

EXAMINATION OF THE RELATIONSHIP BETWEEN LONGITUDINAL PROFILE AND
SEDIMENT MOBILITY WITHIN A FLUVIOKARST
STREAM SYSTEM

John Woodside

70 Pages

December 2008

This study examines the relationship between the longitudinal profile, stream channel morphology and sediment characteristics within a fluviokarst stream system in Kentucky.

APPROVED:

Date Eric W Peterson, Chair

Date Toby Dogwiler

Date David Malone

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The complex drainage systems within karst settings can result in atypical longitudinal profiles. Features, such as cave entrances, can be expressed as anomalous 'bumps' in the longitudinal profile of a stream if down-cutting has continued behind the area in which the water is pirated to the subsurface. Horn Hollow, a fluviokarst valley located in Carter Caves State Park Resort in northeastern Kentucky, was examined for these types of features. The objectives of this study were to determine if a detailed longitudinal profile will reveal anomalous segments along the course of a stream and if sediment mobility can be used as a proxy for these anomalous segments. Additionally, geomorphic observations of the valley characteristics will be used to help differentiate areas of cave collapse from natural down-cutting within the fluviokarst system. The hypothesis is that anomalous areas along the longitudinal profile will correspond to differences in sediment movement potential and that the anomalous sections will have noticeably different sediment sizes and morphological characteristics. To accomplish these

objectives, the longitudinal profile of Horn Hollow Creek and 22 cross-sections of the stream were surveyed. Armor point counts were performed at each cross-section, unless the section was predominantly bedrock. Geomorphic observations of the valley shape and channel characteristics were made along the course of Horn Hollow Creek. Although Horn Hollow's waters have been predominantly pirated to the subsurface, the longitudinal profile of the system has the general appearance of a stream near equilibrium. Anomalous concave-down segments, some more apparent than others, were identified in multiple locations along the profile. The progression of sediment size along the length of the profile is in agreement with conventional thought, with the exception of sediments downstream of cave passages. Many of these exceptions coincide with identified concave-down segments. The analysis indicates that sediment mobility data and a detailed longitudinal survey can be used to identify anomalous segments, or karst features, within a stream's profile which may not be readily apparent in the field. The geomorphic observations of the valley characteristics were of great use in differentiating between cave collapse and natural downcutting, especially in the anomalous segments of the profile.

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JOHN WOODSIDE

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Fulfillment of the Requirements
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CHAPTER I
INTRODUCTION

Introduction

Karst terrains are characterized by closed depressions, subsurface drainage, and caves, which are formed by the chemical dissolution of host rock limestone or other soluble rocks (Ford and Williams, 1989; Palmer, 1991; Gillieson, 1996). Approximately 10-20% of Earth's land area is occupied by karst landscapes (Palmer, 1991; Gillieson, 1996). The degree of karst development varies from one region to another as a result of climatic conditions and relief. The land surface may exhibit gently rolling soil covered plains with slight depressions or it may include deep depressions, isolated towers, and pointed hills (White, 1988).

Although dissolution of the host rock is not always the most prevalent process in a karst region, dissolution plays a more significant role in the development of this landscape than in others (Jennings, 1985). Historically, the quantitative studies of cave and karst geomorphology with respect to dissolutional processes have received the most focus. However, some studies have shown that physical erosional processes may also play a significant role in the formation of karst systems (Aley, 1965; Sanders, 1981; Palmer, 1991; Bosch and White, 2004; Dogwiler and Wicks, 2004).

The formation of karst in suitable rock types requires the movement of water, which can be provided by meteoric or deep-seated sources, with the local relief being the driving force for the water movement (Jennings, 1985). Over time, water draining the basin may transition from a surface dominated

drainage to a subsurface dominated drainage. As a result, rather than having a highly ordered geometry from small streams in the headlands down to major rivers like non-karst drainage basins, karst drainage basins contain tributary streams that may end abruptly in swallets, and high-order streams that emerge abruptly at karst springs (Leopold et al., 1964; White, 1988).

The resulting drainage can include waters from both inside (autogenic) and outside (allogenic) of the physical catchment limits. More specifically, as stated by Ford and Williams (2007), “an autogenic system is one composed entirely of karst rocks and derives its water from that precipitated on them. By contrast, a purely allogenic system derives its water entirely from that running off a neighboring non-karst catchment area.” Autogenic and allogenic systems are end-members; thus, an intermediate mixed system is dominant in practice. An allogenic system can allow a much greater input of water and sediment into a karst drainage system, creating greater potential for chemical and mechanical erosion (Ford and Williams, 2007). A system dominated by allogenic recharge and with a well-developed conduit system has a flashy response to storms, whereas the response of an aquifer system with mostly diffuse flow, poorly developed conduits, and little allogenic recharge is much more subdued (White, 1988). Flashy drainage systems are generally more effective at clastic sediment transport (Bosch and White, 2004).

Karst drainage basins are dynamic; thus, cave development incorporates the entire karst drainage basin, not only the soluble rock. Various clastic sediments may be introduced to conduits over time and can be stored

temporarily or permanently (White and White, 1968; Jennings, 1985; White, 1988; Gillieson, 1996; Bosch and White, 2004). Sources of clastic load within the basin include: insoluble material or beds within the limestone, insoluble rock debris from clastic rocks overlying the allogenic underground drainage system, and organic materials (White and White, 1968).

The mobility of sediments has a significant impact on its role as an abrasive agent (Dogwiler and Wicks, 2004; Sklar and Dietrich, 2001; White and White, 1968). Past studies suggested that karst streams are armored with relatively immobile substrates (White and White, 1968). However, recent work in fluviokarst systems indicates that 50-85% of the stream substrates are capable of transport during bankfull discharge conditions (Dogwiler and Wicks, 2004). Within the Devils Ice Box of Boone County Missouri, a fluviokarst system investigated by Dogwiler and Wicks (2004), stream flows capable of entraining d_{50} and d_{85} particles occur at intervals of 2.4 and 11.7 months, respectively. The frequent partial impact and abrasion by bedload contributes to the loosening and removal of bedrock and creation of greater surface area on the sediment, increasing the rate of denudation by mechanical and chemical processes within the karst system (Whipple et al., 2000).

Understanding where and why rivers erode and deposit sediment is of fundamental importance to geomorphologists interested in landscape evolution. The development of a stream's longitudinal profile is a result of deposition and erosion within the channel, climate and lithology. Erosional processes are dominant in the upper reaches and depositional processes

dominate the lower reaches of a stream; thus, under normal conditions, the profile will be flattest near the mouth and steeper nearest its watershed divide (Leopold, 1964)(Figure I-1). In karst regions, streams can have similar profile characteristics as non-karst streams, but due to the nature of the rocks (i.e. carbonates), water and sediments may be diverted from the surface into the subsurface. By changing the pathways of erosional and depositional processes, the stream profile may be altered. A stream system in equilibrium, or a graded stream, has been defined by Mackin (1948) as a stream whose “diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change.” The controlling factors are discharge, load, and slope.

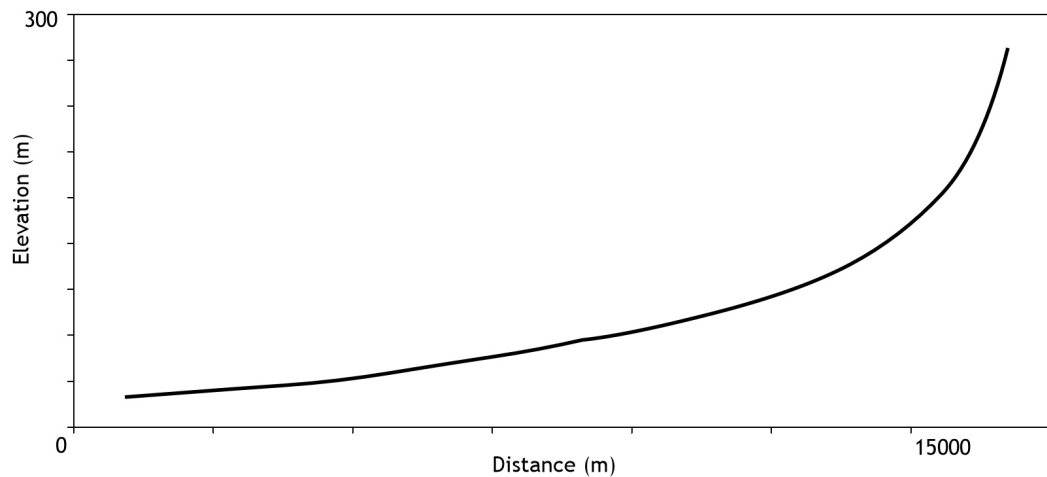


Figure I-1: Longitudinal profile near equilibrium in a non-karst setting.

In karst regions, a profile in equilibrium may contain a concave-downward segment as streambed piracy becomes more complete and better

integrated with the subsurface drainage system (Figure I-2). By rerouting water underground, the surface expression of the stream may not change in that particular reach. However, behind the water sink and at the water resurgence, sediments will continue to transport or deposit, causing the reaches upstream of the sink and downstream of the resurgence to continue their evolution. The concave-downward profile becomes more pronounced as surface stream erosion becomes less effective and shorter-lived during heavy rainfall events (George, 1989). Identification of concave-downward segments along the stream profile may allow for the interpretation of the position of shafts or other underground entrances within the stream channel. It is possible in karst regions that the longitudinal profile will not show concave-downward sections, suggesting a system closer to equilibrium (George, 1989).

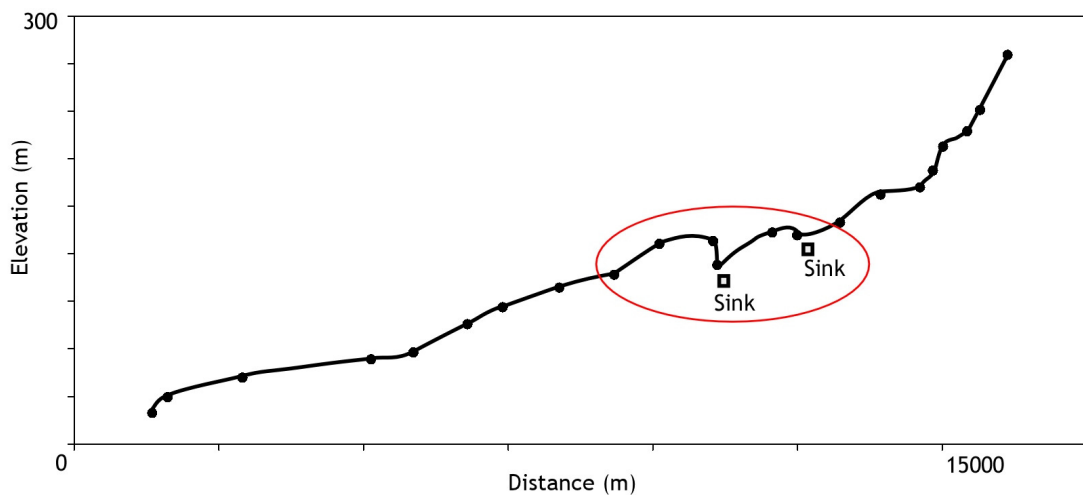


Figure I-2: General depiction of a longitudinal profile in a karst setting, displaying concave-down segments.

