Cave sedimentation, genesis, and erosional history in the Cheat River Canyon, West Virginia

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ABSTRACT

A model of cave sedimentation and genesis is used to gain greater resolution and accuracy in the calculation of an incision rate for Cheat River, West Virginia. Maze caves along the river and their primary sediments were created and deposited beneath base level. Single conduit caves are largely unrelated to basin level and their sediments are derived from overlying strata. A magnetostratigraphic record is reported for cave sediments within the canyon. The magnetostratigraphy of each sample is plotted versus elevation relative to base level and depositional environment ( vadose or phreatic). The resulting chart accurately depicts the range of error associated with using cave sediments as indicators of previous base-level positions. This technique can be applied within any future studies using cave sediments for deriving incision rates of rivers. The calculated incision rate of Cheat River within the study area is between 56.0 and 63.2 mm/k.y.

INTRODUCTION

Studies of the long-term evolution of erosional landscapes are hindered in many areas by the lack of quantitative data regarding incision rates of streams and denudation. Such data are needed to gain a better understanding of the long-term effects of tectonics, climate, and geologic setting on landscape evolution. Schmidt (1982) recognized that multiple, tiered caves associated with surface rivers may record previous base-level positions and might provide long-term records of nearby stream erosion. By examining the magnetostratigraphy of sediments within selected caves, Schmidt was able to derive an incision rate for the Green River in Kentucky. Subsequent studies have used a similar approach to derive incision rates for several surface rivers (Schmidt et al., 1984; Selfridge, 1986; Pease, 1994; Kastning et al., 1995; Sasowsky et al., 1995). Such studies require multiple, tiered caves and the assumption that the tiers and sediments sampled were once associated with base level. Multiple, tiered caves are absent along most rivers, not all tiers represent previous base-level stands, and not all cave sediments are associated with base level (Johnston and Gomez, 1994). Farrant et al. (1995) presented a method to derive an incision rate using magnetostratigraphy and cave wall notches created in response to base level and climatic events. Unfortunately, this method is not applicable to caves lacking notches.

This study presents an incision rate for the Cheat River, despite the absence of multiple, tiered caves along the river, and offers a unique approach to distinguishing between cave sediments related to base level and those that are not. In the study, cave sediments and their relations to previous base levels are determined by examination of cave-passage morphology, geologic setting, Quaternary stratigraphy, and magnetostratigraphy. Future workers can use a similar approach to examine the erosional history of other river basins that lack multiple, tiered caves.

STUDY AREA

The Cheat River Canyon is located in north-central West Virginia (Fig. 1), within the unglaciated Allegheny Mountain section of the Appalachian Plateau physiographic province (Hunt, 1974). This area is characterized by broad, open folds of Paleozoic sedimentary rocks. The canyon is developed where the north-flowing Cheat River turns northwest across regional strike for 22.5 km and crosses two anticlines (Cardwell et al., 1968). Incision of the anticlines by the Cheat River has exposed the Mississippian, carbonate-bearing Greenbrier Formation. The rims of the canyon are armored by the uppermost units exposed in the canyon, resistant sandstones of the Pennsylvania Pottsville Group and overlying Allegheny Formation (Cardwell et al., 1968).

The gradient of the Cheat River through the canyon is 0.0067 (Kite and Linton, 1993). Local relief is more than 300 m and slopes may exceed 33° from river to canyon rim. The banks and bed of the river are composed of massive boulder bars between low bedrock cliffs, with only a narrow, discontinuous flood plain. Despite its large drainage area (3688 km²), the Cheat River is a "flashy river" that undergoes rapid fluctuations in stage (Kite and Linton, 1993).

Within the canyon, fluviokarst is developed upon the Greenbrier Formation, which is 57 m thick (Fig. 2). The thickest shales are found in the Savage Dam Member, which effectively partitions the formation into two distinct cavernous units, each of which is described in Figure 2. Caves in the canyon were described by Springer (1994) and Garton and Garton (1976).

