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Estimating the timing of cave level development with GIS

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Using Geographic Information System to Identify Cave Levels and Discern the Speleogenesis of the Carter Caves Karst Area, Kentucky

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Abstract

Cave level delineation often yields important insight into the speleogenetic history of a karst system. Various workers in the Mammoth Cave System (MCS) and in the caves of the Cumberland Plateau Karst (CPK) have linked cave level development in those karst systems with the Pleistocene evolution of the Ohio River. This research has shown that speleogenesis was closely related to the base level changes driven by changes in global climate. The Carter Caves Karst (CCK) in northeastern Kentucky has been poorly studied relative to the MCS to the west and the CPK karst to the east. Previously, no attempt had been made to delineate speleogenetic levels in the CCK and relate them to the evolution of the Ohio River.

In an attempt to understand cave level development in CCK we compiled cave entrance elevations and locations. The CCK system is a fluviokarst typical of many karst systems formed in the Paleozoic carbonates of the temperate mid-continent of North America. The CCK discharges into Tygarts Creek, which ultimately flows north to join the Ohio River. The lithostratigraphic context of the karst is the Mississippian Age carbonates of the Slade Formation. Karst development is influenced by both bedding and structural controls. We hypothesize that cave level development is controlled by base level changes in the Ohio River, similar to the relationships documented in MCS and the karst of the Cumberland Plateau

The location and elevation of cave entrances in the CCK was analyzed using a GIS and digital elevation models (DEMs). Our analysis segregated the cave entrances into four distinct elevation bands that we are interpreting as distinct cave levels. The four cave levels have mean elevations (relative to sea level) of 228 m (L1), 242 m (L2), 261 m (L3), and 276 m (L4). The highest level—L4—has an average elevation 72 m above the modern surface stream channel. The lowest level—L1—is an average of 24 m above the modern base level stream, Tygarts Creek. The simplest model for interpreting the cave levels is as a response to an incremental incision of the surface streams in the area and concomitant adjustment of the water table elevation. The number of levels we have identified in the CCK area is consistent with the number delineated in the MCS and CPK. We suggest that this points toward the climatically-driven evolution of the Ohio River drainage as controlling the speleogenesis of the CCK area.

INTRODUCTION

Surface rivers play an integral role in the formation of many karst systems. In fluviokarst settings, the formation of phreatic cave passages is thought to occur at, or just below, the water table; hence as the rivers incise, lower levels of conduits are formed at increasingly lower elevation (Ford and Williams, 2007; Palmer, 1987). As a karst system evolves, subsurface drainage at the current base level becomes more efficient at draining the watershed and surface systems and upper cave levels go dry (Kaufmann, 2009). Just as the development of terraces represent periods of river stability in surficial fluvial settings, the formation of cave levels across a region provide an archive recording periods of base level stability (Kaufmann, 2009; Palmer, 1987).

The Ohio River and its tributaries provide ample evidence of this phenomenon. The entrenchment of the Ohio River and its tributaries produced multiple levels in the Mammoth Cave System (MCS) (Granger and others, 2001; Palmer, 1989) and in the Cumberland Plateau region (CPK) (Anthony and Granger, 2004). In the Mammoth Cave region and the Cumberland Plateau, investigators have demonstrated that alternating periods of climate-

