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Incision history of Glenwood Canyon, Colorado, USA, from the uranium-series analyses of water-table speleothems

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Abstract:

Uranium-series analyses of water-table-type speleothems from Glenwood Cavern and “cavelets” near the town of Glenwood Springs, Colorado, USA, yield incision rates of the Colorado River in Glenwood Canyon for the last ~1.4 My. The incision rates, calculated from dating cave mammillary and cave folia calcite situated 65 and 90 m above the Colorado River, are 174 ± 30 m/My for the last 0.46 My and 144 ± 30 m/My for the last 0.62 My, respectively. These are consistent with incision rates determined from nearby volcanic deposits. In contrast, $\delta^{234}\text{U}$ model ages (1.39 ± 0.25 My; 1.36 ± 0.25 My; and 1.72 ± 0.25 My) from three different samples of mammillary-like subaqueous crust collected from Glenwood Cavern, 375 m above the Colorado River, yield incision rates of $271 +58/-41$ m/My, $277 +61/-42$ m/My, and $218 +36/-27$ m/My. These data suggest a relatively fast incision rate between roughly 3 and 1 Ma. The onset of Pleistocene glaciation may have influenced this rate by increasing precipitation on the Colorado Plateau starting at 2.5 Ma. Slowing of incision just before 0.6 Ma could be related to the change in frequency of glacial cycles from 40 to 100 kyr in the middle Pleistocene. This interpretation would suggest that the cutting power of the Colorado River prior to 3 Ma was smaller. An alternative interpretation involving tectonic activity would invoke an episode of fast uplift in the Glenwood Canyon region from 3 to 1 Ma.

Keywords:

incision rate; Colorado River; mammillary; uranium-series; speleothem; folia

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INTRODUCTION

Certain speleothem types form close to water tables, and our previous study of these water-table-type speleothems showed paleo-water tables in eastern and western Grand Canyon that supported the interpretation for pre-Colorado River western Grand Canyon development (Polyak et al., 2008). That study supported two stages of Grand Canyon evolution: an older Western Grand Canyon that was partially cut slowly by a more localized river, and a younger Eastern Grand Canyon that was carved by the modern-day Colorado River. By the same means, here we provide an incision history of the Colorado River in Glenwood Canyon, Colorado, USA, situated on the northeastern edge of the Colorado Plateau. Previous results based on volcanic rock data indicate an incision history for Glenwood Canyon that goes back 10 Ma (Bryant et al., 2002; Kunk et al., 2002; Aslan et al., 2010). These studies give conflicting results

on whether the incision rates were stable (steady state) or dynamic (varying with time). Our speleothem-based results help resolve the conflict. Here, on the basis of radiometric ages of pre-existing basalt and ash, and supported by new speleothem uranium-series ages we propose an incision history that favors the dynamic interplay between tectonic uplift and climate-driven acceleration of incision.

Water-table-type speleothems used in this study, and in our previous work in Grand Canyon, include mammillary coatings, folia, cave rafts, and gypsum rinds (Hill & Forti, 1997; Davis, 2012). In both of these study areas these are found in intimate association with each other in settings not associated with vadose dripstones and flowstones in caves and “cavelets” (caves too small for human entry) that have formed by hypogene speleogenesis, a process described by Klimchouk (2007) and Palmer (1991, 2007). In other words, these speleothem types are found in contexts that make them relevant to the dating of water-table levels.

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Two sites along the Colorado River in Glenwood Canyon are Glenwood Cavern (375 m above the river) and surface-exposed “cavelets” near the city of Glenwood Springs (65 and 90 m above the Colorado River). Uranium-series (U-series) dating of samples from these sites has produced a record of incision that goes back about 1.4 My.

Glenwood Canyon and Glenwood Cavern

Glenwood Canyon is located in west-central Colorado where the south end of the broad, elongate dome of the White River uplift is intersected by the southwest-flowing Colorado River (Fig. 1) (Kirkham et al., 1996). Downcutting by the Colorado River incised Glenwood Canyon into the southern part of the uplift, exposing progressively older Paleozoic and Precambrian rocks toward its core. The west side of the White River uplift is bounded by the Grand Hogback monocline (Fig. 1), which marks the east edge of the Piceance basin and is also the boundary between the Rocky Mountain orogenic province and the Colorado Plateau. West of the city of Glenwood Springs, the Colorado River flows obliquely through the Grand Hogback monocline, cutting across progressively younger strata toward the Piceance basin to the west (Fig. 1), where Eocene strata are exposed. The Colorado flows into Utah where it is joined by the Green River, then continues southwestward through the Grand Canyon to the Gulf of California.

