6.8 Reconstructing Landscape Evolution by Dating Speleogenetic Processes

VJ Polyak and CA Hill, University of New Mexico, Albuquerque, NM, USA

© 2013 Elsevier Inc. All rights reserved.

6.8.1 Introduction
6.8.2 Geochronologic Applications
6.8.3 Stable and Radiogenic Isotope Applications
6.8.4 Example Studies of Landscape Evolution from Chronology of Cave Sediments/Speleothems
6.8.4.1 Guadalupe Mountains
6.8.4.2 Grand Canyon
6.8.4.3 Jewel/Wind Caves
6.8.4.4 Mammoth Cave Region
6.8.4.5 Sierra Nevada Mountains, California, USA
6.8.4.6 Bighorn Mountains Wyoming–Montana
6.8.4.7 Rates of Valley Incision in Switzerland
6.8.4.8 Kraushöhele, Austria

References

Glossary

Cave mammillaries A speleothem which is a variety of rounded subaqueous coating consisting of carbonate layers lining bedrock and which forms phreatically at or near the water table due to the degassing of CO₂.

Cosmogenic ($^{26}$Al/$^{10}$Be) isotope dating In relation to cave studies, this is a technique of 'exposure-burial' dating, where $^{26}$Al and $^{10}$Be are produced in materials at the Earth’s surface by bombardment of cosmic radiation, and where these surface materials are transported into caves and thereafter protected from cosmic radiation. Measurement of the two isotopes yields the time since those materials were transported into the caves.

Folia A speleothem type which consists of interlocking, wavy ribs of carbonate material and which forms at the surface of the water table, commonly directly overlying mammillary speleothems.

Gypsum rinds A form of speleogenetic gypsum where the gypsum actually replaces limestone bedrock due to the reaction of sulfuric acid and limestone, the by-product of which is a crust-like rind that overlies bedrock.

Hypogene caves Caves that owe their dissolution to processes occurring beneath the Earth’s surface where solutional aggressiveness is generated at or below the water table.

Paléokarst An ancient karst that has been subsequently destroyed (or partially destroyed) through burial, infilling, collapse, compaction, brecciation, cementation, or structural fragmentation.

Radiometric dating A technique of absolute dating of materials using the difference between the measured abundance of a naturally occurring radioactive and its decay products.

Sulfuric acid speleogenesis The process by which caves are formed (speleogenesis) due to a sulfuric acid mechanism, where the acid is generated from hypogene (generally hydrocarbon) sources.

Abstract

Speleology and karst geomorphology are making important contributions to evolution of landscapes, thanks to more refined dating techniques, more specialized and advanced instruments, and intensive studies of caves and karst terrains. This chapter provides eight cases where cave and karst studies have made, or are making, new strides in the reconstruction of landscape evolution by dating cave deposits. Some of these study areas include world renowned caves such as Carlsbad Cavern and Lehchuguilla Cave in the Guadalupe Mountains of New Mexico, Jewel and Wind caves in the Black Hills of South Dakota, and Mammoth Cave in Kentucky. The authors offer added detail on the caves of the Guadalupe Mountains and Grand Canyon.
6.8.1 Introduction

Only a few decades ago, determining the age and origin of caves was only deemed possible by relating the origin of caves to their surface geology (Thornbury, 1969). Today, karst geomorphologists and speleologists are successfully reversing this approach by combining speleology and geochronology. The question now on the minds of many speleologists and karst geomorphologists is – how can the study of caves make significant contributions to other sciences such as geomorphology? Determining the age of cave sediments and speleothems contributes not only to the age of the caves that hold these deposits, but also to the determination of surface processes such as canyon incision rates, the placement of water table positions over time, paleoclimate reconstructions, paleontological evolution, and human history. The solving of these histories offers insights of what landscapes looked like in the past and this ultimately helps us envision how, and how fast, landscapes will evolve in the future. This chapter explores several examples of landscape reconstruction using the chronology of cave materials with special focus on the caves of the Guadalupe Mountains (Carlsbad Cavern and Lechuguilla Cave), and caves in Grand Canyon.