METHODS OF INVESTIGATION

The criteria of Palmer (1975; 1991) and White (1988) were used to categorize cave patterns and passage cross sections. The relationship between cave passages and sediments to the river was investigated by determining active or inactive recharge points and their relationship to the river, examining stratigraphy and sedimentary structures, and examining horizontal and vertical relationships between sediments and geomorphic features. The textures were described using U.S. Department of Agriculture textural classification terms. Bulk samples were taken from every significant stratigraphic unit and particle size was determined using the pipette withdrawal method described by Galehouse (1971) and adopted with minor modifications by the West Virginia University Quaternary Lab (J. S. Kite and A. Bell, unpub. data). Samples for paleomagnetic analysis were collected in pairs and analyzed using techniques described by Schmidt (1982) and Schmidt et al.

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(1984). Paired samples were taken to ensure accuracy of results. All samples underwent alternating field (AF) step-wise demagnetization and were progressively demagnetized until 90% of their initial natural remanent magnetization (NRM) strength was removed. Analysis was performed at the Paleomagnetism Laboratory of the Department of Geology and Planetary Science at the University of Pittsburgh using a cryogenic rock magnetometer.

CAVE MORPHOLOGY AND SEDIMENTS

Single conduit cave segments are those that lack contemporaneously developed, linked, closed loop passages. Multiple, contemporaneous passages that form closed loops are termed mazes (Palmer, 1991). Three basic cave patterns are present in the Cheat River Canyon. These are single conduit, network maze, and anastomotic maze (Fig. 3). The characteristic passage morphologies and sedimentary facies of these cave patterns are discussed below. Only Cornwell Cave displays segments with network maze patterns. The network segments merge with anastomotic maze segments in the cave and display the same sediment facies. Therefore, anastomotic and network mazes are discussed together.

**Single Conduit Cave Segments**

Single conduit cave passages in the canyon are typically joint-oriented, stream-carrying passages with canyon or rectangular cross sections (Fig. 3). Canyons range from 2 to 11 m high, and rarely exceed 2 m wide. Canyon passages are best represented by the 2-km-long main passage of Druid Cave. Passages with rectangular cross sections range from 1 to 4 m high and wide and are best represented by the 190-m-long stream passage of Beaverhole Upper Cave. The rectangular passages are typically developed atop resistant strata at the intersection of a bedding plane and joint. The joint is commonly enlarged and forms a small channel in the passage ceiling (Fig. 3). The canyons form by vertical incision along joints.

The floors of single conduit passages are armored by clastic sediments eroded from upslope strata and carried into the cave by streamflow. Such allogetic sediments can be distinguished from in-cave, autogenic weathering deposits by the distinctive petrology of the sand fraction of some upslope sedimentary units. Units such as the Pottsville Group sandstones produce angular, opaque quartz grains. Quartz grains derived from the Loyalhanna Member are rounded, frosted, and translucent. The Wymps Gap Member lacks sand-sized clastic grains.

Stream sediments are typically clast-supported, poorly sorted gravels and cobbles. Sand, silt, and clay (fines) are limited to matrix deposits between larger clasts and within pooled stretches of the cave stream. Manganese oxides coat most clasts and imbrication is weak, except in very fine gravels. Where fines accumulate, the most common sedimentary structure is cross-stratification of alternating light clastic and dark organic laminae.

**Figure 1.** Location of the study area (Cheat River canyon) and selected caves. D—Druid Cave, B—Beaverhole Upper Cave, Cb—Colluvium Breath Cave, Co—Cornwell Cave.

**Figure 2.** Measured section of the Greenbrier Formation in the Cheat River Canyon. The majority of caves in the canyon are developed in the Loyalhanna Member. Member names are adopted from Brezinski (1989).
Residuum is common in caves developed within the Loyalhanna Member (Table 1).

Most single conduit segments with lengths of more than 20 m possess perennial streams. The Cornell and Beaverhole Lower canyons are fed by infiltrating surface water from the slopes above and display only small variations in flow. Prominent vertical joints intersecting the caves and valley wall divert diffuse recharge to the caves from overlying colluvium and soil.

No cave streams in the Cheat River Canyon have significant tributaries. The limited outcrop of the Greenbrier Formation severely restricts locations available for recharge, and hence development of a branchwork pattern. With the possible exception of Druid Cave, no active cave streams reach a piezometric surface while underground. The Druid Cave stream forms a spring on the south bank of the Cheat River.

All examined single conduit passages are stratigraphically perched. The Druid canyon is perched atop resistant sandy and shaley interbeds. The Cornell canyon is perched at the base of the Loyalhanna Member upon sandstone of the underlying Price Formation. Both canyons follow down-dip joints and have flow directions opposite that of the Cheat River. The streams of Beaverhole Lower and Spring Falls caves are perched atop thin shales within the Wymps Gap Member and follow joints at angles between 15° and 45° to the dip direction.

