because they may have migrated into deeper fractures in the aquifer, and they are harder to direct by altering the hydraulic gradient. With either type of NAPL, but especially with DNAPLs, one must be very careful to case wells properly in a contaminated area. An open borehole is an excellent way to transmit dissolved contamination or DNAPL to an underlying, formerly uncontaminated aquifer.

Soils

When an NAPL is spilled, it often passes through soil, which can be collected for quantitative laboratory analysis. Soil sampling may be useful for verifying the type of NAPL and whether any former spills took place at the site. Soil sampling in a sinkhole is not recommended, due to possible piping failure. Soil gas sampling may be very useful, especially for LNAPLs. Contaminants can volatilize, with the resulting gas moving up through the soil. Depending on the season, the contaminant, and the subsurface configuration, soil gas sampling may be a helpful technique for identifying and locating an NAPL product.

SUMMARY

Due to the heterogeneous nature of the karst subsurface, the rate of either water or NAPL transport through karst aquifers is highly variable. Both the quantity and timing of NAPL releases are important for understanding how the pollutant might be trapped in the aquifer. Individual NAPL characteristics such as density, solubility, vapor pressure, and viscosity are also key to recovering a contaminant from soils or groundwater. Over time, NAPL held in the epikarst or matrix can dissolve into the aqueous phase. Aqueous concentrations can be toxic and persist for many years, especially in the case of chlorinated compounds, which are naturally degraded more slowly than hydrocarbons. However, NAPL from large spills may move through a conduit on the order of kilometers per hour. All information about a specific karst system, including dye traces, spring response, depth to and shape of the bedrock surface, is important for evaluating the potential of NAPLs to be held in and transported through the subsurface. The study of NAPL contamination in karst aquifers is a relatively new aspect of karst science, and in the future will certainly be enhanced by additional case studies and research.

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COSMOGENIC ISOTOPE DATING OF CAVE SEDIMENTS

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INTRODUCTION

Natural curiosity prompts both cave explorers and first-time visitors to wonder "How old is this cave?" and "Why is it here?" Scientists have more specific reasons to study and date cave sediments. For example, geomorphologists use caves to learn about landscape evolution, or the sequence of events that shaped the rivers, hills, and valleys around us. Paleontologists study fossils in cave sediments to learn about animal and plant evolution and about the ecological communities that lived long ago. Paleoanthropologists study our ancestors' bones that are found in caves—whether from cave dwellers, or often those that were eaten in the caves. These fossils and their dates help teach us about our own human origins. Archaeologists search for clues about human use of caves. Some scientists also study caves for their own sake, to learn about how water flows through rock, and how the spectacular and labyrinthine underground environment is formed. All of these various fields require information about the age of the cave and its contents.

Caves are important across so many fields of science because the conditions underground are so protected and stable that minerals, rocks, and fossils can be preserved in exquisite condition for millions of years. Sediments and fossils on the ground surface are gradually but constantly weathered and eroded over time. The landscape on the surface changes slowly but surely as hillslopes are worn down, rivers incise or fill their beds with sediment, and forests grow and recede. By contrast, caves and their sediments can be nearly pristine, with delicate minerals, fossils, and sediments still intact. Although the hill or mountain that a cave is formed in may change over time, the cave itself is contained in solid rock, so it can maintain its original shape until the entire mountain itself is eventually eroded away.

Because knowing the age of a cave or its sediments is critical for learning about the past, several techniques for dating cave sediments and minerals have been developed. Each dating scheme has its own advantages and limitations. Some of the dating techniques such as paleomagnetism, uranium-series disequilibrium, and radiocarbon dating have become well established and widely used. This article concerns another, relatively new, dating technique that employs radioactive nuclides to date when sediment was brought into a cave. The method is called *cosmogenic nuclide burial dating* (Granger and Muzikar, 2001).

