Darlene M. Anthony and Darryl E. Granger - A Late Tertiary origin for multilevel caves along the western escarpment of the Cumberland Plateau, Tennessee and Kentucky, established by cosmogenic $^{26}$Al and $^{10}$Be. *Journal of Cave and Karst Studies*, v. 66, no. 2, p. 46-55.

# A LATE TERTIARY ORIGIN FOR MULTILEVEL CAVES ALONG THE WESTERN ESCARPMENT OF THE CUMBERLAND PLATEAU, TENNESSEE AND KENTUCKY, ESTABLISHED BY COSMOGENIC $^{26}$AL AND $^{10}$BE

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*Cosmogenic burial dating of quartzose cave sediments deposited in multilevel caves beneath the western margin of the Cumberland Plateau dates ~5.7 Ma of cave development in step with episodic incision of the Upper Cumberland River. These particular cave systems are characterized by hydrologically abandoned, low-gradient passages concentrated at common levels above the modern water table. Previous studies recognized morphometric differences between the majority of smaller, hydrologically active "plateau-margin" caves and large, abandoned "fossil" or "Cumberland-style" caves. This study links the origin of multilevel caves on the western margin to a prolonged period of Late Tertiary water table stability, and the development of levels to distinct episodes of Plio-Pleistocene river incision. In this study, clastic sediments in multilevel cave passages are dated using cosmogenic $^{26}$Al and $^{10}$Be, and are shown to correspond with 1) deposition of upland ("Lafayette-type") gravels between ~3.5 Ma and ~5 Ma; 2) initial incision of the Cumberland River into the Highland Rim after ~3.5 Ma; 3) development of the Parker strath between ~3.5 Ma and ~2 Ma; 4) incision of the Parker strath at ~2 Ma; 5) shorter cycles of incision after ~1.3 Ma associated with terraces above the modern flood plain; and 6) regional aggradation at ~0.8 Ma. Burial ages of cave sediments record more than five million years of incision history within the unglaciated Appalachian Plateaus and constrain the developmental history of multilevel caves associated with the Upper Cumberland River.*

In the southeastern United States, karst features are developed on two topographic surfaces of regional extent known locally as the Cumberland Plateau and Highland Rim (Fig. 1). The most extensive and elevated of the two is the Cumberland Plateau, a rugged upland (550–610 m ASL) bounded on the east by the Valley and Ridge Province and on the west by the solutional surface (275–350 m ASL) of the Eastern Highland Rim. Nearly 180 million years of differential lowering between the sandstone-capped Cumberland Plateau and the limestone surface of the Highland Rim has formed a highly-dissected, eastward-retreating escarpment along the western margin of the Cumberland Plateau.

The lithologic change from sandstone to limestone along the western escarpment provides an optimum hydrogeologic setting for cave development. Crawford (1984) was the first to describe the "plateau-margin" model of cave development (Fig. 2). In this model, surface streams undersaturated with respect to calcite cross the sandstone caprock of the Cumberland Plateau, sink at the contact between sandstone and limestone, and form cave passage in the vadose zone leading to the local water table. Cave streams emerge as springs along the base of the escarpment or valley wall. Morphometric characteristics of plateau-margin caves include small passage dimensions (in terms of surveyed length and cross-sectional area) and a vertically developed profile (Fig. 3).

Of thousands of caves explored along the western escarpment of the Cumberland Plateau, a few do not fit the physical

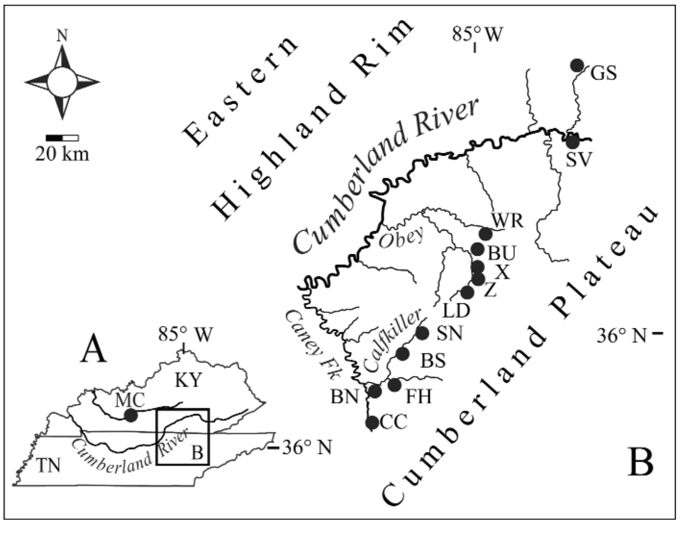


**Figure 1. The study area in Kentucky and Tennessee (A) with Mammoth Cave (MC) on the Green River, KY. A portion of Upper Cumberland River basin (B) drains the study area, and includes twelve caves on the western margin of the Cumberland Plateau. CC-Cumberland Caverns; BN-Bone Cave; FH-Foxhole Cave; BS-Blue Spring Cave; SN-Skagnasty; LD-Lott Dean (Mountain's Eye System); Z-Zarathustra's Cave; X-Xanadu Cave; BU-Buffalo Cave; WR-Wolf River Cave; SV-Sloan's Valley Cave; GS-Great Saltpetre Cave.**