Iron Mountain, north of the town of Glenwood Springs, is a prominent topographic feature comprised of south-dipping, mostly pre-Pennsylvanian carbonate and clastic strata resting on Precambrian crystalline rocks. The dip slope on the south side of Iron Mountain is composed of Leadville Limestone and contains numerous caves, including Glenwood Cavern (Fig. 1). In this area, the Leadville Limestone is a 61-m-thick unit composed of gray to bluish-gray, coarse to finely-crystalline, fossiliferous limestone with abundant chert nodules in the lower part (Kirkham et al., 1997). In Iron Mountain, it is locally altered to hydrothermal dolomite (Inden & Humphrey, 2002; DuChene, 2011). The upper surface of the Leadville is an unconformity overlain by gray to black shale and conglomerate of the Pennsylvanian Belden Formation. The Leadville rests unconformably on the Gilman Sandstone of the Upper Devonian Chaffee Group (Kirkham et al., 1997). In the Colorado River and Roaring Fork valleys

at Glenwood Springs, downcutting and erosion removed most of the less-resistant Pennsylvanian and younger strata, exhuming the more resistant Mississippian Leadville Limestone on the southwest-dipping limb of the Grand Hogback monocline. Near the top of Iron Mountain, small patches of Belden Formation are preserved, and there are deposits of gravel that contain rounded pebbles and cobbles of mixed lithologies (Kirkham et al., 1997)

Limestone dissolution that formed Glenwood Cavern occurred in a mixing zone where rising thermal waters containing dissolved carbon dioxide (CO_2) and hydrogen sulfide (H_2S) merge with oxygenated water near the Colorado River; this process is probably active at present in younger cavities at the base level. There are twelve hot springs and six seepage areas along the Colorado River on the north side of Glenwood Springs. These springs and seepage areas cumulatively discharge hot water at a rate that ranges from 15–19 m^3/sec . Springs issue from either the Leadville Limestone or from overlying alluvium. The springs are supplied by water migrating up through fractures and faults and emerging from the Leadville Limestone (Barrett & Pearl, 1978; Gelden, 1989, page 20-21). Water temperatures range from 44° to 47°C (Gelden, 1989, p 71). Water from two test wells on the north side of Glenwood Springs near the Colorado River contains dissolved H_2S ranging from 1.2 to 2.1 mg/L. A CO_2 concentration of 110 mg/L was reported in water from one of these wells (Gelden, 1989, Table 3, p. 32-33).

Glenwood Cavern (formerly Fairy Cave) is developed in the Leadville Limestone near the top of Iron Mountain (Fig. 1). The historic Fairy Cave entrance is near the top of the mountain and the highest point in the known cave is at 2,156 m (7,073 ft) elevation, 399 m (1,309 ft) above the Colorado River. The cavern has 4.83 km (3.0 mi) of known passage and vertical relief of 84.7 m (278 ft) (Anderson & Barton, 2002). The Leadville Limestone in Glenwood Cavern dips 40° southwest (Kirkham et al., 1997). The cavern is of phreatic origin, formed primarily by dissolution of calcium carbonate by carbonic acid, but with a late-stage secondary overprint from sulfuric acid dissolution. Most of the limestone dissolution took place in rising water that contained carbonic acid from dissolved CO_2 , as well as sulfuric acid from the mixture of hypogenic H_2S and O_2 -rich meteoric water. Nearby examples of deeply corroded Leadville Limestone are located in quarry faces at the foot of Iron Mountain, north of the Colorado River, where joints have been enlarged by dissolution and later filled with river gravel.

While caves were enlarging at depth by calcite dissolution, much carbon dioxide was simultaneously lost to the atmosphere near the water table. This caused near-surface water to become supersaturated with respect to calcite, resulting in subaqueous deposition of calcite crusts that were mammillary-shaped and therefore referred to as mammillary layers. In the upper levels of the cave, fluctuations in water level and/or water chemistry interrupted calcite deposition, resulting in deposition of multiple stacked mammillary layers. Typical mammillaries in Glenwood Cavern range from 9 to 10 cm thick (Fig. 2).

Base level in this area gradually fell in response to downcutting by the Colorado River. As this occurred, progressively deeper phreatic cave passages became air-filled over time. At the water table, H_2S escaped into the

Fig. 1. Glenwood Canyon is located in west-central Colorado, USA at the eastern margin of the Colorado Plateau.

overlying cave atmosphere, to be reabsorbed into films of oxygenated meteoric and condensation water on gallery walls and other surfaces. Here, the H_2S was converted to sulfuric acid, which rapidly reacted with the calcite mammillaries and limestone and partially altered them to gypsum. Most of this gypsum was dissolved by water that partly filled passages and was transported out of the cave. In protected areas where there is little seepage of meteoric water, gypsum crust on passage ceilings, walls and floors is preserved (DuChene et al., 2003). This process has been documented in active sulfuric acid caves, such as Cueva de Villa Luz in Tabasco, Mexico (Hose et al., 2000).