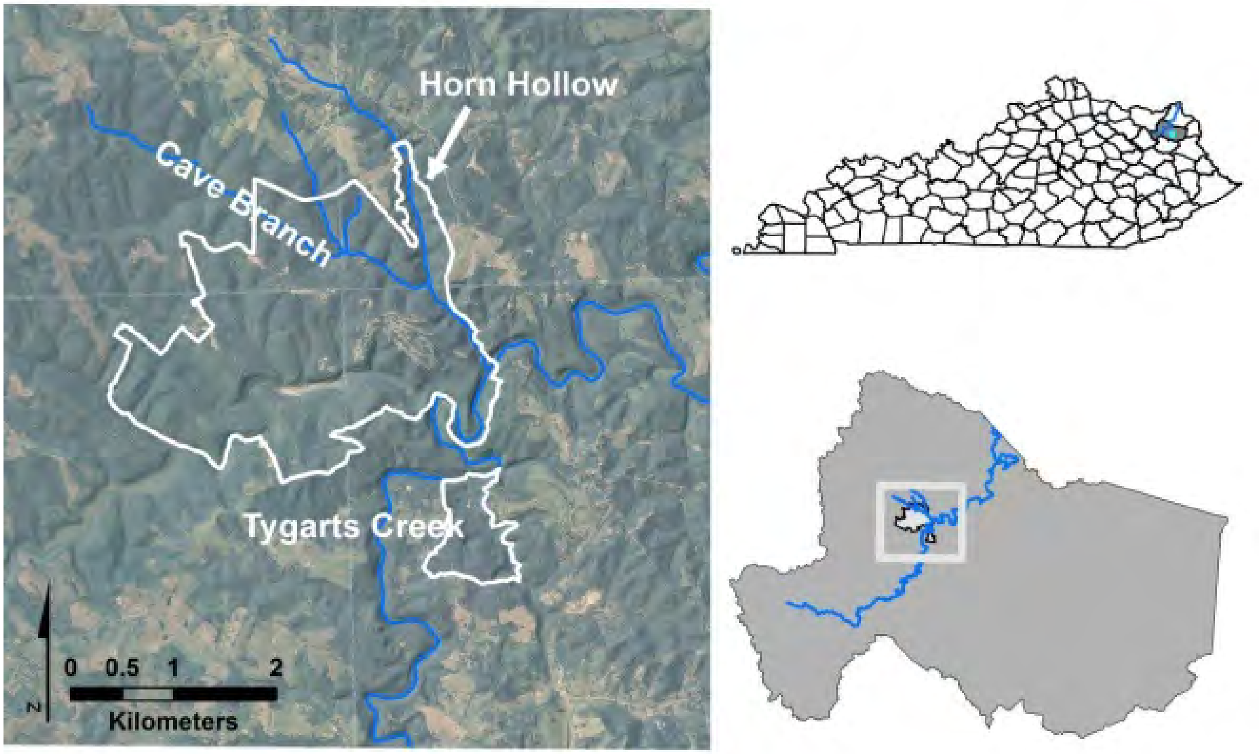

Figure 1. Location of the study area, highlighting Carter Caves State Resort Park. In the aerial image on the left, the park boundary is outlined in white. Rivers are represented as blue lines. The location of Carter County is shown in the map in the upper right. The location of the state park within Carter County is shown in the lower right figure**.**

driven incision and aggradation of the Ohio River have strongly influenced the evolution of the those karst systems over the past 3-5 million years (Anthony and Granger, 2004; Granger and others, 2001). In both cases, pre-existing cave systems experienced significant vertical development and modification during the Plio-Pleistocene due to changes in erosional base level, which forced alternating periods of incision and aggradation in river valleys south of the glacial margin (Teller and Goldthwait, 1991). Isostatic responses of the continental crust to the waxing and waning of ice sheets and the resulting transmission of glacially-derived sediment packages down the Ohio River valley also played a role in the rates of stream erosion and deposition (Granger and others, 2001; Potter, 1955).

The MCS has four main cave levels[1] (Granger and others, 2001) which generally correlate with similar levels in the CPK (Anthony and Granger, 2004). These cave levels all ultimately coincide with base level changes in the Ohio River and its predecessor drainages. The oldest and highest cave levels formed in the Pliocene during a period of extremely low rates of river incision and landscape denudation. This led to long-term stabilization of water table levels and the development of extensive and large conduit systems (e.g., Collins Avenue in the MCS). With the onset of Pleistocene glaciation and the evolution of the modern Ohio River drainage, base level stability ended and a sequence of rapid incision and aggradation led to the development of several new cave levels. We hypothesize that the Carter Caves Karst (CCK) in Carter County, northeastern Kentucky, developed due to a similar speleogenetic response to the reorganization of the Ohio River drainage.

