G.S. Springer, H.D. Rowe, B. Hardt, F.G. Cocina, R.L. Edwards, and H. Cheng – Climate driven changes in river channel morphology and base level during the Holocene and Late Pleistocene of southeastern West Virginia. *Journal of Cave and Karst Studies,* v. 71, no. 2, p. 121–129.

CLIMATE DRIVEN CHANGES IN RIVER CHANNEL MORPHOLOGY AND BASE LEVEL DURING THE HOLOCENE AND LATE PLEISTOCENE OF SOUTHEASTERN WEST VIRGINIA

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Abstract: Rivers commonly respond to climate change by aggrading or incising. This is well documented for North American rivers in arid and proglacial regions, but is also true of rivers in unglaciated, humid-temperate regions. Here, we present a record of Holocene hydroclimatology for a humid, temperate watershed in the Appalachian Mountains of eastern North America. We use stable isotope geochemistries of a stalagmite and clastic cave sediments to reconstruct Holocene climate and ecology in the Greenbrier River catchment (3,600 km^2) of southeastern West Virginia. Independently, we use river-deposited cave sediments to construct a history of incision, aggradation, and morphological change in the surface channel. The clastic cave deposits display enriched (less negative) values of sedimentary $\delta^{13}C_{org}$ during the Holocene Climatic Optimum (HCO), which regional pollen records indicate was warm compared to later climes. The river channel had aggraded by >4 m during or prior to the HCO and adopted an alluvial morphology, probably due to the mobilization of hillslope sediments accumulated during the colder, drier full-glacial conditions of the Late Pleistocene. As climate moistened during the Holocene, the Greenbrier River incised through channel-filling sediments and back onto bedrock, but not until ~3,500 cal. years B.P. Therefore, the bedrock morphology of many streams in the Appalachian Mountains may not have existed for much of the Holocene, which highlights the effect of climate variability on channel processes. The base-level rise is more evidence that bedrock incision by rivers is often episodic and that slow, long-term incision rates reported for Appalachian Rivers are probably not representative of short-term incision rates.

Introduction

Average global temperatures have been rising in recent time and climate change is expected to measurably affect stream hydrology (Kundzewicz et al., 2007). As such, societal interactions with rivers will change, including those related to flooding. The magnitudes and directions of these changes are uncertain and new, more quantitative data are needed to predict future responses and prepare society for the changes ahead (Wood et al., 2002; Maurer et al., 2004; Lettenmaier et al., 2006). High-resolution studies are especially needed because of the scale mismatch between climatic models and catchments, as the latter are the functional units of the terrestrial hydrosphere (Kundzewicz et al., 2007). Climate change affects a host of stream variables, including channel morphology, which is a good predictor of stream behaviors and processes (Montgomery and Buffington, 1997). In the simplest case, a decrease in net precipitation can cause channels to infill with sediment (aggrade) and change from an incised channel to a broader, shallower channel (Knighton, 1998). Conversely, an increase in precipitation, stream discharge, or gradient can also cause channels to infill if sediments stored on alluvial fans and valley bottoms are remobilized and transported into the stream (Schumm, 1973). In such a generalized scenario, channel aggradation raises base level, which leads to increased flooding on terraces and floodplains (e.g., Bull, 1988). However, corresponding changes in stream morphology may change stage-discharge relationships and thereby increase or decrease peak flood stages (e.g., Stover and Montgomery, 2001). Thus, predicting changes in base level and channel morphologies are important steps toward understanding future stream behaviors and risks.

Here, we reconstruct Holocene changes in channel morphology and base-level elevation in a mountainous watershed draining the Eastern Continental Divide (ECD) of North America (Fig. 1). The sedimentology of river-

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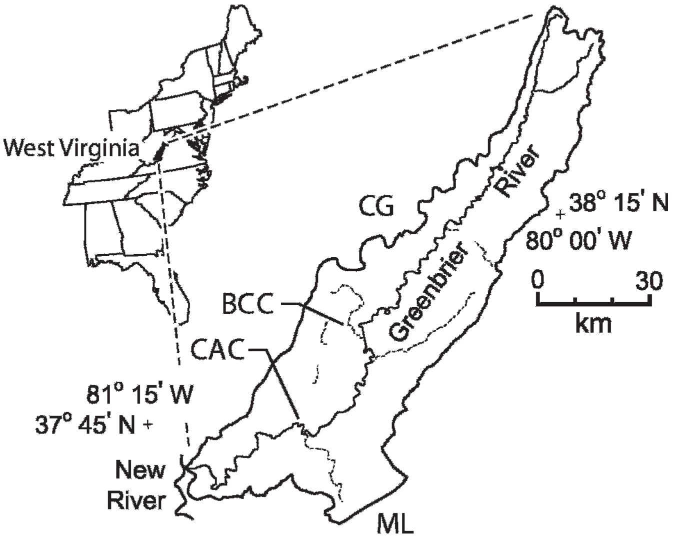

Figure 1. Colonial Acres Cave (CAC) and the associated surface channel are located along the Greenbrier River in southeastern West Virginia. The Greenbrier River watershed abuts the Eastern Continental Divide along its north and east boundaries. The CAC/Greenbrier River sedimentary record is compared to paleoclimate records drawn from Buckeye Creek Cave (BCC), Cranberry Glades (CG), and Mountain Lake, Virginia (ML).

deposited slackwater sediments is used to construct a history of stream hydrology and morphology, which is compared to a record of Holocene climates. We reconstruct climate using stalagmitic $\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$ values, bulk organic values of $\delta^{13}C_{org}$ in clastic cave sediments, and previously published palynological data. Ours is the first detailed simultaneous examination of the climate and river hydrology within the source region of large Appalachian rivers (Fig. 1).

