CHAPTER 8

IS THE EARTH OLD ENOUGH FOR EVOLUTION?

THE PROBLEM

One of the most important passages in Voyage of the Beagle is Darwin's description of his explorations in the Andes Mountains. He had climbed the mountains in Chile, observing marine fossils at high elevation and noting that the higher he went, the more they differed from those at the shore. He was pondering Lyell's remarks about them and debating their origin. When he returned to Santiago, he observed the effects of an earthquake that had occurred while he was in the mountains. The land had lifted approximately three feet, and shelves of land that had formerly been in shallow water were now lifted above the water, and the shellfish that lived there were dead and drying. Seeing this, Darwin wondered if the Andes had been lifted by such incremental shifts as Lyell had proposed. The frequency of earthquakes and their effects had been noted since the Spanish had occupied the land 500 years before. Using these figures: height of Andes, feet lifted per episode, and number of episodes in 500 years, Darwin was able to calculate an approximate age of the Andes. The figure that he came up with, 100,000 years, proved to be quite inaccurate, but it served one major purpose. The figure was way beyond the theological age of 4000 years, and suggested that the earth was much older than that.

HOW DO YOU MEASURE THE AGE OF THE EARTH?

How old is the earth? And how could we possibly measure something like the age of the earth? To measure something one needs a ruler, a scale, or a clock. The measuring device must be calibrated in some fashion, even if the calibration is crude. For instance, an inch was the length of the end segment of the thumb (it still retains the name "thumb" in French) and a foot was the length of the king's foot. It can be more precise, such as a specific fraction of the earth's diameter (kilometer) or the weight of a specific volume of water at a specific temperature (gram), but one aspect of calibration and measurement is that you must be able to establish both ends of the measurement. We can get very accurate clocks, but you cannot just read a clock backwards to find a beginning of time. It is a problem like that of a digital clock. If the power goes off, the clock stops. It will restart, showing midnight, when power is restored, and will continue from that point on. If you come home, for instance, at 6 PM, to find that the clock has stopped and restarted, and that it now reads 2 AM, you can conclude that power was restored two hours earlier, at 4 PM. However, you cannot determine at what point power was lost.

Scientists in several disciplines asked if there were any way to judge the age of the earth. During the 18th and 19th centuries, a few techniques became accessible, and we have several far more complex means today, and they all converge on a common number. The presentation of this story emphasizes two major issues of scientific inquiry: the convergence of evidence from multiple, independent means of evaluation, and the concept of falsification of a hypothesis. Dating by tree rings is discussed in Chapter 6, page 75–76. Others are described below.

In the time since Galileo had first seen craters on the moon, astronomers had recognized that the craters resembled those made by the impact of meteorites on the earth, and the realization grew that they were in fact meteorite impact craters. On the moon, there is no wind and no water, so that a crater, once formed, does not deteriorate, erode, or fill up with silt or dust. There are two features about such craters that allow one to make an estimate of the age of the moon. First, meteorites still strike the moon, so that at least the current rate of formation can be calculated. Second, one can determine the order in which the impacts occurred. For instance, in the photograph in Figure 8.1, the small, heavily shadowed crater just below and

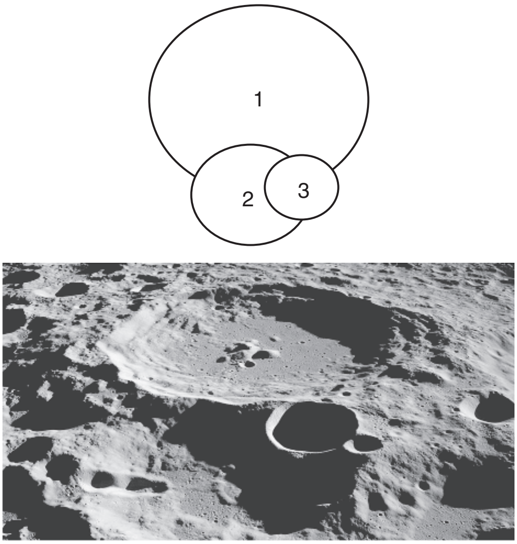

Figure 8.1. When one impact follows another, the second will obliterate the first. A. drawing of sequence. The impacts occurred in the succession 1, 2, 3. B. Photograph of sequential impacts in craters on the moon. The sequence of several craters can be seen. From the Apollo 11 flight. Credits: http://www.hq.nasa.gov/office/pao/History/alsj/a11/AS11-44-6609.jpg

to the right of the center sits in the wall of a heavily eroded crater in the lower half of the picture. Therefore, the bottom crater must have formed first and was partially buried or destroyed by the second impact.