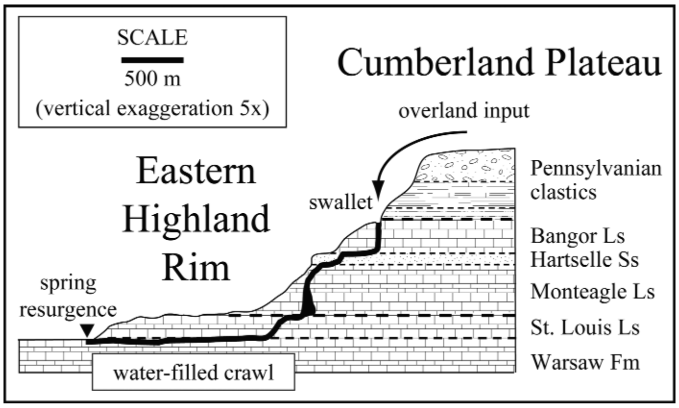


**Figure 2. Schematic plateau-margin model of cave development (after Crawford, 1984). Surface streams originating on sandstone bedrock of the Cumberland Plateau flow down the escarpment and sink at the contact between sandstone and limestone. Sinking streams form cave passages in the vadose zone leading to the local water table, and emerge as springs along the base of the valley wall.**

**Figure 3. Passages in plateau-margin caves are typically narrow, vertical canyons leading down to the modern water table.**

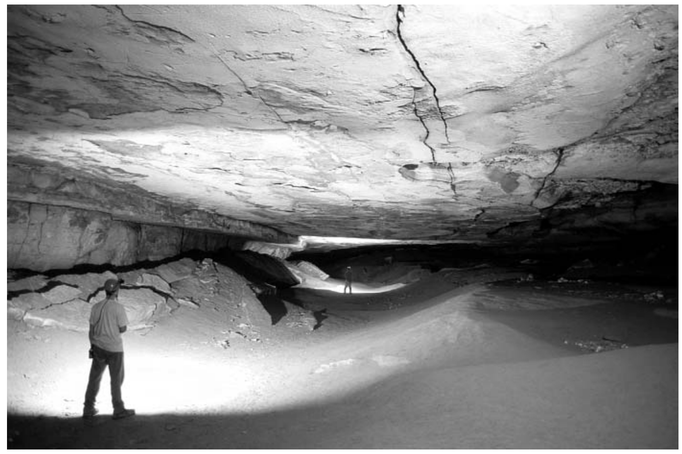

**Figure 4. The large, hydrologically abandoned Ten Acre Room in Cumberland Caverns, TN is a passage of phreatic origin above the modern water table. These passages are referred to as "fossil" caves or "Cumberland-style" caves in the literature. (Photo Bob Biddix.)**

characteristics of the plateau-margin model, although they clearly developed in the same hydrogeologic setting. These were named "fossil caves" (Mann 1982) and later, "Cumberland-style" caves (Sasowsky 1992). Physical attributes of "fossil caves" included large, hydrologically abandoned passages of phreatic origin (Fig. 4). Recharge from the plateau combined with backflooding from surface discharge springs was speculated to produce high hydrostatic pressure in phreatic conduits, which led to the development of large passages under pipe-full conditions (Mann 1982).

In a later study, large caves on the western margin were named "Cumberland-style" by geographic association with the highly dissected western margin of the Cumberland Plateau (Sasowsky & White 1994). Characteristic features were similar to those of the "fossil caves," including abandoned trunk passages concentrated at one or more levels above the modern river level. However, this model linked passage morphology with a different type of speleogenesis. In the Cumberland-style model, large trunk passages were observed to generally follow topographic contours parallel to a surface valley containing a master stream. Subsurface diversion of the master stream is an important constraint for this model, and large caves are hypothesized to be the result of this diversion (Sasowsky *et al*. 1995). The Cumberland-style model attributes large, horizontal passages to high discharge.

Both the modified plateau-margin model and the Cumberland-style model require that large, low-gradient horizontal passages form under high discharge conditions. Following either model, abandoned trunk passages could have formed at any time during the past, given the right hydrologic conditions. An alternative hypothesis is that large, multilevel caves on the western Cumberland Plateau escarpment developed synchronously during long periods of river stability. These long periods of time provide an opportunity for modest discharge to dissolve exceptionally large trunk passages.

Because solution kinetics ultimately control the enlargement rate of conduits, the maximum diameter of a phreatic tube will depend on the length of time the passage is filled with undersaturated water (White 1977; Palmer 1991). Under the base-level stability model, large multilevel caves on the western margin are related to each other temporally because they all drain to a water table controlled by the elevation of the Cumberland River. To test this hypothesis, we examined cave morphology and sediment structures, and dated sediments in twelve large multilevel caves on the western margin using cosmogenic $^{26}Al$ and $^{10}Be$.

### Burial dating using cosmogenic nuclides.

The ability of accelerator mass spectrometry (AMS) to measure small amounts of radionuclides has led to a new way of dating cave sediments up to five million years old (Granger & Muzikar 2001; Muzikar *et al.* 2003). This dating method involves cosmogenic nuclides produced in rocks near the ground surface by cosmic rays (Lal & Peters 1967). The cosmogenic radionuclides aluminum-26 ($^{26}Al$) and beryllium-10 ($^{10}Be$) are produced in quartz crystals by reactions with secondary cosmic ray neutrons, which change silicon atoms to $^{26}Al$ and oxygen atoms to $^{10}Be$ in an approximate 6:1 ratio. Together, these two radionuclides can be used to date when a quartz crystal was carried into a cave.