Geologic Context

The CCK is located about 40 km south of the Ohio River in northeastern Kentucky (Fig. 1) and has a stratigraphic and geologic setting similar to that of the MCS. The system has been described by several authors including (e.g., McGrain, 1966; Tierney, 1985). More recently, Engel and Engel (2009) provide a thorough and

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[1] In MCS and CPK the cave levels are lettered with level ‘A’ representing the upper-most level in the system. In CCK we designated our lowest level ‘L1’ and increased the number (i.e., ‘L2’, ‘L3’, ‘L4’) with each higher elevation.

up-to-date discussion of the local geologic setting, including an updated synthesis of the area's stratigraphy. Unlike the larger karst systems in western Kentucky or West Virginia, karstification in the Carter Caves area is constrained by a relatively thin sequence of karstifiable carbonates (Engel and Engel, 2009). The carbonate sequence is Mississippian (latest Osagean to late Chesterian times) in age and is sandwiched between Mississippian and Middle Pennsylvanian siliciclastics (Ettensohn and others, 1984).

Northeastern Kentucky has experienced a complex drainage evolution through the Plio-Pleistocene as the Teays River system was abandoned and reorganized into the Ohio River drainage (Andrews, 2006; Rhodehamel and Carlston, 1963; Teller and Goldthwait, 1991; Ver Steeg, 1946). Prior to the onset of Pleistocene glaciation, northeastern Kentucky was part of the Teays River basin (Janssen, 1953). Currently, the CCK area is highly dissected and characterized by deeply-incised stream valleys that are graded to Tygarts Creek, the regional baselevel. Tygarts Creek flows north through Carter and Greenup Counties toward its confluence with the Ohio River. Locally, Tygarts Creek has a very low gradient of 0.0007 m/m.Tygarts Creek is currently incised through the carbonate sequence into the shales of the underlying Borden Formation (Engel and Engel, 2009; Tierney, 1985). Thus, the lower stratigraphic limit of surficial karst development has been reached. Within the study area, Horn Hollow Creek drains to Cave Branch which in turn flows to Tygarts Creek. These tributary valleys are steeply graded (average of 0.053 m/m) and are underlain by the karst-forming carbonates. The tributary streams are characterized by numerous small waterfalls, sinking streams, and numerous resurgent springs. In Horn Hollow the stream is diverted into the subsurface by several caves (during floods, some flow is diverted to normally dry surface channels).

The CCK is a fluviokarst system and is comprised of the surface and subterranean drainage associated with Tygarts Creek and its tributaries. The karst system includes a number of watersheds tributary to Tygarts Creek. Engel and Engel (2009) attribute the consistent distribution of caves with the same stratigraphic units throughout the various watersheds as evidence of simultaneous karstification. Engel and Engel (2009) also note two morphologically distinct cave passage types. The first are large trunk passages, that are stratigraphically high and whose development is controlled both by structure and stratigraphy. The second passage type are smaller passages, that are stratigraphically lower in the bedrock section and are characterized by simple passage segments with morphologies indicative of incision-driven water table lowering. The development of these passages was strongly controlled by bedrock fractures. Engel and Engel (2009) interpret these passage types as representing at least two distinct periods of karstification.

Methodology

Our objective is to assess the feasibility of applying the incision driven model of speleogenesis derveloped for the MCS(Granger and others, 2001) and the Cumberland Plateau region(Anthony and Granger, 2004) to the CCK. More specifically, we posit that if cave levels can be distinguished in the CCK system, it may be possible to link them to the evolution of the Ohio River drainage, and thus devise a model for the timing and style of speleogenesis in CCK. The evolution of those systems has been worked out using sophisticated and expensive geochemical analysis, particularly of speleothems and cave sediments. Herein, we attempt to extrapolate the results of those studies in combination with GIS-based analysis of remotely-sensed data and direct observations into a robust model for the speleogenetic history of the CCK. Such an approach may be attractive to workers deciphering systems that lack the geoarchives (i.e., well-understood and wide spread sediments) that exist in these other systems or the technical and financial resources required for the requisite analytical methodologies employed in those systems. Studies such as ours may also provide a framework and an impetus for employing sophisticated analytical methods such as those used in MCS and CPK.