Such observations allow the construction of a crude calendar. If one assumes that the rain of meteorites is constant—it is not, but the simultaneous impacts can be identified—then by counting the number of impacts, one can establish an estimate of how long ago the first impact occurred, in the same manner that one can determine the age of a tree by counting rings and knowing that one ring is formed each year.

LORD KELVIN AND THERMAL COOLING

You are certainly familiar with the fact that when a hot object is removed from the source of the heat, it cools slowly, with the outside becoming cool before the inside. If a large object and a small object are heated to the same temperature, for instance by being placed in boiling water, the smaller object will cool faster than the larger object. The total amount of heat in the object is called heat capacity. The rate at which an object cools depends on its size, how much surface it has, its heat capacity, the difference between its temperature and that of its surroundings, and the ability of the surroundings to absorb the heat. Each of these factors is known or can be measured. Thus by 1841 Lord Kelvin (for whom the Kelvin temperature scale is named) had calculated the temperature of the sun, based on the fact that the color emitted by an object changes with temperature (red hot steel is about 1800° K (2800° F), white hot steel is 5500° (9500° F), and a hot blue flame is 16,000° K (28,000° F)). Knowing from miners and from volcanoes that the center of the Earth was hot, he made the theoretical assumption (hypothesis) that the earth had broken free from the sun, starting at the same temperature, and from that time was a VERY large spherical object cooling in space. Using the same laws of heat transfer that were used for common objects, and correcting for the warming effect of the sun, he calculated how long it would take for the Earth to cool to its present temperature, testing his hypothesis by seeing if he could come up with a reasonable figure. He came up with a value that the world was hundreds of millions of years old. He later revised his calculations, finally settling on somewhat less than 20 million years, but it was still at least 5,000 times longer than the biblical age. This calculation proved to be very inaccurate, since radioactivity, of which he knew nothing, contributes substantial heat to the earth. Nevertheless, it was a further argument that the Earth was quite old. Today's calculations, corrected for radioactivity, give a figure in the low billions of years.

EROSION

Erosion can be measured in several ways. A fairly easy one, if one has a historical record, is to follow the change in shape of land over time, and to recognize the extent that the earth reflects a continuous process. For instance, barrier islands usually shift or recede with time, and the changes can be followed by comparing

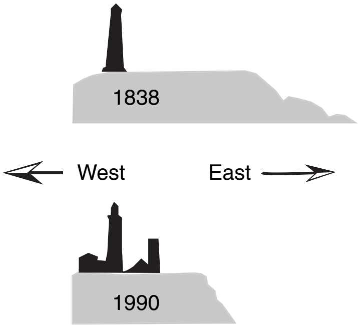

Figure 8.2. Erosion on a barrier island. Judging by the position of the lighthouse, the eastern end of Long Island, New York is disappearing at approximately one foot per year. Credits: Montauk - Redrawn from http://www.montauklighthouse.com/erosion.htm

documents. The eastern end of Long Island, New York, is receding at approximately one foot per year, as can easily be determined by comparing 19th C measurements to those of today (Fig. 8.2). Similarly, Niagara Falls has worked its way back from the original cliff face over approximately twelve thousand years, and the Mississippi

Figure 8.3. Deposition of sediment. Salt water can hold much less sediment than fresh water. Thus mud flowing from the Mississippi is deposited in the Gulf of Mexico in an alluvial plain. Modern deposition is quite prominent in this satellite image, and the entire region south of New Orleans has been built in this fashion. Credits: Mississippi delta - http://eol.jsc.nasa.gov/sseop/clickmap/ cite as above image Miss_deltaISS011-E-5949

River has continually deposited mud where it meets the Gulf of Mexico, forming a large delta (Fig. 8.3).

