GEOMORPHIC AND HYDROGEOLOGIC EVOLUTION OF KARST IN THE BURNSVILLE COVE, VIRGINIA, USA: NEW EVIDENCE AND PERSPECTIVES

BENJAMIN F. SCHWARTZ[1] and DANIEL H. DOCTOR[2]
[1]Department of Biology, Texas State University, San Marcos, TX 78666, USA
[2]U.S. Geological Survey, 12201 Sunrise Valley Dr., MS 926A, Reston, VA, USA

The Burnsville Cove in Bath County, Virginia, hosts an extensive karst system (>100 km of mapped passages) developed under a complex synclinal valley in the Silurian-Devonian Keyser Limestone of the Helderberg Group. Observable patterns of cave development are the result of hydrogeologic controls on paleo-conduit formation, landscape evolution, and several episodes of conduit modification as the subterranean drainage system adjusted to changes in surface drainage and morphology. Currently, most of the mapped caves contain vadose free-surface streams that drain north-northeast toward the Bullpasture River, which flows south into the James River. However, many passages are dominated by solutional and sedimentary features indicative of former phreatic conditions and substantially different paleo-drainage characteristics. Widespread evidence of deep phreatic development under low-velocity conditions exists throughout the Burnsville Cove in cave passages between 0 and >230 m above modern spring elevations. Mineralogical and geological evidence of hydrothermal fluid migration and volcanism in the area has recently been recognized and may have contributed to the formation of proto-conduits which influenced early stages of karstification.

Observations of surface topography and cave passage morphologies indicate at least two stages of phreatic passage development in the Burnsville Cove. The first was low-velocity deep circulation and dissolution that predates all modern landscape controls and karst drainage features. Prior to the development of the current surface drainage pattern, groundwater (and surface water) may have flowed to the south toward what is now Dry Run Gorge. This early stage of development was likely disrupted by the incision of the Bullpasture River Gorge, which pirated the river to the east near what is now Williamsville. After the initial piracy and lowering of the water table, the second stage of phreatic development was related to a stable period during incision of the Bullpasture River Gorge. Incision redirected drainage toward a paleo-spring in the incipient Bullpasture River Gorge and initiated development of a large, nearly horizontal phreatic trunk. Most recently, renewed and rapid incision of the Gorge lowered the water table again, rearranging drainage patterns and dissecting what may originally have been one larger drainage basin into the four smaller basins which exist today.

1. Introduction and Background

The Burnsville Cove is located in Bath County, Virginia (Fig. 1). This region is in the center of the Appalachian Mountains, which are part of the Valley and Ridge physiographic province. Speleology in the Burnsville Cove has a long history of integrated exploration and scientific observation, particularly from the early 1950s through 1970s. In 1982, the Burnsville Cove Symposium volume of the NSS Bulletin (Davis et al. 1982) was published and represented, at that time, the current state of understanding with respect to several areas of scientific investigation in the Butler-Sinking Creek Cave System and the Burnsville Cove (the Cove). Since then, tremendous advances have been made in the Cove, primarily with respect to exploration. In some ways, scientific examination and interpretation of the more recently discovered caves has lagged behind exploration because of their difficult nature and resulting inaccessibility to most people (Clemmer 1988a; Clemmer 1988b; Clemmer 1992, 1993; Schwartz 1994-95, 1999; Shifflett 2003). In this paper we present a new model for the speleogenetic and geomorphic evolution of the Cove. It is based both on new evidence and re-interpretations of old observations. While this paper is not meant to be the final word on the evolution of this large and complex karst region, we believe that an abundance of new physical evidence requires new interpretation and explanation.

