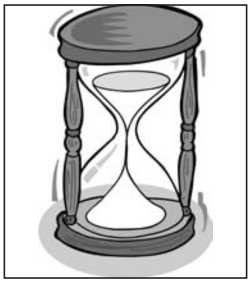


How Old Is It? How Do We Know? A Review of Dating Methods—Part One: Relative Dating, Absolute Dating, and Non-radiometric Dating Methods

Davis A. Young

Davis A. Young

The essential ideas behind the major methods for assessing the relative ages of geological and archeological materials and events are reviewed. These include the principles of original horizontality, superposition, inclusion, cross-cutting relations, and cross-dating by index fossils (biological succession) or artifacts. Some general principles of absolute dating are introduced, and, as representatives of non-radiometric methods, tree-ring, thermoluminescence, obsidian hydration, and amino acid racemization dating are discussed with examples.

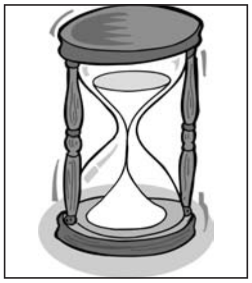
Until the mid-eighteenth century, Christians assumed that the history of the human race could be deciphered from Scripture, monuments, artifacts, and documents. No one conceived that the Earth had a very lengthy pre-human history. After all, Genesis presumably taught that God created the Earth mere days before he created Adam and Eve. Martin Rudwick has documented that, throughout the late eighteenth and early nineteenth centuries, "savants" and "natural historians" began to realize that the Earth does have an extensive pre-human history that can be deciphered from such natural "documents" and "monuments" as rock strata and fossils.[1] In the nineteenth century, archeology and paleo-anthropology began to extend the timescale of human history. Since then, researchers in a wide range of disciplines have developed a host of methods for determining both "relative" and "absolute" ages of rocks, minerals, fossils, trees, pottery, tools, occupation sites, art objects, and much else.

What, then, are the grounds on which we can assert that a particular body of rock is older than some other body of rock (*relative dating*)? And how do we know that a particular stratum in an ancient Near Eastern tell is younger than another stratum? How can we be confident that a certain granite intrusion in the Sierra Nevada of California is 82 million years old rather than 80,000 years old or that an artifact is 12,000 years old (*absolute dating*)?

In this first part of a three-part series, we begin to answer these questions in a very brief review of fundamental principles of relative and absolute dating and of non-radiometric methods.[2] The second article will deal with radiometric dating methods used for determining ages of crystallization of minerals, rocks, and meteorites. The final article will address radiometric dating that involves cosmogenic nuclides, fission-track dating, and U-He dating, and will also consider some theological implications.

Since [the nineteenth century], researchers in a wide range of disciplines have developed a host of methods for determining both "relative" and "absolute" ages of rocks, minerals, [etc.].

After graduating from Princeton University, **Davis A. Young** *received a M.S. degree from Penn State and a Ph.D. degree in geological sciences from Brown University in 1969. Dave then taught geology for five years at New York University, five years at the University of North Carolina at Wilmington, and 26 years at Calvin College. Upon retirement from Calvin in 2004, Dave and his wife Dottie moved to Tucson, Arizona, where they enjoy the view of the Santa Catalina Mountains and Dave vigorously pursues his hobby of birding. A fellow of ASA, Dave continues service as a member of the Editorial Board of* Perspectives on Science and Christian Faith. *He and his wife are members of Catalina Foothills Presbyterian Church in America.*



Article

How Old Is It? How Do We Know? A Review of Dating Methods — Part One: Relative Dating, Absolute Dating, and Non-radiometric Dating

Relative Dating

Relative dating was first applied to rock strata in the mid-seventeenth century by a devout Christian anatomist, Niels Stensen (Steno) in his formulation of several basic stratigraphic principles that are still routinely applied by all geologists and, in modified form, by archeologists.[3]

Relative dating principles of great importance to geology are:

- *the principle of original horizontality,*
- *the principle of superposition,*
- *the principle of inclusion,*
- *the principle of cross-cutting relationships, and*
- *the principle of biological (or fossil) succession.*

The *principle of original horizontality* takes its clue from the observation that modern sediment layers, with exceptions such as the dipping sand layers in dunes and sediments that accumulate on moderate slopes, are commonly deposited very close to the horizontal. In applying this principle to layered sedimentary rocks such as sandstone, conglomerate, and limestone, one may safely infer that a stack of such rock layers that is tilted (dips) at a fairly steep angle must have experienced an episode of tilting subsequent to its original deposition as approximately horizontal layers. Because layered deposits of human origin, such as trench fillings, may be oriented at a steep angle, original horizontality does not always hold for layers at archeological sites.