With the exception of floodwaters and floodborne deposits of the Cheat River, recharge is derived from upslope sources and the associated sediments are therefore derived from upslope strata. Springer and Kite (1997) report that sediments derived from the Cheat River and deposited

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**Figure 3.** Typical plans and cross sections of caves in the canyon. Beaverhole and Druid caves are typical single conduit caves. Cornell displays anastomotic and network maze segments. The Cornell plan is modified from Garton and Garton (1976).

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**TABLE 1: FACIES CLASSES OF THE CHEAT RIVER CANYON CAVES**

<table>
<thead>
<tr>
<th>Phreatic facies class</th>
<th>Vadose facies class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediments deposited beneath base level in maze caves; includes the facies described below.</td>
<td>Sediments deposited above base level; includes the facies described below.</td>
</tr>
<tr>
<td>Diamicton: gleyed, matrix-supported bouldery gravel to loam diamict; becomes finer away from river.</td>
<td>Gravity: poorly sorted, coarse colluvial deposits from overlying valley wall; includes collapse deposits.</td>
</tr>
<tr>
<td>Laminated sand: laminated sands and sandy loams with centimeter-thick beds and some silt interbeds.</td>
<td>Travertine: chemically precipitated calcite and aragonite derived from overlying bedrock and soil.</td>
</tr>
<tr>
<td>Silt-clay rhythmite: silt loams, loamy silts, and loamy clays, displaying rhythmic laminations, fill elliptical-shaped passages.</td>
<td>Overbank: thin, blanketlike deposits of laminar silt, sand, and organics bounded by scour surfaces, mud cracks, and surge marks.</td>
</tr>
<tr>
<td>Sandy clay loam: gleyed, massive sandy clay loams with laminated clay interbeds; sand grains are frosted and well rounded.</td>
<td>Cave stream: sorted fines and gravels with directional flow indicators or cut-and-fill features; associated with discrete input source.</td>
</tr>
</tbody>
</table>

Residuum facies class

Sandy loams to loamy sands mantling bedrock surfaces. Derived from decalcification of bedrock. Possess inherited primary sedimentary structures and secondary structures such as stylolites. Sand grains are well rounded and frosted.

Note: Phreatic facies are exclusively associated with maze passages having elliptical cross sections. Vadose facies are associated with single-conduit and modified maze segments. Residuum facies are associated with both single-conduit and maze cave segments.
TABLE 2: FACIES OBSERVED WITHIN SELECTED CAVES OF THE CHEAT RIVER CANYON

<table>
<thead>
<tr>
<th>Cave Location</th>
<th>Type of cross section</th>
<th>Height above base level</th>
<th>Overbank</th>
<th>Travertine</th>
<th>Cave stream</th>
<th>Gravity</th>
<th>Diamictic</th>
<th>Laminated sand</th>
<th>Silt-clay</th>
<th>Sandy loam</th>
<th>Residuum</th>
<th>Trend relative to river</th>
<th>Stratigraphic unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Druid Canyon</td>
<td>Rectangular</td>
<td>0–100</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Beaverhole Upper</td>
<td>Rectangular</td>
<td>35–38</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Perpendicular</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Beaverhole Lower</td>
<td>Canyon</td>
<td>152</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Oblique</td>
<td>Wymps Gap</td>
<td>Parallel</td>
<td>No</td>
<td>Parallel</td>
<td>Wymps Gap</td>
</tr>
<tr>
<td>Spring Falls</td>
<td>Canyon</td>
<td>16</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Wymps Gap</td>
<td>Parallel</td>
<td>No</td>
<td>Parallel</td>
<td>Wymps Gap</td>
</tr>
<tr>
<td>South Side</td>
<td>Rectangular</td>
<td>0–1</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Darby Pit</td>
<td>Canyon</td>
<td>0–1</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Cowanell</td>
<td>Canyon</td>
<td>14</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Beaverhole Upper</td>
<td>Elliptical</td>
<td>44 and 48</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Cornwell</td>
<td>Elliptical</td>
<td>35–39</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Coliseum Rapids</td>
<td>Elliptical</td>
<td>5–7</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Coliseum Tube</td>
<td>Elliptical</td>
<td>14</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Parallel</td>
<td>Loyalhanna</td>
<td>Parallel</td>
<td>Yes</td>
<td>Parallel</td>
<td>Loyalhanna</td>
</tr>
<tr>
<td>Unnamed (plugged)</td>
<td>Elliptical</td>
<td>1</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>No</td>
<td>Loyalhanna</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Loyalhanna</td>
</tr>
</tbody>
</table>

Note: All attributes refer to the cave passage in which a facies was observed; p—denotes that a particular facies was observed in the cave segment, P—indicates that magnetostratigraphic samples were collected from the facies.