RELATIVE VERSUS ABSOLUTE DATING TECHNIQUES

When attempting to date a particular cave or its contents, there are several possible techniques to consider, depending on the age and the particular fossils or minerals in question. Some of these dating techniques are relative, indicating whether one thing is older or younger than another but not the exact age of either. For example, characteristic fossils in a cave can be used to place it relative to other deposits. Other dating techniques are absolute, meaning they give a numeric age that does not depend on correlations with any other site. Absolute ages are defined using some sort of "clock" that operates at a known and constant rate. By far the most widely used and reliable clock is radioactive decay.

To understand radioactive decay, it is helpful to first review the basic structure of the atomic nucleus. A nucleus is made of protons and neutrons. The number of protons in a nucleus determines to a large degree the way that an atom behaves; in fact, the elements of the periodic table are defined by the number of protons they have. Sometimes two different atoms may have the same number of protons, but different numbers of neutrons. In this case, the atoms are of the same element, but they have different masses. These two atoms are called *isotopes*. For a given element, some isotopes are stable, remaining unchanged over time. Other isotopes are radioactive, in which case the nucleus spontaneously breaks apart, losing mass and energy in radioactive decay. Radioactive decay occurs at a constant rate for any given isotope. If a certain amount of a radioactive isotope is contained in a rock, then half of that amount will decay in a characteristic time called the *half-life*. Half of the remaining half will decay after another half-life and so forth *ad infinitum*. Here is the clock for dating radioactive materials. If the original amount of a radioactive isotope is known, and the remaining amount can be measured, then the difference indicates the amount of time that has passed. The trick for cave scientists is to find a material with a known initial amount of radioactive isotopes. Cosmogenic nuclides provide just such a case.

BURIAL DATING WITH COSMOGENIC NUCLIDES

One way to date cave sediments is by determining the radioactive loss of cosmogenic nuclides. (The term *nuclide* refers to atoms regardless of their element, as opposed to *isotope*, which always refers to atoms of the same element.) Cosmogenic nuclides are produced by cosmic rays—energetic particles coming from outer space that constantly bombard Earth. Most of the cosmic rays are absorbed in the atmosphere, producing particles such as ^{14}C that is used for radiocarbon dating. Some secondary cosmic rays reach the ground surface and cause nuclear reactions inside rocks and minerals found within a few meters of the surface. During these nuclear reactions, the nuclei inside the mineral grains are broken apart, forming lighter nuclides. By chance, some of the products of these reactions are radioactive. For example, we can consider reactions in the mineral quartz. Quartz has a chemical formula SiO_2. Silicon nuclei each have 14 protons, and most of them have 14 neutrons. The common silicon nucleus thus has a mass of 28, written ^{28}Si. An incoming cosmic ray particle will occasionally break apart a silicon nucleus. If a proton and a neutron are lost, then the ^{28}Si is converted into ^{26}Al. Fortunately for dating, ^{26}Al is radioactive, with a half-life of 700,000 years. Another reaction that occurs in quartz is the conversion of ^{16}O to ^{10}Be through the loss of 4 protons and

2 neutrons. Beryllium-10 is also radioactive, with a half-life of about 1.4 million years. These two different radioactive nuclides are produced in the same quartz grain, and are the key to dating sediment burial in caves. A diagram of the reaction producing ^{26}Al is shown in Figure 1.

Over thousands of years, as rocks are exposed to cosmic rays they build up an inventory of ^{26}Al and ^{10}Be. Many repeated measurements of quartz grains on the ground surface have shown that ^{26}Al is produced about 6.8 times faster than ^{10}Be. Since both the production rates and the half-lives are known, the concentrations of ^{26}Al and ^{10}Be in rocks exposed to cosmic rays can be calculated. For most rocks at the ground surface, the ^{26}Al:^{10}Be ratio is 6.8:1. If quartz is brought into a cave, though, the grains are shielded from cosmic rays so ^{26}Al and ^{10}Be are no longer produced.