The *principle of superposition* states that, in a stack of undisturbed layered rocks that were deposited on the surface of the Earth (sedimentary rocks or lava flows), any given layer must have been deposited before the layers above it, and is, therefore, older. Similarly, the layer must have been deposited later, hence is younger, than layers below.[4] For example, there is no field evidence that the layered rocks of the Colorado Plateau, of which the Grand Canyon region is a small part, were flipped upside down. Therefore, the Tapeats Sandstone at the bottom of the horizontally layered sequence exposed in the canyon walls must be older than all the layers above from the Bright Angel Formation to the Kaibab Limestone at the top of the canyon walls. The Redwall Limestone, a unit forming a prominent cliff halfway up the canyon walls, must be older than the strata of the overlying Supai Group and younger than the underlying Muav Limestone. The principle of superposition is also routinely applicable to any stratified archeological site such as the ancient Near Eastern tells of Iraq or Israel, Native American mounds, deposits flooring a rock shelter, and deposits on the floor of a cave. Archeologists must exercise extreme caution in applying superposition given that stacks of sediment layers at archeological sites are commonly subject to disturbance such as excavation of burial sites into older sediments or reworking by organisms.

Steno also introduced what we might call a *principle of inclusion*. A pebble, a crystal, or a fossil normally had an existence that preceded its incorporation into a developing mass of rock. There can be exceptions, however. Some crystals, for example, grow within a pre-existing rock at the expense of surrounding material. In such cases, crystal growth may cause visible deformation of the surroundings. Competent geologists can normally determine whether an included object pre-dates or post-dates its host rock. Similarly, a stone tool, pot, or figurine is generally older than the sediment layer that was deposited on and around it unless it can be demonstrated that it was subsequently buried in a lower layer.

The *principle of cross-cutting relationships* is especially important in deciphering temporal relations of igneous, metamorphic, and vein rocks. When the principle was first formulated is unclear, although James Hutton certainly used it in his claim that granite is an intrusive rock. In 1785, Hutton observed veins and dikes of granite projecting finger-like across the oriented structures of the surrounding gneisses and schists in Scotland's Glen Tilt. From these relations, he inferred that the granite veins must be younger than the gneisses. The principle maintains that a feature which cuts across layering or any other oriented structure of the surrounding rocks must have been emplaced after the surrounding rocks were already in place (Figure 1). This principle also applies to archeological sites. For example, the foundations of walls may have been set by excavation into a lower substrate and have the appearance of transecting the stratification immediately beneath.

Although a skilled geologist can quickly assess the probable sequence of events that affected the rocks exposed in an outcrop or road cut from all four of these principles, there is an additional principle of great importance to geology, the *principle of biological* (or *fossil*) *succession*. Similarly, archeologists may talk of cross-dating with index fossils or artifacts. During the second half of the eighteenth century, several students of the

Earth such as Georg Füchsel and Giovanni Arduino recognized that rock strata typically contain characteristic suites of fossil remains by which they may be distinguished from other strata. Between 1790 and 1810, William Smith in England, and Georges Cuvier and Alexandre Brongniart in France, developed this principle. In conjunction with the principle of superposition, Cuvier and Brongniart especially showed that distinctive suites of fossils can be used to determine the relative ages of rock layers within a given region. Before long, geologists attempted to correlate rock layers in different areas.

On the basis of rock type alone, however, widely separated successions of strata cannot always be physically traced from one to another. Matching of similar rock types in different areas proved to be less than adequate for correlation because successions of strata commonly contain several layers of similar rock types. However, because fossil suites in thick undisturbed stacks of layered sedimentary rocks invariably occur in the same relative order, one could temporally correlate layers containing identical or similar suites of fossils from widely separated groups of rock (Figure 2). In some cases, all that is needed for satisfactory correlation is a single widely distributed fossil species, known as an index fossil, that is generally restricted to relatively small thicknesses of sedimentary rock.