Quartz sediments originating on the Cumberland Plateau caprock are first exposed to cosmic rays, accumulate $^{26}Al$ and $^{10}Be$, and are transported underground as part of the bedload of cave streams in the study area. Once underground, the quartz is shielded from further exposure to cosmic radiation by tens of meters of rock. After burial, concentrations of accumulated $^{26}Al$ and $^{10}Be$ diminish over time due to radioactive decay, with $^{26}Al$ decaying roughly twice as fast as $^{10}Be$. The present-day ratio of remaining cosmogenic nuclides yields a burial age for the sediment.

### Data analysis and uncertainties.

Burial ages are determined by iterative solution of equations for measured and inherited concentrations of nuclides (after Granger *et al.* 1997). Accumulation of cosmogenic nuclides for the simple case of a steadily eroding outcrop is described by Equation (1), where the preburial $^{26}Al/^{10}Be$ ratio $(N_{26}/N_{10})_0$ changes with erosion rate $E$ as follows:

$$\left(\frac{N_{26}}{N_{10}}\right)_0 = \frac{P_{26}\left(\frac{1}{\tau_{10}} + \frac{E}{\Lambda}\right)}{P_{10}\left(\frac{1}{\tau_{26}} + \frac{E}{\Lambda}\right)} \qquad (1)$$

where $P_{26}$ and $P_{10}$ are the production rates of $^{26}Al$ and $^{10}Be$, $\Lambda$ is the penetration length for neutrons ($\Lambda \approx 60$ cm in rock of density 2.6 g cm$^{-3}$), $\tau_{26} = 1.02 \pm 0.04$ m.y. is the radioactive $^{26}Al$ meanlife, and $\tau_{10} = 1.93 \pm 0.09$ m.y. is the radioactive $^{10}Be$ meanlife. Local cosmogenic nuclide production rates were assumed constant for the region and were calculated as $P_{10}$ = 5.22 at g$^{-1}$ a$^{-1}$ and $P_{26}$ = 35.4 at g$^{-1}$ a$^{-1}$ for a latitude of 36º and an elevation of 0.5 km (Stone 2000, modified for a $^{10}Be$ meanlife of 1.93 m.y.).

After shielding from nuclide production by burial underground, the cosmogenic radionuclide production stops, and $^{26}Al$ and $^{10}Be$ decays according to:

$$N_{26} = (N_{26})_0 e^{-t/\tau_{26}} \qquad (2)$$

and

$$N_{10} = (N_{10})_0 e^{-t/\tau_{10}}$$

where $t$ is burial time. Because $^{26}Al$ decays faster than $^{10}Be$, the ratio $N_{26}/N_{10}$ decreases exponentially over time according to:

$$\frac{N_{26}}{N_{10}} = \left(\frac{N_{26}}{N_{10}}\right)_0 e^{-t\left(1/\tau_{26} - 1/\tau_{10}\right)} \qquad (3)$$

where $N_{26}$ and $N_{10}$ are the concentrations of $^{26}Al$ and $^{10}Be$ measured by AMS. Equations 1–3 solve for converging solutions of $E$, $(N_{26}/N_{10})_0$, and $t$ after a few iterations (Granger *et al.* 1997).

Burial age is reported with two uncertainties; the first is one standard error of analytical uncertainty. The second includes systematic uncertainties in radioactive decay rates, $P_{26}/P_{10}$, and production rates, which are added in quadrature and shown as total uncertainties in parentheses. Analytical uncertainties are used when comparing burial ages with each other. Total uncertainties are used when comparing burial ages with other dating methods.

## Methods

### Sample sites.

Twelve caves in the Upper Cumberland River basin (Fig. 1) were selected for this study based on: 1) one or more abandoned levels of large cross-sectional area connected by narrow canyons; 2) extensive horizontal development; 3) in-place channel deposits (Fig. 5) with no sediment remobilization from upper levels or surface. [Five caves previously identified as "Cumberland-style" included Xanadu Cave, Zarathustra's Cave, Mountain's Eye (Lott Dean), Bone Cave, and Cumberland Caverns (Sasowsky 1992).] Some caves are fragments beneath plateau outliers, with no connection to the modern water table due to escarpment retreat and loss of recharge area. Others have remained connected to their recharge area, and have an active base level conduit today. Extensive horizontal cave passages were grouped by similar heights above the modern river level. The assumption was made that the modern river longitudinal profile was not different from the paleoprofile; therefore caves would develop at similar heights (White & White 1983). Passages were correlated with fluvial

**Figure 5. Graded sediments and cut-and-fill structures in the Muster Ground of Bone Cave, TN indicate open-channel flow. Water bottle for scale.**

**Figure 6. Quartz pebbles weathered from the plateau caprock are easily identified in cave sediments and collected for cosmogenic nuclide measurements.**

surface features in the Upper Cumberland River valley, that included the Eastern Highland Rim, the Parker strath, and terraces in the Upper Cumberland River basin (Table 1).

Target materials for $^{26}Al$ and $^{10}Be$ isotopic measurements were rounded quartz pebbles (Figure 6) and sand weathered from the Rockcastle Conglomerate caprock and deposited in (now) hydrologically abandoned cave passages. Approximately 500 grams of quartz pebbles or one kilogram of cross-bedded sand were collected at each sampling site.

COSMOGENIC NUCLIDE CHEMISTRY.