Maze Caves

The maze caves of the Cheat River Canyon are characterized by anastomotic and network maze segments (Fig. 3). All mazes are developed in the Loyalhanna Member. The maze caves are not meander cutoff diversions of the Cheat River and are developed parallel to straight stretches of the river and in cliffs along the outside bends of long-wavelength meanders.

Three distinct shapes of passage cross sections are present in the maze caves: uniform elliptical tubes with maximum widths between 0.5 and 4 m, dip-oriented canyonlike passages, and low, wide tubes typically displaying a half-tube in the ceiling (Fig. 3). The floors of each are composed of fine-grained sediments.

The uniform elliptical and low, wide tubes typically form anastomotic maze segments that are recognized by their frequent, irregular junctions (Palmer, 1991). The canyonlike forms are more typically associated with network maze segments in Cornwell Cave that have regular, cross-shaped junctions. The canyons display passage enlargements on the same horizontal plane as meandering elliptical tubes that intersect the canyons at roughly right angles. The enlargements are inferred to represent elliptical tubes developed along the intersection of dip-oriented joints and bedding planes within the Loyalhanna Member (Fig. 3). Beneath the ceiling joints of the maze canyons are 0.25–1-m-deep channels in the fine-grained sediments that compose their floors. The channels are the product of vadose scour by water entering through the vertical joints. Enlargement of the joints and coincident scour of the passage floors has modified the elliptical tubes into canyon cross sections.

Where exposed by subsequent stream erosion, the cross-sectional area of cave sediments is at least equal to the cross-sectional area of the open passage above them. Nonresidual, fine-grained clastic sediments overwhelmingly dominate all exposures, and texture generally becomes finer away from the river. Disturbance of primary structures is largely the result of faunal bioturbation, tree roots, and scour by vadose recharge.

To assess the nature of vadose and phreatic facies, nine sedimentary facies based on texture, sedimentary structures, and setting are present in the mazes (Tables 1 and 2). All passages displaying elliptical cross sections or ceiling tubes contain one or more sedimentary units assignable to the phreatic facies class. The basal member of each sediment package rests on bedrock or residuum. Sediments of the vadose facies class overlie or penetrate the phreatic facies (Tables 1 and 2). Only sediments belonging to the vadose and residuum facies classes are present in single conduit passages.

CAVE SEDIMENTATION, GENESIS, AND EROSIONAL HISTORY

The irregular passage cross sections of the single conduit passages are typical of vadose cave development (White, 1988). Sediments within the single conduit passages are clearly associated with vadose streams sinking on the overlying valley wall and display sedimentary structures typical of vadose streams. Therefore, the single conduit caves and most of their sediments are unrelated to base level. Because the caves are not directly related to base level and may have developed long after the Cheat River incised below their elevation, they are not accurate indicators of previous base-level positions. Such sediments may, however, be used to infer minimum dates for which the river must have incised below their elevation. Those deposited by overbank flooding of the Cheat River may be useful indicators of base-level position if the maximum peak flood stage of the river is known (discussed below).

The smooth, elliptical passage cross sections of the maze caves are typical of passages that develop under pipe-full or phreatic conditions, typically associated with piezometric surfaces or base-level stands (Palmer, 1987; White 1988). However, such passages are not always associated with phreatic flow (Palmer, 1987; Johnson and Gomez, 1994). Less ambiguous evidence of a phreatic origin for the maze passages is found in their sediments.

The basal deposits in maze passages of the Cheat River Canyon are those of the phreatic facies class (Table 1). These sediments have a conformable relationship with sediments of the vadose facies class only within Beaverhole Upper Cave, where a single exposure in an anastomotic maze segment displays a basal laminar silt overlain by interbedded sands from the overlying valley wall and river-derived overbank sediments.