The objectives of this study were to (1) determine if a detailed longitudinal profile would reveal anomalous segments along the course of a stream and, (2) if sediment mobility can be used as a proxy for these anomalous segments. Additionally, geomorphic observations of the valley characteristics were used to help differentiate areas of cave collapse from natural down-cutting within the fluviokarst system. The hypothesis examines whether anomalous sections along the length of the profile will have different sediment sizes and cross-section characteristics from segments that do not bare an anomalous distinction. Based on classical stream power dynamics, sediment size is expected to decrease downstream. Quantitative and qualitative analysis of the relationship between the longitudinal profile, geomorphology, sediment characteristics, and known karst features along the course of the valley will elucidate the geomorphic history of Horn Hollow Valley.

Location and Physiographic Setting

Field work was conducted in the Horn Hollow karst system, at Carter Caves State Resort Park (CCSRP) in northeastern Kentucky (Figure I-3). The study area is located within the northwest-central portion of Carter County, Kentucky. Typical to the geologic region, Carter County has numerous deeply-incised valleys, with elevations ranging from 345 m at the highest point to about 100 m at the lowest point. Approximately one-quarter of Carter County

consists of karst landscapes and there are over 200 named pits and caves within a 40 km radius of CCSRP (McGrain, 1966; Summers and Hobbs, 1995).

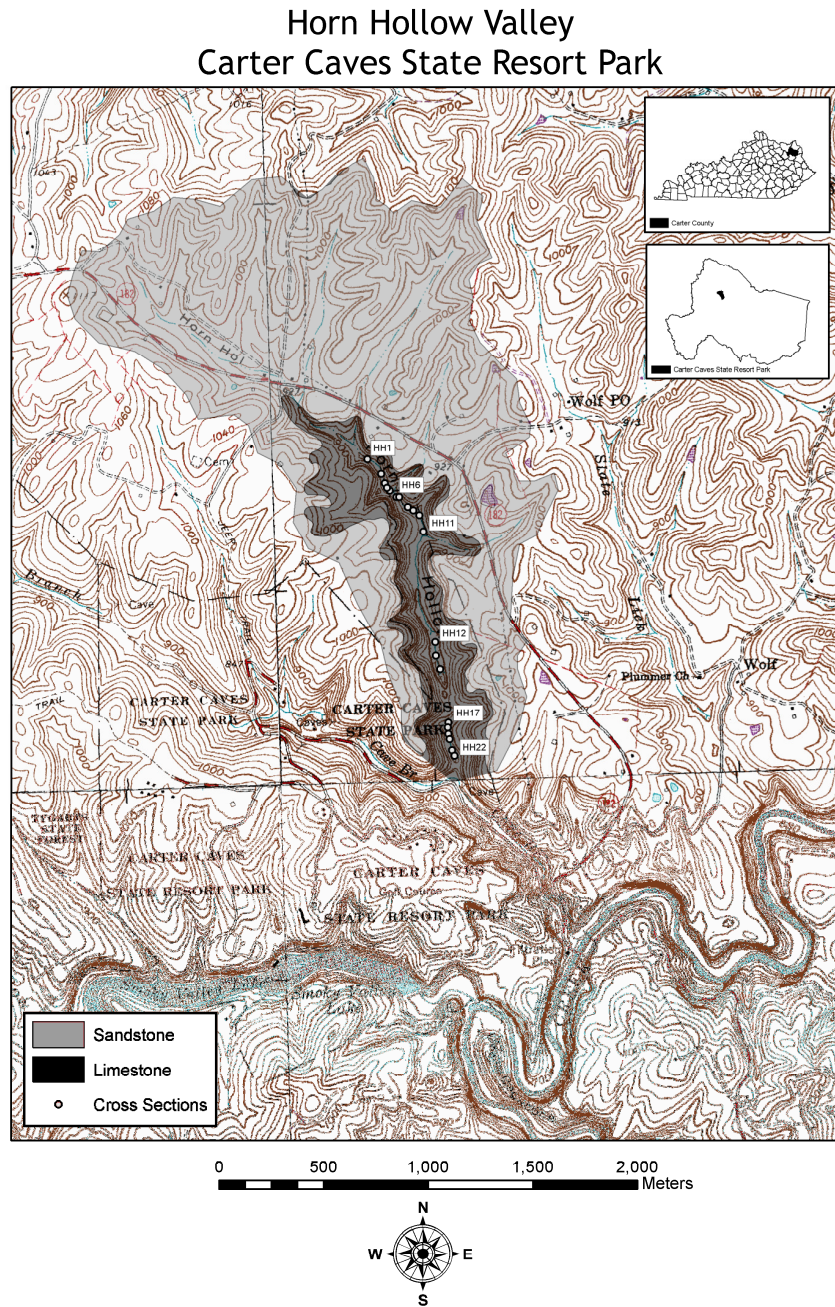


Figure I-3: Location and topography of Horn Hollow Valley at Carter Caves State Resort Park.

The Horn Hollow karst system is a fluvial karst system consisting of the surface and subsurface drainage system associated with Horn Hollow Creek (Dogwiler and Wicks, 2004). The system is located within Horn Hollow Valley, which is a hidden valley perched 14 meters above Cave Branch (CB), the main surface water stream within the park (McGrain, 1966). Horn Hollow Creek is routed through alternating surface reaches and sub-surface cave reaches several times as it moves down gradient through the system. In some areas within the valley, a dry surface channel overlies the cave stream. The presence of a defined dry channel indicates that the stream once dominated the surface and has since been rerouted to the underground. In other sections of the valley, no well-defined surface channel is present, which indicates that subsurface flow has been dominant in these reaches for extended periods of time. The known cave passages through which Horn Hollow Creek traverses through consist of Fudge Ripple, Boundary Cave, Cobble Cave, Horn Hollow Cave, New Cave, H2O spring, and during times of high flow, Laurel Cave as an overflow passage. Horn Hollow Creek is a tributary of CB. Lying 14 meters below Horn Hollow Creek, the base-level of CB serves as a base-level driving force for active downcutting within Horn Hollow Valley. Along its course through the park, CB disappears beneath the ground and reappears three times before it joins Tygarts Creek.

Tygart's Creek (TC) controls the base-level of CB, and is the major stream in the area. The creek meanders northeast through Carter and Greenup counties on its way to the Ohio River. Tygart's crosses 32 km of northeastern

Kentucky's limestone, and most of the substantial cave development in the region occurs within these limestones (Tierney, 1985). Tygart's Creek and its tributaries experienced periods of rapid downcutting during the early glacial events of the Pleistocene (Tierney, 1985).

The development of the Ohio River during the Plio-Pleistocene was of critical importance to the cave forming process in this region (Dougherty, 1985; Granger et. al, 2001; Anthony and Granger, 2004). Previous studies have linked the formation of multiple cave levels in this region to a prolonged period of Late Tertiary water table stability, and the development of levels to distinct episodes of Plio-Pleistocene river incision (Granger et. al, 2001; Anthony and Granger, 2004). These periods of rapid entrenchment and fluctuations in river flow lowered base level throughout major cave areas within Kentucky, resulting in an abundance of levels in Kentucky caves (Dougherty, 1985; Granger et. al, 2001; Anthony and Granger, 2004).

Lithostratigraphy

The Mississippian limestones exposed in this region have been identified as the same limestones found in similar stratigraphic position in other parts of the state. However, in northeastern Kentucky, the Mississippian and Pennsylvanian periods were times of transgression and regression of inland seas. Barrier islands of sand developed, only to be covered by transgressing seas. Limestone interface with sandstones to show the transitional energies

that were occurring at the time. In the region, the maximum thickness of good homogeneous limestone available for solution is 27 m (Tierney, 1985).

The early Mississippian (Osagian) Bordon Formation is the oldest unit exposed in the region, which is approximately 60 m thick (Figure I-4). The Bordon Formation consists of alternating layers of green and red silty shales with siltstone beds and forms an irregular contact, possibly representing an unconformity, with the overlying Newman Formations (Summers and Hobbs, 1995). The Newman limestone, also Mississippian in age, formed during the Mermec and Chester times. The formation can be as much as 60 m in thickness and is composed of three distinct units, which are (from oldest to youngest) the St. Louis Limestone (0 - 4.5 m), the Ste. Genevieve Limestone (18 - 34 m), and the Upper Member Limestone (4.5-24 m). The St. Louis Limestone is an impure limestone which is not readily dissolved, and serves as the bed for Cave Branch in lower reaches within the park. The Ste. Genevieve serves as the bed for Cave Branch further upstream. The Ste. Genevieve Limestone is a heavily cross-bedded limestone and serves as the primary cave forming unit within Horn Hollow Valley (Hobbs and Pender, 1985). The Upper Member Limestone is the uppermost member of the Newman Limestone Formation, serving as the host rock for other caves within CCSRP. Overlying the Upper Member Limestone is the unconformable Pennsylvanian Carter Caves Sandstone of the Pennington Formation. This sandstone unit occurs irregularly as it is associated with beach berm deposits. Precipitation falling on this unit runs off into the limestone, both into the stream channel and into pit caves along the valley,

which allows the Horn Hollow karst system to be classified as allogenic.

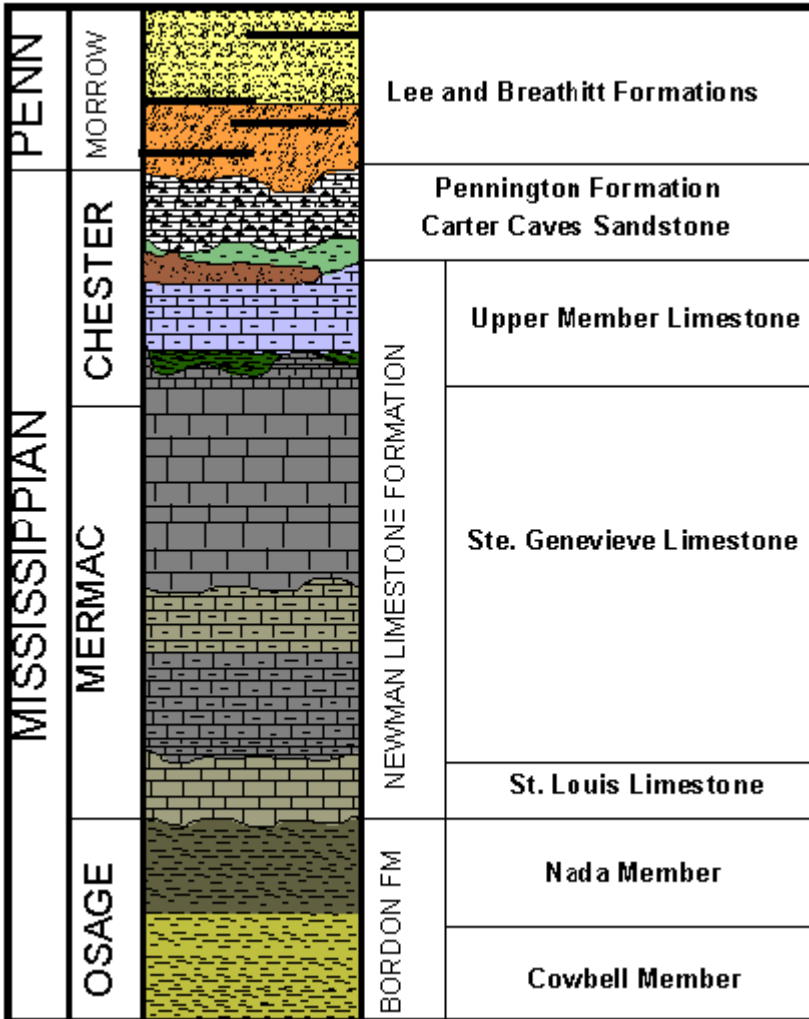


Figure I-4: Stratigraphic column of the region.