The mixing zone where most limestone dissolution occurred was at or near the water table. As the water table dropped in response to lowering of base level, the mixing zone (and zone of limestone dissolution) also dropped. Consequently, the oldest cave passages are topographically highest, and they become progressively younger with depth.

On the basis of U-series dating of wall crusts in Wind Cave, South Dakota, Ford et al. (1993) suggest that calcite deposition took place over a vertical range of roughly 70 m below the water table. However, this estimate is based on the downward increase in calcite solubility with pressure, rather than by CO_2 degassing. The mammillary crusts described in our paper show strong evidence for having formed in response to degassing of CO_2 in rising water, which

would concentrate calcite deposition within a few meters of the water table.

“Cavelets” above Colorado River near Glenwood Springs

At the downriver end of Glenwood Canyon, just upstream from the town of Glenwood Springs, the Colorado River is cutting through the Leadville Limestone, where it is about 60 meters (200 ft) thick. At river level, thermal springs, issuing from the Leadville, are presently dissolving small phreatic and water-table caves such as those in the Yampah Spa Vapor Caves. Upriver, the limestone along the rims of Glenwood Canyon rises steeply in a series of cliffy southwestward-dipping blocks, offset by a series of faults. Along these faults and associated fractures are a number of such caves and associated smaller cavities, now abandoned by water flow, which increase in age upward in the canyon walls.

Our model, modified from Polyak et al. (2008), has these caves forming from water originally aggressive to calcite at moderate depths below the water table, with the water chemistry shifted to depositional near and at the water table before the water table dropped below the cavities, resulting in linings of subaqueous calcite mammillary coating below the water surface. As the water table descended through these cavities, calcite precipitated at the fluctuating water surface, accreting to the walls as small-scale calcite folia (downsloping, interleaved calcite shelves projecting up to ~2 cm out from the bedrock walls). At the same time, piles of calcite rafts accumulated. Examples of these speleothems are shown in Fig. 3.

Most of these cavities were solution pockets and crevices that never grew large enough for human entry

Fig. 2. Mammillary calcite in Glenwood Cavern. a) remnant mammillary layer after partial collapse of the cave wall. The mammillary calcite coats recesses in the wall; b) mammillary coating of a vug in the artificial access tunnel to the cave (photos by V.J. Polyak).

Fig. 3. Cave mammillaries, folia, and rafts exposed on the surface in association with cavelets (photos by A.N. and M.V. Palmer).

before the time of speleothem growth—hence our designation as “cavelets.” However, many of them are now being exposed by cliff retreat and incision of steep gullies tributary to Glenwood Canyon. This erosion process is baring some of the previously hidden cave deposits at the present surface, where they are accessible in the partially dissected cavities. Those sampled for this study are along southwest-facing ledges of a steep ravine about 1 km northeast of Glenwood Springs and 65 to 90 m above present river level.

Incision History of Glenwood Canyon

Mechanisms that drive fluctuations in incision rates of rivers in the western United States are generally considered to be related to tectonic activity, climate change, or a blend of both (Dethier, 2001). Based on Lava Creek B ash deposition in the western United States, incision rates of rivers in the Glenwood Canyon region averaged 100 and 150 m/My over the last 0.6 My (Dethier, 2001). Dethier favored increased fluvial cutting power during the late Pleistocene due to increased glacial runoff rather than epeirogenic uplift as a way to explain these seemingly high incision rates. It has recently been suggested that mantle/crust processes (more specifically, removal of lithospheric crust below the Colorado Plateau from the margins inward), resulted in Pliocene uplift of the Plateau, explaining higher incision rates (>100 m/My) on the Plateau and volcanic activity around the margins of the Plateau during this period (Levander et al., 2011). Incision rate history of Glenwood Canyon is based on Miocene and Pliocene basalt flows and the Lava Creek B ash bed, all located near the head of Glenwood Canyon near the town of Gypsum (Fig. 1). Bryant et al. (2002) and Kunk et al. (2002) reported an incision history that covers the last 8 My based on a 7.8 Ma basalt that cap what they interpret to be Colorado River gravels on Spruce Ridge about 5 km south of Glenwood Canyon, as well as a 3.0 Ma basalt capping valley sediments on Gobbler Knob about 2 km east of the Spruce Ridge locality, and a 1.4 Ma basalt capping stream sediments on Triangle Peak towards Aspen, Colorado, near the town of Basalt (Fig. 1). The Gobbler Knob basalt is interpreted to have been deposited onto sediments close to Colorado River level. The Triangle Peak basalt is interpreted to have been deposited over sediments that were close to the level of the Roaring Fork River. These data produce a dynamic history of incision, with slow incision rates from 8 to 3 Ma (~25 m/My), and faster incision rates from 3 to 0.6 Ma (240 to 290 m/My). The Lava Creek B ash at the head of Glenwood Canyon (Dethier, 2001; Aslan et al., 2010) of 140 m/My indicates a slowing of incision over the last 0.64 My, relative to incision rates derived from the 3.0 and 1.4 Ma basalts. Aslan et al. (2010) point out that the 3.0 and 1.4 Ma basalts on Gobbler Knob Ridge and Triangle Peak are not capping actual Colorado River sediments, and seemingly favor a more static incision history (110 m/My) for the last 8 My. Independent dates in the 1–6 My interval would allow us to distinguish between the two competing models. In other parts of the Colorado Plateau, such as the Grand Canyon (Polyak et al., 2008), speleothems sensitive to