The basal deposits in the maze passages become finer away from the valley wall (Cheat River). The diamictons may contain clasts as large as 15 cm in diameter within 10–15 m of Cheat River, but grade to loams away from the river. The arrangement of the facies relative to the valley wall is depicted in Figure 4. The most dis-
tal deposits are massive, sandy clay loams interbedded with brown, laminar clays observed in Cornwall Cave. The sand particles within the sandy clay loams are rounded, frosted quartz grains. Grain-size analysis of the sandy clay loam and residuum indicates similar grain-size distributions. Hence, the sandy clay loams are autogenic deposits. Their presence within passages that have elliptical cross sections suggests pipe-full dissolution of the passage walls with accompanying deposition of the insoluble residue. The interbedded brown clays are inferred to represent infrequent influxes of turbid water or expansion of the adjacent silt-clay rhythmite facies zone.

The nature and arrangement of the phreatic facies indicates that the river was the primary source of the sediments. Hence, the maze caves and their sediments are the products of dissolution by waters of the Cheat River and allogenic and autogenic sedimentation. Aggressive waters were likely injected into the host rock during episodes of elevated head. Small (<10 cm diameter) anastomotic tubes exposed along bedding planes within cliff faces above the river were also produced in the same manner. The one remaining question is, Where did the caves form relative to the Cheat River—at river level, slightly above river level during episodic flooding, or below river level? A naturally exposed, completely filled cave passage near Coliseum Rapids on Cheat River helps answer this question.

The cave (Fig. 5) is a 4-m-wide elliptical tube exposed in a cliff face 1.5 m above the Cheat River. The tube is plugged with laminated sand and silt-clay rhythmites that become finer upward. The tube displays ceiling pendants, projections of bedrock from the passage walls, and 2-cm-wide anastomosing tubelike pendants on the passage ceiling, both of which are characteristic of pipe-full flow (White, 1988).

The larger pendants are preserved upright within the clay loam despite their being detached from the cave ceiling. This is a product of paragenesis, whereby a cave ceiling progressively rises as sediment accumulates on the passage floor and impinges upon the roof. The pendants formed by paragenesis and were detached by dissolution of their attachment to the ceiling. Paragenesis is attributed to cave development beneath the piezometric surface (Palmer, 1987) though only pipe-full flow is required. Plugged and partially open cave passages similar to the tube depicted in Figure 5 are found in nearby, dissected maze caves. None, however, display pendants.

Figure 4. Measured sections from caves, arranged to show observed lateral and vertical relationships of phreatic facies. Sediments become finer away from Cheat River. Columns GS-92-6 and GS-93-4 are from Colluvium Breath Cave. Others are from Cornwall Cave.
Exposures of sediments within elliptical passages lack evidence of periodic exposure and hence sedimentation at or above base level. Evidence of periodic exposure might include cut and fill features, scour surfaces, reworking of sediments, bioturbation, or mud cracks. These features are associated with overbank sediments deposited in caves of the canyon (Springer and Kite, 1997).

Given the evidence of paragenesis, close proximity and relationship to the river, and the lack of sedimentary evidence suggesting periodic exposure to vadose conditions, the maze caves and phreatic facies sediments formed below local base level, the Cheat River. No phreatic vertical conduits are known from the 6.4 km of observed maze passages. Barring such conduits, maze development can only begin when the Loyalhanna Member is breached by incision of the overlying sediments. Anastomosing, tubelike pendants cover ceiling (A).

Sediments of the vadose facies class found within the maze caves are the products of secondary invasion of the caves following their emergence from beneath base level. Interbedded sediments of the phreatic and vadose facies classes in Beaverhole Upper Cave may reflect the intersection of a valley wall stream with the piezometric surface. Alternately, nondeposition and nonerosion between emergence of the basal sediments above base level and later burial by cave stream sediments could account for the interbedding of these sediments.

