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P.J. Gibson, P. Lyle, and D.M. George - Application of resistivity and magnetometry geophysical techniques for near-surface investigations in karstic terranes in Ireland. *Journal of Cave and Karst Studies*, v. 66, no. 2, p. 35-38.

APPLICATION OF RESISTIVITY AND MAGNETOMETRY GEOPHYSICAL TECHNIQUES FOR NEAR-SURFACE INVESTIGATIONS IN KARSTIC TERRANES IN IRELAND

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Extensive glacial surficial deposits in Ireland prevent the identification of many karst features. Surface magnetic and resistivity geophysical measurements have been used to identify unknown karstic features. Two dimensional resistivity imaging has located an unknown 210-meter-long, 70-meter-wide and 25-meter-deep collapse feature in eastern Ireland beneath the surficial sediments. A resistivity survey over the Cloyne cave system in County Cork has identified the position of an unknown cave. A magnetic investigation of an infilled paleokarst collapse structure produced a 40 nanoTesla anomaly and illustrates that the technique can be employed in Ireland to locate unknown ones.

Although most karstic regions are characterised by caves, collapse features or passageways, such features often do not have a surface expression, and their presence may go unrecorded. Approximately 35% of Ireland's land surface is underlain by Mississippian limestone, and karst landforms are known from Counties Roscommon, Fermanagh, Galway and the Burren in County Clare (Figure 1). However, most of the limestone is extensively covered by Quaternary glacial sediments, especially in the Irish midlands. It is believed that widespread karstification occurred in Ireland during the Tertiary, but the character of such karst landscapes is wholly unknown because of this surficial cover (Drew 1997). Geophysical surveying can, in certain circumstances, provide us with the means of locating karst features. A commonly employed geophysical technique employed in karst terranes is gravity surveying because the density contrast between air and rock is large. This has been employed to a limited extent in Ireland (Hickey & McGrath 2003), but a drawback of this technique is the large number of corrections — latitudinal, elevational, topographical, tidal and drift — that have to be applied to the data before they can be modeled. However, there are other geophysical techniques which can be used in karst terranes, two of which are considered here: magnetometry and resistivity (Gibson *et al*. 1996; El-Behiry & Hanafy 2000). The former technique is used to investigate a paleokarst structure and the latter technique employed to discover an unknown collapse structure and cave in Ireland. The resistivity data were collected and modeled in the field on a laptop computer in less than one hour. The magnetometry study took less than 20 minutes, providing near real-time acquisition of subsurface information which can be acted on while still in the field.

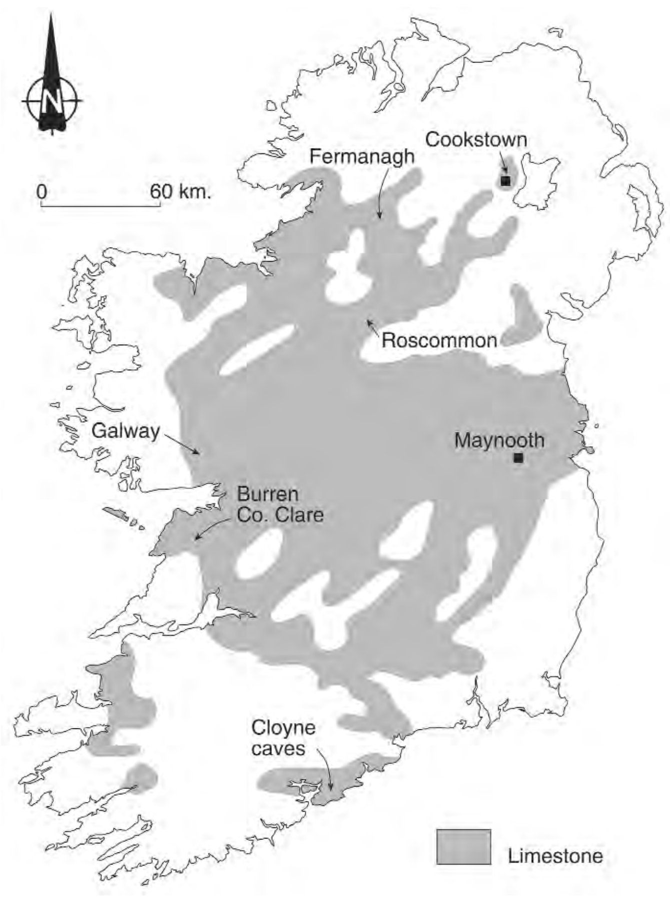

Figure 1: Location map showing localities mentioned in the text.

Figure 2: Paleokarst collapse feature in the Carboniferous limestone in County Tyrone, northern Ireland.

MAGNETIC CASE STUDY

A proton precession magnetometer was used to measure the Earth's total magnetic field which varies with latitude, from about 30,000 nanoTesla (nT) near the equator increasing to around 65,000 nT near the poles. The theoretical principles regarding such magnetometers can be found in standard geophysical texts (Sharma 1997; Gibson & George 2003).

Magnetic susceptibility is a property of a body and is a measure of how easily it can be magnetized. Limestone has an extremely low susceptibility, thus a collapse feature infilled by sediment with a higher susceptibility will be associated with higher magnetic readings. Collapse features are known to exist near Cookstown, northern Ireland, but other unknown ones, which pose a potential risk of collapse, are suspected. A magnetic study was made of a known one to ascertain if this approach could be adopted in the search for unknown ones. Figure 2 shows a funnel-shaped 15m-deep paleokarst collapse feature. The structure is 8 meters across nearest the surface and is capped by a 1.5 meter thick grainstone which indicates a return to marine conditions after the sub-aerial erosion phase during which the structure formed. The collapse feature is infilled by fine-grained unstratified red-brown sediment which is possibly of aeolian origin. The mass specific susceptibility (χ) and percentage frequency dependent susceptibility (χfd%) of the infill and the limestone were obtained using an MS2 Bartington laboratory magnetic susceptibility system. A plot of χfd% against χ shows that the limestone is virtually non-magnetic but the infilled sediment has a mass specific susceptibility that is considerably higher (Figure 3a). A magnetic traverse taken across the feature shows a conspicuous positive 40 nT anomaly (Figure 3b) illustrating that the technique can be successfully employed in such Irish terranes.

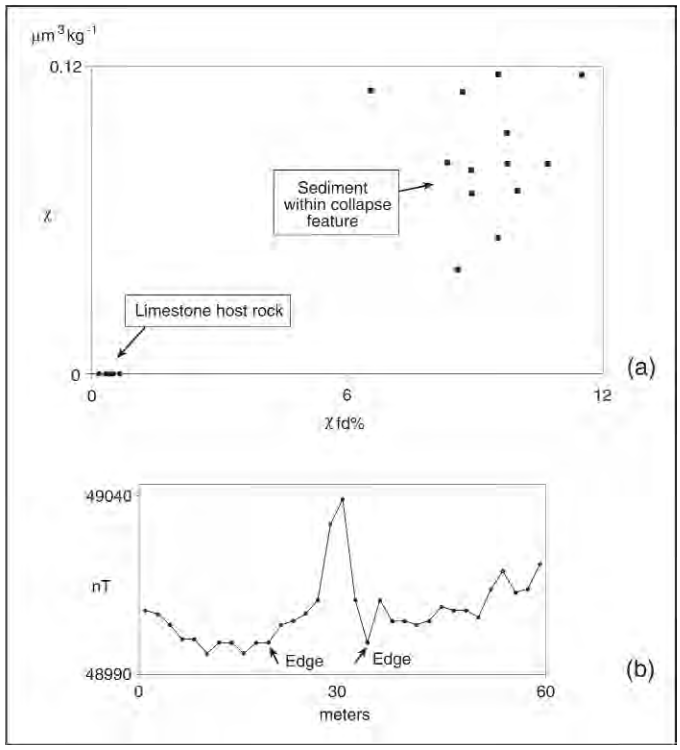

Figure 3: (a) Magnetic susceptibility plot of limestone and infilled sediment for paleokarst collapse feature near Cookstown, County Tyrone, northern Ireland. (b) Results of magnetometer traverse across the same feature.

RESISTIVITY CASE STUDIES

Electrical resistivity techniques involve inputting current into the ground via two source electrodes and measuring the potential difference between two sink electrodes — see Gibson & George (2003) for further details. In this study the process was automated using a multi-core cable and 25 electrodes and a two-dimensional apparent resistivity pseudosection was produced. The pseudosection was modeled using RES2DINV program which utilizes a least-squares optimization approach in order to determine how the true resistivity varies with depth (Loke & Barker 1995; 1996). In the examples shown here, errors are of the order of 5 per cent.

COLLAPSE FEATURE

Figure 4a shows the results of a resistivity traverse across a flat football pitch in the town of Maynooth, eastern Ireland (see Figure 1 for location). The limestone in this region is covered by 10m of Quaternary glacial sediments and there are no known karstic features. Other resistivity traverses in this locality have shown that the resistivity of the limestone is typically 500–1000 ohm meters. The acquired data indicate the presence of an unknown collapse feature in the underlying limestone. Bedrock is quite near the surface at the beginning (0–50) and end (170–220) of the traverse and is shown as a red-pink color (Fig. 4a). The central portion of the image is characterized by

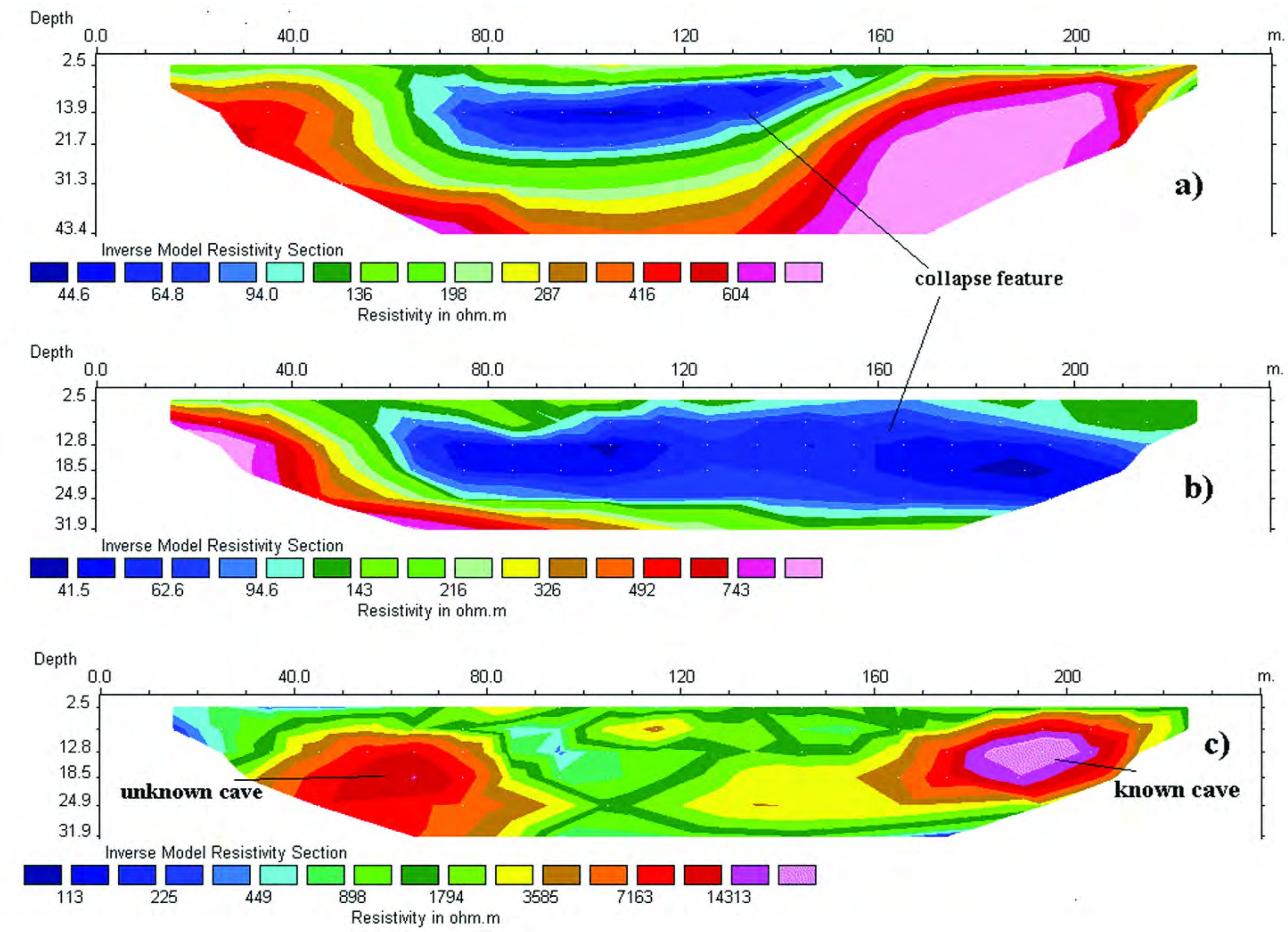

Figure 4: (a) Resistivity traverse across unknown collapse feature in Maynooth, County Kildare, eastern Ireland. (b) Resistivity traverse across same feature at right angles to (a). (c) Resistivity traverse across a known and unmapped cave.

resistivity values an order of magnitude less than those expected for the limestone and are shown in blue. These low values are similar to those obtained for glacial sediments in the vicinity, and the observed pattern is interpreted as an unknown infilled collapse feature approximately 70 meters wide and 25–30 meters deep. A second traverse was taken at right angles to Figure 4a in order to determine its extent. The results show that in this direction the feature is considerably longer (Fig. 4b). A number of such traverses were undertaken and they indicate that the feature is about 25 meters deep, with a 210-meter-long axis oriented NW/SE, and a 70 meter shorter axis oriented approximately at right angles to the long axis.