After the quartz-bearing sediment is brought into the cave, radioactive decay gradually lowers the concentrations of both ^{26}Al and ^{10}Be. Aluminum-26 decays faster than ^{10}Be, so the original ^{26}Al:^{10}Be ratio decreases over time. After 700,000 years half of the ^{26}Al is gone, but only 30% of the ^{10}Be has decayed. The original ratio of 6.8:1 has thus been lowered to about 4.8:1. The ^{26}Al:^{10}Be ratio provides the radioactive clock that we can use to date cave sediments, with an original ratio of 6.8:1 that decreases exponentially over time. Figure 2 shows the decay of the two nuclides, and the ^{26}Al:^{10}Be ratio as a function of time. As the concentrations of ^{26}Al and ^{10}Be get smaller and smaller over time, they become more difficult to measure. The practical limit to measurement usually occurs after about 5 million years of burial for this reason.

Aluminum-26 and ^{10}Be in sediment can only be measured using a very sensitive technique called *accelerator mass spectrometry* (AMS). This is because the concentrations of the cosmogenic nuclides are extremely small. For example, only 5 atoms of ^{10}Be may be produced in a gram of quartz in an entire year, and a sample

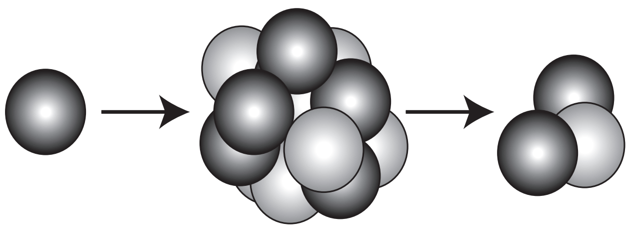

FIGURE 1 An example of a spallation-type nuclear reaction, in which an incoming cosmic ray neutron (left) impacts a ^{28}Si nucleus (center), to knock off two neutrons and a proton (right), making radioactive ^{26}Al. Neutrons are indicated by the darker-colored spheres, protons by the lighter-colored spheres.

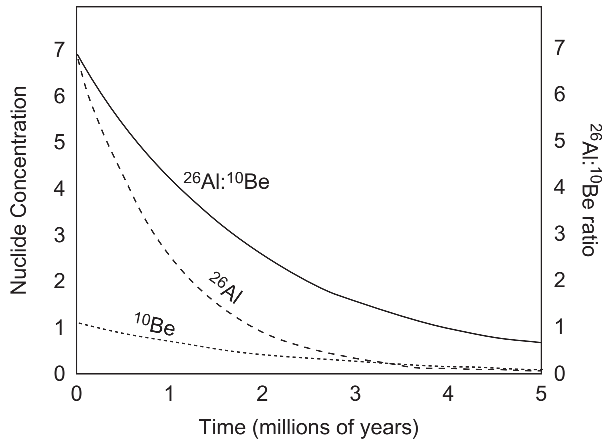

FIGURE 2 A graph of the concentrations of ^{26}Al and ^{10}Be (arbitrary units), and the ^{26}Al:^{10}Be ratio in quartz grains over time. The grains are washed into a cave with an original ^{26}Al:^{10}Be ratio of 6.8:1. Because ^{26}Al decays faster than ^{10}Be, the ^{26}Al:^{10}Be ratio decreases over time. The ^{26}Al:^{10}Be ratio can thus be used to date when the sediment was deposited in the cave.

may contain less than a million atoms of ^{10}Be. AMS is capable of measuring an isotope ratio (*e.g.*, ^{10}Be/^{9}Be or ^{26}Al/^{27}Al) as low as 10^{-16}. That is, if there are 10^{16} atoms of the common isotope ^{27}Al, then AMS can detect a single atom of cosmogenic ^{26}Al.