SEDIMENTATION

Mud and stones settle out of water onto the bottom, and the character of what is being washed into the water changes the nature of the sediment, forming layers. From the patterns of sedimentation, one can easily interpret the order of events. For instance, the later sediment will be on top of the earlier sediment (Fig. 8.4) and, in a single incident, larger stones will settle out faster than pebbles and sand. This argument was well and forcefully made by Nicholas Steno at the end of the 17th C (page 40). Thus one can distinguish between sediment brought by a flood and sediment building slowly as a muddy river settles out. The limitation of this

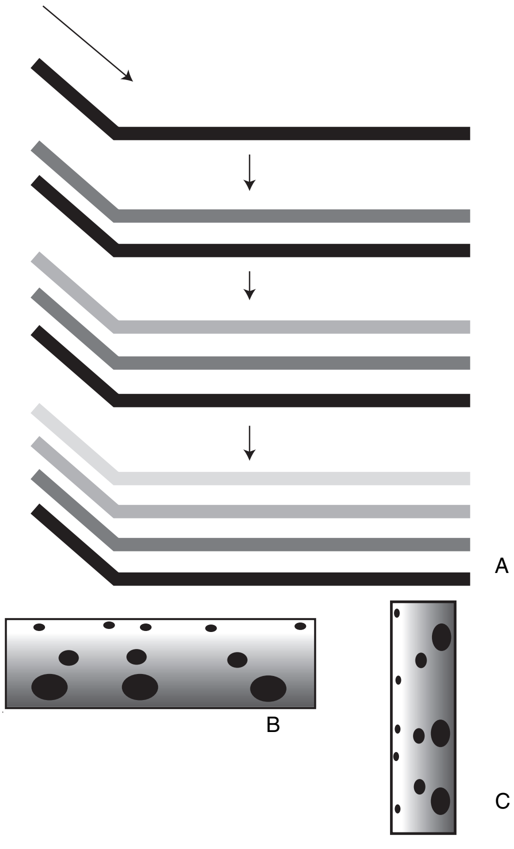

Figure 8.4. Reading sedimentation lines. A: Owing to gravity, later sediments are on top of earlier sediments. B: in one period of rapid deposition, heavier stones will settle out faster than smaller stones or pebbles, so that the original orientation can be determined even if the piece is tilted (C)

analysis is that, although the order of events is clear, it is difficult to establish a time scale. A river might silt out at a rate that accumulates an inch of soil every ten years, but a major flood might bring enough sediment to add ten inches of sediment in one event. What made this question important was the realization that there were massive depths of soil that appeared to be sedimentary. Some of the best examples are found in the American West (Figs. 8.5 and 8.6). The striping indicated three aspects of considerable interest. First, conditions must have alternated during the formation of these soils. For instance, the red stripes were red because they contained a lot of iron (rust), which indicated that they contained sea salts and were formed in sea water. The alternating white stripes represented more freshwater

Figure 8.5a.

Figure 8.5b. Extensive sedimentation lines, Bryce Canyon, Arizona. In this and the following figures, these lands are 5–7,000 feet above sea level

conditions. Black stripes usually contained much organic matter and evidence of marshland plants, but the white stripes with which they alternated were white because of the remnants of shellfish, indicating deeper water. Thus the level of the sea relative to the land must have fluctuated. Second, allowing any reasonable rate of accumulation of sediment comparable to what we can observe today, it must have taken many thousands of years, perhaps even millions, to build sediment in this

Figure 8.6. Extensive sedimentation lines, unnamed hill, Arizona

fashion. This would be much longer than the Biblical 6000 years for the age of the earth. If one argued for the continuity of processes, or gradual formation of soils, as Lyell argued (page 168) as opposed to a catastrophic, sudden formation of these soils, then there was a conflict to be resolved. Finally, these sedimentary rocks are found at considerable elevation (over 5000 feet) and far inland in the United States. Why should one find marine sediments a mile in the air, and over one thousand miles from the sea? Minimally, it was plausible to argue that the earth might be older than 6000 years. This argument would be particularly forceful in the instance of the Grand Canyon (Fig. 8.7), which, though first seen by Europeans earlier, was studied with considerable interest in the early 19th C. Not only were the depths of sediment enormous, but by making the supposition that the Colorado River had cut the canyon—which seemed reasonable based on its appearance and the obvious structure of small canyons and creek beds in the West (Fig. 8.8)—then one was faced with the possibility that it took hundreds of thousands of years for the river to cut the canyon. Furthermore, there are marine fossils at the top of the canyon, at 7,000 feet (see Fig. 3.6, page 41). Making even reasonable estimates for rates of accumulation of sediment and rates of erosion, we come up with numbers that, prior to the exploration of the world, would have been inconceivable. Current dating indicates that the sediment was laid down over a period of 1.6 billion years and that the Colorado River cut through 4,600 feet of this accumulation in approximately 5 million years. Although for the reasons suggested above the true numbers were

