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Estimating the Timing of Cave Level Development with GIS

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Abstract: *Identifying cave levels provides insight into cave development and climatic changes that have affected a karst system over time. Cosmogenic dating has been used to interpret levels in Mammoth Cave and the Cumberland Plateau. This absolute dating technique has proven successful in determining cave paleoclimates and regional geomorphic history, but is expensive. The study presented here is a preliminary method to cosmogenic dating that can outline a region's speleogenesis using a Geographic Information System (GIS) and published denudation rates. The Carter Cave system in northeastern Kentucky is within the karst landscape found along the western edge of the Appalachians and contains multiple daylighted caves at various elevations along valley walls. These characteristics make the Carter Caves an ideal location to apply GIS to cave level identification and evolution as described by Jacoby et al. (in review), who identified the cave levels within the area. The authors concluded that an argument can be made for either four or five cave levels in the Carter Cave system; however, studies identified four levels in both Mammoth Cave and the Cumberland Plateau. Further analysis indicated that the fifth level formed as a result of a change in lithology rather than an event that influenced the local base level. This research is an extension of the conclusions presented by Jacoby et al. (in review). The GIS was used to calculate the volume of surficial material lost within each level as a result of degradational geomorphic processes. Then, level thickness lost and published denudation rates were used to calculate the relative time required to form each level. There was not one denudation rate applicable to each level within the cave system, but the rates varied between 12 m/Ma and 40 m/Ma. This study concludes that the cave system took between 3.4 and 5.7 Ma to form. This study did not perform an absolute dating of cave sediments or assess any detailed stratigraphic influence.*
Keywords: *Carter Cave, 3D Analysis, Speleogenesis. Mammoth Cave, Denudation.*

Introduction

In karst systems, extended periods of static base level along with active dissolution lead to the development of large passageways. Passages that are identified at similar elevations are believed to be formed by the same event and are collectively termed a level (Palmer, 1987). Knowing the position of levels gives insight into periods of constant baseflow and limited downcutting, revealing information about what was occurring climatically as the levels were forming. Static base level can be related to global glaciations as water is limited and consumed by glaciers. Multiple cave levels form from intermittent local base level lowering caused by changes in regional discharge, river patterns, catchment areas, or climate (Audra et al., 2007; Palmer, 1987). The cave level boundary is identified where steep vadose passages (i.e. canyons, shafts) change to low gradient phreatic passages (i.e. tubes, caverns). Determining the duration of level development provides insight on the periods of constant baseflow and on the geomorphic history of the area. Developing a timeline of events can combine with other area studies to develop an understanding of paleoclimate and demonstrate how upstream events affect regions downstream. Engel and Engel (2009) suggest that by understanding the timing of cave development, researchers can begin interpreting a region's paleoclimate and hydrologic systems.

Open cavities underground are pathways for groundwater flow and storage areas for sediment. The use of cave sediment to uncover paleoclimate and hydrologic history has only been occurring in the past few decades (White, 2007). Through dating the cave sediment, geologists are able to develop a more definite history of a cave system (Anthony and Granger, 2004). Sediments accumulate in mature cave passages during static base level and remain in the passages even after they are abandoned by flow during renewed incision. The deposited sediment provides a record of when water ceased

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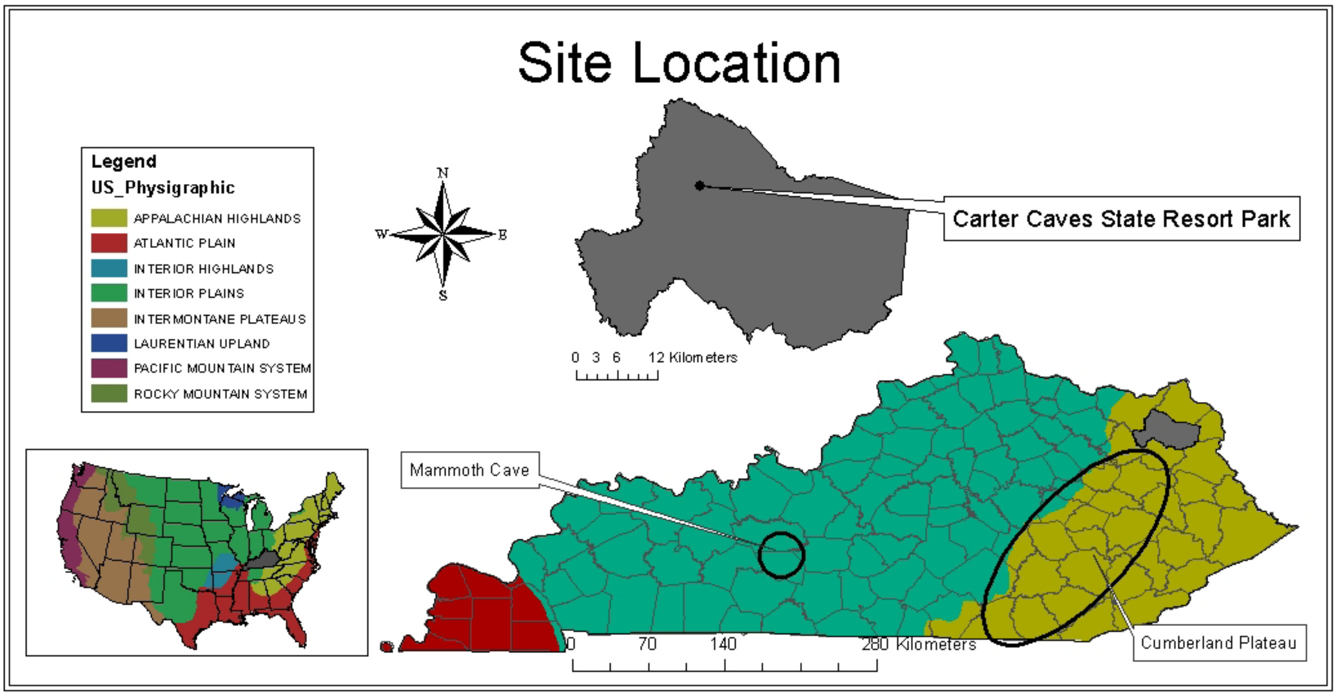