Structure

The region of Paleozoic strata is 0.3° to 2° to the east-southeast (McGrain, 1966). However, the bedding attitudes are generally difficult to determine in the field due to the extensive cross-bedding in most of the Ste. Genevieve Limestone exposures (Summers and Hobbs, 1995).

The Carter Caves area is extensively fractured and jointed, with a mean fracture orientation of 330° , or NW-SE, trending parallel to the regional dip direction (Summers and Hobbs, 1995). There are sub-dominant fracture sets as well, and the mean orientation of streams in the region trend parallel to this conjugate fracture direction at 40° . Cave passages have developed within lithologically similar units and caves show evidence of horizontal water movement along bedding planes. Caves have also developed along joints in the area, suggesting that the karst may have formed from structural and stratigraphic controlling mechanisms (Tierney, 1985; Summers and Hobbs, 1995).

CHAPTER II
METHODOLOGY

Field data were obtained in Horn Hollow Creek beginning near the contact between the Carter Caves Sandstone of the Pennington Formation and the Upper Member of the Newman Limestone to the upstream entrance of Laurel Cave (LC). Survey data were collected using a Trimble GeoExplorerXT, a Nikon Pulse Laser 333 Station (NPLS), and a Laser Atlanta Advantage C1 Laser Range Finder with Dual Encoding Tripod. Surveys along the thalweg of the stream channel were performed with the NPLS, with the exception of the cave stream channel through Horn Hollow Cave (HHC), which was surveyed using the LRF. In many cases, water was not present within the valley, so geomorphic indicators, such as sediment distribution and low points within the streambed, were used to approximate thalweg location. Along the course of the valley, the Trimble GeoExplorerXT was used to record the coordinates of the survey base stations and various karst features. Real time correction produced data with error on the scale of tens of centimeters on the x and y. The GPS coordinates were used to orient the survey data properly in space when the data were plotted graphically. In conjunction with the longitudinal profile, cross-sectional profiles were surveyed at locations where channel morphology and sediment distribution appeared to have unique characteristics setting it apart from upstream characteristics. Specifically, the observations used to choose cross-sectional locations included changes in channel morphology, distinct differences in sediment distribution of the bed material, and proximity to known karst features and tributaries. The cross-sectional profiles were

surveyed using either the NPLS or the LRF. Each cross-section was sketched and photographed for reference. Within this thesis, cross-sections will be referred to as HH# for brevity, with the # being replaced by the actual cross-section number (Figure III-1).

Along the course of Horn Hollow Creek, the stream water enters and exits a number of caves. One of the larger caves is HHC. HHC was surveyed using the LRF; a Suunto Tandem surveying compass and a measuring tape were also used as a backup and to ensure accuracy of the survey. The data were collected through HHC to tie in the uncovered portions of Horn Hollow Creek upstream and downstream of the cave.

At cross-sections where sediment was available, Wolman counts were performed in an area bracketed from 1 meter upstream of the cross-section to 1 meter downstream of the cross-section. Sediment was collected based on the procedures set forth by Wolman (1960). Each Wolman count consisted of 100 samples, with the exception of cross-section number one, because of the large amount of small particles at that location. The sediment was measured along the intermediate axis using an Albert Scientific Gravelometer.

The potential for sediment movement was examined using the critical shear stress (τ_c), which represents the tractive force at which particle erosion begins to occur and can mathematically be expressed as

$$\tau_c = \Theta_{ec} (\gamma_s - \gamma)d$$

where θ_{ec} is the critical dimensionless shear stress, γ_s is the weight density of sediment in N m^{-3} , γ is the weight density of water in N m^{-3} , and d is the particle diameter in m. Within the Horn Hollow karst system, because of the large amount of water necessary to cause flow along the stream surface, any amount of flow through the valley would be turbulent. With this in mind, the Shield's parameter for fully turbulent flows is equal to 0.044. As most common sediments have a weight density of $26,000 \text{ N m}^{-3}$ and water has a weight density of 9800 N m^{-3} , the τ_c equation may be rewritten as

$$\tau_c = 0.044(26,000 - 9800)d = 713d$$

resulting in units of N m^{-2} . Thus, τ_c is a function of particle size.

The sediment statistics gathered at the cross-sections were used to calculate critical shear stress values for the d_{50} and d_{85} particles. The d_{50} and d_{85} particle sizes were determined by creating cumulative frequency plots for each pebble-count and determining what grain-size coincided with the 50th and 85th percentile, respectively. The d_{50} was selected because it is a measure of half of the sediment load. The d_{85} was selected because it represents a threshold at which the armor destabilizes; if the armor is moved, the stream substrate becomes largely mobile, creating greater potential for mechanical erosion.

The sediment data were also used to compare the mean sediment size from one cross-section to another by using an independent samples t-test. The resulting p-values indicate whether or not one cross-section is statistically

different from another. The t-test used an alpha of 0.05 and equal variance was assumed in the calculation. For thoroughness, each cross-section was compared to one another (e.g. HH1 to HH2, HH1 to HH3, HH1 to HH4, and so on); however, the most important comparisons involved cross-sections immediately adjacent to one another (e.g. HH1 to HH2, HH8 to HH9, and so on). Naturally, if a cross-section consisted primarily of bedrock, no statistical comparison could be made.

CHAPTER III

RESULTS

Longitudinal Profile

The longitudinal profile of Horn Hollow Creek was surveyed during baseflow conditions (Figure III-1). The starting position for the stream survey was located in the northern portion of Horn Hollow Valley and was set as the 0 m location for both distance and elevation.

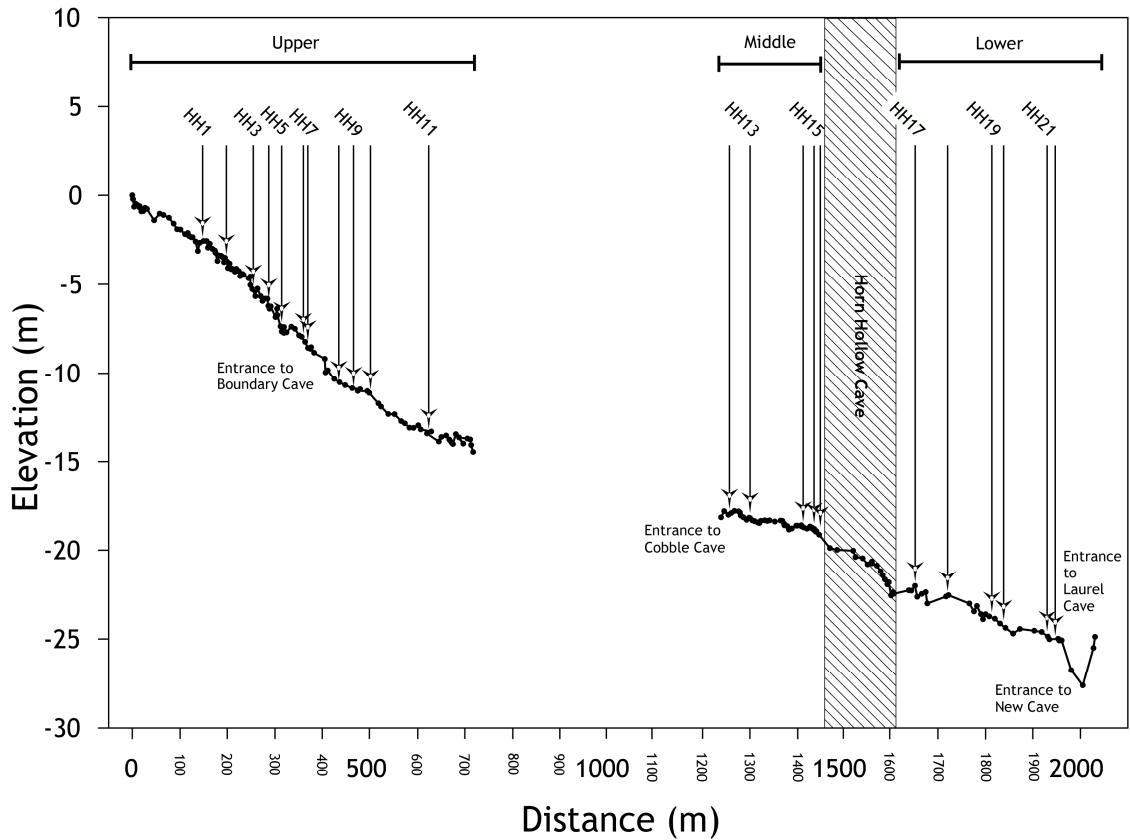


Figure III-1: The longitudinal profile of Horn Hollow Creek showing cross-section and cave locations.

Upper Segment

The upper segment (0 - 720 m) of surveyed data is dry along the surface during baseflow conditions. The gradient of the upper section is 0.02. Detailed cross-sections, sediment distributions and sediment statistics are located in Appendix A. With regards to sediment characteristics, the d_{50} and d_{85} grains generally decrease downstream along the profile, following a classical downstream progression (Figure III-2 and Table III-1). The majority of grains are angular to sub-angular.