Requirements for Burial Dating

As with any dating technique, it is important to consider the circumstances for which dates will be reliable, and those for which dates will be unreliable or impossible to obtain. Burial dating has several rather strict requirements. First, the sediment must have washed into the cave from outside, that is, it must be allochthonous. Otherwise, there would be none of the cosmogenic nuclides to begin with. Second, the sediment must contain the mineral quartz, because that is the mineral for which we know the production rates of ^{26}Al and ^{10}Be. Quartz is not always common in cave-forming bedrock, so even if there is allochthonous sediment in the cave it may not be datable. Third, the sample must be buried underground by at least 20 meters for the technique to be reliable over millions of years. It is possible to date more shallowly buried samples, but this introduces higher uncertainties. Fourth, there are limitations on the burial times. The sediment cannot have been buried more than about 5 million years, or the ^{26}Al and ^{10}Be are no longer detectable. Uncertainties in measuring ^{26}Al and ^{10}Be are usually 3–5%, making it difficult to achieve burial dates more precise than about 100,000 years. So the sediment must have been buried for at least 100,000 years. Finally, the sediment must come into the cave without a prior history of burial. If the sediment were, for instance, buried at the bottom of a doline for a million years and then washed into the cave, then the burial age would account for the total time spent buried, not just that in the cave. Although these uncertainties limit the application of burial dating somewhat, there are many situations for which the technique is ideal. We describe two examples below.

Example 1: The Development of Mammoth Cave, Kentucky

Mammoth Cave, the longest known cave in the world, has developed alongside the Green River in Kentucky. It is an example of a water-table cave, or one that has developed nearly horizontal passages that are closely controlled by the level of groundwater flow (Palmer, 1981). At Mammoth Cave, the water level is in turn controlled by the elevation of the Green River. Rainfall on the nearby Pennyroyal plateau quickly infiltrates the karst bedrock until it reaches cave passages that are filled or nearly filled with water. These underground streams then flow toward the Green River, passing through a sandstone-capped limestone plateau to discharge as springs on the Green River. In addition to the large recharge area that captures abundant rainfall, the sandstone-capped plateau is a major reason why Mammoth Cave is so long. The sandstone is a rock made of cemented quartz sand that is very resistant to erosion. Over time, as the Green River has cut through the sandstone and into the underlying limestones, cave passages have formed at successively lower levels. In many landscapes, the old cave passages above would be destroyed by erosion as new cave passages were formed below. However, at Mammoth Cave the sandstone is so resistant to erosion that the older passages have not eroded away. The sandstone forms ridges beneath which are preserved stacks of cave passages, the oldest passages near the top and the youngest passages at modern river level.

The preservation of old passages at Mammoth Cave provides a wonderful opportunity for studying how the cave has developed, and how the Green River has incised and aggraded over time. Geologist and hydrologist Art Palmer has spent many years carefully working out the sequence of events that are encrypted within Mammoth Cave's passages. It is very difficult, though, to decipher the history of the cave without dates that can be used to tie passages together across the cave system, and to match episodes of cave development with other geologic events. Burial dating with cosmogenic nuclides has provided a set of dates that helps show how the development of the Mammoth Cave System has been strongly influenced by climate change and the growth of ice sheets across North America. Although ice sheets did not reach Mammoth Cave itself, they did impact the Green River, which alternately incised and aggraded, forming sets of passages beneath the ridges at Mammoth Cave.

Burial dating works at Mammoth Cave because quartz pebbles from conglomerates within the sandstone upland are carried into the cave by sinking streams. These streams carry the pebbles through the cave system and into the Green River. When the river incises deeper, new passages are formed at lower elevations. The old passages are no longer occupied by streams, so whatever quartz pebbles were being carried through the cave are left in place, to sit within the now-abandoned cave passages. These packages of quartz-bearing sediment can be found throughout nearly the entire cave system. It is important to realize that the sediments indicate not when the passage formed, but when the passage was abandoned. It is only through careful analysis of the cave that the abandonment of one passage can be linked to the growth of another.

