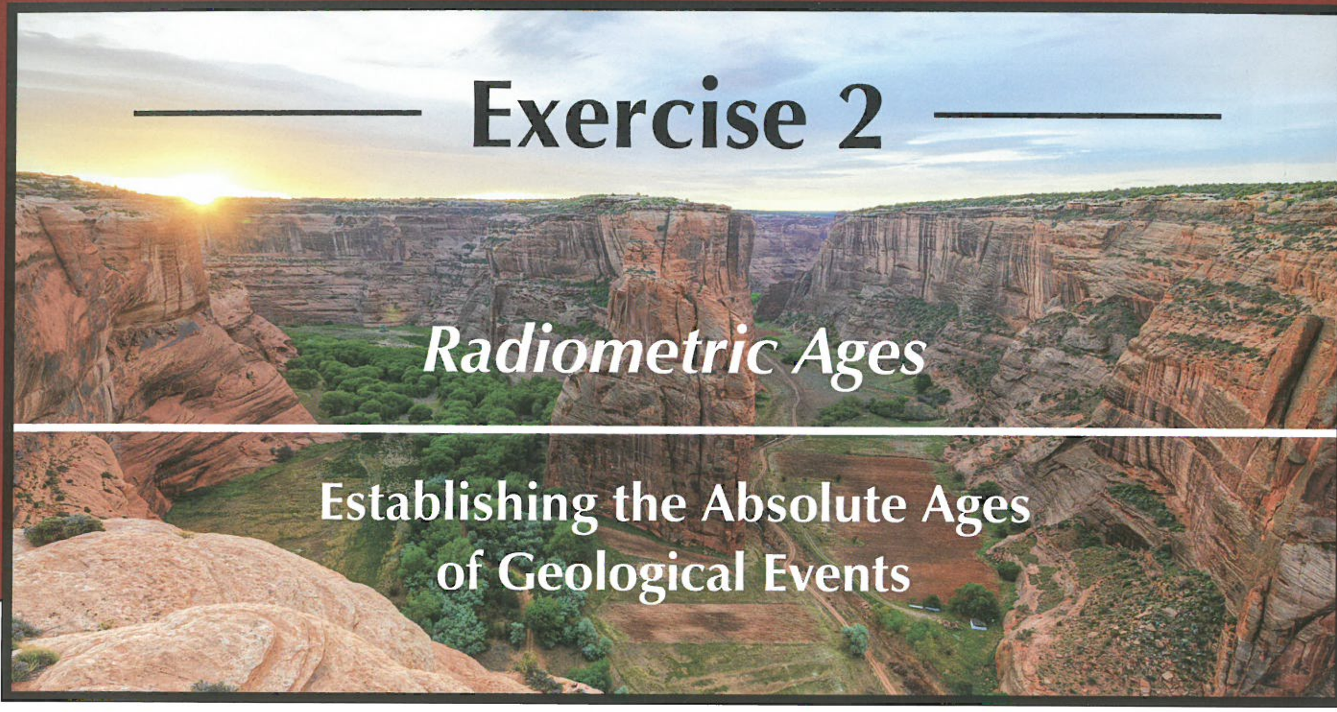
# Exercise 2

## Radiometric Ages

### Establishing the Absolute Ages of Geological Events



**LEARNING OBJECTIVES** **After completing this exercise, you will:**

1. be able to explain why radioactive decay provides a means for calculating the ages of geological materials;
2. be able to define the concept of half-life as it pertains to radioactive materials;
3. have familiarized yourself with the parent-daughter isotope pairs most commonly used to calculate ages of geological materials;
4. be able to indicate the types of source materials that contain radiogenic uranium, potassium, rubidium, and carbon;
5. be able to calculate the absolute ages of materials given the ratio of parent-daughter isotopes and the appropriate decay constant; and
6. know how radiometric dating of chiefly igneous bodies can be used to determine the ages and durations of eons, eras, periods, and epochs (which were chiefly determined on the basis of sedimentary rocks).