Figure 1. Location of Carter Caves State Resort Park (CCSRP).

flowing through the area. This record can be correlated to surface events and can aid in developing a region's climate and geomorphology history.

Mammoth Cave in central Kentucky (Figure 1) is an example of where successful sediment dating research has exposed information on the development of a cave system. Granger et al. (2001) developed a precise evolution of the Mammoth Cave system in relation to the incision of the Green River using cosmogenic dating of ^{26}Al and ^{10}Be isotopes in cave sediments. Their results showed incision occurred during the Pliocene-Pleistocene in response to various glacial events and the area maintained erosion rates of 2-7 meters per million years (m/my) for the past 3.5 my, despite increased river incision rates of 30 m/my during the Pleistocene. Granger et al. (2001) identified seven events that alternated between static base level and valley incision that controlled the development of the cave system. The authors concluded that as a result of multiple incision events, a minimum of four levels developed within Mammoth Cave National Park. The authors describe the presence of a fifth level; however, they did not strongly differentiate between the two levels at the highest elevations.

Located directly west of the Valley and Ridge Providence of the Appalachian Mountains (Figure 1), the Cumberland Plateau area is another heavily karstified area in Kentucky. According to Anthony and Granger (2004) this region has experienced about 180 million years of differential lowering between the sandstone units at the top of the plateau and the underlying limestone units. The differential lowering is linked to drops in the elevation of the water table. When the water table elevation maintained one elevation, time allowed for the development of passages and subsequently, levels. As the water table lowered again, rapid incision would terminate level development until the water table reached and maintained a stable elevation and the pattern would repeat itself. Anthony and Granger (2004) dated cave sediments through cosmogenic dating of ^{26}Al and ^{10}Be isotopes and found the clastic sediments in the area correlated well with known past deposition, uplift, and incision events in the area. Additionally, the authors correlated cave level development to incision by the Green River and Cumberland River, which occurred at times similar to those of the Mammoth Cave area. They also found that the area had a similar lithology and climate history to the Mammoth Cave system. Both systems are located within the unglaciated Ohio River Basin and their history of cave development went into the Pleistocene.

While numerous work has been published on the denudation in karst systems (Balazs, 1973; Corbel, 1959, 1965; Gabrovšek, 2007; Gams, 1981; Jennings, 1985; Oleksynowa and Oleksynowa, 1971; Plan, 2005; Pulina, 1971; Smith and Newson, 1974; White, 2009), there is limited published research that examines the calculation of the volume lost within a karst system, and none of the published work uses GIS to find the amount of sediment lost within a given karst system. There have been other varieties of volume calculation studies that used GIS including applications in dam removal and storage (Roberts et al., 2007; Vijay et al., 2005), glacial volume (Bocker, 1996; Clarke et al., 2009), gully monitoring (Marzolff and Poesen, 2009), and isostatic rebound of lakes (Yang and Teller, 2005), among others. Collectively, these studies demonstrate that using GIS and DEMs for volume calculations is an innovative and successful approach.

Approximately 290 kilometers east-northeast of Mammoth Cave is the Carter Cave system (Figure 1). The majority of the Carter Caves karst system is located within Carter Caves State Resort Park (CCSRP). The state park is located within Carter County, where approximately a quarter of the area is karstified (Engel and Engel, 2009). McGrain (1966), Ochsenbein (1974), Engel and Engel (2009), Peterson et al. (2011), and Jacoby et al. (*in review*) all discuss in detail the geology and the hydrogeology of the area. Below is a brief summary of those studies. CCSRP contains about 106 kilometers of deeply incised valleys. Cave Branch and Horn Hollow Stream are the primary tributaries in the park. Cave Branch flows into Horn Hollow Stream, and Horn Hollow Stream eventually joins Tygarts Creek. Tygarts Creek controls the local base level and flows north to the Ohio River. The Borden Formation is the oldest formation in the park, consisting of fine-grained sandstone, siltstone, and shale. This unit is overlaid by the Newman Formation which contains the caves the area is known for. The Newman Formation is made up of the St. Louis Limestone, the St. Genevieve Limestone, and the Upper Member of the Newman Formation. Capping the Newman Formation is the Pennington Formation which contains the Lee and Carter Caves sandstones. The units at CCSRP are similar to those found at Mammoth Cave, but have a thinner unit thickness. CCSRP has not been explored to the extent of Mammoth Cave, but is an ideal location to identify cave levels because of the amount of daylighted-caves at various elevations. Cave data can be used to establish the evolution of the cave system.

