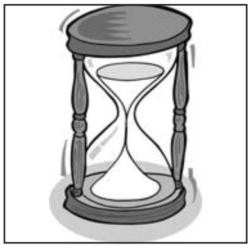

Article

How Old Is It? How Do We Know? A Review of Dating Methods— Part Three: Thermochronometry, Cosmogenic Isotopes, and Theological Implications

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This final installment of the three-part series examines U-Th/He and fission-track dating, so-called thermochronometric methods that provide cooling times from which uplift and erosion chronologies can be constructed. Also discussed is a range of methods based on the decay of cosmogenically produced isotopes such as ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl that provide insight into the ages of sediments, glaciers, organic materials, and erosion surfaces. The article concludes with a brief reflection on the theological implications of an Earth that is billions of years old.

Because FTRZ (fission-track retention zone) temperature ranges of minerals differ, it is possible to determine when rocks cooled to various temperatures and depths to reconstruct uplift history of mountain ranges.

Thermochronometry

In Part Two we noted that ^{40}K-^{40}Ar data may provide an indication of how long it has been since a given body of igneous rock cooled below the closure temperatures of various minerals. If we know that the closure temperature for Ar retention in biotite is around 325°C and around 475°C for hornblende, it is possible to estimate the depths at which a given biotite- or hornblende-bearing rock attained these temperatures. For example, if the *geothermal gradient*, the rate at which temperature increases with depth, is determined to be 30°C per kilometer, then a rock body would attain a temperature of 325°C at a depth of approximately 11 kilometers, whereas a temperature of 475°C would be reached at a depth of approximately 16 kilometers. The K-Ar cooling age for hornblende will normally be older than the cooling age for biotite from the same rock, and from those ages one can calculate the approximate rate of uplift from 16 to 11 kilometers for the rock body in question.

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The ^{40}Ar/^{39}Ar method also provides insight into the cooling ages of biotite and hornblende and the uplift history of the rocks in which they are contained, but space limitations prevent further discussion.[1]

The U-Th/He Method

Although U-He was the first radiometric dating method to be developed, its use was soon discontinued because of the problem of He loss from the minerals in which it was being produced by decay of uranium. In recent decades, detailed studies of He diffusion in the mineral apatite indicated that apatite begins partial retention of He as it cools and eventually completely retains He. Subsequent studies that clarified the relationships among closure temperature, grain size of apatite, and cooling rate have suggested a He closure temperature in apatite of about 70°–75°C for apatite grains with a radius around 70–90 μm and cooling rates on the order of 10°C per million years. For larger grains, the closure temperature is slightly higher, and for faster cooling rates, the closure temperature is somewhat lower. He-diffusion studies have also been conducted for other common minerals such as titanite, monazite, hematite, and zircon, all of which are common accessory minerals in igneous and metamorphic rocks.[2] Available data indicate that titanite has the highest closure temperature (~200°C), whereas zircon has values a few degrees lower, and apatite lower yet. Because these minerals have somewhat different He closure temperatures, it is now possible, by measuring the amounts of U and Th isotopes and He in apatite, titanite, and zircon, to calculate "cooling ages," that is, amounts of time that have elapsed since each mineral cooled to the pertinent closure temperature at which He was completely retained.[3]

Because the closure temperatures in these minerals differ, each mineral in a rock reaches its He closure temperature at a different depth. In general, apatite achieves complete He retention at a shallower depth than titanite, and, therefore, the cooling age of apatite is normally less than that of titanite from the same rock sample. Because He closure temperatures in apatite, titanite, and zircon are much lower than Ar closure temperatures of feldspar, mica, and hornblende, the depths at which complete He retention becomes important are much shallower than the depths at which complete Ar retention occurs. Thus, biotite should retain Ar at a greater depth than the depth at which apatite from the same rock retains He. As a result, U/Th-He dating of apatite, titanite, zircon and other minerals in rock samples from a given region of high relief, especially when coupled with K-Ar and ^{40}Ar/^{39}Ar dating of biotite, hornblende, and feldspar, makes it possible to reconstruct the uplift and cooling history of such regions.