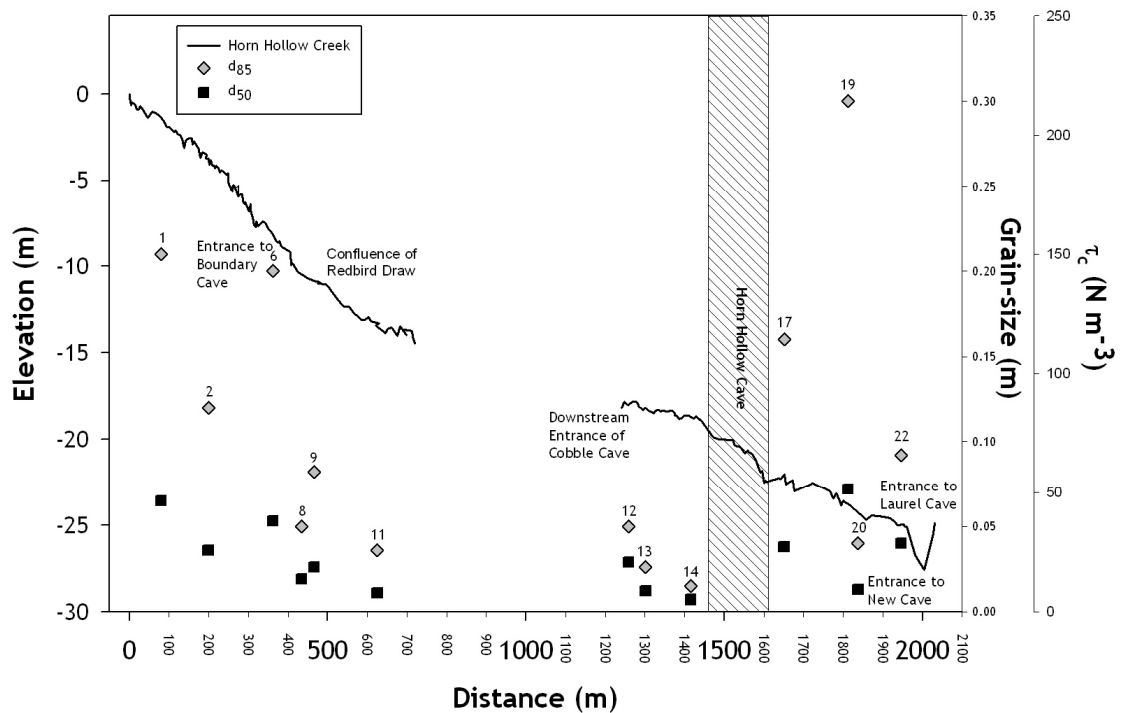


Figure III-2: The grain-size and critical shear stress values at cross-sections along Horn Hollow Creek. Since critical shear stress is a function of grain size, τ_{c50} and τ_{c85} plot directly on top of d_{50} and d_{85} , respectively.

Table III-1: Sediment statistics derived from Wolman pebble counts

Cross Section	Sample Size	Number of Samples representing bedrock	Mean (\pm Standard Deviation) (m)	d_{50} (m)	d_{85} (m)	τ_{c50} N/m ²	τ_{c85} N/m ²
1	65	0	0.117 (± 0.109)	0.065	0.21	46.35	149.73
2	98	2	0.080 (± 0.098)	0.036	0.12	25.67	85.56
3	NA*						
4	NA*						
5	NA*						
6	100	0	0.041 (± 0.067)	0.053	0.2	37.79	142.6
7	NA*						
8	100	0	0.107 (± 0.110)	0.019	0.05	13.55	35.65
9	100	0	0.055 (± 0.081)	0.026	0.082	18.54	58.47
10	NA*						
11	100	0	0.027 (± 0.050)	0.011	0.036	7.84	25.67
12	100	0	0.037 (± 0.019)	0.029	0.05	20.68	35.65
13	93	7	0.030 (± 0.061)	0.012	0.026	8.56	18.54
14	99	1	0.011 (± 0.009)	0.007	0.015	4.99	10.7
15	NA*						
16	NA*						
17	100	0	0.081 (± 0.102)	0.038	0.16	27.09	114.08
18	NA*						
19	100	0	0.143 (± 0.143)	0.072	0.3	51.34	213.9
20	100	0	0.037 (± 0.062)	0.013	0.04	9.27	28.52
21	NA*						
22	100	0	0.079 (± 0.095)	0.04	0.092	28.52	65.6

*NOTE: NA indicates that the bed was composed of bedrock

From cross-sections 1 (HH1) to 7 (HH7) (0 - 369 m), the valley consists primarily of heavily vegetated channels, lined by steep slopes with little to no apparent floodplain, and little sediment available within the channel.

Cross-section 1 (80 m) is approximately 4.5 m wide, is very heavily vegetated throughout the channel, has bedrock walls immediately adjacent to the channel, which are approximately 3 m in height and are followed by steep slopes to the valley's ridge. The sediments at HH1 are poorly sorted, ranging in size from 0.001 m to 0.362 m in diameter, with a d_{85} of 0.210 m.

The morphological characteristics of HH2 (199 m) are very similar to those present at HH1, with the exception of the grain-sizes. The grains at HH2 were skewed towards the upper end (larger) of the grain-size cumulative frequency plot, and the comparison of means between HH1 and HH2 indicates that the grain-sizes at the two locations are significantly different (See Appendix A 1 and Table III-2).

The channel at HH3 and HH4 (288 m) consisted of bare bedrock surface riddled with dissolved pathways. The main channel is approximately 5 m wide at HH3 and 4 m wide at HH4. The walls of the channel consist of rock, thin soil and vegetation. Since the main channel was entirely bedrock, no pebble count could be done. In fact, the entire section of the profile in which HH3 through HH5 is located consists of bare bedrock surfaces.

Bare bedrock comprised the channel at HH5 (313 m) as well. At this section, free-karren features were present within the main channel. The downstream left (DSL) rock exposure is approximately 0.5 meters thick and the

downstream right (DSR) rock exposure is approximately 3 m thick. Above the rock walls, soil and vegetation continue up the slope to the valley's ridge.

Table III-2: Significance of p-values generated by a comparison of means using independent samples t-test.*

Cross-Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
1		2				2		1	2		2	2	2	2			2		1	2			2
2						2		1	1		2	2	2	2			1		2	2			1
3																							
4																							
5																							
6									2	1		1	1	1	2			2		2	1		2
7																							
8									2		2	2	2	2				1		1	2		1
9											2	2	2	2				2		2	1		1
10																							
11												1	1	2				2		2	1		2
12													1	2				2		2	1		2
13														2				2		2	1		2
14																		2		2	2		2
15																							
16																							
17																				2	2		1
18																							
19																						1	2
20																							2
21																							
22																							

*Note: The p-values have been converted to either a '1' or a '2' to indicate whether or not the comparisons made between cross-sections were significant ($p < 0.05$). A '1' indicates a pair of cross-sections with a significant comparison. A '2' indicates a pair of cross-sections that are significantly different.

From HH3 through HH5, the valley has a v-shaped expression, indicative of rapid downcutting. Although these three particular cross-sections are bare bedrock, there is abundant sediment at HH6. The materials at HH6 do not appear to be remnants of cave collapse. Instead, it is likely they are derived from the exposed bedrock along the sides of the channel. Considering these morphological characteristics, this area is interpreted as one that has been naturally downcut.

While there are pit caves along the slopes in the upper area of the valley, Boundary Cave is the first identified karst feature located within the channel and marks the position of HH6 (362 m). Boundary Cave is a pit cave, whose entrance is approximately 1m above the base of the streambed on the DSR. The entrance requires a 3 m rappel into the main channel of the cave. Surface waters pirated into Boundary Cave are transported along a separate level. As opposed to the previous three cross-sections, abundant sediment is present at HH6. The more active portion of the surface channel (DSR) is approximately 2 m wide and consists of gravel and very little vegetation, and the less active portion of the channel (DSL) is approximately 3 m wide and has noticeably more vegetation within it. The presence of the pit cave does not mark the beginning or end of any apparent surface anomalies, but is located almost precisely in the middle of one (Figure III-3). Additionally, the d_{50} and d_{85} at HH6 are an exception to the natural progression within the upper segment (Figure III-2 and Table III-1). The d_{85} and d_{50} are comparable in magnitude to HH1. While the d_{85} is rather large, previous work in this area has

shown that basal shear stresses overcome the critical shear stress of the overall average of d_{85} ; hence, these materials are capable of transport during bankfull conditions and, in some locations, during baseflow conditions (Dogwiler and Wicks, 2004). Thus, it is very possible these materials have been transported to this location and will continue to be transported downstream during future events. On the whole, the sediments within HH6 are sub-angular and poorly sorted, creating a nearly linear plot on a cumulative frequency curve (See Appendix A).

Downstream of Boundary Cave, at HH7 (369 m), the main channel is approximately 2.5 m wide and consists of bare bedrock. The DSL bank is predominantly vegetated with a small exposure (~0.5 m) of bedrock exposed about 3 m above the channel surface. The DSR bank exhibits roughly 1.5 m of bedrock exposure, followed by a vegetated slope. Sediment was not abundant at this location, so a Wolman count was not performed

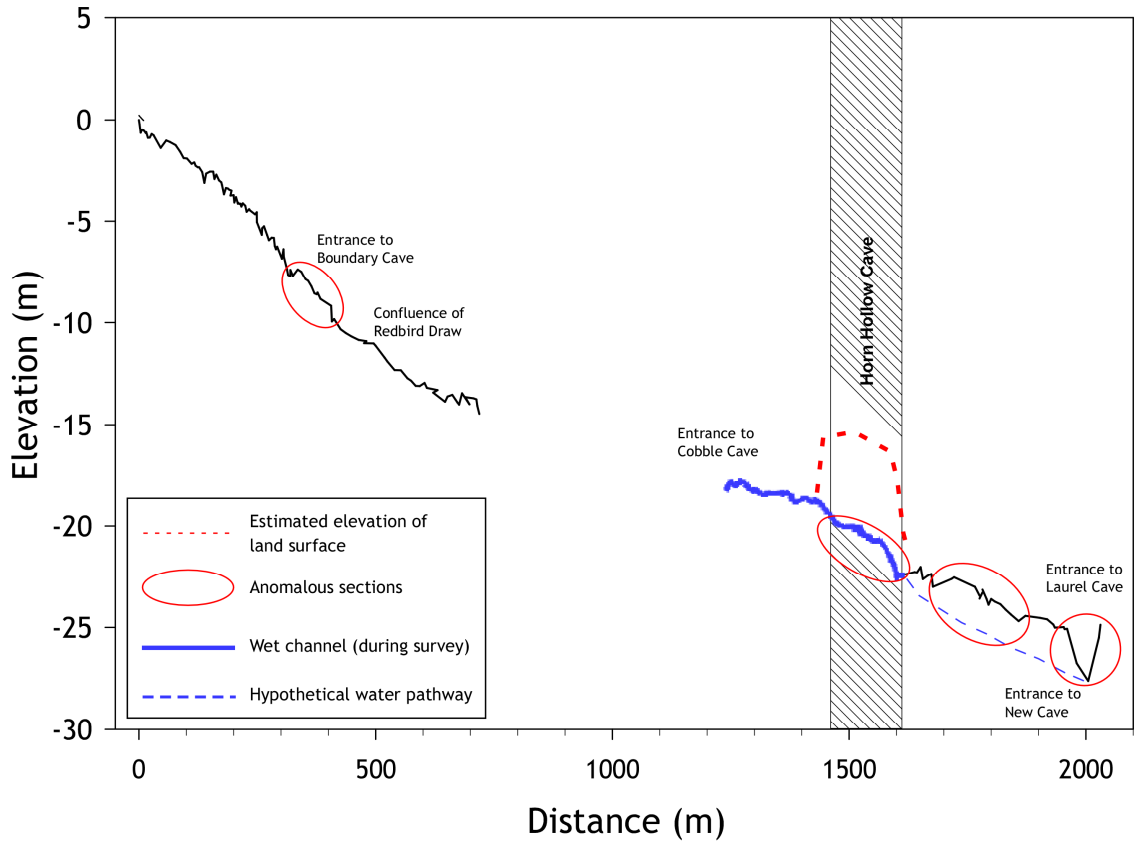


Figure III-3: Locations of anomalous sections along the longitudinal profile of Horn Hollow Creek.

