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FIELD TRIP GUIDE
Hydrogeologic Framework of the Northern Shenandoah Valley Carbonate Aquifer System

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Abstract

The carbonate aquifer system of the northern Shenandoah Valley of Virginia and West Virginia provides an important water supply to local communities and industry. This is an area with an expanding economy and a growing population, and this aquifer is likely to be further developed to meet future water needs. An improved understanding of this complex aquifer system is required to effectively develop and manage it as a sustainable water supply. Hydrogeologic information provided by a detailed aquifer appraisal will provide useful information to better address questions about (1) the quantity of water available for use, (2) the effects of increased pumpage on ground-water levels and instream flows, (3) the relation between karst features and the hydrology and geochemistry of the surface- and ground-water flow systems, and (4) the quality of the ground-water supply and its vulnerability to current and potential future sources of contamination. To answer these questions, a hydrogeologic framework is necessary to look at the relationship of water resources to the geology.

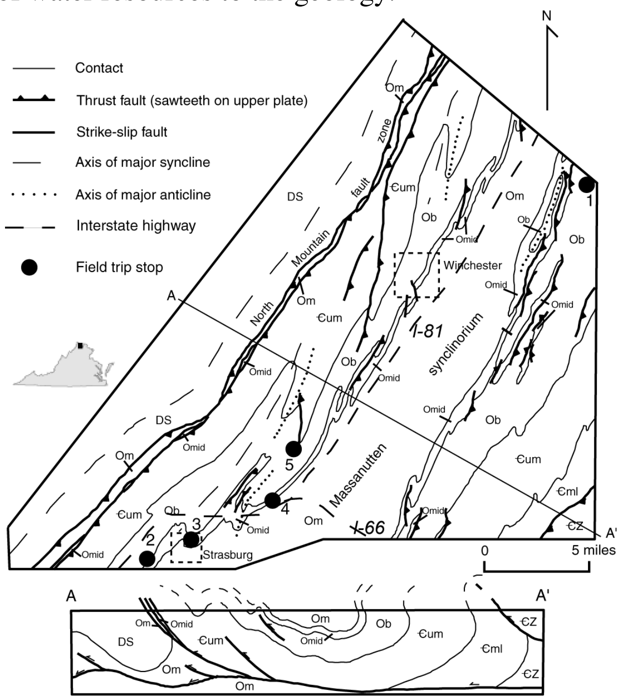

Figure 1. Generalized geologic map, and cross section of the Shenandoah Valley of northern Virginia and location of field stops. DS-Devonian and Silurian rocks; Om-Upper and Middle Ordovician rocks of the Martinsburg Formation; Omid-Middle Ordovician carbonate rocks; Ob-Middle and Lower Ordovician rocks of the Beekmantown Group; Ꞓum-Upper and Middle Cambrian carbonate rocks of the Conococheague and Elbrook Formations; Ꞓml-Middle and Lower Cambrian rocks of the Waynesboro and Tomstown Formations; ꞒZ-Cambrian and Neoproterozoic rocks of the Blue Ridge Province.

INTRODUCTION

In October 2000, the U.S. Geological Survey began an investigation to better characterize the carbonate aquifer system of Frederick County, Virginia (fig. 1) and provide relevant hydrogeologic information that can be used to guide the development and management of this important water resource. This investigation forms the foundation of a regional study of the karst system that will use hydrologic and geologic information to improve the understanding of the aquifer system, its relationship to surface features, and potential hazards over a multi-county area of Virginia and West Virginia. A geologic and karst framework will aid in the understanding of how water enters the aquifer system and how ground water moves through it. Detailed geologic mapping along with fracture analyses, conduit analyses, and mapping of karst features will form this framework. This field trip will visit surface features such as sinkholes, springs, and streams, and venture into a commercial cave to look at the conduit system. We will also look at a stratigraphic section of carbonate rock to examine the various rock formations and fracture system.