The age of Earth is approximately 4.6 billion years. This age, which was based upon radiometric dating, is dramatically older than ages calculated by previous means. For example, in 1899, John Joly attempted to estimate the age of Earth by measuring the amount of salt the rivers of the world carry to the sea annually and comparing that to the total salt in the ocean. Since the oceans' salt is derived from weathering of rocks on Earth's surface, Joly estimated 90 million years had elapsed since the first freshwater oceans condensed on Earth's surface. Since Earth is much older than this, the oceans should be much saltier than they are. Clearly there are mechanisms by which salt is removed from the oceans.

Several scientists have approached the age of Earth by studying the thickness of sedimentary rocks on Earth's surface and comparing them with modern rates of accumulation for these rock types. The resulting ages range from 17 million years to as much as 1.5 billion years. With a modern understanding of plate tectonics we recognize the problems with this approach. Deposition of sediment is interrupted and sediment is recycled.

Lord Kelvin approached this problem by studying the cooling of Earth. He measured the increase in temperature of the crust by depth in deep mines. We call the increase in temperature with depth in Earth's interior the geothermal gradient. He calculated how long it would take for a molten Earth to cool so that the geothermal gradient in Earth's crust matched his measurements. He estimated that this would take 24 million years. Kelvin did not understand that the natural decay of radioactive isotopes produces heat. He also did not know that convection in the mantle heats the lithosphere from below, raising the geothermal gradient he measured. Thus, his estimate was also far too young.

In 1896, a French physicist, Henry Becquerel, discovered radioactivity, a process whereby isotopes of certain elements, uranium for example, spontaneously break down to form isotopes of new and lighter elements such as lead. Using the principle of radioactivity to study the decay of uranium to lead, in 1907 an American chemist, Bertram Boltwood, calculated ages for rocks in various parts of the geologic column. In spite of his rough calculations, Boltwood's calculated dates were remarkably close to presently accepted ages for the same rocks.

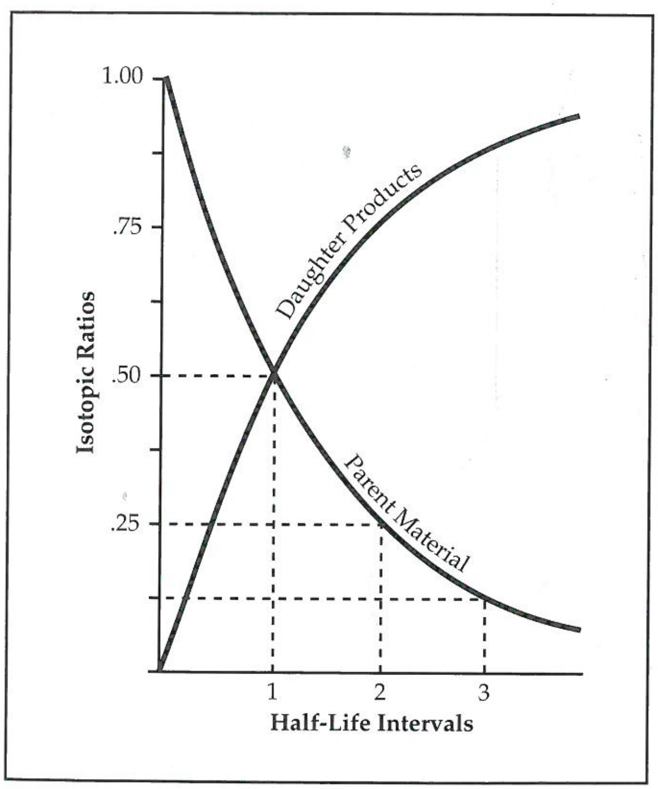



**FIGURE 2.1** Graph showing decay of parent material with simultaneous buildup of daughter products over half-life intervals of time.