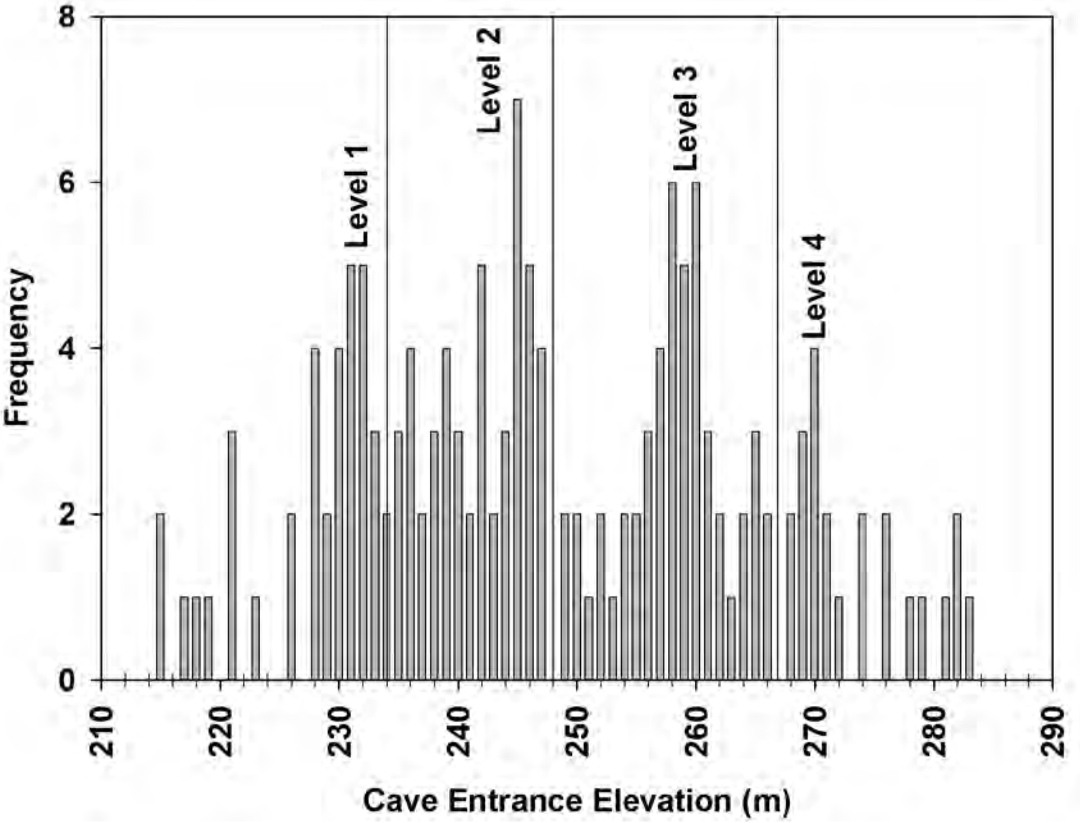

Figure 2. Histogram of all the cave entrance elevations in CCK. Cave levels were delineated based on where there was a high frequency of caves at one elevation with breaks on either side or a reverse in the frequency trend.

We employed a GIS (ESRI ArcMap™ 9.2) to visualize and analyze various data from the karst system. Although the use of GIS to study karst has grown in the last decade, many early applications of GIS to karst focused on GIS as a database and management tool for information (e.g., Florea and others, 2002; Gao and others, 2006; Ohms and Reece, 2002). More recently, the use of GIS has increasingly included sophisticated data analysis, geoprocessing, and modeling as a central aspect of the research endeavor. For example, GIS has been used to indentify sinkholes, faults, and fractures (Angel and others, 2004; Florea, 2005; Seale and others, 2008), to model depressions (Yilmaz, 2007), to create virtual field trips through caves (McNeil and others, 2002), to model karst hazards (McNeil and others, 2002), to delineate karst watersheds (Choi and Engel, 2003; Glennon and Groves, 2002), and to identify critical source areas of contaminants (Dockter and Dogwiler, 2010).