There are over 130 documented caves at CCSRP and over 18 kilometers of mapped passageways. Phreatic caves, active and inactive, in CCSRP tend to follow bedding planes and their development was controlled by preferential flow along less resistant beds within the limestone (Engel and Engel, 2009). Base level lowering has led to many of the caves in CCSRP displaying an overprinted vadose morphology on the phreatically formed conduits. Caves are found in all limestone units within the park, however the majority are found in the St. Genevieve Limestone.

Preceding Pleistocene glaciations, the region's landscape developed rather slowly and the base level remained at a stable elevation as compared to changes in the area after the beginning of the Pleistocene (Granger et al., 2001). The base level stability is believed to have contributed significantly to the development of large upper-level trunk conduits at Mammoth Cave (Granger et al., 2001), Cumberland Plateau (Anthony and Granger, 2004), and CCSRP (Engel and Engel, 2009; Peterson et al., 2011). At this time, the headwaters of the Teays River were located on the edge of the Piedmont Plateau in North Carolina, flowing north through CCSPR and onto west-central Ohio (Janssen, 1953; Ver Steeg, 1946). Once the Pleistocene began, the region was greatly influenced by the period's glaciations even though the area is south of the glacial maximum. As glacial meltwaters incised the area, sediments accumulated in the valleys. Engel and Engel (2009) suggest that remnants of these deposits can be found in the upper levels at CCSRP (i.e. Saltpetre Cave). As changes in base level continued, caves were forming at or below the water table (White, 1988). Granger et al., (2001) and Anthony and Granger (2004) have identified similar base level changes in two separate cave systems.

There is limited published information available that specifically examines CCSRP; however, the volume of research is growing. An unpublished database concerning the geographic locations of cave openings has been assembled by the Wittenberg University Speleological Society (WUSS). Sediment entrainment dynamics and frequency of the Cave Branch and Horn Hollow systems have been studied by Dogwiler and Wicks (2004). Woodside (2008) surveyed and analyzed the surface features within Horn Hollow in order to evaluate if they were true surface features or collapsed caves. His research has helped to identify false levels and to understand the cave network. Harlan (2009) and Peterson et al. (2011) began the work of identifying cave levels within the park through relating the cave data found by WUSS to a digital elevation model (DEM) with a 30-meter by 30 meter horizontal resolution. Those authors proposed a preliminary delineation of four levels within the park. Those findings correlate to the results in Mammoth Cave and the Cumberland Plateau, which are in a region similar to CCSRP (Anthony and Granger, 2004; Granger et al., 2001). Following the methods provided by Harlan (2009), Jacoby et al. (*in review*) refined level elevations using a 10-meter by 10-meter DEM and introduced the possibility of a fifth level (Table 1).

Advancing the work of Jacoby et al. (*in review*), the objective of this study is to determine the volume of material eroded during the level development and the interval of time required for each level to develop within CCSRP. Calculating the development time provides a better understanding of the evolution of the park. These calculated times will be analyzed to see how they compare to the speleogenesis of the Mammoth Cave system and the Cumberland Plateau system and to the incision history of the Ohio River Valley. Correlation between the systems would provide insight to the role of base level changes and paleoenvironments on karst development as well as provide more insight into the complicated karst hydrogeology. A secondary hypothesis examined in this work is that the number of cave entrances within each level correlates with the duration of time required to develop that level; that is, longer periods of static flow will result in more cave development. This hypothesis relies on the assumption that the number of cave openings was a proxy for passage size. We assumed the number of caves entrances (exits) to be directly related to the duration of cave development because longer exposure to water results in more dissolution greater passage development. Thus, as the river incises through the limestone, more cave entrances would be exposed. Unfortunately, as will be presented below, this hypothesis was shown to be invalid.

Table 1.

Level Summary Data for Options 1 and 2.

Option 1							
	Range of Level Elevations (m)[1]	Mean Cave Elevation (m)	Number of Caves	Percentage of Caves (%)	Volume (m^3)	Area (m^2)	Equivalent thickness lost (m)
Level 4	253-274	262	52	36	399,196,336	14,135,946	28.2
Level 3	240-253	247	44	30	120,945,389	5,969,867	20.3
Level 2	228-240	234	37	25	61,563,967	3,052,859	20.2
Level 1	214-228	222	13	9	39,026,737	2,472,838	15.8
Option 2							
	Range of Level Elevations (m)[1]	Mean Cave Elevation (m)	Number of Caves	Percentage of Caves (%)	Volume (m^3)	Area (m^2)	Equivalent thickness lost (m)
Level 5	263-274	268	27	19	253,014,693	8,909,453	28.4
Level 4	253-263	259	25	17	146,181,642	5,226,493	28.0
Level 3	240-253	247	44	30	120,945,389	5,969,867	20.3
Level 2	228-240	234	37	25	61,563,967	3,052,859	20.2
Level 1	214-228	222	13	9	39,026,737	2,472,838	15.8

[1] (Jacoby et al., in review).