From cross-section 8 to 11, the channel has a more defined floodplain, with the steep valley walls set further back from the channel, and more available sediment within the channel.

Cross-section 8 (434 m) exhibits a wider (5 m), flatter channel with heavily imbedded materials. The DSL bank is approximately 2 m in height and covered by vegetation. The DSR bank has at least two terraces, the first being 0.5 m high and 4.5 m wide, and the second terrace has similar measurements. Both terraces are covered by vegetation. Above the second terrace, the surface slopes up and away from the channel. The sediment within the channel is poorly sorted, and contains a small fraction of grains between 0.064 m and 0.362 m (See Appendix A). The d_{50} and d_{85} , and the corresponding shear stress values, are less than the values at HH6 (Figure III-2 and Table III-1). HH8 is just downstream of the first readily noticeable upward concavity encountered within the upper segment, which begins at the downstream end of the first anomalous area of the profile (Figure III-2). If water was discharging from this location in the past, it would be possible that the addition of water and sediment caused increased erosion near the point of resurgence, thus creating this upward concavity in the longitudinal profile.

The entire channel at HH9 is 6.5 m wide, but only the downstream leftmost 3.5 m of the channel is not vegetated. The DSL bank is approximately 2.5 m in height, and the DSR is approximately 1.5 m. Both sides of the channel are vegetated. The sediments at HH9 are moderately sorted and are heavily imbedded.

Cross-section 10 (502 m) consists entirely of bedrock and contains dissolution features similar to those found at HH5. The cross-section shape is unusual to the valley, exhibiting a 1 m wide by 1 m deep pathway in the middle of it. On either side of the pathway, bedrock extends to the banks (1.5 m on DSL; 2 m on DSR). The vegetated banks of the channel are 1.5 m high and lead to a floodplain. The heavily imbedded nature of the rocks at HH9 may prevent transport of sediment to an extent; thus, not supplying this section with abundant sediment. In addition, and perhaps more importantly, the confluence of Redbird Draw is just upstream of this HH10. Although sediment would be delivered to the channel through this tributary, the force of the water may be too great to allow much, if any, sediment to be deposited here. This lack of deposition, or increase in erosion, is made apparent by the concave upward section beginning at HH10 (Figure III-1).

Cross-section 11 is located near the end of the upper segment. The channel is very narrow, measuring only 2 m across. The cumulative frequency plot of this section is representative of much the valley (See Appendix A). The d_{50} and d_{85} , and the corresponding shear stress values, are less than the values at HH9 (Figure III-2 and Table III-1).

Between the upper segment and the middle segment, the stream channel was unable to be surveyed for three primary reasons: (1) to the presence of impounded water behind a large beaver dam midway through the valley; (2) dense vegetation; and (3) limited time was available in the field, and the middle and lower segments contained features believed to be

important to the study. The distance and elevation of the gap was accounted for by determining the stream length from a topographic map of the area and using the GPS data to verify distances and elevation.

Middle Segment

Up to this point in the survey, the surface channel had been dry. The middle segment (1240 m - 1450 m) of the longitudinal profile begins with the emergence of water following Cobble Cave and ends at the upstream entrance of HHC. The gradient of the middle segment is 0.005; however, because the middle segment and HHC are the only sections with flowing water at the surface under normal conditions, and during the survey for this study, it may be more appropriate to consider the gradient of the entire section. The gradient from the beginning of the middle segment through HHC is 0.01, which is less than the upper segment (0.02). Within the middle segment grain-sizes decrease along the course of the profile, but begins with grain-sizes larger than what was seen upstream at HH11 (Figure III-2 and Table III-1). Without sediment data and profile information from the section between the upper and middle segments, it is difficult to determine what the cause may be for the increase in grain-size.

Immediately downstream of Cobble Cave at cross-section 12 (1259 m), the channel is 8 m wide, lacks vegetation in the main channel, has a developed floodplain, and contains well-sorted sediments.

Downstream, at cross-section 13 (1302 m), the downstream right side of the channel has a steeply sloping, nearly vertical, bedrock wall. A portion of the water within the channel flows into anastomotic pathways cut into the rock wall, presumably by dissolution processes. Sediment is deposited along the DSL side of the channel, forming a point bar-like feature. Based on the comparison of means using an independent samples t-test, the relationship of the sediment at this location and cross-section 12 is statistically significant (Table III-2). A steep slope, approximately 1.5 m in height composed of alluvium, leads to the small flood plain on the DSR. Beyond this, the steep valley walls, composed of bedrock and vegetation, are present.

Further downstream, nearing HHC, the bedrock wall does not stay in contact with the stream channel the entire way; however, rock outcrops are present a few meters up slope and are in contact with the stream closer to HHC. The channel opens up progressively more and more as one draws nearer to HHC. Breakdown materials are present outside of the upstream entrance to HHC. The stream is pirated to the subsurface near the cave entrance.

The middle segment does not contain readily apparent anomalies with respect to the shape of the longitudinal profile or the sediment distribution. However, based on the geomorphology of this segment, an interpretation of its history can be made. First, different from what was present in the upper segment, some of the valley walls in this segment are nearly vertical. Downcutting would have to be extremely rapid to incise the valley in this manner, and similar characteristics would be expected upstream. Second, the

middle segment is bounded by two active passages, CC and HHC. It is highly plausible that these two caves, which are close in elevation and distance, were once connected. The vertical walls present along the valley between these two passages can be interpreted as walls of an ancestral passage whose roof has collapsed. No large materials resembling cavern breakdown are present within this segment; however, the deposition 3 ft of alluvium present on the DSL of the channel indicates an extended period of time has likely passed since the passage was intact. Within this extended time frame, much of the breakdown material may have been broken down by mechanical and chemical erosion. Dogwiler and Wicks (2004) indicates that this system is capable of transporting the d_{85} materials on a frequent basis, which is useful to this interpretation in that much of this breakdown material may have been transported downstream and broken down into smaller fragments.

Horn Hollow Cave

Horn Hollow Cave (1450 - 1607 m) is a phreatic passage, with stream water often flowing through it. The extent of breakdown material within the cave is limited to the up and downstream entrances of the cave passage. The cave has sediment deposits throughout the passage. The most notable characteristic of the profile through HHC is the steep drop in elevation from the upstream entrance to the downstream entrance of HHC. The survey data goes through the active passage, as opposed to staying on dry land and going over the cave passage. Had the dry route been taken, like the upper segment,

a very apparent anomaly would be present in the profile (Figure III-3). The estimated elevation in Figure III-3 was taken from a topographic map of the area.

Lower Segment

The lower section (1607 - 2031 m) begins at the downstream entrance of HHC, and has a gradient of 0.006 from HHC exit to LC, which is less than the combined middle segment and HHC gradient (0.01). Immediately outside of HHC, the water exiting the cave pools up and enters a swallet. No linear progression of grain-size is present in this segment. The grains here are notably larger than upstream, most of which appears to be breakdown from HHC (Figure III-2 and Table III-2).

Cross-section 17 (1651 m) is located near the downstream entrance to HHC. The 7 m wide cross-section intersects overhanging rock outcrops on either side, creating a unique cross-sectional shape (See Appendix). The sediment is poorly sorted at this site, creating a nearly linear line on the cumulative frequency plot. The sediment at this location is considered anomalous because of the dramatic increase in size of the d_{85} material (Figure III-2 and Table III-2). The sediments are very large at this particular location and, because of their angular nature and very close proximity to HHC, are interpreted as breakdown derived from HHC.

As the channel meanders downstream of HH17, and bare bedrock is exposed along the channel floor. Cross-section 18 (1651 m) is approximately 9

m wide, and is located approximately 10 m downstream of an identified anomalous section (Figure III-2). The DSL bank is composed of 3.5 m of bedrock, which is capped by vegetation. The DSR bank slopes gently into vegetation. Although this cross-section is slightly wider than previous, the bare bedrock surface, the vertical wall on the DSL and sharp meander to the DSR indicates the flow of water is very rapid. Any load moving past this section is carried further downstream and deposited when the channel and flood plain widen.

Progressing downstream, within a few meters up and downstream, as well as at HH18 bedrock is exposed along the walls of the channel. In some areas, the rocks resemble the overhanging features present at HH17, and in other areas, the rocks create a near vertical wall.

Approaching cross-section 19 (1812 m), the channel widens (~14 m wide) and has a more developed floodplain leading to the valley walls, but has no bedrock walls immediately next to the stream. The channel morphology in this reach is similar to that of the middle segment; broad, flat, alluvial banks (~1.5 m in height) with a more developed flood plain. The sediments in this location are large, angular, heavily imbedded and poorly sorted, forming a nearly linear line on the cumulative frequency plot (See Appendix A). Much of this material closely resembles the sediment present at HH17, which indicates that these materials may have been transported to this location and/or resulted by means of cave collapse at or very near this section. The vertical bedrock walls

present between HHC leading up to HH19 are indicative of cave passage collapse.

The channel width decreases to roughly 6 m at HH20 (1837 m). Two vegetated terraces are present on the DSL of the bank, which leads to the more developed flood plain. The DSR is also vegetated, with one terrace present which matches the upper terrace on the DSL. The sediment in the channel heavily imbedded and is moderately sorted, with a smaller percentage of large materials than are present at HH17, 18, and 19. However, based on the comparison of means using an independent samples t-test, the relationship between HH19 and HH20 is significant (Table III-2).

Cross-section 21 (1931 m) is ~8 m in width, bedrock, and has vegetated alluvium banks on either side of it. The center of HH21 had a very small amount of sediment present (sand and smaller). The insufficient amount of sediment did not allow for a pebble count.

The entrance to H₂O Cave is located on the DSL of HH22. The entire channel is approximately 18 m wide; the DSL portion of the channel (10 m) consists of bare bedrock and drops 2 m on the right edge towards the entrance of H₂O Cave. From that lower surface to the edge of the bank is approximately 8 m, and has a sufficient amount of sediment for a pebble count. The sediments are fairly sorted, with the larger percentage being between 0.0226 - 0.0900 m (See Appendix A).

