Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **32**, 874–887 (2007)
Published online 21 November 2006 in Wiley InterScience
(www.interscience.wiley.com) **DOI:** 10.1002/esp.1446

A new chronology for the age of Appalachian erosional surfaces determined by cosmogenic nuclides in cave sediments

Darlene M. Anthony* and Darryl E. Granger
Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907-2501, USA

Correspondence to: D. M. Anthony, Dept. of Mathematics and Natural Sciences, Roane State Community College, 276 Patton Lane, Harriman, TN 37748-5011, USA. E-mail: anthonyd@roanestate.edu

Received 17 February 2006; Revised 11 August 2006; Accepted 24 August 2006

Abstract

The relative chronology of landscape evolution across the unglaciated Appalachian plateaus of Kentucky and Tennessee is well documented. For more than a century, geomorphologists have carefully mapped and correlated upland erosional surfaces inset by wide-valley straths and smaller terraces. Constraining the timing of river incision into the Appalachian uplands was difficult in the past due to unsuitable dating methods and poorly preserved surface materials. Today, burial dating using the differential decay of cosmogenic ^{26}Al and ^{10}Be in clastic cave sediments reveals more than five million years of landscape evolution preserved underground. Multilevel caves linked hydrologically to the incision history of the Cumberland River contain *in situ* sediments equivalent to fluvial deposits found scattered across the Eastern Highland Rim erosional surface. Cave sediments correlate with: (1) thick Lafayette-type gravels on the Eastern Highland Rim deposited between *c.* 5·7 and *c.* 3·5 Ma; (2) initial incision of the Cumberland River into the Eastern Highland Rim after *c.* 3·5 Ma; (3) formation of the Parker strath between *c.* 3·5 Ma and *c.* 2·0 Ma; (4) incision into the Parker strath at *c.* 2 Ma; (5) formation of a major terrace between *c.* 2·0 Ma and *c.* 1·5 Ma; (6) shorter cycles of accelerated incision and base level stability beginning at *c.* 1·5 Ma; and (7) regional aggradation at *c.* 0·85 Ma. Initial incision into the Appalachian uplands is interpreted as a response to eustasy at 3·2–3·1 Ma. Incision of the Parker strath is interpreted as a response to eustasy at 2·5–2·4 Ma. A third incision event at *c.* 1·5 Ma corresponds with glacial reorganization of the Ohio River basin. Widespread aggradation of cave passages at *c.* 0·85 Ma is interpreted as the beginning of intense glacial–interglacial cycling associated with global climate change. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: river incision; cosmogenic nuclides; cave sediments; Eastern Highland Rim; Parker strath

Introduction

Observations made across the Appalachian Plateaus of North America in the late 19th and early 20th centuries laid the foundation for many modern concepts in regional geomorphology, including those of process, structure and stage. Cyclical landscape evolution and the concept of the peneplain originated in the Appalachian Plateaus, where it was introduced by Davis (1889) in his classic *Rivers and Valleys of Pennsylvania*. The idea of an eroded, then rejuvenated landscape was enthusiastically applied to concordant elevations everywhere, eventually leading to a backlash against identifying older erosional surfaces (Beckinsdale and Chorley, 1968). Of the many peneplains first identified in the interior Appalachian plateaus, only a few are widely accepted today. These include the Lexington surface in Kentucky (Campbell, 1898) and the Highland Rim in Tennessee (Hayes, 1899), which were later correlated with each other (Stout and Lamb, 1938) and with the Harrisburg surface of Ohio, Pennsylvania and West Virginia (Fenneman, 1938). Attempts to determine the age of this surface included analyses of residual soils in carbonate bedrock (Parizek and White, 1985), measurements of geomagnetic reversals in cave sediments (Schmidt, 1982), and correlation of alluvial gravels left on concordant upland surfaces (Fisk, 1944; see Sevon (1985) and White and White (1991) for discussion). These studies enjoyed mixed success, as the results ranged anywhere in relative age from Pleistocene to early Eocene.

Rivers that cross the Eastern Highland Rim in Kentucky and Tennessee (Figure 1) are characterized by deeply entrenched meanders that cut 60–100 m into its surface (Fenneman, 1938). The Upper Cumberland River is an excellent example, with more than 400 km of meandering channel incised into bedrock (Figure 2a). The incision history of the Cumberland River was first determined by field mapping and correlation of upland gravel deposits, meander scars, straths and terraces (Lusk, 1928; Jillson, 1948; Wilson, 1948; see Thornbury (1965) for regional discussion). Deposits of cherty, water-worn gravel called Lafayette in western Tennessee and Kentucky (Hilgard, 1892) and Irvine in eastern Kentucky (Campbell, 1898) are found scattered across the surface of the Eastern Highland Rim. Lusk (1928) and Wilson (1948) reported the presence of Lafayette-type gravels on the Eastern Highland Rim of Tennessee within the upper reaches of the Cumberland River basin, where they became progressively thinner

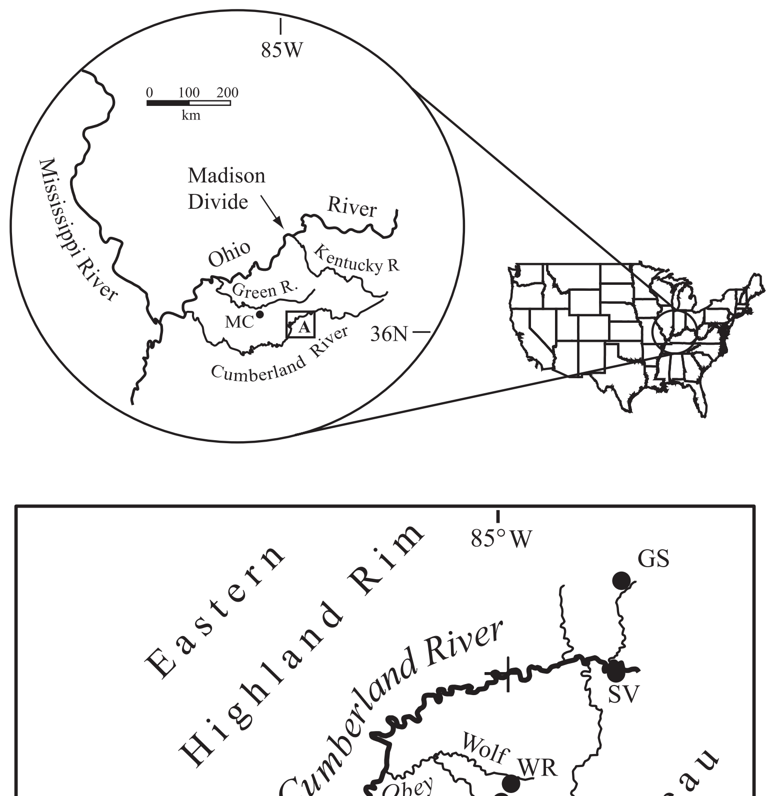

Figure 1. Study area A includes the Upper Cumberland River as it crosses the Cumberland Plateau and Eastern Highland Rim of Kentucky and Tennessee. Twelve caves hydrologically linked to episodic incision of the Cumberland River include: BN (Bone Cave); BS (Blue Spring); BU (Buffalo); CC (Cumberland Caverns); FH (Foxhole); GS (Great Saltpetre); LD (Lott Dean); SN (Skagnasty); SV (Sloan's Valley); WR (Wolf River); X (Xanadu); Z (Zarathustra's). The Mammoth Cave System (MC) is linked to episodic incision of the Green River. The Cumberland River and the Green River are part of the pre-glacial Ohio River, which headed at the Madison Divide.