METHODS AND SAMPLE LOCATIONS

STALAGMITE BCC-002

A calcite stalagmite (BCC-002) from Buckeye Creek Cave (BCC) (Fig. 1) is used to develop a stable isotope record of climate for interpretation of the causes of significant changes in slackwater stratigraphy in Colonial Acres Cave (CAC) (Fig. 2) (Springer et al., 2008). BCC is within the Greenbrier River watershed of southeastern West Virginia. The watershed is a major tributary of the westward-flowing New River and across the ECD from the eastward-flowing Potomac and James Rivers. The 200-mm-long stalagmite was fed by a soda straw stalactite with a slow, but incessant drip rate. Temperature and humidity are stable in the cave passage and air movement is slow. Springer et al. (2008) provide a picture of the sawn, polished stalagmite in their online supplemental material.

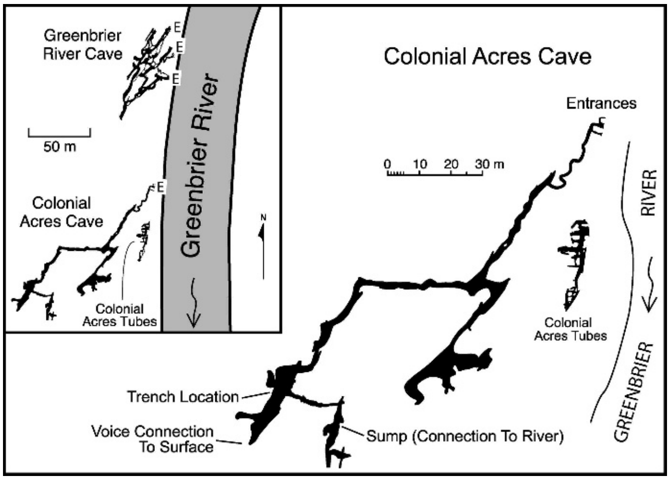

Figure 2. The examined stream reach contains three large caves developed in the river-right bank of the Greenbrier River (inset). Colonial Acres Tubes contain no usable sediments. Greenbrier River Cave (GRC) contains slackwater sediments deposited by historic and ancient floods, but no evidence of Holocene base level fluctuations has been found GRC. This probably reflects its vertical position relative to the river; much of GRC lies 7 m above the low water surface of the Greenbrier River. The slackwater sediments discussed in this study are from a modest-size room and excavated trench in Colonial Acres Cave (CAC). Greenbrier River floodwaters can reach the room from impassable pathways within a voice-transmitting collapse at the south end of the trench room, a series of tubular passages originating at three side-by-side entrances, and a small passage emanating from a sump hydrologically connected to the river (all shown).

The $\delta^{18}O$ values in stalagmites vary with changes in the meteoric water (Hendy, 1971), which predictably varies in response to changes in temperature, precipitation amount, and moisture source (Dansgaard, 1964; Rozanski et al., 1993). While speleothems in tropical regions exhibit a dominant response to the amount effect (i.e., Wang et al., 2001), mid-latitude sites have a larger temperature component (i.e., Dorale et al., 1998). Here, we assume that 1) changes in $\delta^{18}O_{calcite}$ largely reflect past changes in above-cave air temperature and precipitation source, and 2) $\delta^{13}C_{calcite}$ and $\delta^{13}C_{org}$ are proxies for floral and soil community composition, productivity, and relative moisture levels (Kirby et al., 2002; McDermott, 2004). Post-2,000 cal. years B.P. values of $\delta^{13}C_{calcite}$ are not interpreted because of anthropogenic disturbances to the BCC watershed (White, 2007).

Fourteen $^{234}U/^{230}Th$ age estimates were obtained along the growth axis of BCC-002 using U/Th dating techniques developed for carbonates (Broecker, 1963) and adapted for measurement on a mass spectrometer (Edwards et al., 1987). Calcite powders were milled with a dental drill, dissolved, and spiked with a ^{233}U-^{236}U-^{229}Th tracer. Uranium and thorium were separated using anion exchange resin, and the clean U and Th were run separately