Figure 8.7. Sedimentation lines extending thousands of feet as exposed in the Grand Canyon

Figure 8.8. Incipient formation of a canyon, seen as the creek cuts through the land. The hillside in the background was probably formed by the same creek in an earlier era

not known in the 19th C, the possibility that the numbers might be very large was shocking.

MOUNTAIN BUILDING

Lyell had proposed that lands could be lifted from the seas by unknown processes that we would describe today as mountain building. Although the mechanisms were not known, the existence of marine fossils on the slopes again argued that such processes did occur and must be painfully slow. Lyell and others tried to estimate the speed at which they occurred, again arguing that the process was gradual rather than catastrophic. Darwin took Lyell's latest book with him on the Beagle (Chapter 7, page 81) and, encountering an earthquake on the coast of Chile, used it to examine Lyell's hypothesis. In brief, he did a simple calculation. The earthquake lifted the shoreline approximately 3 feet. According to records kept since the Spanish had been in Chile, earthquakes of this magnitude occurred approximately every twenty years. The Andes reach heights of 14,000 feet. How old are the Andes, if this hypothesis is correct?

$$3\,\text{feet}/20\,\text{years} = 14{,}000\,\text{feet}/\text{X years}$$

$$\text{X} = \frac{14{,}000\,\text{feet} * 20\,\text{years}}{3\,\text{feet}} = 94{,}000\,\text{years}$$

This figure is far from what we calculate today, but its importance is that it is very far from the estimate of the Bible, and it began to address the biggest conundrum for the acceptance of the hypothesis of evolution, that there was not enough time for it to occur. That humans could breed dogs or fish or corn or peaches to their liking was undisputed, but the issue was that, in 6000 years, there was no way to create the variety of living things seen on earth. To believe in evolution, one would have to believe that the earth was very old.

All of these measurements are highly suggestive and provocative, but they are relative and are based on assumptions. It is rather like the old joke in which the watchmaker tells the church bell-ringer that he is so impressed with the precision of the bell ringer that he sets the clock he has on display by the noon bells. The bell ringer answers, "That's interesting, because I ring the bells according to the display clock." In other words, there was no means of calibrating clocks based on sedimentation or erosion.

RADIODECAY

One type of clock that can be read backward is that of radioactivity. Although it was unknown to Darwin, once radioactivity had been discovered by Pierre Jolie and the Curies toward the end of the 19th C, physicists quickly determined its primary properties. The one that is most relevant to our argument is that radioactive decay occurs among individual atoms without reference to other atoms. This property, called zero-order kinetics, means that the rate of decay is constant and depends neither on the concentration of the radioisotope nor on temperature. First-order reactions, which depend on the encounter of two molecules such as an acid and a base, increase in rate as the temperature increases (speeding up the molecules) or the concentration increases (increasing the likelihood of a collision between the molecules). For zero-order reactions, the rate of change is constant regardless of temperature or concentration. For instance, if there are one million atoms of tritium, 500,000 will decay in 11 years whether the tritium is found in Antarctica or Brazil, and whether the tritium is found as an extremely low percentage of water or as a concentrated pure laboratory preparation. Radioactive decay can also be detected in vanishingly small amounts of chemicals. Tritium can be easily detected if there is 5×10^{-15} g of radioactive water present. To put this in perspective, if you take the smallest amount of a fine powder such as powdered sugar that you can see, dissolve it in a bathtub, and then remove one drop of this solution, you can easily detect the tritium. There is also one other property of interest: A radioactive molecule decays to an identifiable molecule. Thus ^{238}uranium (the radioactive form of uranium) decays to ^{208}lead. As is explained below, these properties can be used to calculate the age of a rock and thus, potentially, the earth.