water table position have provided decisive data. The caves and karst features of Glenwood Canyon contain these same speleothem types. Here we demonstrate the potential for determining incision-rate histories from these speleothem types using U-series analyses.

Cave sediments (chemical and clastic) as indicators of landscape evolution

Studies of caves are producing impressive records of river incision and landscape history. Absolute $^{26}\text{Al}/^{10}\text{Be}$ dating of cave sediments has been used in Mammoth Cave, Kentucky, USA, and in caves of the nearby Cumberland Valley in Tennessee, to record changes in base level of local rivers, and headward incision of river tributaries caused by a resistant sandstone bed (Granger et al., 2001; Anthony & Granger, 2004). A similar technique has been used to determine incision-rate histories in the Sierra Nevada Mountains of California and in the Bighorn Mountains of Wyoming and Montana, USA (Stock et al., 2004; 2006), and to reconstruct the valley incision history for Aare Valley, Switzerland (Haeuselmann et al., 2007). U/Pb dating of water-table-type speleothems was used to determine paleo-water tables in Grand Canyon, Arizona, USA (Polyak et al., 2008). Speleothems in Grand Canyon caves include mammillary calcite, folia, rafts, and gypsum rinds, which are all related to the final phases of hypogene speleogenesis. Glenwood Canyon exhibits the same suite of speleothem types.

Mammillary crusts

Of the water table type speleothems, mammillary crusts are the most essential to this type of study because they are thicker and therefore the calcite in their interior is more likely to be preserved. Preservation of calcite/aragonite is necessary to obtain the U/Pb chronology for these studies. Equally essential is the geochemical model that explains the origin of mammillary crusts and the near-water table environment in which they form.

Mammillary calcite crusts on cave walls are generally produced by the escape of CO_2 from rising groundwater at and just below the water table. The source of dissolved calcite can be anywhere along the groundwater flow path. As the water rises from depth it cools, and the solubility of calcite increases because its dissolution is an endothermic reaction. However, as the water approaches the water table, the hydrostatic pressure decreases enough to allow CO_2 degassing and calcite precipitation. Bubbling of the dissolved gas takes place when its partial pressure exceeds the static pressure of the surrounding water. The CO_2 partial pressure (P_{CO_2}) in typical karst groundwater ranges from roughly 0.01 to 0.1 atm, but in deep groundwater values of 1.0 atm or more are possible. Spontaneous degassing of CO_2 is limited to a depth of roughly 10 m below the water table for each atmosphere of partial pressure. At typical values of P_{CO_2} , therefore, calcite precipitation in rising groundwater is limited to a zone that extends no more than a few meters below the water table. Calcite precipitation can also be enhanced slightly by upward diffusion of dissolved CO_2 along the concentration gradient.

Calcite mammillaries deposited in this way can be considered a valid proxy for former positions of the water table. Their vertical positions along canyon walls of highly permeable carbonate rocks, as in Glenwood Canyon, should correlate closely with contemporaneous levels of fluvial entrenchment.