6.8.2 Geochronologic Applications

Radiometric dating of cave materials provides speleologists with data necessary to make interpretations related to landscape evolution. Generally, the ages required to make such interpretations are hundreds of thousands of years to millions of years ago (Ma). The radiometric methods needed for these old ages are uranium (U)–thorium (Th) dating, U–lead (Pb) dating, argon–argon (Ar) dating, and cosmogenic aluminum (Al)–beryllium (Be) dating. Carbon-14 (14C) dating can only be applied to materials less than 60,000 years old. Other more universal methods that can be used in combination with the U/Pb method for samples less than 2.5 Ma in some cases.

The U/Pb dating methods (238U/206Pb and 235U/207Pb) are more universally applicable to speleothem-related studies that go back past 600,000 years. Using these methods, it is possible to date cave materials as young as a few hundred thousand years (Richards et al., 1998) and as old as tens to hundreds of millions of years (Lundberg et al., 2000). 238U/206Pb dating uses the 238U decay scheme that undergoes numerous decay steps before eventually decaying to 234U's stable isotope daughter 206Pb. The half-life of 238U is 4.468 billion years (Jaffey et al., 1971). 206Pb is the final and stable daughter isotope. Considerable amounts of common 206Pb (not from the decay of the accompanying 238U at time of calcite deposition) can get incorporated into calcite when a calcite speleothem is formed, so the 206Pb component of this common Pb needs to be determined and corrected out. The common 206Pb and 207Pb isotopes are contributed by the ground water forming the calcite. This dating method incorporating the correction for common Pb usually requires construction of an isochron. Ideally for this method to be applicable, the U/Pb ratio in the speleothem calcite needs to be sizeable (≫1), and the calcite system must have remained closed in regard to 238U and all of its daughters including 206Pb. Speleothems are ideal samples in this regard, especially in arid to semi-arid regions, because caves are protective depositories. Given that U/Pb ratios are high enough, the 235U/207Pb method can also be used in the same way. 235U has a shorter half-life, 703,810 years (Jaffey et al., 1971), but 235U is 137.88 times less abundant in the samples, making it more difficult to apply in many cases.

Another absolute dating using U and Th generally involves the 238U radioactive decay scheme where 238U decays to 234U which itself decays to 230Th, and where 234U/238U and 230Th/234U ratios are used to construct the age. All of these are radioactive isotopes. This method is commonly used because Th is relatively immobile in the carbonate groundwater system, so the daughter product of the 234U to 230Th decay scheme is negligible at time = 0. Measurement of 235U is commonly used to determine the quantity of 238U, with the assumption that 238U/235U in nature is 137.88. Measurement of 238U is also needed to make corrections for the physical fractionation of 235U in most groundwater systems resulting in 234U/235U activities greater than or less than unity. The radioactive half-life – the time needed for half of the parent isotope to decay – of 230Th is 75,690 years (Cheng et al., 2000). The maximum age that can be determined using this 230Th/234U dating method is less than 10 half-lives of the 230Th half-life or about 600,000 years using mass spectrometry. Beyond 600,000 years of landscape evolution, other methods are needed. The radioactive half-life of 234U is 2,450,250 years. The 234U/238U geochronometer can also be used to extend the period of interest from 600,000 years (600 Ka) to roughly 2 million years (2 Ma). The setback with this system is that the initial 234U/238U activity, which cannot be determined in most cases, needs to be known, and therefore only estimates of ages can be made. The 234U/238U geochronometer, however, can be used in combination with the U/Pb method for samples less than 2.5 Ma in some cases.

Cosmogenic isotope dating of cave sediments involves two isotopes, 26Al (half-life ~ 7.2 × 105 years) and 10Be (half-life = 1.51 × 106 years). This method includes the production of these radioisotopes by cosmic radiation on the Earth’s surface where 26Al is produced about 6 times faster than 10Be. 26Al and 10Be in surface sediment that is ultimately washed into caves and capped by at least 20 m of overburden are no longer produced and can only decay radioactively. As a result, the 26Al/10Be ratio decreases over time and is used to calculate the time that the sediment has resided in the cave (Granger et al., 2001; Granger, 2006).
6.8.3 Stable and Radiogenic Isotope Applications