Rates of uplift and erosion in the western Basin and Range province of the United States have been evaluated by means of U-Th/He dating. The pattern of He ages from apatite collected from the White Mountains of eastern California suggests a period of gradual uplift, erosion, and cooling followed by an episode of rapid uplift, erosion, and cooling about 12 million years ago. In western Nevada, He ages from both zircon and apatite in the Wassuk Range indicate an episode of rapid uplift, erosion, and cooling about 15 million years ago.[4]

Fission-Track Dating

Fission-track dating is another method that is used in conjunction with the K-Ar, ^{40}Ar/^{39}Ar, and U-Th/He methods for reconstruction of the uplift and cooling histories of mountain belts.[5] Fission tracks are produced in minerals that contain trace amounts of uranium, such as zircon, apatite, titanite, allanite, garnet, and micas as well as in U-bearing silicic volcanic glasses. In such materials ^{238}U atoms undergo infrequent spontaneous fission events into two less massive nuclides that generally have atomic numbers (Z) between those of zinc (Z = 30) and terbium (Z = 65) accompanied by a few light particles. The products of a fission event, propelled through a mineral or glass at very high energies that depend on the atomic mass of the nuclides involved, leave behind tracks of radiation damage. Positively charged ions produced by the passage of these high-energy particles repel one another to create numerous vacancies in the crystal structure.

Fission tracks rapidly fade in minerals at high temperatures as ions fill the vacancies upon return to their normal positions in the crystal structure. In addition, if a zircon or garnet is re-heated to a few hundred degrees Celsius, fission tracks that accumulated at lower temperatures will be obliterated. As a result, the simplest application of fission-track dating concerns minerals or glasses that have not been re-heated subsequent to their original formation. As a rock cools, any fission tracks that form fade until each U-bearing mineral reaches a critical temperature, the value of which depends on cooling rate, at which the mineral begins to retain a very small fraction of the fission tracks.[6] The mineral cools through a temperature interval called a fission-track retention zone (FTRZ) in which the percentage of fission tracks formed increases as temperature drops (Figure 1). Eventually, the mineral cools below a

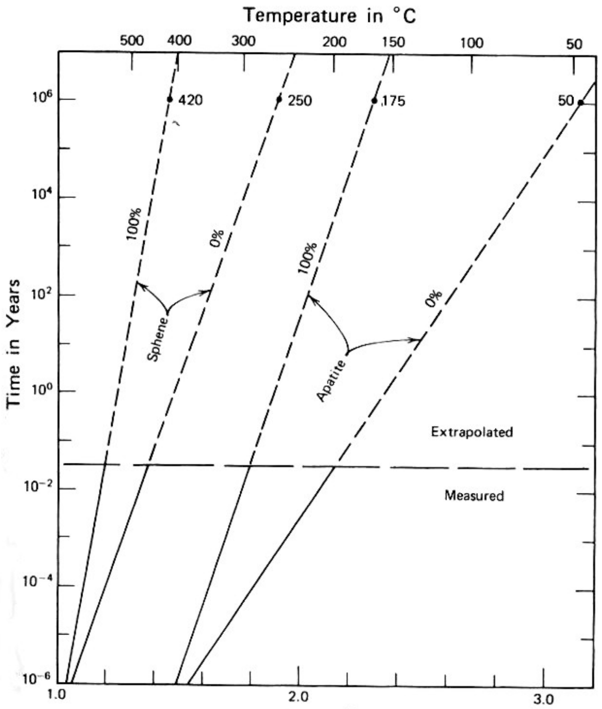
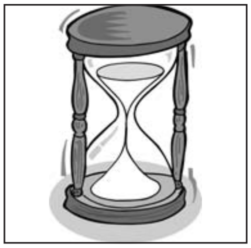