Cave System

One of the largest subsurface resistivity contrasts is that between solid rock and air such as can occur in a cave system (Morgan *et al*. 1999; Roth *et al*. 1999, 2000). In practice, air-filled caves are typically associated with resistivity values greater than about 15,000 ohm meters, the actual resistivity obtained depending on the size of the caves. Figure 4c shows a 2D resistivity image taken over the Cloyne cave system in Co. Cork, Ireland. The very high resistivity values of over 30,000 ohm meters between 180–210 meters were acquired over a mapped region in which caves are known to exist. However, a similar anomaly associated with high resistivity values can be observed in the 40–70 meter range at a depth of about 20 meters. This area has not been explored and the anomaly is interpreted as an unmapped cave.

Conclusion

Magnetometry and resistivity are geophysical techniques that can provide useful subsurface information in karst regions. The resistivity of air-filled caves is always significantly higher than the bulk rock and, because limestone is virtually non-magnetic, even infill with a low magnetic susceptibility will often yield a magnetic contrast. The techniques have been employed in Ireland to show that karst features can be located by such means and to discover an unknown cave and a large unknown collapse feature below the glacial deposits.

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Katie Schneider and David C. Culver - Estimating subterranean species richness using intensive sampling and rarefaction curves in a high density cave region in West Virginia. *Journal of Cave and Karst Studies*, v. 66, no. 2, p. 39-45.

ESTIMATING SUBTERRANEAN SPECIES RICHNESS USING INTENSIVE SAMPLING AND RAREFACTION CURVES IN A HIGH DENSITY CAVE REGION IN WEST VIRGINIA

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Species richness in a group of caves in the 21.25 km² corner of the USGS 7 ½ minute Williamsburg quadrangle, West Virginia, was investigated to (1) increase our knowledge of species richness for this area, (2) determine how many caves need to be sampled to achieve an accurate estimate of species richness and (3) estimate how many species are present in this area. Eighteen subterranean invertebrate species were collected from 65 caves within the study area. Seven caves were needed to collect 95% of the species. By sampling only the largest seven caves, 89% of the species were captured. However, the species accumulation curve did not reach an asymptote, and estimations based on species rarity show that half of the species were not collected at all. Therefore, the observed patterns should be interpreted with caution, and more data are needed.

Biological sampling and biodiversity mapping have become key components to the understanding of subterranean ecosystems in the face of environmental and anthropogenic threats (Culver *et al*. 2001), and promoting the assessment of the status and vulnerability of cave species facilitates their preservation and protection. Mapping biodiversity is an important step in this endeavor, serving as a tool for education, research, and conservation planning (Culver *et al*. 2001).

The information incorporated into maps of species richness in caves can come from a variety of sources, such as inventory or census information or from known occurrence records (Conroy & Noon 1996). The accuracy of these maps and eventual protection of biological diversity therefore hinges on the completeness of these data (Kodric-Brown & Brown 1993, Keating *et al*. 1998). However, there is an inherent bias in relying on occurrence records and compiled lists, in that most of these lists are incomplete and not all caves have been carefully and repeatedly studied, if they have been studied at all. In addition, sites that have been sampled but in which no species were found are typically not displayed on biodiversity maps, making them indistinguishable from unsampled sites (Deharveng 2001).

Sampling incompleteness can result in misleading patterns in community structure and species rarity, as Kodric-Brown and Brown's (1993) study of the effect of different levels of sampling of fish species richness in Australian desert springs shows. This is often compounded by sampling bias towards accessible sites, such as cities and highways (Bojórquez-Tapia *et al*. 1994) and field stations (Pearson & Cassola 1992), as well as bias towards certain taxa (Bojórquez-Tapia *et al*. 1994), that affect the reliability of occurrence data (Bojórquez-Tapia *et al*. 1995). As a consequence of incomplete sampling, not all species may be represented, leading to inaccurate estimates of species richness (Nichols *et al*. 1998), and possible poor decision making in conservation planning and management (Conroy & Noon 1996). Inventories of subterranean fauna may be so inadequate that many species may go extinct before being discovered (e.g., Croatia [USAID 2000]).

Thus far, richness estimates for cave faunas have been derived based on extrapolation from a small number of well-studied caves, which often tend to be the largest and most accessible (Culver *et al*. in press). It is unclear how inaccurate and/or misleading our knowledge of subterranean biodiversity may be. To date, no cave area has been sampled completely, except possibly for the Canary Islands (Izquierdo *et al*. 2001). The Derbyshire region of Britain has had 27% of the 210 caves sampled (Proudlove 2001) and may be the second most completely sampled region. In West Virginia, an area thought to be well-sampled (Culver & Holsinger 1992), less than 10% of the caves have been biologically sampled (Krow & Culver 2001), even though between 1962 and 1973, 152 caves were biologically investigated (Holsinger *et al*. 1976).

When variation between sites in species richness is great (as is the case for West Virginia caves), a larger sampling effort is required (Hammond 1994) to estimate total species richness. Sampling effort must be sufficient to minimize sampling bias in order to determine if inventory data are accurate (Hammond 1994). It is therefore critical that the sample of caves be large and unbiased (Krow & Culver 2001).

We sampled 65 caves within a high cave density and species-rich area of West Virginia. By sampling a large percentage of caves in an area, it is possible to discover how many species are missed when only a portion of the caves are sampled. We then used these data to examine how many caves need to be sampled to get an accurate estimate of species richness for the study area. Lastly, we predict how many species are indeed present in the study site using rarefaction curves and equations based on species rarity.

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STUDY SITE

West Virginia is reported to have 3754 caves (Jones 1997). Of these 195 (5.2%) are reported to have obligate cave-dwelling species (Culver, unpublished data). There are 76 known obligate cave species reported from the state (Culver & Sket 2000).

As far back as the 1950s, it was acknowledged that Greenbrier County, West Virginia, was rich in cave numbers, possessing some 105 caves — one quarter of all of the caves of West Virginia (Davies 1958). Today, the number of known caves from both locations has increased tenfold, with 1030 known caves from the county (Jones 1997). Greenbrier County is also a national hotspot of cave biodiversity (Culver *et al*. 2000).

An area centered around the Buckeye Creek Basin in northeastern Greenbrier County (Fig. 1) was chosen as the study site in part due to its high concentration of caves. The study site was chosen because of its high cave density on a limited number of properties, its proximity to the West Virginia Association of Cave Studies field station, and our good working relationship with the local landowners. We had access to all areas within the study area.

The invertebrate fauna of the study area was poorly known, and no systematic survey had been performed prior to this study (Fong & Culver 1994). Only 9 of the 148 caves previously had been biologically sampled, and 10 cave-limited species were reported from this study site (Holsinger *et al*. 1976, Fong & Culver 1994).

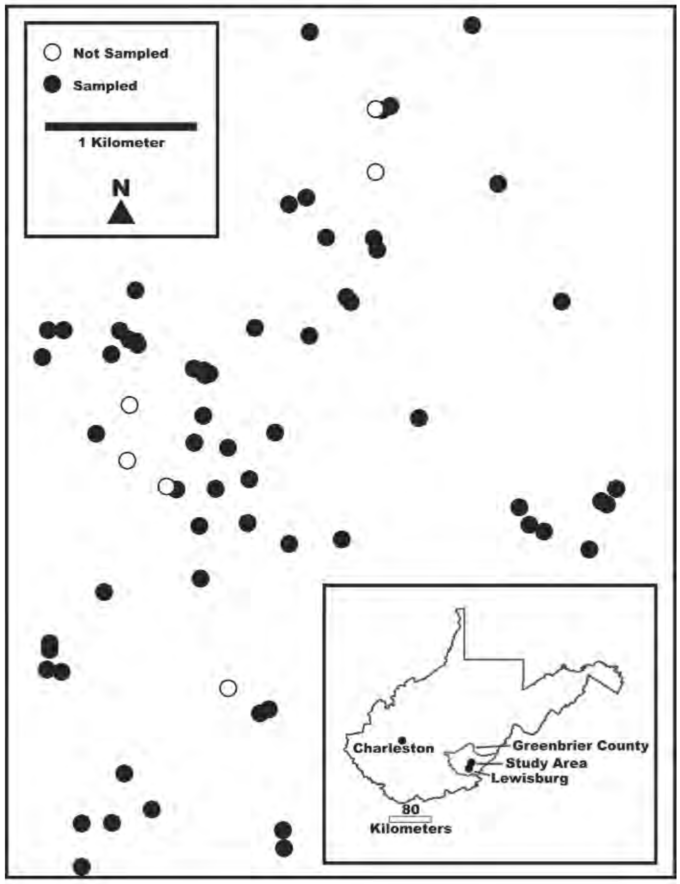

Figure 1. Locator map of the study site. The study site is a ca. 20 km² area located north of Lewisburg, in Greenbrier County, West Virginia. Of the 148 caves located in the study site, 73 were enterable. Of these 73 caves, 65 were sampled during this investigation.

METHODS

Cave locations were obtained from files of the West Virginia Speleological Survey (WVSS). The following criteria were used to select caves to be sampled. First, the caves must be located within the study area where 3' of latitude and 2'30" of longitude in the northeast corner of the USGS 7½ minute Williamsburg quadrangle was determined to be within the study area and representing an area of 21.25 km². Second, cave enterability was usually assessed by inspection and in some cases from the descriptions in Dasher and Balfour (1994).

Caves were located in the field using UTM coordinates, with a map provided by WVSS, and with the help of cavers and local residents. If more than two hours were spent unsuccessfully searching, the cave was classified as "failed to locate." Located caves were included in the study if they could be safely entered and had a dark zone. Entrances of study caves were then flagged and UTM coordinates recorded to facilitate relocating caves during the sampling period.

Sampling took place between June 3, 2002 and July 21, 2002. Once inside a cave, a visual census of organisms on the walls, floor, ceiling, and aquatic areas (if present) was performed for one-person hour, recording all species found. Only potential troglobites and stygobites were collected and these were placed in 70% ethanol. As a general rule, one to five specimens, an adequate number for positive identification to species, were hand-collected from each cave.

Terrestrial pitfall traps were constructed of 150 mL plastic jars filled with isopropyl alcohol and covered with 7.5 cm × 7.5 cm pieces of 1 cm hardware cloth to exclude cave-crickets, salamanders, and other larger animals. Pitfall traps were baited with limburger cheese and placed in soft mud banks, where mud banks were present. Aquatic traps were constructed of an ordinary kitchen scrubber with a mesh size of approximately 1 cm. The tube of mesh was baited with raw shrimp and tied at both ends. Aquatic traps were placed in slow-running shallow streams or rimstone pools. Traps were placed near areas of high abundance and diversity, as determined by visual sampling.

Generally, one terrestrial and one aquatic (if water was present) trap was placed in each cave. If the cave contained various habitats (e.g., rimstone pools and streams, mudbanks and silty shores, etc.), one to three additional traps of each type were placed. This was the case for most caves more than 100 m long. Traps remained in place for two to three days. Prior to trap removal, the surrounding area was examined and additional individuals attracted to the bait were collected. Animals from pitfall traps were transferred from isopropyl alcohol to ethanol in the laboratory.

Specimens were sorted and identified either by using keys or sending specimens to expert taxonomists. All species remained in ethanol except for the beetles which were transferred to Barber's fluid, a relaxant used to prevent brittleness and breakage of the specimens (Borror *et al*. 1989).

Maps were created using ArcMap GIS (Environmental Systems Research Institute, Redlands, CA, USA) and the UTM data were transformed using Datumpro (Linden Software Ltd, Lincs, United Kingdom). Data were analyzed using Excel (Microsoft Corporation, Redlands, CA, USA), SPSS (SPSS Inc., Chicago, IL, USA), and JMP (SAS Institute, Cary, NC, USA).

Rarefaction curves were made by repeatedly sampling all of the collected species at random (Gotelli & Colwell 2001). Rarefaction curves indicate the expected number of species from a collection of random samples and represent what is statistically expected from the accumulation curve (Gotelli & Colwell 2001). With rarefaction curves, differences are no longer attributed to sample size. Rarefaction curves were created using EstimateS software (Colwell, 1997; http://viceroy.eeb.uconn.edu/estimates).

Due to incomplete sampling, estimators have been derived to predict the true number of species based on rare species in a sample (Colwell & Coddington 1994). This was done using the equation from Chao (1984),

$$S_2^* = S_{obs} + \left(L^2 / 2M\right) \tag{1}$$

where *Sobs* is equal to the number of species observed in a sample, *L* is the number of observed species represented by a single individual (i.e., singletons), and *M* is the number of observed species represented by two individuals in the sample (i.e., doubletons).

The variance on this equation was estimated as

$$\text{var}\left(S_2^*\right) = M\left[\left(\frac{L/M}{4}\right)^4 + \left(L/M\right)^3 + \left(\frac{(L/M)}{2}\right)^2\right] \tag{2}$$

Colwell and Coddington (1994) recommend the application of Burnham and Overton's (1978) jackknife estimators in order to reduce estimation bias in estimating species richness. We calculated this second-order jackknife estimate:

$$S_4^* = S_{obs} + \left[\frac{L(2n-3)}{n} - \frac{M(n-2)^2}{n(n-1)}\right] \tag{3}$$

where *n* is the number of samples. No direct formula for the calculation of the variance is available.

