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LITHOLOGY AS AN EROSIONAL CONTROL ON THE CAVE BRANCH AND HORN HOLLOW FLUVIOKARST WATERSHEDS IN CARTER COUNTY, KENTUCKY

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Abstract
Variation in rock erodibility controls the rate of surface development providing information on the landscape evolution. In fluviokarst systems, the contrast between carbonate and non-carbonate rocks may alter the topographic evolution of the system. In Carter County, Kentucky, the Cave Branch and Horn Hollow fluviokarst systems comprise limestone overlain and capped by sandstone. Streams in the watersheds illustrate erosional differences associated with lithology. Developing as a function of the rock erodibility, uplift rates, and stream power, longitudinal stream profiles provide a means to evaluate variability in denudation rates. Using the integral method of channel profile analysis, we examine if variation in lithology has created a state of disequilibrium in the Cave Branch and Horn Hollow watersheds and if the overall development of the system is a function of erosional resistance and of differential weathering between sandstone and limestone. By scaling erosion with drainage area, the integral method allows for the comparison of streams of varying watershed areas. Streams within the sandstone portions of the watersheds displayed a greater degree of equilibrium than the limestone watersheds. Limestone stream segments generated a greater steepness index, mean value of 0.03, than sandstone segments, mean 0.01. The greater degree of disequilibrium and greater steepness index of the limestone are related to the soluble nature of limestone and the glacial-fluvial development of this area. The erosion signature recorded in the sandstone appears to represent the conditions prior to the Ohio River incision. The rapid development of the karst system is in response to the Ohio River incision disproportionally eroding the limestone. The erosional differences between the limestone and sandstone segments represent the response of the fluvial system during glacial and interglacial periods.

Introduction
Weathering and erosion of a landscape will leave a record of the factors involved in the topographic development. One way to interpret past environmental conditions and to understand landscape evolution is to examine longitudinal stream profiles (Bishop, 2007; Duvall et al., 2004; Goldrick and Bishop, 2007; Larue, 2011). A longitudinal stream profile plots the bed elevation against the length of the stream. Stream profiles are useful in the evaluation of a landscape as they set the boundary for hillslope processes, which is responsible for the denudation of a landscape (Whipple and Tucker, 1999). As landscape denudation occurs, a stream works to reach equilibrium conditions, where the amounts of erosion and deposition area equal. Equilibrium conditions result in a smooth concave-up profile (Goldrick and Bishop, 2007; Mackin, 1948; Phillips and Lutz, 2008). Factors, including tectonics, climate, change in base level, and variation in erodibility and lithology, influence the rates of erosion and deposition causing a stream to deviate from equilibrium and lose its equilibrium profile. In bedrock streams, dominant erosional forces are closely related to lithology and structure of the underlying bedrock (Miller, 1991; Wohl, 2013; Wohl and Ikeda, 1998).

Stream profiles are quantified using stream power equations (Bishop, 2007; Carlston, 1969; Duvall et al., 2004; Goldrick and Bishop, 2007; Hack, 1973). Stream power is a measure of the sediment-transport capacity for a stream as it is related to discharge and slope (Anthony and Granger, 2007; Hack, 1973; Knighton, 1998; Phillips and Lutz, 2008). Stream power equations can predict the amount of erosion occurring along a profile of a stream; any significant deviation from this prediction represents a state of disequilibrium (Phillips and Lutz, 2008). A common stream power equation used to evaluate a stream profile is expressed in terms of drainage area, which serves as a proxy for discharge, and slope (Phillips and Lutz, 2008):

$$\frac{dz}{dt} = U - KA(x)^m \left(\frac{dz}{dx}\right)^n \qquad \text{Eq. 1}$$

Where z is elevation, t is time, x is horizontal distance, U is rock uplift rate, K is an erodibility constant, A is drainage area, and m and n are positive constants related to hydrologic conditions. Exponents m and n are a function of standard flow resistance and stream power relations (Phillips and Lutz, 2008; Sklar and Dietrich, 2013). Generally, topographic steady-state is assumed, $\frac{dz}{dt} = 0$, simplifying Eq. 1 to

$$\frac{dz}{dx} = \left(\frac{U}{K}\right)^{\frac{1}{n}} A(x)^{\frac{-m}{n}} \qquad \text{Eq. 2}$$

The ratio of m/n represents the concavity index of a stream profile (Phillips and Lutz, 2008; Whipple and Tucker, 1999). Eq. 2 reveals a negative power-law relationship between drainage area and slope. When transient conditions prevail, stream profiles deviate from the power-law relationship because of variation in rock uplift rate or erodibility (Royden and Perron, 2013; Whipple and Tucker, 1999).