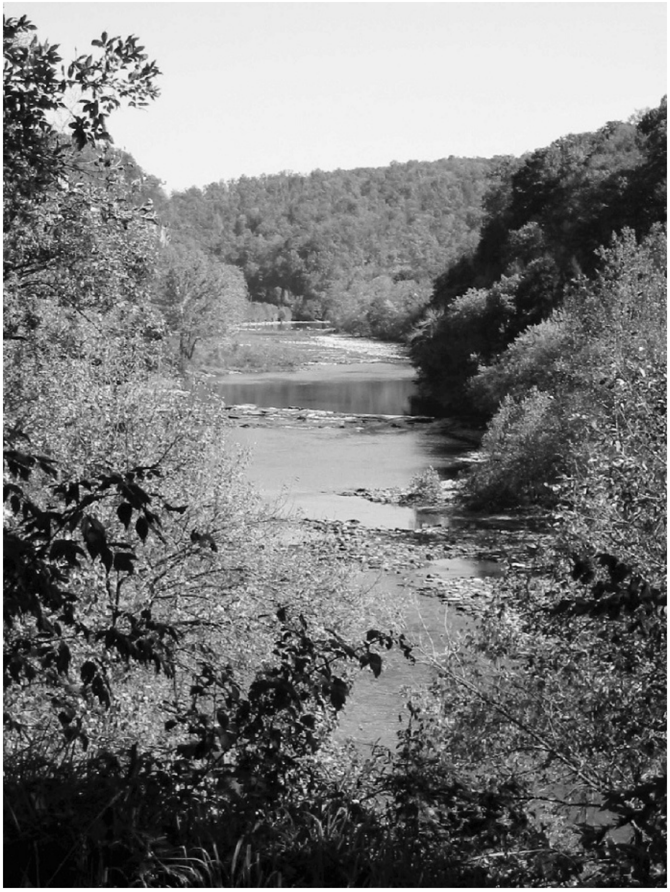

Figure 3. The Greenbrier River at Colonial Acres Cave (CAC) flows in a narrow valley containing narrow or no floodplains, but many limestone cliff banks. Flow is toward the viewer (out of the page). Channel morphology is pool-riffle or pool-rapid with boulders and large cobbles dominating bedload. Bedrock is exposed in many riffles and most pools. CAC lies 300 m downstream of the lower-right corner of this picture.

on an inductively coupled plasma mass spectrometer (Shen et al., 2002) along with a chemical blank. Ages were calculated using the decay constants determined by Cheng et al. (2000).

Clastic Slackwater Sediments

Clastic slackwater sediments deposited by the Greenbrier River in CAC are used to infer past hydrological relationships between the cave and river (Fig. 2). As demonstrated by Springer et al. (1997), Springer (2002), and Bosch and White (2003), the hydrological relationships are used to determine relative (to the cave) base-level elevations, paleoflood stages, and surface channel hydrologies. Presently, the surface channel has a bedrock morphology (>50% rock-lined), with coarse cobbles and small boulders composing the bedload (Fig. 3). The drainage area upstream of the cave is 3,600 km^2. There are no indications of significant subsurface piracy of the 60-m-wide river, which is perennial. Locally, mean annual discharge is 57 m^3 s^{-1} (n = 111) with a peak historic discharge of 2,600 m^3 s^{-1} (Springer, 2002).

CAC lies behind a vertical bank of the river. We examined a 2-m-thick package of slackwater sediments deposited by the river in a small room (Fig. 2). The room ends in collapse against the riverbank. Voices and, therefore, water readily pass through the collapse, although light does not. The Greenbrier River is the only significant source of water and sediment to CAC and completely fills the room during and above medium recurrence-interval floods. In addition to the collapse, floodwaters enter the cave room via a 210-m-long, 1.5-m-diameter passage originating at the cave entrance and via a 0.75-m-diameter passage connected to a sump (Fig. 2) that is a permanently flooded connection to the river. Sump depth varies with river stage.

A 2-m-deep trench was excavated in CAC slackwater sediments. Seven AMS-^{14}C dates were obtained from charcoal in the upper 70 cm of the trench. The ages of underlying sediments are extrapolated using a sedimentation rate calculated from the upper 70 cm (175 mm ka^{-1}). Only general conclusions are drawn from sediments below 70 cm because of age uncertainties. Each identifiable stratigraphic unit was sampled for grain size analysis (sieving). The sediments were contiguously sampled at a 2-cm interval for determination of bulk sedimentary $\delta^{13}C_{org}$. Herein, the fraction of sand present is reported and used to evaluate energy levels of the formative floodwaters. To obtain stable isotopic values for organic carbon ($\delta^{13}C_{org}$), dry sediment powders were weighed into silver capsules, repeatedly acidified with 6% sulfurous acid, and analyzed using a Costech 4010 elemental analyzer coupled via a Conflo III Device to a ThermoFinnigan DeltaPlusXP isotope-ratio mass spectrometer (IRMS). Values for $\delta^{13}C_{org}$ are reported relative to V-PDB, and precision for the isotopic standard (USGS-24) and unknowns is <0.1‰. Temporal variations in sedimentary $\delta^{13}C_{org}$ represent a watershed-integrated record of ecological change upstream of the deposit. The $\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$ were also determined using the ThermoFinnigan DeltaPlusXP isotope-ratio mass spectrometer, although standard carbonate sample preparations were performed.