DOI: 10.1002/esp

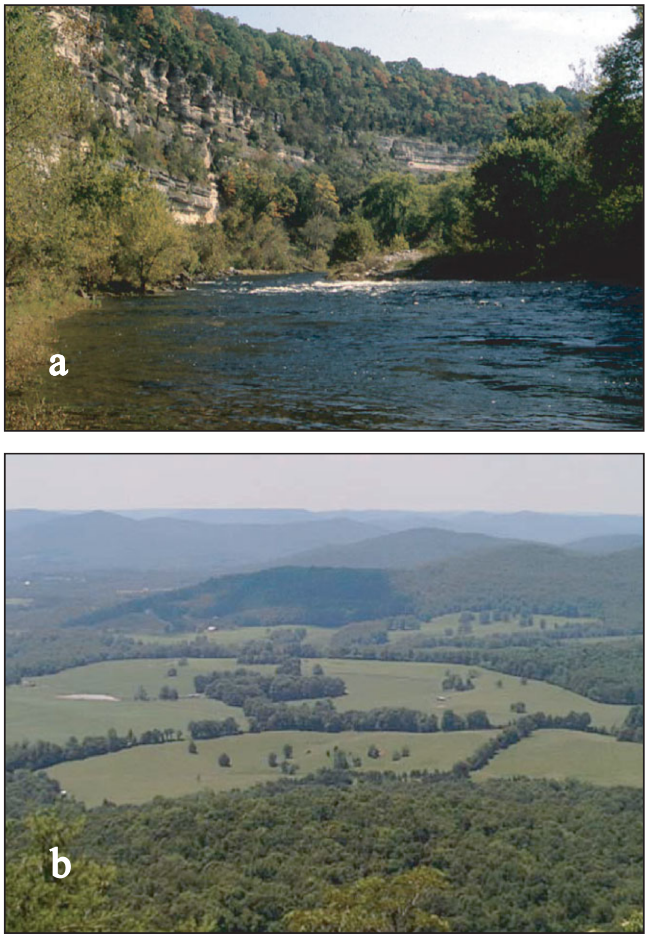

Figure 2. (a) Rivers within the unglaciated Ohio River basin, including the Cumberland River and its tributaries, are characterized by deeply entrenched meanders. (b) The Cumberland Plateau (background) rises over 300 m above the surface of the Eastern Highland Rim (foreground). Photos: (a) Kentucky Geological Survey file photo; (b) D. Anthony. This figure is available in colour online at www.interscience.wiley.com/journal/espl

upstream (Jillson, 1948). Investigations variously considered the gravel to be Eocene (Lusk, 1928), post-Miocene (Jillson, 1948), Pliocene (Potter, 1955), or mid- to late Tertiary (Thornbury, 1965) in age.

The first episode of river incision after deposition of the upland gravels caused the Cumberland River and its tributaries to entrench nearly 65 m into the surface of the Eastern Highland Rim. This was followed by a stillstand that formed a wide valley called the Parker strath (Butts, 1904; Wilson, 1948). Remnants of the Parker strath are also recognized along the Kentucky River (Campbell, 1898) and the Green River (Miotke and Palmer, 1972) (Figure 1). Lafayette-type gravels found on the Parker strath are interpreted to have been swept off the Eastern Highland Rim during the widening of the Parker strath (Thornbury, 1965). A second incision episode downcut the Parker strath and was followed by a brief stillstand that formed a major terrace beneath the Parker strath (McFarlan, 1943; Miotke and Palmer, 1972). Shorter periods of accelerated incision punctuated by brief pauses came afterwards, forming several discontinuous terraces above the modern flood plain (McFarlan, 1943; Miotke and Palmer, 1972).

Entrenchment into the Eastern Highland Rim was initially attributed to regional uplift (modelled after Davis) followed by partial erosion cycles that either formed wide valleys like the Parker strath or deepened valleys along major streams (Fenneman, 1938; Thornbury, 1965). These same landforms were later interpreted as cycles in base-level changes by Hack (1966, 1975) and ascribed to Plio-Pleistocene glaciation (Miotke and Palmer, 1972; Teller and Goldthwait, 1991). The debate over what caused episodic incision was never effectively settled because there were no absolute ages with which to correlate changes in the landscape with records of epeirogenic uplift, eustatic sea level changes, and/or climate changes.

DOI: 10.1002/esp

Two major problems are associated with determining an absolute age for landscape features in this region. First, there is a lack of suitable material to date. Hillslope erosion and mass wasting destroy ancestral meander scars seen today as curvilinear scarps in the upland topography (Ray, 1996). Petrologic analyses of gravels show the Lafayette-type upland gravel was swept from the Highland Rim and redeposited onto lower straths and terraces, mixing with younger gravels (Potter, 1955). Additionally, there are no fossils or volcanic ash deposits with which to constrain an age for fluvial deposits. Second, a suitable dating method for the suspected age range was unavailable. If the depositional age of fluvial sediments does in fact range from recent to several million years old, an appropriate dating method is required.

The problem of erosional loss is solved in this study by using cave sediments in place of terrace deposits. Within the Upper Cumberland River basin, horizontal cave passages developed at the water table during periods of regional river stability (Anthony and Granger, 2004). These passages contain clastic sediments eroded from the higher elevations of the Cumberland Plateau (Figure 2b) and carried as bedload of underground streams. As the Cumberland River incised into the surface of the Highland Rim, local water tables were lowered and cave passages were abandoned in favour of a lower level. Sediments deposited in the caves are equivalent to fluvial deposits, but are unaffected by surface processes. These sediments may now be dated by using the differential decay of cosmogenic aluminium-26 (^{26}Al) and beryllium-10 (^{10}Be) in quartz exposed to cosmic radiation at the surface, then buried underground. This method has proved appropriate for dating buried quartzose sediments ranging in age from *c*. 0·3–5·5 Ma (Granger *et al*., 1997; Anthony and Granger, 2004; 2006).

Caves and Regional Landscape Evolution

A large body of literature exists with regard to cave formation and its relation to the regional hydrologic system; in particular, the correlation between cave levels and the local water table (see Palmer (1987) for discussion). In multilevel cave systems, horizontal passages, or levels, appear to be 'stacked' one above the other within narrow ranges of elevation above the modern water table. The lithologic change from clastic to carbonate bedrock moving downslope on the western escarpment of the Cumberland Plateau provides a near-perfect hydrogeological setting for the development of multilevel solution caves (Figure 3; modified after Crawford, 1984). Surface streams that originate on the sandstone caprock of the Cumberland Plateau sink at the sandstone–limestone contact and follow the hydraulic gradient to the local water table. Horizontal, phreatic passages (Figure 4a) form at the water table and represent periods of base-level stability. Narrow, vadose canyons (Figure 4b) form above the water table. Vadose canyons incised into the floors of abandoned cave passages are thought to form in response to rapid lowering of the water table. Multilevel caves in the study area develop in step with changes in the elevation of regional rivers (Anthony and Granger, 2004). Cave passages formed