The entrances to New and Laurel Cave (2005 m and 2031 m, respectively) are encountered at the end of the lower segment. The steep

drop located at 2005 m is the entrance to NC, and LC is the last point on the profile (2031 m). The drop into New Cave may be the beginning of a new knick point in the stream and/or may mark the beginning of another anomalous bump in the profile. Had the overland pass of Laurel Cave been surveyed or estimated, a form similar to that over HHC would be present (Figure III-3).

CHAPTER IV
DISCUSSION

Using qualitative observations of the geomorphology of the valley and stream channel in conjunction with the sediment data collected, the speleogenesis of Horn Hollow Valley can be further developed. The hypothesis was that anomalous areas, such as changes in profile shape, cross-section size and shape, and grain-size distribution, coinciding with karst features such as caves or swallets, would be very prominent along the profile.

The longitudinal profile of Horn Hollow Creek, in general, resembles the concave-up shape often associated with streams at or near equilibrium (Figure I-1 and Figure III-1). In reality, the stream does not assume a smooth concave-up profile; instead, numerous 'bumps', or irregularities, are present along the entire length of the profile. In both karst and non-karst fluvial settings, these bumps can often be attributed to pool-riffle sequences (Mackin, 1948). The longitudinal profile of Horn Hollow Creek resembles this 'bumpy' description (Figure III-2). However, it is possible that the numerous bumps along the profile are not all attributed to pool-riffle sequences. Within a fluvio-karst setting, in addition to pool-riffle sequences, the bumps can also be related to water being rerouted beneath the surface, serving as indicators of karst features (Figure III-3)(George, 1989). Along the course of Horn Hollow Creek, four recognizable anomalies have been identified (Figure III-3). They are located near Boundary Cave (HH6), Horn Hollow Cave, between HHC and New Cave (near HH18), and the entrance to NC.

Other geomorphic adjustments to the longitudinal profile can be related to the addition of water and sediment from tributaries to the channel. The

stream receives contributions of water and debris from every part of its drainage basin, but the additions are concentrated largely at tributary junctions and the ratio of water to debris varies from place to place. Superimposed on, and in part the result of, the change in load and discharge are changes in the channel characteristics; these affect the hydraulic efficiency of the channel and hence the slope of the stream. The effects of tributary additions on profile shape are visible at the confluence of Redbird Draw with Horn Hollow Creek (Figure III-2). A distinct concave-up shape has resulted from the addition of water and sediments being added to Horn Hollow Creek that extends from the confluence to the end of the upper segment. At the confluence, erosional processes dominate as water and sediment is flushed from the tributary, and depositional processes dominate further downstream.

The grain-size distribution along the profile provided some indication of karst feature locations. Within the upper segment, Boundary Cave (HH6) was the only cave encountered within the stream channel. The d_{85} material is larger at HH6 (0.200 m) than the sections immediately before and after (HH5: bedrock and HH8: 0.050 m), and slightly smaller than that present at HH1 (0.210 m). During periods of high-flow, water flows into the pit, carrying part of the suspended load and bed-load with it. As the water flows into the pit, the stream loses some capacity and competence, resulting in larger particles dropping out of suspension and a decrease in bed-load size. Therefore, these materials appear to be present because of the hydraulics of the section as opposed to collapse of cave passage.

The upper segment most commonly exhibits a v-shaped channel and lacks the near vertical channel walls present in the middle and lower segments. Additionally, no large materials indicative of cave breakdown are present. The absence of these materials does not make it impossible for this segment to have contained ancestral passages, but rather the lack of vertical rock walls that are exposed in conjunction with the absence of large, breakdown-like materials indicate natural downcutting rather than cave collapse as a mechanism for valley development.

The middle segment begins at the downstream entrance of Cobble Cave (CC), where water is flowing along the surface. The grain distribution at the first cross-section (HH12) did not reflect the large particle sizes present at HH6; however, there was an increase in grain-size from HH11, and a decrease at the following cross-sections within the middle segment. Without survey data or sediment data from this middle section, the reason for this is speculative. One hypothesis is that larger materials have eroded from the watershed into the stream after HH11 and have been transported through the stream and CC. As water moves out of the confines of CC into the uncovered portion of the stream, the area of the channel increases, leading to a decrease in velocity. Consequently, larger sediments are deposited at this location and grain-size decreases through the middle segment. At HH13, a nearly vertical bedrock wall lies immediately adjacent to the stream on the DSR and contains anastomotic features at its base, which a portion of the stream flows through.

Beyond the banks of the channel on the DSL, bedrock exposures are present along the valley walls.

There is no apparent evidence within the longitudinal profile or grain analyses to indicate a karst feature in this segment. However, based on observations of the geomorphology, the vertical rock exposures along the valley and channel do not reflect a natural downcutting; instead, they appear to be the result of cavern collapse, leaving remnants of cave passage walls. Based on these geomorphologic observations and the location of this section between CC and HHC, this segment is interpreted as ancestral cave passage. The presence of 3 ft thick alluvium deposits along portions of the valley indicate that an extended period of time may have passed since the existence of this passage. This evidence suggests that enough time may have passed since the breakdown of the passage that the rocks could have been broken down, both mechanically and chemically, and transported further downstream.

The downstream entrance of HHC marks the beginning of the lower segment. Immediately outside of HHC, Horn Hollow Creek pools up and enters a swallet. The longitudinal profile at the end of HHC displays the steep drop out of the cave into the swallet. Just beyond the pool, HH17 was measured and a Wolman count was performed. The grain-sizes at HH17 (d_{85} : 0.160 m) and HH19 (d_{85} : 0.300 m), which is 200 m downstream of HH17, resemble a magnitude of grain-sizes similar to those of HH1 (d_{85} : 0.210 m) and HH2 (d_{85} : 0.120 m). Since sediment is expected to have a general decreasing trend downstream, the data at HH17 and HH19 indicate that other processes may be

occurring within that reach. The channel in this area is predominantly lined by bedrock walls, and large materials on the surface of the channel appear to be a result of collapse, not a result of transport, as they are heavily embedded, very angular, and often exceed a meter in length (on the b axis). Also, some material immediately outside of HHC sits at angles on the ground or against the outer walls of the cave that suggest recent collapse (Appendix A). These geomorphic features, grain-size, channel morphology, and vicinity to HHC, indicate that the channel between HHC and HH19, and possibly beyond, is likely ancestral cave passage.

Beyond this reach, near the entrance to NC and H₂O, the grain-size increases from HH20 to HH22 as a result of waters flowing over a bedrock ledge into H₂O and NC. As the water pools up and enters the two passages, some of the sediment load is deposited and some is transported through H₂O.

The objectives of this study were designed to expand upon the geomorphic history of the Horn Hollow Valley within Carter Caves State Resort Park in northeastern, Kentucky. The approach to completing the objectives was creating a detailed longitudinal profile of Horn Hollow Creek, examining the sediment distribution along the course of the stream, and making observations of the geomorphology of the valley. Using the longitudinal survey and sediment data, anomalous reaches coinciding with present or relict karst features were identified. Primarily based on geomorphic observations of valley shape, the formational mechanism of these reaches was interpreted as either a result of natural downcutting or cave collapse. The formational mechanism for

the upper reaches of Horn Hollow Creek is interpreted as natural downcutting, while portions of the middle and lower segments are interpreted as regions of cave collapse.

CHAPTER V
CONCLUSIONS

The longitudinal profile of Horn Hollow creek revealed anomalous concave-down features that help indicate the presence of karst features, past or present, along the course of the stream channel. These downward concavities are present at or near Boundary Cave, Horn Hollow Cave, between HHC and New Cave, and at NC. The approximate location of karst features (e.g. cave passages) were also indicated by irregularities in sediment deposition, specifically an increase in grain-size when compared to cross-sections in close proximity upstream. These increases were present at the entrance to Boundary Cave, the downstream entrance of Cobble Cave, the downstream entrance of Horn Hollow Cave, and near the entrance to New Cave. The sediment analysis alone does not suggest the presence or absence of ancestral cave passage, but may be used in conjunction with geomorphic observations to better support the interpretation of the valley's history. However, the hypothesis that anomalous sections along the length of the profile will have different sediment sizes is supported. In terms of collapse or natural downcutting, the geomorphic expressions of the various segments differ. The upper segment's rock exposures along the v-shaped channel imply natural downcutting, whereas the near vertical rock exposures combined with the vicinity of active cave passages implies that the channel within the middle segment and at least a portion of the lower segment are former cave passages that have collapsed.

The development of the Ohio River during the Plio-Pleistocene was of critical importance to the cave forming process in this region (Dougherty, 1985;

Granger et. al, 2001; Anthony and Granger, 2004). As a tributary to Tygart's Creek, which is connected to the Ohio River, Horn Hollow Creek experienced periods of rapid downcutting during the early glacial events of the Plio-Pleistocene (Tierney, 1985). These periods of rapid entrenchment and fluctuations in river flow lowered base level throughout major cave areas within Kentucky (Dougherty, 1985; Granger et. al, 2001; Anthony and Granger, 2004). As a direct result in Horn Hollow, water sought more rapid pathways to the newly formed base level. In many areas along the valley, the water followed fractures in the underlying rock, exposing them to increased dissolution, resulting in the formation of numerous pit caves. The water was also able to cut rapidly through the surface channel and into the underlying carbonates. In some cases, the water may have cut down into phreatic passages, exposing them to the surface and possibly cutting through their roofs in the process. These events would have drastically altered the morphology of Horn Hollow Valley, changing it into something similar to what is present there today.