Granger *et al.* (2001) dated sediments from throughout the Mammoth Cave System. These samples reach ages up to 3.5 million years old in the uppermost levels of the cave, and tell an interesting story of how the cave developed over time. First, the dates show that the Mammoth Cave System is quite old. If the sediments that fill the cave are up to 3.5 million years old, then the cave itself must be significantly older than that! The upper levels of the cave system substantially predate the ice ages, which began roughly 2.5 million years ago. The cave, then, reveals how the landscape of central Kentucky responded to this major climate change. The initial response to climate change seems to be that the entire cave system filled up with sediment. Visitors to Mammoth Cave will notice telltale signs of sediment everywhere, even in nooks and crannies on the passage ceilings. These sediments show that most of the cave was filled up at about 2.4 million years ago, which in turn indicates that the Green River valley must be filled up as well. The landscape response to climate change was river aggradation, perhaps due to increased hillslope erosion that would have supplied more sediment than the river could carry. The next chapter in the story of Mammoth Cave is river incision and cave development at lower levels. Mammoth Cave is developed in levels, indicating that river incision was episodic. Each new level represents a pulse of river incision. Granger *et al.* (2001) found that these incision pulses correlate with large glaciations that covered most of eastern Canada and the northeastern United States, advancing as far as the northern edge of Kentucky. These large ice sheets completely reorganized river systems that were either buried beneath the ice or blocked by great ice dams. In fact, the modern courses of rivers such as the Ohio River, the Missouri River, and the northern Mississippi River were shaped along the edges of ice sheets. Each time that the Ohio River or Mississippi River incised due to glaciation or sea-level lowering, the Green River followed closely behind. Mammoth Cave thus records in its passages a key to the history of eastern North America over the past 3.5 million years.

Example 2: Caves and Human Evolution

Caves have always held an important place in human evolution, because so many fossils have been found in them. This is not necessarily because early humans lived in caves, but because the bones are so well-preserved, and often because predators or scavengers carried the bones there. Cave deposits, though, have been difficult to date beyond a few hundred thousand years. Cosmogenic nuclide burial dating has provided a new tool for dating these old fossils.

One example is found at the caves of Atapuerca, Spain. These are multilevel caves formed as the nearby Arlanzon river incised. A railroad cut through the limestone breached into the caves, and revealed that at several places the cave had filled with sediment from above, where shafts connected the passages to the surface. These sedimentary infills contain an abundance of fossils, including human ancestors.

The sedimentary infill at Atapuerca known as Sima del Elefante fills a vertical canyon 18 meters deep. The lower part of the infill contains some of the oldest fauna found at Atapuerca, including weasels, beavers, cave bears, and European jaguar. In 2007, a partial jaw and teeth from a human ancestor were discovered, as were several stone tools. Two samples of sediment were taken from very near the fossil for cosmogenic dating. The two samples agree closely, and give an average burial age of 1.18±0.12 million years. This makes the bone the oldest dated fossil of a human ancestor in Europe (Carbonell *et al.*, 2008).

A second example comes from Zhoukoudian, near Beijing, China. This is a vertical cave that was completely filled with sediment. The site is famous for the discovery of "Peking Man" in the late 1920s. Peking Man was among the first discovered human ancestors, and played an important role in the early development of the science of paleoanthropology. The age of Peking Man has been debated for many years, with most people believing that the fossil is about 500,000 years old. Cosmogenic nuclide burial dating provides a way to determine the age absolutely.

Shen *et al.* (2009) collected six samples of quartz sediment from the cave infill, and also four stone tools made of quartz. Out of these ten samples, six were used to date Peking Man. These samples have an average age of 0.77±0.08 million years, substantially older than previously thought. They were able to correlate sedimentation of the cave with global climate cycles, and together with the cosmogenic burial ages suggested that Peking Man occupied northern China during a cold phase, when Beijing was cooler and drier than today. This has important implications for the types of environments that early humans were capable of colonizing.

SUMMARY

These two examples of burial dating with cosmogenic nuclides show only the beginning of what the dating technique can do. The sediments in the Mammoth Cave System were an integral part of how the cave was formed. The sediments reveal the evolution of the cave system, and how cave development is tightly coupled to river incision and aggradation. In this case, Mammoth Cave was ideal because it was a water-table cave that carried quartz from local bedrock. In contrast, Atapuerca and Zhoukoudian are sedimentary infills where sediment (and animals) fell into a preexisting cavity. Such cave infills are the norm in archaeology and paleoanthropology because they collect bones and artifacts over long periods of time. In this case, the cosmogenic nuclides dated the sedimentary infill rather than the cave itself. There are many more situations where geomorphologists, paleoanthropologists, and other scientists can benefit from dating cave sediments over the past 5 million years.