Radiometric ages are calculated in number of years and are referred to as absolute rather than relative ages. The basis for radiometric ages is natural radioactivity—the spontaneous decay of certain isotopes, called **parent isotopes**, to produce unique end products called **daughter products**, which accumulate as the parent material decays, as shown in figure 2.1. The decay rate, as well as the type of radioactive particle emitted, is unique for each radioactive isotope. The time period required for half of the atoms to decay is called the **half-life**.

## Modes of Decay

Most radioactive isotopes decay by one of the following types of radiation:

- **Alpha radiation:** Alpha particles are composed of two protons and two neutrons from the parent isotope's nucleus. The loss of an alpha particle, therefore, reduces the parent isotope by four mass units (atomic weight) and reduces the atomic number by two. For example, parent uranium-238 decays to daughter lead-206. The decrease in mass number is four. Thorium has an atomic number of 90, whereas uranium has 92. Thus, the atomic number, or number of protons, decreases by two. All of this results from the emission of one alpha particle. Thorium-234, in turn, is also radioactive, and a series of decays eventually lead to the formation of lead-206, which is stable.

- **Beta radiation:** Beta decay is a high-energy electron released from the nucleus, converting a neutron into a proton. The parent material changes only by the addition of a single proton in its nucleus, or an atomic number increase of 1. Mass number remains the same because the mass of the emitted electron is insignificant compared to the masses of the neutrons and protons. Beta radiation can also result by capture of an electron by the nucleus. The result of this change is the same except the atomic number decreases by 1. Rubidium-87 decaying to strontium-87 is an example of losing an electron and increasing the atomic number by one. Potassium-40 decaying to argon-40 illustrates electron capture and a decrease in the atomic number by one.

- **Gamma radiation:** Energy release is similar to X-rays.

## Limitations to Radiometric Age Determination

Radiometric ages have limitations, depending upon a number of factors. Some methods are more precise, some less, depending upon a variety of conditions. Some issues associated with radiometric ages include:

1. For many, but not all, methods of measuring the absolute age of a rock or mineral, the sample must have remained closed. This means that neither parent nor daughter isotope has been gained or lost from the sample by reheating, chemical weathering, or some other process.
2. The equipment used, usually a mass spectrometer, must have sufficient accuracy and precision.
3. The result must be properly interpreted and the technique(s) must be appropriate for a specific geologic problem. For example, one technique applied to a metamorphosed pluton might reveal the age of metamorphism. Another technique applied to the same rock might estimate the age of the protolith. These ages could be very different, so care must be taken to chose the correct method and then interpret the results carefully.

## The Radioactive Decay Law

The principle of radiometric age determination can be expressed by the following simple relationship:

$$\frac{A}{A_o} = \exp(-\lambda t)$$

where

$A$ = the activity per unit weight of some radioactive parent isotope at some time $t$ in a sample of interest

$A_o$ = the activity per unit weight of the parent isotope when the sample formed

$\lambda$ = the decay constant

$t$ = the age of the sample

The age of the sample is thus:

$$t = -\frac{1}{\lambda}\ln\left(\frac{A}{A_o}\right)$$

It is very valuable to understand what the decay constant ($\lambda$) represents. We can do this by assuming that one half-life of the parent isotope has passed:

$$\frac{A}{A_o} = \frac{1}{2} = \exp\left(-\lambda t_{1/2}\right)$$

Thus the decay constant ($\lambda$), after rearrangement, is defined as:

$$\lambda = \frac{\ln(2)}{t_{1/2}}$$

The decay constant ($\lambda$) is really just another way to express the half-life. This relationship is true for all radiometric techniques.