Figure 1. Percent of loss of fission tracks upon heating and percent of retention of fission track upon cooling for apatite and sphene (titanite). Fission-track fading (loss) and retention are functions of temperature and rate of cooling. Thus, for example, sphene (titanite) begins to lose its fission tracks if heated to 250°C for one million years and will lose all its tracks at 420°C. In contrast, apatite that is cooled for one year at 275°C just begins to retain tracks and if cooled for one year at 160°C retains all its tracks. Reproduced from Fig. 20.2 in G. Faure, *Principles of Isotope Geology*, 2d ed. (New York: John Wiley and Sons, 1986), p. 349, by permission of John Wiley and Sons.



temperature, again dependent on cooling rate, at which 100% of fission tracks are retained. Because the FTRZ temperature ranges of minerals differ, it is possible to determine when rocks cooled to various temperatures and depths and to reconstruct uplift history of mountain ranges.

The fission-track method has been used in some cases for determining the ages of volcanic ash layers and archeological artifacts and implements such as obsidian tools or ceramics. Because volcanic ash, composed of glass shards, and obsidian cool extremely rapidly to surface temperature, virtually all fission tracks in glass or zircon should be retained such that the time of eruption can be determined. Fission-track dating can yield both the age of manufacture of an obsidian tool and, in other instances, the solidification age of obsidian, in which case such information can provide clues to the source region of an obsidian fragment. Fission tracks in fired pottery, in contrast, can indicate only the age of the pottery but not the geologic age of its minerals, because fission tracks present in mineral grains will be obliterated upon firing.

> *[Dating] methods involving cosmogenic isotopes typically entail measurement of the present activity of a radioactive isotope in a sample by counting disintegrations or determination of the isotopic concentration by mass spectrometry.*

Determination of fission-track ages entails counting fission tracks on a specified polished surface for a given volume of sample. The fission tracks are rendered more readily observable by optical microscopy by chemical etching with acids. The fission-track age is calculated from the fraction of decays of ^{238}U that produce a fission track within a given volume of sample; the amount of ^{238}U in the sample volume; the areal density of fission tracks on a polished surface produced by spontaneous fission of ^{238}U in the natural sample; the areal density of fission tracks on the polished surface that have been induced by irradiation of ^{235}U in the sample by thermal neutrons; the thermal neutron flux of the reactor in which the sample is irradiated; and the capture cross-section of ^{235}U for thermal neutrons. Terms that are difficult to determine directly are evaluated by irradiating the sample of interest together with standard minerals or glasses of known age and similar if not identical properties to the sample. Age corrections for track fading are also applied on the basis of analysis of track-size distributions.

In the Afar triangle in Ethiopia, a sequence of Pliocene sediments rich in vertebrate remains, including hominid fossils, contains several beds of tephra (volcanic ash). Glass shards from the uppermost BKT-3 tephra, covered by Acheulean gravels, gave a fission-track age of 2.05 million years.[7] Approximately 125 meters below BKT-3 is the Sidi Hakoma Tuff which yielded a fission-track age of 3.53 million years, in fairly good agreement with a more precise ^{40}Ar/^{39}Ar age of 3.40 million years old. About 45 meters beneath the Sidi Hakoma Tuff is the Moiti Tuff, fission-track dated at 3.89 million years, in very good agreement with a more precise ^{40}Ar/^{39}Ar age of 3.89 million years. Not only do the data provide an indication of the approximate age of the hominid remains, but the fission-track ages are also consistent with the stratigraphic position of the ash layers—the oldest at the bottom, the youngest at the top.

At the Choukoutien cave in China, layers 3 (younger) through 11 (older) contain fossil remains or other evidence of *Homo erectus pekinensis* including evidence for the use of fire.[8] Several hundred grains of titanite were collected from fired ash in these layers, and the fission-track records of the grains were completely reset by the firing. Fission-track dating of titanite from layer 4 yielded an age of 306,000 years, and titanite from layer 10 yielded an age of 462,000 years, consistent with the stratigraphy.