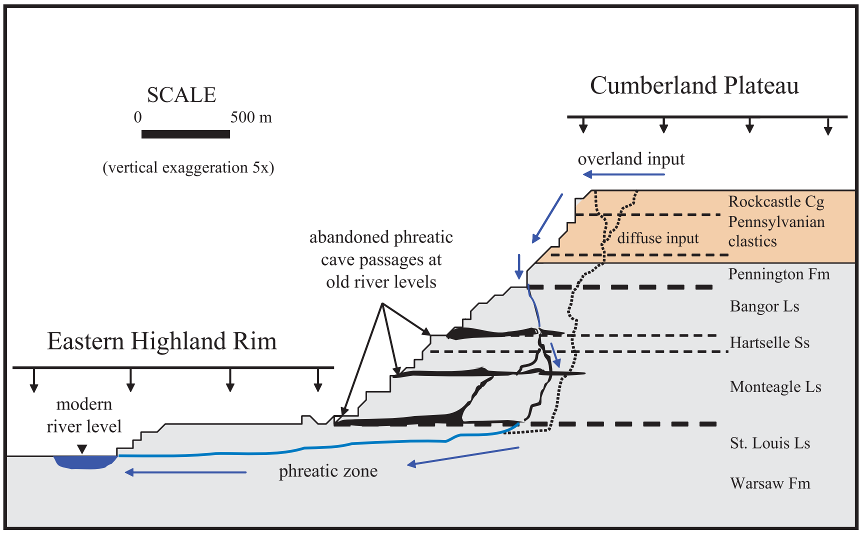

Figure 3. Schematic diagram of multilevel cave development on the western margin of the Cumberland Plateau. Surface streams originating on sandstone bedrock of the Cumberland Plateau flow down the escarpment and sink at the contact between sandstone and limestone. Horizontal passages develop in step with regional river incision. This figure is available in colour online at www.interscience.wiley.com/journal/espl

DOI: 10.1002/esp

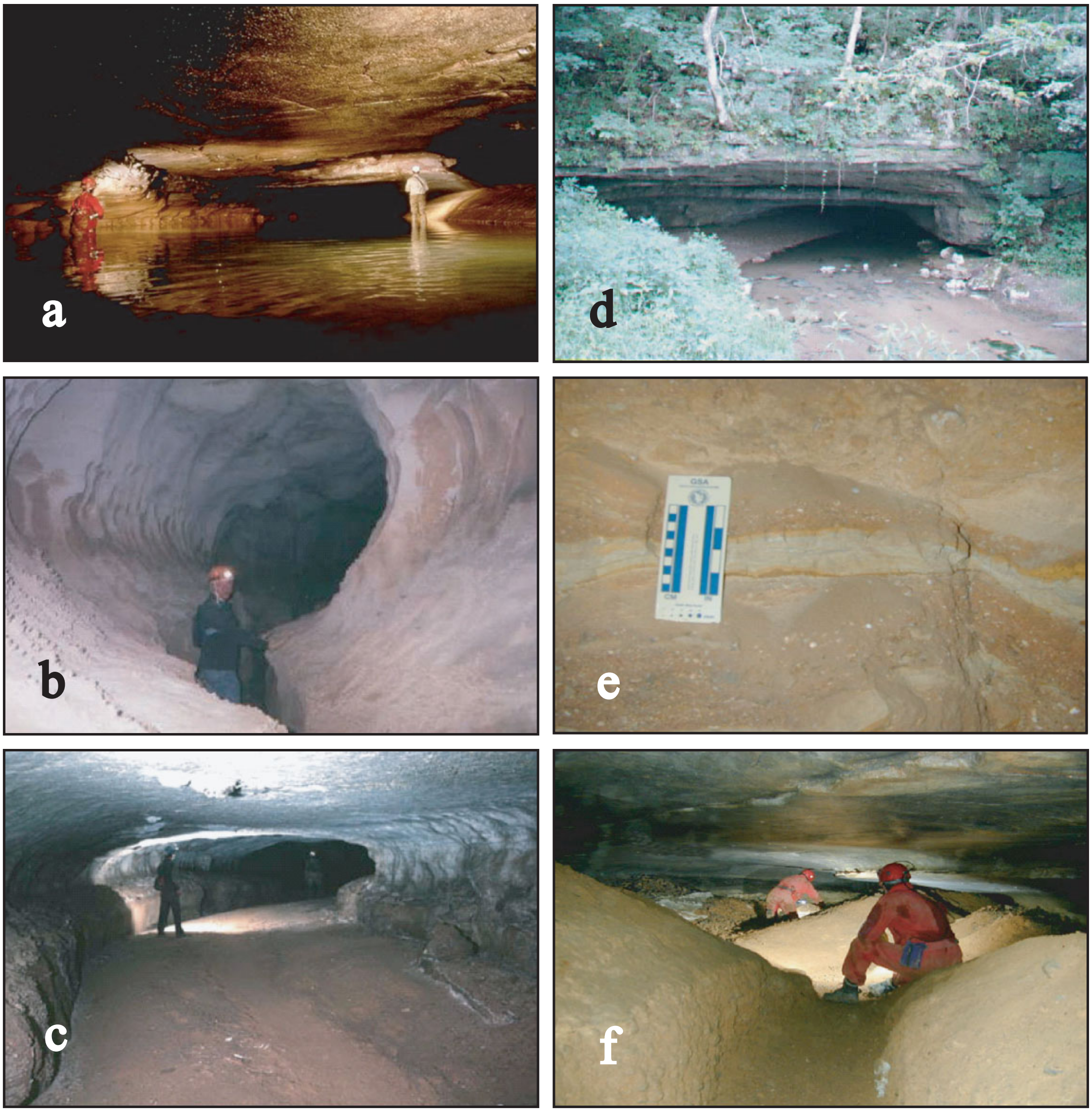

Figure 4. (a) Horizontal cave passages form at the water table. (b) Narrow, vertical canyons form in response to water-table lowering. (c) Hydrologically abandoned passage contain fluvial sediments. (d) Active base-level cave streams exit as springs. (e) Cave sediments retain fluvial features. (f) Regional aggradation filled the lower passages of caves in the study area. Photos: (a) Chris Groves; (b) Peter and Ann Bosted; (c) D. Granger; (d, e) D. Anthony; (f) George Jaegers. This figure is available in colour online at www.interscience.wiley.com/journal/espl

in the phreatic zone closely represent previous elevations of the Upper Cumberland River, as there is little difference between the elevation of the local water table and the regional base level in the study area (White and White, 1983).

Caves are among the longest-preserved components of the landscape by virtue of their location deep within the bedrock (Ford, 1997). Multilevel cave systems preserve the fluvial history of regional rivers unlike surface streams, which almost always destroy their own records of channel morphology, discharge and sediment load through processes of lateral erosion and slope retreat (White, 1988). Sediments enter the underground system as bedload of sinking streams, and are left behind upon diversion of the cave stream to a lower level. Cave sediments (Figure 4e) may remain virtually untouched by weathering or erosion for millions of years (White, 1988; Sasowsky *et al*., 1995). They preserve features of flow conditions prior to passage abandonment and can be interpreted in much the same way as alluvium-mantled strath terraces (Granger *et al*., 1997). Fluvial sediments deposited in abandoned cave passages (Figure 4c) represent the last time the conduit was at the local water table, and therefore may be used to constrain the timing of river incision.

DOI: 10.1002/esp

Dating clastic cave sediments

The most common method for dating clastic sediments in caves prior to radionuclide burial dating was the identification of palaeomagnetic reversals in fine-grained sediments (Schmidt, 1982; Sasowsky *et al*., 1995; Stock *et al*., 2005). Palaeomagnetic dating of sediments in cave passages involves the construction of a local magnetostratigraphic column based on the orientation of magnetic grains in fine sediments, and subsequent comparison with the global palaeomagnetic record. Sediments in caves are analysed to establish normal or reversed magnetic sequences, the latter implying that the sediments are a minimum of 0·78 Ma in age (Cande and Kent, 1995). A missed reversal in a vertical sequence of cave sediments is always a possibility, which may lead to the misidentification of a magnetic reversal in the absence of independent dating methods (see Partridge *et al*. (2003) for discussion of misidentified magnetic reversals in hominid-rich cave sediments).