From the late eighteenth well into the nineteenth centuries, geologists gradually constructed a geologic timescale by applying formal names to the groups of rocks containing distinctive fossil remains. Thus, assignment of Carboniferous age to a group of strata on the basis of its fossils means that the rocks in question are younger than underlying Devonian rocks and much younger than underlying Cambrian strata, and much older than overlying Tertiary rocks. The principle of biological succession has its archeological counterpart. Widely separated sites might be temporally correlated thanks to the occurrence of fossil bones from identical species at each site. Correlation can also be done with cultural artifacts such as distinctive styles of pottery or tools. For example, Clovis points have typically been regarded as older than Folsom points.

Figure 1. Pegmatite dike cutting across foliation (preferred orientation) of schist at base of Sugarloaf, Rio de Janeiro. In accord with the principle of cross-cutting relationships, the dike is younger than the schist. Photo by the author.

Absolute Dating

Neither geologists nor archeologists are content with knowing when a given rock or occupation level was formed relative to other rocks or occupation levels. They also want to know exactly *when* the rock or layer was formed. A geologist might confidently state that a fossiliferous limestone formation has a Cambrian age and is, therefore, relatively quite old. But—how old? It is one thing to determine that a given stratum or rock body is older or younger than another stratum (relative dating). It is an entirely different matter to determine exactly when a given stratum or rock body was formed (absolute dating). Was it 50,000 years ago or 50 million years ago? Absolute dating makes historical reconstruction more accurate, provides insight into the lengths of geological events or culturally significant periods, and allows for calculation of the rates at which geological processes and cultural developments occurred.

Relative dating forms the basis of all absolute dating. Because there is no compelling reason to doubt that a layer at the bottom of a stack of undisturbed layers of sedimentary rock was deposited prior to deposition of all the layers above it, the principle of superposition serves as an important check on the *reliability* of claimed absolute dates. If an absolute dating method indicates that layer B is 50 million years old and that layer A is 20 million years old, but layer B

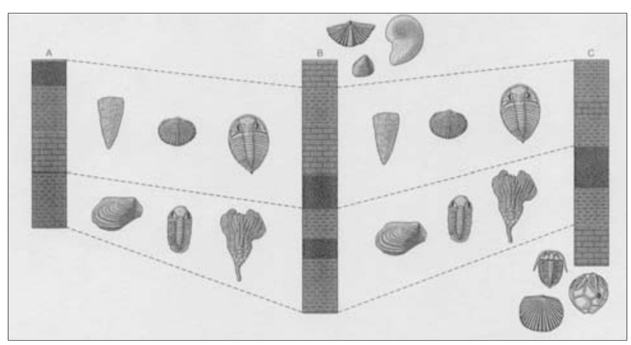
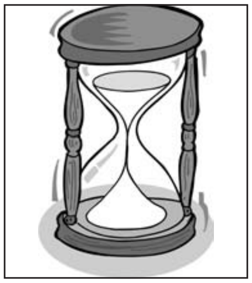


Figure 2. Diagram illustrating application of the principle of biological succession to temporal correlation of widely separated sequences of fossiliferous strata. Formations with similar fossil content are regarded as coeval. Reproduced from R. Wicander and J. S. Monroe, *Historical Geology* (Pacific Grove, CA: Brooks/Cole, 2000), 58.



Absolute dating makes historical reconstruction more accurate, provides insight into the lengths of geological events or culturally significant periods, and allows for calculation of the rates at which geological processes and cultural developments occurred.

is superposed on layer A and there is no physical evidence that the layers have been turned upside down, then either the absolute dating method is flawed, the analysis was done incorrectly, or the application of the method neglected some relevant factor. Likewise if we date a dike of igneous rock that cuts across a layer that we know is no older than 100 million years old, we should suspect the validity of our results if an absolute age of the dike is determined to be 370 million years old. Something is suspect in the absolute dating method employed.