Showing that caves are connected to surface or to deep-seated processes is important for reconstructing landscapes. Although absolute chronology is essential, stable and radiogenic isotopes are generally used to support these chronological reconstructions. Oxygen (O) and carbon (C) isotopes are the most common stable isotopes utilized, and they are especially useful for determination of past climatic conditions on the surface above caves. In addition to O and C, two other stable-isotope elements, sulfur (S) and strontium (Sr), offer much promise. Sulfur isotope ratios are particularly useful to show the hypogenic origin of caves, as exemplified by the tying of the Permian Basin hydrocarbon deposits to cave genesis in the Guadalupe Mountains, New Mexico, USA. Sulfur isotope values on gypsum rinds in Grand Canyon caves are establishing a connection between hypogene gases/fluids coming from volcanic or hydrocarbon sources in the subsurface and a water-table environment for the mammilary-folia-cave-raft-gypsum rind speleothem assemblage in these caves. Sr isotope values are less commonly utilized, but the Sr system has great potential – and not just for hypogene cave systems. For example, dripstone speleothems record changes in Sr isotope values of water coming from the surface. A volcanic-rich sediment mantle overlying caves generates drip waters having a volcanic Sr isotope signatures, whereas removal of that mantle changes the drip water Sr isotope values, thus demonstrating the corresponding changes in the overlying landscape.

6.8.4 Example Studies of Landscape Evolution from Chronology of Cave Sediments/Speleothems

Eight examples where cave studies have made contributions to landscape evolution are offered. Six of these are from North American sites, whereas two are from European sites. They include: (1) the Guadalupe Mountains of southeastern New Mexico and West Texas; (2) Grand Canyon, Arizona; (3) Jewel and Wind Caves, South Dakota; (4) the Mammoth Cave region of Kentucky and Tennessee; (5) the Sierra Nevada Mountains, California; (6) the Bighorn River region, Wyoming and Montana; (7) the Aare Valley, Switzerland; and (8) Kraushoehe, Austria. Most of these examples represent areas where the history of landscape evolution from caves goes back millions of years. Equally important are the techniques used in each of these examples.

6.8.4.1 Guadalupe Mountains

Four stages of speleogenesis have been identified in the Guadalupe Mountains, southwestern USA (Hill, 1987, 1990; Figure 1(a)). Two of these stages comprise the larger caves that contain speleothems suitable for use in landscape evolution studies. One of those, referred to as the spar cave genesis (solution stage 3; Hill, 1987), likely took place tens of millions of years ago (Hill, 1996) and as early as 90 Ma (Lundberg et al., 2000). This episode produced single chamber caves lined with large calcite crystals (spar). These chambers are large geodes, sometimes up to 50 m in diameter.

The most prominent stage of speleogenesis in the Guadalupe Mountains is the sulfuric acid stage (solution stage 4; Hill, 1987), which truncated the spar caves and formed the magnificent chambers exhibited by Carlsbad Cavern and Lechuguilla Cave as well as by other caves in the Guadalupe Mountains. Migration of hydrogen sulfide (H2S) generated in underlying hydrocarbon deposits in the adjacent Permian Basin (Hill, 1987), or in other adjacent hydrocarbon deposits (Duchene and Cunningham, 2006), migrated upward into the freshwater Capitan aquifer where it was oxidized to sulfuric acid (H2SO4) (Figure 1(b)). Migration of carbon dioxide (CO2) produced carbonic acid as well. The mixing zone of hypogene waters with freshwater created an environment perfect for dissolving large amounts of limestone and dolostone by a sulfuric acid mechanism. By-products of this phase of speleogenesis included minerals such as alunite, jarosite, hydrotbasaluminate, gypsum, hydrated halloysite (endellite), dolomite, tuyumunate, gibbsite, nordstrandite, opal, quartz, and Fe-sulfates. One of these minerals, that is, alunite, contains sufficient amounts of K to be successfully dated using the 40Ar/39Ar method (Polyak et al., 1998, 2006).

Several episodes of sulfuric acid speleogenesis for the Guadalupe Mountains have been reported, with the timing of these episodes correlating with elevation of the by-products left behind (Polyak et al., 1998). The highest deposits are the oldest (Figure 2(a)). Because the mixing-zone environment for speleogenesis ideally took place near the water table, the position of the water table relative to the strata can thus be tracked over time. The alunite age data indicated that the water table (relative to the strata) dropped 1000 m in 12 Ma, which was most likely the response of 12 Ma of uplift of the Guadalupe block (Figure 2(b)).