We used the algorithm of Csuti *et al*. (1997) to find the minimum number of caves needed to "capture" 95% of the reported troglobites and stygobites.

RESULTS

The WVSS (West Virginia Speleological Survey) database showed 148 caves, pits and FROs (for the record only) in the study site. We were able to locate and enter 65 of these caves in the summer of 2002 (Fig. 1). Of the remaining 83 locations, we were unable to locate a physically enterable entrance for 75 of them either because of faulty location data or because the WVSS database contained non-cave karst features. The eight additional enterable caves were located too late to be included in the study (January 2003), but are worth revisiting and sampling in future studies.

The average cave length was 165.3 m ±64.6 m and varied between 2 m and 3719 m. Most of the caves were short, with 44 of the 65 caves being less than 30 m long. Cave depth averaged 9.8 m ±1.4 m with a range of one to 30 m. Twenty-one of 33 caves for which depth data were available were less than 10 m deep. All caves had terrestrial habitats, but only 38 had aquatic habitats. An aquatic habitat was defined as an aquatic area in which a trap could be placed.

Overall, six classes, 11 orders, 12 families, 14 genera, and 18 species were collected (Table 1). The two most commonly encountered orders were the Collembola (springtails) and Coleoptera (beetles), followed by the Amphipoda (amphipods), Chordeumatida (millipedes), and Diplura (diplurans).

Three rarefaction curves are shown in Figure 2 — one for all caves, one for caves less than 15 m in length, and one for caves greater than 15 m in length. All three curves showed no sign of reaching an asymptote, but the rate of species accumulation for caves greater than 15 m was more than twice that of caves less than 15 m.

Two estimates of total species richness are provided in Table 2. The two estimates are 36 and 48, and both are considerably higher (between two and three times) than the observed number of 18.

Table 3 shows that seven caves are needed to find 17 of the 18 reported species and suggests which caves need to be sampled in order to collect 95% of the total species collected in the study. If the seven largest caves are used, the result is nearly as good, with 16 of the 18 reported species found in these caves, which implies that 89% of the total species are collected if the largest seven caves are sampled (Table 4). The largest caves themselves are not arranged in order of size but rather in order of their successive contribution of new species, so that in fact that last two caves added to the analysis do not result in the inclusion of any new species.

Table 1. Cave-limited species encountered during the study and their habitats.

Class	Order	Family	Species	Reference	Habitat
Turbellaria	Tricladida	Kenkiidae	*Macrocotyla hoffmasteri*[a]	(Hyman, 1954)	Aquatic
Mollusca	Gastropoda	Hydrobiidae	*Fontigens tartarea*[a]	Hubricht, 1963	Aquatic
Crustacea	Amphipoda	Crangonyctidae	*Stygobromus emarginatus*	(Hubricht, 1943)	Aquatic
Crustacea	Amphipoda	Crangonyctidae	*Stygobromus spinatus*	(Holsinger, 1967)	Aquatic
Crustacea	Isopoda	Asellidae	*Caecidotea holsingeri*	(Steeves, 1963)	Aquatic
Crustacea	Decapoda	Cambaridae	*Cambarus nerterius*	Hobbs, 1964	Aquatic
Diplopoda	Chordeumida	Cleidogonidae	*Pseudotremia* sp. nov.[a]	…	Terrestrial
Diplopoda	Chordeumida	Cleidogonidae	*Pseudotremia* sp.	…	Terrestrial
Insecta	Diplura	Campodeidae	*Eumesocampa* sp.[a]	…	Terrestrial
Insecta	Diplura	Campodeidae	*Litocampa fieldingae*[a]	(Condé, 1949)	Terrestrial
Insecta	Collembola	Sminthuridae	*Arrhopalites clarus*[a]	Christiansen, 1966	Terrestrial
Insecta	Collembola	Entomobryidae	*Pseudosinella gisini*	Christiansen, 1960	Terrestrial
Insecta	Collembola	Entomobryidae	*Sinella hoffmani*[a]	Wray, 1952	Terrestrial
Insecta	Coleoptera	Carabidae	*Pseudanopthalmus grandis*	Valentine, 1931	Terrestrial
Insecta	Coleoptera	Carabidae	*P. higginbothami*	Valentine, 1932	Terrestrial
Insecta	Coleoptera	Carabidae	*P. hypertrichosis*	Valentine, 1931	Terrestrial
Arachnida	Acari	Rhagidiidae	*Rhagidia varia*[a]	Zacharda, 1985	Terrestrial
Arachnida	Pseudoscorpionida	Chthoniidae	*Kleptochthonius henroti*	(Vachon, 1952)	Terrestrial

Note: *Pseudotremia fulgida* was previously reported from the study area (Loomis, 1943) but was not collected during the present study.
[a] Not previously recorded from study area.

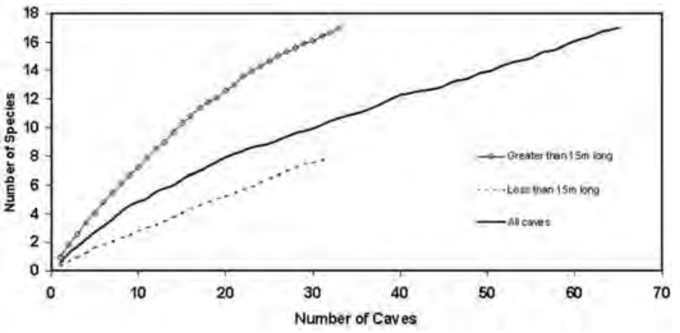

Figure 2. Rarefaction curves for number of caves versus number of species, for all caves (*n* = 65), caves less than or equal to 15 m (*n* = 32), and caves greater than 15 m (*n* = 33). Curves generated using EstimateS with the patchiness parameter set to 0.8 as recommended in Gotelli and Colwell (2001).

DISCUSSION

Prior to this study, knowledge of species richness from caves in this ca. 20 km² area was based on sampling of 9 caves (Holsinger *et al*. 1976; Fong & Culver 1994). In most of these collections, techniques other than hand sampling were not used (Holsinger *et al*. 1976). There are striking omissions from the previous faunal list, such as cave snails and flatworms, most likely due to a lack of an adequate census in the area (Fong & Culver 1994). There were 10 species known prior to our study.

Our study also had omissions. In spite of extensive hand collections and trapping, no spiders were recovered during our study. As a result of our efforts, the number of caves sampled in this area increased from nine to 65, the number of species recorded from this area increased from 10 to 18 (Table 1). When looking only at the nine caves that were resampled in the current investigation, seven species records were confirmed, and eight new localities were added for species previously reported from the study area. New taxonomic groups were also collected from these nine caves, including planarians, diplurans, collembola, millipedes and mites. As a result of this study, there were 93 new records of species, including eight new species, added to this roughly 20 km² area.

The eight species new to the study area are all known from West Virginia. Among the most notable species that we collected was the undescribed dipluran, *Eumesocampa* sp., which has only been collected from one other cave (Steeles Cave, Monroe County, West Virginia). Recent attempts to recollect this species in Steeles Cave have not been successful (L. Ferguson, pers. comm., 2002).

The findings of this research showed that subterranean biodiversity for this area had been greatly underestimated. Clearly, by focusing solely on the minimal information known from nine of 148 caves, many species would be unreported and the distributions of others incompletely known.

Ideally, homogeneous sampling and intensive sampling are preferred; however, subterranean areas are difficult and expensive to sample and the risk of overcollecting is usually a concern. Therefore, it is necessary to know the minimal sample size needed to get an accurate estimation of species diversity for an area. Using the "simple greedy" algorithm of Csuti *et al*. (1997), we found that only a small number of caves need to be sampled in order to collect all known species in the study area.

Table 2. Estimates of total cave-limited species richness in the study area.

Item	Estimate
Number of Caves	65
Number of Singletons	21
Number of Doubletons	12
Observed Number of Species	18
Chao's S_2*	36.4 ±1.1
Burnham and Overton's S_4*	47.6

Table 3. Cumulative numbers of cave-limited species based on the "simple greedy" algorithm of Csuti *et al*. (1997) applied to those caves that need to be sampled in order to collect 95% of total species.

Cave	New sp.
Buckeye Creek Cave	8
Matt's Black Cave	3
Upper Buckeye Creek Cave	2
Rapps Cave	2
Nellie's Cave	1
Hannah Caverns, Raceway Pit, Sunnyday Pit, Trilium Cave, Seep Cave 2, Short Stuff Cave, Tin Cave, or Wake Robin Cave	1
Total Species Collected	17

Table 4. Cumulative numbers of cave-limited species based on the "simple greedy" algorithm of Csuti *et al*. (1997) applied to the largest seven caves.

Cave	New sp.
Buckeye Creek Cave	8
Matt's Black Cave	3
Upper Buckeye Creek Cave	2
Rapps Cave	2
Hannah Caverns	1
McFerrin Water (Spur) Cave	0
Spencer Cave	0
Total Species Collected	16

We found that seven caves were sufficient to capture 95% of the known species (Table 3) although *a prioi* knowledge of which seven caves to sample is lacking. However, using cave length as a surrogate for species richness gives nearly the same results. By examining only the largest seven caves, 89% of the species were collected. This finding has conservation implications, as many of the species (including many of the rare species) could be protected by protecting the largest caves. Izquierdo *et al*. (2001), in a conservation application of Csuti *et al*.'s greedy algorithm, proposed that in order to maximize the number of species protected in a limited number of sites, conservation decisions should be focused on the cave with the most species, followed by the cave with the most species different from the first cave, and so on. If conservation decisions in the study area were indeed based according to this standard, then conservation priority would be given to the cave with the most species, in this case Buckeye Creek Cave. The next cave of concern would be the cave with the largest number of species different from the first, in this case, Matt's Black Cave. Here, following the guidelines of Izquierdo *et al*. and their application of the greedy algorithm, it would only take seven caves to protect 95% of the species. With this approach, many of the largest caves (and the species therein) would be protected. Protecting the largest caves does result in the protection of the greatest biodiversity, and the species accumulated in the larger caves represent most of the species found in the smaller caves.

Rarefaction curves generated from our data did not reach an asymptote, and the curve rose more steeply for larger caves than for smaller caves (Fig. 2) because species accumulated more quickly in larger caves. When no new taxa are added, an asymptote should, in principle, be reached (Gotelli & Colwell 2001). Due to the failure to reach an asymptote, total troglobitic and stygobitic species richness was estimated using equations provided by Colwell and Coddington (1994). Using Chao's estimate, S_2*, total species richness was 36 species, and it was 48 using the second-order jackknife estimate, S_4* (Table 2). Colwell and Coddington point out that in practice, the upper bound of the estimate for S_4* is approximately twice the observed number, i.e., 36, and the upper estimate for S_2* is approximately half the square of the observed number, i.e., 81. This in turn suggests that S_4* estimate is unreliable. If we use the S_2* value of 36 as the best estimate of the number of species, we have found only half of the species.

How did nearly half of the species evade collection? Over 90% of sampled caves in West Virginia have at least one troglobitic species (Culver *et al*. 2004). Here, only 69% of the sampled caves (45 of 65 caves) had at least one troglobite/stygobite collected and approximately one-third of the caves sampled yielded no troglobites or stygobites at all. Repeated visits often are necessary to collect all of the species found in a single cave. In one Italian cave, for example, Fabio Stoch determined that it took six trips to collect all 12 stygobites present (quoted in Culver *et al*. in press). In the nine caves that had been previously examined in our study area, we did not confirm 13 previous species occurrence records. This result could reflect either inadequate sampling or extirpation of these populations. We also did not sample all known caves. An additional 8 caves were found too late to be included in the study, and at least some of the 75 localities in the WVSS database that were reported as having a possible entrance may actually represent cave, at least for the species involved, even if they are not enterable.

With an increased sampling size, the detection of rare species increases (Huston 1994). That accumulation curves did not reach an asymptote (Fig. 2) indicates that not all species were discovered. This could indicate heterogeneity within the samples (Culver *et al*. 2004), because caves that have a majority of the troglobites and stygobites are few, whereas caves with few or no troglobites or stygobites are numerous. This could reflect the rarity of cave-limited taxa and differences in observability among species. The need for repeated sampling is evident. We estimated that the true number of species in this area is 36, twice the number of species collected in this study.

SUMMARY

Although our data set is incomplete, it appears that (1) Previous estimates of richness for this 20 km² area were quite low and increasing the number of caves sampled from nine to 65 increased the number of species from 10 to 18; (2) Only a small number of the caves need to be sampled in order to collect all of the species observed; and (3) Based on rarefaction curves and mathematical estimations, half of the species from the study area were not collected despite this effort of intensive sampling. This study advances our understanding of cave-limited species, by providing insights into the richness and distribution of stygobites and troglobites, and assessing the efficacy and accuracy of current methods of quantifying subterranean biodiversity.