1. Methods

Jacoby et al. (*in review*) used a Geographic Information System (GIS) to find and visualize the location of levels within CCSRP. The authors referred to the levels within CCSRP as either Option 1, which consisted of 4 levels, or Option 2, which consisted of 5 levels. The difference between the two options is that Level 4, Option 1 is divided to form levels 4 and 5 in Option 2. Level elevations found are as follows: Level 1 is between 214-228 meters, Level 2 is between 228 and 240 meters, Level 3 is between 240 and 253 meters, Level 4, Option 1 is between 253 and 274 meters, Level 4, Option 2 is between 253 and 263 meters, Level 5, Option 2 is between 263 and 274 meters (Table 4). Jacoby et al. (*in review*) results were used in ESRI's ArcGIS 9.3™ to calculate the volume of material lost between consecutive levels. The volume calculations in conjunction with denudation rates from the literature were used to determine the time required to erode the material between each level. The following data sources were used in this analysis: latitude and longitudes of cave entrance (exit) locations provided by WUSS and a 1/3 arc second (approximately 10 meter) digital elevation model (DEM) at a 1:24,000 scale downloaded from seamless.usgs.gov. The DEM was used to calculate the area and volume of surficial material lost within each level. According to the National Standard for Spatial Data Accuracy (NSSDA) horizontal accuracy associated with these 10 meter DEMs is approximately 13.906± meters while the vertical accuracy is approximately 0.3632± meters (Blak, 2007).

To calculate surface area and volume of removed material with the least amount of distortion, the DEM was converted to the North America Albers Equal Area Conic projection. The level elevations from Jacoby et al. (*in review*) (Table 1) were used in the 3D Analysis extension of ESRI's ArcGIS 9.3™ to calculate the volume and area of material lost beneath each level. 3D Analysis connects raster cell centers, creating a triangulated irregular network (TIN), and determines its contribution to area and volume. The output volume is the surface area times the vertical distance between a specified reference plane (or elevation) and the top of the surface (ESRI, 2010) (Figure 2a and 2b). The output volume is only a measurement of the material lost within the valleys. Note that this tool only provides the volume of material lost on the surface and does not measure the volume of material lost within the non-daylighted karst system. Another issue is that an assumption is made that all material that was removed was removed during the development of the next level, which is not true given erosional process will be continuous. The implication of this assumption is presented in the discussion. As illustrated in Figure 2, the volume and surface area of each level was calculated through subtraction as presented in Equation (1):

Total Level Volume = (Volume Beneath Top of Level) – (Volume Beneath Base of Level) (1)

The calculation for the total thickness of material lost needs to consider the variation in topography as seen in the DEM. Therefore, calculating the difference between level elevations is not an accurate estimation of material lost and the quotient of volume over area must be used. To calculate the thickness of lost material, Equation (2) was used. Again, this value is a measurement of thickness lost within the valley, not the thickness of material lost within the existing cave passageways.

Total Thickness Lost = (Level Volume) / (Level Area) (2)