Fluviokarst

Fluviokarst is a landscape with surface and subsurface drainage, consisting of both fluvial and karst features (White and White, 1983). These systems typically occur at the contact of carbonate and non-carbonate rocks (Bočić, 2003; Jakucs, 1977). Lithology is a key component in the development of fluviokarst, with the difference in erosional resistance between lithologies influencing the landscape as a whole. Non-carbonate rocks, specifically siliciclastic rocks, weather primarily by physical processes due to their low solubility as compared to limestone (Nesbitt et al., 1997). Limestone is susceptible to both physical and chemical weathering, with physical weathering being more common than had been previously reported (Dogwiler and Wicks, 2004). With respect to chemical weathering, streams in limestone bedrock can have unique features. Diversion of flow to the subsurface and its subsequent reemergence downstream, develop unique stream profile signatures (George, 1989; White and White, 1983; Woodside et al., 2015). Woodside et al. (2015) identified surface anomalies along a limestone bedrock stream. The anomalies, which occur downstream of swallets, are an increase in stream elevation, suggesting that they are a result of erosional process continuing upstream of the subterranean diversion and downstream of the water reemergence but with limited erosion of the surface channel between these points. Schroeder et al. (2015) reported the absence of surface anomalies in a fluviokarst system of southeastern Minnesota. A prevailing question as to why one fluviokarst system exhibits an atypical profile while another system exhibits a typical profile exists. Both systems are composed of non-carbonate rocks overlying carbonate rocks.

To understand this dichotomy, evaluating differences in erodibility based on lithology would be useful. Thus, we posit that lithology is a controlling factor in the development of a fluviokarst system. Specifically, we examine the Cave Branch and Horn Hollow fluviokarst systems in the Carter Caves area of northeastern Kentucky. The objectives of this study are to (1) determine if a state of disequilibrium exists because of a variation in lithology; (2) determine whether the limestone or sandstone is more resistant to erosion based on stream power; and (3) assess how erosional resistance is related to the overall development of the Cave Branch and Horn Hollow systems.

Study Area

This study will focus on the Cave Branch and Horn Hollow Basins (Figure 1), each with sections inside and beyond the boundaries of Carter Caves State Resort Park (CCSRP) in northeastern Kentucky. The fluviokarst watersheds, which have been extensively studied (Angel and Peterson, 2015; Dogwiler and Wicks, 2004; Engel and Engel, 2009; Jacoby et al., 2011a; Jacoby et al., 2011b;

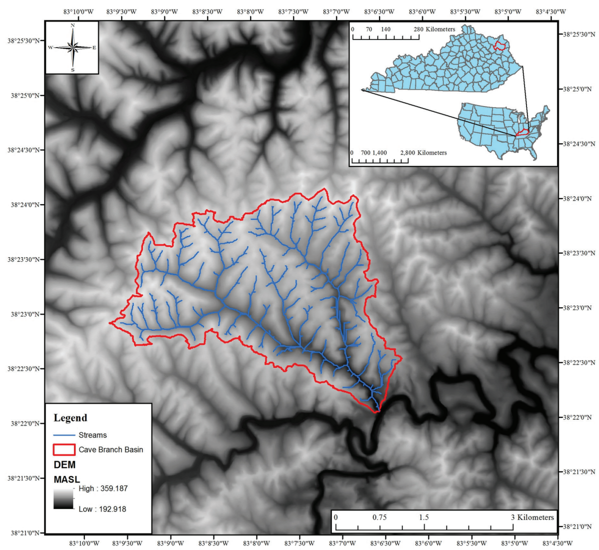

Figure 1. *Cave Branch Basin, including its tributary Horn Hollow. Horn Hollow constitutes the northeastern branch of the watershed.*

Jacoby et al., 2013; Peterson et al., 2011; Woodside et al., 2015), contain rocks of Mississippian and Pennsylvanian age, with approximately 25 meters of carbonate bedrock bounded by siliciclastic units (Figure 2). Engel and Engel (2009) provide a detailed description of the regional stratigraphy and salient descriptions of bedrock within the area. CCSRP includes surface exposure of three bedrock formations: the Borden Formation, the Slade Formation, and the Paragon Formation. The Borden Formation, the lower-most Mississippian unit, is a series of siliciclastic rocks, sandstones and shales. The Slade Formation is primarily carbonate rocks with interbedded chert, silt, and sand in the upper member. The upper most unit, the Paragon Formation, consists of siliciclastic rocks, primarily sandstones. The contact between the Slade Formation and the Paragon Formation is reported at 274 meters above sea level (MASL) (Jacoby et al., 2013). The headwaters of the basins originate in the Carter Caves Sandstone. Streams transition from clastic to carbonate to clastic moving towards the regional base level defined by Tygart's Creek, which flows along the Borden Formation and below all karst development.

Jacoby et al. (2011a) identified four cave levels within the CCSRP with the use of a 10-meter DEM (digital elevation model). The cave levels developed due to changes in base level associated with glacio-eustatic processes, which coincided with the formation of the Ohio River and the abandonment of the Teays River Valley.

Methods

To address the three objectives in this study, streams were evaluated using a stream power model. The integral method introduced by Royden and Perron (2013) and Perron and Royden (2013) was used to conduct the profile analyses. The main reach and the tributaries a watershed should erode at relatively the same rate. A benefit of the integral method is that it scales erosion with drainage area. This characteristic is crucial to this study because it allows the analysis of the watershed as a whole, or