In the nineteenth century, geologists could only estimate absolute geologic time. One method entailed measuring thicknesses of sedimentary rock sequences of different geologic ages, estimating the rates at which the sediments were deposited and compacted, and calculating ages from that information. Rough estimates of the duration of the various geologic time periods such as the Cambrian Period or eras such as the Mesozoic Era were advanced. Estimates of the age of the Earth based on sediment thicknesses ranged from three million to six billion years![5]

A method for estimating the age of the ocean was based on the accumulation of salt in the ocean. The age was calculated by measuring the concentrations of salts (primarily sodium) dissolved in the ocean and in the rivers of the world and by estimating the rates at which dissolved salts are added to and removed from the oceans.[6] Approximations of the ages of the Sun and the Earth were based on estimates of the Sun's and the Earth's initial temperatures, evaluation of additions of heat, and calculations of the rate at which these bodies had cooled. In 1862, Lord Kelvin estimated that the Sun was probably no more than 100 million years and certainly no more than 500 million years old and that the Earth took 20 to 400 million years to solidify.[7] By 1899, Kelvin lowered his estimate for the age of the Earth to between 20 and 40 million years, with a bias toward the smaller value.[8]

These methods entailed far too many variables and uncertainties to yield reliable estimates of the age of the Earth, and the last two were not even capable of providing absolute ages of specific rock bodies. Since the beginning of the twentieth century, scientists have developed a broad set of methods for calculating accurate absolute ages that entail physical, biological, or geological processes that proceed at known, measurable rates. Such processes include, among others, the spontaneous decay of radioactive isotopes in minerals, rocks, and glasses; the conversion of left-handed amino acids in organic materials to right-handed forms; the annual growth of tree rings; the growth of hydration rinds in obsidian fragments; or the dislocation of electrons in crystal structures by environmental radiation.

No single method is capable of dating geological and archeological materials from the entire range of ages. For example, the Sm-Nd radioactive decay method is useful only for dating minerals and rocks that are typically hundreds of millions to billions of years old. One cannot accurately date a 3,000-year-old piece of pottery by the Sm-Nd method. In contrast, radiocarbon or thermoluminescence methods are useful for dating materials that are only hundreds to a few tens of thousands of years old. These methods are of no value for dating a mineral that crystallized 250 million years ago. The K-Ar method is valuable for dating materials that are in the range of hundreds of thousands to a few millions of years.

No single method is capable of dating all kinds of geological events. To employ a suitable method geochronologists must ask what geologic event is being dated. Does an age obtained from analysis and calculation refer to the time of original crystallization, time of metamorphism, time during the cooling history of a rock when an accumulated daughter product ceased to diffuse out of the sample, time when a meteorite was first exposed to cosmic rays or when a rock was first exposed to the atmosphere, time of sediment deposition, time of diagenesis, time of uplift, time of burial, time of heating, or time of death?[9] Not all dates have the same meaning. Because specific methods are generally well suited to dating only specific kinds of events, employment of a wide range of methods is most useful in reconstructing different aspects of the history of a given geological region.

No single method can be applied to any and every kind of geological and archeological material. A crystal of quartz cannot be dated by

Rb-Sr methods whereas thermoluminescence may yield information about quartz. One cannot accurately date a sample from a *submarine* basaltic lava flow by the K-Ar method because such lava flows commonly trap argon gas that was already dissolved in the original magma. As a result, any measured age will likely be spuriously high inasmuch as some of the ^{40}Ar in the sample was already present when the lava was extruded and did not result from the radioactive decay of ^{40}K in the sample. One cannot date zircon by the obsidian hydration method, but U-Pb methods are very effective when applied to zircon crystals.

Ideally geochronologists would like to apply as many methods that are applicable to the situation of interest as are affordable and feasible. The results may serve as a check on each another and yield greater insight into the history of a set of rocks than the results from only one method.

Non-radiometric Dating Methods

There are numerous non-radiogenic methods that are especially useful in archeological applications. We will briefly examine four of these methods. Other methods not discussed include amino acid epimerization, archeomagnetic dating, electron-spin resonance, and methods based on periodically laminated sediments.