Quartz-rich sediments washed into caves provide an ideal circumstance for radiometric burial dating using ^{26}Al and ^{10}Be. For example, quartz pebbles eroded from conglomeratic sandstone accumulate ^{26}Al and ^{10}Be at two different production rates in an approximate P_{26}/P_{10} ratio of 6:1 (Lal and Peters, 1967). When washed into a cave passage, the pebbles are instantly shielded by up to tens of metres of solid rock, and production of cosmogenic radionuclides stops (Gosse and Phillips, 2001; Granger and Muzikar, 2001). If the cave stream is diverted to a lower level (as in the case of sudden base level lowering), pebbles in the abandoned passage remains *in situ*, and the concentrations of ^{26}Al and ^{10}Be will diminish over time following two different radioactive decay curves (Lal and Arnold, 1985). Sediment burial dating with ^{26}Al and ^{10}Be takes advantage of the relatively rapid decay of ^{26}Al (radioactive meanlife τ_{26} = 1·02 Ma) with respect to ^{10}Be (radioactive meanlife τ_{10} = 1·93 Ma). Measuring the ratio of ‘leftover’ or inherited ^{26}Al to ^{10}Be in buried sediments yields a burial age for the sediment (assuming a single exposure history) following iterative solutions of equations for pre-burial nuclide concentrations, pre-burial erosion rates, and burial time (see Granger *et al*., 1997).

Caves in the Upper Cumberland River basin

Twelve multilevel caves in the Upper Cumberland River basin (Figure 1) were chosen for cosmogenic dating based on: (1) one or more abandoned cave levels corresponding with major surface features, and (2) in-place clastic sediments exhibiting cross-bedding, graded bedding, imbrication, and other evidence of open-channel fluvial deposition. Cave levels in the Upper Cumberland River basin are concentrated within five elevation ranges as determined by in-cave survey using tape, compass and inclinometer. In general, passages 60–90 m above the modern river level (AML) developed at a time when the Upper Cumberland River flowed at the elevation of the Eastern Highland Rim. Passages at 40–55 m AML correspond to the Parker strath, and at 30–40 m AML correspond to a major terrace inset beneath the Parker strath. These cave levels are hydrologically abandoned and are above the modern flood zone. Cave passages at 15–30 m AML correspond to smaller, discontinuous terraces above the modern floodplain, and are still within the modern flood zone. At 0–15 m AML, passages are hydrologically active and represent the modern river level (Figure 4d).

Burial Dating Methods

Target materials for ^{26}Al and ^{10}Be isotopic measurements were quartz pebbles and sand found in open-channel deposits. Quartz pebbles were crushed to a grain size of less than 0·5 mm, and sand was sieved to 0·25–0·5 mm size to exclude occasional chert fragments weathered from limestone. Quartz from each sample site (*c*. 120 g) was purified by chemical dissolution (Kohl and Nishiizumi, 1992), dissolved in HF and HNO_3, and spiked with *c*. 0·7 mg ^9Be in a carrier solution. Aluminium and beryllium were separated and purified by ion chromatography, selectively precipitated as hydroxides, and oxidized at 1100 °C. Accelerator mass spectrometry (AMS) determination of $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ was performed at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab) and the Lawrence Livermore National Laboratory. (See Muzikar *et al*. (2003) for discussion of AMS in geologic research.)

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

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

DOI: 10.1002/esp

Table I. Cosmogenic nuclide data for cave sediments in Upper Cumberland River basin

Cave name	Elevation (m) above modern rivers	Correlated surface feature	[^{26}Al] (10^6 at/g)	[^{10}Be] (10^6 at/g)	[^{26}Al]/[^{10}Be]	Burial age[1] (Ma)
Bone Cave	91	Highland Rim	0·017 ± 0·012	0·038 ± 0·001	0·46 ± 0·32	5·68 ± 1·09 (1·21)
Cumberland Caverns	66	″	0·158 ± 0·042	0·116 ± 0·004	0·79 ± 0·29	3·52 ± 0·42 (0·49)
Foxhole Cave	43	Parker strath	0·308 ± 0·022	0·139 ± 0·003	2·64 ± 0·16	1·97 ± 0·10 (0·17)
Blue Spring Cave	49	″	0·380 ± 0·038	0·124 ± 0·009	3·07 ± 0·38	1·66 ± 0·23 (0·28)
Skagnasty Cave	45	″	0·334 ± 0·026	0·069 ± 0·006	4·11 ± 0·49	0·89 ± 0·21 (0·22)
Wolf River Cave	43	″	0·189 ± 0·077	0·077 ± 0·005	2·46 ± 0·62	2·15 ± 0·47 (0·52)
Buffalo Cave	48	″	1·127 ± 0·264	0·346 ± 0·012	3·26 ± 0·77	1·45 ± 0·42 (0·45)
Xanadu Cave	54	″	1·036 ± 0·134	0·283 ± 0·005	3·66 ± 0·48	1·23 ± 0·24 (0·27)
Xanadu Cave	52	″	0·208 ± 0·026	0·066 ± 0·014	3·13 ± 0·76	1·64 ± 0·46 (0·48)
Zarathustra's Cave[2]	40	″	1·278 ± 0·228	0·482 ± 0·011	2·65 ± 0·48	1·80 ± 0·31 (0·36)
Xanadu Cave	42	first terrace	0·763 ± 0·149	0·171 ± 0·003	4·46 ± 0·88	0·85 ± 0·37 (0·38)
Sloan's Valley Cave[3]	48	″	1·218 ± 0·202	0·282 ± 0·010	4·32 ± 0·73	0·89 ± 0·31 (0·33)
Great Saltpetre Cave	31	″	1·227 ± 0·062	0·108 ± 0·008	4·31 ± 0·66	0·95 ± 0·29 (0·31)
Zarathustra's Cave	28	″	0·580 ± 0·053	0·130 ± 0·003	4·47 ± 0·42	0·86 ± 0·17 (0·19)
Zarathustra's Cave	13	lower terraces	0·899 ± 0·101	0·200 ± 0·005	4·50 ± 0·52	0·83 ± 0·21 (0·22)
Lott Dean Cave	0	modern river	1·416 ± 0·107	0·214 ± 0·007	6·60 ± 0·54	0·02 ± 0·13 (0·13)

[1] Uncertainties represent one standard error measurement uncertainty. Systematic uncertainties in production rates, production rate ratio, and radioactive decay constants are added in quadrature and shown as total uncertainty in parentheses.
[2] Highest passage of three levels in this system.
[3] Passage developed less than 1 km from mainstem Cumberland River.

where P_{26} and P_{10} are the production rates of ^{26}Al and ^{10}Be, Λ is the penetration length for neutrons ($\Lambda \approx 60$ cm in rock of density 2·6 g cm^{-3}), $\tau_{26} = 1{\cdot}02 \pm 0{\cdot}04$ million years for radioactive ^{26}Al meanlife, and $\tau_{10} = 1{\cdot}93 \pm 0{\cdot}09$ million years for radioactive ^{10}Be meanlife. Local cosmogenic nuclide production rates were assumed constant for the region and were calculated as $P_{10} = 5{\cdot}22$ at g^{-1} a^{-1} and $P_{26} = 35{\cdot}4$ at g^{-1} a^{-1} for a latitude of 36°N and an elevation of 0·5 km (Lal, 1991; Table I). Quartz samples in this study were sufficiently shielded by depth from post-burial nuclide production.