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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

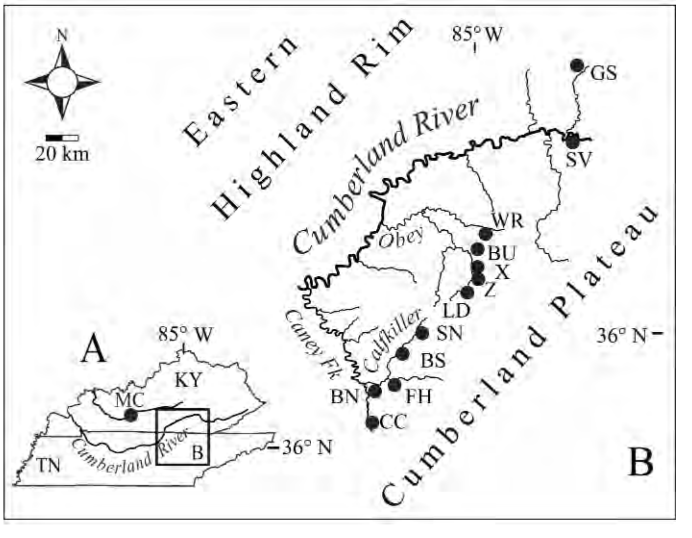

Figure 1. The study area in Kentucky and Tennessee (A) with Mammoth Cave (MC) on the Green River, KY. A portion of Upper Cumberland River basin (B) drains the study area, and includes twelve caves on the western margin of the Cumberland Plateau. CC-Cumberland Caverns; BN-Bone Cave; FH-Foxhole Cave; BS-Blue 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.

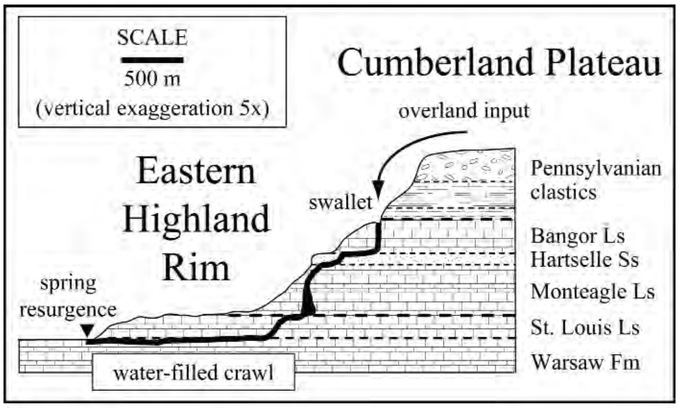

Figure 2. Schematic plateau-margin model of cave development (after Crawford, 1984). Surface streams originating on sandstone bedrock of the Cumberland Plateau flow down the escarpment and sink at the contact between sandstone and limestone. Sinking streams form cave passages in the vadose zone leading 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, Λ 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:

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

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.

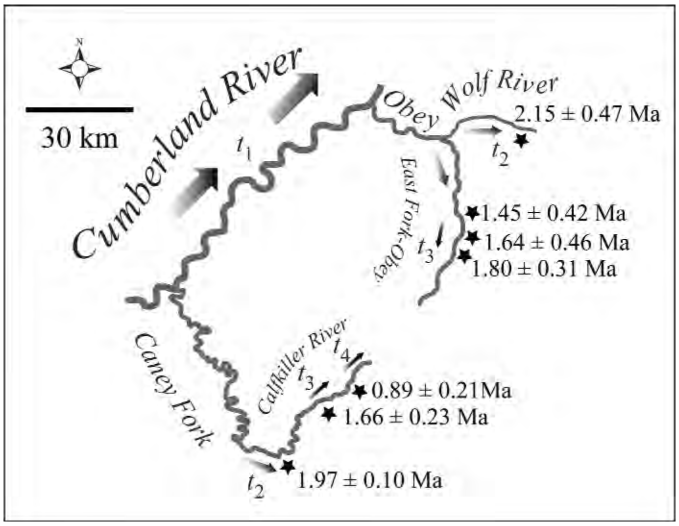

Figure 7. Schematic diagram showing knickpoint migration on Caney Fork-Calfkiller River and Obey River-Wolf River. Incision pulses originating on the Cumberland River at t_1>2 Ma migrated up the Caney Fork and Obey-Wolf River, lowering the local water table and abandoning Foxhole Cave and Wolf River Cave at $t_2 \approx 2$ Ma. At $t_3 \approx 1.6$ 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 $t_4 \approx 0.9$ 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 km² and 260 km² 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

Figure 10. The Second River Crossing in Blue Spring Cave, TN. This large phreatic passage at the modern river level drains roughly 260 km² of the Cumberland Plateau. (Photo Bernard Szukalski.)

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.

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.

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DEEP CAVES OF THE WORLD

Compiled by Bob Gulden

	CAVE NAME	COUNTRY	STATE	DEPTH METERS	LENGTH METERS
1	Voronja Cave (Krubera Cave)	Georgia	Abkhazia	1710.0	-----
2	Lamprechtsofen Vogelschacht Weg Schacht	Austria	Salzburg	1632.0	50000
3	Gouffre Mirolda/Lucien Bouclier	France	Haute Savoie	1626.0	13000
4	Torca del Cerro del Cuevon (T.33)-Torca de las Saxifragas	Spain	Asturias	1589.0	4000
5	Sarma	Georgia	Abkhazia	1543.0	6370
6	Reseau Jean Bernard	France	Haute Savoie	1535.0	20536
7	Cehi 2 “la Vendetta”	Slovenia	Rombonski Podi	1533.0	5061
8	Shakta Vjacheslav Pantjukhina	Georgia	Abkhazia	1508.0	5530
9	Sistema Cheve (Cuicateco)	Mexico	Oaxaca	1484.0	26194
10	Sistema Huautla	Mexico	Oaxaca	1475.0	55953
11	Sistema del Trave	Spain	Asturias	1441.0	9167
12	Sima de las Puertas de Illaminako Ateeneko Leizea (BU.56)	Spain/France	Navarra/Nafarroa	1408.0	14500
13	Sustav Lukina jama - Trojama (Manual II)	Croatia	Mt.Velebit	1392.0	1078
14	Evren Gunay Dudeni (Sinkhole)	Turkey	Anamur	1377.0	-----
15	Sniezhnaja-Mezhonnogo (Snezhaya)	Georgia	Abkhazia	1370.0	19000
16	Sistema Aranonera (Sima S1-S2)(Tendenera connected)	Spain	Huesca	1349.0	36468
17	Gouffre de la Pierre Saint Martin	France/Spain	Pyrenees-Atlantiques	1342.0	53950
18	Siebenhengste-hohgant Hohlensystem	Switzerland	Bern	1340.0	145000
19	Slovacka jama	Croatia	Mt.Velebit	1320.0	2519
20	Abisso Paolo Roversi	Italy	Toscana	1300.0	4000
21	Cosanostraloch-Berger-Platteneck Hohlesystem	Austria	Salzburg	1291.0	30076
22	Cueva Charco	Mexico	Oaxaca	1278.0	6710
23	Gouffre Berger - Gouffre de la Fromagere	France	Isere	1271.0	31790
24	Neide - Muruk Cave	Papua New Guinea	New Britain	1258.0	17000
25	Torca dos los Rebecos	Spain	Asturias	1255.0	2228
26	Pozo del Madejuno	Spain	Leon	1252.0	2852
27	Crnelsko brezno (Abisso Veliko Sbrego)	Slovenia	Rombonaki Podi	1241.0	8090
28	Vladimir V. Iljukhina System	Georgia	Abkhazia	1240.0	5890
29	Sotano Akemati	Mexico	Puebla	1226.0	4918
30	Kihaje Xontjoa	Mexico	Oaxaca	1223.0	31373
31	Schwer-hohlensystem (Batmanhole)	Austria	Salzburg	1219.0	6101
32	Abisso Ulivifer (Olivifer)	Italy	Toscana	1215.0	10000
33	Gorgothakas	Greece	Crete	1208.0	-----
34	Dachstein-Mammuthohle	Austria	Oberosterreich	1199.0	57583
35	Complesso del Monte Corchia (Fighiera,Farol.)	Italy	Toscana	1190.0	52300
36	Cukurpinar Dudeni	Turkey	Anamur	1190.0	3550
37	Vandima	Slovenia	Rombonski Podi	1182.0	2800
38	Jubilaumsschacht	Austria	Salzburg	1173.0	2380
39	Gouffre du Bracas de Thurugne 6 (Reseau de Soudet)	France/Spain	Pyrenees-Atlantiques	1170.0	10340
40	Abisso Vive le Donne	Italy	Lombardia	1170.0	3800
41	Anou Ifflis	Algeria	Bouira	1170.0	2000
42	Sima 56 de Andara(Torca del Cueto de los Senderos)	Spain	Cantabria	1169.0	5620
43	Torca Idoubeda	Spain	Asturias	1167.0	-----
44	Sistema de las Fuentes de Escuain(Badalona B15-B1)	Spain	Huesca	1151.0	11450
45	Tanne des Pra d'Zeures	France	Haute	1148.0	3900
46	Complesso del Foran del Muss	Italy	Friuli	1140.0	20000
47	Sistema del (Pozu) Xitu (Jitu)	Spain	Asturias	1135.0	6100
48	Sistem Molicka Pec	Slovenia	DleskovskaPlanto	1130.0	3827
49	Abisso Saragato	Italy	Toscana	1125.0	6000
50	Arabikskaja (Kuibyshevskaja/Genrikhova Bezdn)	Georgia	Abkhazia	1110.0	3250
51	Kazumura Cave (Lava Tube)	U.S.A.	Hawaii	1101.5	65500
52	Schneeloch	Austria	Salzburg	1101.0	4200
53	Sima G.E.S.M.de los Hoyos del Pilar	Spain	Malaga	1101.0	3000
54	Gouffre des Partages	France	Pyrenees-Atlantiques	1097.0	23920
55	Zoou Cave (Dzou)	Georgia	Abkhazia	1090.0	6000

LONG CAVES OF THE WORLD

Compiled by Bob Gulden

	CAVE NAME	COUNTRY	STATE	LENGTH METERS	DEPTH METERS
1	Mammoth Cave System	U.S.A.	Kentucky	579364	115.5
2	Optimisticeskaja (Gypsum)	Ukraine	Ukrainskaja	214000	15.0
3	Jewel Cave	U.S.A.	South Dakota	209170	192.7
4	Holloch	Switzerland	Schwyz	189026	940.0
5	Lechuguilla Cave	U.S.A.	New Mexico	180096	489.0
6	Wind Cave	U.S.A.	South Dakota	179442	202.4
7	Fisher Ridge Cave System	U.S.A.	Kentucky	172747	108.6
8	Siebenhengste-hohgant Hohlensystem	Switzerland	Bern	145000	1340.0
9	Sistema Ox Bel Ha (Under Water)	Mexico	Quintana Roo	133439	33.5
10	Ozernaja (Gypsum)	Ukraine	Ukrainskaja	122000	8.0
11	Gua Air Jernih (Clearwater Cave-Black Rock)	Malaysia	Sarawak	109000	355.1
12	Reseau Felix Trombe/Henne-Morte	France	Haute-Garonne	105767	975.0
13	Toca da Boa Vista	Brazil	Bahia	102000	50.0
14	Systeme de Ojo Guarena	Spain	Burgos	100400	163.0
15	Sistema Purificacion	Mexico	Tamaulipas	93755	953.0
16	Bullita Cave System (Burke's Back Yard)	Australia	Northern Territory	92985	23.0
17	Zolushka (Gypsum)	Moldova/Ukraine	Moldarskaja	90200	30.0
18	Hirlatzhohle	Austria	Oberosterreich	86606	1009.0
19	Raucherkarhohle	Austria	Oberosterreich	82686	758.0
20	Friars Hole Cave System	U.S.A.	West Virginia	73288	191.4
21	Easegill System	United Kingdom	Yorkshire	70500	211.0
22	Ogof Draenen	United Kingdom	South Wales	66120	97.8
23	Kazumura Cave (Lava Tube)	U.S.A.	Hawaii	65500	1101.5
24	Organ (Greenbrier) Cave System	U.S.A.	West Virginia	63569	148.1
25	Sistema Nohoch Nah Chich (Under Water)	Mexico	Quintana Roo	61143	71.6
26	Reseau de l'Alpe	France	Isere Savoie	60247	655.0
27	Cueva del Valle (Red Del Silencio)	Spain	Cantabria	60223	502.0
28	Bol’shaja Oreshnaja (Conglomerate)	Russia	Russia	58000	240.0
29	Barenschacht	Switzerland	Bern	57800	946.0
30	Dachstein-Mammuthohle	Austria	Oberosterreich	57583	1199.0
31	Botovskaya	Russia	Lrkutsk	57256	6.0
32	Arresteliako ziloa(Souffleur de Larrandaburu)	France	Pyrenees	57061	835.0
33	Kap-Kutan/Promezhutochnaja	Turkmenistan	Turkistan	57000	310.0
34	Cenote Dos Ojos (Under Water)	Mexico	Quintana Roo	56671	119.2
35	Schwarzmooskogelhoehlensystem-Kaninchohle	Austria	Steiermark	56073	1030.0
36	Sistema Huautla	Mexico	Oaxaca	55953	1475.0
37	Systeme du Granier	France	Isere/Savoie	55327	564.0
38	Kolkbluser-Monster-Hohlensystem	Austria	Salzburg	55000	711.0
39	Mamo Kananda	Papua New Guinea	Southern Highlands	54800	528.0
40	Gr. Caverna de Palmarito	Cuba	Pinar del Rio	54000	0.0
41	Gouffre de la Pierre Saint Martin	France/Spain	Pyrenees-Atlantiques	53950	1342.0
42	Blue Spring Cave (Saltpeter)	U.S.A.	Tennessee	53431	71.0
43	Complesso del Monte Corchia (Fighiera,Farol.)	Italy	Toscana	52300	1190.0
44	Martin Ridge System (Wig.,Jackpot,Martin)	U.S.A.	Kentucky	51884	95.7
45	Reseau de la Dent de Crolles	France	Isere	50101	673.0
46	Lamprechtsofen Vogelschacht Weg Schacht	Austria	Salzburg	50000	1632.0
47	Ogof Ffynnon Ddu	United Kingdom	South Wales	50000	308.0
48	Carlsbad Cavern	U.S.A.	New Mexico	49680	315.5
49	Sima del Hayal de Ponata (SI-44,SI-57,SR-7)	Spain	Alava/Vizcaya	49000	415.0
50	Sistema Rubicera-Mortero de Astrana	Spain	Cantabria	48000	546.0
51	Santo Tomas (gran caverna de)	Cuba	Pinar del Rio	46000	0.0
52	Crevice Cave	U.S.A.	Missouri	45385	0.0
53	Grotte de Saint-Marcel	France	Ardeche	45247	233.0
54	Cumberland Caverns (Saltpeter)	U.S.A.	Tennessee	44444	61.0
55	Scott Hollow Cave	U.S.A.	West Virginia	43452	174.0

GUIDE TO AUTHORS

The *Journal of Cave and Karst Studies* is a multidisciplinary journal devoted to cave and karst research. The *Journal* is seeking original, unpublished manuscripts concerning the scientific study of caves or other karst features. Authors do not need to be members of the National Speleological Society but preference is given to manuscripts of importance to North American speleology.