There is one slight complication, but one that is easily resolved by mathematics. This is that a specific fraction of radioactive atoms will decay in a given time. What this means is that if one has 1000 atoms of tritium, 500 of them (half of them) will decay during the first 11 years. Of the remaining 500 atoms, another half, or 250, will decay during the next 11 years. We define this property as the half-life of the isotope. It is the period during which half of the remaining radioisotopic

Table 8.1. Decay of radioisotopes as a function of half life

Starting time	Radioactive atoms	Decayed atoms
0	1,000,000	0
11 years	500,000	500,000
22 years	250,000	750,000
33 years	125,000	875,000
44 years	67,500	942,500

atoms decay. The curve of radioactive decay will not be linear but will gradually decline in a mathematical form called an asymptotic decline (Table 8.1, Fig. 8.9). During the first half life, half of the atoms will decay. During the next half life, half of the remaining half, or one quarter of the total, will decay. During the next half life, half of the remaining quarter, or one eighth of the total, will decay. This will continue until the last atom decays. Different types of isotopes have different half-lives, ranging, for common isotopes, from hours to billions of years (Table 8.2).

How does all this help us to measure the age of the earth? Suppose, as Lord Kelvin suggested, that the Earth was molten at first. In liquids, heavier materials such as metals will sink (toward the center of the earth), while lighter materials will float toward the top. As the earth cooled, the materials would solidify. Some materials would contain substantial amounts of metals. Now suppose that in one rock there is a measurable amount of ^{238}uranium, which can decay at a known rate, independent of the temperature or the concentration of uranium, to ^{205}lead. The amount of lead will increase, and the amount of uranium will decrease, as a function of time. In 4.5 billion years, half of the original uranium will have turned

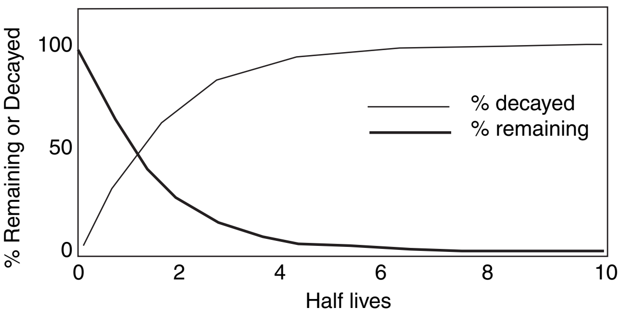

Figure 8.9. Radioactive decay. Over time, a defined percentage of the remaining radioactive atoms will decay, leading to an exponential decrease in the total radioactivity and an exponential increase in the product of the decay. Half lives for different elements range from fractions of seconds to hundreds of thousands of years. Although these are curves rather than straight lines, it is easy mathematically to determine the age of the material by comparing the ratio of precursor radioactive atom to product atom, or the ratio of precursor radioactive atoms to non-radioactive atoms. Not all atoms are radioactive. For instance, approximately one atom of carbon in one trillion is radioactive

Table 8.2. Half lives of elements

Uranium 238 (used in bombs)	4.5 billion years
Carbon 14 (used to measure age of earth)	5,730 years
Strontium 90 (can get into bone)	29 years
Tritium (Hydrogen 3, used in watch dials)	11 years
Phosphorus 32 (used in medicine)	14.3 days
Iodine 131 (used in medicine)	8 days
Most material from Three Mile Island	Less than one second

to lead. Using a similar logic, the time that the uranium had been in the rock could be calculated from the ratio of lead to uranium. Using this type of logic, scientists looked all around the Earth for rocks containing uranium. In several locations, most notably in western Canada and Australia, some rocks gave calculated ages of 2.5 billion years or more.