Holocene Climate Of Greenbrier River Watershed

The $\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$ values from stalagmite BCC-002 show pronounced variations during the Holocene (Fig. 4A, B). The closest published palynological record is from Cranberry Glades (Watts, 1979), located 56 km north of BCC-002 and only 5 km from the Greenbrier River watershed (Fig. 1). The bog lies at an elevation of 1024 m, which is 350 m higher than the land surface above BCC-002. Comparing BCC-002 to the bog, $\delta^{18}O_{calcite}$ values are heaviest during the mid-Holocene when hardwood pollen abundance increases (notably *Carya* (hickory), *Fagus*

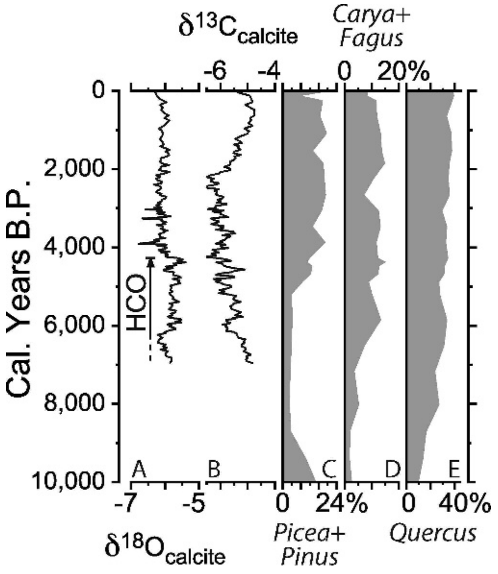

Figure 4. Slackwater stratigraphy is compared to independent paleoclimate proxies from Buckeye Creek Cave stalagmite BCC-002 (A and B; Springer et al., 2008) and Cranberry Glades pollen (C–E; Watts, 1979). The $\delta^{18}O_{calcite}$ values are heaviest (most enriched) between 4,200 and 7,000 cal. years B.P. At approximately the same time, Holocene temperatures peaked during what is known as the Holocene Climatic Optimum (HCO) (Kaplan and Wolfe, 2006). Locally, enriched $\delta^{18}O_{calcite}$ values record a warm HCO climate at BCC and Colonial Acres Caves (CAC). Declining $\delta^{18}O_{calcite}$ values after 4,200 cal. years B.P. record an abrupt cooling, after which temperatures were comparatively stable for the remainder of the Holocene (A). The $\delta^{13}C_{calcite}$ values decrease between 7,000 and 2,000 cal. years B.P., which records a general moistening or increasing precipitation (B). The abrupt enrichment of $\delta^{13}C_{calcite}$ values after 2,000 cal. years B.P. records landscape disturbances attributable to Native Americans (White, 2007; Springer et al., submitted). The warm temperatures inferred from $\delta^{18}O_{calcite}$ values are consistent with low spruce (*Picea*) and pine (*Pinus*) pollen abundances at that time (C). However, increasing abundances of hickory (*Carya*), beech (*Fagus*), and oak (*Quercus*) are attributable to the moistening recorded in the $\delta^{13}C_{calcite}$ record (D–E). Figure modified from Springer et al. (2008).

(beech), and *Quercus* (oak)), pollen abundance from sub-boreal trees (principally *Picea* (spruce)) reach a Holocene low (Fig. 4), and pollen counts of the moisture sensitive Family *Cyperaceae* (sedges) decline by several orders of magnitude and to zero for short intervals (not shown). Coincident with changes in *Cyperaceae* abundance is the appearance of *Nyssa* (tupelo) pollen in lacustrine sediments found 100 km to the east of BCC-002 (Watts, 1979; Kneller and Peteet, 1993). Tupelo prefers warm temperatures and is mostly absent from regional pollen records, except during the mid-Holocene, when values peak. Collectively, $\delta^{18}O_{calcite}$ values and pollen abundances indicate a warm mid-Holocene climate, which is recognized elsewhere as the Holocene Climatic Optimum (HCO) or Hypsithermal (Kaplan and Wolfe, 2006). The HCO began >6,500 cal. years B.P. and ended at 4,200 cal. years B.P. when $\delta^{18}O_{calcite}$ values abruptly decrease by 0.4‰ (Fig. 4A). Reported starting and ending dates of the HCO vary by region, but termination of the HCO at Buckeye Creek Cave coincides with purported mega-droughts and climatic shifts throughout the upper Midwest of the USA, northern Africa, the Middle East (see review by Booth et al., 2005), and New Jersey (Li et al., 2007).

Mid-Holocene values of $\delta^{13}C_{calcite}$ are enriched (less negative) (Fig. 4B), which suggests that soils overlying BCC-002 were drier or less productive than those of the Late Holocene (McDermott, 2004). In fact, clay mineralogies and weathering profiles of paleosols in the floodplain of a Greenbrier River tributary (41 km NNE of BCC-002) record warmer, drier conditions during the HCO (Driese et al., 2005). *Pinus* (pine) pollen abundances reach their Holocene low during the HCO, despite the existence of a strong, positive correlation between the percentage of *Pinus* pollen in modern, mid-Atlantic sediments and temperatures of the preceding January ($R^2 = 0.91$) (Willard et al., 2005). *Pinus* pollen abundances are also correlated with moisture and increase post-HCO, which is observed elsewhere along the eastern margin of North America and is attributed to a general moistening (Watts, 1979; Webb, 1987; Willard et al., 2005). Presumably, (seasonal?) soil moisture was the major HCO control on *Pinus* abundance or its pollen productivity. Post-HCO values of $\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$ are comparatively depleted (more negative) than those of the HCO, and the Cranberry Glades pollen record is dominated by tree species that favor cooler, wetter climates (Fig. 4C–E).