GEOLOGIC SETTING

The northern Shenandoah Valley lies between the mountains of the Blue Ridge Province on the east and North Mountain to the west (fig. 1). Carbonate rocks exposed in the Valley range from Early Cambrian to Middle Ordovician in age and can be divided into belts of the eastern and western limbs of the Massanutten synclinorium. The Middle and Upper Ordovician Martinsburg Formation underlies the axis of the synclinorium. The Blue Ridge Province to the east is comprised of rocks of Proterozoic and Cambrian age that are folded and thrust faulted over the younger strata of the Shenandoah Valley. To the west, the Valley is bounded by the North Mountain fault zone; a complex thrust fault system that places the Cambrian and Ordovician units over Silurian and Devonian units to the northwest. The rocks of the Shenandoah Valley are folded and faulted, and contain numerous joints and veins of calcite and quartz. Folds are northeast trending and are generally overturned to the northwest in the eastern limb and upright in the western limb of the synclinorium. The geology of the area of this field trip has been mapped at various scales by Butts and Edmundson (1966), Edmundson and Nunan (1973), Rader and others (1996), and Orndorff and others (1999).

KARST FEATURES

Karst in the study area is expressed by sinkholes, caves, springs, and areas of poorly developed surface drainage on carbonate rock. Lithologic characteristics, fracture density of the bedrock, and proximity of carbonate rock to streams are controlling factors in sinkhole development (Orndorff and Goggin, 1994). Sinkholes are more abundant and increase in size near incised streams. This relationship can be seen along Cedar Creek (stop 3) and the Shenandoah River. Hubbard (1983) attributed the greater development of sinkholes near streams to the steepened hydraulic gradient and increased rate of ground-water flow in these areas.

Springs in the Shenandoah Valley mostly are structurally controlled, occurring where fault planes intersect the surface. Several springs within the city of Winchester and Vaucluse Spring (stop 5) are examples of this relationship. Travertine deposits are associated with many springs in the Shenandoah Valley and in areas where stream waters are supersaturated in respect to calcium carbonate.

GEOLOGIC CONTROLS ON SINKHOLE AND CAVE DEVELOPMENT

Although hydraulic gradient is the primary control on the development of sinkholes, lithostratigraphy plays a role. In areas where the hydraulic gradient is low, carbonate rocks of the Rockdale Run Formation, Pinesburg Station Dolomite, New Market Limestone, Lincolnshire Limestone, and Edinburg Formation show higher occurrences of sinkholes than the Elbrook Dolomite, Conococheague Formation, and Stonehenge Limestone (Orndorff and Goggin, 1994). In areas with a high hydraulic gradient, this lithologic control on sinkhole development is less evident.

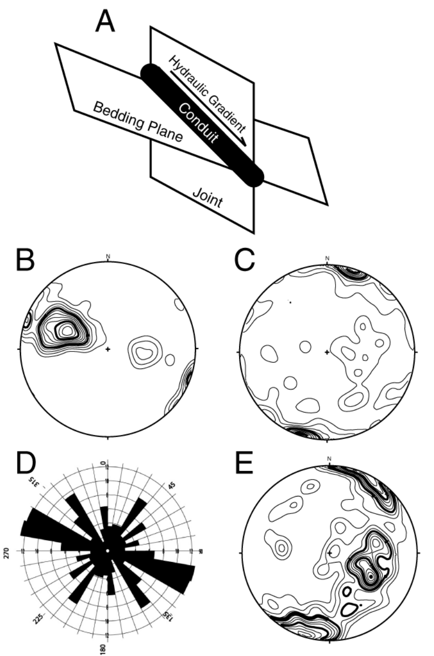

Figure 2. Diagrammatic representations of the importance of the intersection of bedding planes and joints to conduit development. A) Three dimensional diagram of the preferred location of a conduit at the intersection of two planes; B) Lower hemisphere equal area stereographic projection of poles to bedding in the Winchester area of Frederick Co., Virginia contour interval is 1 percent of 1 percent area, n=72; C) Lower hemisphere equal area stereographic projection of poles to joints in Winchester area; contour interval is 1 percent of 1 percent area, n=284; D) Compass-rose diagram showing orientation of joints in the Winchester area, circle interval is 2 percent of total, n=284; E) Lower hemisphere equal area stereographic projection of lineation defined by the intersection of bedding and joints showing shallow plunging northeast and southwest trend to the lineation and a steep southeast trending lineation, contour interval is 0.5 percent of 1percent area, n=259.