The timing of this uplift/water table drop in the Guadalupe Mountains is supported by studies of jarosite from mines throughout the Rio Grande Rift (Lueth et al., 2005). One interpretation of this uplift utilizes the Alvarado Ridge concept (Duchene and Cunningham, 2006), a late Laramide- or middle Cenozoic-aged uplift of the region caused by compressional tectonic processes. This theory suggests that a significant amount of the uplift that forms the Guadalupe Mountains took place prior to 12 Ma and perhaps as early as 35 Ma, and that sulfuric acid speleogenesis is an expression of later processes related to Rio Grande Rifting. The timing of deposition of the large scalenohedral calcite crystals lining the spar caves that formed before sulfuric acid speleogenesis can at least narrow the window for formation of a proposed Alvarado Ridge uplift in the area of the Guadalupe Mountains. The first U/Pb date performed on one of these crystals is ~90 million years ago (Lundberg et al., 2000) and allows ample time to uplift the Guadalupe Mountains region before sulfuric acid speleogenesis. However, should some of these crystals have younger ages (i.e., Basin and Range, ~30 Ma), then interpretations should favor a tilted but relatively low-lying region or at least a region with relatively gentle topography until Rio Grande Rifting shaped the landscape starting ~10–15 Ma (Lueth et al., 2005). The chronology worked out for sulfuric acid speleogenesis has also led to interpretations related to canyon incision rates in, and the mass wasting history of, the Guadalupe Mountains (Duchene and Martinez, 2000).
Decades of intensive geologic studies have produced little absolute data contributing information regarding the incision history of Grand Canyon, Arizona, southwestern United States (Figure 3). The top of pre-Colorado River lacustrine deposits in the Lower Colorado River Corridor below Grand Canyon has recently been dated to 5.7 Ma, showing that the Colorado River did not flow west off the Colorado Plateau and into the Basin and Range until that time (Faulds et al., 2001; Spencer et al., 2001). It has traditionally been assumed that Grand Canyon was entirely cut by the Colorado River, and hence that the entire Grand Canyon is less than 6 million years ago (Karlstrom et al., 2008). However, other studies – one of which is our karst study – have suggested that a canyon was forming in the area of the present-day western Grand Canyon prior to the arrival of the Colorado River 6 million years ago (Young, 2008; Polyak et al., 2008).
The only incision rate data prior to our geochronological karst study have come from the travertines and basalt flows just above the present position of the Colorado River. These rates were derived from deposits less than 100 m above the current river, and less than 0.75 million years ago, and show that the western Grand Canyon during the last half of the Pleistocene has been cutting deeper at a slower rate (70 m Ma⁻¹/C0) than the eastern Grand Canyon (150 m Ma⁻¹/C0) (Figure 3; Karlstrom et al., 2007). Since Grand Canyon is 1600 m deep, more evidence higher above the Colorado River has been needed to help unravel the incision history of the entire Grand Canyon.

Finding deposits in Grand Canyon that preserve its incision history has proved to be difficult because Colorado River incision and canyon erosion have removed the deposits that provide such data. Caves, however, are unique repositories. They have not been totally obliterated by canyon processes, and they contain deposits that tell us something about the incision history of the canyon over time. Within the Grand Canyon are hundreds of caves, most of which have formed in the Redwall-Muav limestones. In these caves is a sequence of speleothem deposition that represents mineralization: (1) deep below the regional water table; (2) at that water table; and (3) above that water table (Hill et al., 2001). This sequence of deposition provides important information about the history of Grand Canyon.

The most revealing deposits in Grand Canyon caves are those interpreted to be water-table indicators. These deposits...
The Grand Canyon of northern Arizona showing the location of caves where mammillary speleothems were collected for dating. By determining the age of formation of the mammillaries, a position of a preexisting water table can be established. Most Grand Canyon caves are located in the Redwall-Muav Limestones. Modified from Figure 2 in Polyak, V., Hill, C., Asmerom, Y., 2008. Age and evolution of Grand Canyon revealed by U–Pb dating of water-table-type speleothems. Science 319, 1377–1380, with permission from AAAS.