GIS Data Sources

Digital topography, hydrography, a digital elevation model, and orthophotos layers for the study area were obtained from the Kentucky Geological Survey[2] and the United States Geological Survey[3] web sites. The DEM for the study area has a spatial resolution of 30m. DEM accuracy is expressed in terms of root mean square error (RMSE) and is assessed based on ground control points, the National Map Accuracy Standards (NMAS), and the National Standard for Spatial Data Accuracy (NSSDA). The NMAS is the RMSE that bounds 90 percent of the values, while the NSSDA is the RMSE that bounds 95 percent of the values. Based on these various methods of assessment the CCK DEM accuracy ranges from 3.74 m to 7.34 m. The hydrography data were derived from the USGS National Hydrography Dataset (NHD), which was created from 1:24,000 Digital Line

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[2] http://www.uky.edu/KGS/gis/kgs_gis.htm

[3] http://seamless.usgs.gov/

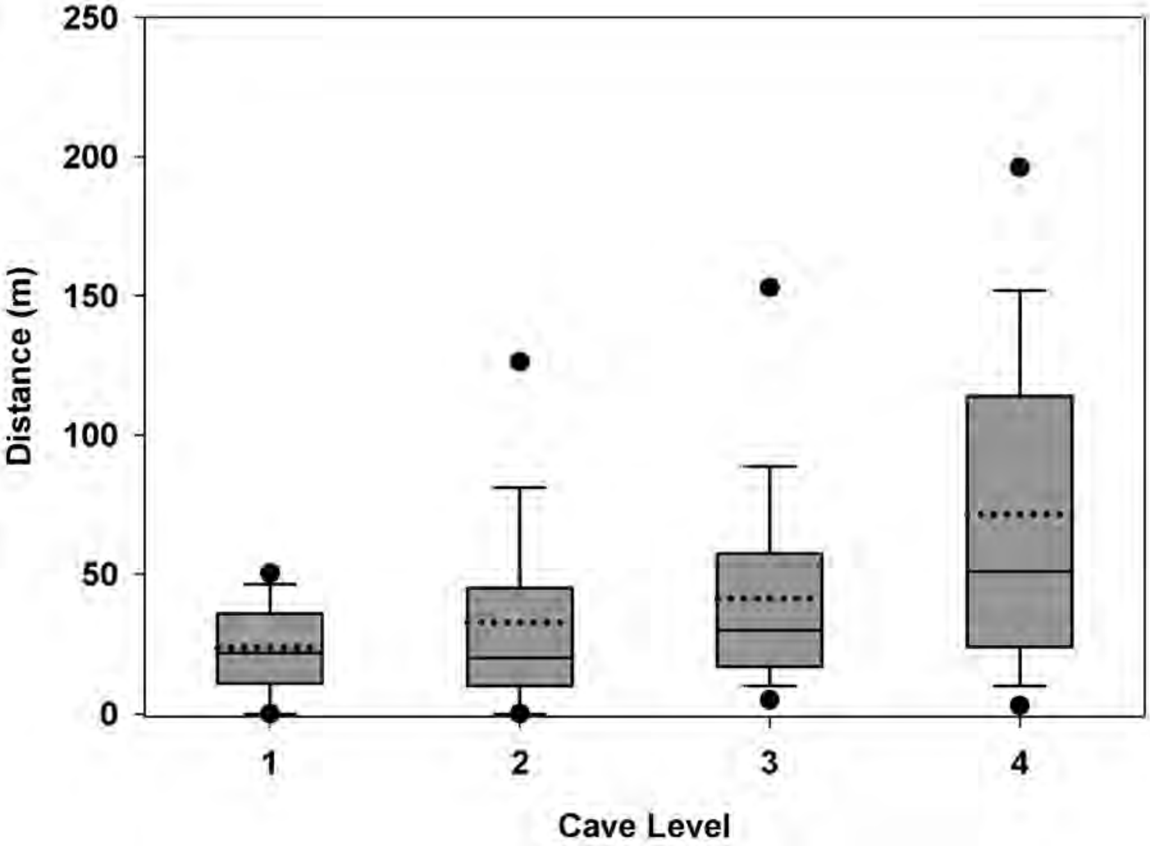

Figure 3. Box plots of the distance cave entrances are from streams. The ends of the boxes represent the 25th and 75th percentiles with the solid line at the median; the error bars depict the 10th and 90th percentiles, and the dots represent the 5th and 95th percentile. The dotted line represents the mean.

Table 1. Summary of cave level elevations, lateral distance to the stream valley axis, and selected example caves from each level. Harlan (2009, p. 32-34) provides a detailed description and statistical summary of each of the cave levels. Engel and Engel (2009) provide additional description and context regarding the specific caves.

