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Bedrock structural controls on the occurrence of sinkholes and springs in the northern Great Valley karst, Virginia and West Virginia

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ABSTRACT

Recent geologic mapping at a scale of 1:24,000 has enabled a qualitative correlation of the occurrence of springs and sinkholes with bedrock structures and ground-water conditions in the northern Great Valley of Virginia and West Virginia. Sinkholes tend to be concentrated in zones of faulting, local minor folding, and clustered within susceptible bedrock units at the noses and axes of large plunging folds. Alignment of sinkholes mainly occurs along strike of bedding. Enhanced rock solution and conduit formation correlates with carbonate units of greater limestone purity and finer grain size, suggesting some lithologic control on karst formation. In addition, there is an apparent topographic correlation, with sinkholes usually formed in elevated and flat (<5 degrees slope) areas, as well as frequent sinkhole occurrence proximal to entrenched surface streams. Density of sinkhole occurrence tends to increase in areas where water-table fluctuations are large. Large perennial springs occur along faults, and may lie above base level streams indicating upward flow gradients particularly where cross-strike faults and joints intersect bedding planes and strike-parallel faults. Sinkhole formation also frequently occurs in areas proximal to entrenched surface streams, reflecting subsequent vadose-zone modification and excavation of sediment-filled conduits where downward ground-water flow gradients are most steep. Geologic evidence indicates that deep karst development may have taken place by rising fluids under confined (hypogenic) conditions in the distant geologic past in this region.

INTRODUCTION

Demand for detailed assessments of land vulnerability to subsidence and water contamination hazards in karst areas is growing within the United States. In particular, the karst regions of the northern Great Valley in Virginia and West Virginia have been subjected to rising development pressures in the past decade. Lands once used primarily for agriculture are rapidly yielding to housing and commercial development. Maps of karst extent, and associated risk assessments of subsidence hazards and ground-water availability and contamination are increasingly sought by land-use planners. The U.S. Geological Survey provides the base information for the inventory of karst resources, geologic framework for hydrologic studies, and information necessary for land-use vulnerability assessments.

Several well-known sinkhole plains in the United States have developed in bedrock strata that are generally flat-lying, with subtle geologic structure (e.g., Pennyroyal Plateau, KY, Mitchell Plain, IN, Ozarks Plateau, MO, Hollandale Embayment, MN). In these regions, bedrock control on sinkhole formation is primarily related to vertical fracturing along master joint sets and faults (e.g., Florea, 2005). In the intensively folded and faulted carbonate-rock terrain of the Appalachian Valley and Ridge province, additional geologic structures exert control on the localization of karst development. Locations of closed depressions occur in close association with several types of bedrock structures, especially fold axes, thrust faults, cross-strike faults, fold limbs, and fold noses.

PREVIOUS WORK

Hack (1965) provided a map of sinkhole locations for a portion of Page County, Virginia and first noted the structural influence of folds on sinkhole occurrence. Hubbard (1983) mapped the distribution of selected karst features throughout the northern Virginia Valley and Ridge province using aerial photographic methods. Hubbard's map was the first attempt at a comprehensive inventory of closed depressions in the Virginia karst lands. Due to limitations of resolution inherent to the approach, only a fraction of existing karst features were included on the maps, so that those areas that do not contain specific karst features do not imply a lack of such features (Hubbard, 2001). Orndorff and Goggin (1994) supplemented Hubbard's karst inventory through detailed mapping of bedrock geology. Currently, 1:24,000 scale mapping continues in the northern Great Valley (Orndorff and others, 1999; Weary and others, 2006). As more detailed bedrock information is gathered, the controls that bedrock structures exert on the occurrence of karst subsidence features becomes increasingly apparent.

METHODS

The results we present here are based upon 1:24,000 scale geologic mapping that include karst feature inventories. Identification of closed depressions was aided through the use of aerial orthophotography provided by the Commonwealth of Virginia, and through a 10-meter digital elevation model constructed by the U.S. Geological Survey. These data were added as layers within a geographic information system (GIS), and karst features were digitally outlined. Identified closed depressions were field-checked. The combined layers of information permitted the qualitative observations between sinkholes and geologic structure. In addition, ground-water flow in the region highlights the geologic and hydrologic factors that combine to result in karst features.

