chapter 9

Radioactive Dating

In Chapter 1, we briefly discussed the discovery of radioactivity and the work of Becquerel, the Curies, and Rutherford in the early twentieth century. Their research led to the discovery of many stable, and some unstable, elements as the century progressed.

The Chemistry of Unstable Elements

The decay of an unstable mother element into a stable daughter element is the basis for determination of absolute ages. New methods had to be invented to deal with all the newly discovered unstable elements, particularly the extraction of tiny elements from microscopic fluid, solid, and gaseous samples. These techniques were developed in several physics laboratories worldwide. Their acceptance by the geological community, however, proceeded slowly, though steadily, during the first 50 years of the twentieth century. Today, radioactive dating has developed into one of the most spectacular and promising disciplines of modern geology, relating the calculated absolute ages to certain rocks and tectonic events, and providing a stronger framework for describing tectonic evolution. As an example of present-day accuracy, the age of a 4-billion-year-old rock can be determined with three digits behind the decimal point! However, the needed techniques, such as mass spectrometry to separate elements and their isotopes, proved to be complex and difficult to develop.

Isotopes are different forms of one element, all having the same number of protons, but different numbers of neutrons in the nucleus. They began to play a special role in nuclear physics after scientists discovered that an unstable (radioactive) element disintegrates to form atoms with various isotopes of a different element. The analysis of these isotopes is carried out in different laboratories, specialized for greater and lesser ages.

During the second half of the twentieth century it became possible to analyze particles with a very small concentration of radioactive elements, such as the rare-earth element *neodymium* and its mother element *samarium*, which has an extremely long decay time (more than 100 billion years). This method developed into one of the most important dating techniques for large ages, together with the *uranium-lead* and *rubidium-strontium* calculations. Methods for determining small ages, i. e., for studies of climate or prehistory, require elements with short decay times. One procedure for dealing with such small ages is the carbon dating technique, which will be described at the end of this chapter.

Decay

The decay of radioactive elements is connected with the emission of particles and energy, which changes the number of protons (Z) and neutrons (N), and thus possibly also the nucleon number A ($A = Z + N$). From a mother element (M), a daughter element (D) is created. The daughter may be unstable, too, and then further decay until finally a stable daughter element is reached.

There are three kinds of decay processes, each of which is related to α-, β-, and γ-radiation. Through α-radiation, Z and N are lowered by 2 units, β- radiation increases Z and N by 1 unit, and γ- rays leave Z and N unchanged (see Figure 9.1). Mother elements decay exponentially with time, while daughter elements increase accordingly. The time it takes before only half of a mother element is left is called half-life (t_H). Based on the known half-life of different unstable elements, the ages of the oldest rocks and even the origin of the Earth can be determined.

Determining the Age

Radioactive age determination starts with the well-known *law of radioactive decay*, which states that the rate of decay $\mathrm{dM}/\mathrm{d}t$ is proportional to the mother element M:

$$-\mathrm{dM}/\mathrm{d}t = \lambda \mathrm{M}$$

where λ is the individual decay constant. The solution of this equation is $-\ln \mathrm{M} = \lambda t + \ln \mathrm{M}_0$. The integral form $\mathrm{M} = \mathrm{M}_0 + e^{\lambda t}$, shows the exponential form of the decay. The daughter element is $\mathrm{D} = \mathrm{M}_0 - \mathrm{M}$, where M_0 is the initial concentration of the mother element.

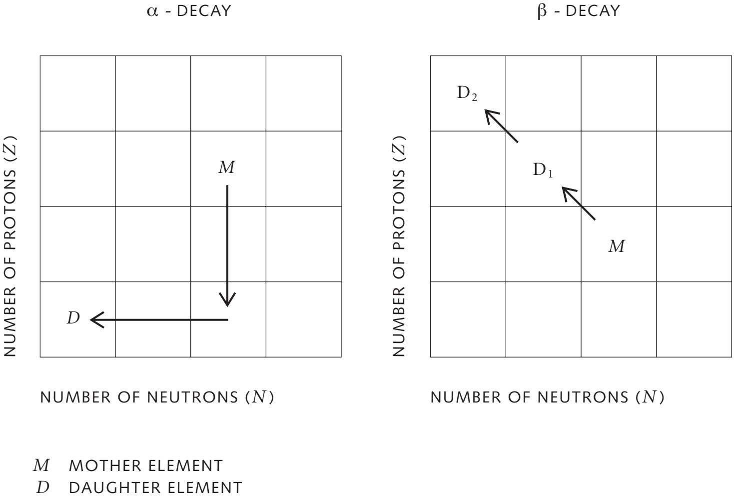

FIGURE 9.1 α- and β-decay.