Globally, the most thoroughly studied cave mammillaries are those of Devils Hole, Nevada, a narrow tectonic fissure that extends at least 140 m below the water table. Over that entire depth the walls are lined with calcite mammillaries up to 40 cm thick, and one core from this deposit provided a continuous paleoclimate record beginning at 560 ka (Winograd et al., 1992). Deposition ceased at 60 ka, even though the fissure remained water-filled. Studies of additional cores have provided most of the missing 60 ka of record (Spötl & Dublyansky, 2012). Measurements by Plummer et al. (2000) show that the present groundwater has $P_{\text{CO}_2} = 0.016$ atm and is only slightly supersaturated with calcite (saturation index = +0.16 to +0.21, calculated as $\log[\text{ion activity product}/K_{\text{calcite}}]$). The P_{CO_2} value is within the normal range for shallow groundwater but at least an order of magnitude less than that of most rising hypogenic water (Palmer, 1991). Above the present water table are relict calcite mammillaries, as well as folia, flowstone, and evaporative botryoids (“cave popcorn”), which provide evidence for Pleistocene water-table fluctuations (Kolesar & Riggs, 2004). Mammillaries with such a large vertical extent are rare. However, contrary to our interpretation of those in Glenwood canyon, the mammillaries in Devils Hole appear not to have formed by rising groundwater, or that at present any rising component is minor and diluted. The Devils Hole fissure appears to be simply a window into a horizontal part of the flow system, rather than a conduit for rising high- P_{CO_2} water. The Devils Hole recharge area is estimated to extend more than 100 km to the northeast, while the nearest discharge area is located about one kilometer to the southwest (Winograd et al., 1992). Thus Devils Hole does not provide a close modern analog to the Glenwood model for mammillary deposition, because its recharge is largely lateral, rather than upward as is probable for the recharge to Glenwood Canyon.

Calcite wall crusts can also be deposited in vadose cave pools above the water table. However, in contrast to phreatic mammillaries, these deposits show evidence for deposition by inflowing gravitational water, such as gravitationally-oriented stalactitic growths that have been engulfed by calcite deposited in perched pools. Vadose pool deposits also tend to be rimmed by prominent shelves of calcite that have grown inward from their shorelines along pool surfaces. Shelfstone of this type requires that water levels be stabilized by long-lived thresholds composed of sediment deposits, piles of collapse material, or barriers of chemical precipitates. Rising phreatic water seldom produces such shelves because of the relatively great amplitude and frequency of water-table fluctuations.

Folia

The presence of calcite folia in close proximity to mammillaries helps to support the water-table interpretation of the deposits analyzed for this study. All known examples of actively forming calcite folia are located at or near the surfaces of cave pools where CO_2 degassing is active (Hill & Forti 1996).

The origin of folia is considered to be the accretion of adherent particles at a fluctuating interface, and that interface is not strictly restricted to the water-table environment (Davis, 2012). Our setting necessitates modifying this definition to include chemical precipitation as a supplement to accretion of adherent particles as explained in Fig. 4. The folia in Glenwood Canyon, like those of Grand Canyon, are intimately associated with mammillaries, rafts, and gypsum rinds (in Glenwood Cavern). Furthermore, in hypogene speleogenesis in carbonate rocks, the folia fit the water-table environment. In Glenwood Canyon, the processes involved in forming the water-table-type speleothems are not far removed in both space and time from the Glenwood hot springs, which are an active example of the process that forms the caves and these speleothem types.

Dating of these associated speleothem types can produce a history of paleo-water tables. This is possible if the samples are sufficiently thick, densely crystalline, and well preserved. Mammillary calcite is useful in this respect, but folia are rare and small, making them more vulnerable to alteration. The sample of folia used in this study is relatively young and still well preserved, as shown in Fig. 4. In Grand Canyon, the water-table speleothems are too old for typical U-series dating, so the U/Pb dating method was applied, in some instances along with the $^{234}\text{U}/^{238}\text{U}$ geochronometer (Polyak et al., 2008). However, our study of Glenwood Canyon incision was accomplished using U-series dating alone.

Fig. 4. Thin section of Glenwood Canyon folia. Note the growth layering. Petrographic examination shows fibrous calcite. Dissolution of calcite in the lab revealed only trace amounts of detrital material (photo by V.J. Polyak).

RESULTS

Results from "cavelets"

A sample of thick mammillary calcite located 65 m above the Colorado River was dated twice with ^{234}U - ^{230}Th (uranium-series) dating. See Asmerom et al. (2010) and Cheng et al. (2013) for methods and improved ^{234}U and ^{230}Th half-lives. The two subsample powders from this sample contained 0.5 to 1 parts per million (ppm) of uranium (U), and less than 500 parts per trillion (ppt) of thorium (Th), making the calcite very suitable for U-series dating. The ages were 357 ± 8 , and 363 ± 5 ka. At $65 \text{ m} \pm 10 \text{ m}$ above the river, the apparent incision rate of the Colorado River over this time period is $174 \pm 30 \text{ m/My}$. A sample of folia at 90 m above the river produced a U-series age of $623 +67 -47 \text{ ka}$, and yielded an incision rate of $144 \pm 30 \text{ m/My}$. A sample of cave rafts also at 90 m above the river yielded a U-series age of $462 \pm 23 \text{ ka}$, and a maximum incision rate of $199 \pm 20 \text{ m/My}$. The mammillary crust and folia are more likely linked to the paleo-water table, and incision rates generated by these agree with each other within their reported errors and show an average incision rate of Glenwood Canyon by the Colorado River of 160 m/My over the last 650,000 years.