Figure 3

Figure 4

Figure 5

Reconstructing Landscape Evolution by Dating Speleogenetic Processes

are mammillary calcite, folia, cave rafts, and gypsum rinds (Figure 4). Mammillary calcite characteristically forms just below the water table, whereas folia is considered by speleologists to be a water-table speleothem (Hill and Forti, 1997; Palmer, 2007; Audra et al., 2009). In Grand Canyon caves, cave rafts – a speleothem type that forms on water surfaces – are intimately associated with mammillary calcite, folia, and 1–6 cm-thick gypsum rinds that coat bedrock and mammillaries. This cycle of deposition represents the history of a water table's descent through the caves. By dating any one of these speleothem types, the water table can be placed at a particular position in the canyon at a particular time. Because the mammillaries are relatively thick, well preserved, and have a U/Pb ≥ 1, they can be dated using the U/Pb technique. Eight mammillaries have been recently dated, four in the western Grand Canyon and four in the eastern Grand Canyon (Polyak et al., 2008). These ages varied from 17 to 0.9 Ma, and the elevations of these mammillaries ranged from 100 to 1200 m above the Colorado River. The lowest-in-elevation data yielded canyon incision rates that matched those reported from basalts and travertine deposits, but the higher-elevation, eastern Grand Canyon results produced greater canyon incisions rates.

The general concept of this study is given in Figure 5. When the potentiometric surface of the Redwall-Muav aquifer (the limestone aquifer in Grand Canyon) was above the Redwall limestone and up into the impermeable mudstones and siltstones of the Supai Group, the Redwall-Muav aquifer was under confined conditions. As the potentiometric surface descended into the Redwall-Muav caves, it was no longer confined and a water table developed within the limestone as shown in Figure 5(a). This water table is envisioned to have been relatively flat, especially in the paleokarstic upper part of the Redwall limestone. Because hypogene solutions containing H₂S and CO₂ rose along joints and mixed with aquifer water, conditions became conducive for the precipitation of calcite near and at the water table in the caves, and it was here that the mammillaries, folia, cave rafts, and gypsum rinds precipitated (Figure 4). A perched water table developed on top of the Bright Angel Shale after the water table dropped below the Redwall/Muav (Figure 5(b)). This is the hydrologic condition present in much of Grand Canyon today.

None of the mammillaries in Grand Canyon should be greater than 6 million years ago if the Colorado River cut the entire canyon from the top of the plateaus down to the river's present position in less than 6 Ma. However, two water table positions from mammillary ages in the western Grand Canyon predate the arrival of the Colorado River, and these ages have been interpreted by us as an early drop in the water table by canyon-forming processes from 17 to 6 Ma. In other words, our study of speleothems suggests that the western Grand Canyon was being cut prior to the arrival of the Colorado River (Figure 6).

Karst-related concepts have led to a new theory for connecting a younger eastern Grand Canyon with an older western Grand Canyon, with the integration of the Colorado River between the two sections occurring at ~6 Ma. Hill et al. (2008) recently suggested that the Colorado River followed a karst route under a high-ground barrier known as the Kaibab arch (Figure 3). Water descending via sinks in the overlying
sequence of deposition of four water-table-type cave deposits, mammillaries, folia, cave rafts, and gypsum rinds, in relation to the position of the water table. Spar linings form deep below the water table, mammillaries form at or just below the water table, cave folia and rafts form at the surface of the water table (not shown), gypsum rinds form just above the water table, whereas speleothems such as stalactites form above the water table in the subaerial zone. Reproduced from Polyak, V.J., McIntosh, W.C., Provencio, P., Guven, N., 1998. Age and origin of Mississippian paleokarst zones are widely exposed in South Dakota, where cave formation was exceptionally active and preserved as paleokarst breccia exposed in the walls of these caves. As in the case of Grand Canyon paleokarst, a vast Mississippian plain of the same or similar age also existed in South Dakota, where cave formation was exceptionally active. There is evidence that the region was subject to karstic processes at least 330 Ma (Palmer and Palmer, 2008). The main phase of speleogenesis in the case of Jewel and Wind Caves is believed to have taken place in the Cenozoic, but the earliest speleogenesis events took place in the Mississippian and are preserved as paleokarst breccia exposed in the walls of these caves. In the case of Jewel and Wind, the presence of cave-rafted calcite and the timing of these early phases of speleogenesis can be determined using the 40Ar/39Ar dating of alunite. Science 279, 1919–1922, with permission from AAAS.