[All units are in meters]

Cave Level	# of Entrances	Mean / Mode Elevation	Elevation Range	Mean Distance to Stream ± Std. Dev.	Example Caves
L4	25	276 / 270	268 – 283	72 ±56	X Cave, Coon-in-the-Crack Cave
L3	49	261 / 260	249 – 266	41 ± 37	Saltpetre Cave, Rat Cave
L2	47	242 / 245	234 – 247	33 ± 37	Cool James Cave
L1	36	228 / 231	215 – 234	24 ± 15	Laurel Cave, Lake Cave

Graphs (DLG). The NHD accuracy is reported as 98.5 percent.

ESRI's ArcCatalog™ was used to build a geodatabase for data collected in the field. Cave locations and descriptions were obtained from the Wittenberg University Speleological Society. These data represent a thorough and systematic reconnaissance of the study area and surrounding areas and represents most—if not all—of the discoverable karst features in the area. The Wittenberg data lacked elevations of the documented features. All elevation data used in our analysis were obtained from the DEM and compared to elevations directly determined for selected features and fixed reference locations in the field using a combination of a differential GPS, an electronic altimeter, and an analog altimeter (Gorecki, 2008). Based upon temporally repeated measurements of fixed reference locations within the study area we estimate the electronic altimeter error at ±3.2 to 4.3 m and the analog altimeter error at ±0.6 to 0.9 m. The accuracy of the post-processed digital GPS data was limited at many locations by the steep topography and dense tree canopy. Most positions had a vertical accuracy of 1 to 5 m (one standard deviation error).

Cave levels were determined based on the elevations of the cave entrances. The karst features geodatabase was filtered to remove vertically oriented features, such as vadose pits and sinks. Although the pits and sinks generally represent a vertical connection between the surface and an underlying cave, the depth from the surface to the cave was not known.Thus, the pits and sinks were not incorporated into the cave level determination. The elevation of cave entrances was determined based on the elevation of the corresponding DEM cell. The distribution of cave entrance elevations was analyzed statistically in ArcMap (described more thoroughly in Harlan, 2009). The ArcGIS™ algorithm '*Natural Breaks Classifier*' was used to generate a histogram showing the frequency of cave entrances by elevation (Fig. 2). Cave levels were delineated based on where there was a high frequency of caves at one elevation with breaks on either side or a reverse in the frequency trend.

In addition to identifying the cave entrance elevations, we determined the shortest distance of each cave entrance to the channel of the current surface stream valley. This was accomplished by deriving a stream line network based on the DEM and then using the *'Euclidean Distance'* tool in ArcGIS™ to determine the distance of each DEM cell from the nearest stream line. The resulting raster of values was queried for each cave entrance using the *'Extraction'* tool to yield the distance values which were added as an attribute to the karst features geodatabase.

RESULTS

Error Analysis

Forty-three field-collected elevations for cave entrances and the fixed reference locations were compared to elevations obtained from the DEM. The DEM provides slightly higher elevation values. The mean error between the field-collected and DEM-derived elevations is -0.48 m, with a 95percent confidence interval of 1.25 m. However, the DEM elevations are statistically similar to the field-collected elevations [t(43) = -0.19, p = 0.85]. The RMSE between the field-collected elevations and the DEM elevations is 3.96 m. This error is only slightly higher than the 3.74 m RMSE of the DEM, but is below the NMAS and the NSSDA values of 6.15 m and 7.34 m, respectively. Both the mean error and the RMSE are within the error associated with electronic altimeter and DGPS; only the mean error is within the error of the analog altimeter. Overall, the data indicate that the DEM provides acceptable estimates of elevations.

Cave Levels

The location of 157cave entrances were analyzed in this study. Based on our analysis of the distribution of cave entrances by elevation we have delineated four cave levels (Figure 2, Table 1). We have denoted these levels as L1 (mean elevation of 228 m above sea level), L2 ($\bar{x}$ = 242 m), L3 ($\bar{x}$ = 261 m), and L4 ($\bar{x}$ = 276 m). The mean lateral (horizontal) distances of entrances in each cave level to the nearest stream valley axis are shown in table 1. In general, L4 cave entrances were furthest from the streams, as would be expected if the cross-sectional (normal to flow) valley shape is approximated by the classic 'V-shaped' valley of fluvial origin. Because the slope of valley walls varies significantly, there is also a reasonable expectation that this metric will show significant overlap in the lateral distances ranges. Nonetheless, analysis of variance (ANOVA) suggests that the cave levelsare a significant predictor of the lateral cave entrance to valley axis dimension [F(3, 156) = 8.78, p = <0.001].