A uranium evolution curve was generated for these data to test for open-system behavior. This test showed no obvious anomalies (Fig. 5), and the calcite of the samples chosen for U-series analyses shows no physical evidence of alteration or diagenetic effects. We avoided portions of samples that exhibit evidence of re-solution or surface hydration.

The incision rate estimated from the cave rafts is higher and just beyond the 2σ absolute error of the mammillary and folia incision rates. While cave rafts are considered in this paper to be water-table-type speleothems, they also commonly form in calcite-saturated pools of all types. Our anomalously higher incision rate from the cave raft data may indicate that they formed on vadose pools fed by infiltrating

water rather than at the water table. Also, cave rafts are essentially two-dimensional speleothems and therefore more prone to alteration.

A coating of calcite with a slightly more brownish color was collected in the cavelet setting. Other than the slight color difference, the coating resembled a mammillary. For this sample we obtained two U-series ages, within the 2σ absolute error margin of each other, 148 ± 1.4 and $147 \pm 0.7 \text{ ka}$. These ages are significantly younger than the mammillary crust and folia and suggest that this deposit is a thin flowstone or vadose pool deposit. The brownish color probably indicates soil-derived organic material in the calcite.

Results from Glenwood Cavern

Samples from Glenwood Cavern contained only 0.5 to 1.0 ppm U and too much lead (Pb) (1 ppm) for U-Pb dating of such young samples. However, U-series analyses of GC-2011-1, GC-HD1, and GC-HD2 produced $^{234}\text{U}/^{238}\text{U}$ activity ratios (number of atoms of an isotope times its decay constant) of 1.040 ± 0.001 , 1.044 ± 0.001 , and 1.016 ± 0.001 , also expressed as $\delta^{234}\text{U}$ in permil (‰), 40‰, 44‰, and 16‰, respectively, where $\delta^{234}\text{U} = (^{234}\text{U}/^{238}\text{U}_{\text{activity}} - 1) \times 1000$ (Cheng et al., 2000). The ^{230}Th - ^{234}U data indicate that the samples are too old for ^{230}Th - ^{234}U chronology, $> \sim 600 \text{ ky}$. However, model ages can be generated using the $^{234}\text{U}/^{238}\text{U}$ geochronometer if the initial $\delta^{234}\text{U}$ value can be estimated and used in the following relationship: $\delta^{234}\text{U}_{\text{measured}} = \delta^{234}\text{U}_{\text{initial}} \exp(\lambda_{234}t)$, where λ_{234} = the decay constant for ^{234}U , and t = years (Edwards et al., 1987). Using as endmembers the initial $\delta^{234}\text{U}$ of the mammillary and folia, 1766 and 3105 ‰, respectively, an age and absolute error can be calculated with the assumption that the Glenwood Cavern sample had a value similar to the more modern mammillary calcite samples from the cavelet sites. In single samples, phreatic and vadose, initial $\delta^{234}\text{U}$ values can show consistency over long periods of time (Ludwig et al., 1992; Woodhead et al., 2006). Our results are from different samples and sites, so a large possible variation in initial $\delta^{234}\text{U}$ values is needed. Using the largest variation in initial $\delta^{234}\text{U}$ values from the four samples yielding U-series ages, the $\delta^{234}\text{U}$ model age for sample GC-2011-1 is $1.39 \pm 0.1 \text{ Ma}$. More conservatively, using lower and higher initial $\delta^{234}\text{U}$ values of 1000 and 4000 ‰ produces essentially the same age, but with greater uncertainty ($1.39 \pm 0.25 \text{ Ma}$). Applying the same procedure for GC-HD1 and GC-HD2 yields $\delta^{234}\text{U}$ model ages of $1.36 \pm 0.25 \text{ Ma}$ and $1.72 \pm 0.25 \text{ Ma}$. These ages are close to that reported by DuChene et al. (2003) for cave development at 1.34 to 1.69 Ma, with the assumption that these water-table speleothems formed soon after the cave did. The DuChene et al. (2003) value is obtained by projecting constant incision history based on the 3.03 My old Spruce Ridge basalt positioned 732 m above the Colorado River (Bryant et al., 2002; Kunk et al., 2002). Our mammillary-like speleothem from Glenwood Cavern, GC-2011-1, indicates incision rates of $271 +58/-41 \text{ m/My}$, $277 +61/-42 \text{ m/My}$, and $218 +36/-27 \text{ m/My}$, at $375 \pm 20 \text{ m}$ above the Colorado River. These compare well with the 241 m/My incision rate for the last 3.03 My obtained from the basalt dates.