Summarizing the stalagmite, paleopedological, and palynological data, the HCO was warmer and (seasonally?) drier than the Late Holocene in the Greenbrier River watershed. Climate was comparatively stable throughout the Late Holocene (Fig. 4A), but Holocene values of $\delta^{13}C_{org}$ from alluvium in BCC and CAC are typical of forested landscapes (-24.5 ± 1‰) (White, 2007). Although forest composition evolves with time (Fig. 4C–E), $\delta^{13}C_{org}$ values indicate that the watershed remained heavily forested throughout the Mid- to Late-Holocene. Observed changes in $\delta^{13}C_{calcite}$ and $\delta^{13}C_{org}$ post-HCO are attributable to changes in soil productivity and respiration, but not attributable to major changes in C3 or C4 abundances (e.g., Dorale et al., 1998). However, the absence of pre-HCO data prevents interpretation of vegetation types during the Early Holocene and near the onset of the HCO.

HOLOCENE HYDROLOGY OF THE GREENBRIER RIVER

The Greenbrier River deposits slackwater sediments in CAC during intermittent floods. As a result, CAC contains a sedimentological record of stream hydrology. Sediments

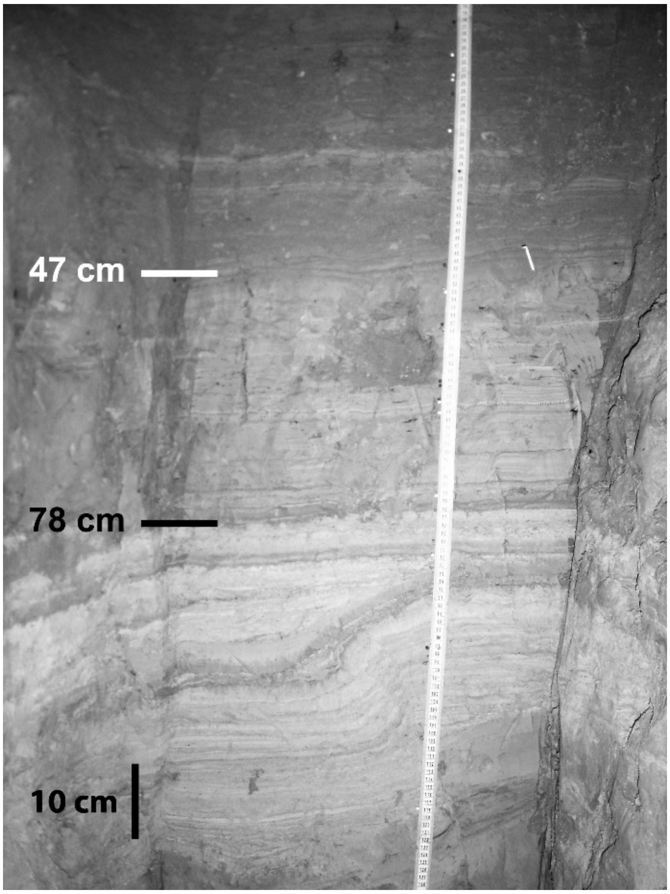

Figure 5. Three major units can be recognized in the slackwater sediments excavated in Colonial Acres Cave. These consist of sands (pale lower unit), which are overlain by dense, clayey silts (47 to 78 cm). The black, horizontal line indicates their contact. The white line highlights the contact between the clayey silts and overlying sandy silts and silty sands. All units are laminated and have undergone minimal bioturbation, although the lower sands underwent soft sediment deformation as they subsided into an underlying clay unit. The latter is not visible in this photograph. Contrast has been digitally enhanced to make the laminations and bed contacts more easily visible.

are excellently preserved and consist of laminated silts and sands, which have undergone minimal bioturbation (Figs. 5 and 6). However, the sedimentological record is censored. At present, the slackwater deposit is only inundated after river stage exceeds ~4 m and there are no high water marks correlative to individual slackwater beds because the most recent flood obliterated the high water mark of the previous flood, as that flood did to its predecessor's, ad infinitum. However, as will be shown, the censored record can be used to determine whether the cave was permanently or only intermittently flooded at particular points in time.