Table 2.1 lists the radioactive parent isotopes most commonly used for radiometric age determination. Also listed are the decay products (daughter isotopes), calculated half-lives, and sources of radioactive geological materials. Using table 2.1, we can apply radiometric dating to calculate the age of a

| Parent Isotope | Daughter Isotope | Duration of Half-Life ($T$) | Source Materials |
|---|---|---|---|
| Uranium-238 | Lead-206 | 4.5 billion years | Zircon, uraninite |
| Uranium-235 | Lead-207 | 713 million years | Zircon, uraninite |
| Potassium-40 | Argon-40 | 1.3 billion years | Biotite, muscovite, whole volcanic rock |
| Rubidium-87 | Strontium-87 | 48.6 billion years | Mica, feldspar, hornblende |
| Thorium-232 | Lead-208 | 14.0 billion years | Igneous rocks |
| Carbon-14 | Nitrogen-40 | 5,730 years | Wood, bone, coral |

**TABLE 2.1** **Chart showing various isotopes used in radiometric dating, their daughter isotopes, duration of one half-life, and source materials for the parent isotope.**

material. For example, let's say that a zircon crystal originally contained 100 million uranium-238 atoms and zero lead-206 atoms. It now contains 84.1 million atoms of U-238 and 15.9 atoms of Pb-206. Since 84% of the parent isotope remains, using figure 2.2 we see that one-quarter of a half-life has elapsed. We can now calculate the age of the material as follows:

$$\left(\begin{array}{c}\text{half-lives}\\\text{elapsed}\end{array}\right) \times \left(\begin{array}{c}\text{duration of}\\\text{half-life}\end{array}\right) = \text{age in years}$$

or

$$0.25 \times 4.5 \text{ billion years} = 1.125 \text{ billion years}$$

| Percentage of Parent Isotopes | Percentage of Daughter Isotopes | Number of Half-Lives Elapsed | Age in Years (see table 2.1 for values of ***T***) |
|---|---|---|---|
| 100 | 0.0 | 0.0 | 0.000 x ***T*** |
| 98.9 | 1.1 | 1/64 | 0.015 x ***T*** |
| 97.9 | 2.1 | 1/32 | 0.031 x ***T*** |
| 95.8 | 4.2 | 1/16 | 0.062 x ***T*** |
| 91.7 | 8.3 | 1/8 | 0.125 x ***T*** |
| 84.1 | 15.9 | 1/4 | 0.250 x ***T*** |
| 70.7 | 29.3 | 1/2 | 0.500 x ***T*** |
| 50.0 | 50.0 | 1 | 1.000 x ***T*** |
| 35.4 | 64.6 | 1.5 | 1.500 x ***T*** |
| 25.0 | 75.0 | 2 | 2.000 x ***T*** |
| 12.5 | 87.5 | 3 | 3.000 x ***T*** |
| 6.25 | 92.75 | 4 | 4.000 x ***T*** |
| 3.13 | 96.87 | 5 | 5.000 x ***T*** |

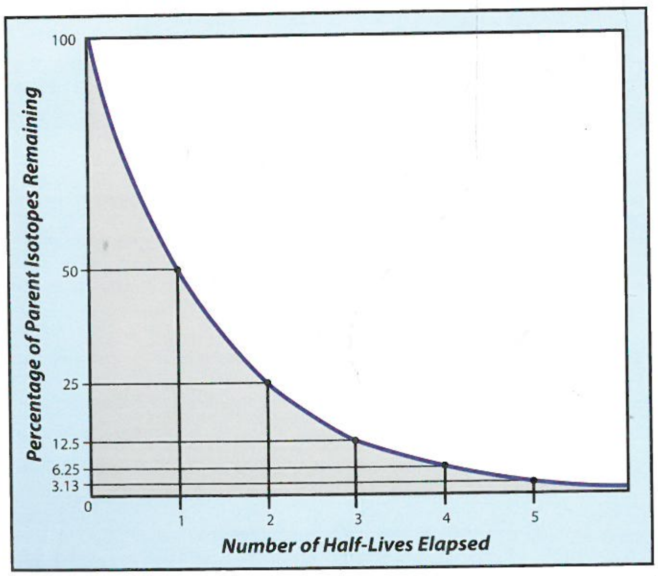



**FIGURE 2.2** **Graph showing decay curve for radiogenic isotopes.**

# PROCEDURE

The eons, eras, periods, and epochs of the geological timescale (figure 1.1) were constructed by applying the principles of relative dating to fossil-bearing sedimentary rock sequences in England and elsewhere. Sedimentary rocks are not conducive to radiometric dating because they are comprised of sedimentary particles derived from older source materials. Radiometric dating of sedimentary rock particles indicates the age of the igneous or metamorphic rock from which the particle was derived, not the age of sedimentary deposit to which it now belongs. Depositional ages are calculated by extrapolation from the ages of associated igneous and metamorphic rock bodies.