Quartz from each sample site (~120 g) was purified by chemical dissolution (Kohl & Nishiizumi 1992), dissolved in HF and $HNO_3$, and spiked with ~0.7 mg $^{9}Be$ in a carrier solution. Fluorides were driven out with $H_2SO_4$. Aluminum and beryllium were separated and purified by ion chromatography, selectively precipitated as hydroxides, and oxidized at 1100ºC. AMS measurements of $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ isotope ratios were made at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab) and the Lawrence Livermore National Laboratory, CA.

## RESULTS AND INTERPRETATION

Cosmogenic burial dating of sediments shows that caves on the western escarpment were an active part of the regional hydrology in the Late Miocene and throughout the Pliocene (Table 1). The oldest sediments in the study area are found in caves beneath plateau outliers and heavily dissected margins of the Cumberland Plateau, and have no active base level today. Progressively younger burial ages are found in passages at elevations that maintain the modern river profile along two major Cumberland River tributaries. A widespread, regional aggradation signal occurs in the lowermost levels of multilevel caves across the entire basin. Each of these events is discussed in detail below.

**1. Abandonment of Bone Cave at 5.68 ± 1.09 (1.21) Ma.** Bone Cave is located beneath Bone Cave Mountain, an elongate spur almost completely separated from the western margin of the Cumberland Plateau. Bone Cave has no physical connection with the modern water table. Stream-deposited quartz pebbles from the main passage of Bone Cave (Muster Ground) yield a burial age of 5.68 ± 1.09 (1.21) Ma, with a large uncertainty due to the very small amount of remaining cosmogenic $^{26}Al$. A small, discontinuous phreatic level beneath the Muster Ground indicates that incision to a lower level was underway when the cave stream was cut off from its recharge source. The burial age shows that the Muster Ground in Bone Cave carried sediments at a water table nearly 90 m above the modern river level during the Late Miocene, and was abandoned at ~5.7 Ma. A loss of recharge by surface stream piracy may have caused passage abandonment.

**2. Aggradation and abandonment of Cumberland Caverns at 3.52 ± 0.42 (0.49) Ma.** Cumberland Caverns lies beneath Cardwell Mountain, a remnant outlier of the Cumberland Plateau separated by a distance of 2.4 km from the retreating edge of the western escarpment. Passages in Cumberland Caverns have no physical connection with the

**Table 1. Cosmogenic nuclide concentrations, burial ages, and correlated surface features from Cumberland Plateau caves.**

| Cave and passage name | Elevation above modern rivers (m) | Surface feature | Sample type | $[^{26}Al]$ ($10^6$ at/g) | $[^{10}Be]$ ($10^6$ at/g) | $[^{26}Al]/[^{10}Be]$ | burial age[a] (Ma) |
|---|---|---|---|---|---|---|---|
| Bone (Muster Ground) | 91 | Highland Rim | pebbles | 0.017 ± 0.012 | 0.017 ± 0.012 | 0.46 ± 0.32 | 5.68 ± 1.09 (1.21) |
| Cumberland (Volcano Room) | 66 | Highland Rim | sand | 0.158 ± 0.042 | 0.158 ± 0.042 | 1.39 ± 0.37 | 3.52 ± 0.42 (0.49) |
| Foxhole (B-survey) | 43 | Parker strath | pebbles | 0.308 ± 0.022 | 0.308 ± 0.022 | 2.53 ± 0.23 | 1.97 ± 0.10 (0.17) |
| Blue Spring (Ship's Prow) | 49 | Parker strath | pebbles | 0.380 ± 0.038 | 0.380 ± 0.038 | 3.07 ± 0.38 | 1.66 ± 0.23 (0.28) |
| Skagnasty (A-survey) | 45 | Parker strath | pebbles | 0.334 ± 0.026 | 0.334 ± 0.026 | 4.61 ± 0.68 | 0.89 ± 0.21 (0.22) |
| Wolf River (Upper Borehole) | 43 | Parker strath | pebbles | 0.189 ± 0.077 | 0.189 ± 0.077 | 2.46 ± 0.62 | 2.15 ± 0.47 (0.52) |
| Buffalo (Main Saltpetre) | 48 | Parker strath | sand | 1.127 ± 0.264 | 1.127 ± 0.264 | 3.26 ± 0.77 | 1.45 ± 0.42 (0.45) |
| Xanadu (Steven's Ave.) | 54 | Parker strath | sand | 1.036 ± 0.134 | 1.036 ± 0.134 | 3.66 ± 0.48 | 1.23 ± 0.24 (0.27) |
| Xanadu (Cumberland Ave.) | 52 | Parker strath | pebbles | 0.208 ± 0.026 | 0.208 ± 0.026 | 3.13 ± 0.76 | 1.64 ± 0.46 (0.48) |
| Zarathustra's (Heaven)[b] | 40 | Parker strath | sand | 1.278 ± 0.228 | 1.278 ± 0.228 | 2.65 ± 0.48 | 1.80 ± 0.31 (0.36) |
| Xanadu (Sand Hills) | 42 | first terrace | sand | 0.763 ± 0.149 | 0.763 ± 0.149 | 4.46 ± 0.88 | 0.85 ± 0.37 (0.38) |
| Sloan's Valley (Appalachian Trail)[c] | 48 | first terrace | sand | 1.218 ± 0.202 | 1.218 ± 0.202 | 4.32 ± 0.73 | 0.89 ± 0.31 (0.33) |
| Great Saltpetre (Dressing Room) | 31 | first terrace | sand | 1.227 ± 0.062 | 1.227 ± 0.062 | 4.31 ± 0.66 | 0.95 ± 0.29 (0.31) |
| Zarathustra's (Elephant Walk) | 28 | first terrace | pebbles | 0.580 ± 0.053 | 0.580 ± 0.053 | 4.47 ± 0.42 | 0.86 ± 0.17 (0.19) |
| Zarathustra's (B-survey) | 13 | lower terraces | pebbles | 0.899 ± 0.101 | 0.899 ± 0.101 | 4.50 ± 0.52 | 0.83 ± 0.21 (0.22) |
| Lott Dean (upstream sump) | 0 | modern river | pebbles | 1.416 ± 0.107 | 1.416 ± 0.107 | 6.60 ± 0.54 | 0.02 ± 0.13 (0.13) |