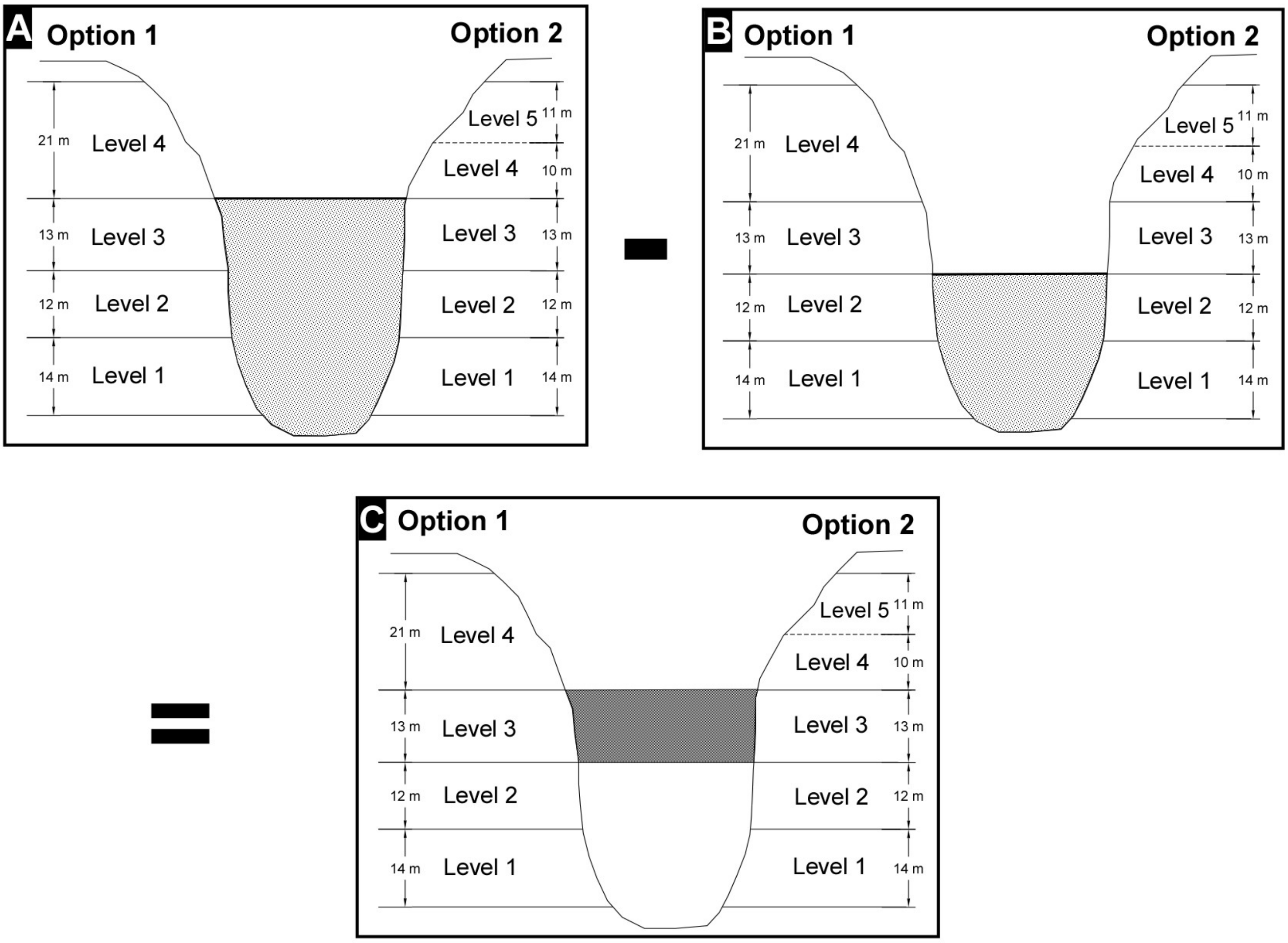

Figure 2. Visual depiction of how the 3D Analysis tool is used to calculate the volume of material removed and the surface area as represented for the study area. The GIS outputs the area and volume of the open space below a specified elevation (light gray, 2a and 2b). To find the area and volume for each level, 2a was subtracted from 2b, which gave the volume and area for each level (2c). Note that this figure is a schematic drawing and does not represent any specific location within the park.

Once the thickness of material lost (Table 1) was calculated, the amount of time required to remove the material was determined. Time was calculated using equation (3) (Gabrovšek, 2007; White and White, 1991). The most reasonable rate will be identified based on how the time calculations compares to regional isotopic dating studies (Table 2).

Time = (Thickness Lost) / (Denudation Rate) (3)

Denudation rates were obtained from the literature (Table 3). Because denudation rates vary based upon fluvial gradients and rock type, multiple rates were used in the modeling. White (2009) has established a rate of 30 m/Ma for the Appalachian region, which includes the CCSRP area. However, simulations were conducted with denudation rates greater than and less than to 30 m/Ma to determine the most representative rate. Denudation rates were chosen based on their common occurrence in the literature or their relationship to 30 m/Ma (Table 3). There are multiple denudation rates presented for comparison, thus allowing for an understanding of how sensitive the time calculations are to denudation rates.

2. Results

Table 1 shows the volume and area calculation results for options 1 and 2. Regardless of the option designation, the volume, area, and equivalent material thickness lost for each level increases with level elevation and age. Level 1 has an estimated volume loss of 39 million cubic meters and a thickness loss of approximately 15.8 meters. Level 2 has an estimated volume loss of 62 million cubic meters and a thickness loss of approximately 20.2 meters. Level 3 has an estimated volume loss of 121 million cubic meters and a thickness loss of approximately 20.3 meters. Level 4, Option 1 has an estimated volume loss of 400 million cubic meters and a thickness loss of approximately 28.2 meters. Level 4, Option 2 has an estimated volume loss of 146 million cubic meters and a thickness loss of approximately 28.0 meters. Level 5,

Table 2

The extent of level formation at Mammoth Cave and the Cumberland Plateau. Level A and B were crossed out because these data were estimated and not used for comparisons in this study. Note that levels in for Mammoth Cave and Cumberland Plateau are in reverse order of the designation at CCSRP. Therefore, A and 1 are the oldest and highest elevation at Mammoth Cave and Cumberland Plateau, respectively.