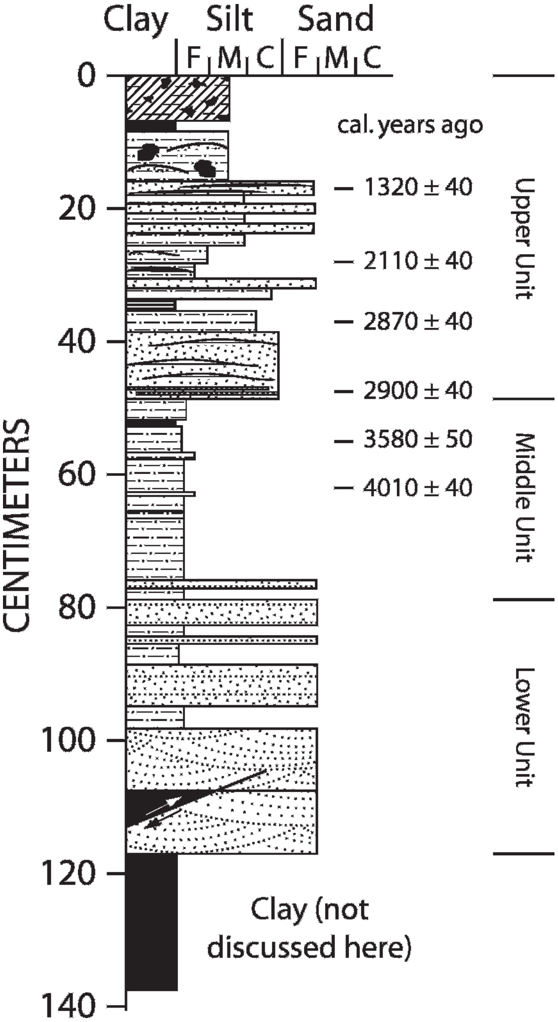

Figure 6. Sieving and pipette-withdrawal were used to determine the particle sizes of each significant bed in the Colonial Acres Cave (CAC) trench, and these results are the basis for this stratigraphic column. A clayey silt (48 to 75 cm) separates the lower sands (75 cm to 118 cm) from the younger sandy silts and silty sands (0 to 48 cm). Based upon AMS-^{14}C ages of charcoal (positions as indicated), deposition of the clayey silt ended at ~3,500 cal. years B.P., which we attribute to incision of the Greenbrier River below CAC. Ultimately, the trench was dug to a depth of 200 cm, which revealed soft clays (>118 cm) below the sand unit and a basal layer of river cobbles (not depicted). Unfortunately, repeated collapses of the lower trench face prevented detailed investigation of the clays and cobbles.

The slackwater sediments can be divided into three principle units: 0–47 cm, 47–78 cm, and >78 cm (Figs. 5–7). Short horizontal lines demarcate the boundaries between the units in Figure 5. The upper two units record very different hydrologic regimes. The capping unit of silts and sandy silts contains partially articulated bat bones along with other vertebrate bones and organic detritus. Deposition of these sediments began at ~3,500 cal. years B.P. and has continued to present. The bat bones demonstrate that the Greenbrier River has been below the observed slackwater

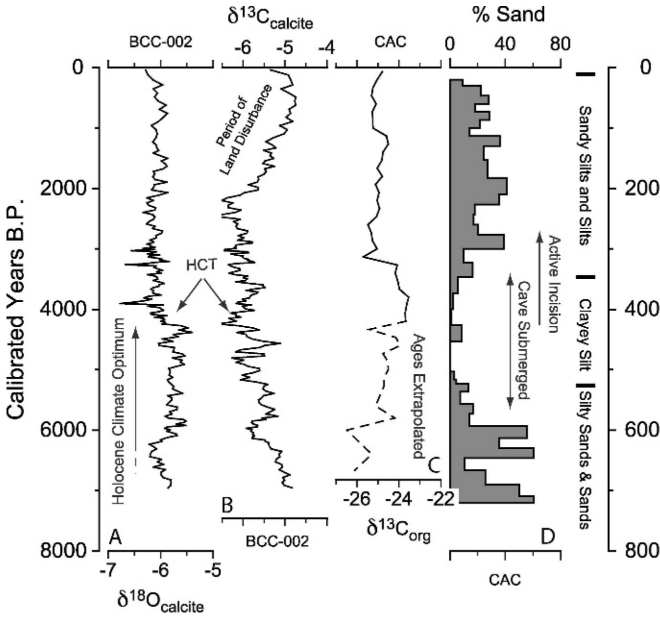

Figure 7. Paleoclimate proxies ($\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$) from stalagmite BCC-002 (A and B) are compared to data obtained from the Colonial Acres Cave (CAC) slackwater sediments (C and D). Note that sample ages from CAC are estimated below 4,000 cal. years B.P. using a sedimentation rate calculated for the upper, age-dated portion of the trench. And only six $\delta^{13}C_{org}$ values were obtained from CAC sediments below 5,000 cal. years B.P. Ignoring the period of land disturbance, $\delta^{13}C_{calcite}$ and $\delta^{13}C_{org}$ values were most enriched during the mid-Holocene and values decrease thereafter as the climate moistened (B and C). Submergence of CAC began prior to 5,000 cal. years B.P. and, assuming a low sedimentation rate for the clayey silts (see text), submergence probably began before the local Holocene Climatic Optimum (HCO)(A). Deposition of the clayey silt ended ~3,500 cal. years B.P. (D), and the overlying silts and sands contain abundant bat bones indicating incision of the river below the cave.

sediments since ~3,500 cal. years B.P. Today, there are extensive bedrock exposures in the channel banks and bed, and this bedrock channel morphology has probably existed for much of the last 3,500 years.