[a] Uncertainties represent one standard error measurement uncertainty. Systematic uncertainties in production rates (20%), production rate ratio (Stone, 2000) and radioactive decay constants are added in quadrature and shown as total uncertainty in parentheses.

[b] Highest passage of three levels in this system.

[c] Passage developed less than 1 km from mainstem Cumberland River.

modern water table. Observations of vadose/phreatic transitions in the cave suggest major phreatic development ended with the abandonment of the main passage (Ten Acre Room) via a smaller phreatic passage (Dish Pan Alley). Aggradation after the development of Dish Pan Alley filled Dish Pan Alley to the top of the Volcano Room with over 10 m of sediment, which has been partially removed by minor stream activity. Samples from the top and bottom of the sand fill yielded an average age of 3.52 ± 0.42 (0.49) Ma (weighted by inverse variance), which is interpreted as the time of separation of Cardwell Mountain from the Cumberland Plateau (see Barr, 1961 for discussion) and loss of recharge area for phreatic development of Cumberland Caverns. The Ten Acre Room is inferred to be older than ~3.5 Ma.

**3. Abandonment of caves along the Caney Fork-Calfkiller Rivers.** Cave passages concentrated between 40 m and 55 m above the modern river level of the Caney Fork and Calfkiller River (Fig. 1) contain graded stream deposits of quartz pebbles, sandstone gravel, and sand. Burial ages for cave sediments are oldest in caves closest to the Cumberland River, and become progressively younger upstream (Fig. 7). Foxhole Cave (B-survey) was abandoned at 1.97 ± 0.10 (0.17) Ma; Blue Spring Cave (Ship's Prow) at 1.66 ± 0.23 (0.28) Ma; and Skagnasty Cave (A-survey) at 0.89 ± 0.21 (0.22) Ma. These data suggest that caves on the Caney Fork-Calfkiller River were abandoned in sequence as a knickpoint, or waterfall, migrated upstream. Knickpoint migration would have been initiated by incision of the Cumberland River prior to ~2 million years ago.

**4. Abandonment of caves along the Obey River.** Wolf River and the East Fork-Obey River (East Fork) are branches of the Obey River, a major tributary of the Cumberland River (Fig. 1). Cave passages concentrated between 40 m and 55 m above the modern river level contain graded deposits of quartz pebbles, sandstone gravel, and cross-bedded sands. Burial ages of sediments in these passages show that Wolf River Cave (Upper Borehole) was abandoned at 2.15 ± 0.47 (0.52) Ma; Buffalo Cave (Saltpetre Passage) at 1.45 ± 0.42 (0.45) Ma; Xanadu Cave (Cumberland Avenue) at 1.64 ± 0.46 (0.48) Ma; and Zarathustra's Cave (Heaven) at 1.80 ± 0.31 (0.36). There are no significant differences in ages between caves on the East Fork-Obey River, which is not surprising due to the caves' close proximity to each other. Data from the Obey River watershed are consistent with migration of a knickpoint initiated by incision of the Cumberland River prior to ~2 Ma (Fig. 7). Synchronous abandonment of Blue Spring Cave (Ship's Prow) and Xanadu Cave (Cumberland Avenue) suggests the same incision episode on the Cumberland River is responsible for initiating knickpoints on the tributaries.

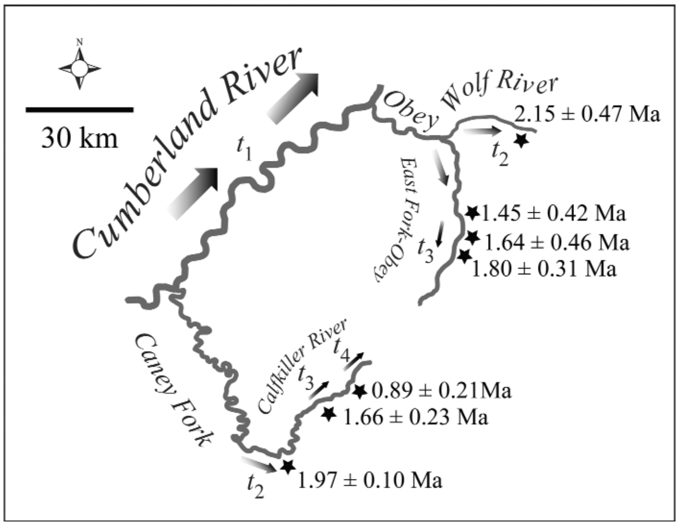


**Figure 7. Schematic diagram showing knickpoint migration on Caney Fork-Calfkiller River and Obey River-Wolf River. Incision pulses originating on the Cumberland River at $t_1$>2 Ma migrated up the Caney Fork and Obey-Wolf River, lowering the local water table and abandoning Foxhole Cave and Wolf River Cave at $t_2$ ≈ 2 Ma. At $t_3$ ≈ 1.6 Ma the pulse had migrated up the Calfkiller River and East Fork-Obey River, abandoning Blue Spring Cave and the caves in the East Fork. Skagnasty Cave was abandoned at $t_4$ ≈ 0.9 Ma.**