LANGUAGES

The *Journal of Cave and Karst Studies* uses American-style English as its standard language and spelling style, with the exception of allowing a second abstract in another language when room allows. In the case of proper names, the *Journal* tries to accommodate other spellings and punctuation styles. In cases where the editor finds it appropriate to use non-English words outside of proper names (generally where no equivalent English word exist), the *Journal* italicizes them (i.e., *et al*.). Authors are encouraged to write for our combined professional and amateur readerships

CONTENT

Each paper will contain a title with the authors' names and addresses, an abstract, and the text of the paper, including a summary or conclusions section. Acknowledgments and references follow the text.

ABSTRACTS

An abstract stating the essential points and results must accompany all articles. An abstract is a summary, not a promise of what topics are covered in the paper.

STYLE

The *Journal* consults The Chicago Manual of Style on most general style issues.

REFERENCES

In the text, references to previously published work should be followed by the relevant author's name and date (and page number, when appropriate). All cited references are alphabetical at the end of the manuscript with senior author's last name first, followed by date of publication, title, publisher, volume, and page numbers. Geological Society of America format should be used (see http://www.geosociety.org/pubs/geoguid5.htm). Please do not abbreviate periodical titles. Web references are acceptable when deemed appropriate. The references should follow the style of:

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Authors should submit three copies of their manuscript (include only copies of the illustrations) to the appropriate specialty editor or the senior editor. Manuscripts must be typed, double spaced, and single-sided. Electronic mail submissions are encouraged. Authors will be requested to submit an electronic copy of the text, a photograph, and brief biography upon acceptance of the paper. Extensive supporting data will be placed on the *Journal*'s website with a paper copy placed in the NSS archives and library. The data that are used within a paper must be made available. Authors may be required to provide supporting data in a fundamental format, such as ASCII for text data or comma-delimited ASCII for tabular data.

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Critical discussions of papers previously published in the *Journal* are welcome. Authors will be given an opportunity to reply. Discussions and replies must be limited to a maximum of 1000 words and discussions will be subject to review before publication. Discussions must be within 6 months after the original article appears.

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All measurements will be in Systeme Internationale (metric) except when quoting historical references. Other units will be allowed where necessary if placed in parentheses and following the SI units.

FIGURES

Figures and lettering must be neat and legible. Figure captions should be on a separate sheet of paper and not within the figure. Figures should be numbered in sequence and referred to in the text by inserting (Fig. x). Most figures will be reduced, hence the lettering should be large. Once the paper has been accepted for publication, the original drawing (with corrections where necessary) must be submitted to the editor. Photographs must be sharp and high contrast. Color will generally only be printed at author's expense.

TABLES

See the "Guidelines for Authors for Producing Tables" on pages 60-61.

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It is the author's responsibility to clear any copyright or acknowledgement matters concerning text, tables, or figures used. Authors should also ensure adequate attention to sensitive or legal issues such as land owner and land manager concerns or policies.

PROCESS

All submitted manuscripts are sent out to at least two experts in the field. Reviewed manuscripts are then returned to the author for consideration of the referees' remarks and revision, where appropriate. Revised manuscripts are returned to the appropriate associate editor who then recommends acceptance or rejection. The Senior Editor makes final decisions regarding publication. Upon acceptance, the author should submit all photographs, original drawings, and an electronic copy of the text to the editor. The senior author will be sent one set of PDF proofs for review. Examine the current issue for more information of the format used.

ELECTRONIC FILES

The *Journal*'s final layout is done using Quark Xpress. Microsoft Word is used in word processing and all figures and photographs should be submitted in either EPS or TIF format. The *Journal* is printed at 305 dpi. Thus, illustrations that are to be printed at 3.5 inches wide require at least 1068 pixels.

GUIDELINES FOR AUTHORS FOR PRODUCING TABLES FOR THE *JOURNAL OF CAVE AND KARST STUDIES*

Table 1. Measured ^{222}Rn equlibrium activity and specific conductivity for selected sampling stations.

Sample Name	Location Lat. (°N)	Location Long. (°W)	^{222}Rn Activity[a] (kBq m^{-3})	Specific Conduct.[b] (μS s^{-1})	Description
Wells					
Municipal Well	39°29′00″	77°20′21″	15.21 ± 2.74	0.390	Principal drinking-water well for town populace.
Dairy Well	39°29′25″	77°20′21″	···	0.380	Principal water-supply well for watering dairy cows.
Farm Well	9°29′25″	77°20′22″	6.44 ± 2.52	0.448	Farmhouse drinking-water well.
Springs					
Willow Spring	39°29′29″	77°20′22″	9.66 ± 4.26	0.545	Small seepage spring.
Fountain Rock Spring	39°28′30″	77°22′00″	7.77 ± 2.63	0.520	Large flowing spring used for fish hatchery.[c]

Note: Samples were collected during a very wet period (1992); dryer conditions would likely yield different results.

[a] Measured equilibrium activity determined by liquid scintillation counting.

[b] The arithmetic mean for all measured specific conductivity values is 4.85×10^{-1} μS s^{-1}; no measurements ever exceeded 7.60×10^{-1} μS s^{-1}.

[c] Fountain Rock Spring is no longer used as a fish hatchery.

Parts of a typical table.
Highlighted numbers are explained by numbered items in the text.

TABLE CAPTION

1. Number tables in the order in which they are cited in the paper. Follow the number with a period and two blank spaces, then the caption. Capitalize only the first letter in the caption, except symbols from chemical elements (e.g., Rn) AND the first letter of formal names and scientific names (except species epithets). Capitalize abbreviations for years before present only whe appropriate (e.g., Ma and ka). End the caption with a period. Italicize all scientific names. Left justify and boldface the entire table caption on one or more lines at the top of the table.

2. Separate the caption from the rest of the table with a thick horizontal line. In the example shown, line thickness is 0.08 em[1].

TABLE HEADINGS

3. Where appropriate place a very thin line underneath a subheading. In the example shown, line thickness is 0.03 em[1].

4. Start all column headings just below the thick horizontal lines. Left justify the first column; center all other column headings. Capitalize each initial letter for each heading item unless other capital letters are required (e.g., scientific names or chemical symbols).

5. Abbreviate units of measurement and place them in parentheses on a separate line just below the rest of the heading. Use only Le Système International d'Unités (SI) units of measurement[2]. Enlarge parentheses as necessary to enclose unit of measure completely (i.e., to account for superscripts and subscripts).

6. Separate the headings from the body of the table with a thin horizontal line. In the example shown, line thickness is 0.05 em[1].

TABLE BODY

7. Start all columns just below the thin horizontal line at the base of the column headings. Left justify the first column and center all the other columns. Do not show units of measurement in the column if they can be abbreviated and placed in parentheses just below the column heading.

8. Align columns of numbers on the decimal or other appropriate marker (e.g., the ° symbol). Use a zero before the decimal point for values less than one.

9. Align text entries on the left and indent each line after the first and end each sentence with a period. Use only an initial capital for each complete sentence unless other capitals are required.

10. Separate sections of the table with line spaces. Label these sections with a very thin lined heading that is left justified. In the example shown, line thickness is 0.03 em[1]. Indent subitems one space.

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[1]One em is the width of a capital 'M' in the current font.

[2]See Nat. Inst. of Stan. and Tech. Publ. 330 and 811 at http://physics.nist.gov/cuu/Units/bibliography.html for correct SI units.

11. Do not leave blank spaces in the body of the table. These should be marked '...' (no data), 'N.A.' (not applicable) or otherwise as appropriate, and the abbreviations should be marked with a footnote for explanation.

12. Follow the body of the table with a thick horizontal line. In the example shown, line thickness is 0.08 em[1].

FOOTNOTE SYMBOLS

- If several items in a table require footnotes, use relative position in the table to determine the order in which footnotes are assigned. Start at the top of the table, work from left to right, then from top to bottom.
- Use lowercase alphabetical characters for footnotes: a, b, c ... z.

TABLE FOOTNOTES

13. Treat each footnote as a separate paragraph; indent the first line three spaces and end the footnote with a period. Place general information about the table in the first footnote. Precede this entry with 'Note:' in italics rather than with a symbol.

14. Footnotes should appear in the same order as the symbols were used in the table. Use only an initial capital letter for each sentence in each footnote.

ADDITIONAL REQUIREMENTS

15. Scale SI units using appropriate SI prefixes (e.g., k, µ, etc.)

16. Always use the mathematical minus sign, '–' to indicate subtraction when using mathematical formulae; never substitute an hyphen '-', an en-dash '–', or an em-dash '—' for a minus sign '–' in mathematical formulae.

17. When reporting data using scientific notation always use the symbol for multiplication, × (e.g., 7.60×10^{-1} µS s^{-1}).

- If a separate section is to be incorporated into the table (e.g., different dates for different sampling events) then separate these sections with a centered and italicized caption within the body of the table. Do not boldface this caption, only capitalize the inital letter of the first word in the caption except as required (e.g., scientific names), and do not end this caption with a period.
- Never use vertical lines anywhere in the table.
- Never boldface any part of the table other than the caption.
- Never use English units of measurement except as allowed (see EXCEPTIONS).
- Never italicize units of measure.
- Never use nonSI units of measurement except as permissible under specific SI guidelines (e.g., liter).
- When reporting data using scientific notation never use the letter ex, 'x' and never report data using either 'e' or 'E to indicate the exponential as would be obtained from a computer program (e.g., 7.60E–1 µS s^{-1}).
- Never substitute a spreadsheet for a properly constructed table.

EXCEPTIONS

- If appropriate, some units of measurement may be used in place of SI units of measurements (e.g., hours may be more appropriate than seconds for long time periods).
- In rare instances it may be reasonable to list the correct SI unit of measure followed by its English equivalent enclosed in brackets. For example: (m^3 s^{-1}) [cfs]; subsequent English numerical values also enclosed in brackets would follow the SI numerical values in the body of the text.
- The combination of thick and thin lines may be replaced with a set of uniformly-thick lines.

SPECIAL EXCEPTION

- If for some reason a proposed data table cannot reasonably match the example shown, then please contact the Editor of the *Journal of Cave and Karst Studies* for consideration of a special exception.
- For those individuals using software or equipment other than MS Word®, WordPerfect®, or LATEX, (e.g., typewriter) then please contact the Editor of the *Journal of Cave and Karst Studies* for consideration of a special exception and/or assistance.

Eko Haryono and Mick Day - Landform differentiation within the Gunung Kidul Kegelkarst, Java, Indonesia. *Journal of Cave and Karst Studies*, v. 66, no. 2, p. 62-69.

LANDFORM DIFFERENTIATION WITHIN THE GUNUNG KIDUL KEGELKARST, JAVA, INDONESIA

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The Gunung Kidul karst is the western part (65%) of the larger Gunung Sewu (Thousand Hills) karst area, which is generally considered a type example of cone- or kegelkarst (Lehmann, 1936). This classification is an over-simplification, however, in that the karst landscape within the Gunung Sewu is considerably differentiated in terms of landform morphology and genesis. In the Gunung Kidul, this differentiation is evident from aerial photographs, which provide basic information about landform patterns, including lineament information. These observations were confirmed by field investigation, which incorporated landform measurement and acquisition of lithological information. These detailed studies distinguish three Gunung Kidul karst subtypes: labyrinth-cone, polygonal, and residual cone karst. The labyrinth-cone subtype occurs in the central Gunung Kidul karst where hard, thick limestones have undergone intensive deformation. Polygonal karst has developed in the western perimeter on hard but thinner limestone beds. The residual cone subtype occurs in the weaker and more porous limestones (wackestones or chalks), despite considerable bed thickness.