Dendrochronology, or tree-ring dating, is the most accurate and precise chronometer because normally each tree ring represents an annual growth.[10] Ideally each ring can be precisely dated to the year of its growth. As a result, dendrochronology has served as the standard for the last 10,000 years by which other methods such as radiocarbon are calibrated. Most tree species typically produce annual growth rings characterized by a light-colored earlywood band that grades into a dark-colored latewood band. The following year's growth ring is sharply demarcated from the preceding year's growth ring. Although many trees generate rings of approximately constant thickness from year to year, trees sensitive to stressful changes in environmental conditions such as temperature and humidity will produce rings that vary in thickness from year to year. Growth is generally promoted by higher average temperature and high precipitation. It is the *sensitive* tree species that are the best suited to dendrochronological dating because, to determine when a tree lived and died, portions of its ring pattern are matched to ring sequences with similar relative thickness variations in a standard master chronology (Figure 3).

Master chronologies are constructed from the ring patterns of numerous trees of diverse ages of the same species that grew in the same general region. Because these trees all experienced very similar environmental conditions, they each produced sequences of growth rings of similar relative thickness (Figure 3). Master chronologies

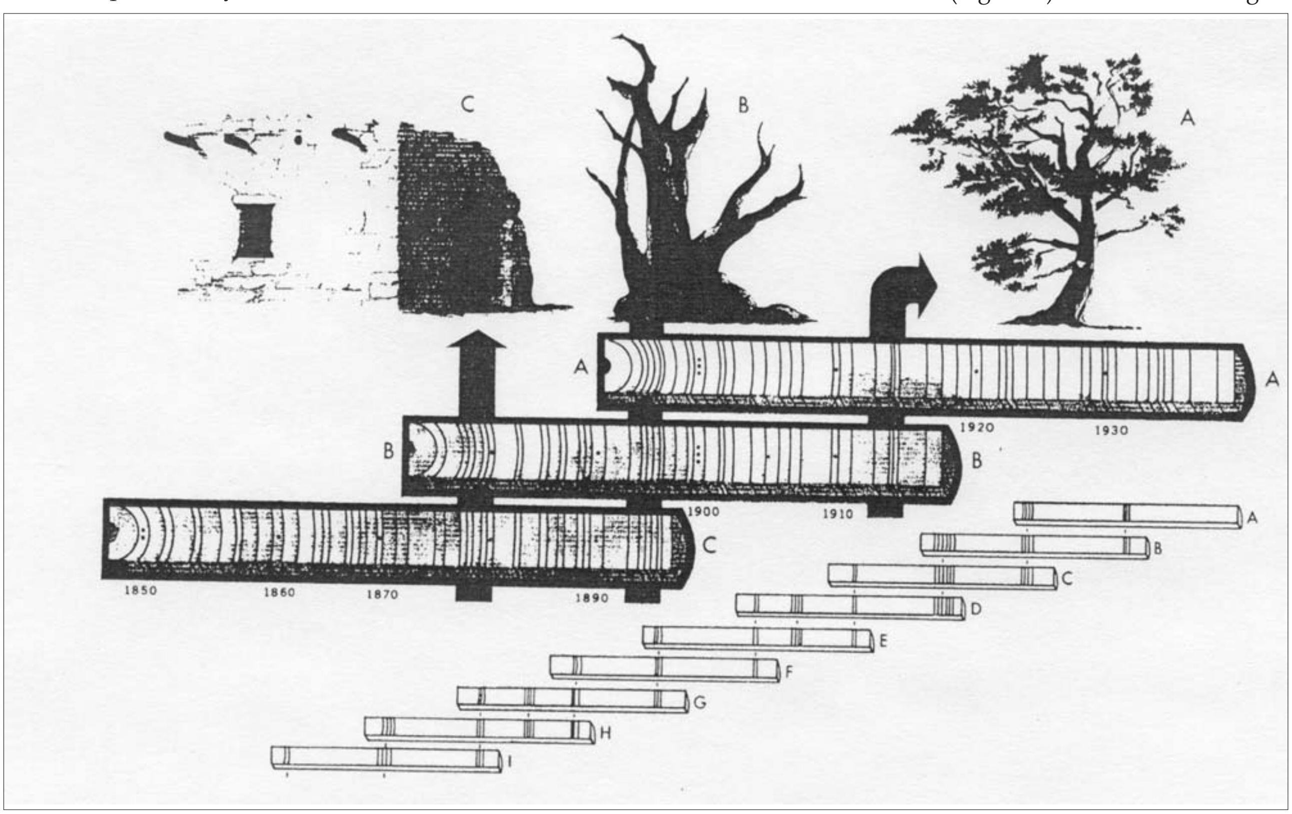
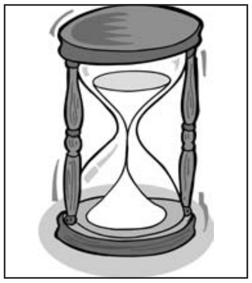