Mammoth Cave[1]			CCSRP[2]			Cumberland Plateau[3]		
Cave Level	Age (Ma B.P.)[4]	Extent (Ma)	Option 1 Age (Ma B.P.)	Cave Level	Option 2 Age (Ma B.P.)	Cave Level	Age (Ma B.P.)	Extent (Ma)
			NA	5	5.74	1	5.7-3.5	2.2
~~A~~	~~3.25~~	~~0.95~~	3.38	4	3.37	2	3.5-2	1.5
~~B~~	~~2.3~~	~~0.38~~				3	2-1.5	0.5
C	1.92	0.53	1.97	3	1.97			
D	1.39	0.15	1.46	2	1.46	4	1.5-.8	0.7
E	1.24	0.54	0.79	1	0.79	5	0.8	0.8

[1](Granger et al., 2001)
[2](Peterson et al., 2011)
[3](Anthony and Granger, 2004; White, 2007)
[4]Ma B.P. stands for millions of years before present.

Table 3

Table displaying chosen denudation rates and their corresponding geographic location

Rate (m/Ma)	Geographic Location	Climate Conditions (if provided)
9.5	Logatec Doline, Slovenia (Gams, 1981)	TEMPERATE
12-13	Clare-Galway, Ireland (Jennings, 1985) Poland (Pulina, 1971) Logatec Doline (Gams, 1981)	TEMPERATE TEMPERATE TEMPERATE
20	Krakow Plateau (Corbel, 1965) Aggtelekm, Hungary (Balazs, 1973)	TEMPERATE TEMPERATE
30	Appalachians, USA (White, 2009) Yucatan, Mexico (Corbel, 1959)	TEMPERATE TROPICAL
40	Austrian Alps (Plan, 2005) Laboratory derived maximum rate (Gabrovšek, 2007)	ALPINE N/A
50	Mendips, England (Smith and Newson, 1974) Poland (Oleksynowa and Oleksynowa, 1971)	TEMPERATE TEMPERATE

Option 2 has an estimated volume loss of 253 million cubic meters and a thickness loss of approximately 28.4 meters.

After using the equivalent thickness lost from Table 1 and the denudation rates from Table 3, the range of level development extent times were found (Table 3). It is possible that speleogenesis took anywhere from 1.69 Ma (at 50 m/Ma) to 11.85 Ma (at 9.5 m/Ma) to occur (Table 4). Regional karst formation is believed to have begun after 5.6 Ma before present (B.P.) (White, 2009 and Anthony and Granger, 2006). The estimation concerning the beginning of karst formation can help narrow down an appropriate denudation rate for CCSRP. Whether the system has four or five levels present, a rate of 20 m/Ma appears to fit the literature well. Considering this rate, development of Level 5, Option 2 took 1.42 Ma to form, Level 4, Option 2 took 1.40 Ma to form, Level 4, Option 4 took 1.41 Ma to form, Level 3 took 1.01 Ma to form, Level 2 took 1.01 Ma to form and Level 1 took 0.79 Ma to form. This equates to the speleogenesis represented by Option 2 taking 5.63 Ma to form and the speleogenesis represented by Option 1 taking 4.22 Ma to form.

The extent of level development in Mammoth Cave and Cumberland Plateau are shown in Table 2. After comparing the timing calculations to isotopic dating studies performed at Mammoth Cave and the Cumberland Plateau, it is evident that one denudation rate is not efficient for revealing the region's speleogenesis. Taking this possibility into consideration, it

Table 4

The timing of level development based rates chosen (Table 1). Geologist studying the Appalachians have found 30 m/Ma (White, 2009), outlined here in bold, to represent overall denudation occurring in the area. Gray cells represent denudation rates that best fit the time of level development for the Cumberland Plateau and Mammoth Cave studies

Option 1

	Equivalent thickness lost (m)	9.5 m/Ma	12 m/Ma	20 m/Ma	30 m/Ma	40 m/Ma	50m/Ma
		Length of Time for Level Development (Ma)					
level 4	28.2	2.97	2.35	1.41	0.94	0.71	0.56
level 3	20.3	2.13	1.69	1.01	0.68	0.51	0.41
level 2	20.2	2.12	1.68	1.01	0.67	0.5	0.4
level 1	15.8	1.66	1.32	0.79	0.53	0.39	0.32
Total system development time possible (Ma)		8.89	7.04	4.22	2.81	2.11	1.69

Estimated system development time (Ma) based on chosen rates: 3.38

Option 2

	Equivalent thickness lost (m)	9.5 m/Ma	12 m/Ma	20 m/Ma	30 m/Ma	40 m/Ma	50m/Ma
		Length of Time for Level Development (Ma)					
level 5	28.4	2.99	2.37	1.42	0.95	0.71	0.57
level 4	28.0	2.94	2.33	1.4	0.93	0.7	0.56
level 3	20.3	2.13	1.69	1.01	0.68	0.51	0.41
level 2	20.2	2.12	1.68	1.01	0.67	0.5	0.4
level 1	15.8	1.66	1.32	0.79	0.53	0.39	0.32
Total system development time possible (Ma)		11.85	9.38	5.63	3.75	2.81	2.25

Estimated system development time (Ma) based on chosen rates: 5.74

appears that Level 5, Option 2 took 2.37 Ma to form at a rate of 12 m/Ma, Level 4, Option 2 took 1.40 Ma to form at a rate of 20 m/Ma, Level 4, Option 1 took 1.41 Ma to form at 20 m/Ma, Level 3 took 0.51 Ma to form at a rate of 40 m/Ma, Level 2 took 0.67 Ma to form at a rate of 30 m/Ma, and Level 1 took 0.79 Ma to form at 20 m/Ma. This equates to Option 2 taking approximately 5.74 Ma to form and Option 1 taking 3.38 Ma to form. These values fit well with the timing established by Anthony and Granger (2004) and Granger et al. (2001).

