacy River terrace deposits. In some places, more than 6 m (19 ft) of terrace gravels were excavated down to the top of bedrock and removed. Geologic and karst mapping prior to excavation revealed only a small number of sinkholes near the Frederick-Grove contact. Following removal of the terrace deposits, numerous sinkholes developed, both within the Lime Kiln Member of the Frederick Formation and the Ceresville Member of the Grove Formation. Although a few of these active sinkholes formed in a storm-water management area, most formed where the bedrock had been laid bare and left uncovered and unvegetated. The disruption caused by development activity apparently contributed to the formation of these sinkholes. It is noteworthy that no sinkholes were identified within the Rocky Springs Station or Adamstown members of the Frederick Formation in this area, either prior to or after excavation.

CONCLUSIONS

Geologic factors are an important part in the distribution of karst features in the Frederick Valley. A redefined, precise stratigraphy helps to delineate the stratigraphic intervals most susceptible to karstification. The Lime Kiln Member of the Frederick Formation and the Fountain Rock, Ceresville, and Woodsboro members of the Grove Formation are intervals of especially high active sinkhole formation. An elevated risk of sinkhole development is likely where altered surface stream drainage, unlined road drainage, storm-water management areas, active quarrying, and soil mantle removal are in proximity to these stratigraphic units.

REFERENCES CITED

Boyer, B. W., 1997, Sinkholes, soils, fractures, and drainage: Interstate 70 near Frederick, Maryland: Environmental and Engineering Geoscience, v. 3, p. 469–485.

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

Brezinski, D. K., 2004b, Geologic map of the Frederick quadrangle, Frederick County, Maryland: Maryland Geological Survey digital geologic map, scale 1:24,000, 1 sheet .

Brezinski, D. K., and J. Edwards, Jr., 2004, Geologic map of the Woodsboro quadrangle, Frederick County, Maryland: Maryland Geological Survey digital geologic map, scale 1:24,000, 1 sheet.

Brezinski, D. K., and J. P. Reger, 2002, Stratigraphy-karst relationships in the Frederick Valley of Maryland, *in* E. Kuniansky, ed., U.S. Geological Survey Karst Interest Group Proceedings, Shepherdstown, West Virginia, August 20–22, 2002: U.S. Geological Survey Water Resources Investigations Report 02-4174, p. 59–65.

Jonas, A. I., and G. W. Stose, 1938, Geologic map of Frederick County, and adjacent parts of Washington and Carroll counties: Maryland Geological Survey geologic map series, scale 1:62,500, 1 sheet.

Kochanov, W. E., 1999, Sinkholes in Pennsylvania: Pennsylvania Geological Survey (4th Series) Educational Series 11, 33 p.

Lee, K. Y., 1977, Triassic–Jurassic geology of the northern part of the Culpeper Basin, Virginia and Maryland: U.S. Geological Survey Bulletin, v. 1422, p. C1–C17.

Lee, K. Y., and A. J. Froelich, 1989, Triassic–Jurassic stratigraphy of the Culpeper and Barboursville basins, Virginia and Maryland: U.S. Geological Survey Professional Paper 1472, 52 p.

Reinhardt, J., 1974, Stratigraphy, sedimentology, and Cambro-Ordovician paleogeography of the Frederick Valley, Maryland: Maryland Geological Survey Report of Investigations 23, 73 p.

Southworth, S., 1996, The Martic fault in Maryland and its tectonic setting in the central Appalachians, *in* D. K. Brezinski and J. P. Reger, eds., Studies in Maryland geology, in commemoration of the centennial of the Maryland Geological Survey: Maryland Geological Survey Special Publication 3, p. 205–221.

Southworth, S., and D. K. Brezinski, 2003, Geologic map of the Buckeystown quadrangle, Frederick and Montgomery counties, Maryland, and Loudoun County, Virginia: U.S. Geological Survey geologic quadrangle map GQ-1800, scale 1:24,000, 1 sheet.