Figure 3. Schematic illustration of the construction of tree-ring chronologies from cross-dated ring sequences from A) living tree, B) dead tree, and C) old human structure. With the kind permission of Springer Science and Business Media this figure is reproduced from J. S. Dean, "Dendrochronology," in R. E. Taylor and M. J. Aitken, eds., *Chronometric Dating in Archaeology* (New York: Plenum Press, 1997), 38.



have been constructed for several regions around the world where environmental conditions promote variation in ring width. Examples include several chronologies that span more than 8,000 years based on bristlecone pine in the Great Basin of the western United States; a 3,220-year sequoia chronology for the Sierra Nevada in California; a 1,600-year baldcypress chronology for the southeastern United States; a 3,622-year alerce chronology for Chile; a chronology that encompasses 9,000 years for the eastern Mediterranean region; and a 12,000-year oak chronology for Europe.

There are numerous non-radiogenic methods that are especially useful in archeological applications. … Dendrochronology, or tree-ring dating, is the most accurate and precise chronometer …

Furniture, art objects, utensils, statues, tools, and timbers all provide suitable material for dating. The eruption of Sunset Crater in northern Arizona was dated at AD 1064 from timbers in nearby structures that contained ash from the volcano, and cliff dwellings in northeastern Arizona have been dated to the thirteenth century.[11]

Several methods are based on the accumulation of electrons trapped in higher energy states within the crystal structures of minerals like quartz and calcite. We will consider thermoluminescence as an example.[12] Thermoluminescence dating is effective with materials that have been subjected to severe heating such as pottery, baked flint, or fragments of volcanic rock. Such episodes of intense heating restore already trapped electrons in the material to normal crystallographic sites. The thermoluminescence clock is thereby set at zero. Subsequent to the heating event, a piece of pottery or a fragment of flint is exposed to various sources of radiation including radioactive minerals in the surrounding soil, radioactive minerals within the sample, and solar and cosmic radiation if the sample remains on the surface. To minimize effects of solar radiation, buried samples are normally collected for dating. The energy transferred to the sample by radiation dislocates electrons to higher energy levels. Over time, the number of electrons that are trapped in crystal defects at these higher energy levels increases. When a sample to be dated is reheated to 300–500°C, electrons return to their normal energy levels in crystallographic positions, and low-intensity light is emitted from the sample (hence the term thermoluminescence).

To obtain a reliable age, the radiation dose must be determined by evaluating the energies and relative contributions of the various sources of radiation in both the sample and the environment in which it was buried. The rate at which the sample would accumulate trapped electrons in the radiation environment experienced by the sample must also be determined experimentally. As examples of applications, burnt flints associated with skeletons in cave sites in the Levant have suggested the presence of anatomically modern humans around 100,000 years ago, and stone artifacts in the lowest occupation levels of Malakunanja II in the Arnhem land of northern Australia indicate ages between 50–60,000 years.[13]

