daughter ratio of two different radioactive elements in the same mineral. For example, naturally occurring uranium consists of both uranium 235 and uranium 238 isotopes. Through various decay steps, uranium 235 decays to lead 207, whereas uranium 238 decays to lead 206 (Fig. 9-19). If the minerals containing both uranium isotopes have remained closed systems, the ages obtained from each parent-daughter ratio should be in close agreement and therefore should indicate the time of crystallization of the magma. If the ages do not closely agree, other samples must be taken and ratios measured to see which, if either, date is correct.

## Long-Lived Radioactive Isotope Pairs

Table 9-1 shows the five common, long-lived parent-daughter isotope pairs used in radiometric dating. Long-lived pairs have half-lives of millions or billions of years. All of these were present when the Earth formed and are still present in measurable quantities. Other shorter-lived radioactive isotope pairs have decayed to the point that only small quantities near the limit of detection remain.

The most commonly used isotope pairs are the uranium-lead and thorium-lead series, which are used principally to date ancient igneous intrusives, lunar samples, and some meteorites. The rubidium-strontium pair is also used for very old samples and has been effective in dating the oldest rocks on Earth as well as meteorites. The potassium-argon method is typically used for dating fine-grained volcanic rocks from which individual crystals cannot be separated; hence the whole rock is analyzed. However, argon is a gas, so great care must be taken to assure that the sample has not been subjected to heat, which would allow argon to escape; such a sample would yield an age that is too young. Other long-lived radioactive isotope pairs exist, but they are rather rare and are used only in special situations.

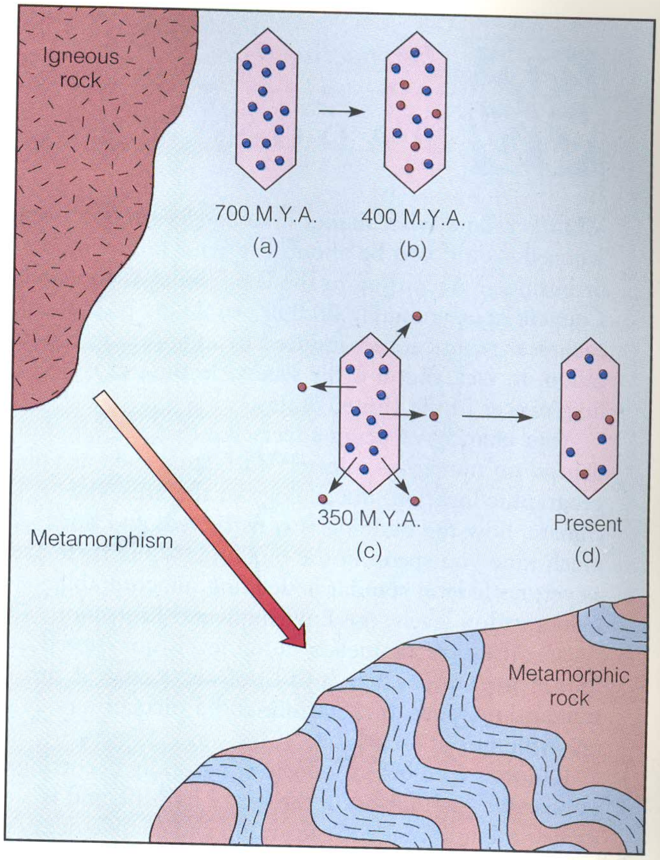

**FIGURE 9-22** The effect of metamorphism in driving out daughter atoms from a mineral that crystallized 700 million years ago (M.Y.A.). The mineral is shown immediately after crystallization (*a*), then at 400 million years (*b*), when some of the parent atoms had decayed to daughter atoms. Metamorphism at 350 M.Y.A. (*c*) drives the daughter atoms out of the mineral into the surrounding rock. (*d*) Assuming the rock has remained a closed chemical system throughout its history, dating the mineral today yields the time of metamorphism, while dating the rock provides the time of its crystallization, 700 M.Y.A.

## Radiocarbon Dating Methods

Carbon is an important element in nature and is one of the basic elements found in all forms of life. It has three isotopes; two of these, carbon 12 and 13, are stable, whereas carbon 14 is radioactive. Carbon 14 has a half-life of 5,730 years plus or minus 30 years. The **carbon 14 dating technique** is based on the ratio of carbon 14 to carbon 12 and is generally used to date once-living material.

The short half-life of carbon 14 makes this dating technique practical only for specimens younger than about 70,000 years. Consequently, the carbon 14 dating method is especially useful in archaeology and has greatly aided in unraveling the events of the latter portion of the Pleistocene Epoch.

Carbon 14 is constantly formed in the upper atmosphere by the bombardment of cosmic rays, which are high-energy particles (mostly protons). These high-energy particles strike the atoms of upper-atmospheric gases, splitting their nuclei into protons and neutrons. When a neutron strikes the nucleus of a nitrogen atom (atomic number 7, atomic mass number 14), it may be absorbed into the nucleus and a proton emitted. Thus, the atomic number of the atom decreases by one,