Generally, we do not know the initial concentration M_0. We first express it in terms of the daughter D and then perform a calibration by introducing the non-radioactive daughter D_n, and eventually obtaining $D/D_n = D_0/D_n + (M/D_n)\,(e^{\lambda t} - 1)$.

D_0, the initial concentration of the radioactive daughter, is always rather small. The term $e^{\lambda t}$ can be approximated by λt. There are two possibilities for determining the time of origin t, as shown in Figure 9.2. We can plot D/D_n on the ordinate and either M/D_n or t on the abscissa. In the chart on the left, a straight line displays λt (and hence the time t) as a gradient; it also provides the *initial value* D_0/D_n as the intercept. On the right, we start with several samples and get several straight lines for different concentrations of the mother element. The most important experimental task is to determine D and M in a mass spectrometer (or by other techniques).

Age Determination in Closed Systems

Different minerals have different closing (blocking) temperatures, meaning that they solidify out of a melt at different temperatures. Once solidified, however, the mineral is a *closed system*, and no mothers and daughters can escape or be exchanged. The radioactive clock begins to tick and records the starting time t. Knowing the temperature T and the pressure of solidification p, we can even track the paths of a rock in a pressure-temperature-time diagram (Figure 9.3).

When radioactive dating techniques were first used, metamorphosis caused serious problems, and many age determination efforts established the time of the *last* metamorphosis where many minerals melted and mixed. Rocks are modified during metamor-

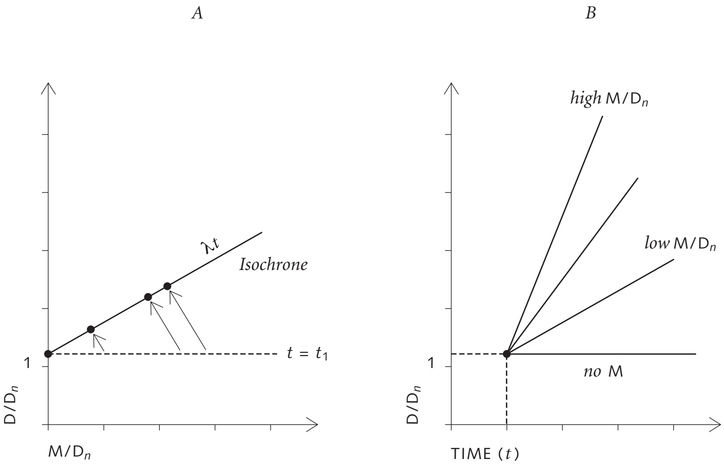

FIGURE 9.2 Two types of radioactive dating. A: The gradient, or isochrone, provides the absolute age *t*. B: The gradients show various mother-daughter relations.

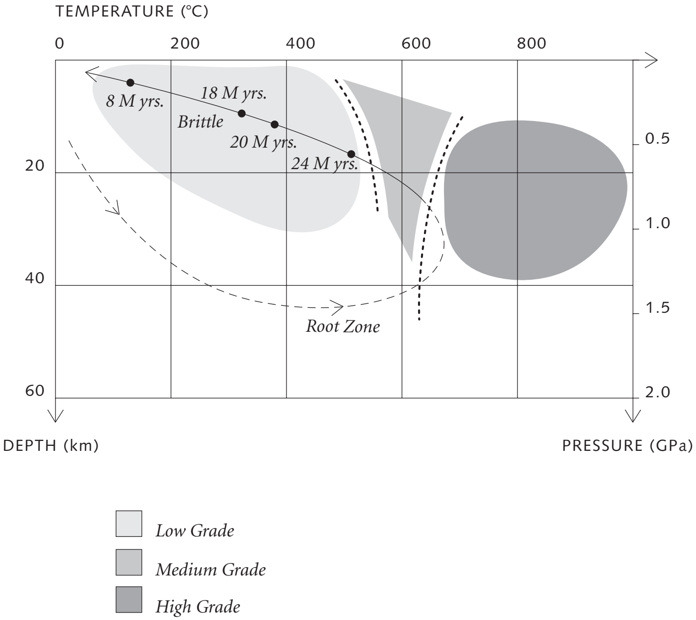

FIGURE 9.3 The circle-like path of a rock experiencing metamorphosis. The marked ages of solidification (24 to 8 million years ago) are confirmed by various minerals that formed closed systems at known temperatures.

phosis, and some minerals migrate, especially those with a low melting point. Using several rocks and concentrating on the minerals with the highest melting point, the metamorphosis and the origin of the rock can be determined. But if the rock was totally re-melted (in a general melt called *anatexis*), only the new solidification can be measured.