Cosmogenic Isotopes

Several dating methods take advantage of radioactive and stable isotopes produced by the interaction of cosmic rays and cosmic-ray induced neutrons with atoms in the atmosphere or in common minerals exposed at Earth's surface.[9] Cosmic rays, typically consisting of protons, neutrons, and alpha particles, originate in the Sun and in distant sources outside the solar system. Galactic cosmic rays, that is, those originating beyond the solar system, generally have higher energies than solar cosmic rays and are, therefore, more likely to produce cosmogenic isotopes during collisions. Among the more important radioactive cosmogenic isotopes are ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl, all of which are radioactive.

Methods involving cosmogenic isotopes typically entail measurement of the present activity of a radioactive isotope in a sample by counting disintegrations or determination of the isotopic concentration by mass spectrometry. Cosmogenic isotopes have a wide array of geological and archeological applications including determination of ages of marine or lacustrine sediment layers, glacial ice, coral reefs, organic material, and exposure to the atmosphere or to space. Several of the methods are useful for determination of ages ranging from only tens to hundreds of years, whereas others are suitable for dating materials that may be tens of millions of years old. Some methods also provide information about rates of processes such as sedimentation.[10]

Radiocarbon Dating

Radiocarbon (^{14}C) atoms are produced by collision of cosmic ray-induced thermal neutrons with ^{14}N atoms in the atmosphere where they combine with oxygen to form $^{14}CO_2$ molecules.[11] Atmospheric circulation thoroughly mixes $^{14}CO_2$ on a global scale before plants remove CO_2 during photosynthesis. All living plant material is radioactive because it contains ^{14}C. As long as a plant is alive, it continues to take up $^{14}CO_2$, while some of the ^{14}C already taken in decays. Eventually equilibrium is established between intake and decay. After the plant dies, no more ^{14}C is taken up, and the remaining ^{14}C gradually disintegrates to ^{14}N. By measuring the activity of ^{14}C in a dead plant by counting β emissions and comparing the activity with standards of known ^{14}C concentration, one can calculate the time elapsed since the death of the plant.

By the same token, animals eat living plants and, therefore, ingest $^{14}CO_2$ from the plants. The animals also exhale $^{14}CO_2$, and equilibrium is established between ingested and exhaled ^{14}C. When the animal dies, breathing and metabolism stop, and ^{14}C is no longer released. The ^{14}C in tissues decays through time and, again, the measured activity of ^{14}C indicates age. Samples to be dated must be free of contamination by radiocarbon from groundwater, precipitation, or other sources. Because atmospheric ^{14}C production has not been constant through time due to changes in intensity of Earth's geomagnetic field, variations in sunspot activity, bomb testing, and other factors, deviations between radiocarbon ages and accurately known ages of various artifacts are commonplace. A radiocarbon age on material of unknown age must, therefore, be corrected with the use of calibration curves that are constructed by plotting radiocarbon ages obtained from materials of known age versus those known ages. The most recent set of calibration curves is based on carefully cross-dated tree-ring sequences that go as far back as 12,460 BP (BP = before present with the present defined as the year 1950).[12] Data on marine corals that have been dated by U/Th methods and foraminifera collected from dated varve sequences extend the calibration curves back to 26,000 BP.[13]

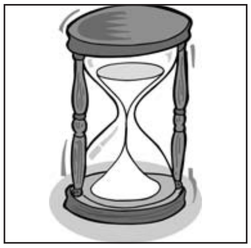
Radiocarbon has a half-life of 5,730 years. As a result, ^{14}C in a sample decays to virtually undetectable amounts in a few tens of thousands of years. In the late 1970s, accelerator mass spectrometry (AMS) was developed for direct measurement of ions of carbon isotopes accelerated to very high energies in a particle accelerator and then passed through a mass spectrometer. Because the new method can measure much lower concentrations of ^{14}C than is achievable by direct measurement of the ^{14}C decay rate, it has the potential for modest extension of the time range of radiocarbon dating. AMS also allows for analysis of smaller samples and provides faster analyses.