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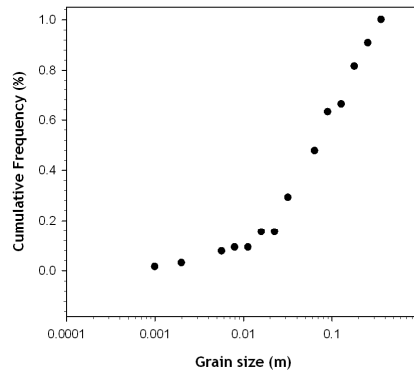
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APPENDIX A
HORN HOLLOW CREEK
CROSS-SECTION DATA

Longitude Latitude
-83.119902288 38.38904724

Cross Section	1
Sample Size	65
Number of samples representing bedrock	0
mean (m)	0.117
standard deviation (m)	0.109
d50 (m)	0.065
d85 (m)	0.210
d50:d85	3.231
Tc50 (N m ²)	46.35
Tc85 (N m ²)	149.73

Horn Hollow cross-section 1



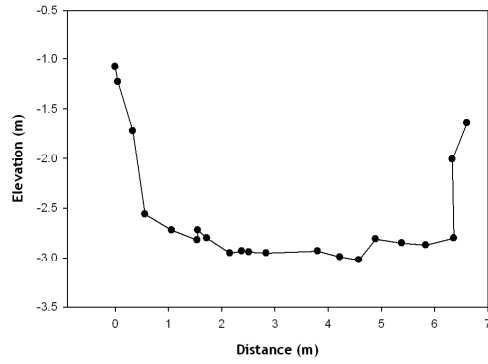
(No cross-section available)

(No photo available)

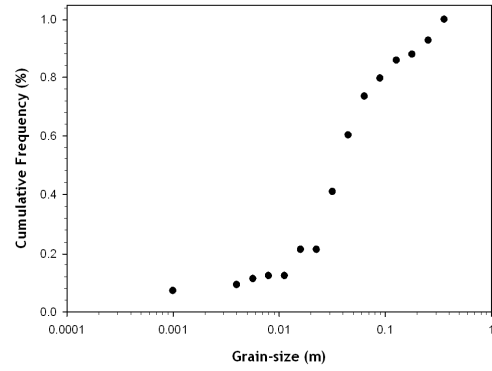
Longitude Latitude
 -83.118745817 38.38832507

Cross Section	2
Sample Size	98
Number of samples representing bedrock	2
mean (m)	.080362
standard deviation (m)	.0981126
d50 (m)	0.036
d85 (m)	0.120
d50:d85	3.333
Tc50 (N m ²)	25.67
Tc85 (N m ²)	85.56

Horn Hollow cross-section 2



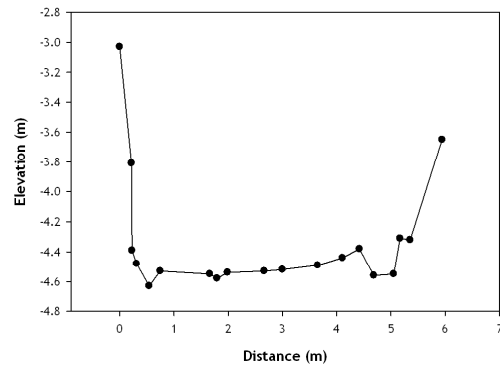
Horn Hollow cross-section 2



Longitude Latitude
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(All bedrock - no statistics)

Horn Hollow cross-section 3

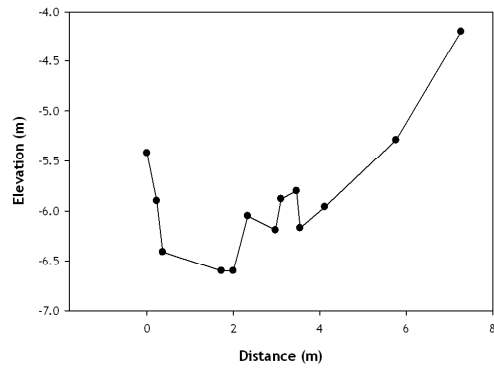


(No photo available)

Longitude Latitude
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(All bedrock - no statistics)

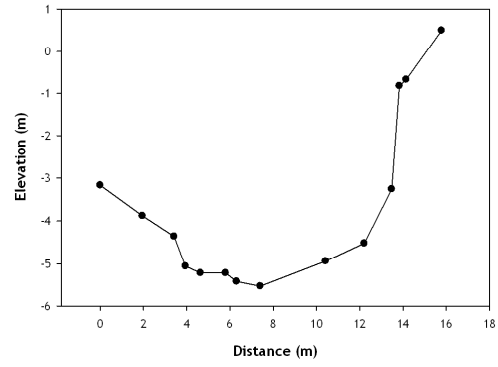
Horn Hollow cross-section 4



Longitude **Latitude**
-83.118549140 38.3876678

(All bedrock - no statistics)

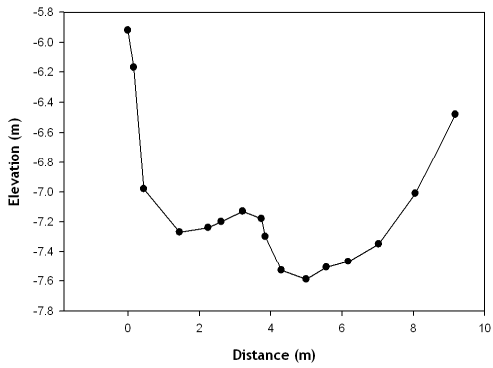
Horn Hollow cross-section 5



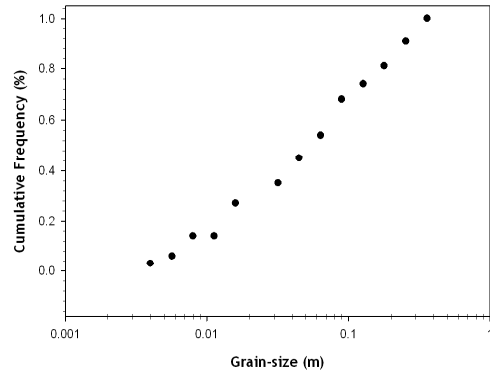
Longitude Latitude
 -83.117992575 38.38726986

Cross Section	6
Sample Size	100
Number of samples representing bedrock	0
Mean (m)	0.041
Standard deviation (m)	0.067
d50 (m)	0.053
d85 (m)	0.200
d50:d85	3.774
Tc50 (N m ²)	37.79
Tc85 (N m ²)	142.60

Horn Hollow cross-section 6



Horn Hollow cross-section 6

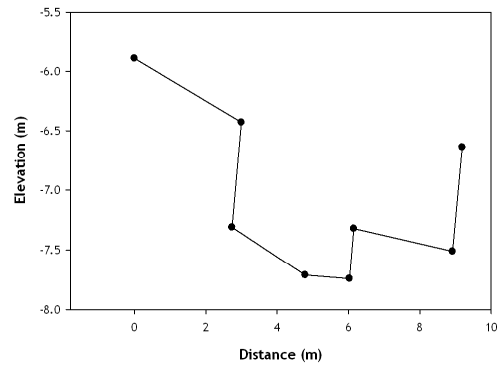


(No photo available)

Longitude Latitude
-83.117976403 38.38723539

(All bedrock - no statistics)

Horn Hollow cross-section 7

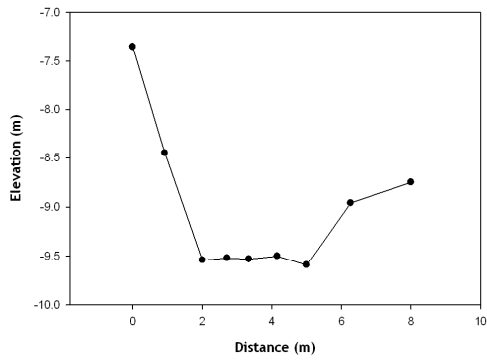


(No photo available)

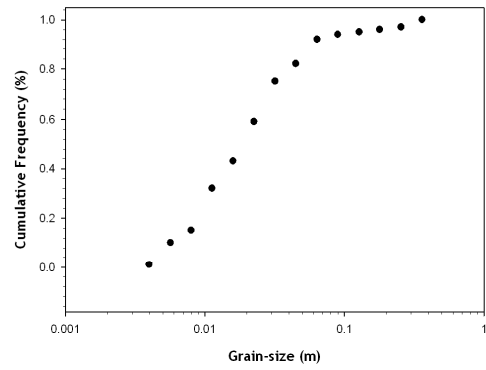
Longitude Latitude
 -83.117456411 38.38683694

Cross Section	8
Sample Size	100
Number of samples representing bedrock	0
mean (m)	0.106
standard deviation (m)	0.110
d50 (m)	0.019
d85 (m)	0.050
d50:d85	2.632
Tc50 (N m ²)	13.55
Tc85 (N m ²)	35.65

Horn Hollow cross-section 8



Horn Hollow cross-section 8

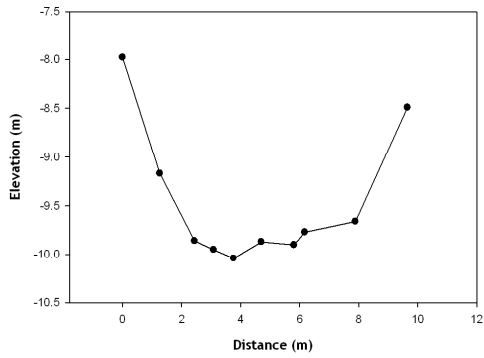


(No photo available)

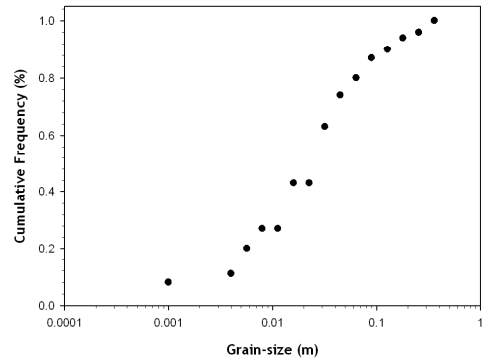
Longitude Latitude
-83.117155736 38.38669903

Cross Section	9
Sample Size	100
Number of samples representing bedrock	0
mean (m)	0.055
standard deviation (m)	0.081
d50 (m)	0.026
d85 (m)	0.082
d50:d85	3.154
Tc50 (N m ²)	18.54
Tc85 (N m ²)	58.47

Horn Hollow cross-section 9

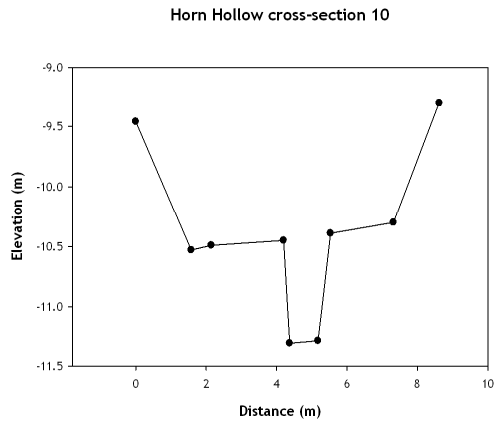


Horn Hollow cross-section 9



Longitude Latitude
-83.116898477 38.38644934

(All bedrock - no statistics)

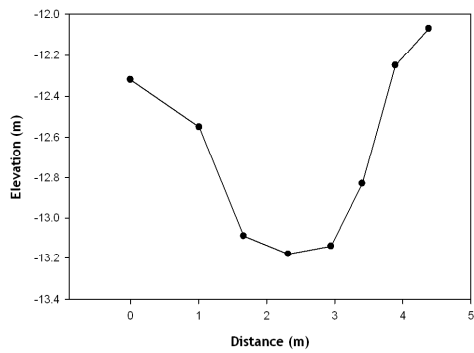


(No photo available)