LITHOLOGY

The karst of the northern Great Valley occurs in carbonate rocks of Cambrian and Ordovician age. These formations are nearly all composed of mixed beds of limestone and dolomite, and vary greatly in siliceous mineral content. The carbonate units exposed in the study area are, from oldest to youngest, the Elbrook Formation, Conococheague Limestone, Beekmantown Group (limestone and dolomite rocks), New Market Limestone, Lincolnshire Limestone, and Edinburg Formation. Overlying the Edinburg is the Martinsburg Formation, a siliciclastic unit comprising shale and interbedded sandstone and siltstone.

The Elbrook Formation is composed of thin interbedded silty dolomite and limestone, and does not form good outcrop. Surface karst features are not as prevalent in the Elbrook as in other units; however, numerous springs as well as a few caves do occur in the Elbrook. The occurrence of karst features seem to be limited to zones of faulting and tight minor folds in the Elbrook.

The Conococheague Limestone consists of interbedded limestone, dolomite, and sandstone. The limestone contains dolomitic laminae ranging in thickness from a few millimeters up 2 cm. Much of the rock is intensively laminated and takes on a ribbon-like appearance. Prominent coarse quartz-sandstone beds occur intermittently within the formation and hold up topographic ridges, while the purer limestones weather to valleys and often host karst features, including caves.

The Beekmantown Group is composed of limestone and dolomite, generally of higher purity (less siliceous mineral content) than the Elbrook and Conococheague. These include the Stonehenge Limestone, the Rockdale Run Formation, and the Pinesburg Station Dolomite. Karst development is abundant and several caves in the Valley occur within the Beekmantown.

The New Market Limestone, Lincolnshire Limestone, and Edinburg Formation are relatively thin units, and thus are referred to collectively as the Middle Ordovician limestones. These limestones all host karst development. The New Market is an especially pure limestone, and solution features are commonly found within outcrops. The Lincolnshire notably contains interbedded black nodular chert. The Edinburg is mixed shale and limestone, with nodular limestone common in outcrops.

Mcoy and Kozar (2007) determined that sinkhole density is highest in the Beekmantown Group (3.5-4.0 sinkholes per square mile), followed by the Conococheague Limestone (2.5-3.0 per square mile), and roughly equivalent between the Middle Ordovician limestones and the Elbrook formation (1.3-1.5 per square mile).

FOLDS

Folds have been repeatedly recognized as important structural features associated with sinkhole development (Hack, 1965; Hubbard, 1983; Orndorff and Goggin, 1994). Axial planar cleavage and jointing, especially in anticlines, results in enhanced solution along fold axes due to fracturing. Noses of both anticlines and synclines are particularly prone to sinkhole development (Fig. 1). Zones of tight folding also show preferred sinkhole development. In less siliceous limestones and dolomitic rocks, such as the Beekmantown

Group, depressions are common within folds. However, in the shaly dolomite of the Elbrook Formation, areas of tight folding tend to result in springs more often than closed depressions or cover-collapse sinkholes (Fig. 1A and 1C).