Obsidian hydration dating is based on the fact that a freshly spalled fragment of obsidian, a silica-rich volcanic glass, gradually absorbs water from its surroundings.[14] As water diffuses into the glass, a hydration rind develops and increases in thickness. Rind thickness, as a function of time, is measured optically. To determine the age of a spalled obsidian fragment, it is necessary to determine the appropriate equation relating the age and thickness of the hydration rim. On the basis of experimentally induced hydration, most researchers assume that the age is approximately proportional to the square of the thickness such that $a = kt^2$ where a is the age, k is a constant and t is the thickness of the rim. The value of the appropriate proportionality constant is a function of chemical composition, temperature, and humidity and must be assessed experimentally from obsidians of the same chemical composition and environmental temperature and humidity as the obsidian to be dated. Because these variables are not easy to assess with high precision, obsidian hydration dating is best used in conjunction with other methods. In many instances, however, obsidian dating has yielded results in excellent agreement with ages provided by radiocarbon, thermoluminescence, and other methods. Obsidian hydration dating of Timber Butte obsidian fragments at the Western Idaho Archaic Burial Complex sites suggests an age of about 4,500 years.[15]

The final method we will note is amino acid racemization, a technique that is useful for dating shell and teeth and, to a lesser extent, bone.[16] Virtually all amino acids in living organisms such as serine, aspartic acid, and isoleucine exist as left-handed isomers.[17] After the organism dies, amino acids gradually convert to the right-handed isomer, a process called *racemization*. Experiments on selected amino acids in various shelly and dental materials must be performed to determine the rates at which racemization occurs as a function of temperature. Then samples of unknown age are analyzed to determine the ratio of right-handed to left-handed isomers of specific amino acids, and the age is determined from the analyzed ratio. As an example, ostrich eggshell fragments were found at an archeological site in Botswana believed to be less than 30,000 years old.[18] These shell fragments occurred in the vicinity of numerous pits that had been dug by Late Stone Age inhabitants into lower and, therefore, older occupation levels. The shell fragments had ratios of left-handed to right-handed isomers that indicated an age older than 30,000 years, consistent with a radiocarbon date of 37,200 years for the eggshells. From these data, it was inferred that the shell fragments had been dug up from the older occupation level.

In the March 2007 issue, Part Two of this article will examine radiometric dating methods used for determining ages of crystallization of minerals, rocks, and meteorites.

⁂

Notes

1Martin J. S. Rudwick, *Bursting the Limits of Time: The Reconstruction of Geohistory in the Age of Revolution* (Chicago: University of Chicago Press, 2005). This magnificent work by Rudwick, arguably the prince among historians of geology, is an absolute must read for anyone wishing to understand the earliest recognition of the Earth's considerable antiquity in relation to Christian faith. Another valuable work that focuses on the role of fossils in understanding Earth history is Martin J. S. Rudwick, *The Meaning of Fossils*, 2d ed. (New York: Science History Publications, 1976).

2For details on geologically important absolute dating systems, see Gunter Faure and Teresa M. Mensing, *Isotopes: Principles and Applications*, 3rd ed. (Hoboken, NJ: Wiley, 2005) and Alan P. Dickin, *Radiogenic Isotope Geology* (Cambridge: Cambridge University Press, 1997). Also of great value are G. Brent Dalrymple, *The Age of the Earth* (Stanford, CA: Stanford University Press, 1991) and G. Brent Dalrymple, *Ancient Earth, Ancient Skies: the Age of Earth and Its Cosmic Surroundings* (Stanford, CA: Stanford University Press, 2004). For relative dating methods, consult any textbook on stratigraphy. For a review of archeologically important absolute dating methods, see R. E. Taylor and Martin J. Aitken, eds., *Chronometric Dating in Archaeology* (New York: Plenum Press, 1997). For stratigraphic principles pertaining to relative dating in archeology, see Edward C. Harris, *Principles of Archaeological Stratigraphy*, 2d ed. (London: Academic Press, 1989) and especially Michael J. O'Brien and R. Lee Lyman, *Seriation, Stratigraphy, and Index Fossils: The Backbone of Archaeological Dating* (New York: Kluwer Academic/ Plenum, n.d.). This latter work emphasizes relative dating with particular reference to American archeology.

3On the life of Steno, see Alan Cutler, *The Seashell on the Mountaintop: A Story of Science, Sainthood, and the Humble Genius Who Discovered a New History of the Earth* (New York: Dutton, 2003). For Steno's enunciation of stratigraphic principles, see Niels Stensen, *Prodromus Concerning a Solid Body Enclosed by Process of Nature within a Solid* (New York: Hafner, 1968). In this paper, I have omitted discussion of the *principle of original lateral continuity*, also developed by Steno.