**Figure 8. A regional aggradation signal at ~0.8 Ma is found throughout the study area, including this passage in Xanadu Cave, TN (Sand Hills Passage). (Photo Sean Roberts.)**

**5. Regional aggradation of lower levels at ~0.85 Ma.** Sediments collected in levels beneath those discussed above indicate widespread aggradation (Fig. 8). Passages that record this event include Xanadu Cave (Sand Hills) at 0.85 ± 0.37 (0.38) Ma; Zarathustra's Cave (B-survey) at 0.83 ± 0.21 (0.22) Ma; Zarathustra's Cave (Elephant Walkway) at 0.86 ± 0.17 (0.19); Sloan's Valley Cave (Appalachian Trail) at 0.89 ± 0.31 (0.33) Ma; and Great Saltpetre Cave (Dressing Room) at 0.95 ± 0.29 (0.31) Ma. These data suggest a widespread regional aggradation event filled one or more of the lower cave levels, overprinting sediment deposited during passage development.

**Figure 9. The Lott Dean passage of the Mountain's Eye System, TN is a modern analog for abandonment in progress. Phreatic development beneath the main conduit transmits base flow for the karst aquifer, and the main conduit carries overflow during storm events. (Photo Brian A. Smith.)**

**6. Measurement of sediment in active base level passages.** The Lott Dean section of the Mountain's Eye System is an active base level conduit for subsurface drainage of the East Fork-Obey River. Lott Dean is a modern analog for abandonment in progress; a small phreatic tube beneath the floor of the main conduit (Fig. 9) carries the base flow component of the karst aquifer, with the main conduit carrying overflow from storm events (see Hess & White 1989 for discussion of base flow in karst aquifers). Measurements of cosmogenic nuclides from quartz pebbles collected in the overflow conduit yield an age of 0.02 ± 0.13 (0.13) Ma, indistinguishable from a zero burial age found in pebbles on the surface. This confirms that base level conduits carry sediment from the surface, an important assumption in the interpretation of cave sediment burial age.

## DISCUSSION

In general, horizontal cave passages in this region form by active solution at a stable water table, and multilevel caves form due to episodic lowering of the local water table in response to changes in the regional base level (White & White 1970; Palmer 1987, 1991). The shape and configuration of multilevel caves on the western margin of the Cumberland Plateau reflect this type of episodic water table lowering, and suggest a common history linked to the changing position of the Cumberland River and its tributaries. Dating sediments in different cave levels can help to firmly establish this history, and constrain the time needed to form large passages.

### THE ASSOCIATION OF MULTILEVEL CAVES WITH LANDSCAPE EVOLUTION

These caves can be related to features long recognized on the surface. Rivers produce wide straths and alluvial terraces during periods of base level stability, with entrenchment indicative of sudden change in the rate of incision (Fenneman 1938). Widespread fluvial gravels ("Lafayette-type") scattered across the surface of the Eastern Highland Rim (Potter 1955) are evidence of a wandering, low-gradient Cumberland River prior to initial incision into its present valley (Fenneman 1938; Thornbury 1965). Following incision, a period of stability resulted in development of a wide valley called the Parker strath 65 m beneath the Highland Rim (Butts 1904; Wilson 1948). Discontinuous terraces at 10–15 m intervals beneath the Parker strath represent shorter episodes of incision (McFarlan 1943; Miotke & Palmer 1972). However, determining the exact timing of episodic incision was difficult in the past due to a combination of unsuitable dating methods and poorly preserved surface materials.

The development of large cave passages along the western margin may be correlated with periods of base level stability, and their abandonment with incision of the Cumberland River. Large passages in Bone Cave and Cumberland Caverns were moving sediment at least three to five million years ago at a water table controlled by the Cumberland River as it flowed on top of the Eastern Highland Rim. These data constrain initial incision of the Cumberland River into the Highland Rim to a time after ~3.5 Ma. Cave passages along the Caney Fork-Calfkiller River and the Obey River were fully developed in cross-sectional area when abandoned by knickpoint migration initiated by the Cumberland River at least two million years ago. These passages formed simultaneously with the Parker strath during a period of base level stability. We suggest these passages developed over a period of ~1.5 m.y. between initial incision into the Highland Rim and incision of the Parker strath, with limited areas of recharge from the Cumberland Plateau.

### MODERN PHREATIC PASSAGES ON THE WESTERN MARGIN

Two large, active, base level conduits that drain 172 $km^2$ and 260 $km^2$ of the Cumberland Plateau cannot be explained by a long period of base level stability. Presently, the Mountain's Eye System (Lott Dean) and Blue Spring Cave (Fig. 10), drain the largest recharge areas of the Cumberland Plateau. Climate over the past two million years has changed rapidly and repeatedly as ice sheets grew and receded in North America. Although the Cumberland River was south of the farthest ice extent, it has nonetheless alternately aggraded and incised, raising and lowering the local water table along the Cumberland Plateau margin. Large base level caves that form today thus require large discharges, because the Cumberland River has not maintained a stable position over the past two million years. In contrast, a relatively stable climate in the Late Tertiary resulted in long-term river stability, so large caves could develop from small recharge areas over millions of years.