The clayey silts deposited prior to ~3,500 cal. years B.P. are devoid of bones and visible organic matter is rare. However, the clayey silts do contain insoluble cm-scale bedrock chips derived from thin claystone dikes in the cave ceiling. Paleozoic, coarsely crystalline marine fossils, such as blastoid thecas, are also present and derived from the host limestone. The coarsely crystalline fossils dissolve slower than the fine-grained limestone and stand in relief on existing cave walls and ceilings. Shale fragments and fossils found in the slackwater sediments fell or sank after the surrounding limestone was dissolved. Concentration of low solubility particles is a slow process and occurs when cave passages are permanently flooded and where sedimentation rates are slow (Reams, 1968; Springer et al., 1997). The corresponding depositional environment exists below low-water river surfaces and its products are known as backswamp or quietwater sediments (Springer et al., 1997; Bosch and White, 2003).

The clayey silts were deposited while the low-water surface of the Greenbrier River was higher than the cave room. In addition to the backwater sedimentological features, this conclusion is supported by the absence of terrestrial animal bones, desiccation features (e.g., mudcracks), and organic detritus such as has been carried into the cave by post-3,500 cal. years B.P. floodwaters. As an alternative hypothesis, all conduits connecting the cave and river could have been plugged during deposition of the clayey silts. This could have produced sustained backflooding. However, we reject this idea because of the improbability of every possible opening in a karstified riverbank being plugged such that a flooded cave could exist within meters of an open cliff. The simplest interpretation is that all openings were themselves permanently flooded, which would only be possible if base level were higher than present. Base-level rise is most commonly accomplished by sediment infilling a channel (aggradation).

Laminated and cross-bedded sands containing some visible organic detritus underlie the clayey silts (Figs. 6 and 7). Cross-bed orientations indicate that flow entered the room from the 210-m-long entrance passage and sediments prograded across the room floor. Currently, the floor of the first 100-m of the entrance passage consists of cross-bedded sands largely devoid of organic detritus, but overlain by woody flotsam. Presumably, the sands underlying the clayey silt in CAC were deposited in a manner similar to the modern sands, and were the product of episodic flooding above the low-water surface of the Greenbrier River.

In conclusion, the low-water surface of the Greenbrier River was below CAC during deposition of the lower sands, but subsequently aggraded above the cave (Fig. 8). The river re-incised below CAC at ~3,500 cal. years B.P. and has remained below the cave since then. BCC-002 and CAC values of $\delta^{13}C_{calcite}$ and $\delta^{13}C_{org}$, respectively, decrease after ~4,000 cal. years B.P. The enriched $\delta^{13}C_{calcite}$ and $\delta^{13}C_{org}$ values continue beyond the period of record, which suggests that deposition of the lower sands occurred during or prior to the HCO. Given the order of magnitude of the previously calculated sedimentation rate, deposition of the clayey silt probably began during the Early Holocene or the earliest part of the HCO. Thus, CAC slackwater sediments record a major aggradational event (≥4 m) in the Greenbrier River during the Early Holocene.

SUMMARY DISCUSSION

The Greenbrier River aggraded no later than the Early Holocene and may have begun aggrading during the Late Pleistocene. The implied increase in the sediment supply

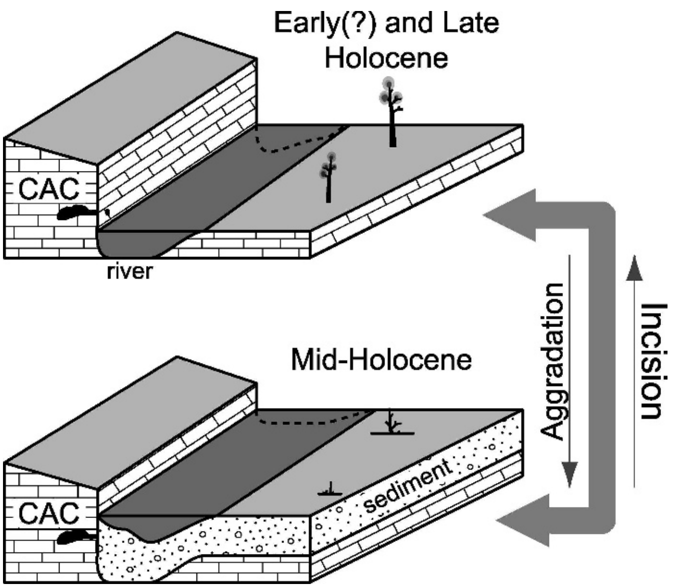

Figure 8. The sequence of events we interpret to have occurred begins with Colonial Acres Cave (CAC) lying above the Greenbrier River, which presumably had a bedrock channel morphology (upper diagram). Subsequently, the channel aggraded as a wetter Holocene climate allowed Pleistocene-age colluvium to be remobilized and carried into the river where transport capacity was initially less than sediment input, resulting in aggradation. The channel infilling may have created an alluvial channel morphology (bottom diagram). Eventually, the sediment wave was transmitted downstream and the river incised below CAC during the Late Holocene (upper diagram). This sequence of events is known to have occurred elsewhere in the Appalachians (Eaton et al., 2003).