4An undisturbed stack of layers such as those in the Grand Canyon-Colorado Plateau region has not been overturned, has not had another set of layers thrust on top of it, and has not been injected by sills. Competent field geologists, recognizing any overturned layers, overthrusts, or sills, will still be able to apply the principle of superposition appropriately because they will understand points at which the temporal order of the rock layers has been disrupted.

5For a review of attempts to determine the age of the Earth by means of sedimentary rock succession thicknesses, see Charles D. Walcott, "Geologic Time, As Indicated by the Sedimentary Rocks of North America," *Journal of Geology* 1 (1893): 639–76.

6Building on the idea of Edmund Halley, John Joly was the foremost expert on the use of dissolved salts to compute the age of the ocean. See John Joly, "An Estimate of the Geological Age of the Earth," *Scientific Transactions of the Royal Dublin Society* 7 (1899): 23–66 and John Joly, "Geological Age of the Earth," *Geological Magazine*, New Series, Decade 4, 7 (1900): 220–5.

7William Thomson, "On the Age of the Sun's Heat," *Macmillan's Magazine* (March 1862): 388–93 and William Thomson, "On the Secular Cooling of the Earth," *Royal Society of Edinburgh Transactions* 23 (1862): 157–9.

8Lord Kelvin, "The Age of the Earth as an Abode Fitted for Life," *Science* 9 (1899): 665–74, 704–11. For an excellent overview of the efforts of Kelvin and his contemporaries to determine the age of the Earth, see J. D. Burchfield, *Lord Kelvin and the Age of the Earth* (New York: Science History Publications, 1975).

9Diagenesis is the technical term for the set of processes involved in the conversion of unconsolidated sediment into sedimentary rock.

10For more detail on dendrochronology, see Marvin A. Stokes and Terah A. Smiley, *An Introduction to Tree-Ring Dating* (Tucson, AZ: University of Arizona Press, 1996) and M. G. L. Baillie, Tree-Ring Dating and Archaeology (Chicago, IL: University of Chicago Press, 1982).

11On Sunset Crater, see D. A. Breternitz, "Eruptions of Sunset Crater: Dating and Effects," *Plateau* 40 (1967): 72–6. On Arizona cliff dwellings, see Jeffrey S. Dean, "Chronological Analysis of Tsegi Phase Sites in Northeastern Arizona," *Papers of the Laboratory of Tree-Ring Research 3* (Tucson, AZ: University of Arizona Press, 1969).

12Martin J. Aitken, *Thermoluminescence Dating* (London: Academic Press, 1985).

13On the Levant, see N. Mercier and H. Valladas, "Thermoluminescence Dates for the Paleolithic Levant," in O. Bar-Yosef and R. S. Kra, eds., *Late Quaternary Chronology and Paleoclimate of the Eastern Mediterranean* (Tucson, AZ: Radiocarbon, 1994), 13–20. On Malakunanja, see R. G. Roberts, R. Jones, and M. A. Smith, "Thermoluminescence Dating of a 50,000 year-old Human Occupation Site in Northern Australia," *Nature* 345 (1990): 153–6.

14M. Steven Shackley, ed., *Archaeological Obsidian Studies: Method and Theory* (New York: Plenum Press, 1998).

15M. G. Pavesic, "Cache Blades and Turkey Tails: Piecing Together the Western Idaho Archaic Burial Complex," in M. G. Plew, J. C. Woods, and M. G. Pavesic, eds., *Stone Tool Analysis: Essays in Honor of Don E. Crabtree* (Albuquerque, NM: University of New Mexico Press, 1985), 55–89.

16P. Edgar Hare, Thomas C. Hoering, and Kenneth King, Jr., eds., *Biogeochemistry of Amino Acids* (New York: John Wiley & Sons, 1980).

17Isomers are organic molecules that share the same chemical composition but have different structures. Amino acids can exist as left-handed and right-handed molecules that are mirror images of each other.

18A. S. Brooks, P. E. Hare, J. Kokis, G. H. Miller, R. D. Ernst, and F. Wendorf, "Dating Pleistocene Archeological Sites by Protein Diagenesis in Ostrich Eggshell," *Science* 248 (1990): 60–4.