Herbert Lehmann's (1936) research on the karst of the Gunung Sewu (Thousand Hills) in south-central Java (Figure 1) was the first modern work on humid tropical karst (Sweeting 1981; Jennings 1985) and it made a significant contribution to understanding both the development of the Gunung Sewu landscape itself and tropical karst in general. Subsequent research has revealed that tropical karst morphology varies considerably, particularly as a result of differing geologic environments and hydrologic regimes (Sweeting 1972, 1980; Jennings 1972, 1985; Trudgill 1985; White 1988; Ford & Williams 1989) and the karst of the Gunung Sewu itself demonstrates this differentiation.

Lehmann and more recent workers have described the Gunung Sewu landscape as cone- (or kegel) karst, characterized by sinusoidal or hemispherical hills (kuppen) interspersed with enclosed star-shaped depressions or interconnected valleys (Lehmann 1936; Flathe & Pfeiffer 1965; Balazs 1968, 1971; Verstappen 1969; Waltham *et al*. 1983). These descriptions of the Gunung Sewu landscape as kegelkarst generalize what is really a variety of different residual hill morphologies, with the conical form not actually being the most characteristic (Flathe & Pfeiffer 1965). The Gunung Sewu karst covers an area of more than 1300 km², and incorporates over 10,000 individual hills (Balazs 1968 estimated 40,000), at densities of about 30/km², whose morphology varies considerably more than previous studies suggest.

The diverse forms of residual hills in tropical humid karst are generally considered to be the result of "…structural factors in the broad geomorphological sense." (Jennings 1985, p. 205). Many individual factors govern carbonate karst development in specific locations, including lithology and structure, which influence the efficacy and the distribution of the dissolution process within the rock mass (Sweeting 1980; Trudgill 1985; White 1988). The objective of this research is to begin to identify the geologic variations and the associated karst landform differentiations within the Gunung Sewu karst, thus refining geomorphological understanding of this classic karst landscape. Because of the paucity of existing data, no specific hypotheses are tested in this initial phase of the research, but it is anticipated that such hypotheses will be developed and tested subsequently.

Figure 1. Location of the Gunung Kidul.

THE STUDY AREA

The research documented herein focuses upon the western two thirds of the broad Gunung Sewu karst area, in the Gunung Kidul Regency of Yogyakarta Special Province, Java, Indonesia between 7°57' and 8°12' South latitude (Figure 1). We refer to this study area henceforth as the Gunung Kidul (Southern Hills) karst, reflecting previous and more geographically correct usage (Balazs 1968).

The Gunung Kidul area is adjacent to the Indian Ocean on the south central coast of Java (Figure 1). Elevation range is between zero and 400 m above mean sea level, with resurgence springs such as Baron being at sea level and the highest portions centrally located about 25 km from the coastline.

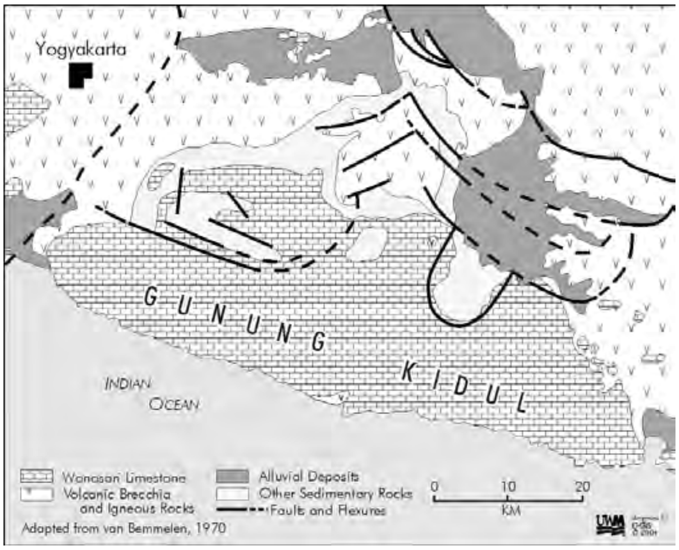

Figure 2. Geology of the Gunung Kidul area (after van Bemmelen, 1970).

Physiographically, the Gunung Kidul karst is part of the southern plateau of Java Island (Pannekoek 1948), which extends some 85 km east-west and slopes gently, at approximately a 2% gradient, southward, being marked by a high (25–100 m) cliff along the south coast.

Geologically, the study area is dominated by Miocene limestones of the Wonosari Formation, which consists of massive coral reef limestones in the south and bedded chalky limestones in the north (Balazs 1968; van Bemmelen 1970; Waltham *et al*. 1983; Surono *et al*. 1992) (Figure 2). Total thickness exceeds 650 m, and the limestones are underlain by volcanic and clastic rocks (Waltham *et al*. 1983). The coral reef limestone is lithologically highly variable, but dominated by *rudstones*, *packstones*, and *framestones*. Breccias with a clay matrix are not uncommon, biohermal structures are identifiable, and lenses of volcanic ash are interspersed among the carbonates (Waltham *et al*. 1983). The bedded, chalky limestones become more prominent towards the north and northeast, and dominate the Wonosari Plateau (Figure 2).

The Wonosari Formation was uplifted during the late Pliocene and/or early Pleistocene and dips gently southward at about a 2% gradient (Balazs 1968; van Bemmelen 1970; Surono *et al*. 1992; Sutoyo 1994). North-south compression associated with tectonic plate convergence produced deformation including intensive northwest-southeast and northeast-southwest jointing and faulting (Balazs 1968; van Bemmelen 1970; Surono *et al*. 1992; Sutoyo 1994). The structure is most complex along the northern boundary, and the northeastern part was downfaulted, forming the Wonosari Basin, within which karstification is limited.

The karst surface within the valleys and depressions is mantled by deeply weathered clays, up to 10 m in thickness, which are remants of volcanic ash intermixed with weathering residue from the limestones (Waltham *et al*. 1983). On the hills, soils are shallow, patchy rendzinas or vertisols, but the karst is intensively cultivated, particularly the red-brown clays in the valleys and depressions, with terracing, irrigation and sophisticated manipulation of available water resources (Uhlig 1980; Urushibara-Yoshino 1993).

Karst development in the Gunung Sewu has been influenced by paleoclimatic conditions (Urishibara-Yoshino & Yoshino 1997). Dry valley formation appears to have been associated particularly with the lower sea levels and the cooler, drier conditions of the last glacial stage 18,000 B.P. By contrast, cone karst development was apparently promulgated during subsequent warmer and wetter periods.

The prevailing contemporary climate in the Gunung Kidul is strongly influenced by the Northwest and Southeast monsoons, which produce a distinct wet season from October to April and a dry season, which may be extremely arid, between May and September. The annual rainfall is about 2000 mm; records from 14 local rain gauge stations between 1960 and 1997 vary between 1500 mm and 2986 mm annually. An earlier mean annual rainfall, based on 33 years of record, was quoted as 1809 mm (Balazs 1968). Mean annual temperature is about 27° C. Seasonal drought is a serious economic problem, because over 250,000 people live within the Gunung Sewu karst, at a density in excess of 300/km² (Uhlig 1980; Waltham *et al*. 1983).

METHODOLOGY

Broad scale interpretation of the karst landforms was based upon 1:50,000 scale black and white panchromatic aerial photography from September 1993. The aerial photographs were used to produce an uncontrolled photo mosaic, which then was used to identify overall landscape patterns, including visible lineaments, and individual landform morphologies within the study area. On this visual basis, three distinctive broad areas of landform assemblages and patterns were identified and, within each of these, 10, 22 and 29 km² sample areas were selected non-randomly, on the basis of photographic quality (absence of clouds) and accessibility, for morphometric analysis and field survey. Valley lineaments were measured from the air photographs, with field verification, and the significance of preferred orientations was tested using one-way analysis of variance.

Fieldwork was conducted in November 1999 in order to verify the results of the initial interpretation of the air photographs. Sites were selected non-randomly to correspond with the sample areas within the different landform patterns that had previously been identified on the aerial photographs. The fieldwork involved observation and measurement of individual landforms, together with macroscopic lithological identification and determination of Schmidt Hammer hardness (Day & Goudie 1977; Day 1980, 1982). Rock porosities were determined from thin-section analysis (Curtis 1971).

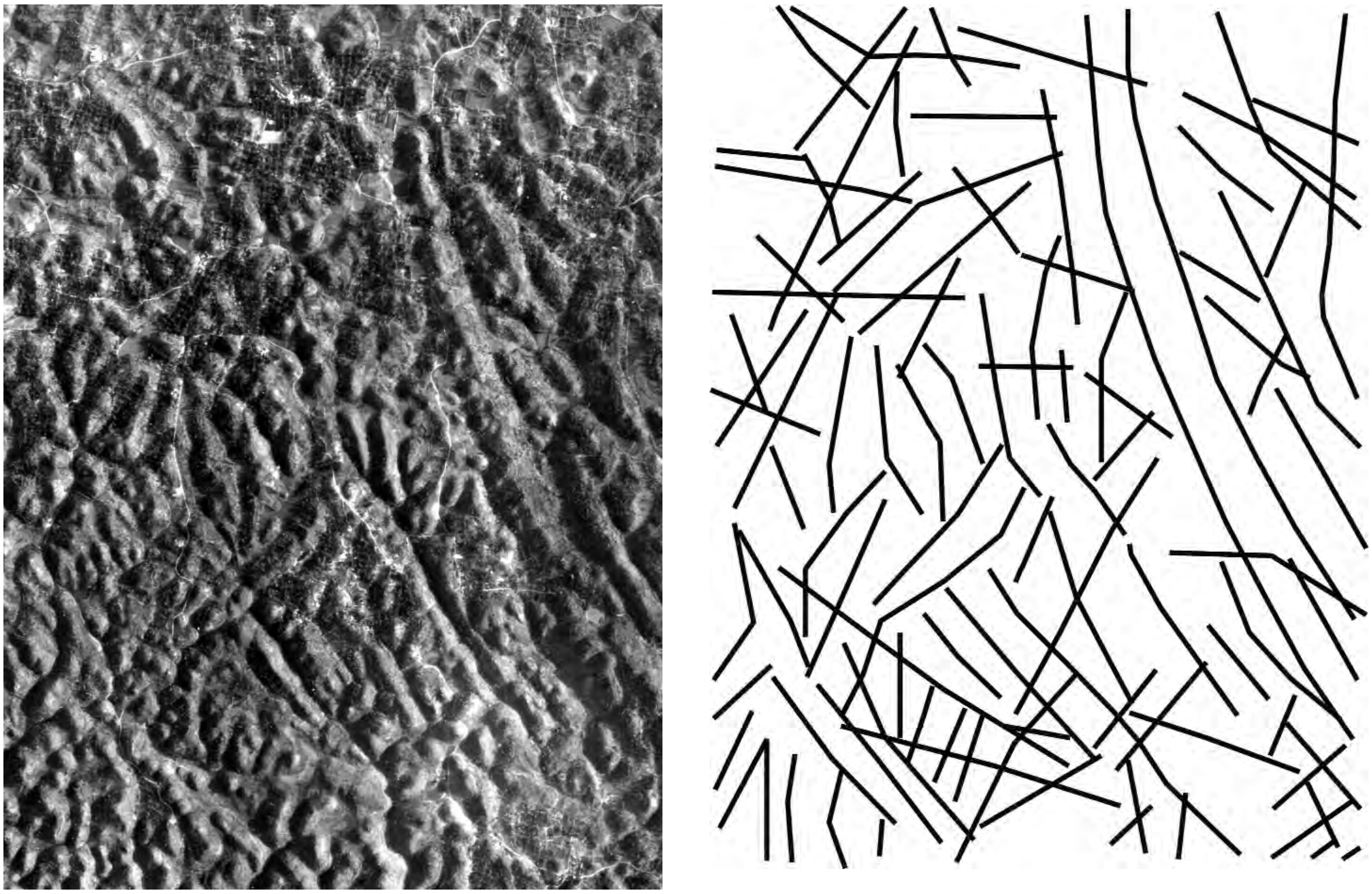

Figure 3. Labyrinth-cone karst: air photograph (left) and lineaments (right).

RESULTS

Although the Gunung Sewu karst is generally classified as kegelkarst, detailed analysis of the aerial photography and field observation in the Gunung Kidul reveals that there are three distinct landscape subsets, which we refer to as labyrinth-cone karst, polygonal karst and residual cone karst. This terminology incorporates a descriptive element (cone) into existing terminology (Ford & Williams 1989).

Labyrinth-Cone Karst

Labyrinth karst (Figures 3 and 4 [page 66]) "…is a landscape dominated by intersecting solution corridors and solution canyons." (White 1988, p. 116) or, alternatively, "…aligned or intersecting corridor topographies." (Ford & Williams 1989, p. 391). Specifics notwithstanding, labyrinth karst development is distinctly linear, incorporating meandering valleys rather than enclosed depressions, and is dominantly controlled by faults or major joints. In the Gunung Kidul area the valley linearity is combined with intervening conical hills, hence we refer to this landscape as labyrinth-cone karst. The labyrinth-cone landscape type is characterized by two series of joint-controlled valleys, which are dry under normal circumstances. In the 29.2 km² study area, the dominant trend of the valleys is northwest-southeast, with a secondary trend northeast-southwest (Figure 3). Lineations in the classes 31–40°, 41–50°, 301–310°, 321–330° and 331–340° are statistically significant at the 0.001 level. Valleys extend up to 4.5 km in length, and are typically 50–250 m wide, bordered by steep to moderate slopes on both sides. Most valley thalwegs are thoroughly disordered, with only minimal evidence of descending tributary-trunk sequences. Between the valleys are elongated, interfluvial residual hills, 80–100 m in height, which form long, serrated, ridge-like chains of conical or flat-topped hills without intervening closed depressions (Figure 4 [page 66]). Enclosed depressions are uncommon within the labyrinth-cone karst, although some have developed within the valley network, where they tend to be large and elongated (Table 1).