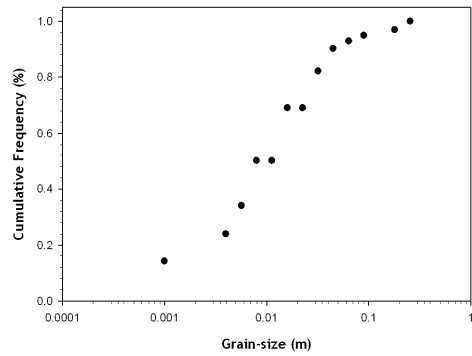
Longitude Latitude
-83.116953088 38.38552074

Cross Section	11
Sample Size	100
Number of samples representing bedrock	0
Mean (m)	0.027
Standard deviation (m)	0.050
d50 (m)	0.011
d85 (m)	0.036
d50:d85	3.273
Tc50 (N m ²)	7.84
Tc85 (N m ²)	25.67

Horn Hollow cross-section 11



Horn Hollow cross-section 11



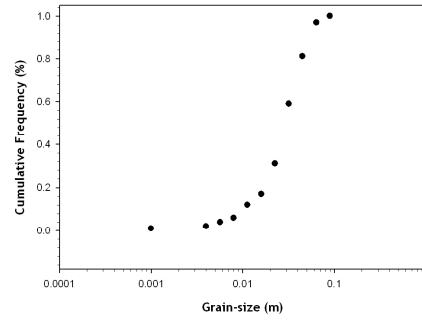
(No photo available)

Longitude Latitude
-83.115980970 38.38037186

Cross Section	12
Sample Size	100
Number of samples representing bedrock	0
Mean (m)	0.037
Standard deviation (m)	0.019
d50 (m)	0.029
d85 (m)	0.050
d50:d85	1.724
Tc50 (N m ²)	20.68
Tc85 (N m ²)	35.65

(No cross-section available)

Horn Hollow Cross-section 12

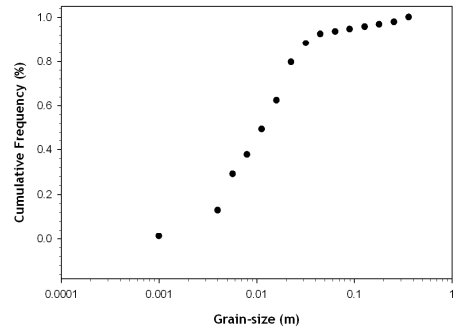


Longitude Latitude
-83.116019951 38.38008062

Cross Section	13
Sample Size	93
Number of samples representing bedrock	7
Mean (m)	0.030
Standard deviation (m)	0.061
d50 (m)	0.012
d85 (m)	0.026
d50:d85	2.167
Tc50 (N m ²)	8.56
Tc85 (N m ²)	18.54

(No cross-section available)

Horn Hollow cross-section 13

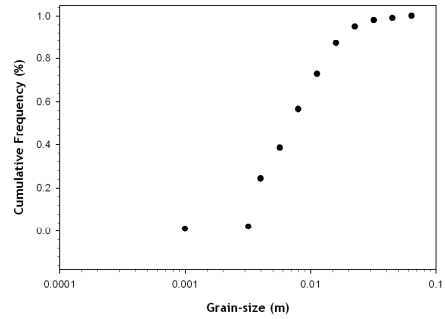


Longitude Latitude
-83.115628406 38.3793606

Cross Section	14
Sample Size	99
Number of samples representing bedrock	1
Mean (m)	0.011
Standard deviation (m)	0.009
d50 (m)	0.007
d85 (m)	0.015
d50:d85	2.143
Tc50 (N m ²)	4.99
Tc85 (N m ²)	10.70

(No cross-section available)

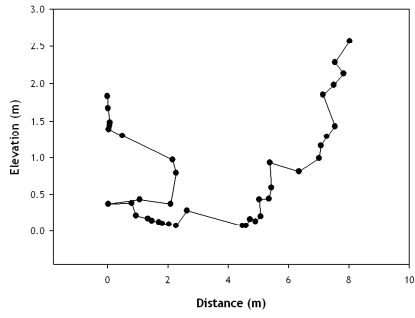
Horn Hollow cross-section 14



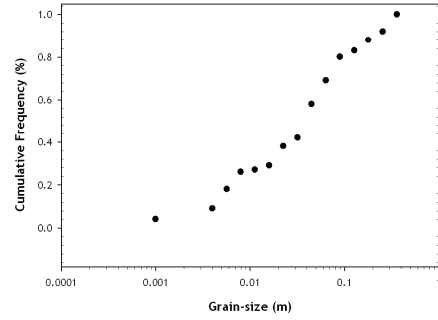
Longitude Latitude
-83.115288571 38.378049

Cross Section	17
Sample Size	100
Number of samples representing bedrock	0
Mean (m)	0.081
Standard deviation (m)	0.102
d50 (m)	0.038
d85 (m)	0.160
d50:d85	4.211
Tc50 (N m ²)	27.09
Tc85 (N m ²)	114.08

Horn Hollow cross-section 17



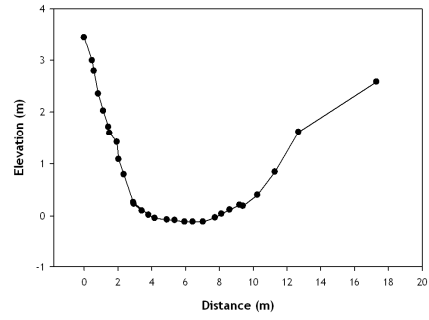
Horn Hollow cross-section 17



Longitude Latitude
-83.115366978 38.37823771

(All bedrock - no statistics)

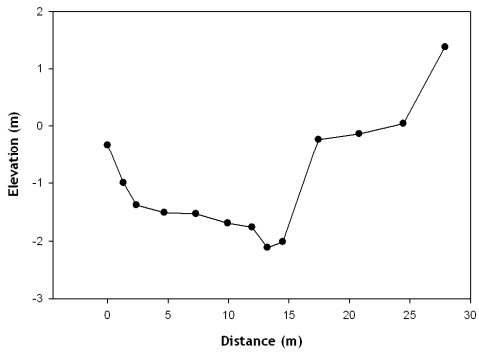
Horn Hollow cross-section 18



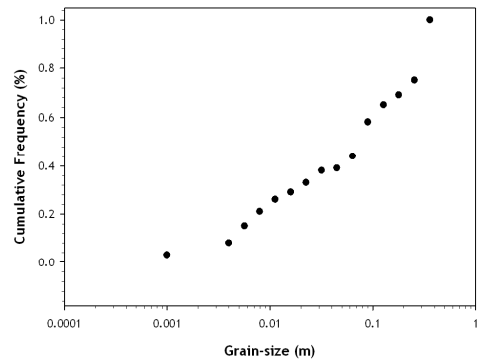
Longitude Latitude
-83.115609505 38.37759747

Cross Section	19
Sample Size	100
Number of samples representing bedrock	0
Mean (m)	0.143
Standard deviation (m)	0.143
d50 (m)	0.072
d85 (m)	0.300
d50:d85	4.167
Tc50 (N m ²)	51.34
Tc85 (N m ²)	213.90

Horn Hollow cross-section 19



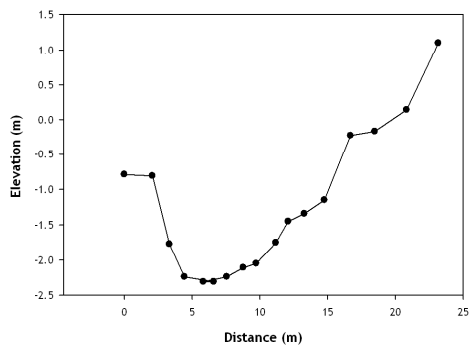
Horn Hollow cross-section 19



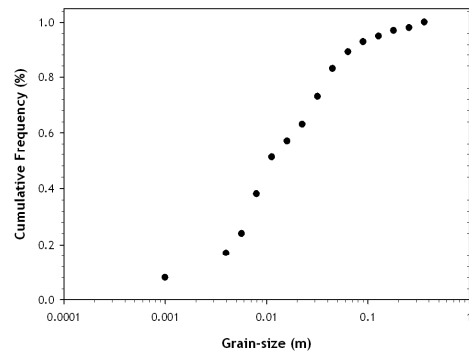
Longitude Latitude
-83.115425353 38.3773704

Cross Section	20
Sample Size	100
Number of samples representing bedrock	0
Mean (m)	0.037
Standard deviation (m)	0.062
d50 (m)	0.013
d85 (m)	0.040
d50:d85	3.077
Tc50 (N m ²)	9.27
Tc85 (N m ²)	28.52

Horn Hollow cross-section 20



Horn Hollow cross-section 20

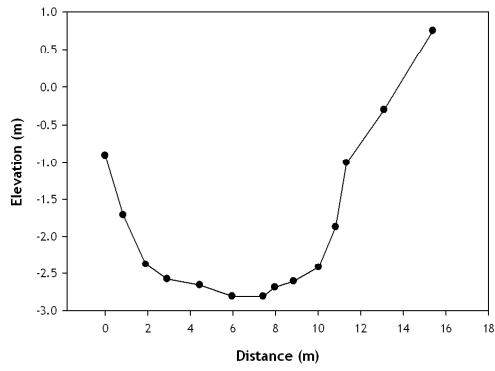


(No photo available)

Longitude Latitude
-83.115441773 38.37681387

(All bedrock - no statistics)

Horn Hollow cross-section 21

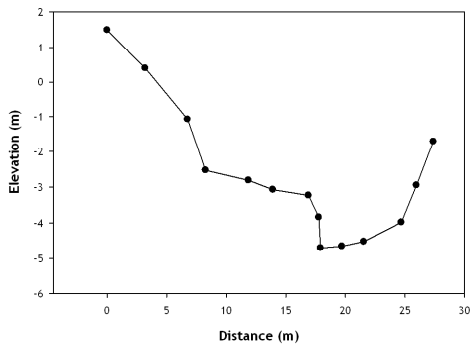


(No photo available)

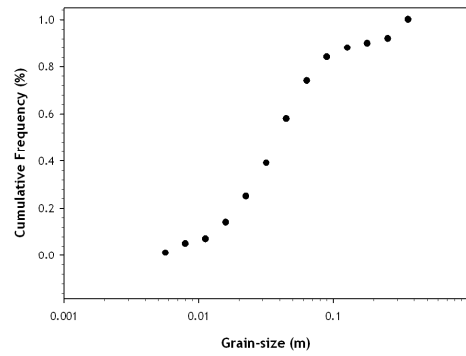
Longitude Latitude
-83.115339897 38.3767553

Cross Section	22
Sample Size	100
Number of samples representing bedrock	0
Mean (m)	0.079
Standard deviation (m)	0.095
d50 (m)	0.040
d85 (m)	0.092
d50:d85	2.300
Tc50 (N m ²)	28.52
Tc85 (N m ²)	65.60

Horn Hollow cross-section 22



Horn Hollow cross-section 22



(No photo available)