Because radiocarbon dating is capable of providing reliable ages up to a few tens of thousands of years, the method has been extremely useful both in archeological applications and in providing ages of extinct organisms and of geologic events, such as glaciation and lake formation, from the end of the Pleistocene Epoch to the present. Among the more widely publicized ^{14}C results are dates on material obtained from the Shroud of Turin ranging from AD 1260–1390. An extinct bison, Blue Babe, that was unearthed from frozen ground in 1979 and is now on display in the Museum of the North in Fairbanks was radiocarbon dated at 36,000 BP.[14]

Exposure-age Methods

Among the methods based on cosmogenic isotopes are several that yield information about the length of time that a rock surface has been exposed to the atmosphere or that a meteorite has been exposed to cosmic rays as it travels through space from the asteroid belt or from Mars to Earth. This information concerns so-called *exposure ages*. Below we will discuss only terrestrial exposure ages.[15] For example, ^{10}Be is produced in the atmosphere by the fragmentation of stable isotopes of oxygen and nitrogen when impacted by cosmic rays. Because the great majority of rocks in Earth's crust are composed of silicate minerals such as quartz, feldspar, mica, and olivine, the likelihood of production of ^{10}Be by interaction of cosmic rays with silicon and oxygen atoms in these minerals is great. ^{26}Al is produced by neutron bombardment of silicon atoms in quartz and other silicate minerals in the rocks. ^{36}Cl forms by the impact of cosmic rays on potassium and calcium atoms that are abundant in common minerals such as feldspar, pyroxene, and mica. Production of cosmogenic isotopes in rocks on Earth's surface opens the possibility for determining the time at which a rock face was first exposed to the atmosphere.

Because cosmic rays are deflected by Earth's magnetic field toward the poles, the intensity of cosmic rays striking the surface at a specific elevation above sea level increases at higher *geomagnetic latitudes*. Therefore, production of cosmogenic isotopes in a rock surface is greater at high latitudes, *all other factors being equal*. As cosmic rays descend through the atmosphere they interact with atmospheric atoms in various ways, and a particle may ultimately be completely absorbed before reaching the surface so that it



If we are serious about the implications of the biblical doctrines of creation and providence, then we are driven to accept the Earth's great antiquity. The incessant disclosure of God-created and God-sustained data and principles forbid us from cavalierly dismissing the powerful evidence that has been discovered about Earth's vast history …

cannot interact with a rock face. Therefore, the intensity of cosmic rays at Earth's surface is also a function of altitude, or, in other words, the thickness of atmosphere through which a cosmic ray travels. As a result, the production rates of cosmogenic isotopes in a rock face are also affected by the *altitude* at which a rock is exposed. The production rate of cosmogenic isotopes should be higher for rock surfaces at high elevation than those at low elevation, *all other factors being equal*.

For a constant flux of cosmic rays, a steeply tilted rock face will experience fewer interactions with cosmic rays per unit area than a gently tilted rock face, and a gently tilted rock face will experience fewer interactions with cosmic rays per unit area than a horizontal rock face. Hence, the production of cosmogenic isotopes will be greater on a horizontal rock face than on a steeply tilted rock face.

The mineral composition of a rock face also affects the production rates of individual cosmogenic isotopes under identical conditions because these rates differ for different minerals. For example, ^{26}Al is produced at more than twice the rate in quartz than it is in the mineral olivine for the simple reason that there are more silicon atoms in a given mass of quartz than there are in olivine, and it is silicon atoms that are impacted by the cosmic rays to produce ^{26}Al.

Exposure dates are calculated from equations that take into account these and various other factors along with the decay constant and the amount or activity of the isotope that is present in the exposed mineral sample. The variables are generally more numerous and more difficult to assess in the case of cosmogenic isotopes than with the methods we discussed in Part Two for determining the ages of rock crystallization. Hence, exposure ages are not always as precise or accurate as crystallization ages. The age is calculated from the number of product atoms such as ^{10}Be, measurable by mass spectrometry; the production rate evaluated from the various factors noted above; and the decay constant of the cosmogenic isotope.