**MAGNETOSTRATIGRAPHIC INTERPRETATION**

Establishment of the relationship between maze caves and base level allowed the deliberate sampling for paleomagnetic analysis of sediments that represent previous base-level stands. Sediments associated with cave streams and overbank flooding of the Cheat River were sampled as well, but in fewer numbers. We took 18 duplicate, paleomagnetic samples from 11 sites in 4 caves. Sampling sites ranged between 7 and 51 m in elevation above modern base level (Fig. 6). Due to a lack of suitable caves, no samples were recovered from between the elevations of 14 and 34 m above base level or above 51 m. The lower three sampled caves (Cornwell, Coliseum Rapids, and Colluvium Breath) are within a 2.5 km stretch of the Cheat River, and the uppermost cave, Beaverhole Upper, is located 7 km from the others (Fig. 1). Using the necessary assumption that the gradient of the river through the canyon has remained constant over recent geologic time, the polarity data from the four caves was combined to create Figure 6.

Using magnetostratigraphic data plotted in diagrams similar to Figure 6, previous workers have calculated incision rates for surface and cave streams by dividing the height of the inferred magnetic subchron boundary by its age (Schmidt, 1982; Schmidt et al., 1984; Selfridge, 1986; Pease, 1994; Kastning et al., 1995; Sasowsky et al., 1995). Using an elevation midway between the highest normal polarity sediments and lowest reversed polarity sediments of option 1 yields an incision rate of 59.1 mm/k.y. (46.6 m in 788 000 yr).

Of the 36 samples examined, 23 displayed normal magnetic polarities, 9 displayed reversed magnetic polarities, and 4 were indeterminate. Natural remanent magnetization varied between $1.42 \times 10^{-5}$ and $2.1 \times 10^{-6}$ kA/m. The polarity of each sample was determined by plotting Zijderveld (1967) vector diagrams and interpreting them using the criteria of Schmidt et al. (1984). Only Beaverhole Upper Cave displayed both normal and reversed polarity sediments.

All sediments display normal polarity below the 44.5 m elevation (Fig. 6). Sediments between the elevations of 48.8 and 51 m display reversed or indeterminate polarities. A magnetic epoch boundary must lie somewhere between the elevations of 44.5 and 48.8 m. No samples were recovered between the elevations of 14 and 34 m. This gap raises the question of whether the magnetic epoch boundary is the Brunhes-Matuyama contact (0.788 Ma; option 1) or the upper contact of the Jaramillo subchron (1.01 Ma; option 2).

Option 1 assumes that the “gap” does not contain a reversed interval and that the Brunhes-Matuyama boundary lies in the range of the highest normal sediments and lowest reversed sediments (respectively, 44.5 and 48.8 m; Fig. 6). Option 2 assumes that the gap hides a reversed polarity epoch (Fig. 6). If this option is correct, the normal sediments overlying the gap would probably be from the Jaramillo subchron. In this option, the normal sediments of Cornwell and Beaverhole Upper caves would represent the Jaramillo and one can derive incision rates for the upper and lower boundaries of the epoch. In addition, by using the boundaries of the Jaramillo subchron one can derive an incision rate for the river during that 95 000 yr interval. The rate, <112 mm/k.y., must be treated with great caution because the flood range could easily span the 12 m represented by this interval. Assuming that the Brunhes-Matuyama boundary lies within the gap between Cornwell and Coliseum Rapids caves, the incision rate would be between 16 and 38 mm/k.y. (Fig. 6). These values are markedly different from those derived using the upper Jaramillo subchron boundaries. Taken together, the incision rates of option 2 would indicate that the Cheat River has incised downward at =46 mm/k.y. during the past 1.01 m.y. However, during the Jaramillo subchron the incision rate tripled before slowing down to an average rate of ≤39 mm/k.y. during the past 0.788 m.y.

The option 2-derived incision rates are comparable to the rates derived from Mammoth Cave (33 mm/k.y.; Schmidt, 1982). Mammoth Cave, however, is located beside the Green River, a low-gradient, meandering river (Sasowsky et al.,...
1995) that has a gradient much lower than that of the Cheat River. Along the Cheat River, the absence of all but a rudimentary flood plain, steep canyon walls, and a boulderly bed suggest a more rapid incision rate.

Unless much of the sediments observed were deposited by high-reaching floods, option 2 also suggests a rapid incision during the Jaramillo subchron. However, most cave passages and sediments examined within this range are closely associated with base level. Hence, the extremely rapid incision rate during the Jaramillo would be correct within that order of magnitude. The high rate of incision would require a significant increase in discharge, regional slope, or incision of a less competent lithology during the Jaramillo.

No evidence exists for such changes. Given that option 2 requires widely fluctuating incision rates incompatible with the existing geomorphology, option 2 is rejected and the simplest solution, option 1, is accepted.