## Determining the Absolute Age of the Carboniferous–Permian System Boundary

Although radiometric dating of each eon, era, and period boundary is based upon somewhat different isotopes, source materials, and stratigraphic relationships, the methodology that you use to date the beginning of the Permian Period is similar to that used in defining the ages of other geologic periods, eras, and eons. In this part of the exercise, you will:

- Determine the placement of the Carboniferous–Permian boundary in the deep-water Usolka River section (figures 2.3 and 2.4) using stratigraphic occurrences of key conodont species.
- Determine the radiometric age of the Carboniferous–Permian boundary by integrating radiometric dates derived from ash beds (bentonites) with the conodont data derived from marine limestones.

The Carboniferous–Permian boundary is defined by the first occurrence of the conodont species *Streptognathodus isolatus* in the sedimentary succession at the Aidaralash Creek type locality in northern Kazakhstan, located a few hundred kilometers south of the Usolka River locality. Strata of beds 1 through 39 (Late Carboniferous–Early Permian) at the type locality consist of deep-water silt and clay, with occasional sand and very coarse sand lenses and coarse ammonoid-, fusulinid-, and conodont-rich limestone beds. Horizons containing pebble and small cobble-size limestone concretions also yield conodonts. Ash beds and other rock types containing radiometrically dateable igneous materials are rare. However, time-equivalent strata exposed along the Usolka River in southern Russia contain conodont-bearing strata