After shielding from nuclide production by burial underground, the cosmogenic radionuclide production will stop, and ^{26}Al and ^{10}Be will decay according to:

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

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:

$$\frac{N_{26}}{N_{10}} = \left(\frac{N_{26}}{N_{10}}\right)_0 \exp[-t(1/\tau_{26} - 1/\tau_{10})] \tag{3}$$

where N_{26} and N_{10} are the measured concentrations of ^{26}Al and ^{10}Be from AMS. Equations 1–3 can be written to solve for converging solutions of E, $(N_{26}/N_{10})_0$ and t. Convergence of the three variables is normally reached after a few iteration loops (Granger *et al*., 1997).

One standard error of analytical uncertainty is calculated from AMS counting statistics and for atomic absorption spectrometry (AAS) measurements. 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. Analytical uncertainties are used when comparing burial ages; systematic uncertainties are used when comparing burial ages with other radiometric dating methods.

Results and Interpretation

Burial dating of sediments in abandoned cave passages (Table I) shows that multilevel caves developed in step with the incision history of the Cumberland River throughout the Plio-Pleistocene. The abandonment of cave passages found at distinct levels above the modern river level allowed reconstruction of approximately five million years of landscape evolution into the Eastern Highland Rim (Figure 5).

Deposition of Lafayette-type gravel on Eastern Highland Rim (Figure 5a)

The oldest deposits of cave sediments in the study area are found in Bone Cave and Cumberland Caverns at 5·68 ± 1·09 (1·21) Ma and 3·52 ± 0·42 (0·49) Ma. Passages in Bone Cave and Cumberland Caverns are the highest in the study area, and are found at 60 to 90 m AML. Cave sediments in these passages approximate the position of the Cumberland River during deposition of Lafayette-type gravel on the Eastern Highland Rim. Abandonment of Bone Cave and Cumberland Caverns occurred after *c.* 3·5 Ma, which implies a minimum age of *c.* 3·5 Ma for upland gravels in the study area and constrains the timing of initial incision into the Highland Rim to after *c.* 3·5 Ma.

Pliocene incision (Figure 5b) and formation of Parker strath (Figure 5c)

During the period of base level stability following initial incision into the Eastern Highland Rim, the Parker strath was formed and underground streams developed a second level of cave passages with spring outlets on the Caney Fork and Obey River tributaries (Figure 1). These passages are now found at 40 to 55 m AML. Sediments deposited in the second level of cave passages approximate the position of the Cumberland River during formation of the Parker strath. The burial age of second-level sediments represents the onset of incision that abandoned the second level for a lower third level of cave passages.

Downcutting of the Parker strath (Figure 5d)

A second incision episode downcut the Parker strath and abandoned the second level of cave passages beginning at 1·97 ± 0·10 (0·17) Ma on the Caney Fork and 2·15 ± 0·47 (0·52) Ma on the Obey River. Burial ages of second-level cave sediments in both the Caney Fork and Obey River tributaries are progressively younger with distance from the Cumberland River, which suggests headward incision by knickpoint migration. Development of the Parker strath is limited to a period of *c.* 1·5 million years between *c.* 3·5 Ma and *c.* 2 Ma, making it a Late Pliocene landscape feature. A period of base-level stability followed the downcutting of the Parker strath and formed a third cave level.

Pleistocene cycles of incision and aggradation (Figure 5e)

A third level of cave passages found at 30–40 m AML corresponds with a major terrace below the Parker strath. A fourth and fifth level of cave passages at 15–30 m AML and 0–15 m AML, respectively, are associated with several discontinuous terraces beneath the larger terrace (McFarlan, 1943; Miotke and Palmer, 1972). Although not as large in cross-sectional area as the first two levels, the third level of cave is larger and more continuous than younger passages beneath. This implies a longer period of time for passage development for the third level (Anthony and Granger, 2004) compared with shorter periods of time associated with the development of the lowest cave levels.

Sediments from the fourth level in each cave in the study area yield a burial age of *c.* 0·85 Ma (Figure 4f). Sediments brought underground by sinking streams completely filled passages to the ceiling and, in some cases, filled the bottom few metres of the third level of caves. The sediment fill has been re-excavated since deposition, but remnants may be found packed into narrow side passages and ceiling potholes. So widespread was this particular burial age throughout the Upper Cumberland River basin that it appears to be a regional aggradation signal.

Incision to modern river level (Figure 5f)

Sediments from aggradation at *c.* 0·85 Ma were removed from most of the fourth cave level during incision to the modern river level. Since their removal, a fifth level of cave passages has formed between 0 and 15 m AML. These hydrologically active cave passages are at grade with the modern Upper Cumberland River and its tributaries. Sediments from these passages yield a burial age indistinguishable from zero (Table I). This shows cave streams at the modern