The slopes of the residual hills in the labyrinth-cone karst are generally steeper than those in other parts of the Gunung Kidul karst, generally ranging between 60 and 70 degrees. Dry valley sides may be near vertical, although in some localities they grade imperceptibly into the cone slopes. The slope steepness may be attributable to lithological factors. The carbonate lithology of the labyrinth-cone karst comprises *floatstones*, *packstones* and *rudstones*, which are usually dense, hard limestones. Whereas the mean regional Schmidt Hammer hardness

Table 1. Enclosed depression measurements in labyrinth-cone karst of Gunung Kidul (All measurements in meters).

Doline Order	Length Range	Mean Length	Width Range	Mean Width	N
0	100–238	161	75–200	124	42
1	150–600	445	100–200	152	15
2	600–925	750	175–625	332	5
3	1225–1650	1427	250–650	426	5

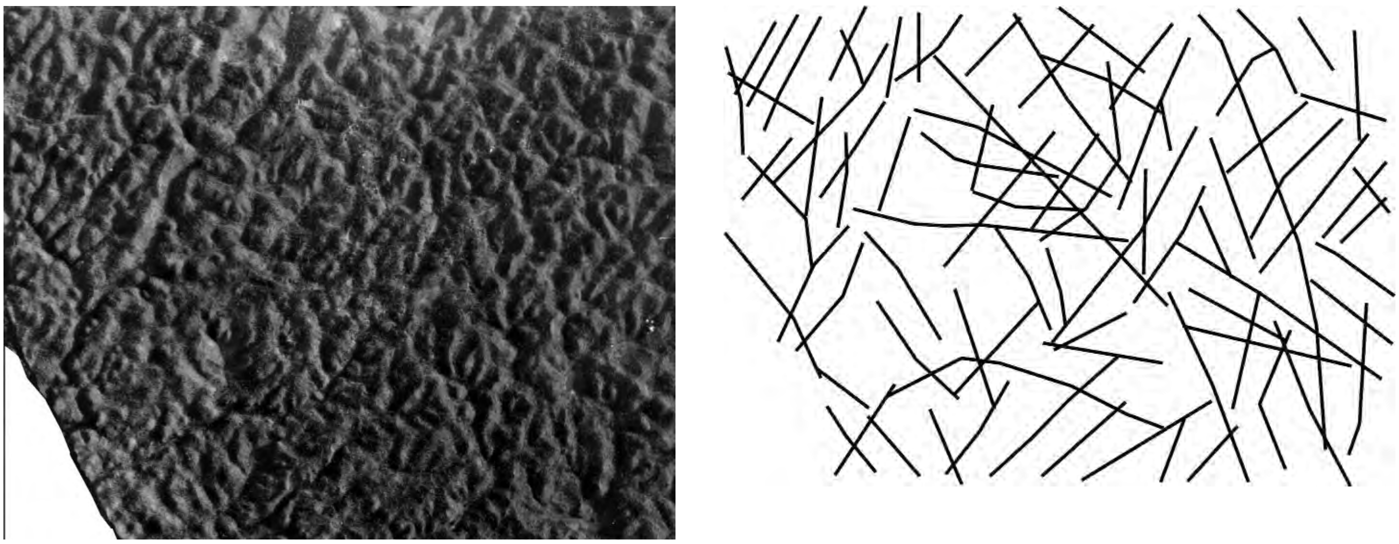

Figure 5. Polygonal karst: air photograph (left) and lineaments (right).

value for the limestones is 40.5 (n=80) for weathered surfaces and 21.2 (n=60) for fresh exposures (Day 1978), the corresponding values for limestones in the labyrinth-cone landscape are 44.3 (n=20) and 24.6 (n=15). Porosity of limestones from the labyrinth-cone karst ranges from 13.0 to 16.6% (n=3), which is quite high for diagenetically mature limestones. More importantly, the bedding is massive, commonly exceeding 5 m.

The labyrinth-cone karst is most pronounced in the southern portion of the Gunung Kidul, where the carbonates are most intensively jointed and faulted. This area was subject to the maximum displacement as a result of the compressional stresses associated with the subduction zone of the Australian Plate (Tjia 1966; Dwiyana 1989).

Polygonal Karst

The most characteristic polygonal karst in Gunung Kidul occurs in the western part of the area (Figures 5 and 6 [page 66]). Polygonal karst is characterized by densely packed or coalesced depressions (cockpits), such that the entire karst landscape, including the residual hills marking the polygonal divides, is consumed by them, and the ratio between closed depression area and karstified area approximates unity (Williams 1971; White 1988).

Although owing much to dissolution, the polygonal karst of Gunung Kidul appears to be strongly influenced by fluvial processes and by the general southerly slope of the plateau. Although enclosed depressions dominate the landscape, dismembered meandering valley networks are also present, and these may become activated during intense wet season rains. Whereas surface flow within the depressions is centripetal, flow within the valley segments is dominantly towards the south. Increased discharge from epikarstic springs is of particular importance in generating this channel flow (Haryono, in preparation). Thirty-two springs have been identified to date, 28 close to the margins of the karst, from which they discharge surface runoff in channels, and four in central valleys, where they generate surface runoff that subsequently sinks into valley beds.

Polygonal karst is particularly well developed in the western part of the Gunung Kidul karst, where the enclosed depressions in some localities resemble the cockpits of Jamaica and Papua New Guinea (Williams 1971 1972a,b). Elsewhere, the depression slopes are more convex, producing rounded hills, or the *sinoid karst* of Flathe and Pfeiffer (1965), resembling the “egg-box” terrane described elsewhere (Ford & Williams 1989). Structural control is also evident in the 9.6 km² polygonal karst study area (Figure 5), where lineations in the 31–40°, 41–50°, 51–60° and 311–320° classes are statistically significant at the 0.001 level. Depression slope steepness and morphology are influenced by the spacing of lineaments, and by the relative rates of vertical and lateral corrosion (Tjia 1969). In the field study area in the western Gunung Kidul

Figure 4. Labyrinth-cone karst: ground photograph.

Figure 6. Polygonal karst: ground photograph.

Figure 8. Residual cone karst: ground photograph.

bedding is less massive, commonly on the order of 2 m, with riser heights reflecting those dimensions. There is also a lithological influence, with steeper slopes (mean 31°) developed on the harder rudstones and framestones (Schmidt Hammer mean hardness 43.0 weathered, 22.7 fresh, n=15 in both cases) and gentler slopes (mean 15°) on softer, impure, marly limestones further north (SH mean hardness 32.6, 19.8, n=10 in both cases). Porosities of the polygonal karst limestones range from 1.1 to 14.0% (n=3). Relative relief ranges considerably, from about 30 m to over 100 m, and enclosed depressions are generally rather smaller than in the labyrinth-cone area and less elongated (Table 2).

Residual Cone Karst

Tower karst consists of residual carbonate hills set in a plain; the residuals may or may not be steep-sided (Ford & Williams 1989). Here we use the term residual cone karst to describe the karst of Gunung Kidul that is characterized by conical isolated hills scattered on a corrosional plain (Figures 7 and 8).

Residual cone karst has developed primarily in the northeast of the study area and locally near the south coast where corrosion plains are close to sea level. The main factor governing the development of residual cone karst in the Gunung Kidul karst appears to be lithology. In the 21.5 km² study area, bedding generally is not obvious, the limestones being massive, but most of this karst is formed in *wackstones*, which here are relatively soft limestones containing a high percentage of *micrite* and perhaps best characterized as chalks. In a wet condition, fresh wackstone is easily broken by hand. Mean Schmidt Hammer hardness is 35.0 weathered (n=35), 19.8 fresh (n=20) and porosities are high, ranging from 23.1 to 48.1% (n=3).

Closed depressions are not numerous in the residual cone karst, having generally been degraded and coalesced within the larger plain, but such as do occur are broad and shallow, with mean lengths of 1230 m and mean widths of 810 m. Lineations are less conspicuous than in the other landscape types (Figure 7), with only the 31–40° class statistically significant at the 0.001 level in the field study area. Hillslope angles vary from 30° to 40° with a mean height of 90 m (Table 3).

DISCUSSION

Although the overall karst assemblage in the Gunung Kidul can be described as cone- or kegelkarst, a more detailed investigation reveals three subtypes: labyrinth-cone, polygonal, and residual cone karst. These are not randomly distributed throughout the Gunung Kidul area, but are spatially distinct and, on the basis of this preliminary investigation, appear to show a close association with structural and lithological variations in the limestones.

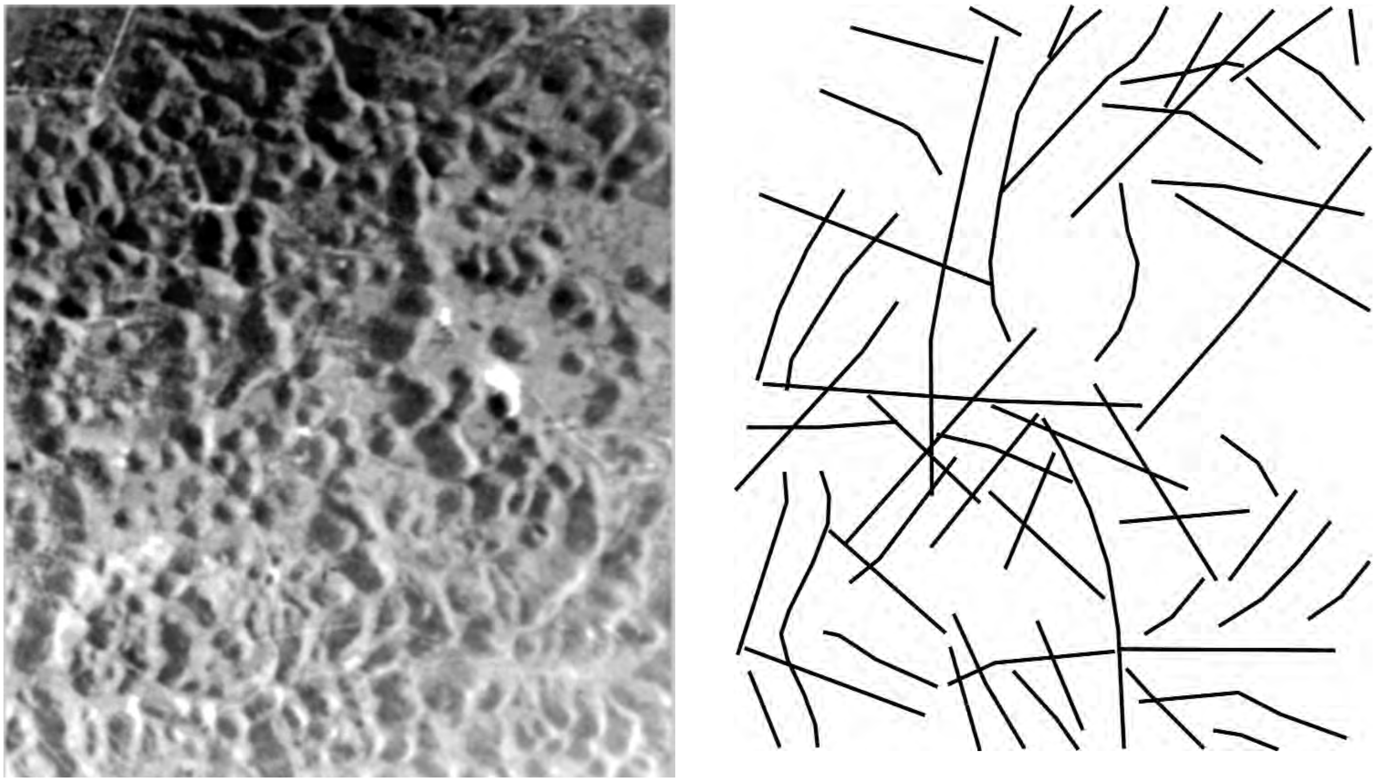

Figure 7. Residual cone karst: air photograph (left) and lineaments (right).

Table 2. Enclosed depression measurements in polygonal karst of Gunung Kidul (m).

Doline Order	Length Range	Mean Length	Width Range	Mean Width	N
0	100–225	160	75–225	145	35
1	275–750	539	200–375	326	6
2	500–1000	713	200–550	459	14
3	980–1450	1215	350–1150	747	3

Table 3. Enclosed depression measurements in residual cone karst of Gunung Kidul (m).

Doline Order	Length Range	Mean Length	Width Range	Mean Width	N
0	900–225	1090	775–1025	887	6
1	…	…	…	…	0
2	…	…	…	…	0
3	975–1800	1230	450–1020	810	4

The labyrinth-cone subtype occurs in the central part of the Gunung Kidul karst, where hard thick limestones have undergone intensive deformation. This karst sub-type conforms to what Lehmann (1936) termed directed, oriented or *gerichteter* karst, and it reflects the significance of faulting in the delineation of tropical karst landscapes, as was suggested earlier by Pannekoek (1948). The general north-south alignment mirrors the distribution of depression long axes measured by Quinif and Dupuis (1985). Although the residual hills do not attain the same dimensions or steepness as in the Chinese karst, this landscape resembles Fencong Valley landscape (Lu 1986; Yuan 1991; Smart *et al*. 1986).