Fig. 5. Uranium-evolution curve, produced with Isoplot (Ludwig, 2001), shows the results of U-series analyses of speleothems used in this study.

They are also close to the 291 m/My incision rate of the Roaring Fork River near Triangle Peak for the last 1.4 My, also based on a basalt age. U-series results for this study are shown in Table 1. The concept of using these speleothem types for interpreting canyon incision is outlined in Fig. 6.

DISCUSSION

A 3 Ma basalt at Gobbler Knob, just south of Glenwood Canyon, caps a paleovalley that is interpreted to be at or very close to the ancestral Colorado River. This basalt is located 732 m above the Colorado River, and suggests an incision rate for the Colorado River in nearby Glenwood Canyon of 241 m/My for the last 3 My (Bryant et al. 2002; Kunk et al., 2002). Only 115 m above the Gobbler Knob basalt is the Spruce Ridge basalt, dated to 7.8 Ma (Bryant et al., 2002; Kunk et al., 2002). From this date, incision rates in Glenwood Canyon were interpreted to be very slow from 7.8 to 3.03 Ma (24 m/My), and then increased after 3 Ma up to at least 1.4 Ma. An incision rate of 132 m/My was reported for the Colorado River at the head of Glenwood Canyon (Dotsero, Colorado) on the basis of the 640 ka Lava Creek B Ash (Aslan et al., 2010). The Dotsero incision rate matches our 144 m/My almost exactly over the same time period (623 vs. 640 ka).

Aslan et al. (2010) question the accuracy of the incision history determined from the Gobbler Knob and Triangle Peak basalts, and suggest that they instead covered a valley fill that was situated at some significant height above the Colorado River at 3 Ma and Roaring Fork River at 1.4 Ma. They emphasize the fact that the Spruce Ridge basalt and other older basalts overlie what are interpreted to be actual Colorado River sediments, and propose that incision by the Colorado River could have been mostly steady at an approximate rate of 120 m/My

Fig. 6. Generalized cross-section at the mouth of Glenwood Canyon showing locations of cave samples used in this study.

over the last 8 or 10 My. However, our Glenwood Cavern SC-2011-1 model age produces an incision rate that is essentially the same as the incision rate generated by the Gobbler Knob and Triangle Peak basalts, and therefore supports the interpretations presented by Bryant et al. (2002) and Kunk et al. (2002). The Glenwood Cavern SC-2011-1 mammillary calcite would need to be 2 My older to fit the static (more steady-state entrenchment) model, and the 16–44 ‰ values of the $\delta^{234}\text{U}$ indicates that the ages of the mammillary calcite samples are less than 2.5 Ma.

Our speleothem-based incision history of Glenwood Canyon, combined with results of other researchers, point to a dynamic rather than static incision-rate history of Glenwood Canyon. The results shown in Fig. 7 suggest that incision was faster between 3 and 0.6 Ma, and slowed with time. Such an increase in incision rate could be produced by accelerated regional uplift, and/or by climatic changes, either of which would affect the erosional power of the Colorado River.

A stage of similarly fast incision in eastern Grand Canyon for approximately the same time period, but not for western Grand Canyon (Polyak et al., 2008) would seem to support tectonic uplift as the cause of

Fig. 7. Age of deposits vs. elevation above the local river level, showing two incision models: a static (steady-state) model, and a dynamic model. The Glenwood Cavern mammillary calcite $\delta^{234}\text{U}$ model age supports a dynamic model, with incision rate increasing significantly between 3 and 1 Ma. The elevation errors for our samples fall within the width of the age error bars.

Table 1. Glenwood Canyon speleothem U-series data.