**DISCUSSION**

**Determination of Incision Rates**

Several assumptions are made when calculating incision rates from diagrams similar to Figure 6. All magnetostratigraphic samples are assumed to be equally representative of base level, hence the elevation chosen as representative of a particular magnetic subchron boundary can be used to calculate an incision rate. The assumption hinges on cave sediments being terracelike deposits within the valley wall. The facies studies presented in this paper show that not all sediments are derived from base level nor do all sediments provide equally representative information about base level.

Another similar assumption is that tiered passages within a multiple-level cave represent previous base-level stands of nearby surface streams (Palmer, 1989). Hence, sediments within the passages can be used to attain ages for previous base-level stands and calculate incision rates for the base-level stream. This assumption cannot be sustained for vadose stream passages in the Cheat River Canyon, nor elsewhere unless there is additional evidence (Johnson and Gomez, 1994).

Using the facies information discussed previously, Figure 7 was composed. This figure not only displays the height of sediments above base level and their polarity, but also graphically displays the uncertainty of their relation to base level at the time of deposition. From the facies studies, sediments can be seen to represent deposition below base level (phreatic facies), in the vadose zone by the Cheat River (overbank facies), and in the vadose zone by cave streams and slope processes unrelated to base level (cave stream, travertine, and gravity facies). Each of these presents a different type of potential error, hence, uncertainty.

All of the mazes are developed within the Loy-althanna Member and beneath significant aquitards of red shale (Fig. 2). Genesis of the mazes could not have begun before these shales were breached. The red shales do not overlie the units containing the caves by more than 20 m. Hence, when phreatic facies sediments were deposited base level must have been no more than 20 m above them. This value is used in Figure 7 as the vertical error bar for all sediments attributed to the phreatic facies class. Because the caves are developed along bedding planes that received horizontal water flow from the Cheat River, it is possible that the 20 m value greatly overstates the degree of uncertainty.

Overbank sediments were deposited by vadose floodwaters of the Cheat River. Springer and Kite (1997) report floodwater depths of 15 m for the largest known flood on Cheat River. This flood is the largest recorded along the Cheat River during the 130 yr of record and twice the discharge of the second largest flood, but could conceivably be surpassed. This value is approximated as 20 m and used in Figure 7 as the vertical error bar for sediments attributed to the overbank facies. The additional 5 m of elevation would result in a discharge twice the current record value.

Sediments of the cave stream, travertine, and gravity facies can be deposited anywhere upslope...
of the river. Hence, they must possess uncertainty bars that extend downward to indeterminate depths. In Figure 7, vertical error bars for sediments from these facies are left dashed on their lower ends to reflect the uncertainty of their position relative to base level during deposition.

The uncertainty of the positions of sediments relative to base level during deposition is compounded by uncertainty of ages. Normal polarity sediments could theoretically represent deposition from 0 to 0.788 Ma and reversed polarity sediments deposition from 0.788 to 0.91 Ma. These uncertainties are represented in Figure 7 as horizontal error bars. The combined error bars for position relative to base level during deposition and age create large error boxes (Fig. 7).

An incision rate for Cheat River can be represented as a line sloping from the origin in Figure 7 upward. The area above such a line represents the vadose zone, and the area below the line represents the phreatic zone. A long-term average incision rate for Cheat River must pass through all error boxes irrespective of depositional environment. The error boxes in Figure 7 allow a range of incision rates, the upper and lower values of which are defined by the corridor through which all possible lines may pass. The range of possible incision rates for the Cheat River is between 56.0 and 63.2 mm/k.y. This range brackets the average rate of 59.1 mm/k.y. calculated using Figure 6 and option 1 and provides a measure of error not previously possible. The range is a long-term average that spans at least the past 0.788 m.y.

**Comparison of Incision Rates**

Behling and Kite (1988) provided the only reported date for terrace sediments in the Cheat River basin. Organic debris within an abandoned channel 20 m above the Cheat River near the upstream terminus of Lake Lynn yielded a radiocarbon date of 39 385 ± 2655 yr B.P. (UGa-1240). However, the date has been revised by Robert Kalin of the examining laboratory to >39 400 yr B.P. (Robert Kalin, 1993, personal commun. to Kite). From this revised age a maximum incision rate of ≤500 mm/k.y. can be calculated.