Caves occur in all of the carbonate units in the Shenandoah Valley and have formed in both limestone and dolostone. Preliminary results show that some caves form along the intersection of bedding planes with joints (fig. 2a). Therefore, it may be important to look at these linear features as a factor in conduit development locally and regionally. Geologic mapping for this study includes collecting data on fracture orientation, persistence, and intensity. Stereographic and compass-rose depiction of the orientation of bedding and joints (figs. 2b, 2c, and 2d) can be used to determine the orientation of the intersection of bedding and joints (fig. 2e). It is important to understand that conduits in conjunction with various fractures form a network that transports the water vertically to the water table and laterally through the ground-water system.

FIELD TRIP STOP DESCRIPTIONS

Field trip stops will show karst hazards (stop 1), stratigraphic sections of karstic rock (stop 2), sinkholes related to high hydraulic gradient (stop 3), relationship of structural geology to conduit development (stop 3), real-time stream gaging (stop 4), and a karst spring (stop 5).

Stop 1 – Collapse Sinkhole, Clarke County, Virginia

In November 1992, a collapse sinkhole developed in northern Clarke County that caused extensive property damage and completely engulfed a home in less than two months (fig. 3). The bedrock at this locality is limestone of the Rockdale Run Formation of the Beekmantown Group and is less than ¼ mile east of a thrust fault that places the Rockdale Run over the Martinsburg Formation (fig. 1). This collapse sinkhole is one of a series of subsidence sinkholes that form a line that trends north-northeast for nearly one mile. This sinkhole exposes 20 to 30 feet of residuum over the bedrock. Periodic visits over the years to the site has shown that the sinkhole has enlarged laterally by several tens of feet, deepened by about 10 feet, and has exposed ever increasing amounts of bedrock along its wall.

Figure 3. Collapse sinkhole with remains of house, Clarke Co., Virginia.

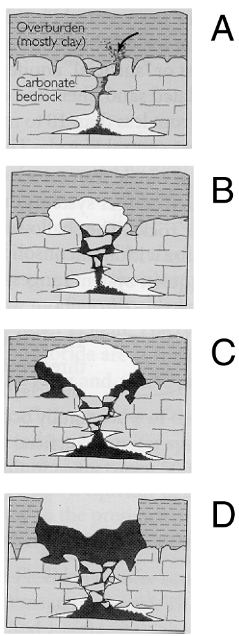

Figure 4. Diagrammatic evolution of a collapse sinkhole (from Galloway and others, 1999). A) Residuum spalls into cavity; B) Resulting void in clayey residuum produces arch in overburden; C) Cavity migrates upward by progressive roof collapse; D) Cavity breaches the ground surface creating sinkhole.

Collapse sinkholes, such as this one, occur due to failure of a soil arch in the residuum above the bedrock (fig. 4). A drop in the water table by drought or excessive water-well pumping, can cause these mass movements. As ground water moves sediments away from the bedrock-residuum interface through enlarged fractures or conduits, a void develops in the residuum and migrates to the surface as more and more soil is removed (fig. 4). At the point where the soil arch can no longer sustain itself, the collapse occurs. Other causes of sinkhole collapse are from extended drought when adhesive properties of water are no longer active, and from extreme rainy periods when the increased soil moisture adds too much weight to the soil arch. In the case of the Clarke County collapse, about one week prior to the collapse a well driller pumped much mud from a new well in the front yard.

Stop 2 – Tumbling Run Stratigraphic Section

Rocks exposed along the road cuts at Tumbling Run, near Strasburg, VA (fig. 1), have been studied for many years as a classic stratigraphic section of Middle Ordovician carbonate rocks. This section of rock records both a tectonic and paleoenvironmental history of the Middle Ordovician and gives us the opportunity to look at the differences in some of the rock units that karst features form. This road cut also shows fractures that are instrumental in forming voids in the rock in which dissolution can occur.

The Middle Ordovician rocks at this stop record a major change in the tectonic history of North America (fig.5). Dolostone of the upper part of the Beekmantown Group exposed on the west side of the bridge over Tumbling Run was deposited in a shallow water, restricted marine (tidal flat or lagoon) environment during a time when the east coast of North America was a passive margin on the trailing-edge continental plate boundary. An unconformity occurs between the rocks of the Beekmantown Group and the overlying New Market Limestone several feet above creek level just north of the bridge. This unconformity marks the change from a