Over the years, scientists have learned that in order to identify the correct age of a rock or mineral, the sample has to be taken from a closed system where no migration of elements takes place. We can also apply the concept of a closed system to larger units, e. g., to a meteorite, a whole class of meteorites, a rock unit, parts of the crust, parts of the mantle, and even the whole Earth. The challenge is to collect representative samples. After observing that many samples from certain closed systems really do provide similar, reliable results and indicate comparable processes, scientists were able to develop even more advanced methods of age determination. For example, scientists have learned how to determine the formation times for various parts of the continental crust, because large parts were formed by a uniform and hot differentiation process of the mantle, providing similar temperatures and temperature histories. This created uniform and comparable ages of solidification. This process, in turn, led to a new method for trace element investigation and close study of enriched and depleted parts of the mantle. For example, the source of the *mid-ocean ridge basalts* (MORB) is depleted in incompatible elements, such as rubidium, barium, thorium, and uranium. The Hawaiian lavas and those from other plume sources (see Chapter 13) are less depleted on average, while the continental crust is strongly enriched in incompatible elements. Thus, any part of the mantle can be affected by crustal "contamination," for example caused by a delamination process (see, again, Chapter 13). Researchers have been able to discover the formation time of huge volcanic provinces as well as the origin and development of mountains or rifts. Even the collapse of the solar nebula and the formation of the Earth and other planetary bodies have been dated. Regarding the Earth's origin, it is interesting that the most different meteorites, such as chondrites from the outer Asteroid Belt (consisting of spherules of primitive matter) or achondrites from the interior Asteroid Belt (consisting of differentiated rocks and iron), all provide the same age of 4.6 billion years, and only an extremely small and special group suggests a slightly older age. The age of solidification is certainly the same as that of the accreting Earth and the adjacent planets.

Applications of Radioactive Dating Techniques

Radioactive dating methods are also put to use to assess ocean and continent drifts. While paleomagnetic studies specify the latitude of drifting continents (as discussed in Chapter 6), radioactive age determination reveals the time of their magnetization. From both observations (magnetization and time), the north–south drift of a continent can be clarified.

In addition, scientists apply radioactive dating methods to estimate the time at which a continent was split apart, or the time of a continent–continent collision. The approach of a continent or a *terrane* (see Chapter 13) can be further observed using paleontological methods to analyze the increasing similarity of fauna and flora before collision, which is just one more example of the steadily growing integration of the different geophysical and geological methods. This collaboration has led to our present knowledge of a mobile Earth.

Carbon Dating

Unstable elements with very short half-lives provide the basis for yet another spectacular form of radioactive dating methods. The carbon dating method has been developed to study materials that are no older than 100,000 years; the half-life of the carbon isotope ^{14}C is only around 5730 years. This method is the only one where the mother element ($^{14}C_0$) is available because it is continuously created in the atmosphere from the nitrogen isotope ^{14}N under the influence of radiation (even though some corrections have to be applied to the mother $^{14}C_0$, since it varies slightly depending on the strength of the magnetic field and the intensity of solar radiation). ^{14}C is absorbed constantly by plants through photosynthesis, and by humans and animals through respiration. Death, however, stops metabolism and respiration. The ^{14}C then begins to decay, starting the radioactive clock.

The age of many organic depositions like peat, moors, remnants of plants and trees, and skeletons of animals and humans can be specified using the carbon dating technique. Archeology, paleontology, and climatology have all contributed to and profited prodigiously from the exactness of this type of age determination. In climatology, for example, the relation of the stable isotopes of oxygen, i. e., the heavy ^{18}O to the lighter ^{16}O, provides reliable data on temperature because evaporation is temperature-dependent and prefers the light ^{16}O. International drilling programs in Antarctica and Greenland investigated air bubbles in ice cores and revealed a great deal about our planet's climate over the last 110,000 years, a period notable for its many advances and retreats of ice and glaciers. The very rugged appearance of the temperature curve of the last 100,000 years, as displayed in Figure 15.3, is one of the most exciting results of $^{16}O/^{18}O$ measurements in deep boreholes.

The human evolution during this period of time has been largely deciphered with the help of the carbon dating method. This was especially complicated because, for about 80,000 years, two species of hominids (the *Homo neanderthalensis* and the *Homo sapiens*) lived at the same time and sometimes even in the same regions. It was (and still is) a challenge for scientists to find out how and when the *Homo sapiens* arrived and the Neanderthals disappeared.

Paleontologists are perhaps the greatest winners of isotope geology. Fossils—their appearance, their mutation, and their extinction—can now be exactly dated, transforming the relative timescale, initiated in the nineteenth century, into an absolute scale. Moreover, an exact clock for the overall history of our planet has become available.