DISCUSSION

Figure 2 shows our delineation of cave levels in the CCK system. The histogram contains many breaks and admittedly lends itself to a number of interpretations. However, an ongoing graduate project at Illinois State University is working to refine the delineation of cave levels presented here, and the preliminary results (Jacoby and Peterson, 2010) support our current interpretation. The development of larger trunk passages in levels L4 and L3 seem to be controlled by subtle changes in dip of the bedrock (Engel and Engel, 2009) and likely pre-date the onset of glaciation to the north of the study area the led to the reorganization of the Ohio and Teays River Drainage systems. Several of the upper level passages in the study area occur at similar vertical elevations and may be truncated remnants of a formerly integrated cave system. The lower cave levels in the CCK system are controlled by a combination of stratigraphic and structural influences and correlate strongly to modern-day surface stream patterns (Engel and Engel, 2009).

The Horn Hollow Valley

We will focus our discussion of cave hydrology and geomorphology in CCK on the Horn Hollow Valley portion of the system (Figure 1). Horn Hollow has numerous caves, sinking streams, springs, sinks, and pits that are all well-studied and documented in the literature (Angel, 2010; Dogwiler and Wicks, 2004; Engel and Engel, 2009; Hobbs and Pender, 1985; McGrain, 1966; Ochsenbein, 1974; Tierney, 1985) . The upper section of Horn Hollow is largely under-drained by an active cave system (variously referred to as Boundary Cave or Upper Horn Hollow Cave). The surface stream channel in this section of the valley is poorly maintained and ill-defined indicating a paucity of flow events large enough to inundate the active cave system and flow across the surface. In several places this section of surface stream is occupied by large blocks of limestone displaying anastomoses, scallops, and other dissolutional features associated with caves. It is likely that at least some of this portion of the surface stream is a former L3 cave that has been hydrologically abandoned and subsequently unroofed.

Several caves higher up in the stratigraphic section occur in the valley flanks. Some, such as Fudge Ripple Cave, are fairly near the contact with the siliciclastic units that overlie the carbonate sequence. Fudge Ripple Cave and another cave—Volcano Cave—appear to be examples of phreatic passages that have been overprinted with a vadose signature formed as waters have cut through the passage floors seeking pathways to lowering water tables. Stratigraphically, and in terms of elevation, these caves represent L3 and L4. In numerous places pits and sinks dot the hillslopes along the valley walls. Currently, the hydrologic function of these caves and pits is to direct water vertically down toward the modern phreatic zone.

Dye tracing and water chemistry data (Angel, 2010), confirm that Bowel Spring (L2), in the central part of the Horn Hollow Valley, is a resurgence point for water flowing from Volcano Cave and Fudge Ripple Cave through Boundary Cave—hydrologically spanning several cave levels. From Bowel Spring the flow alternates from the surface to the subsurface through Cobble Crawl Cave, Horn Hollow Cave, New Cave, and H2O caves. Thus, in the lower part of Horn Hollow Valley, it is possible to explore several of the active L2 and L1 caves. H2O Cave and New Cave are phreatic tubes that meander along bedding planes and drain significant amounts of water during large flow events. H2O Cave (L1) emerges from Horn Hollow as a waterfall along the contact between the St. Louis limestone and the Borden Shale. As such, H2O Cave is formed at the carbonate/siliciclastic contact that forms the lower stratigraphic boundary of cave development in the region.

Comparison to Regional Karst Systems

In Mammoth Cave, Palmer (1987) and Granger and others (2001) identify four levels centered around 150 m, 167 m, 180 m, and 200 m. The number of levels within the MCS corresponds well to the CCK area, but there is an absolute difference of ~80 m between the levels of the two systems. We assume this difference in absolute elevations is a function of regional dips. However, the relative elevation differences between individual levels in each area are roughly comparable. Additionally, the three lowest levels in the MCS are also in the Ste. Genevieve Limestone, which is correlative between the Mammoth Cave and CCK areas.