may be the result of the Late Pleistocene-Holocene climatic transition. The Wisconsin Glaciation peaked ~20,000 cal. years B.P., and evidence for periglacial activity during the Wisconsin of the Appalachian and Blue Ridge Mountains is widespread (Gardner et al., 1991; Eaton et al., 2003; Mills, 2005; Nelson, et al., 2007). The associated pre-Holocene sedimentary deposits are commonly preserved at the bases of hillslopes where they are susceptible to remobilization by streams. The deposits reached valley bottoms via slope wash, solifluction, and gelifluction while climate was considerably cooler than present. The lower elevation limit for such periglacial activity at Mountain Lake, Virginia (50 km southeast of CAC) was ~800 m amsl (Nelson et al., 2007). Most ridges and mountaintops within the Greenbrier River watershed exceed that elevation, and well-developed periglacial landforms are present at 650 m amsl in the Buckeye Creek watershed.

Appalachian hillslope sediment production was enhanced by periglaciation during the Late Pleistocene (Gardner et al., 1991; Eaton et al., 2003; Mills, 2005), but regional palynology indicates that the Late Wisconsin climate was very dry (Kneller and Peteer, 1993). Therefore, it is entirely possible that the enhanced sediment production was not matched by an increase in the sediment transport capacity of regional streams and rivers. Under such a scenario, excess colluvium would have accumulated throughout much of the Greenbrier River watershed prior to the Holocene. The observed post-Pleistocene moistening of the region would have necessarily led to low-order streams remobilizing the accumulated regolith (cf. Eaton et al., 2003) and a large influx of sediment into the Greenbrier River. This sediment influx is probably the cause of the aggradational event recorded in CAC sediments.

We lack the means to establish the depth of infilling of the Greenbrier River channel at CAC. But the distinctive clayey silts associated with submergence are found 4 m above the low water surface of the modern Greenbrier River, which establishes a minimum depth of aggradation. Such infilling would have resulted in an alluvial channel morphology (Fig. 8), although bedrock exposure in pools cannot be ruled out. Significantly, the river began to incise through the accumulated sediments sometime during the Holocene Climatic Optimum (HCO) and incised below CAC by 3,500 cal. years B.P. Climate has moistened since the HCO (Figs. 4 and 7), which has presumably led to an increase in sediment transport capacity.

So, how will the Greenbrier River respond to Global Warming? Climate modelers predict (locally) decreasing runoff as Global Warming advances (Arnell, 2003). If we assume that decreasing runoff will lessen sediment transport capacity in the Greenbrier River, we must conclude that there is the potential for aggradation and morphological change. However, it is possible that heavy or extreme precipitation events may become more common as a result of Global Warming (Emori and Brown, 2005). If so, this could result in a net increase in transport capacity and no aggradation. Thus, it is premature to predict aggradation or incision.

Uncertainties about the future aside, the history of the Greenbrier River offers important insights into the long-term behavior of Appalachian rivers and hillslopes. Late Pleistocene climate variability resulted in significant channel infilling. The accumulated sediments were not fully excavated from the Greenbrier River channel until as late as 3,500 cal. years B.P., or roughly 16,000 years after the last glacial maxima (Webb, 1987). Interestingly, the Greenbrier River was already incised to its present elevation well before the last glacial maxima, and it is probable that very little net incision has occurred in tens of millennia. Incision may occur episodically during and immediately following interglacials, when precipitation totals are high or heavy precipitation events more common. This raises many questions concerning the usefulness of long-term incision rates calculated using paleomagnetic and cosmogenic isotopic data. These latter estimates require averaging incision over many hundreds to thousands of millennia (e.g., Springer et al., 1997; Anthony and Granger, 2004; Anthony and Granger, 2006), so their estimates of actual millennial-scale incision rates may be off by many orders of magnitudes.

FUTURE DIRECTIONS

Stable isotopic records of paleoclimate from speleothems are rapidly becoming available throughout the world. As our study demonstrates, such records can be combined with traditional studies of slackwater stratigraphy to infer past effects of climate change on rivers. As such, there will soon be many opportunities to directly determine relationships between climate and hillslope and fluvial processes. However, such studies will be dependent upon fortuitously situated caves capable of recording the behavior of adjacent surface channels because surficial deposits are rapidly destroyed in many climatic settings (Kite et al., 2002; Springer, 2002). Combined with the subterranean origin of stalagmitic paleoclimate records, we foresee karst studies achieving prominent roles in geomorphology and climatology and encourage others to advance our methodology.

ACKNOWLEDGMENTS

The authors thank Tom Gardner and an anonymous reviewer for helpful suggestions that improved the manuscript. We thank Gene Turner for access to Buckeye Creek Cave and the West Virginia Association for Cave Studies for fieldwork assistance.

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