Kaibab Limestone accessed the Redwall Limestone and essentially flowed westward under the arch to connect with our proposed 17–6 Ma western Grand Canyon. Although no absolute chronology has been established for this karst theory, a chronology based on cave mammillary dates will allow for a possible confirmation of this theory in the future. Our mammillary-derived incision history suggests that the western Grand Canyon was significant in size and depth by 6 Ma. The speleothem data also provide a route and a paleo-surface that would have been utilized by the arrival of the Colorado River ~6 Ma. From other studies (Flowers et al., 2008; Hill and Ranney, 2008), it is also likely that an even earlier, ‘proto-Grand Canyon’ was in existence during the early Cenozoic (40–50 Ma or the Laramide) in the area of the central Grand Canyon. This proto-Grand Canyon drained northward into the Lake Claron basin in the Bryce Canyon, Utah area at that time, and removed a considerable amount of overburden from the Grand Canyon area before 17 Ma. Therefore, a newly proposed story of Grand Canyon evolution – heavily based on our karst studies – is now emerging that incorporates three phases of canyon-forming processes: (1) a 50–40 Ma early Cenozoic proto-Grand Canyon; (2) a middle Miocene (17–6 Ma) western Grand Canyon, and (3) a <6 Ma Colorado River canyon-forming phase that produced the final landscape that we see today.

Grand Canyon also nicely exposes Mississippian-aged paleokarst near the top of the Redwall limestone. This paleokarst includes cave-fill and calcite cements that are similar in age and appearance to those exposed in Jewel Cave, South Dakota (Figure 7). Mississippian paleokarst zones are widely exposed in the caves of both areas, and the paleocaves and sediments filling them provide important clues to the extent and the type of environment that made up the Mississippian karst landscape.

6.8.4.3 Jewel/Wind Caves

Two of the longest caves in the world are located in the Black Hills of South Dakota, USA. Like the Guadalupe Mountain and Grand Canyon caves, Jewel and Wind have formed without any associated surface morphological expression; for example, the topography of the region displays no sinkholes, no tower karst, and no karren fields. Yet these caves have preserved within them abundant clues of past surface geomorphologic history going back to the Mississippian period some 330 Ma (Palmer and Palmer, 2008). The main phase of speleogenesis in the case of Jewel and Wind Caves is believed to have taken place in the Cenozoic, but the earliest speleogenesis events took place in the Mississippian and are preserved as paleokarst breccia exposed in the walls of these caves. As in the case of Grand Canyon paleokarst, a vast Mississippian plain of the same or similar age also existed in South Dakota, where cave formation was exceptionally active (Figure 7). Attempts are now being made to determine the timing of these early phases of speleogenesis by using U/Pb dating of paleokarst-aged calcite spar and perhaps 40Ar/39Ar dating on associated manganese oxides.

Other episodes of early speleothem deposition in Wind and Jewel have been identified by Palmer and Palmer (2008). One of these – an episode of calcite deposition – is a spar lining that coats much of Jewel Cave and is one of the main tourist attractions of the cave. The spar lining was deposited during a time when saturated water engulfed Jewel Cave. On the surface, this time period most likely occurred sometime after a sheet of Oligocene sediment was deposited over the eastern flanks of the Black Hills. A more complete record of karst evolution may be possible to tie the surface geomorphology to the karst geomorphology more accurately using hydrologic models in combination with the U/Pb chronology of spar linings.
Figure 5  Schematic block diagram showing concepts behind the evolution of Grand Canyon based on the dating of speleothems. (a) The Colorado River at 3.5 Ma in eastern Grand Canyon cut into the Redwall/Muav aquifer and as a consequence confined conditions of that aquifer are relieved and the water table is interpreted to behave as relatively flat, especially in the upper Redwall Limestone where paleokarst porosity is high. The water-table elevation mimics the elevation of the Colorado River and so the age of the mammillary speleothems can be related to how deep the canyon has incised over time. (b) Today the Colorado River has cut well below the Redwall/Muav aquifer and is incising Precambrian rocks in much of Grand Canyon. The mostly impermeable Precambrian rocks probably host an irregular water table. Instead of being under confined conditions, as in (a), the Redwall/Muav aquifer contains perched water along the base of the Muav Limestone and on top of the Bright Angel Shale. It is along this perched horizon that water exits today as springs and waterfalls, and where travertine deposits are forming.
6.8.4.4 Mammoth Cave Region