The thickness estimations showed that the greatest volume lost within the system was at the top most levels. The timing estimations indicated that the upper levels also took the longest to form. It is important to note that levels at higher elevations were continuing to erode, even past their suggested “event”. For this reason, the results are partially skewed at the top most elevations because the value of thickness lost includes material lost during the formation of lower levels. In other words, the event causing the formation of Level 5, Option 2 might have been shorter than 2.37 Ma if the amount of material removed during the formation of lower levels could be eliminated from the thickness lost estimation. Although there are previous GIS volume studies (Bocker, 1996; Yang and Teller, 2005) that modeled landscape development through time, the authors did not address the possibility that surface volume lost at higher elevations occurred during the development of lower elevations. Therefore, adjusting for error caused by older levels eroding during the formation of younger levels has not been addressed.

3. Discussion

This study has indicated that one denudation rate is not sufficient for understanding CCSRP speleogenesis. At least four rates, ranging from 12 to 40 m/Ma (Table 4) have influenced this area over time. The actual denudation rate is dependent on the climate, rock characteristics and composition, as well as the amount of precipitation occurring during time of incision (White, 2009). Climate conditions varied during each level formation event and therefore finding multiple denudation rates is not surprising. However, Granger et al. (2001) established that the Appalachian area has maintained a rate of 2-7 m/Ma although the river incision maintained a rate of 30 m/Ma during the Pleistocene. If the denudation rates identified in this study were averaged together, a rate of approximately 24 m/Ma would have been occurring during the extent of development. This value is not far from the denudation rate established by White (2009). White discussed the denudation rate as a result of various glaciation events whereas this study is attempting to specify denudation occurring between glaciation events. That detail could explain the small differences seen here. The fact that the cave development rates are not similar to area erosion indicates that cave development is more in sync with river incision than other area erosion. This is understandable because this cave system is within the valley walls of Horn Hallow and Cave Branch tributaries and both of these tributaries have contributed directly to karst development. Horn Hollow and Cave Branch both empty into Tygarts Creek which extends through most of the Appalachian karst in northern Kentucky.

We expected to find the number of cave openings to correlate to the duration of level development, taking the assumptions that 1) longer periods of static flow results in more cave development and 2) cave openings are a proxy to cave development. The amount of cave openings did not correlate well with level development time (see Table 1, Table 4, and Figure 3). The longest level development time was at 2.37 Ma for Level 5, Option 2 which only contained 27 cave openings (19% of registered caves). The shortest level development time was at 0.51 Ma for Level 3 but contained 44 cave openings (30% of registered caves). A reason for the lack of correlation is that cave openings are not a proxy to the extent of cave development and therefore are not solely representative of the volume lost within a level. Instead, the openings are more the result of fractures, weaknesses, or flow pathways within the rock than a proxy to the size or amount of existing passageways. Another reason for the insignificant correlation between level development time and cave openings present in each level could be due to the error associated with the total volume of material lost for levels at high elevations includes material lost during the formation of lower levels. This study cannot conclude that, because cave openings do not correlate well with the extent of level development, static flow does not create more caves. Levels that took the longest to develop may still contain larger or a higher frequency of passages, even though they contain a small amount of cave openings. Future research should focus on the volume of material lost within a passageway rather than simply the number of cave openings present at the surface in order to find evidence of how static flow affects the system and if a greater volume lost is directly related to development time.

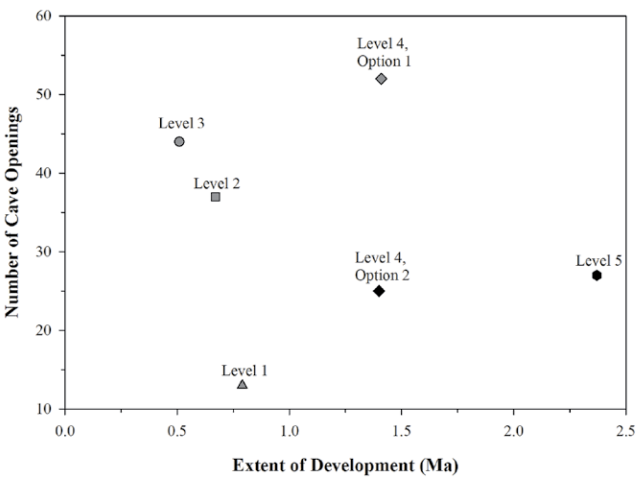

Figure 3. Relationship between the number of cave openings per level (Table 1) and the estimated level development time as calculated in Table 4.