DOI: 10.1002/esp

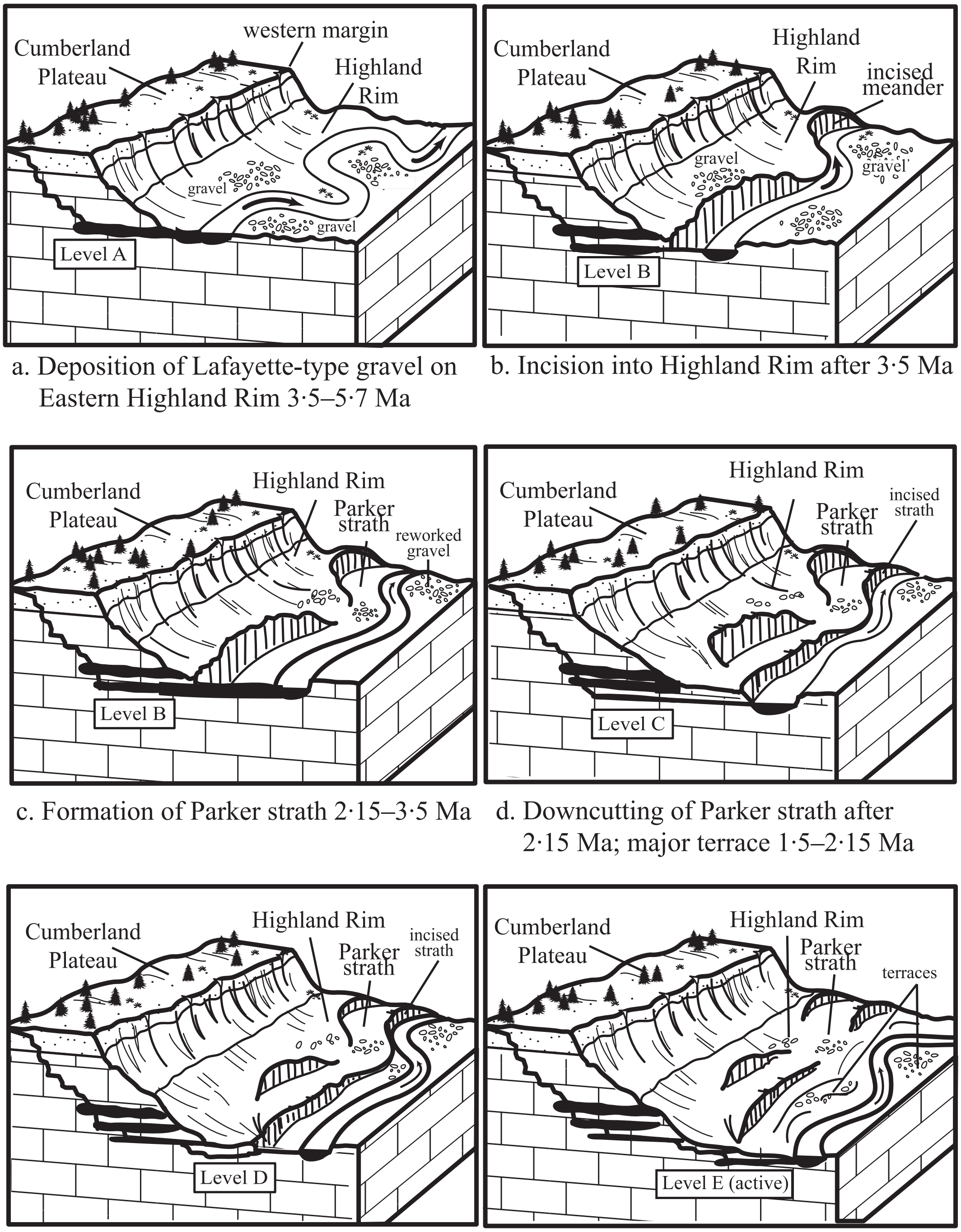

Figure 5. Schematic illustration of landscape development across the Eastern Highland Rim, Kentucky and Tennessee, in response to episodic river incision.

Table II. Burial ages of sediments in Mammoth Cave, Kentucky (after Granger *et al*., 2001)

Level	Elevation (m) above Green River	Typical morphometric characteristics	Associated surface features	Burial age*
A	80+	Large passages (~30 m^2) once filled with sediment	Deposition of Lafayette-type gravels	3·62 ± 0·50 (0·52)
B	50 to 80	Very large passages (>100 m^2) once filled with sediment	Broad straths with thick (6–10 m) gravel	2·15 ± 0·24 (0·25)
C	47	Large passages with little sediment	Strath in Green River valley	1·55 ± 0·12 (0·18)
D	30	Small passages (~10 m^2) 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)

* 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.

water table are moving sediments input directly from the surface, an important assumption in the interpretation of cave sediment burial age.

Discussion

Comparison with burial dating at Mammoth Cave, KY

Burial dating of sediments in the multilevels of the Mammoth Cave System on the Green River, Kentucky (Figure 1) revealed a record of changes in the water table over the past 3·5 million years (Granger *et al*., 2001). (Note that burial ages for Mammoth Cave sediments were recalculated (Anthony and Granger, 2004) using an AMS standard made by the US National Institute of Standards and Technology (NIST) that yielded a ^{10}Be meanlife 14 per cent lower than that previously accepted by workers, and thus were slightly older than those reported in Granger *et al*., 2001.) Incision of the Green River into the Eastern Highland Rim was shown to be episodic, with accelerated incision rates of *c*. 30 m/Ma interspersed with periods of base level stability.

Good agreement exists between levels in Mammoth Cave on the Green River and caves within the Upper Cumberland River basin (Table II). Sediments from the highest level (Level A) of Mammoth Cave represent the final deposition of Lafayette-type gravels on the Eastern Highland Rim surface, which are found scattered across the Kentucky landscape between 215 and 245 m ASL (Ray, 1996). Burial ages of sediments in Level A of Mammoth Cave are 3·62 ± 0·50 (0·52) Ma (Granger *et al*., 2001), which agree with the age of sediments in Cumberland Caverns of 3·52 ± 0·42 (0·49) Ma. Initial incision of the Green River into the Eastern Highland Rim is constrained to after *c*. 3·6 Ma from Mammoth Cave sediments. This compares favourably to initial incision of the Cumberland River into the Eastern Highland Rim after *c*. 3·5 Ma.

A second level (Level B) of cave passages at Mammoth Cave formed during the Parker strath stillstand (*c*. 1·5 million years) between 3·62 ± 0·50 (0·52) Ma and 2·15 ± 0·24 (0·25) Ma. Similar passages formed in the Upper Cumberland River basin between 3·52 ± 0·42 (0·49) Ma and *c*. 2 Ma. A second incision episode downcut the Parker strath on the Green River at 2·15 ± 0·24 (0·25) Ma. Caves along the Cumberland River tributaries record the second incision event at 2·15 ± 0·47 (0·52) Ma and 1·97 ± 0·10 (0·17) Ma.

A period of base level stability following incision of the Parker strath (roughly 500 000 years) formed a third level of cave passages (Level C) at Mammoth Cave, which corresponds with a major terrace beneath the Parker strath. Sediments deposited in Level C of Mammoth Cave are interpreted to date a third incision event at 1·55 ± 0·12 (0·18) Ma, triggered by creation of the modern Ohio River *c*. 1·5 Ma (Granger and Smith, 2000; Granger *et al*., 2001). Sediments from passage abandonment of third-level passages in the Upper Cumberland River basin were masked by a later aggradation event at *c*. 0·85 Ma. However, similarities in passage dimension, elevation above the modern river level, and superposition were enough to consider them equivalent in age to Level C.

Levels at Mammoth Cave are not well defined below Level C; a fourth level (Level D) was abandoned at 1·45 ± 0·12 (0·14) Ma, and is only slightly younger than the abandonment of Level C (Granger *et al*., 2001). The final event identified at Mammoth Cave was aggradation at *c*. 0·85 Ma which filled the lower two levels of cave with sediment. This sediment has been re-excavated to the modern Green River level. In the Upper Cumberland River basin, a major aggradation event at *c*. 0·85 Ma also completely filled the fourth level of cave passages and reached into the bottom few metres of the third level of cave. The sediment fill was later re-excavated to the modern river level.

Table III. Interpretation of Appalachian landscape evolution from burial ages of cave sediments

Age (Ma)[1]	Surface events[2]	Cumberland River and Green River history[2]	Caves in Upper Cumberland River basin[3]	Mammoth Cave (Green River basin)[4]
3·5–5·7	Deposition of Lafayette-type upland gravel	Stable	Development of levels at 60 to 90 m (BC and CC)	Development of level A
after 3·5	Meanders entrenched into Highland Rim	First major incision event	Passages abandoned	Level A abandoned
2·15–3·5	Parker strath developed	Stable	Development of levels at 30 to 60 m (FH, BS, SN, WR, X, Z)	Development of level B
after 2·15	Parker strath incised	Second major incision event	Passages abandoned	Level B abandoned
1·5–2·15	Terrace developed below Parker strath	Stable	Development of levels at 20 to 30 m (X, Z, GS, SV)	Development of level C
0–0·85	Discontinuous terraces above modern floodplain	Brief episodes of incision and stability	Poorly developed levels; aggradation at 0·85 (X, Z, SV, GS)	Poorly developed below level C; aggradation at 0·85

[1] From cave sediments in Cumberland River basin and Mammoth Cave on Green River (Tables I and II).
[2] For discussion of river and landscape, see Fenneman (1938) and Thornbury (1965).
[3] Cave levels in metres above modern river level; letters correspond with caves, Figure 1.
[4] For discussion of levels in Mammoth Cave, see Palmer (1987).

Regional and global implications

The interpretation of Appalachian landscape evolution from burial ages of cave sediments (Table III) has both regional and global significance. The oldest deposits of cave sediments show that caves were actively transporting sediment during the Late Miocene to a stable water table controlled by rivers crossing the Eastern Highland Rim, and correlate with deposition of Lafayette-type gravels. A minimum age of *c*. 3·5 Ma for upland gravels is indicated. The cause of Pliocene aggradation is uncertain, but accumulation of sediments is consistent with a climate regime characterized by extreme global warmth that ended with a transition into cooler climate and the development of northern hemisphere ice sheets (Shackleton *et al*., 1984).