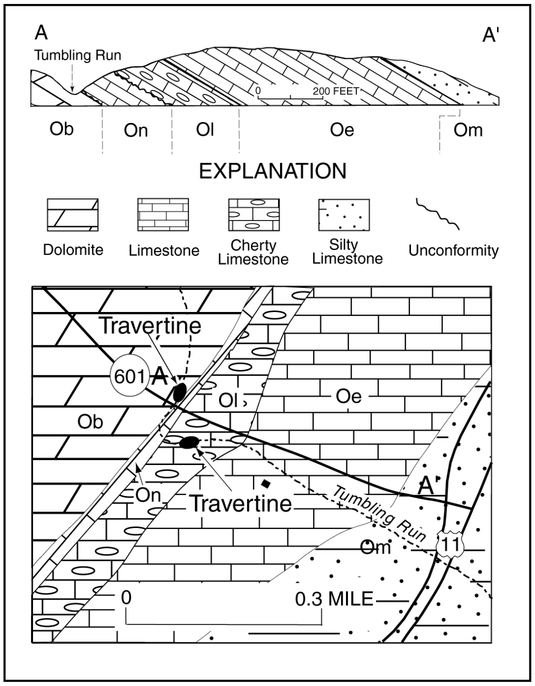

Figure 5. Cross section and geologic map of the Tumbling Run Middle Ordovician stratigraphic section. Ob, Beekmantown Group; On, New Market Limestone; Ol, Lincolnshire Limestone; Oe, Edinburg Formation; Om Martinsburg Formation.

passive margin to an active margin of a convergent plate boundary. Up section to the southeast are rocks that were deposited in progressively deeper water environments, from tidal flat and shallow subtidal marine (New Market Limestone), to open marine, shallow ramp (Lincolnshire Limestone), to deep ramp and slope (nodular facies of the Edinburg Formation), and to anoxic slope and basin (mudstone facies in the Edinburg Formation) (Rader and Read, 1989; Walker and others, 1989) (fig. 5). The overlying rock of the Martinsburg Formation were deposited in a foreland basin that was positioned between North America and a volcanic arc to the east. Volcanic ash or bentonite beds in the Edinburg Formation are evidence for the volcanic activity. A modern analog to this geologic setting is the Java Sea and other seas that exist between mainland Asia and the Indonesian volcanic arc.

Sinkholes and caves form in all of the units exposed at Tumbling Run. Although dolostone is generally less soluble than limestone, karst features do occur in the dolostone of the Beekmantown. Fractures in the carbonate rocks of the Shenandoah Valley occur as bedding plane partings and joints. The joints formed from folding and faulting associated with the Alleghanian orogeny of the Pennsylvanian and Permian. These joints, along with inclined bedding planes, form the pathways for water to move through the aquifer system and initiate dissolution.

One karst feature that occurs in the streambed of Tumbling Run is deposits of travertine. Travertine is usually associated with springs, where water supersaturated with respect to calcium carbonate reaches the surface. A combination of increased temperature and aeration as surface streams flow over rough beds causes degassing of carbon dioxide and loss of calcite supersaturation, resulting in the deposition of calcite (White, 1988). Travertine can be seen in the streambed up stream from the bridge over Tumbling Run and further down stream where water cascades over these deposits. Travertine occurs here due to small springs and seeps that occur in and near Tumbling Run (fig. 5).

Stop 3 – Crystal Caverns, Strasburg, Virginia

The area around Crystal Caverns has many sinkholes and a cave to examine the relationship of stratigraphy and structure to the conduit system (fig. 6a). The area sits on a topographic high north of the confluence of Cedar Creek with the North Fork of the Shenandoah River and the karst is related to the high hydraulic gradient. Seven sinkholes occur within a couple of hundred feet of the parking area for the caverns, many with open throats and soil piping. These sinkholes are generally subsidence sinkholes with gradual movement of

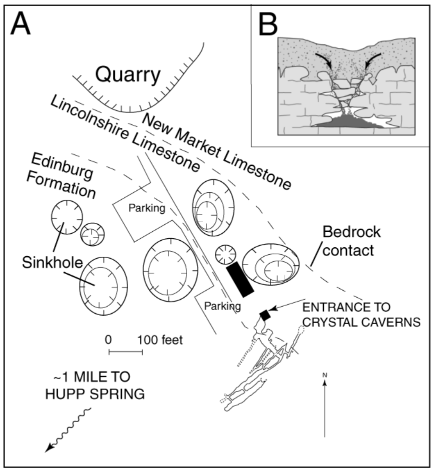

Figure 6. A) Map of Crystal Caverns area showing location of entrance, outline of cave passages projected to surface, and location of sinkholes; B) Diagram showing evolution of a subsidence sinkhole (from Galloway and others, 1999).