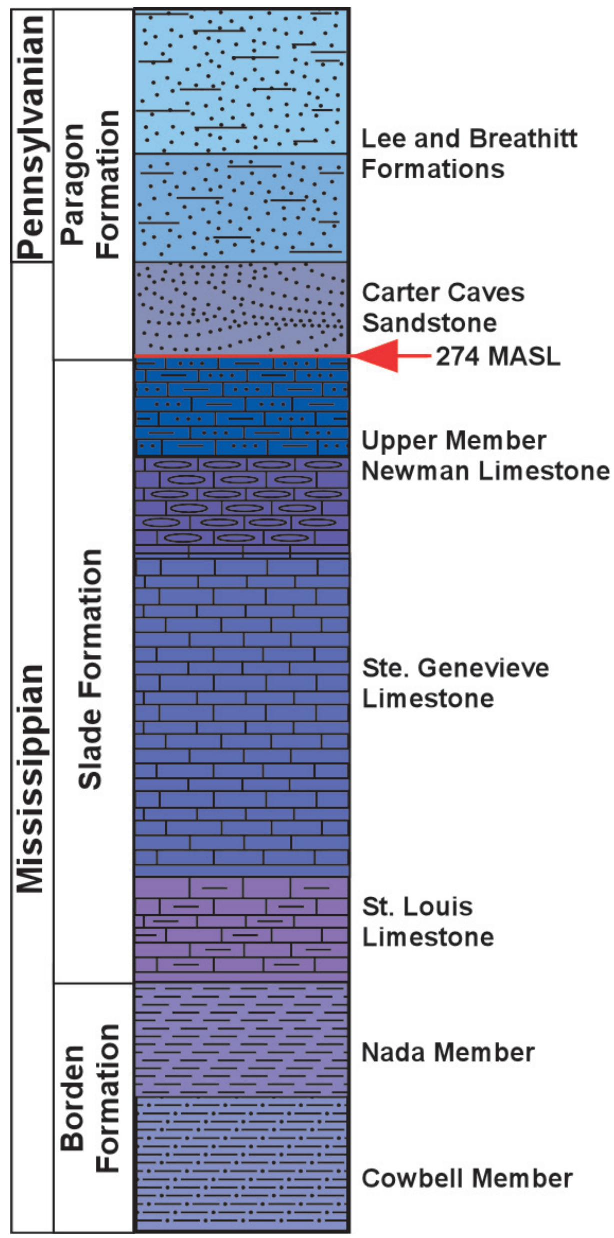

Figure 2. *Stratigraphic column of CCSRP (modified from Engel and Engel, 2009). Red arrow represents 274 MASL.*

as segments of streams, to assess if a system is in a state of equilibrium. Providing a comparison between upstream and downstream segments, the integral method allows assessment of the erodibility of the Carter Caves Sandstone and the Upper Member Newman Limestone.

Integral Method

Derived from Eq. 2, the integral method calculates stream power by using elevation instead of slope as the dependent variable and the spatial integral of drainage area as the independent variable (Perron and Royden, 2013; Royden and Perron, 2013). The slope of a transformed profile, or chi plot, represents the steepness index (SI), which is equal to uplift (*U*) divided by erodibility (*K*). The transformation of a stream profile is calculated from:

$$z(x) = z(x_b) + \left(\frac{U}{KA_0{}^m}\right)^{1/n} \chi \qquad \text{Eq. 3}$$

where

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{m/n} dx \qquad \text{Eq. 4}$$

The variables in Eq. 3 and 4 have been defined above in Eq. 1 and 2, with the addition of A_0, which serves as a reference drainage area, and χ or chi, which is the integral of drainage area. The integral method also removes noise that is a side effect of calculating slope from uncertain topographic data. Thaler and Covington (2016) successfully used the integral method to investigate similar lithology sequences in the Buffalo River Basin.

For a single stream, the chi plot should be linear, and any deviation from that suggests a state of disequilibrium. Because erosion is scaled with drainage area, the chi plot for an entire stream network should exhibit streams with similar slope, or SI.

Geographic Information System (GIS)

Individual watersheds were generated in ArcGIS 10.3.1 (ArcGIS, 2011) from 10-meter DEMs downloaded from the USGS 3D Elevation Program (USGS, 2017). The Cave Branch watershed and sub-watersheds were delineated by employing the Raster Calculator to select all cells with more than 1000 cells draining to it (e.g., the collection points for a significant amount of surface flow). With a 10-meter DEM, a 1000-cell drainage area represents 100,000 m^2. Thus, the threshold of 1000 cells signifies the transition from colluvial to fluvial, which occurs when the drainage area of a watershed ranges from 10^5 to 10^6 m^2 (Whipple and Tucker, 1999). Watershed boundaries were computed by identifying all of the cells with directional flow (from the flow direction layer) leading to that pour point. Watersheds were created for both Cave Branch, upstream from the confluence with Horn Hollow, and Horn Hollow (Figure 3a). Additional delineation of the Cave Branch watershed at the contact between the Carter Caves Sandstone and the Upper Member of the Newman Limestone at the elevation of 274 MASL generates three upstream sub-watersheds, which are named CB274 north, mid, and south (Figure 3b). Within the Horn Hollow watershed, two upstream sub-watersheds were created, HH274 west and east.

MATLAB

The individual watersheds were exported to and analyzed in MATLAB using the Topotoolbox (Schwanghart and Scherler, 2014) and Image Processing Toolbox (The MathWorks Inc., 2016). Topotoolbox is optimized to conduct stream power analysis and incorporates chi plot analysis in the functions.