Mammoth Cave in the east-central United States displays several distinct levels of passage development even though these levels have formed in different strata (Figure 8). These levels were developed under shallow phreatic conditions along a base-level associated with the nearby Green River. Major cave passage development in the Mammoth Cave system occurred during the periods of slower river incision. Once this river system began to incise faster and deeper, phreatic conditions dropped below cave level and vadose conditions occupied the caves, depositing thick layers of sediment (Palmer, 2007). The sediment being transported into the caves once resided on the surface where cosmic radiation bombarded the sediment for a sufficient period of time to produce the isotopes of $^{10}$Be and $^{26}$Al. Granger et al. (2001) used cosmogenic nuclide analyses to measure the ratios of these isotopes to determine the time (using quartz grains) when these sediments were deposited in the caves. By doing this, they were able to determine when phreatic conditions ended and vadose conditions began. Each cave level represents an episode of groundwater conditions interpreted to be periods of slow river incision followed by fast river incision causing vadose entrenchment of the cave passages. In essence, the development of Mammoth Cave records changes in base level of the Green River, and the timing of those changes relates to landscape evolution above the cave. This Mammoth Cave data have also helped to define the timing of integration of the ancient Teays and precursor Ohio rivers into the Green River 2 Ma and 1.5 Ma, respectively (Granger et al., 2001).

6.8.4.5 Sierra Nevada Mountains, California, USA

A contribution to the Cenozoic history of the Sierra Nevada Mountains topographic landscape has recently been made
using caves (Stock et al., 2004). River sediments preserved within caves mark paleo-river levels along the western scarps of the Sierra Nevada Mountains. Vertical distances from the caves to the present river levels and $^{26}$Al/$^{10}$Be cave-sediment ages were used to determine river incision rates over the last 2.7 Ma (Figure 10). Fast incision rates from 2.7 to 1.5 Ma ($>200$ m Ma$^{-1}$), and a significant slowing of incision from 1.5 Ma to the present ($<30$ m Ma$^{-1}$) were yielded from the cave deposits. This was interpreted as rock uplift in the Pliocene inducing rapid incision and eastward knickzone

Figure 8 (a) Major (numbered) cave passages in Mammoth Cave and Floyd Collins Crystal Cave that correlate with the numbered passages in (b). (b) Four distinct levels of cave genesis have been identified in Mammoth Cave and other nearby caves by passage characteristic and by the $^{26}$Al/$^{10}$Be-dating of cave sediments in those passages. Phreatically developed passages formed parallel to water tables and along strike of dipping beds, while vadose passages followed the dipping strata. Each level represents periods of slower river incision and thus differing rates of landscape evolution related to the lowering of the Green River over time. Adapted from Granger, D.E., Fabel, D., Palmer, A.N., 2001. Pliocene- Pleistocene incision of the Green river, Kentucky, determined from radioactive decay of cosmogenic $^{26}$Al and $^{10}$Be in Mammoth Cave sediments. Geological Society of America Bulletin 113, 825–836, with permission from Palmer, A.N., 2007. Cave Geology. Cave Books, Dayton, OH, 454 pp.

Figure 9 $^{26}$Al/$^{10}$Be-dating of cave sediments along tributaries of the Cumberland River just north of Mammoth Cave has yielded ages that become younger upstream along the tributaries, but that are at the same elevations above modern river level in each of the caves. The figure shows how caves can be used to determine headward incision rates of rivers (arrows). Adapted with permission from Palmer, A.N., 2007. Cave Geology. Cave Books, Dayton, OH, 454 pp.
migration for about a million years followed by glacial-driven mantling and slower incision in the Pleistocene. This work also sheds light on the pre-2.7 Ma topography. The remaining 1600 m of relief (not shown in Figure 10) formed prior to 2.7 Ma, showing that large canyon development likely extends back into the Miocene.

6.8.4.6 Bighorn Mountains Wyoming–Montana
Aeolian sand and an ash deposit in two caves in northern Wyoming and southern Montana, western United States, have been used to measure maximum incision rates of the Bighorn River for the last 0.64 million years (Stock et al., 2006). Tephrochronology was used to identify a Yellowstone volcanic (0.639-million-year-ago Lava Creek B) ash bed that had been deposited into Horsethief Cave providing a maximum incision rate of Bighorn River gorge by the Bighorn River of 350 ± 190 m Ma⁻¹. In Spence Cave, nearly 40 km to the south, a ²⁶Al/¹⁰Be age of 0.31 Ma was determined for windblown sand yielding a maximum incision rate of 380 ± 190 m Ma⁻¹ of a canyon that the Bighorn River cuts through the Sheep Mountain anticline. Several other caves are scattered throughout the Bighorn Basin area of northern Wyoming.