sediments into the underground system (fig. 6b) as opposed to the catastrophic collapse type seen at stop 1 (fig. 4). Two of the sinkholes have entrances to small caves that are developed along vertical joints in the bedrock. The active nature of these sinkholes can be attributed to their topographic position in relation to Cedar Creek, and also to the close proximity to a large abandoned quarry to the north that previously had lowered the water table in the local area. Although no dye tracing has been done here, these sinkholes are probably linked in the subsurface to Hupp Spring, which is located about one mile to the south.

The geology of this area is gently dipping Middle Ordovician limestone of the New Market Limestone, Lincolnshire Limestone, and Edinburg Formation that occur near the nose of a southward plunging anticline (Orndorff and others, 1999) (fig. 1). High calcium limestone (as much as 98 percent calcium carbonate (Edmundson, 1945)) of the New Market Limestone was mined from the quarry to the north. The contact between the Lincolnshire Limestone and Edinburg Formation runs northwesterly across the Crystal Caverns property.
Like all karst regions, sinkholes can be entrance points for contamination into the ground-water system that may include agricultural runoff (pesticides, herbicides, and animal waste), industrial pollution, underground storage tanks, landfills, and private septic systems, all of which can be found in the Shenandoah Valley. Historically, sinkholes have been used by land owners as dumping sites for waste. Slifer and Erchul (1989) estimated that there are nearly 1400 illegal dumps in sinkholes and 4600 in karst areas of the Virginia

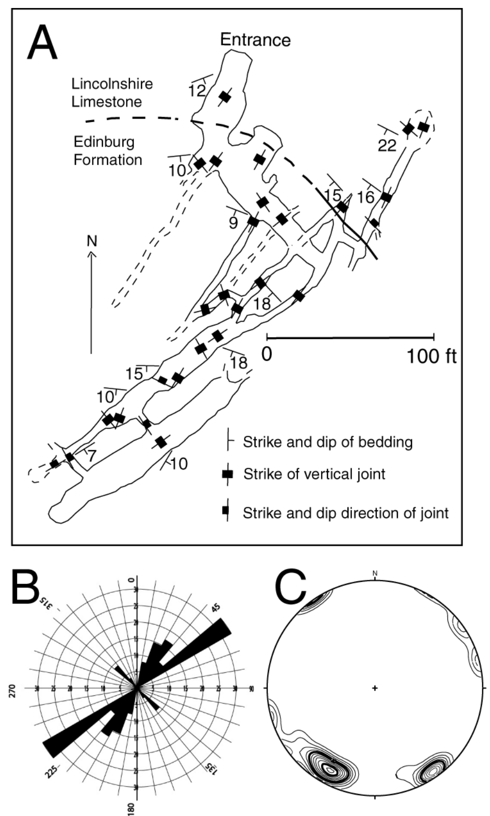

Figure 7. A) Geologic map of Crystal Caverns; B) Compass-rose diagram showing azimuth of cave passages, circle interval is 5 percent of total, n=224 ft; C) Lower hemisphere equal area stereographic projection of the lineation defined by the intersection of bedding planes and joints in Crystal Caverns, contour interval 2 percent of 1 percent area, n=28.

Valley and Ridge Province. An example of this can be seen in the sinkhole north of the caverns entrance.

The passages of Crystal Caverns are part of a conduit system that has developed mostly along joint planes and to a lesser extent along bedding planes (fig. 7a). The major northeast-trending passages parallel the local northeast-trending joint set (fig. 7b). The intersection of the joints with the bedding planes must be important to conduit development because this lineation has a major southwest trend and shallow plunge, and a secondary southeast trend and plunge that are consistent with cave passage orientations (fig. 7c).

Stop 4 – Cedar Creek Gaging Station

As part of the Frederick County carbonate aquifer appraisal, stream gages were constructed on both Opequon and Cedar Creeks in November of 2000. The gages were situated proximal to the contact between the carbonate rock formations and the shale of the Martinsburg Formation. The Cedar Creek gage at US Highway 11 near Middletown, Virginia is situated on the Stickley Run Member (Epstein and others, 1995) of the Martinsburg Formation, which is the transitional unit between the underlying limestone of the Edinburg Formation and the overlying shale of the Martinsburg Formation.