An important aspect of the flow accumulation size is to determine where the transition from colluvial to fluvial conditions occurs. While the threshold typically occurs between 10^5 and 10^6 m^2, the transition for a given watershed can be determined by plotting drainage area against stream slope. The inflection in this graph represents where the transition from colluvial to fluvial occurs (Montgomery and Buffington, 1997). For the entire Cave Branch watershed, including Horn Hollow, the log of drainage area and the log of slope were plotted against each other. The point along the x-axis (drainage area) where the inflection occurs represents the drainage area that was used for the stream networks to be analyzed by the integral method via chi plots. We then modified the stream network to include areas above and below the 274 MASL.

To determine if variation in lithology was creating a state of disequilibrium within the fluviokarst system, we compared the profiles of the sandstone segments above 274 MASL and the limestone segments below

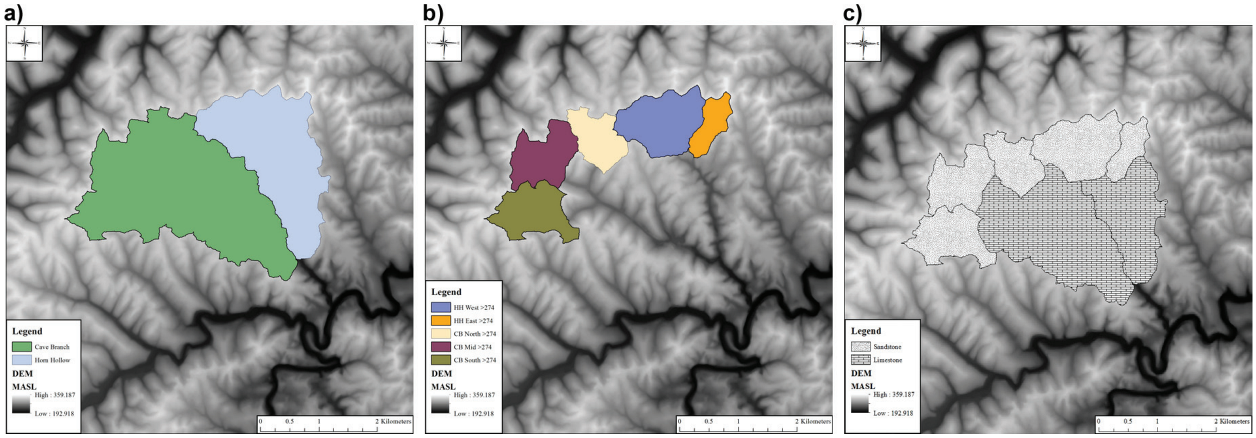

Figure 3. *(a) Cave Branch and Horn Hollow watershed. (b) Sub-watersheds for Cave Branch and Horn Hollow above 274 MAS. (c) Individual watersheds with corresponding lithology. Limestone below 274 MASL, sandstone above 274 MASL.*

274 MASL to the individual Cave Branch and Horn Hollow watersheds. To create the chi plots for all of Cave Branch and Horn Hollow, the chi plot function in the Topotoolbox was run to include all streams above the confluence of the two streams. To create the chi plots for limestone segments, χ analyses were completed on stream segments below 274 MASL. To create the chi plots for the sandstone streams, the upstream watersheds had to be created because an individual chi plot requires that streams drain to one point. The five upstream watersheds (Figure 3) were analyzed using the chi plot function including all streams above their pour point.

Before calculating the degree of equilibrium of watersheds or steepness index of streams, the m/n ratio must be determined. To reiterate, the m/n ratio represents the concavity of a stream. The m/n ratio used for a given chi plot can be established in one of two ways. The first way is to exclude the input value when running the chi plot, which is what is used to determine if variation in lithology was creating a state of disequilibrium. When this course of action is taken, the m/n ratio will automatically be determined by Topotoolbox by running a linear least-squares regression. The m/n ratio that produces the highest R^2 value will then be used. The R^2 value represents the degree of equilibrium for a watershed. The higher the R^2 value, measured on a scale from 0 to 1, the greater the agreement in slope among the streams. A system completely in equilibrium will have a R^2 of 1. We then compared the limestone streams and the sandstone streams to entire watersheds to see if there was a difference in the degree of equilibrium because of varying lithology.

To determine if the limestone or sandstone is more resistant to erosion (thus, having a greater SI) chi plots were analyzed in a different manner. First, subwatersheds were generated based solely on the lithology. The five watersheds with sandstone stream segments were compared to the two with limestone stream segments (Figure 3c). Upstream sandstone watersheds were determined by placing pour points above 274 MASL. The downstream limestone watersheds were created from the Cave Branch and Horn Hollow watersheds, only including streams below 274 MASL. Second, the m/n ratio was entered manually when running the chi plots. Finally, instead of comparing the chi plots of watersheds in terms of R^2, the chi plots of individual limestone and sandstone streams were compared in terms of their SI.

To compare the SI of different streams, limestone against sandstone, the same m/n ratio must be used. The m/n ratio to be used was determined with a sensitivity analysis, run for each watershed to determine the m/n ratio that yielded the highest R^2 value. A range of m/n values between 0.1–0.9 was used because bedrock streams typically have a m/n ratio of 0.2 to 0.6 (Whipple and Tucker, 1999). Using the m/n value with the highest R^2 value, chi plots were generated for each of the watersheds. Once the SI of each individual limestone and sandstone streams were established, the values were evaluated with at *t*-test using an $\alpha=0.05$ to determine if there was a statistical difference between the limestone and sandstone streams.