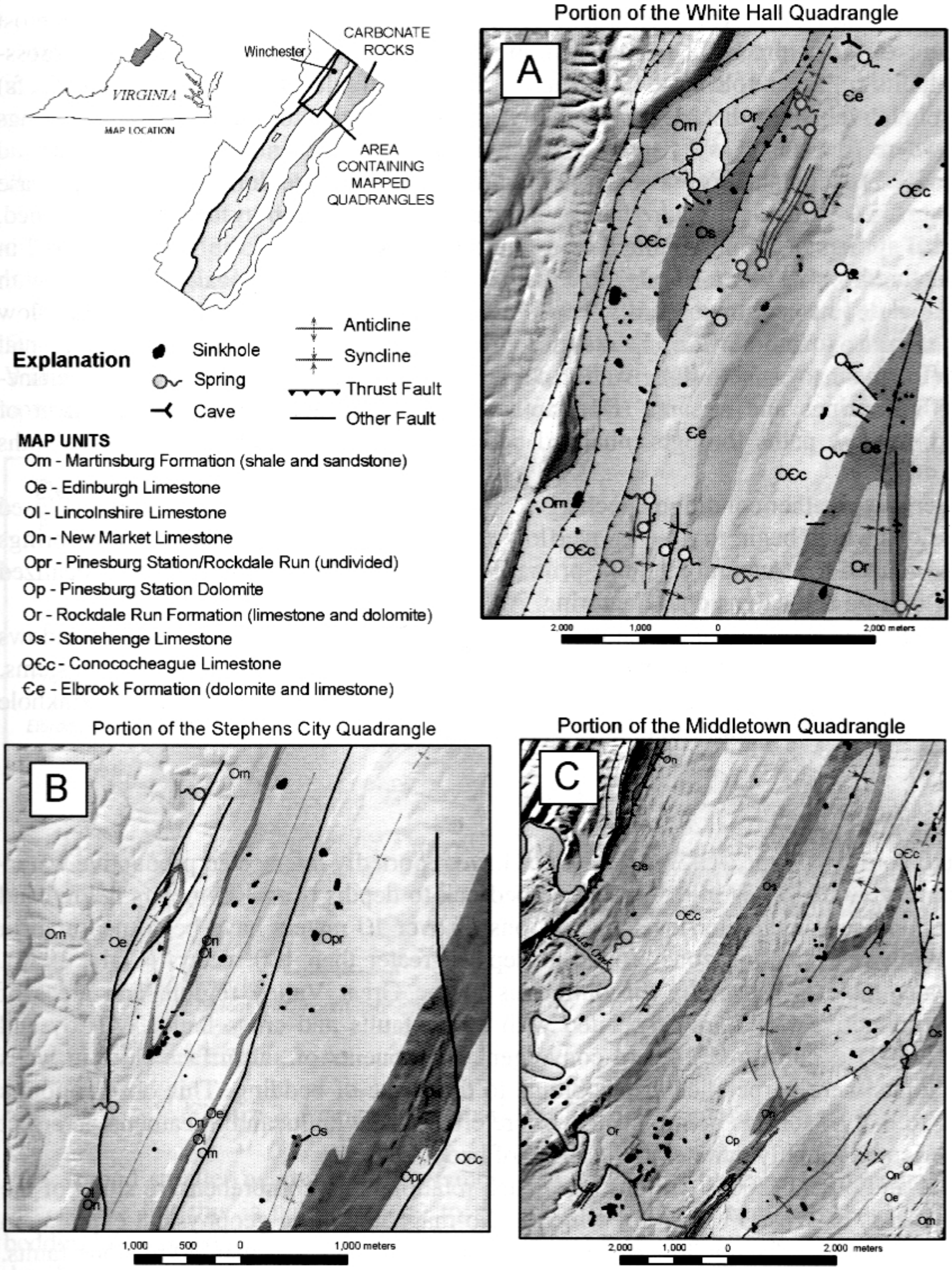

Figure 1. Geology and karst features within portions of the White Hall, Stephens City, and Middletown quadrangles, Virginia. Sizes of karst features have been exaggerated for clarity.

SPRINGS

In the northern Great Valley, sinking streams are uncommon; most surface streams are gaining flow from springs which account for a large proportion (>60%) of streamflow, especially under base flow conditions (Harlow and others, 2005). Springs are most abundant along or proximal to faults, particularly along thrust faults and where cross-strike faults intersect fold limbs, fold axes, and other faults. Larger springs (>0.5 cfs) exhibit relatively low discharge variability (Harlow et al., 2005). Some large springs occur where siliciclastic rocks are in contact with carbonate rocks along faults (Kozar and others, 2007). Perennial springs emerge on average 25 m above the elevation of the base level streams. Thus, although the regional carbonate aquifer system is unconfined, perennial springs are semi-confined or even artesian as a result of the "pipe network" in the fractured-rock system. Truly confined conditions are very local, associated with substantial depths near major faults. Faults provide pathways for deep ground water flow paths to come to the surface. Faults also provide preferential pathways for horizontal water flow near to or below the water table. Faults are often associated with travertine-depositing springs and streams (Herman and Hubbard, 1990). Thus, development of subsurface flow paths through enhanced bedrock solution may extend to great depths (>300 m).

Under wet weather conditions, recharge causes a piston-flow response at certain closed depressions which begin to flow as overflow springs. Locations of these overflow springs are also related to structural features, primarily along faults and within zones of localized intense folding and extensional fracturing. Although relatively uncommon, such features require consideration for they provide windows into the intersection between the epiphreatic and phreatic ground-water flow systems. Areas where the ground-water levels rise and fall are particularly susceptible to sinkhole cover collapse (e.g., Panno and others, 1994).