Sample	^{238}U	^{232}Th	$^{230}\text{Th}/^{232}\text{Th}$	measured initial		corrected	
	(ppb)	(ppt)	activity ratio	$^{230}\text{Th}/^{238}\text{U}$	$\delta^{234}\text{U}$ (‰)	age (Ma)	
cavelet flowstone 1a	4339.4 ± 10.7	317 ± 83	41134 ± 10759	0.984 ± 0.004	273 ± 3	0.148 ± 0.001	-0.001
cavelet flowstone 1b	4443.9 ± 5.2	313 ± 42	42905 ± 5812	0.988 ± 0.002	282 ± 1	0.147 ± 0.001	-0.001
cavelet mammillary 1a	1063.6 ± 2.5	435 ± 35	12860 ± 1023	1.720 ± 0.007	586 ± 1	0.357 ± 0.008	-0.007
cavelet mammillary 1b	560.7 ± 0.3	62 ± 39	49711 ± 31550	1.793 ± 0.004	638 ± 2	0.363 ± 0.005	-0.005
cavelet folia	671.6 ± 1.8	12158 ± 56	296 ± 2	1.755 ± 0.006	535 ± 2	0.623 ± 0.067	-0.047
cavelet rafts	647.3 ± 1.7	18616 ± 56	123 ± 0	1.160 ± 0.004	129 ± 1	0.452 ± 0.023	-0.020
Glenwood Caverns mam1	1135.7 ± 1.2	514 ± 143	7175 ± 1998	1.062 ± 0.002	40 ± 1	model age = 1.39 ± 0.25	
Glenwood Caverns mam HD1	578.8 ± 0.3	394 ± 47	4794 ± 577	1.067 ± 0.001	44 ± 1	model age = 1.36 ± 0.25	
Glenwood Caverns mam HD2	986.4 ± 0.5	53 ± 61	58452 ± 67531	1.032 ± 0.001	15 ± 1	model age = 1.72 ± 0.25	

Corrected ages use a calculated initial $^{230}\text{Th}/^{232}\text{Th}$ atomic ratio 4.4 ppm ± 50%. Million years before present = Ma, where present is AD 2011. All errors are absolute 2σ. Subsample sizes range from 30 to 140 mg. Model age = $\delta^{234}\text{U}$ model age.

the increased incision rates (Karlstrom et al., 2008). Perhaps the eastern Grand Canyon region and the Glenwood Canyon region experienced a phase of accelerated uplift between 3 and 1 Ma, similar to that of the Pliocene uplift of the Colorado Plateau proposed by Levander et al. (2011). If so, our evidence would suggest that the uplift was temporally and spatially non-uniform during the latest Pliocene and Pleistocene.

The onset of the Pleistocene at 2.5 Ma (Clark et al., 1999) may also have caused an increase in cutting power of the Colorado River via increased precipitation in the Colorado Plateau region, in combination with the descent of hydrologic base levels due to lower sea levels. The slowing of incision before 0.65 Ma might be due to the change in ice age frequency during the Middle Pleistocene at ~0.8 Ma, from 40-kyr glacial cycles before 0.8 Ma, to 100-kyr glacial cycles after 0.8 Ma (Clark et al., 1999). Glacially controlled incision rates for the Green River area, Kentucky, USA (Granger et al., 2001) and for the Aare Valley, Switzerland (Haeuselmann et al., 2007) have been derived from analysis of cave sediment. These studies show that glacially induced changes in incision rate show considerable regional variation.

For the western United States, the onset of the Pleistocene alone could have triggered faster incision due to lowering of the hydrologic base via lower sea level. But this seems less likely in our study area because Glenwood Canyon is located far upstream along the Colorado River. A climate-driven explanation of faster incision at 3 to 1 Ma would tie the 40-kyr glacial cycle to increased effective precipitation on the Colorado Plateau. Furthermore, the slowing of incision could have been caused by the onset of the 100-kyr glacial cycle that pushed the storm track south of the study area, resulting in a slightly drier climate over the last 0.8 Ma. Another possible cause for decreased incision rate after 0.8 Ma could be that knickzones triggered by the onset of Pleistocene glaciation migrated through Glenwood Canyon before 0.65 Ma, and were diffused in softer sediments in the Eagle Collapse Center (DuChene et al., 2003) upstream from Glenwood Canyon.

CONCLUSION

The U-series chronology of water-table-type speleothems from caves and cavelets in Glenwood Canyon, Colorado, provides an incision history of the canyon by the Colorado River over the last 1.5 My. The speleothem-based incision rates match previously published rates derived from the Spruce Ridge, Gobbler Knob, and Triangle Peak basalts and the Lava Creek B ash. These data support a non-steady state history of incision in Glenwood Canyon. Tectonic mechanisms for faster incision from 3 to 0.65 Ma would invoke faster uplift of the region during the Pleistocene compared to the Pliocene. While climatic mechanisms would suggest that the onset of the Pleistocene ice ages was responsible for faster incision rates of the Colorado River in Glenwood Canyon, and that incision has slowed down since the middle Pleistocene.

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