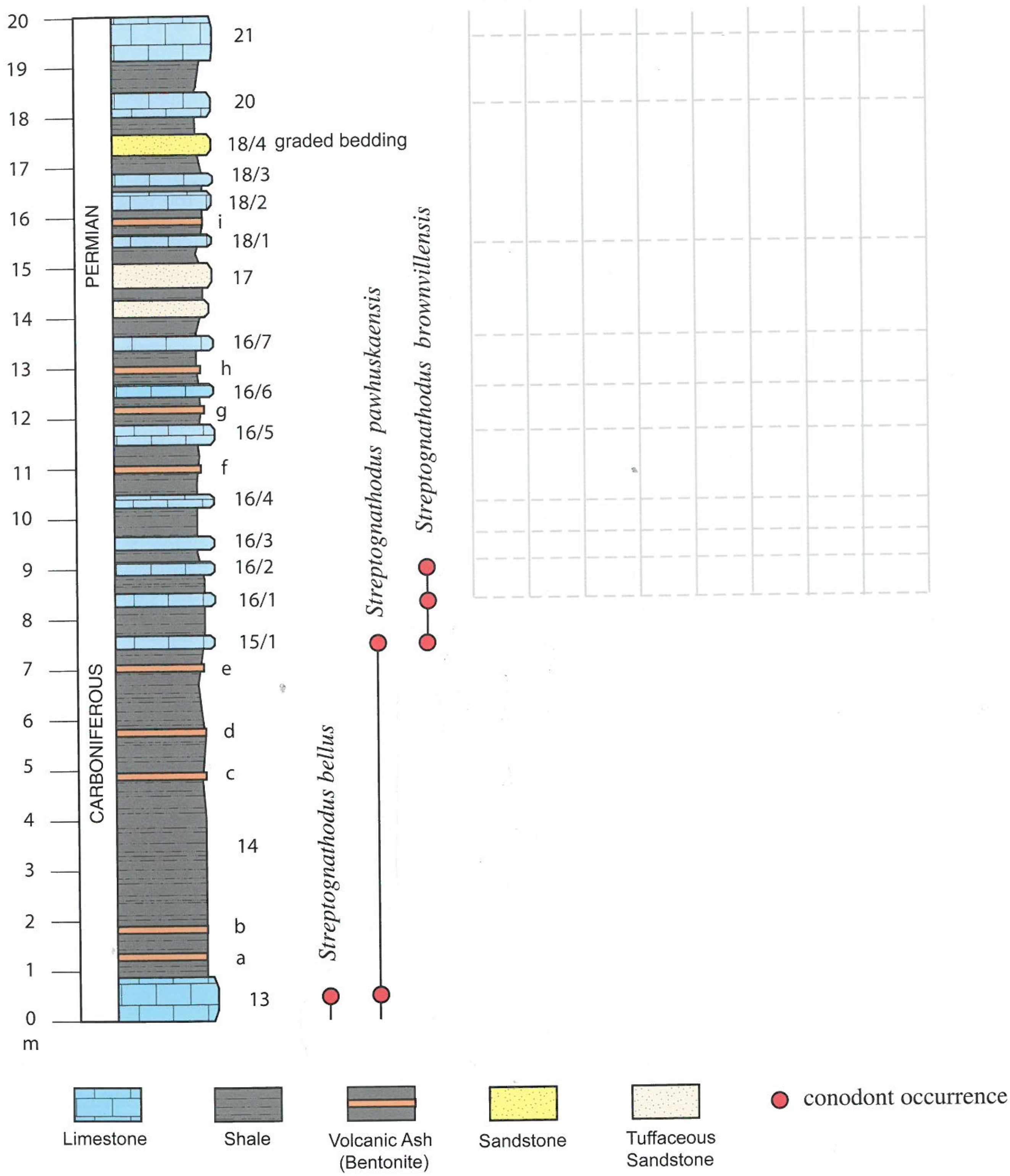



**FIGURE 2.3** Stratigraphy of Carboniferous–Permian boundary strata at the Usolka River section, Russia.

interbedded with volcanic ash layers called bentonites and ash-rich sandstone beds. Laminated green and black shales are the most common rock type at Usolka. The rain of siliciclastic silt and clay was interrupted from time to time by deposition of distal carbonate turbidites (thin limestone beds), sandy turbidites (graded quartz sandstone), and slurries of ash and quartz sand (tuffaceous sandstone). Volcanic ash falls derived from tectonic uplift of the Ural Mountains accumulated as bentonites in this quiet-water setting. Although the deep-water setting was hostile to most forms of life, conodont elements are very abundant in the fine-grained limestones and in selected bentonite beds. These were transported into the basin by turbidity currents or swept from the water column by toxic ash falls.

## Radiometric Ages on the Web

The **International Commission on Stratigraphy (ICS)** (www.stratigraphy.org) is the largest scientific body within the International Union of Geological Sciences (IUGS). One of its major objectives is the establishment of a standard, globally applicable stratigraphic scale, which it seeks to achieve through the coordinated contributions of a network of Subcommissions and Working Groups. The following information concerning the Carboniferous–Permian boundary was modified from the information provided in the section entitled "Chart/Time Scale" on their official website. This location contains information regarding the current definitions of all system and stage boundaries.

## Conodont Data

1. The list below shows the occurrences of key conodont species in the Usolka River section. Using this data, plot the ranges of all conodont species on figure 2.3. Ranges of *S. bellus*, *S. pawhuskaensis*, and *S. brownvillensis* have already been done by way of example.