WELLS

In the northern Great Valley drilled wells have reportedly intersected productive water-bearing cavernous zones in the carbonate bedrock to depths over 400 meters below land surface, and seasonal water-level fluctuations of over 10 meters have been measured in wells with water-bearing zones found at depths greater than 100 meters (Cady, 1936). The water table is especially discontinuous in the Great Valley region, and areas of highly productive wells are associated with thrust faults and cross faults. McCoy and Kozar (2007) documented upward-convergent components of subsurface flow in wells where joints were perpendicular or oblique to the strike of bedding. This observation is similar to that of springs being located where cross-strike faults and lineaments intersect faults oriented roughly parallel to the strike of bedding.

Kozar and others (2007) demonstrated such relations in a comprehensive study of the Leetown area of West Virginia for which audio-magnetotelluric geophysical exploration enabled imaging of discrete low resistivity zones to depths greater than 30 m along faults. Such zones were spatially restricted, and interpreted to represent areas of water rising under artesian head in certain instances where shales and carbonates were brought into contact along thrust faults cut by cross faults (Kozar and others, 2007).

CAVES

In the northern Great Valley, caves are commonly short, discontinuous passages with in-fillings of fine silt and clay that block passage exploration (Hubbard, 1983). Many caves exhibit bedrock structural controls that have guided passage development, especially joints, bedding plane partings, and folds (Bretz, 1942; Orndorff and Harlow, 2002; Hack and Durloo, 1977). Cave morphologies indicate that rising water influenced cavern development of the largest and most extensive caves of the region. Cave entrances often exhibit rising ceiling channels and cupolas indicative of former phreatic flow, and lowermost access is blocked by thick accumulations of clay-rich sediments (Bretz, 1942).

Two caves in the study area provide insight into the character of subsurface voids. The first is Detamore Cave (aka Boyle's Cave) located within the Elbrook Formation in the White Hall quadrangle. This cave is a single phreatically-formed tube that extends upward slightly greater than the dip of the bedrock (Fig. 2).

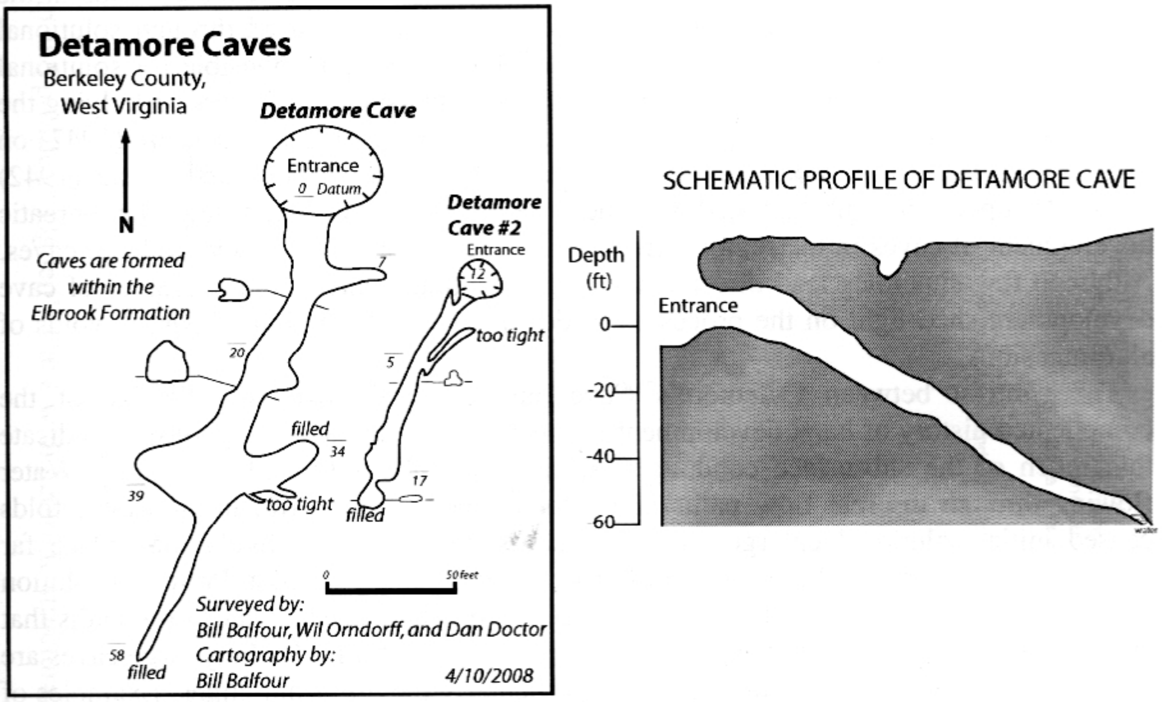

Figure 2. Map and schematic profile of Detamore Caves.