The dating of glacial deposits was formerly dependent almost entirely on stratigraphy and paleontology, but it is now possible to determine, by means of cosmogenic isotope methods, the amount of time that has elapsed since a boulder, deposited in a *moraine* at the margin of a melting glacier, has been exposed to the atmosphere.[16] In the Wind River Range of western Wyoming, the most recent moraines of the Pinedale stage contain large angular boulders and are much less thoroughly weathered than the older moraines of the Bull Lake and Sacagawea Ridge stages on which they are superposed. The dating of fifty-six samples of boulder fragments by the ^{36}Cl method has shown that the Pinedale moraines have ages ranging 15,000 to 23,000 years, the Bull Lake moraines have a minimum age of 120,000 years, and the Sacagawea Ridge moraines have a minimum age of 232,000 years.[17]

As another example, consider Meteor Crater in northern Arizona. A meteorite approximately 150 feet in diameter collided with the Arizona desert and excavated a giant crater that is about three-quarters of a mile in diameter and 550 feet deep. Horizontal bedrock layers of Coconino Sandstone, Kaibab Formation, and Moenkopi Formation that underlie the area around the crater were tilted upward as material was ejected upon impact to cover the adjacent landscape. Surfaces of samples of Kaibab Formation yielded ^{10}Be ages ranging from 51,600 to 14,600 years indicating various times when ejected material was removed by erosion from the underlying rubble of Kaibab Formation. The highest ages, ranging from 44,700 to 51,600 years, were obtained from the "summits" of large ejecta blocks of Kaibab Formation. All of these ages are in excellent agreement with ages obtained by ^{26}Al dating that range from 52,700 to 14,500 years.[18] The same sample yielded the youngest age by both methods, and the four samples with the greatest ^{10}Be ages also yielded the greatest ^{26}Al ages. The ^{36}Cl ages of five Kaibab Formation samples range from 50,400 to 36,500 years. The next lowest value is 47,100 years. The average age of the samples with the four highest values is 49,000 years. The investigators regarded that as a best estimate for the time of impact.[19]

One additional study of Meteor Crater employed the non-radiogenic thermoluminescence method (see Part One of this series). Quartz from four sandstone samples yielded a range of ages from 53,600 to 45,100 years with a mean of 50,400 years.[20] Quartz from four samples of dolomite yielded ages ranging from 50,800 to 37,700 years with a mean of 46,000 years. Several lines of evidence strongly suggest that Meteor Crater was formed around 49,500 years ago. The agreement of the age results obtained by various methods, such as those we have pointed out, has been critical in establishing the scientific community's confidence in the reliability of the dating methods now commonly in use.

Theological Implications

Any assessment of the theological implications of the ages of geological and archeological features far in excess of 6,000 years disclosed by the plethora of dating methods must begin with the recognition that the spectacular successes of the natural sciences are possible only because the message of the Bible is true. The biblical doctrines of creation, providence, covenant, and humanity alone provide a satisfactory basis for the presuppositions of orderliness, uniformity and stability, and intelligibility of the universe that make all the sciences possible. When followed through consistently, competing worldviews like deism or materialistic atheism cannot provide a satisfactory basis for holding all of these presuppositions that are essential to scientific inquiry. Even deism cannot guarantee uniformity and stability.

As adherents of a Christian worldview, we should believe that established scientific data and well-supported theories are giving us a window on *reality*. Thus, the remarkable consistency of the vast complement of dating methods now available reveals something *real* to us about the world, namely the vastness of created time. If we are serious about the implications of the biblical doctrines of creation and providence, then we are driven to accept the Earth's great antiquity. The incessant disclosure of God-created and God-sustained data and principles forbid us from cavalierly dismissing the powerful evidence that has been discovered about Earth's vast history every bit as much as it forbids us from dismissing Stokes' law, the law of mass action, or cell theory.