| | |
|---|---|
| Sample 13 | *S. bellus, S. pawhuskaensis* |
| Sample 15/1 | *S. pawhuskaensis, S. brownvillensis* |
| Sample 16/1 | *S. brownvillensis, S. simplex* |
| Sample 16/2 | *S. brownvillensis* |
| Sample 16/3 | *S. simplex, S. wabaunsensis* |
| Sample 16/4 | *S. wabaunsensis* |
| Sample 16/5 | *S. wabaunsensis, S. isolatus* |
| Sample 16/6 | *S. wabaunsensis, S. isolatus, S. cristellaris, S. longissimus* |
| Sample 16/7 | *S. cristellaris* |
| Sample 18/1 | *S. longissimus, S. constrictus* |
| Sample 20 | *S. longissimus, S. barskovi* |
| Sample 21 | *S. constrictus, S. barskovi* |

FIGURE 2.4 **Outcrop view of the Usolka River section, Russia.**

## Radiogenic Isotope Data

The Carboniferous–Permian boundary beds at Usolka contain nine bentonite beds (labeled "a" through "i"), two tuffaceous sandstone beds, and a graded quartz sandstone bed (figure 2.3). Each of these beds yields zircon crystals (figure 2.5) that contain small amounts of uranium-238 (parent) and lead-206 (daughter). Table 2.2 shows the ratio of Pb-206/U-238 in zircon crystals from ash beds e, f, g, and i and from a graded sandstone bed labeled 18/4.

2. Using the isotopic data listed in table 2.2, calculate the average Pb-206/U-238 values for each sample using data from bed 18/4 as an example. Record your answers in the row labeled "sample average" for each column in table 2.2. Use the average Pb-206/U-238 values to approximate the age of each ash bed using figure 2.6.

3. Do the radiometric ages make sense stratigraphically? Are superpositionally younger strata also radiometrically younger? If not, which date(s) seem(s) to be wrong and why?

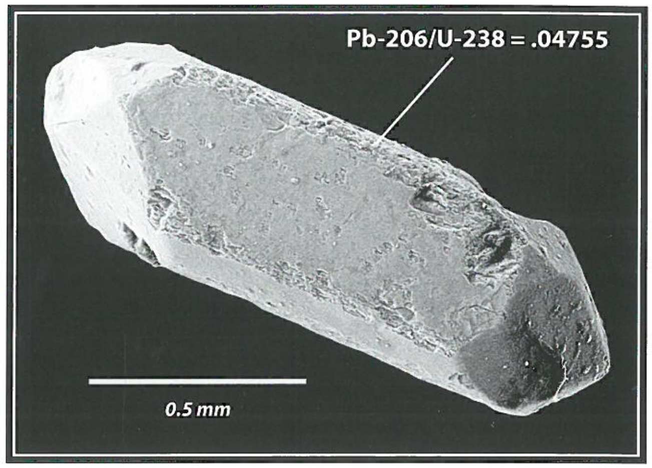



FIGURE 2.5 **Scanning electron microscope image of a zircon crystal.**

4. Use the relationships shown in figure 2.3 along with the conodont and isotopic data provided to calculate the age of the Carboniferous–Permian boundary. Suggest an absolute age for the boundary between the Carboniferous and Permian Systems.

_____________ million years.

Compare your estimate with the date shown on figure 1.1.

| | Bentonite "e" | Bentonite "f" | Bentonite "g" | Bentonite "i" | Bed 18/4 |
|---|---|---|---|---|---|
| | 0.04762 | 0.04753 | 0.04729 | 0.04717 | 0.1712 |
| | 0.04758 | 0.04747 | 0.04726 | 0.04720 | 0.1731 |
| | 0.04767 | 0.04763 | 0.04735 | 0.04723 | 0.1698 |
| | 0.04753 | 0.04738 | 0.04732 | 0.04712 | |
| | 0.04745 | 0.04745 | 0.04724 | 0.04718 | |
| | 0.04772 | 0.04754 | 0.04728 | 0.04719 | |
| | | 0.04751 | 0.04737 | 0.04714 | |
| | | 0.04741 | | | |
| | | 0.04759 | | | |
| Sample average | | | | | 0.1714 |

TABLE 2.2 **Lead-206/uranium-238 ratios of individual zircon crystals from Usolka River samples.**