When the Burnsville Cove Symposium was published, the Butler Sinking Creek Cave system was the longest cave in Virginia at around 27 km in length. Breathing Cave was the only other major cave in the region and contained approximately 7 km of mapped passages. Since 1982,

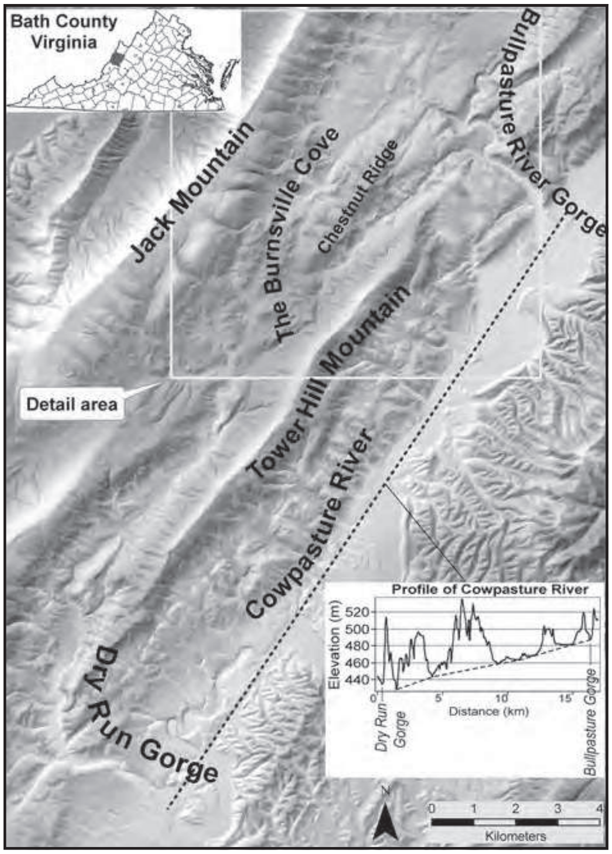

Figure 1: Map showing topography and major features in the study area. Box denotes area of detail in Figure 3.

many significant caves have been discovered including the Chestnut Ridge Cave System (>33 km and composed of Bobcat (Chestnut ridge Blowing), Blarney Stone, and Burns Chestnut Ridge Caves), Barberry Cave (>6 km), Helictite Cave (>12 km), and many other caves between 0.5 and 3 km in length. Not only have there been many new discoveries since 1982, but most of these discoveries have been under the flanks and nose of the Chestnut Ridge Anticline; an area where no significant caves were known prior to the early 1980s.

2. Hydrogeologic Setting

The Burnsville Cove is formed in a large northeasterly plunging synclinal structure which is complicated by the smaller Chestnut Ridge anticline in its center. This anticline also plunges gently to the northeast and divides the region into three structural regions. From northwest to southeast they are the adjacent Sinking Creek syncline, Chestnut Ridge anticline and White Oak Draft syncline. These three structural features are the dominant hydrogeologic controls on the modern karst system. Many other structural features both large and small (faults and folds at a variety of scales) have significantly influenced karst development in the area.

The majority of caves in the Cove are formed in the middle unit of the ~100-m-thick Devonian-age limestone of the Keyser Formation, which is locally divided by at least two thin and probably discontinuous sandstones (Fig. 2). One exception to this is in the northeastern nose of Chestnut Ridge, where most of the known caves are formed in the upper portion of the Helderberg Group.

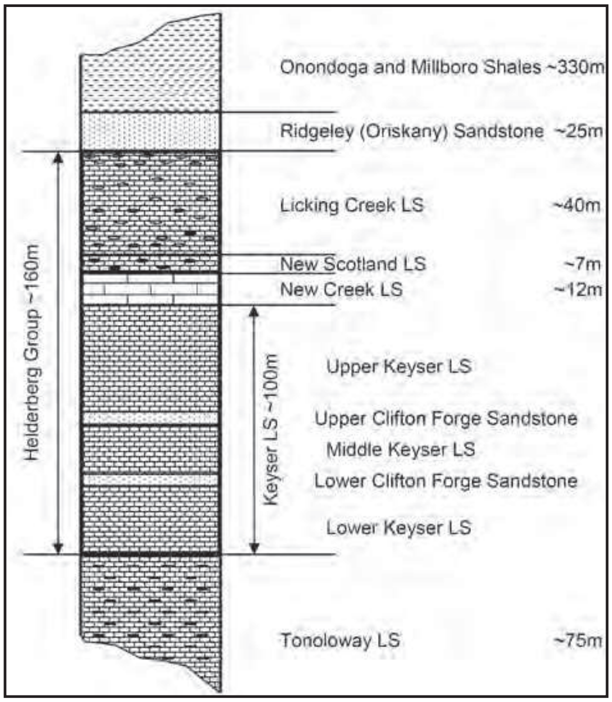

Figure 2: Stratigraphic section of the Helderberg Group. Modified from Davis et al. (1982).