Results

Before creating chi plots, the proper flow accumulation size is needed to be determined by creating a log-log

plot of drainage area against slope for streams within the watersheds (Figure 4). The inflection of the drainage area-slope graph around $10^{5.98}$ m^2 signifies the transition from colluvial to fluvial. Only streams with a drainage area greater than this value were used in the analysis.

Equilibrium Analysis

The equilibrium analysis revealed that the entire Horn Hollow watershed had a greater R^2 than its subwatersheds, and the entire Cave Branch had a lower R^2 than its subwatersheds (Table 1). For both Cave Branch and Horn Hollow, the sandstone segments exhibit a greater R^2 than the limestone segments. The *m/n* values for Horn Hollow and its subwatersheds ranged from –0.599 to 0.646. The *m/n* values for Cave Branch and its subwatersheds ranged from –1.724 to 0.543. A positive *m/n* ratio represents a stream in equilibrium, while a negative *m/n* denotes a stream not in equilibrium. Both watersheds exhibited a range of *m/n* ratios, but the *m/n* ratio of the entire Horn Hollow and Cave Branch watersheds differed by an order of magnitude. The chi plots of the individual watersheds can be seen in Figure 5. The more co-linear the chi plot, the higher the R^2.

Sensitivity Analysis

The sensitivity analysis incorporated a χ analysis for the entire Cave Branch watershed, including Horn Hollow, using the previously mentioned range of *m/n* ratios (Table 2). The *m/n* value of 0.4 generated the highest R^2 value, making it the most representative of the entire watershed.

Steepness Index (SI) Analysis

Upon identifying an *m/n* ratio of 0.4, individual chi plots for the 17 limestone streams and 16 sandstone streams generated SI values for comparison (Figure 6). The mean SI for the streams with limestone bedrock was 0.032 with a variance of 2.0×10^{-4}; for the sandstone streams, the mean SI was 0.012 with a variance of 2.0×10^{-5}. A *t*-test indicates a significant difference in SI values between the limestone and sandstone stream segments ($t(31) = -10.10$, $p<0.001$). The higher SI of the limestone indicates that the limestone stream segments are more resistant.

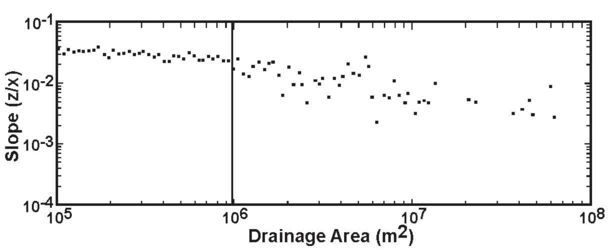

Figure 4. *Log-log drainage area-slope plot used to determine the flow accumulation that constituted a stream in the Cave Branch Basin. The inflection occurs at $10^{5.98}$ m^2, which is represented by the vertical line.*

Watershed	m/n	R^2
Cave Branch (SS&LS)	0.276	0.80
$CB_{less274}$ (ls)	0.502	0.86
$CB_{274south}$ (ss)	0.554	0.98
$CB_{274north}$ (ss)	–0.599	0.79
CB_{274mid} (ss)	0.646	0.94
Horn Hollow (SS&LS)	0.050	0.92
$HH_{less274}$ (ls)	0.543	0.80
HH_{274eas}t (ss)	–1.724	0.86
$HH_{274west}$ (ss)	–0.093	0.86

Note: SS represents sandstone and LS represents limestone.

Table 1. *Results from equilibrium analysis.*

Discussion

The first objective of this study was to determine whether lithology was responsible for a state of disequilibrium. The results of the equilibrium analysis revealed that the degree of equilibrium varied from the sandstone to the limestone sections of Cave Branch and Horn Hollow. Within Horn Hollow (red line on the diagram on Figure 5f), a noticeable change in slope (SI value) occurs at the contact between the sandstone and limestone. The sandstone watersheds are closer to equilibrium, while the downstream limestone segments appear to be in a state of disequilibrium. At the watershed scale, all the factors that can affect the shape of a profile, which include climate, tectonics, changes in base level, are held constant among the sub-basins except for variation in lithology. The results of the equilibrium analysis suggest that the sandstone segments are in a greater degree of equilibrium than the limestone segments.

The second objective was to determine whether the sandstone or limestone reaches were more resistant to erosion based on SI. The statistical difference between SI values for the sandstone and limestone, with limestone stream segments having a greater SI, suggest that limestone in the Carter Caves area is more