A second smaller nearby cave (Detamore Cave #2) may have been connected to the larger cave but this is unknown due to sediment fill. Intersection between a joint and bedding plane parting along the axis of an anticlinal fold evidently controlled the passage development. The cave entrance is approximately 8 meters wide and 2 meters high. The passage descends for approximately 100 m (20 m total vertical relief) at an angle of about 12 degrees, ending abruptly in rock breakdown and sediment. The passage floor is composed of large blocks of rock breakdown from ceiling collapse, as well as fine sand, silt and clay sediment. The water level rises several tens of meters within the passage after heavy rains.

The second cave is Ogden's Cave, formed within the Rockdale Run Formation of the Beekmantown Group, and located in close proximity to Cedar Creek in the Middletown quadrangle. The cave is formed within the western limb of the regional Buffalo Marsh Run syncline (Orndorff et al., 1999). The main passages are linear and are controlled primarily by bedding planes and by joints; however, zones of localized meter-scale folding also enhanced cavern development, particularly in the northeastern end of the cave (Fig 3). Ogden's Cave shows evidence of having been formerly fully saturated, with rising ceiling channels evident within the bedrock at the sinkhole entrance. Today, the cave is drained by an active stream which drains into Cedar Creek. The stream is currently excavating sediment that formerly filled the entire passage; remnants of fine silt and clay fill are observed on high ledges above the entrance passage. A number of large sinkholes are evident on the surface overlying the cave.

DISCUSSION

In karst terrains, sudden sinkhole collapse occurs due to the presence of voids in the subsurface, and springs emerge where groundwater flow is focused through solutional bedrock conduits. Therefore, an examination of the processes responsible for solutional cavern development within geologic context aids in understanding factors underlying the locations of sinkholes and springs. Classic papers by Davis (1930) and Bretz (1942) on origins of caves in limestone included studies of the Great Valley karst. Bretz (1942) expanded upon and substantiated the ideas of Davis (1930) regarding the phreatic development of caves in the region, emphasizing the morphology of several large caves. Although few sinkholes lead directly into large, exporable caves, the processes of cave development shed light on the processes of development of solutional bedrock voids of all dimensions.

The contrast between Detamore's Cave and Ogden's Cave is indicative of the complicated history of karst development in the region. Both cave morphologies indicate that much of the subsurface conduits formed under fully saturated conditions. Water flowing through discrete flow paths along faults and zones of fracturing within folds caused initial solutional enlargement of conduits. Such solution likely took place far below the water table in the distant (millions of years) geological past. Preferred solution within fold noses may result from coalescing of subsurface groundwater flow paths that move along fold limbs, possibly ponding within the nose of a fold. Many large caves are observed to form within the noses of folds, particularly the noses anticlines. Examples of commercial caves formed in noses of folds include Luray Caverns (Hack and Durloo, 1977), Crystal Caverns (Orndorff and Harlow, 2002), and Grand Caverns. Near entrenched surface streams, the water table is lowered to base level. In these areas, focused infiltration of surface runoff and ground water discharge to surface streams along steep gradients has resulted in excavation of caves formerly filled with sediment.