The Chestnut Ridge Cave System (CRCS) is formed around the nose and on the northwestern and southeastern flanks of the northeasterly plunging anticlinal Chestnut Ridge. The ridge lies between the Sinking Creek syncline (containing the Butler-Sinking Creek System) and the White Oak Draft syncline (containing much of the Cathedral drainage and a portion of CRCS) (Fig. 3). The hydrogeology of the Burnsville Cove is dominated by the structural geology: primarily the Sinking Creek syncline and the Chestnut Ridge anticline. Four adjacent karstic drainage basins carry water generally towards the east and northeast toward the local base level defined by the Bullpasture River. Springs along the Bullpasture River associated with these basins, from the farthest upstream to the farthest downstream, are: Emory Spring, Aqua Spring, Cathedral Spring and Blue Spring (Fig. 3). Numerous dye traces in the past 40 years have defined the drainage divides between each of these basins (Davis et al. 1982). These traces and other hydrologic evidence indicate that residence times for conduit flow in Aqua Spring and Cathedral Spring basins are relatively

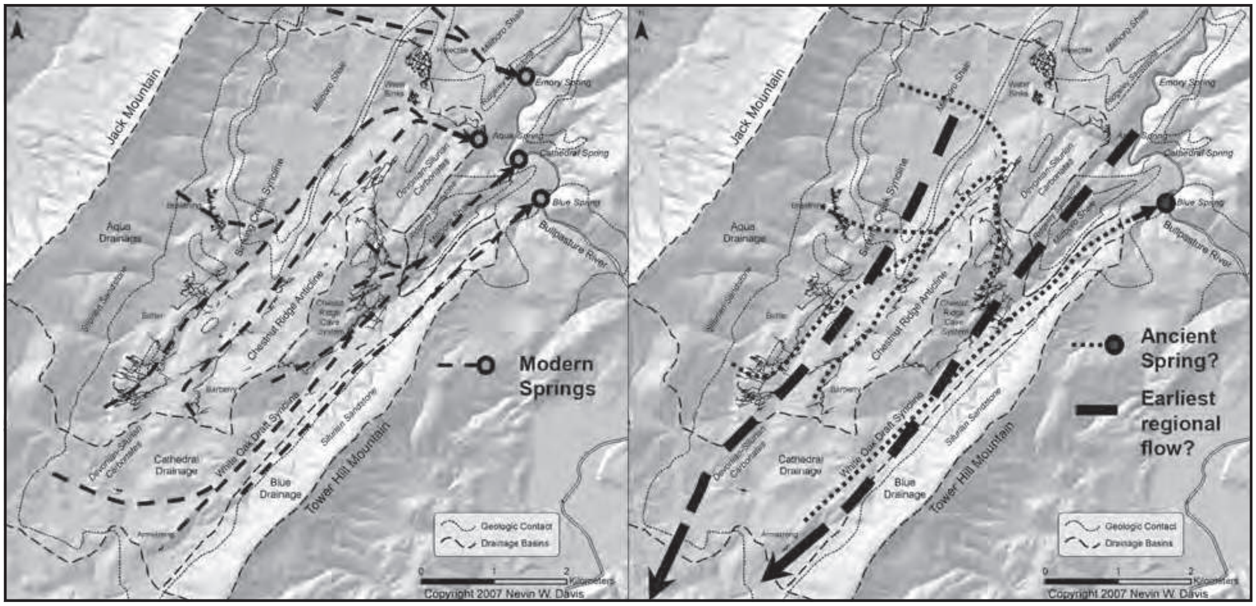

Figure 3: Shaded relief detail map of the Burnsville Cove showing major caves, modern drainage basins, geologic contacts, modern springs and flowpaths (left), and hypothesized ancient spring and earliest regional flowpath (right).

short (usually less than 2 weeks) while Emory Spring and possibly Blue Spring have somewhat longer residence times due to larger phreatic conduit volumes. With the possible exception of Blue Spring, all these springs discharge from strata in the upper one-third of the ~160m thick Helderberg Group.