RED SHIFT

You have probably noticed that as an airplane, a race car, or a train passes, the sound of its motors changes. This is called the Doppler Effect, after the physicist who first described and explained it. It works as follows: Imagine the steady hum of an electric motor, which generates sound according to the 60 cycles/second of the electric current, and the sound comes toward you at the speed of sound, approximately 600 mph. If a jet airplane is heading toward you at near the speed of sound, each peak of the cycle will start closer to you than the last, arriving sooner and effectively increasing the frequency to approximately 120 cycles/second, increasing the tone or pitch of the sound. As the plane passes by you, the frequency will drop to 60 cycles/second. As it goes away from you, each peak will start farther from you and reach you later, effectively delaying the cycles to 30 cycles/second—a distinctly lower pitch (Fig. 8.10). The equivalent to this change in pitch is seen also with light. Because the mechanism is the same for light and sound is the same, the phenomenon is called "red shift". Long wavelength light is red, and short wavelength light is blue (see Fig. 19.2, page 273). (A rainbow is generated because when light is reflected through glass (a prism) or water (a raindrop), the shorter wavelength rays are bent more than the longer ones—see Fig. 8.11.) The equivalent of a lower tone when an object moves away is a change in color toward red; of a higher tone as an object approaches; a change in color toward blue. Fortunately, there are absolute values for light: When sodium is heated, it emits yellow light at a very precise wavelength, termed a "line" on a spectrum of colors. The light from sodium and other elements can be detected in the emissions of stars. If the star is moving toward the Earth, the lines from sodium and other elements will be compressed, or shifted toward blue. If the star is moving away from the Earth, the lines will be shifted toward red. Almost all stars appear to be moving away from the Earth. From the magnitude of the red shift, one can tell how rapidly the star is receding from the Earth. By using figures such as these and other measurements

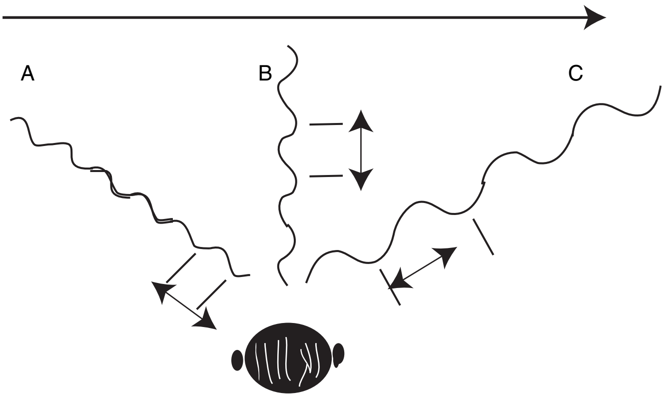

Figure 8.10. Doppler effect or red shift. As an object moves (arrow at top) and at first comes toward the observer (A), since each wave travels at the same speed but the later waves start from a position closer to the observer, the waves are perceived as occurring at higher frequency (higher pitch or shift to the blue end of the spectrum). As it passes directly in front of the observer (B) the pitch is heard correctly. As the object moves away (C), waves are perceived as occurring less frequently (lower pitch; shift toward red). Since the light given off by heated atoms is always at a specific wavelength, the shift of the wavelength to the red or blue indicates the relative motion of the object

that give estimates of the current distances of the stars, one can calculate how long it would have taken the stars to expand from a common starting point, assuming that they continue to move along their original paths (the Big Bang theory). The calculation indicates an approximate age for the beginning of the universe of about 6 billion years ago.

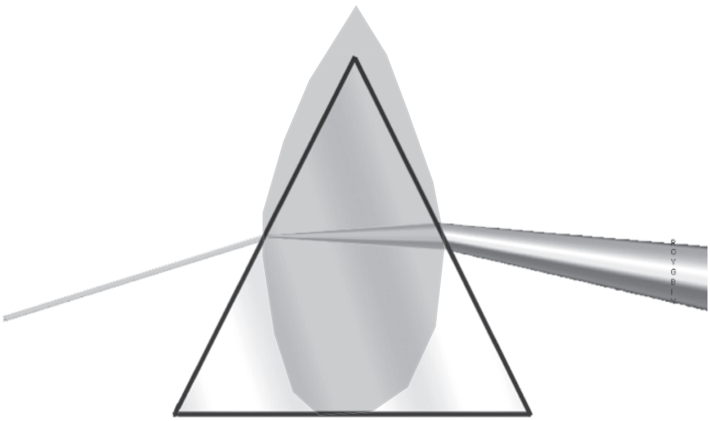

Figure 8.11. When light enters a prism or a raindrop at an angle, it is refracted (bent) during its passage through the medium and back into the air. This is why a spoon in a glass of water can appear to be broken. Short wavelength light (violet) is refracted more than long wavelength light (red), breaking the light into a spectrum (from top to bottom: red, orange, yellow, green blue, indigo, violet)