Knowledge of the base-flow characteristics of streams provides insight into the hydrogeologic flow systems of an area (Nelms and others, 1997). Mean base flow provides a measure of the long-term average contribution of ground water to streams and is commonly referred to as either ground-water discharge or ground-water runoff. The contribution to streamflow from ground-water discharge can be referred to as effective recharge (total recharge minus riparian evapotranspiration, Rutledge, 1992) (fig. 8).

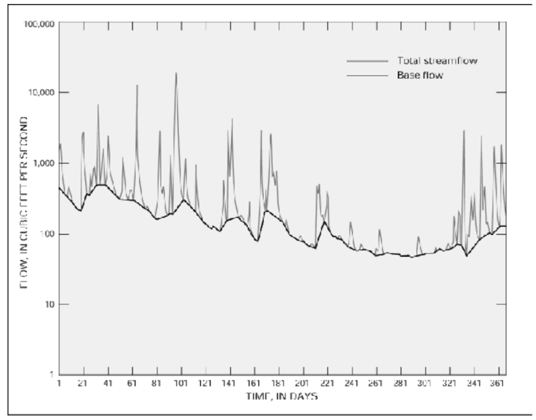

Figure 8. Example of a hydrograph showing the results of the streamflow partitioning method used to provide an estimate of effective recharge (Rutledge, 1992).

Stop 5 – Vaucluse Spring

A number of large springs issue from the carbonate rock formations in the Northern Shenandoah Valley. In the past, many of these springs served as public water supplies. Until recent times, the City of Winchester obtained its water supply from a variety of springs that have included Old Town Spring, Rouss Spring, Shawnee Spring, and Fay Spring. As noted by Cady (1938, p. 67), the occurrence of many of these springs near the contact between carbonate formations of the west limb of the Massanutten synclinorium and the shales of the Martinsburg Formation suggests, "the shale obstructs the eastern movement of the ground water from the limestone and may act as a dam." Additionally, springs commonly occur near lithologic contacts and faults between carbonate rock formations. Springs are natural discharge points for water draining from the ground-water system and provide much of the base flow to streams in the area.

Vaucluse Spring is a large spring issuing from the Beekmantown Group near Vaucluse, Frederick County, Virginia (Cady, 1938, Pl. 4B) (fig. 9) and provides a major component of flow to Meadow Brook. Recent mapping by Orndorff and others (1999) indicates that the spring occurs proximal to a section of the Vaucluse Spring fault where rocks of the Conococheague Formation are thrust over rocks of the Rockdale Run Formation of the Beekmantown Group (fig. 10). Several discharge measurements have been conducted at Vaucluse Spring (Table 1).

Figure 9. Vaucluse Spring issuing from the Beekmantown Group near Vaucluse, Frederick County, Virginia.

Table 1: Discharge measurements at Vaucluse Spring, Frederick County, Virginia

Date	Discharge (ft3/sec)	Discharge (gpm)
1981/07/09	1.92*	860
1984/04/09	5.93*	2,660
1984/10/16	3.04*	1,360
1985/04/18	3.79*	1,700
2001/08/03	1.95	875
2001/08/16	1.98	890
2001/09/26	1.78	800
2001/11/27	1.56	700
2002/03/27	1.29	580
2002/05/01	1.71	770

*Historic unverified measurement.

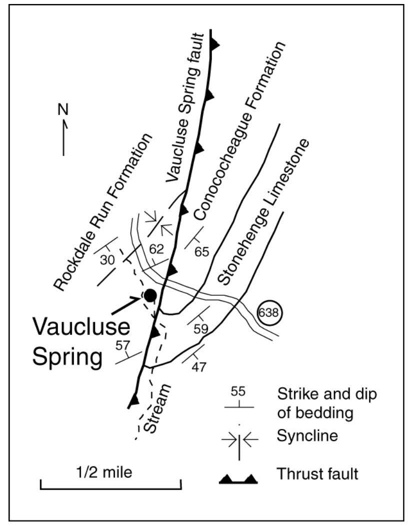

Figure 10. Geologic map of the area around Vaucluse Spring, Frederick County, Virginia (from Orndorff and others, 1999).

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