**Figure 10. The Second River Crossing in Blue Spring Cave, TN. This large phreatic passage at the modern river level drains roughly 260 $km^2$ of the Cumberland Plateau. (Photo Bernard Szukalski.)**

### COMPARISON WITH OTHER WORK

**The modified plateau-margin model.** Our interpretation of speleogenesis differs from that of Mann (1982). The modified plateau-margin model included high hydrostatic pressure in the conduit. We observed in-situ fluvial deposits with cut-and-fill features, cross-stratification, and imbricated sediments in several of the named "fossil caves," which indicate open channel conditions during deposition of the sediment. Sediments in Bone Cave also display several cycles of graded sediments ranging in size from subrounded pebbles 1–2 cm in diameter to flood clays, which indicated periodic flooding of the conduit. We do not think these caves operated under continuous pipe-full conditions.

**The Cumberland-style model.** Our interpretations differ from those of Sasowsky and White (1994) and Sasowsky *et al.* (1995), who relied on paleomagnetic dating of sediments in "Cumberland-style" caves. Paleomagnetic dating of clastic sediments in cave passages involves the construction of a local

**Figure 11. Sediments in Xanadu Cave, TN (Cumberland Avenue) contain a magnetically reversed-over-normal sequence, and were dated at ~1.6 Ma using cosmogenic nuclides. The burial age identifies the reversal as the younger end of the Olduvai Event. (Photo Dave Bunnell.)**

magnetostratigraphic column based on the orientation of magnetic grains in fine sediments, and subsequent comparison with the global paleomagnetic record. In the absence of absolute dating means, sediments in caves are analyzed to establish normal or reversed magnetic sequences, the latter implying a minimum of 0.78 Ma in age (Cande & Kent 1995). Paleomagnetic dating of sediments in Xanadu Cave's Cumberland Avenue (Fig. 11) revealed one reversed-over-normal polarity transition moving stratigraphically upwards, which was interpreted as the younger end of the Jaramillo event at 0.91 Ma (Sasowsky *et al*. 1995). A "missed" reversal in sediments deposited in lower levels of Xanadu Cave would have placed this transition at the younger end of the Olduvai event (1.66 Ma) but was not considered likely by the authors, as sediments in lower levels were of normal polarity.

We report a burial age of 1.64 ± 0.46 (0.48) Ma from cosmogenic nuclides in sediments from the same location in Cumberland Avenue, which places the reversed-over-normal sequence at the younger end of the Olduvai Event (1.66 Ma). Where then is the signal from the Jaramillo Event? Lower-level passages in Xanadu Cave (Sand Hills) and Zarathustra's Cave (B-survey) contain sediment with measured normal polarity (Sasowsky et al. 1995). We report burial ages of 0.85 ± 0.37 (0.38) Ma and 0.83 ± 0.21 (0.22) Ma for these same sediments in Xanadu Cave and Zarathustra's Cave. Based on the paleomagnetic data, we suggest that these sediments are actually younger than 0.78 Ma, which agrees with our data to within measurement uncertainties. This younger sediment fill has likely masked the Jaramillo event in the lower levels of the caves. (Future researchers may want to look for pockets of in-place sediments at the very top of the Sand Hills passage in Xanadu Cave.)

If the reversed sequence in Xanadu Cave were actually 0.91 Ma, this would imply that three major cave levels developed within 50 m of elevation above the modern river level over the past 910,000 years (Sasowsky *et al*. 1995). Thus, the cave passages must have formed rapidly, requiring high discharge. According to the Cumberland-style model, the discharge of the East Fork-Obey River (roughly 4.5 $m^3\ s^{-1}$ at its point of inflow 10 km upstream from Xanadu Cave) was diverted through both Zarathustra's Cave (Heaven) and Xanadu Cave (Cumberland Avenue) (Sasowsky 1992). Independent evidence from scallops, however, demonstrated these passages carried low discharge. Scallops in Xanadu Cave (Cumberland Avenue) averaging 25 cm in diameter were used to calculate a paleodischarge of ~0.6 $m^3\ s^{-1}$ using Curl's equations for cylindrical passages (Curl 1974). Scallops in Zarathustra's Cave (Heaven) averaging 20 cm in diameter were used to calculate a paleodischarge of 0.3 $m^3\ s^{-1}$. These discharges are an order of magnitude smaller than that of the East Fork-Obey River, but are within limits of recharge gathered from small drainage areas of side tributaries such as Lint's Cove (5.4 $km^2$) and Pratt Branch (7.4 $km^2$).

**Comparison with Mammoth Cave, KY.** Strong correlation between burial ages of sediments in Mammoth Cave (Fig. 1) and multilevel caves on the western margin of the Cumberland Plateau indicates synchronous incision of both the Green River and Cumberland River. Mammoth Cave shares many similarities with large multilevel caves along the western margin of the Cumberland Plateau, including a location within the unglaciated Ohio River basin, similar lithology and climatic history, and a history of cave development reaching well into the Pliocene. Burial ages of cave sediments at Mammoth Cave reveal a common thread between large caves throughout the Kentucky-Tennessee region and firmly link the speleogenesis of multilevel cave systems to the history of regional river incision.