The results presented in this study suggest that level formation at CCSRP is similar to the level evolution at the Cumberland Plateau (Table 2). The calculated development times closely match those of the Cumberland Plateau. The correlation could be because both areas have a similar Appalachian terrain while Mammoth Cave is on the western edge of the Appalachian Plateau. The Cumberland Plateau also has a similar contact between the karst and capping silicicalstic units. The lithology change likely contributes to a concentrated area of cave formation at the contact as water proceeds to infiltrate the limestone. The similarities between the regions are further evidence to support the presence of five levels in CCSRP.

Sediments found within the caverns of Cumberland Plateau concede that there was active sediment transport between approximately 5.7 and 3.5 Ma B.P. (Anthony and Granger, 2006). The time frame for the Cumberland Plateau supports the result of this study that the Carter Caves system was beginning to form between 5.74 and 3.38 Ma B.P. The event that contributed to the formation of Level 5, Option 2, Level 4, Option 2, or Level 4, Option 1 was not able to be determined during this study. If there is a fifth level present, its formation is possibly the result of a stratigraphic or bedrock change rather than an event causing a change in base level. Transitions from levels 4 through 1 were found by correlating calculated times to regional paleoclimate studies. Multiple authors (Anthony and Granger, 2006, Cronin, 1988, Phillips, 2009, and Teller and Goldthwait, 1991) state that sea level dropped between 3.2 and 2.0 Ma B.P. This sea level drop was due to climate cooling and growth of continental glaciers. This drop in sea level likely contributed to the transition of Level 4 (of both options) to Level 3. Global warming occurred at 3.0 Ma B.P., followed by another cooling progression at 2.4 Ma B.P. According to evidence in the Cumberland Plateau region (Anthony and Granger, 2004), this event did not last longer than about 1.5 million years. After 2.4 Ma B.P., there was a major sea regression which likely caused the tributaries to quickly incise. The transition from Level 3 to Level 2 likely occurred near 2.0 Ma B.P. during an incision pulse at Parker Strath (Anthony and Granger, 2004). Following the incision event, there was a brief pause in river base level. Prior to 1.3 Ma B.P., the transition between Level 2 to Level 1 occurred. From 1.3 Ma B.P. on, there were oscillating events between incision and base level stability. The youngest sediments found in caves at Mammoth Cave (Granger et al., 2001) and Cumberland Plateau (Anthony and Granger, 2004) date back to 0.8 Ma B.P.

4. Conclusions

This study found that volume of material removed, surface area, and the thickness (relative volume) of lost surficial material within each level increases with level age and level elevation. Levels at higher elevations formed over a longer time period than levels at lower elevations. Longer level development appears to correlate to greater material removal, especially at high elevations. However, there needs to be caution taken with these statements since the volume of material lost for the older levels incorporates material that would have eroded during subsequent level development. There appears to be different denudation rates for various levels indicating there is not a universal rate for the system. If one denudation rate had to be chosen from this study, it would be 20 m/Ma. Currently, level development appears to have begun between 3.4 and 5.7 Ma B.P.

There is evidence that supports five cave levels within this system. Both the Mammoth Cave and Cumberland Plateau studies have strong evidence for four levels. However, both studies also mentioned that a fifth level was possible. We propose that the fifth level is not a result of a base level change, but a result of water flowing along a bedding plane at 274 meters, the contact between limestone and sandstone units. A limitation of this method is that it requires the results of area absolute dating studies in order to find reasonable results. Choosing the correct denudation rate with this method is difficult without guidance. In addition, the calculation of volume and area was possible for the CCSRP area because the stratigraphy is relatively flat lying. Significantly dipping beds would influence calculating the timing of development because karst development would have to be considered in relationship to structure-changing events. Furthermore, the 3D Analysis tool only calculates volume and area beneath a horizontal surface. A significantly dipping bed would require further research into how to use GIS tools to calculate its volume and area. Challenges that are common with volume studies include quality of data, identification of boundaries, computing process time, organizing data, software expertise, and varieties within the method chosen.

There is a significant future that lies ahead for volume calculations using GIS. As DEMs become more detailed and LiDAR data becomes more available, volume calculations will become more accurate. Better accuracy will encourage a wider use of GIS in volume and area calculations. The current application of GIS volume analysis is diverse ranging from urban planning to reconstructing paleoenvironments. Finding new applications for GIS area and volume calculations will only increase the versatility of this technology. This research has demonstrated one unique approach, but there are others yet to be discovered. Future work could explore how better resolution data improves analysis or how to accurately calculate volume within underground passages.

Overall, this method has proven successful in estimating the volume of material removed, surface area, and the thickness of removed surficial material from cave levels in a given area. The modeling work confirms that only four levels are a result of static baseflow periods. The timing calculated is also consistent to other area level studies. Research in similar landscape conditions is needed to support this study's results and to expand GIS applications in karst landscapes. This work contributes to the understanding of the Carter Caves system's evolution and introduces new ways of approaching karst geology.

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