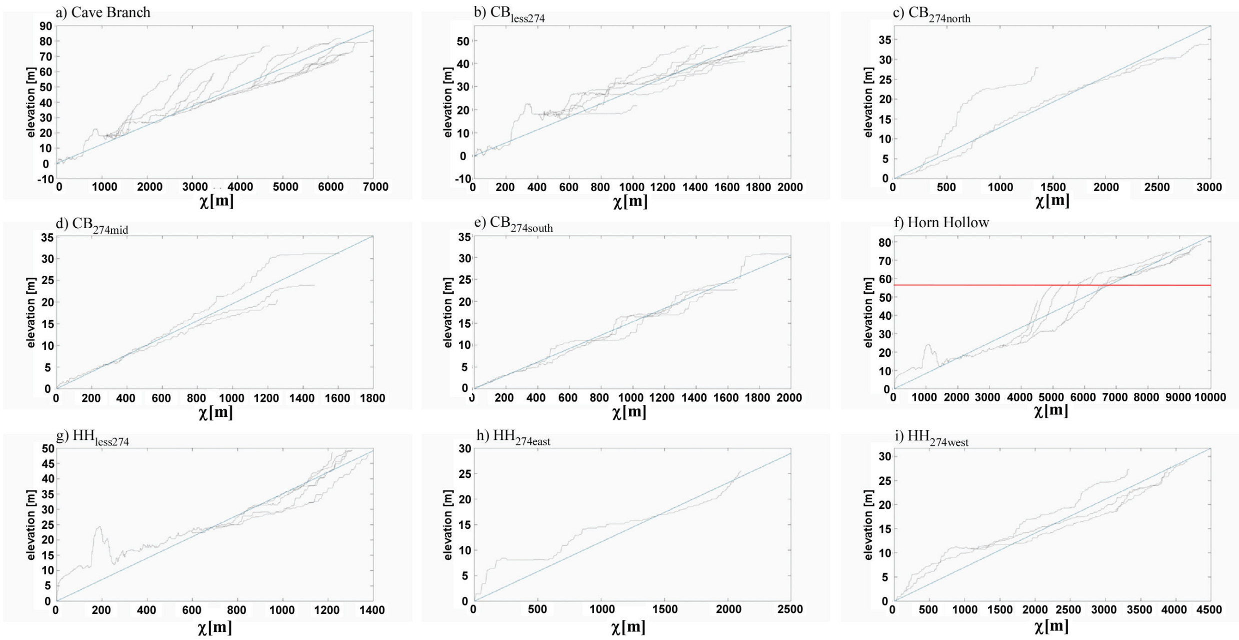

Figure 5. *Chi plots for the Cave Branch and Horn Hollow segments. Gray lines represent chi plot individual streams and the blue line represents best fit for the watershed. (a) Cave Branch, including sandstone and limestone segments. (b) $CB_{less274}$, limestone streams in Cave Branch below 274 MASL. (c) $CB_{274north}$, sandstone streams in Cave Branch above 274 MASL. (d) CB_{274mid}, sandstone streams in Cave Branch above 274 MASL. (e) $CB_{274south}$, sandstone streams in Cave Branch chi plot above 274 MASL. (f) Horn Hollow including sandstone and limestone streams- red line indicates 274 MASL. (g) $HH_{less274}$, limestone streams in Horn Hollow below 274 MASL. (h) $HH_{274east}$, sandstone streams in Horn Hollow above 274 MASL. (i) $HH_{274west}$, sandstone streams in Horn Hollow above 274 MASL.*

m/n	R^2	Steepness index
0.1	0.76	0.008
0.2	0.80	0.011
0.3	0.82	0.015
0.4	0.83	0.021
0.5	0.80	0.028
0.6	0.74	0.037
0.7	0.63	0.047
0.8	0.47	0.595
0.9	0.25	0.073

Table 2. *Sensitivity analysis of m/n ratio for the Cave Branch Basin.*

resistant than the sandstone. Thaler and Covington (2016) identified high steepness values for limestone underlying a sandstone caprock. They conclude that the steepness values for the limestone are a result of shielding by the caprock. This is a possible explanation, but not necessarily the case when all variables are considered.

One explanation for the different observed SI in the sandstones and limestone is the difference in weathering processes. As previously stated, sandstones are vulnerable to physical weathering, and limestone can be weathered by physical and chemical processes. In the limestone segments, streams can be diverted to the subsurface. The reason streams are diverted into the subsurface in a specific location is that water moving from a sandstone to a limestone is going to be more dissolutionally aggressive, having yet to be neutralized. The more aggressive water is likely to encourage dissolution and subsurface piracy, once in contact with soluble limestone. In the subsurface, the stream maintains an equilibrium profile, leaving a ‘bump’ in the profile where erosion is not occurring (White and White, 1983; Woodside et al., 2015). Furthermore, the difference in SI between limestone and sandstone streams could be due to the continued denudation in the limestone areas of Cave Branch and Horn Hollow. As streams in the limestone sections are diverted into the subsurface, the continued downcutting along the flowpath in the subsurface increases the gradient between the tributary and main

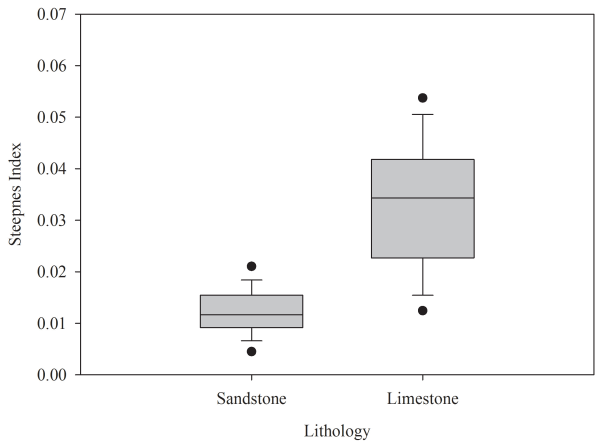

Figure 6. *Box plot of SI values of sandstone and limestone streams. The ends of the boxes represent the 25th and 75th percentiles with the solid line at the median and the dashed line at the mean; the error bars depict the 10th and 90th percentiles and the points represent the 5th and 95th percentiles.*

stem. Woodside et al. (2015) observed evidence of cave collapse in Horn Hollow. Instead of the typical v-shaped valley that develops along a bedrock stream, Horn Hollow displays vertical valley walls in areas. In areas where cave collapse has occurred, the steeper gradient is exposed to the surface. The existence of cave collapse would also explain the greater degree of equilibrium observed in the sandstone watersheds.