The Cheat River is a tributary to the Monongahela River (Fig. 1). Jacobson et al. (1988) examined terrace deposits along the Monongahela River downstream of its junction with the Cheat River. Using pedological analysis, paleomagnetic histories, and stratigraphic correlation, they recognized four distinct groupings of terraces traceable for between 40 and 210 km and assigned ages to the terraces on the basis of apparent soil ages. Although not done by Jacobson et al. (1988), incision rates can be calculated using ages assigned to the terraces. The rates are ≤114 mm/k.y. for pre-Illinoian, paleomagnetically reversed Lake Monongahela terraces; 218–500 mm/k.y. for Illinoian terraces; and 200–240 mm/k.y. for early Wisconsinan terraces near Point Marion, Pennsylvania.

Thompson and Long (1968) reported "varved clays" in an abandoned channel of the Tygart River. The abandoned channel lies 46 m above the confluence of the Tygart and West Fork Rivers, which marks the beginning of the Monongahela River. The varved clays were attributed to glacial Lake Monongahela, and other such "varved" facies at similar, nearby elevations display reversed magnetic signatures (Jacobson et al., 1988). Assuming that the abandoned channel sediments are correlative to the sediments observed by Jacobson et al. (1988), an incision rate of 60 mm/k.y. is calculated. The value, however, is a maximum incision rate because Lake Monongahela may have inundated the area after the channel was abandoned and left as a relict on the valley wall. Therefore, the value is properly given as ≤60 mm/k.y. This value sharply contrasts with the values calculated using other data by Jacobson et al. (1988).

Elsewhere, studies of the paleomagnetic histories of cave sediments and base level have provided incision rates for several nonglaciated rivers. Slack-water sediments within the Bone-Norman cave system, West Virginia, provided Selfridge (1986) with a preliminary incision rate for the Greenbrier River of between 31 and 58 mm/k.y. These values were subsequently refined to ≈46 mm/k.y. Cave sediments of the East Fork of the Obey River in north-central Tennessee give a similar incision rate of 55 mm/k.y. (Sasowsky et al., 1995). Schmidt (1982) studied slack-water sediments in Mammoth Cave, Kentucky, and calculated an incision rate of ≈33 mm/k.y. for the nearby Green River (Schmidt, 1982). The above values were reported using a 0.73 Ma age for the Bruhnes-Matuyama boundary, and were recalculated for this paper using the 0.788 Ma age reported by Spell and McDougall (1992) and Baksi et al. (1992).
The incision rate calculated for the Cheat River is similar to the lower, more accurate rates calculated for the nearby Monongahela River and is in general agreement with other studies in the eastern United States. The use of facies analysis to define the relationship of sediments to base level should allow more confident calculation of incision rates. Removing the prerequisite of multiple, tiered caves will allow the reconstruction of erosion histories along a greater number of rivers, and in areas where karst is poorly developed, but thin limestones are present at varying elevations above base level.

CONCLUSIONS

Single conduit caves of the Cheat River Canyon are of vadose origin and are indistinguishable from previous base-level positions. Maze caves of the canyon were developed by floodwaters of the Cheat River prior to their emergence from beneath base level. Sediments within caves of the canyon are not equally representative of base level and fall within three distinct facies classes. These classes are vadose, phreatic, and residuum. The vadose sediments represent deposition following emergence or during development of the caves above base level. The phreatic facies represent sedimentation beneath local base level within maze caves. Residual deposits are autogenic products of in situ decalcification of bedrock and occur in both the phreatic and vadose zone.

The exact position of sediments relative to base level during deposition is uncertain. Phreatic facies sediments can theoretically be deposited as much as 20 m below active base level. Vadose sediments deposited by the river can be deposited as high as 20 m above active base level. Vadose sediments deposited by processes not directly related to base level can be deposited over a wide range of elevations relative to base level. By using the uncertainties of position relative to base level at the time of deposition and age uncertainties, total error boxes can be constructed to help constrain the value of the long-term incision rate.

Future workers attempting to use magnetostratigraphic records within caves to derive incision rates for surface rivers can incorporate facies studies within their work. Facies analysis will allow greater accuracy in determination of incision rates and allow more accurate reporting of incision rates. The calculated average incision rate for the Cheat River for the past 0.788 m.y. is between 56.0 and 63.2 mm/k.y.

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