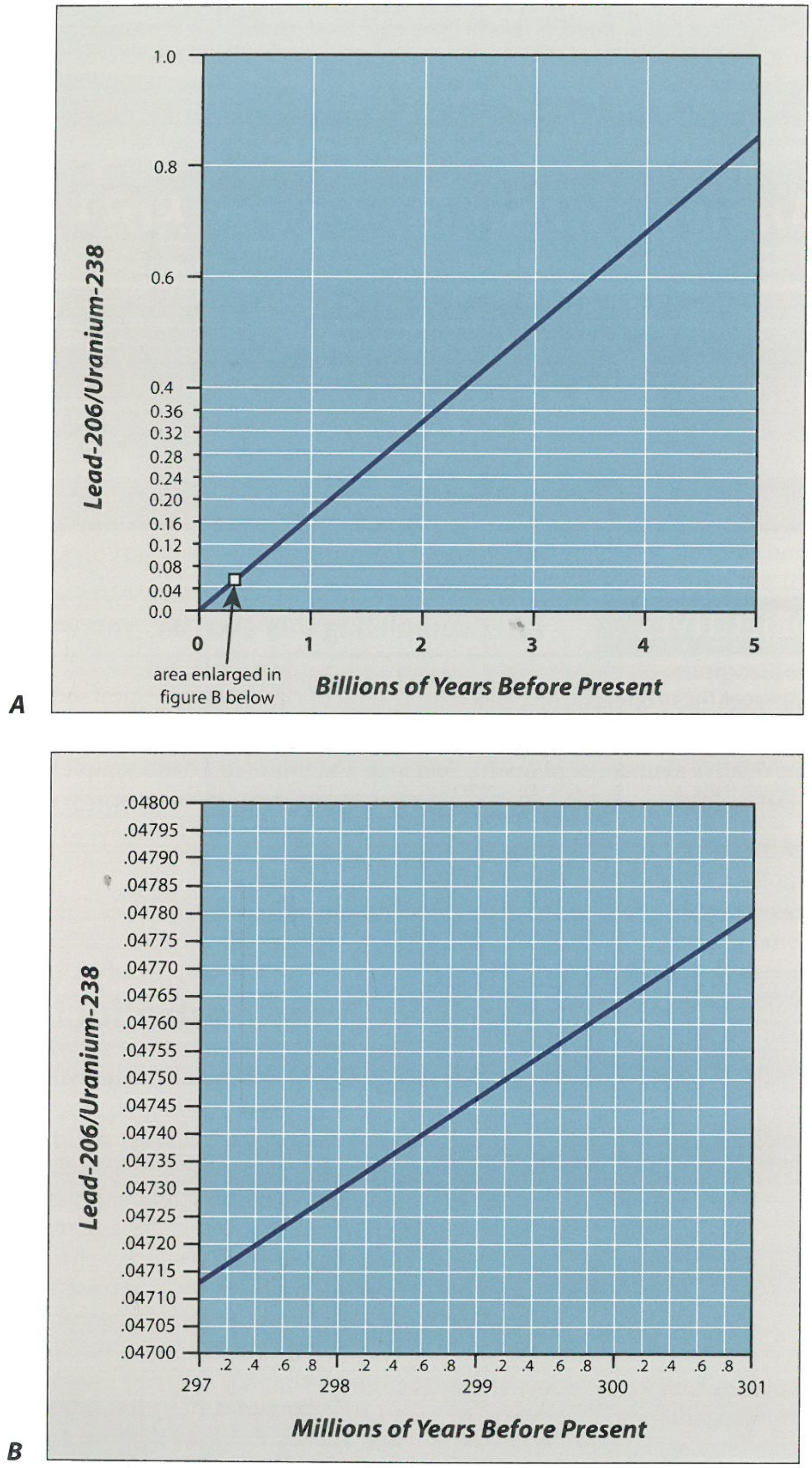



**FIGURE 2.6** **Graphs showing lead-206/uranium-238 ratio relationship to age of sample.**