3. Old Ideas and Problems

3.1. Paleo-flow direction prior to most recent incision of the Bullpasture River

Some of the most prominent karst features in the Cove are the four major springs which collectively drain the karst and discharge at or near river level in the Bullpasture River Gorge. Surveyed cave passages containing active streams all drain towards these springs and carry water generally from the southwest to the northeast. However, there are several pieces of evidence which indicate that a similar drainage arrangement in the past is unlikely.

First, the elevation of a regionally extensive abandoned phreatic trunk passage in CRCS is inconsistent with its current position within the hydrogeologic setting of the Cove. For such large-scale phreatic development to have occurred in Chestnut Ridge, the water table must have been at least as high as the uppermost portions of this passage: currently ~120 m higher than both the sumps in the cave system and the corresponding spring elevations. Therefore, the regional base level was at least 120m higher than at present, which means that the Bullpasture River's channel was also ~120 m higher. If this were the case, what is now the Bullpasture River Gorge would have been largely or entirely covered by substantial amounts of Ridgeley Sandstone (~25 m) and impermeable Millboro Shale (~330 m).

In a similar geologic setting, a breccia body associated with volcanic rocks near Monterey, Virginia, in Highland County, contains chips of the now-eroded overlying Millboro shale. This has been interpreted to represent a history of at least 330 m of erosion since Eocene volcanism (Tso and Surber 2006). Although erosion rates remain unconstrained in the Burnsville Cove, such a cap of siliciclastic rocks would have prevented the formation of large springs in locations similar to the modern Emory, Aqua and Cathedral Springs. It would not, however, have prevented deep circulation and dissolution from occurring. With no outlet available near the location of modern springs, water would have been forced to find the most hydraulically efficient discharge point. There is no concrete evidence indicating exactly where the paleo spring may have been, but there is evidence in CRCS which indicates that the most probable location is in the vicinity of Blue Spring. Blue Spring currently drains a long narrow strip of steeply dipping limestone which is bounded on the southeast by the Silurian siliciclastics which form Tower Hill Mountain. This strip of nearly vertical carbonates may have been the only outcrop exposed in the early Bullpasture River channel and may also have been the most efficient discharge point. In CRCS, a large horizontal trunk passage has been explored to a sediment fill just east of the axis of the White

Oak Draft Syncline (Fig. 3). This trunk passage extends for approximately 3 km along strike from the nose of Chestnut Ridge to White Oak Draft where further exploration has been stopped by a sediment plug. It seems probable that this passage curves to the north beyond this obstacle and continues along the strike toward a paleo-resurgence near the modern Blue Spring (Fig. 3).

Unfortunately, scallops indicating the paleo-flow direction have not been found in the large phreatic horizontal trunk passage in CRCS. This is probably due to the combined effect of two factors: extremely low flow velocities and highly deformed and thin-bedded limestone interbedded with sub-mm to mm-scale shale beds. The first definitive evidence of a flow direction was recently discovered in an area of CRCS known as Leprechaun Forest. Here, the large trunk passage diminishes in size to a crawlway for ~30 m, likely owing to sediment fill in a descending loop in the passage. On the southeastern side of this restriction, a large mound of sediment was identified as a deposit caused by flow and transport from generally north to south, which is away from the modern springs. As water moves through a restriction it is able to transport sediment. When the passage volume increases and flow velocities decrease, this sediment load drops out (Fig. 4). The morphology of the sediment pile and a small excavation in the side of it confirmed the direction of flow.

Figure 4: The sediment pile in CRCS which provided the first evidence of paleo flow to the southeast in the abandoned phreatic trunk passage. Flow was from left to right in the picture. Photo by: Benjamin Schwartz.