In the MCS the upper levels (Level A, 200m and Level B, 180 m) formed in the Pliocene and early Pleistocene due to slow valley deepening and aggradation, while the lower levels (Level C, 167 m and Level D, 150) developed during the Pleistocene glacial intervals during periods of base level stability (Palmer, 1987). Using cosmogenic ^{26}Al and ^{10}Be dating, Granger and others (2001) determined that Levels A and B were both formed prior to 3.25 Ma and constrain the formation of Levels C and D as prior to 1.39 Ma and 1.24 Ma, respectively.

The CPK also has four levels (Anthony and Granger, 2004). Cosmogenic ^{26}Al and ^{10}Be analysis demonstrates that the upper-most level (Level 1) was formed between 5.7 and 3.5 Ma, the second level was formed between 3.5 and 2.0 Ma, the third level was formed between 2.0 and 1.5 Ma, and the fourth level was formed after 1.5 Ma. Thus, levels one and two formed in the Pliocene and levels three and four formed in the Pleistocene.

MCS, CPK, and CCK are geographically close (within 300 km of one another), contain many of the same stratigraphic units, and are ultimately controlled by the base flow of the Ohio River. Thus, it is reasonable to hypothesize that CCK may share a similar history of cave development. However, unlike the Green River and the Cumberland Rivers which flowed west into the Old Ohio River in pre-Glacial times (Granger and others, 2001; Teller, 1973), northeastern Kentucky was part of the southern branch of the Teays River drainage that flowed from eastern North Carolina toward northwestern Ohio and Indiana (Hansen, 1995; Janssen, 1953). Whereas, the Green and Cumberland joined their master streams south of the glacial margin, the Teays drainage downstream of Kentucky was overrun by advancing ice sheets and flow was impounded south of the glacial margin (Andrews, 2006; Teller, 1973). It is difficult to ascertain precisely what effect these events had on karst development in CCK and how its progression may have differed from the other two karst systems.

Nonetheless, we believe that enough similarities in cave level sequences, bedrock geology, and relative elevations exist between the three systems to pose some preliminary hypotheses regarding the development of the CCK system. Certainly, these hypotheses would benefit from future geochronology studies of CCK sediments and additional geomorphic field work in the study area. The L4 and L3 trunk passages in CCK, such as Saltpetre Cave and the upper level of Laurel Cave likely correlate with the upper cave levels in MCS and CPK and represent Pliocene or early Pleistocene karst development. These passages contain fine- to coarse-grained silt and sand deposits that Engel and Engel (2009) suggest are fluvial in origin. These sediments may be suitable for cosmogenic or paleomagnetic analysis.

The Ohio River initially occupied its current course approximately 1.4 Ma and drove a rapid incision event that is attributed to the formation of MCS level D (Granger and others, 2001). After 1.24 Ma, the incision and aggradation history of the Ohio River becomes more complicated and Granger and others (2001) attribute the relative instability of the river level to the lack of well-defined levels below level D. During this time period in northeastern Kentucky, it is possible that Tygarts Creek incised at times well into the siliciclastics underlying the carbonates—leaving the CCK hydrologically abandoned. Whereas, L4 and L3 cave entrance elevations are tightly distributed across narrow distributions, cave entrance elevations in L2 and L1 are more broadly distributed. Thus, the "noise" in the L2 and L1 distributions may represent the complex base level evolution of the Ohio River drainage over the last 1.24 Ma.

CONCLUSIONS

The number of levels within the CCK shows that the area has experienced changes in the elevation of the water table. We posit that the upper-level trunk passages in the CCK may represent the remnants of a more extensive karst system that developed in the Plio-Pleistocene during a period of relatively slow landscape denudation prior to the abandonment of the Teays River network and the development of the Ohio River drainage. The lower level caves in the CCK system likely formed during periods of base level stability during the wax and wane of the Pleistocene ice sheets.

We propose that accepted models for the Plio-Pleistocene development of the Mammoth Cave and Cumberland Plateau karst systems are appropriate starting points for deciphering the history of cave level development in the CCK area. Additional geomorphic analysis of the system, including geochronologic analysis of the cave sediments, could provide important insight into the demise of the Teays drainage and development of the modern Ohio River.

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