Geological and archeological dating methods are a divine gift that has given us better insight, not just about our world, but also about the teaching of Scripture. The dating methods are important tools that have led us to recognize that the traditional view of Genesis 1 as a strictly historical and scientifically valid account of the first 144 hours of Earth's (or the universe's) existence must be fatally flawed. If so, it should be abandoned.[21] But God in his providence has not left us in the dark regarding a more acceptable interpretation of Genesis 1 with which to replace the traditional view. By means of another divine tool, namely, archeology, God has also granted us over the past century and a half previously unrecognized knowledge of the cultures, worldviews, cosmologies, and literary conventions and symbolisms of the ancient Near East. If we take that knowledge seriously, we can begin to see Genesis 1 as a theological critique of the false polytheistic religions of Israel's neighbors that was cast in the literary characteristics of the ancient Near East rather than as a report of a sequence of scientifically verifiable geological and astronomical events.

John Calvin, *contra* Augustine, observed that God created the world in six days rather than all together in one moment in order to give us opportunity to reflect more deeply on God's marvelous works. May we not, along the same lines, suggest that an earth that has journeyed through an incredibly long, complex, dynamic 4.55-billion-year history provides us, by God's grace, with far more material for reflection on his majesty, power, and breathtaking imagination than an earth that is only a few thousand years old?

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Notes

[1] On argon-argon dating, see Ian McDougall and T. Mark Harrison, *Geochronology and Thermochronology by the ^{40}Ar/^{39}Ar Method*, 2d ed. (New York: Oxford University Press, 1999).

[2] Accessory minerals typically form very tiny grains that normally comprise only a fraction of one percent of the rock in which they are found. Zircon, apatite, titanite, magnetite, ilmenite, and hematite are the most abundant accessory minerals.

[3] For a summary of U-Th/He dating, see Kenneth A. Farley "U-Th/He Dating: Techniques, Calibrations, and Applications," *Reviews in Mineralogy and Geochemistry* 47 (2002): 819–44.

[4] On the White Mountains, see Daniel F. Stockli, Kenneth A. Farley, and Trevi A. Dumitru, "Calibration of the Apatite (U-Th)/He Thermochronometer on an Exhumed Fault Block, White Mountains, California," *Geology* 28 (2000): 983–6, and on the Wassuk Range, see Daniel F. Stockli, "Application of Low-Temperature Thermochronometry to Extensional Tectonic Settings," *Reviews in Mineralogy and Geochemistry* 58 (2005): 411–48.

[5] For a brief review of fission-track dating including relevant equations and procedures, see John Westgate, Amanjit Sandhu, and Philip Shane, "Fission-track dating," in R. E. Taylor and Martin J. Aitken, eds., *Chronometric Dating in Archaeology* (New York: Plenum Press, 1997), 127–58. For more detail on fission-track dating, see Günther A. Wagner and Peter van den Haute, *Fission-Track Dating* (Stuttgart: Ferdinand Enke Verlag, 1992). On ^{40}Ar/^{39}Ar, U-Th/He, and fission-track thermochronometry generally, see Peter W. Reiners and Todd A. Ehlers, eds., *Low-Temperature Thermochronology: Techniques, Interpretations, and Applications (Reviews in Mineralogy and Geochemistry* 58) (Chantilly, VA: Mineralogical Society of America, 2005).

[6] The slower the rate of cooling, the greater percentage of tracks that can be formed and retained at a given temperature.

[7] On the Ethiopian tephra layers, see R. C. Walter and J. L. Aronson, "Age and Source of the Sidi Hakoma Tuff, Hadar Formation, Ethiopia," *Journal of Human Evolution* 25 (1993): 229–40, and T. D. White, et al., "New Discoveries of *Australopithecus* at Maka in Ethiopia," *Nature* 366 (1993): 261–4.

[8] On Choukoutien cave, see Guo Shilun, et al., "Age and Duration of Peking Man Site by Fission Track Method," *Abstracts, 15th Annual Conference on Particle Tracks in Solids*, Marburg.