Figure 10  Caves on the western flanks of the Sierra Nevada, California provide an incision history of rivers along those flanks that goes back 2 Ma. The speleothem data indicate that incision rates determined by ²⁶Al/¹⁰Be-dating of cave sediments changed drastically between 2.7 and 1.4 Ma, probably reflecting a change in uplift rate and the onset of glaciation. Modified from Haeuselmann, P., Granger, D.E., Jeannin, P.-Y., Lauritzen, S.-E., 2007. Abrupt glacial valley incision at 0.8 Ma dated from cave deposits in Switzerland. Geology 35, 143–146, with permission from GSA.
Preliminary results by the researchers of this study indicate the great potential for the future study of these and other types of cave sediments toward advances in landscape evolution of this area using caves.

6.8.4.7 Rates of Valley Incision in Switzerland

Cave sediments in Switzerland have shown the effectiveness of glaciers in rapidly forming valleys. Haueuselmann et al. (2007) recently reported the incision history resulting from glacial processes in the Aare Valley of Switzerland over the past 4 Ma using U-series and cosmogenic $^{26}$Al/$^{10}$Be dating of cave sediments. These studies have shown that incision accelerated from $\sim 120$ m Ma$^{-1}$ to as high as $1200$ m Ma$^{-1}$ between 0.8 and 1.0 Ma (Figure 11). This timing indicates that: (1) acceleration of valley incision started about a million years after the onset of local glaciations; (2) incision rates were $\sim 120$ m Ma$^{-1}$ from 5 to 1 Ma; and (3) something triggered an abrupt base-level drop at approximately 1 Ma. The researchers of this study pointed out that a global change in glacial cycle periodicity from 41 ka prior to 1 Ma to 100 ka after 1 Ma is this study pointed out that a global change in glacial cycle. The orange ellipses are extents of errors associated with incision history started about a million years after the onset of local glaciations; (2) incision rates were $\sim 120$ m Ma$^{-1}$ from 5 to 1 Ma; and (3) something triggered an abrupt base-level drop at approximately 1 Ma. The researchers of this study pointed out that a global change in glacial cycle periodicity from 41 ka prior to 1 Ma to 100 ka after 1 Ma is this study pointed out that a global change in glacial cycle. The orange ellipses are extents of errors associated with 0.8 Ma from the $^{26}$Al/$^{10}$Be-dating of cave sediments (large arrow points to the significant incision rate change). The timing of this change coincides with an acceleration of the periodicity of the glacial cycle. The orange ellipses are extents of errors associated with ages and elevations. Modified from Figure 3 of Haueuselmann, P., Granger, D.E., Jeannin, P.-Y., Lauritzen, S.-E., 2007. Abrupt glacial valley incision at 0.8 Ma dated from cave deposits in Switzerland. Geology 35, 143–146, with permission from GSA.

6.8.4.8 Krausshoehle, Austria

Research is currently being conducted in Austria on a sulfuric acid cave. U-series dating of speleothems and $^{39}$Ar/$^{40}$Ar dating of speleogenetic alunite are making contributions to the incision history of the gorge that exposed this hypogene cave (De Waele et al., 2009). Preliminary dates indicate that the lower portions of this cave formed $< 160$ ka, showing that the gorge that exposed this cave is being cut rapidly. This is only the second place globally – after the Guadalupe caves – where speleogenetic alunite has been used in this way.

References


Biographical Sketch

Victor Polyak is a senior research scientist in the Department of Earth and Planetary Sciences at the University of New Mexico, Albuquerque, New Mexico. His interests are finding ways to integrate speleology and radiogenic isotope geochemistry toward cave related studies. These studies include paleoclimate and landscape evolution research.

Carol Hill is an adjunct professor in the Department of Earth and Planetary Sciences at the University of New Mexico. She is the author of the books Cave Minerals of the World, Geology of Carlsbad Cavern and Other Caves in the Guadalupe Mountains, and Geology of the Delaware Basin, as well as articles on the Grand Canyon in Science, Geomorphology, and Journal of Hydrology.