The third objective was to determine how erosional differences in the limestone and sandstone are related to the overall development. To answer this question, the assessments made from the first and second objectives must be considered concurrently. The greater degree of equilibrium in the sandstone watersheds and the greater steepness in the limestone streams is a function of both the soluble nature of limestone and the glacial-fluvial development of northeastern Kentucky. The rapid development of the fluviokarst system in northeastern Kentucky lead to the development of four distinct cave levels (Jacoby et al., 2013). The caves in the Horn Hollow and Cave Branch represent the levels of cave development linked to a common static base level. During these periods of stable base level, streams in the limestone segments were diverted to the subsurface. While in the subsurface, these limestone streams can maintain their equilibrium profile (White and White, 1983; Woodside et al., 2015). Over time, a subterranean stream can be exposed to the surface because of cave collapse. Woodside et al. (2015) saw evidence of cave collapse in Horn Hollow Creek. The disequilibrium in the limestone sections of Horn Hollow and Cave Branch is the result of cave collapse, which exposes the elevation differences between surface reaches and subsurface reaches. The greater SI in the limestone streams is a result of the subsurface piracy and eventual cave collapse. As the main stem continued to erode in the subsurface, the gradient between it and the tributaries increased. The sandstone streams, which generally had a greater degree of equilibrium had started to develop prior to glaciation when the system was a part of the Teays drainage system.

Within fluviokarst system in southeastern Minnesota, Schroeder et al. (2015) reported the absence of anomalous segments along the limestone streams. The difference between the fluviokarst system in southeastern Minnesota and the one in northeastern Kentucky appears to be the influence of glacial-fluvial events. The disequilibrium of the fluviokarst system in Kentucky, as indicated by dissimilar *m/n* values among stream reaches, suggests rapid development associated with glacial and interglacial periods has created the anomalous sections and the difference in equilibrium between the limestone and sandstone watersheds.

Conclusion

The purpose of this study was to determine how the variation in lithology was influencing the development of the fluviokarst system in CCSRP in northeastern Kentucky. To do this, streams were compared using an integral approach to the stream power equation that allows for the degree of equilibrium of watersheds and SI values of streams to be compared. The analyses reveal that sandstone watersheds were generally in a greater degree of equilibrium than the limestone watersheds and that the limestone streams had a greater SI. SI is a measure of a streams resistance to erosion, but when the differences in weathering processes in limestone and sandstone are considered, SI reveals more than just resistance to erosion. The soluble nature of limestone lends itself to the development of karst, while sandstone is eroded only by physical processes. The difference between the limestone and sandstone segments is due to the rapid development of the Ohio River valley in response to the glacial and interglacial periods. The glacial-fluvial influence explains the difference between the fluviokarst system in northeastern Kentucky as compared to the one in southeastern Minnesota.

One uncertainty that remains from this study are the result of the equilibrium analysis. While there was generally a greater degree of equilibrium in the sandstone watersheds than in the limestone watersheds, the entire Horn Hollow watershed had a greater degree of equilibrium than the individual subwatersheds. In contrast, the entire Cave Branch watershed had a lower R^2 than three of its four subwatersheds. While the R^2 values indicated that the entire Horn Hollow watershed was in a greater state of equilibrium than its subwatersheds, the transition from negative to positive *m/n* values suggests that, as a whole, the system is in a state of disequilibrium. Further investigation is warranted to understand the difference and the significance of R^2 and the application of *m/n*. This would allow for a better understanding of the differences between Cave Branch and Horn Hollow.

References

Angel JC, Peterson EW. 2015. Nitrates in karst systems: comparing impacted systems to a relatively unimpacted system. Journal of Geography and Geology 7 (1): 65–76.

Anthony DM, Granger DE. 2007. An empirical stream power formulation for knickpoint retreat in Appalachian Plateau fluviokarst. Journal of Hydrology 343 (3–4): 117–126.

ArcGIS E. 2011. Release 10: Redlands, CA, Environmental Systems Research Institute.

Bishop P. 2007. Long-term landscape evolution: linking tectonics and surface processes. Earth Surface Processes and Landforms 32 (3): 329–365.

Bočić N. 2003. Relation between karst and fluviokarst relief on the Slunj Plateau (Croatia). Acta Carsologica 32 (2): 137–146.

Carlston CW. 1969. Longitudinal slope characteristics of rivers of the midcontinent and the Atlantic East Gulf Shores. International Association of Scientific Hydrology. Bulletin 14 (4): 21–31.

Dogwiler T, Wicks CM. 2004. Sediment entrainment and transport in fluviokarst systems. Journal of Hydrology 295 (1–4): 163–172.

Duvall A, Kirby E, Burbank D. 2004. Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California. Journal of Geophysical Research: Earth Surface 109 (F03002): 18.