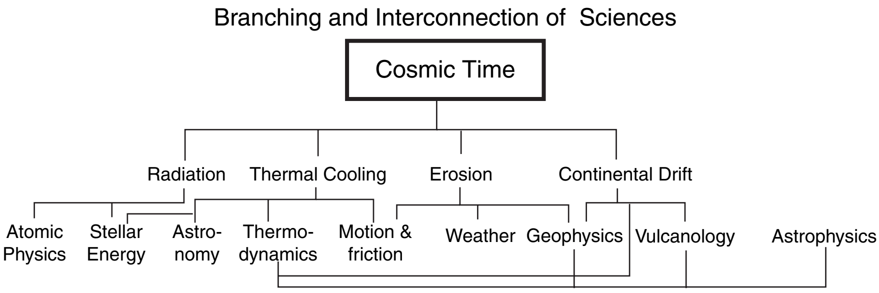

Figure 8.12. The age of the earth is identified through many sciences, each using different methods. Some of the methods serve more than one function, but all converge on a common understanding of the age of the earth

Of the many lessons to be learned here, one more general principle is quite important. The **convergence of multiple independent means of assessment** provides very solid argument in support of a hypothesis. This topic is the subject of Chapter 9, immediately following, but it is worth noting that the mechanisms of erosion, of earthquakes, of thermal cooling, of red shift, and of radioactive decay, in no way depend on each other. Nevertheless, when all factors are taken into account (for instance, that radioactivity adds to the heat of the earth), they all give dates for the age of the earth that are consistent with each other. We can conclude that the value that they give does not derive from our misunderstanding of our means of measurement, such as using an inaccurate thermometer or mistaking a centimeter ruler for a yardstick. All these sciences, and more, give the same result (Fig. 8.12). To claim that one interpretation is false would require us to disprove the findings of all the other sciences as well. There is essentially no doubt that the world is very old.

REFERENCES

Dalrymple, G. Brent, 1991, *The Age of the Earth*: Stanford, Calif., Stanford University Press, 474 p.

Darwin, C., The Origin of the Species

Harland, W.B.; Armstrong, R. L.; Cox, A.V.; Craig, L.E.; Smith, A.G.; Smith, D.G., 1990. A Geologic Time Scale, 1989 edition. Cambridge University Press: Cambridge, p.1–263

Powell, James Lawrence, 2001, *Mysteries of Terra Firma: the Age and Evolution of the Earth,* Simon & Schuster

Wilde S. A., Valley J.W., Peck W.H. and Graham C.M. (2001) *Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago.*

Nature, v. 409, pp. 175–178 http://nationalacademies.org/evolution/ (free downloads) http://pubs.usgs.gov/gip/geotime/age.html

STUDY QUESTIONS

1. A hospital that uses ^{131}iodine spills a little. Assuming that a safe level is 1/1000 of the amount that is spilled, how long will it take to get to that level if it is not cleaned up?

2. The next time that a jet airplane passes overhead or a high-speed trans-continental freight train passes, notice the change of tone as it passes. Diagram how this works.
3. Why do we not notice the red shift in the sound of a passing car or a color change when a baseball is thrown past us?
4. Take two similarly shaped containers, for instance two jars, of very different sizes. Fill both with hot water from the same source, and cover the jars. Without otherwise disturbing them, measure the temperature of the water inside the jars and the temperature of the surfaces of the jars for several hours after you begin the experiment.
5. If you *really* want to try something challenging, try to extrapolate this measurement to the size of the earth. Suppose that your small jar has a diameter of 5 cm (about 22½ inches) and your large jar has a diameter of 10 cm. The surface temperature of the small jar dropped from 60° C (about 140° F) to 30° C in 30 minutes, or 1° C/minute. The surface temperature of the large jar dropped from 60° to 45° in the same time, or 0.5°/minute. You can plot these results with diameter on the X axis and rate of cooling on the Y axis. Now assume that the jar is as wide as the earth—12,700 km, or 12,700,000 m, or 1,270,000,000 cm. How long would it take for the jar to cool so that the surface was a comfortable 25° C? (Obviously the calculation is much more complex, but this is essentially what Kelvin did.)
6. If you live along the west coast of the US, identify a suitable website or library source that can give you an estimate of the rate at which earthquakes lift the land. Now look up the height of the mountains in the region. How long would it take for earthquakes to create those mountains?
7. How far has Niagara Falls moved since the last ice age?
8. What evidence in your area is there for the age of the earth?