Polygonal karst develops in the western area on similarly hard but thinner limestone beds. Although the polygonal karst resembles that described elsewhere, many of the residual hills retain their distinctly rounded shape, particularly resembling the Chocolate Hills area of Bohol, in the Philippines (Voss 1970). Overall, this sub-type approximates Karst Hill Depression landscape (Lu, 1986; Yuan, 1991; Smart *et al*. 1986).

The residual cone subtype occurs in weaker limestones (wackestone) with high porosities but relatively thick beds in the northeast of the study area. The influence of thicker beds on residual cone formation echoes the ideas of Tjia (1969), but the overriding control appears to be the softness and the high porosity of the chalks. Again bearing a striking resemblance to the karst on the periphery of the Chocolate Hills in Bohol, this sub-type resembles a subdued version of the Fenglin Valley landscape of China (Lu 1986; Yuan 1991; Smart *et al*. 1986).

It is as yet unclear whether these three different subtypes represent a definite zonation of the overall karst landscape that is related to former surface drainage systems (cp. Smart *et al*. 1986), although this seems quite possible given the existence of obvious valley systems in the contemporary terrain and evidence of previous valley systems (Lehmann 1936; Waltham *et al*. 1983; Quinif & Dupuis 1985). Waltham *et al*. (1983) raised the possibility of the landscape developing by dissection of an anticline, and Quinif and Dupuis (1985) postulated preliminary fluvial development on a Pliocene erosion surface. More recently, Urushibara-Yoshino (1995) and Urushibara-Yoshino and Yoshino (1997) have postulated that the valley systems, and subsequently the cone karst, developed on marine terraces, with the valley systems developed under drier conditions with lower sea levels during the last glacial stage of the Pleistocene, and with karstification more prevalent during wetter interglacial periods.

CONCLUSIONS

General variation in the landscape morphology, and in the form of individual residual hills, has been observed previously (Tjia 1969; Balazs 1971), although the lithological, structural and hydrologic influences have not been examined in detail before. The evident role of lithology in influencing the karst landscape morphology echoes the results of other studies in tropical karst (e.g. Day 1982; Smart *et al*. 1986), in that the greatest local relief is developed on the limestones with the greatest bed thickness and hardness. The lithological heterogeneity is in contrast to earlier accounts of the carbonate geology, which suggested that homogeneity was the rule (Lehmann 1936), and the landform differentiation also reveals greater geological influence than recognized previously (Waltham *et al*. 1983). Structural variability is also greater than was previously acknowledged, although broadly it is the northeast-southwest and northwest-southeast lineations that are statistically significant.

In addition to lithology and geological structure, regional slope also plays a role in influencing karst landscape development and individual karst landforms. The southerly regional 2% slope controls karst development indirectly through promoting slope-directed runoff, which results in linear depressions or valleys being more numerous than enclosed depressions. This is particularly notable in the southern part of the Gunung Kidul. In this context, Lehman's (1936) model of karst development progressing from an initial stage dominated by surface runoff and surface valleys to a later stage in which the valleys become increasingly underdrained and dismembered by the development of enclosed depressions seems not inappropriate, particularly given the empirical evidence (Quinif & Dupuis 1985) and the supporting theory put forward since (Smith 1975; White 1988).

ACKOWLEDGEMENTS

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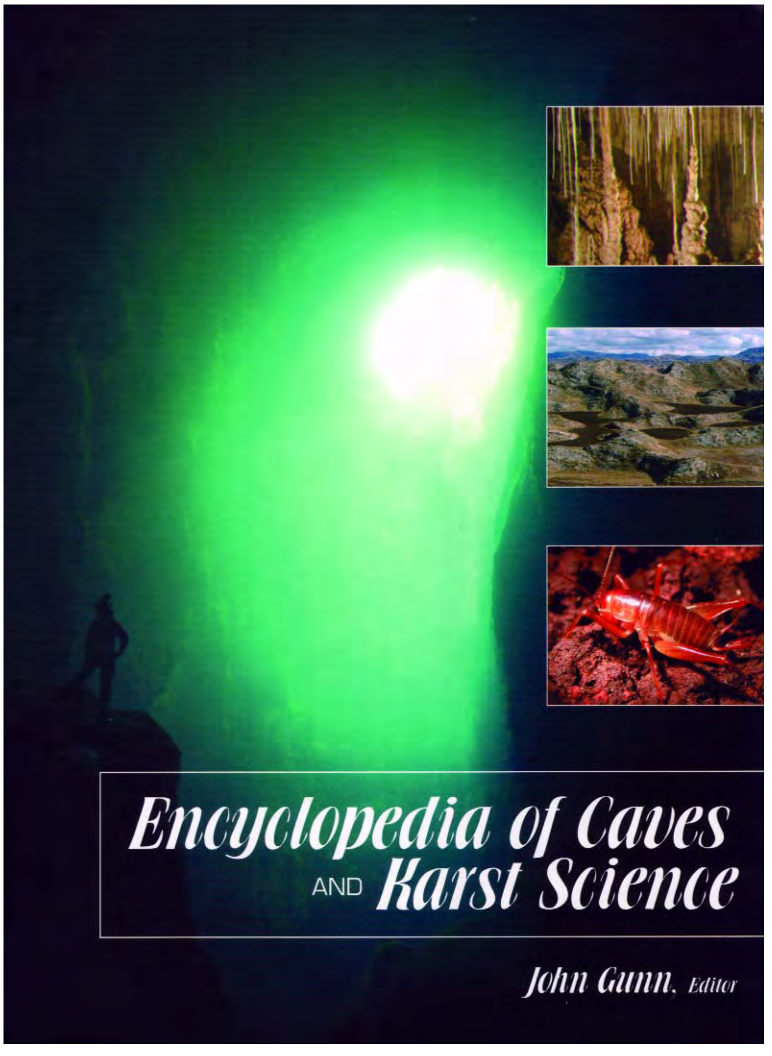
ENCYCLOPEDIA OF CAVES AND KARST SCIENCE

John Gunn, Editor with Board of Advisers: Andrew Chamberlain, Emily Davis, Derek Ford, David Gillieson, William Halliday, Elery Hamilton-Smith, Alexander Klimchouk, David Lowe, Arthur Palmer, Trevor Shaw, Boris Sket, Tony Waltham, Paul Williams, and Paul Wood. First Edition (2004). Routledge Taylor and Francis Group. Routledge, New York, NY, 902 p. ISBN 1579583997. $150 (US) and $225 (CAN). Order on-line at http://www.routledge-ny.com/books.cfm?isbn=1579583997.

Also available on-line at http://www.Amazon.com for $200 (US) with 24-hour shipping. Amazon also had "5 used & new from $167.69" (US) at the time of this writing. (Actually four of the five were listed as new and only one of the five was listed as "like new" but I can't comprehend why anyone wouldn't keep this book after purchasing a copy!)



Encyclopedia of Caves and Karst Science, published in 2004, is a significant addition to the subject of karst in all its various forms and one which the Editor, Board of Advisers, and various authors (who too numerous to mention here) should be proud. This monograph contains over 350 entries (353 according to Mixon 2004, p. 89) and over 500 black-and-white photographs, maps, diagrams, and tables. Fifty-one color photographs are grouped together near the middle of the encyclopedia. All photographs, maps, and diagrams are very clear and relevant to the text, so that clarity is added to material that is difficult to explain, although some diagrams (e.g., Fig. 1 and 2 under the heading "Chemistry of Natural Karst Waters") may be confusing to non-specialists but not greatly so.

According to the Editor's Introduction, "This is the first encyclopedia on the subject of Caves and Karst Science and provides a unique, comprehensive, and authoritative reference source that can be used both by subject-specialists who wish to obtain information from outside of their immediate area of knowledge and by non-specialists who wish to gain an understanding of the diverse and multi-disciplinary nature of caves and karst science." This introductory statement by the Editor basically says it all; if you want to learn something new about almost any aspect of caves and karst, you will most likely find it in this monograph.

Although not intended as a geographical atlas, the encyclopedia does address scientifically important karst areas at the continent, country, region and/or site-specific level. In terms of karst science, it addresses "archaeology, biology, chemistry, ecology, geology, geomorphology, history, hydrology, paleontology, physics as well as exploration, survey, photography, literature, and art." (As with any undertaking of this nature there are always going to be some omissions and errors.) The breadth and scope of the coverage of subcategories of general science in the encyclopedia is a significant accomplishment.

As pointed out by Mixon (2004, p. 89), the 202 authors from 36 countries developed exceptionally readable entries which further lends credit to the level of effort by the editor. The articles are relatively short as would be expected for an encyclopedia—one to several pages of two-column 9-point type. Each article ends with a bibliography listed as "works cited" or "further reading" which is probably appropriate for an encyclopedia and for non-scientists, but as a professional scientist, I would have looked for more formal detailed citation/reference list typical of scientific work. However, if a typical scientific citation/reference list had been chosen, then this monograph would probably have increased in length by a factor of 10 or greater. Given the impossibility of such an increase in length and the bibliographic sources listings, I am quite satisfied at being able to find those references that most interest me.

An interesting and appropriate aspect of this monograph is the importance placed on exploration and basic science. The study of caves and karst is unique in that cave exploration and science are complementary, which draws individuals from extremely diverse backgrounds together to discuss new findings or new thoughts on older ideas. To integrate exploration and science, the Board of Advisers spent considerable time and energy developing and revising a list of the "world's important karst areas and most important caves." Having developed this list, the Board of Advisers then drew up a list of "topical entries considered to be of primary importance to their particular branch of science." This undertaking has resulted in a good mix of exploration and science, although interested readers will need to do some searching in the "Alphabetic List of Entries," "Thematic List of Entries," and/or index (93 pages) to locate all of the items of interest.

Many of the exploration and scientific entries may require some extra effort by the reader to fully understand the material presented if the subject entry is not a specialty of the reader. For example, entries such as the "Encantado, Sistema del Rio, Puerto Rico," "Krubera Cave, Georgia," "Peak District, England" and other foreign cave and/or karst entries use some geological terms and locality-specific terms that may be unfamiliar to some readers. For the most part, however, the exploration entries are pretty straightforward. The scientific entries are also fairly readable but may be somewhat more difficult for non-specialists. For example, the entry "Dissolution: Carbonate Rocks" and "Dissolution: Evaporite Rocks" necessarily include discussions of the physics and chemistry of dissolution kinetics of carbonates and evaporites.

One aspect not readily apparent from the title of this monograph or from the introduction, or flyers announcing its availability, is the inclusion of a significant amount of non-exploration and non-science material. For example, a discussion of "Journals on Caves" with source availability was compiled with a discussion covering two pages. This entry is quite useful for scientists and non-scientists alike because the subject of caves and karst is very diverse, with small publishing groups spread far-and-wide. A somewhat stranger entry is "Caves in Fiction" which chronicles the history of stories revolving around caves and which falls into the nonscience material. "Art Showing Caves" is a similarly strange entry.

So what about omissions and errors? As mentioned above, such was bound to occur in an undertaking of this magnitude. According to Mixon (2004, p. 89), an error occurs in the "America, Central" entry in which some Mexican caves were mislocated on the area map, as well as some confusion over when cave research began in Mexico. There are perhaps more errors of this sort but I suspect not many.

Omissions are a minor issue as well. Invariably at any given time, any particular reader will be frustrated that a specific subject of interest to that reader may not have been included in the encyclopedia. Given the immensity of this undertaking and the need to find authoritative authors for each subject entry while keeping the monograph to a "manageable" size, it was necessary that some topics be excluded. For example, I was unable to locate an entry addressing the epikarstic (subcutaneous) zone. I scoured the encyclopedia but the only discussion I could find on the epikarstic zone occurred under the heading "Dolines" and brief mention under the headings "Groundwater in Karst" and "Groundwater in Karst: Conceptual Models." In all likelihood the epikarstic zone is probably addressed in other parts of this monograph, but it should have had its own entry.

Overall I feel that this encyclopedia is a must purchase for anyone with more than a passing interest in caves and karst, including the nonscience entries much of which I found to be interesting reading. It contains a wealth of information that far outweighs its $150 price tag ($225 Canadian) and its relatively insignificant "problem" areas. Students, researchers, cavers, geotechnical consultants, and environmental professionals will all consider this book well worth the purchase price.

References

Mixon B. 2004, Review of Encyclopedia of Caves and Karst Science, NSS News, National Speleological Society, p. 89.

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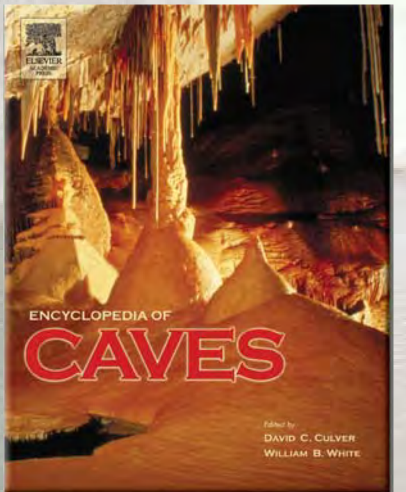

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