3.2. Questions about the earliest phreatic development

One of the most interesting characteristics of Breathing Cave and much of the upstream portion of Butler Cave is that many of the passages clearly formed under phreatic conditions, perhaps even with ascending water. Such a phreatic hypothesis was previously put forth for Breathing Cave (Deike 1960). Upper wall and ceiling morphologies in both caves preserve records of phreatic conditions with very low velocities. From the evidence in Butler Cave, we know that these passages are at least 230 m higher than current spring elevations. Upper-level passages in Butler Cave show a strong dependence on geologic structure for their development, both along strike-oriented bedding planes and folds, and along dip-oriented joints. The lack of horizontal levels of passages that cut across the structural planes of weakness provides no indication that these passages were formed near the water table. In fact, passages formed along joints that parallel the dip on the western flank of the syncline exhibit morphologies that indicate water once flowed upward against the dip (Fig. 5).

Figure 5: A set of rising cupolas in Butler Cave. These features formed along a dip-oriented joint in the Daves Gallery passage and indicate phreatic flow upwards along the dip. Boulder chockstone is approximately 0.5m in width. Photo by: Dan Doctor.

This is a distinctly different setting from the one that currently exists, which is an extensive network of abandoned dry passages with a few active vadose infeeder passages carrying water down toward the axis of the Sinking Creek Syncline. In Butler Cave, a large trunk passage roughly follows the axis of the syncline. Water flows to the northeast in this trunk, alternately following the trunk passage and disappearing into inaccessible parallel passages below and to the southeast of the main trunk. Ultimately, all streams sump at the northeastern terminus of the explored cave. A small stream in Breathing Cave also sumps as it drains towards the axis of the syncline. Both Breathing and Butler caves contain abundant evidence of more recent modification by vadose action, including directional scallops and erosional features at floor level. Many passages that were once completely filled with clastic material derived from Jack Mountain have been and continue to be re-excavated by vadose stream action.

In addition to evidence for early deep-phreatic flow and passage development, other geologic evidence in the region indicates that hydrothermal fluid migration affected the rocks that host caves in Burnsville Cove. Numerous Eocene igneous intrusions occur in northern Highland County, about 20 km north of the Burnsville Cove (Tso et al. 2004). Breccia bodies associated with some of these volcanic intrusions are interpreted as having formed via a mechanism of hydrovolcanic diatreme emplacement in which dikes propagated upward along joints, encounter groundwater, and explosively form diatremes (Tso and Surber 2006).

Recently, an igneous intrusion was found in a cave in southern Bullpasture Mountain (Schwartz 2003). This is a considerable southern extension to the known range of igneous intrusions in Highland County, and places confirmed igneous activity within 13km of Butler Cave. Additionally, a lithium-bearing manganese oxide mineral [Lithiophorite (Al, Li)Mn4+O2(OH2)] has recently been identified in Butler Cave (Schwartz et al. 2008). This mineral is most commonly associated with hydrothermal deposits. Herkimer Diamonds and milky quartz veins are also associated with hydrothermal fluid migration and are abundant in the highly deformed Keyser Limestone. The link between karstification and the hydrothermal activity that affected the carbonate rocks is as yet unclear.