Initial incision of the Green River and the Upper Cumberland River into the Eastern Highland Rim is now constrained to after *c*. 3·5 Ma from burial ages of cave sediments. Examination of sea level positions during the Pliocene (Krantz, 1991), from deep sea, middle Atlantic Coastal Plain and Gulf of Mexico sediments, shows that the North American continental shelf margin was exposed at 3·2 Ma during a major marine regression. Global cooling at 3·2 to 3·1 Ma triggered a 75 to 100 m eustatic sea level drop (Galloway *et al*., 2000) large enough to initiate an incision pulse up the Mississippi–Ohio–Cumberland River and Ohio–Green River. Incision into the Eastern Highland Rim may be interpreted as a response to eustasy at 3·2 Ma.

Global warming at 3·0 Ma followed by progressive cooling to 2·4 Ma (Keigwin, 1987; Curry and Miller, 1989) occurred after initial incision into the Highland Rim. The Parker strath began to form during this period of time, and underground streams in the Upper Cumberland River basin developed large cave passages with spring outlets on the Caney Fork and Obey River tributaries. Progressively younger burial ages from level 2 passages suggest that a major incision pulse on the Upper Cumberland River moved past the confluences of the Caney Fork and Obey River prior to *c*. 2 Ma, triggering incision pulses up these tributaries. Incision of the Green River triggered abandonment of passages in Mammoth Cave at *c*. 2·15 Ma. Geomorphic and geological evidence from the Eastern Highland Rim support incision by knickpoint migration as a response to sudden base-level lowering. Sea-level records from the Gulf of Mexico show a major marine regression at 2·4 Ma, large enough to initiate a second incision pulse up the Mississippi–Ohio River. Incision into the Parker strath may be interpreted as a response to eustasy at 2·4 Ma.

A brief stillstand following incision at *c*. 2 Ma formed a major terrace beneath the Parker strath and a third level of cave passages. The third level (Level C) of Mammoth Cave was abandoned by incision at 1·55 ± 0·12 (0·18) Ma. This correlates with a large marine regression and its corresponding North American ice sheet at *c*. 1·6 Ma (Royall *et al*., 1991). At this time, major north-flowing rivers were diverted at the Madison Divide (Figure 1) into the headwaters of the Ohio River system at 1·5 ± 0·3 Ma (Granger and Smith, 2000; Granger *et al*., 2001). The sudden increase in discharge caused rapid entrenchment of the upper Ohio River channel, at times as much as 60 m below the modern river level (Miotke and Palmer, 1972). The Green River and the Cumberland River were soon out of grade with the newly lowered Ohio River, which triggered incision pulses on both. The third cave level was abandoned in response to this incision event, which may be attributed to drainage reorganization caused by glaciation.

In the Upper Cumberland River basin, burial ages from the third level of cave passages in the study area did not indicate a pattern of headward incision; instead, they revealed a very different story. Sediments gathered from the bottom elevations of the third level of passages are from a regional aggradation event dating to *c*. 0·85 Ma, and are superimposed over sediments left during passage abandonment. Sediment from the *c*. 0·85 Ma aggradation partially fills some of the lowest elevations of Level C passages at Mammoth Cave (equivalent to the third cave level in the Upper Cumberland River basin), implying that this was indeed a regional aggradation event. Aggradation triggered by an increase in the sediment load-to-discharge ratio coincides with the beginning of intense glacial–interglacial cycling associated with global climate change (Groot, 1991).

Several discontinuous terraces beneath the major terrace marked shorter cycles of incision down to the modern channel (McFarlan, 1943; Miotke and Palmer, 1972). Two levels of cave passages lower in elevation than Level C at Mammoth Cave and lower than the third level of cave in the Upper Cumberland River basin were filled with sediment at *c*. 0·85 Ma that has since been removed. In active cave streams at base level, sediments have a burial age of zero, which shows they are input from the surface with no prior burial history.

Conclusions

A geochronology for incision events and landscape response is established for the Eastern Highland Rim erosional surface, using cave passages and sediments as proxies for strath terraces and alluvial deposits. This chronology shows that:

- caves draining the western margin of the Cumberland Plateau in Kentucky and Tennessee were an active part of the regional hydrology during the Late Miocene, when regional rivers flowed across the Eastern Highland Rim;
- deposition of Lafayette-type gravel on the Eastern Highland Rim by the Green River and the Cumberland River occurred until *c*. 3·5 Ma;
- initial incision of the Eastern Highland Rim occurred after *c*. 3·5 Ma (possibly driven by eustasy);
- development of the Parker strath is constrained to a period between *c*. 3·5 Ma and *c*. 2 Ma;
- incision of the Parker strath began at *c*. 2 Ma (possibly driven by eustasy);
- development of a major terrace beneath the Parker strath is constrained to a period between *c*. 2 Ma and *c*. 1·5 Ma;
- incision of a major terrace occurred after *c*. 1·5 Ma (possibly driven by North American drainage reorganization);
- regional aggradation occurred at *c*. 0·85 Ma (possibly driven by climate change).

Cosmogenic burial dating of cave sediments is a powerful tool that provides important information in our understanding of landscape evolution. Burial ages of cave sediments in the unglaciated southeastern United States are being used to settle old arguments about the Appalachian landscape. For example, the classic textbooks by Fenneman and Thornbury on North American geomorphology and physiography could only suggest relative ages for landscape features such as the Parker strath. Today, we can show with absolute ages that the Parker strath was indeed developed during the Pliocene. The development of multilevel caves represents a much bigger picture than simply speleogenesis; the relationship between caves and regional rivers is shown to be a key for unlocking the history of river (and landscape) response to regional and global changes.

Acknowledgements

The authors wish to acknowledge the contributions of 19th and early 20th century geologists and geographers whose field observations in the Appalachians remain unequalled. Financial support for this work was obtained from: National Science Foundation (0092459-EAR); National Speleological Society (Ralph W. Stone Award); Geological Society of America; Purdue Research Foundation; and Sigma Xi, the Scientific Research Society.

References

Anthony DM, Granger DE. 2004. 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* **66**: 46–55.

Anthony DM, Granger DE. 2006. Five million years of Appalachian landscape evolution preserved in cave sediments. In *Perspectives on Karst Geomorphology, Hydrology, and Geochemistry – A Tribute Volume to Derek C. Ford and William B. White*, Harmon RS, Wicks C (eds). GSA Special Paper **404**: 39–50.

Beckinsdale RP, Chorley RJ. 1968. History of geomorphology. In *The Encyclopedia of Geomorphology*, Fairbridge RW (ed.). Dowden, Hutchinson, and Ross: Stroudsburg, PA; 410–416.

DOI: 10.1002/esp

Butts C. 1904. *Description of the Kittanning quadrangle*. United States Geological Survey, Folio 115.

Campbell MR. 1898. *Description of the Richmond quadrangle*. United States Geological Survey, Folio 46.

Cande SC, Kent DV. 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research B*: **100**: 6093–6095.

Crawford NC. 1984. Karst landform development along the Cumberland Plateau Escarpment of TN. In *Groundwater as a Geomorphic Agent*, LeFleur RG (ed.). Allen and Unwin: Boston; 294–338.

Curry WB, Miller KG. 1989. Oxygen and carbon isotopic variation in Pliocene benthonic foraminifers of the equatorial Atlantic. *Ocean Drilling Program Scientific Results* **108**: 157–166.