[9] For a good review of cosmogenic isotope dating, see T. E. Cerling and H. Craig, "Geomorphology and In-Situ Cosmogenic Isotopes," *Annual Review of Earth and Planetary Sciences* 22 (1994): 273–317.

[10] ^{10}Be is especially useful for dating marine and sediments because it is swept by precipitation into the ocean where it is adsorbed onto clay particles that gradually accumulate on the sea bottom.

Another set of methods that have important applications to sediments deposited within the past few hundred thousand years are based on disequilibrium between different isotopes in the ^{238}U decay scheme.

[11] On radiocarbon dating, see Royal Ervin Taylor, *Radiocarbon Dating: An Archaeological Perspective* (Orlando, FL: Academic Press, 1987).

[12] On the calibration of radiocarbon dates, see Paula J. Reimer, et al., "INTCAL 04 Terrestrial Radiocarbon Age Calibration, 0–26 cal kyr BP," *Radiocarbon* 46 (2004), 1029–58.

[13] For calibration of radiocarbon dates to tree-ring chronologies, see Michael Friedrich and seven others, "The 12,460-year Hohenheim Oak and Pine Tree-Ring Chronology from Central Europe—A Unique Annual Record for Radiocarbon Calibration and Paleoenvironment Reconstruction," *Radiocarbon* 46 (2004): 1111–22.

[14] On the Shroud of Turin, see Paul E. Damon, et al., "Radiocarbon Dating the Shroud of Turin," *Nature* 237 (1989): 611–5. On Blue Babe, see R. Dale Guthrie, *Frozen Fauna of the Mammoth Steppe: The Story of Blue Babe* (Chicago: University of Chicago Press, 1990).

[15] For further information on exposure ages of meteorites, see chapter 23 on cosmogenic nuclides in Gunter Faure and Teresa M. Mensing, *Isotopes: Principles and Applications*, 3d ed. (New York: John Wiley and Sons, 2004).

[16] A terminal moraine is an accumulation of gravel consisting of rock fragments of a wide range of sizes that were deposited at the leading edge (margin) of a glacier where the ice is melting. Other moraines form along the sides or base of a glacier.

[17] Fred M. Phillips, Marek G. Zreda, John C. Gosse, Jeffrey Klein, Edward B. Evenson, Robert D. Hall, Oliver A. Chadwick, Pankaj Sharma, "Cosmogenic ^{36}Cl and ^{10}Be Ages of Quaternary Glacial and Fluvial Deposits of the Wind River Range, Wyoming," *Geological Society of America Bulletin* 109 (1997): 1453–63.

[18] K. Nishiizumi, C. P. Kohl, E. M. Shoemaker, J. R. Arnold, J. Klein, D. Fink, and R. Middleton, "*In situ* ^{10}Be-^{26}Al Exposure Ages at Meteor Crater, Arizona," *Geochimica et Cosmochimica Acta* 55 (1991): 2699–703.

[19] Fred M. Phillips, Marek G. Zreda, Stewart S. Smith, David Elmore, Peter W. Kubik, Ronald I. Dorn, and David J. Roddy, "Age and Geomorphic History of Meteor Crater, Arizona, from Cosmogenic ^{36}Cl and ^{14}C in Rock Varnish," *Geochimica et Cosmochimica Acta* 55 (1991): 2695–8.

[20] S. R. Sutton, "Thermoluminescence Measurements on Shock Metamorphosed Sandstone and Dolomite from Meteor Crater, Arizona: 2, Thermoluminescence Age of Meteor Crater," *Journal of Geophysical Research* 90 (1985): 3690–700.

[21] I have documented how the Christian Church has adjusted its understanding of the Flood narrative in light of extra-biblical information drawn from geological, archeological, and other studies. See Davis A. Young, *The Biblical Flood: A Case Study of the Church's Response to Extra-biblical Evidence* (Grand Rapids MI: William B. Eerdmans, 1995).