If extensive networks of passages that are now >230 m above base level were clearly developed under phreatic conditions, then this is evidence of a karst system which developed under conditions which were much different than those we observe today. This idea was put forth earlier by Deike (1960) regarding the development of Breathing Cave. Since that time, several pieces of new evidence support this hypothesis of deep-phreatic flow. The first is that explored conduits in Aqua and Cathedral Springs rise from depths of at least 85m and 50m, respectively (Simmons 1991; Simmons 2000). In both cases, the conduits continue and exploration was halted due to diving logistics. The second piece of evidence is from a karst system which lies adjacent to and north of the Emory Spring drainage. Here, the Chestnut Ridge anticline plunges to the north and probably flattens out into the much larger Bullpasture Valley syncline. This syncline exposes the Helderberg Group carbonates on the flanks of Jack Mountain to the west and Bullpasture Mountain to the east. The Bullpasture Valley is floored with the stratigraphically higher Millboro Shale. Dye tracing from high on the flank of Jack Mountain revealed that water sinking there flows under the Bullpasture Valley, rises at a large karst spring on the eastern flank of the valley before flowing back to the west and into the Bullpasture River (Davis 1991). A third piece of evidence is discharge observations at Emory Spring, which has no explored cave passages associated with it. Emory Spring responds differently than Aqua and Cathedral Springs to flood events. Although discharge increases significantly after a rain event, large volumes of clear water discharge before muddy water arrives at the spring. In contrast, Aqua and Cathedral Spring begin discharging muddy water much more rapidly. Combined, these pieces of evidence tell us that not only is it probable that deep-phreatic development occurred in the region, but that these conditions still exist.

Based on geomorphic patterns (Fig. 1) and evidence found in the caves, we believe that the system may have originally drained towards an outlet farther to the south near Dry Run. Deike (1960) noted that, “Breathing Cave, as explored, does tend to parallel the local strike southward, and this may reflect a tendency for the water to go around the structures, parallel to the strike and hence to the structure contours, rather than directly beneath the anticlines and synclines.” Currently, the southern end of the Burnsville Cove karst system is bounded by the erosive exposure of underlying sandstones that prevent karst development. However, this exposure creates a relatively narrow divide between two karst systems: the Burnsville Cove and the Dry Run karst system to the south. Dry Run, as its name implies, is dry for most of the year downstream from where the streambed encounters carbonates. Below this point, a deeply incised gorge carries floodwaters to the Cowpasture River while the karst system discharges from one or more springs to the west of the Cowpasture River. While we are still in the initial stages of investigation, a basin-size vs. gorge depth analysis suggests that the Dry Run Gorge is oversized and over-incised for its current size. The Dry Run basin drains ~80 km^2 through its gorge while the Bullpasture River basin drains ~340 km^2 through its gorge. In essence, the Dry Run basin contains <25% of the drainage area in the Bullpasture River basin, yet it has a developed a gorge of similar dimensions and in a similar geologic setting. Both topographic features and an elevation profile along the Cowpasture River valley (Fig. 3) show that the Cowpasture River has a steeper channel gradient and is incising a gorge near its confluence with Dry Run Gorge. While this is still speculative, it may indicate that this portion of the Cowpasture River has experienced a relatively recent increase in erosion – perhaps because of an increase in erosive power after capturing the Bullpasture River.

4. Conclusions

We hypothesize that ancient drainage of both the early karst system and the Bullpasture River was toward the southwest where the nearly abandoned Dry Run Gorge intersects the Cowpasture River ~17 km SW of the Burnsville Cove. During the time of maximum cave enlargement, widespread deep-phreatic development occurred along structural features, and possibly along preexisting hydrothermally-formed proto-conduits, under low-velocity conditions. Mineralogical and geological evidence of hydrothermal fluid migration and volcanism in the area has recently been recognized and deep (>100 m) phreatic pathways still exist in the northern portion of the Cove's drainage, as well as farther to the north in the Bullpasture River Valley where water sinks high on the western flank of the valley and follows deep flow paths to discharge at a spring on the east side of the valley. Incision of the Bullpasture River Gorge, which continues today, significantly rearranged regional surface and subsurface drainage. As the gorge incised, it created new and more efficient discharge points along the ancestral Bullpasture Gorge, which drained phreatic passage networks and induced free-surface stream flow and sediment transport in many of the caves. There may have been an extended period of relative stability in the Cove during which time a large phreatic trunk passage formed along strike around the Chestnut Ridge anticline. Drainage rearranged again as the gorge probably experienced a second episode of rapid incision. This second period of incision may have been related to either climate variability or the erosive removal of geologic controls (i.e., resistant sandstone beds in the river channel). Much of the karst system as it exists today is in a state of disequilibrium as streams in the cave modify and/or abandon earlier passages in favor of newer vadose flow paths.

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