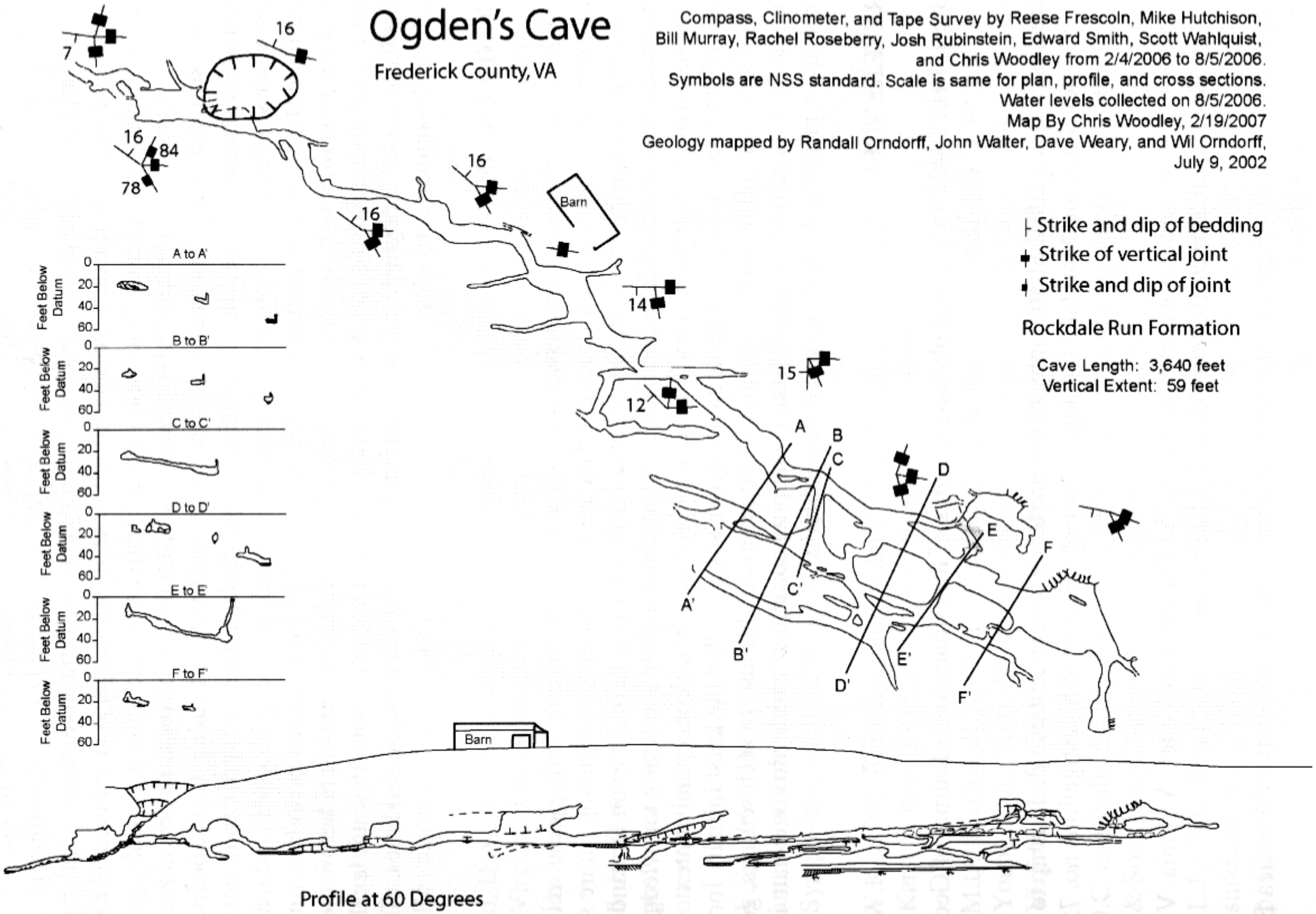

Figure 3. Map and profile of Ogden's Cave with geologic structural data.

The prevalence of phreatically developed caves, overflow springs in closed depressions, a lack of sinking streams, and sediment-filled depressions as opposed to open-throated sinkholes indicates a karst that likely developed far below the water table early in its geomorphic history. Subsequent lowering of the land surface through erosion has effectively exposed the fossil circulation system to surface weathering and capture of surface runoff, and an extensive unconfined flow system has also developed as a result of near-surface karstification. Thickness of regolith in carbonate units is typically greater than 10 meters, and the water table generally occurs below the regolith-bedrock contact. Areas stripped of regolith in quarries reveal a well-developed epikarst, with bedrock pinnacles several meters tall. Although drainage through the regolith is rapid, potential for water storage within conduits in the upper bedrock zone may be great, and may facilitate storage of contaminants spilled at the surface for extended periods of time due to absorption onto sediments and ponding within bedrock conduits at or below the water table. Subsurface movement of sediment in response to fluctuations in water levels results in closed topographic depressions and surface cover collapse sinkholes, often induced by human activities.

CONCLUSION

Given the correspondence between geologic structures such as faults, joints and folds, geologic maps showing such structural data are useful tools for predicting future sinkhole occurrence (see paper by K. Z. Doctor et al., this volume). In order to understand the processes that cause sinkhole occurrence in any karst region, a working knowledge of the regional geomorphologic history is needed to provide a basic conceptual context. In the case of the Great Valley, the geologic evidence suggests that the karst initially formed by rising aggressive fluid under confined (hypogenic) conditions. In such settings, geologic structural information obtained through mapping combined with hydrologic data is crucial for predicting future sinkhole susceptibility.

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