Davis WM. 1889. The rivers and valleys of Pennsylvania. *National Geographic Magazine* **1**: 183–253.

Fenneman NM. 1938. *Physiography of the Eastern United States*. McGraw-Hill: New York.

Fisk HN. 1944. *Geological Investigations of the Alluvial Valley of the Lower Mississippi Rive*r. Mississippi River Commission: Vicksburg, MS.

Ford DC. 1997. Dating and paleo-environmental studies of speleothems. In *Cave Minerals of the World*, Hill C, Forti P (eds). National Speleological Society: Huntsville, AL; 271–283.

Galloway WE, Ganey-Curry PE, Li X, Buffler RT. 2000. Cenozoic depositional history of the Gulf of Mexico basin. *AAPG Bulletin* **84**: 1743–1774.

Gosse JC, Phillips FM. 2001. Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Review* **20**: 1475–1560.

Granger DE, Muzikar PF. 2001. Dating sediment burial with in-situ produced cosmogenic nuclides: theory, techniques, and limitations. *Earth and Planetary Science Letters* **188**: 269–281.

Granger DE, Smith AL. 2000. Dating buried sediments using radioactive decay and muogenic production of ^{26}Al and ^{10}Be. *Nuclear Instrumentation and Methods in Physics Research B: Beam Interactions with Materials* **172**: 822–826.

Granger DE, Kirchner JW, Finkel RC. 1997. Quaternary downcutting rate of the New River, Virginia, measured from differential decay of cosmogenic ^{26}Al and ^{10}Be in cave-deposited alluvium. *Geology* **25**: 107–110.

Granger DE, Fabel D, Palmer AN. 2001. Plio-Pleistocene incision of the Green River, KY from radioactive decay of cosmogenic ^{26}Al and ^{10}Be in Mammoth Cave sediments. *GSA Bulletin* **113**: 825–836.

Groot JJ. 1991. Palynological evidence for late Miocene, Pliocene, and Pleistocene climate changes in the middle U.S. Atlantic coastal plain. *Quaternary Science Reviews* **10**: 147–162.

Hack JT. 1966. *Interpretation of the Cumberland Escarpment and Highland Rim, south-central Tennessee and northeast Alabama*. United States Geological Survey Professional Paper 524-C: 16.

Hack JT. 1975. Interpretation of erosional topography in humid temperate regions. In *Planation Surfaces; Peneplains, Pediplains, and Etchplains*, Adams GF (ed.). Dowden, Hutchinson, and Ross: Stroudsburg, PA; 129–146.

Hayes CW. 1899. Physiography of the Chattanooga district. *United States Geological Survey 19th Annual Report* **2**: 1–58.

Hilgard EW. 1892. The age and origin of the Lafayette Formation. *American Journal of Science* **43**: 389–402.

Jillson WR. 1948. American fluvial Pliocene deposits bordering the western margin of the Cumberland Plateau. *International Geological Congress Report*, 18th Session.

Keigwin LD. 1987. Toward a high-resolution chronology for latest Miocene paleoceanographic events. *Paleoceanography* **2**: 639–660.

Kohl CP, Nishiizumi K. 1992. Chemical isolation of quartz for measurement of *in-situ* produced cosmogenic nuclides. *Geochimica et Cosmochimica Acta* **56**: 3583–3587.

Krantz DE. 1991. A chronology of Pliocene sea-level fluctuations. *Quaternary Science Reviews* **10**: 163–174.

Lal D. 1991. Cosmic ray labeling of erosion surface: In-situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* **161**: 231–241.

Lal D, Peters B. 1967. Cosmic ray produced radioactivity on the Earth. In *Handbuch der Physik*, Flugge S (ed.). Springer-Verlag: Berlin; 551–612.

Lusk RG. 1928. Gravel on the Highland Rim Plateau and terraces in the Valley of the Cumberland River. *Journal of Geology* **36**: 164–170.

McFarlan AC. 1943. *Geology of Kentucky*. University of Kentucky Press: Lexington, KY.

Miotke F, Palmer AN. 1972. *Genetic Relationship Between Caves and Landforms in the Mammoth Cave National Park Area*. Bohler-Verlag Press: Wurtzburg.

Muzikar PF, Elmore D, Granger DE. 2003. Accelerator mass spectrometry in geologic research. *GSA Bulletin* **115**: 643–654.

Palmer AN. 1987. Cave levels and their interpretation. *NSS Bulletin* **49**: 50–66.

Parizek RR, White WB. 1985. Application of Quaternary and Tertiary geological factors to environmental problems in central Pennsylvania. *Guidebook to 50th annual Field Conference of Pennsylvania Geologists*; 63–119.

Partridge TC, Granger DE, Caffee MW, Clarke RJ. 2003. Lower Pliocene hominid remains from Sterkfontein. *Science* **300**: 607–612.

Potter PE. 1955. The petrology and origin of the Lafayette gravel, part 2: Geomorphic history. *Journal of Geology* **63**: 115–132.

Ray JA. 1996. Fluvial features of the karst-plain erosion surface in the Mammoth Cave region. *5th Mammoth Cave National Park Science Conference*, Mammoth Cave, KY; 137–156.

Royall PD, Delcourt PA, Delcourt HR. 1991. Late Quaternary paleoecology and paleoenvironments of the central Mississippi alluvial valley. *GSA Bulletin* **103**: 157–170.

Sasowsky ID, White WB, Schmidt VA. 1995. Determination of stream-incision rate in the Appalachian plateaus by using cave-sediment magnetostratigraphy. *Geology* **23**:415–418.

Schmidt VA. 1982. Magnetostratigraphy of sediments in Mammoth Cave, KY. *Science* **217**: 827–829.

Sevon WD. 1985. Pennsylvania's polygenetic landscape. *Guidebook for the 4th Annual Field Trip of the Harrisburg Geological Society.*

Shackleton NJ, Backman N, *et al*. 1984. Oxygen isotope calibration of the onset of ice-rafting and the history of glaciation in the North Atlantic region. *Nature* **307**: 620–624.

Stock GM, Granger DE, Sasowsky ID, Anderson RC. 2005. Comparison of U-Th, paleomagnetism, and cosmogenic burial methods for dating caves: Implications for landscape evolution studies. *Earth and Planetary Science Letters* **326**: 388–403.

Stone JO. 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* **105**: 753–759.

Stout W, Lamb GT. 1938. Physiographic features of southeastern Ohio. *Ohio Journal of Science* **38**: 49–83.

Teller JT, Goldthwait RP. 1991. The Old Kentucky River; a major tributary to the Teays River. In *Geology and Hydrogeology of the Teays-Mahomet Bedrock Valley System*, Melhorn WN, Kempton JP (eds). GSA Special Paper 258: 128.

Thornbury WD. 1965. *Regional Geomorphology of the United States*. John Wiley and Sons: New York.

White WB. 1988. *Geomorphology and Hydrology of Karst Terrains*. Oxford Press: New York.

White WB, White EL. 1983. Karst landforms and drainage basin evolution in the Obey River Basin, north-central Tennessee. *Journal of Hydrology* **61**: 69–82.

White WB, White EL. 1991. Karst erosion surfaces in the Appalachian Highlands. In *Appalachian Karst*, Kastning E, Kastning K (eds). National Speleological Society: Huntsville, AL.

Wilson CW. 1948. The geology of Nashville, Tennessee. *Tennessee Division of Geology Bulletin* **53**.

DOI: 10.1002/esp