Engel AS, Engel SA. 2009. A field guide for the karst of Carter Caves State Resort Park and the surrounding area, northeastern Kentucky. In: Engel AS, Engel, SA, editors. Field Guide to Cave and Karst Lands of the United States, Karst Waters Institute Special Publication 15. Leesburg, VA: Karst Waters Institute. p. 154–171.

George AI. 1989. Caves and drainage north of the Green River. In: White WB, White, EL, editors. Karst hydrology: concepts from the Mammoth Cave area. New York: Van Nostrand Reinhold. p. 189–222.

Goldrick G, Bishop P. 2007. Regional analysis of bedrock stream long profiles: evaluation of Hack's SL form, and formulation and assessment of an alternative (the DS form). Earth Surface Processes and Landforms 32 (5): 649–671.

Hack JT. 1973. Stream-profile analysis and stream-gradient index. Journal of Research of the US Geological Survey 1 (4): 421–429.

Jacoby BS, Peterson EW, Dogwiler T. 2011a. Identifying the stream erosion potential of cave levels in Carter Cave State Resort Park, Kentucky, USA. Journal of Geographic Information Systems 3 (4): 323–333.

Jacoby BS, Peterson EW, Dogwiler T, Kostelnick JC. 2011b. Estimating the timing of cave level development with GIS. Speleogenesis and Evolution of Karst Aquifers 11: 52–61. http://www.speleogenesis.info/content/?vmode=article&id=10280.

Jacoby BS, Peterson EW, Kostelnick JC, Dogwiler T. 2013. Approaching cave level identification with GIS: A case study of Carter Caves. ISRN Geology 2013 (160397): 7.

Jakucs L. 1977. Morphogenetics of karst regions: variants of karst evolution. New York: Wiley.

Knighton D. 1998. Fluvial forms and processes: A new perspective. New York: Routledge.

Larue J-P. 2011. Longitudinal profiles and knickzones: the example of the rivers of the Cher basin in the northern French Massif Central. Proceedings of the Geologists' Association 122 (1): 125–142.

Mackin JH. 1948. Concept of the graded river. Geological Society of America Bulletin 59 (5): 463–512.

Miller JR. 1991. Controls on channel form along bedrock-influenced alluvial streams in south-central Indiana. Physical Geography 12 (2): 167–186.

Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109: 596–611.

Nesbitt HW, Fedo CM, Young GM. 1997. Quartz and feldspar stability, steady and non-steady-state weathering, and petrogenesis of siliciclastic sands and muds. Journal of Geology 105 (2): 173–192.

Perron JT, Royden L. 2013. An integral approach to bedrock river profile analysis. Earth Surface Processes and Landforms 38 (6): 570–576.
Peterson E, Dogwiler T, Harlan L. 2011. Using GIS to identify cave levels and discern the speleogenesis of the Carter Caves karst area, Kentucky. In: Kuniansky EL, editor, U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Arkansas (April 26–29, 2011). Reston, Virginia: United States Geological Survey. p. 94–103.
Phillips JD, Lutz, JD. 2008. Profile convexities in bedrock and alluvial streams. Geomorphology 102 (3): 554–566.
Royden L, Perron, JT. 2013. Solutions of the stream power equation and application to the evolution of river longitudinal profiles. Journal of Geophysical Research-Earth Surface 118 (2): 497–518.
Schroeder K, Peterson EW, Dogwiler T. 2015. Field validation of DEM and GIS derived longitudinal stream profiles. Journal of Earth Science Research 3 (3): 43–54.
Schwanghart W, Scherler, D. 2014. Short Communication: TopoToolbox 2 - MATLAB-based software for topographic analysis and modeling in Earth surface sciences. Earth Surface Dynamics 2: 1–7.
Sklar L, Dietrich WE. 2013. River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply. In: Tinkler KJ, Wohl E, editors. Rivers Over Rock: Fluvial Processes in Bedrock Channels. American Geophysical Union. p. 237–260.
Thaler EA, Covington MD. 2016. The influence of sandstone caprock material on bedrock channel steepness within a tectonically passive setting: Buffalo National River Basin, Arkansas, USA. Journal of Geophysical Research: Earth Surface 121 (9): 1635–1650.
The MathWorks Inc. 2016. MATLAB and Image Processing Toolbox Release 2016b, Volume 2016b: Natick, Massachusetts, The MathWorks, Inc.
USGS. 2017. 3D Elevation Program (3DEP), Volume 2017, United States Geological Survey.
Whipple KX, Tucker, GE. 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. Journal of Geophysical Research: Solid Earth 104 (B8): 17661–17674.
White EL, White WB. 1983. Karst landforms and drainage basin evolution in the Obey River basin, north-central Tennessee, U.S.A. Journal of Hydrology 61 (1–3): 69–82.
Wohl EE. 2013. Bedrock channel morphology in relation to erosional processes. In: Tinkler KJ, Wohl E, editors. Rivers Over Rock: Fluvial Processes in Bedrock Channels. American Geophysical Union. p. 133–151.
Wohl EE, Ikeda H. 1998. Patterns of bedrock channel erosion on the Boso Peninsula, Japan. The Journal of Geology 106 (3): 331–346.
Woodside J, Peterson EW, Dogwiler T. 2015. Longitudinal profile and sediment mobility as geomorphic tools to interpret the history of a fluviokarst stream system. International Journal of Speleology 44 (2): 197–206.