See Also the Following Articles

Clastic Sediments in Caves
Multilevel Caves and Landscape Evolution
Mammoth Cave

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CRUSTACEA

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INTRODUCTION

Crustaceans are one of the oldest and most diverse arthropods as well as one of the most successful groups of invertebrates on Earth, with approximately 40,000 extant species described and some 150,000 species recognized. They have been extremely successful in aquatic habitats, yet some species have become adapted on land as well. Their fossil record indicates that they are an ancient group, having occupied marine environments since the lower Cambrian period yet very early in their evolutionary history they invaded freshwater habitats. Although about 90% of the currently recognized taxa are widespread in marine systems, the remaining 10% are found in diverse inland waters and assume important roles in various ecosystem processes of many surface and subterranean lotic and lentic habitats (Hobbs 2000). This article focuses on the hypogean members, specifically on those crustaceans that are highly adapted to dwelling in groundwater ecosystems and generally referred to as *stygobionts* (obligate hypogean aquatic forms).

In addition to being taxonomically diverse, crustaceans are anatomically disparate, having evolved an assortment of body forms accomplished by developing highly specialized body segments and appendages as well as by fusing various segments. As a group, crustaceans are bilateral, having internal and external segmentation, and an open hemocoel. They have a rigid, chitinous exoskeleton composed of a thin proteinaceous epicuticle and a thick multilayer procuticle that in many groups is hardened by small inclusions of calcium carbonate. Their bodies are generally divided into the cephalon (head), thorax, and abdomen (with the former two sometimes combined as the cephalothorax). The many jointed appendages are biramous (or secondarily uniramous), may occur in all regions of the body, and these arthropods possess paired antennules (uniramous in all crustaceans except malacostracans), antennae, mandibles, and maxillae.

Crustaceans have invaded the hypogean realm, occupying interstitial and other groundwater habitats, including anchialine waters (inland groundwater with subsurface marine connections harboring unique fauna) in karst (see article entitled "Anchialine Caves" in this volume) as well as in other landforms (*e.g.*, lava). Some species of amphipod and isopod crustaceans have abandoned the groundwater and have been successful in the terrestrial hypogean environment. Most species dwelling in subterranean environments exhibit a suite of characteristic traits that are adaptive for life in such extreme ecosystems. Examples include reduction or loss of eyes and pigments, elongation of appendages, increased chemical and tactile sensitivity, degeneration of circadian rhythms, lowered fecundity and metabolic rates, and increased longevity and ovum volume. These embody behavioral, ecological, morphological, and physiological modifications that include both the reduction or loss of characters (regressive evolution) as well as the augmentation of others (constructive evolution). These various adaptations combine to generate the convergence characteristic of most obligate, cave-adapted organisms that is referred to as *troglomorphy* (see Culver and Wilkens 2000).

Crustacean taxonomy continually undergoes reevaluation and revision and the classification structure used herein (generally based on Martin and Davis, 2001) reveals five classes having subterranean representatives: Branchiopoda, Remipedia, Maxillopoda, Ostracoda, and Malacostraca (Table 1); a brief discussion of the classes and their hypogean representatives (predominantly stygobionts) is presented next.

SYNOPSIS OF STYGOBIOTIC CRUSTACEAN TAXA

Class Branchiopoda

Branchiopods are relatively small heterogeneous crustaceans that share few characteristics, including small to vestigial head appendages with similar mouthparts, flattened leaflike thoracic legs called *phyllopods* that usually decrease in size posteriorly, and a pair of spines or claws on the ultimate body segment. Classification of branchiopods has undergone numerous revisions and, of the currently recognized orders, only Diplostraca has subterranean members. There are about 100 species of the suborder Cladocera (450 total species) that occupy the subterranean environment (Table 1).

They are known from subterranean waters (especially the interstitial/hyporheos) on all continents, but especially well in Bosnia and Herzegovina, France, Romania, Slovenia, and Spain. These small transparent crustaceans have a carapace that is laterally compressed and attached dorsally to the body around which it is wrapped, excluding the head. Troglomorphic adaptations are very minor except in a few species of the genera *Alona* and *Spinalona*, evident by a lack of eyes