Burial dating of sediments using cosmogenic nuclides in the Mammoth Cave System (Table 2) records nearly four million years of water table position along the Green River (Granger *et al*. 2001). In the Mammoth Cave study, level A of Miotke and Palmer (1972) is older than 3.62 ± 0.50 (0.52) Ma; both levels A and B were aggraded at 2.61 ± 0.16 (0.27) Ma. Excavation of sediments in levels A and B occurred around 2 Ma, when the Green River incised and paused for nearly one-half million years to form level C. Renewed incision of the Green River occurred to level D at 1.55 ± 0.12 (0.18) Ma, abandoning level C and marking the end of well-developed levels (Palmer 1989). Incision at 1.45 ± 0.12 (0.14) Ma and aggradation at 0.85 ± 0.13 (0.16) Ma followed the abandonment of level D. Sediment fill in level D was re-excavated by incision to the modern river level. [Note: burial ages for Mammoth Cave sediments are recalculated in this paper using an AMS standard made by the U.S. National Institute of Standards and Technology (NIST) that yields a $^{10}Be$ meanlife 14% lower than that previously accepted, and thus are slightly older than those reported in Granger *et al*. 2001.]

**Dissolution kinetics and the age of Cumberland Avenue.** Burial ages of cave sediments indicate that large passages such

**Table 2. Cave levels, burial ages, and correlated surface features from the Mammoth Cave System, Kentucky (after Granger *et al.* 2001)**

| Level | Elevation above Green River (m) | Typical morphometric characteristics | Associated surface features | Burial age[a] |
|---|---|---|---|---|
| A | 80+ | Large passages once filled with sediment | Deposition of "Lafayette-type" gravels | 3.62 ± 0.50 (0.52) |
| B | 50-80 | Very large passages (>100 m²) once filled with sediment | Broad straths with thick (6-10 m) gravel | 2.15 ± 0.24 (0.25) |
| C | 47 | Large passages (~30 m²) with little sediment | Strath in Green River valley | 1.55 ± 0.12 (0.18) |
| D | 30 | Small passages (~10 m²) with little sediment | Strath in Green River valley | 1.45 ± 0.12 (0.14) |
| lower | <30 | Small passages with undefined levels | Alluvial sediment in Green River | 0.85 ± 0.13 (0.16) |

[a] Burial ages inferred from simultaneous solution of equations; uncertainties represent one standard error measurement uncertainty, with systematic uncertainties added in quadrature and shown in parentheses.

as Cumberland Avenue in Xanadu Cave, with a typical diameter of 20 m and a length of 1 km, formed over roughly 1.5 million years. Cleaveland Avenue (level C of Mammoth Cave) is less than 10 m in diameter over a length of 1.5 km and formed over a somewhat shorter interval of 0.5 million years. To first order, this suggests a long-term passage enlargement rate of roughly 0.01 mm/yr. Theoretical maximum enlargement rates calculated from dissolution kinetics are roughly 0.2–1 mm/yr (Palmer 1991, 2000; Dreybrodt & Gabrovšek 2000), which are over an order of magnitude faster than our data suggest. However, these theoretical maximum rates are calculated for highly undersaturated water. Both Palmer (2000) and Dreybrodt and Gabrovšek (2000) caution that natural waters often enter conduits with significant calcium in solution, and thus natural rates of cave enlargement may be 1–2 orders of magnitude less than the theoretical values. Our data indicate this to be the case.

## CONCLUSIONS

Large, multilevel caves on the western margin of the Cumberland Plateau (including some previously named as "fossil" or "Cumberland-style" caves) formed during a stable, Late Tertiary climate. The development and abandonment of horizontal passages at concentrated elevations above the modern river level is attributed to distinct episodes of stability and accelerated Plio-Pleistocene incision of the Cumberland River and its tributaries, for which there is good geomorphic and geologic evidence to suggest that river incision occurred as knickpoint migration. A chronology for the development of multilevel caves on the western margin may now be written to include:

- Uppermost levels of cave passages formed prior to ~5.7 and ~3.5 Ma, when the Cumberland River and its tributaries flowed across the Eastern Highland Rim.
- A second level of cave passages formed between ~3.5 and ~2 Ma during a major stillstand of the Cumberland River. Incision of the Cumberland River abandoned the second level beginning at ~2 Ma.
- A third level of cave passages formed between ~2 Ma and ~1.5 Ma during a brief stillstand of the Cumberland River. Incision of the Cumberland River abandoned the third level beginning at ~1.5 Ma.
- A fourth level of cave passages formed after ~1.5 Ma; regional aggradation at ~0.8 Ma filled the fourth level and into the third group of cave passages.
- Incision to the modern river level removed much of the ~0.8 Ma sediment fill.

## ACKNOWLEDGMENTS

We thank the countless number of cavers who participated in exploration and survey of multilevel caves on the western margin, especially those who continue the task today. The authors are deeply indebted to Phil Bodanza, Nick Crawford, Bill Deane, Ralph Ewers, Chris Groves, Sid Jones, Chris Kerr, Brad Neff, Art Palmer, Ira Sasowsky, Jeff Sims, Bill Walter, and Will White for spirited discussions concerning the origin and development of these particular caves. Access and permission to collect samples was granted by private landowners and the State of Tennessee Department of Environment and Conservation. Financial support for this work was obtained from the National Science Foundation (0092459-EAR); the National Speleological Society (Ralph Stone Research Award); the Geological Society of America; Purdue Research Foundation; and Sigma Xi, the Scientific Research Society.

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